
**Fine ceramics (advanced ceramics,
advanced technical ceramics) —
Weibull statistics for strength data**

*Céramiques techniques — Analyse statistique de Weibull des données
de résistance à la rupture*

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 206, *Fine ceramics*.

This second edition cancels and replaces the first edition (ISO 20501:2003), which has been technically revised. It also incorporates the Technical Corrigendum ISO 20501:2003/Cor.1:2009.

The main changes compared to the previous edition are as follows:

- the terms and definitions in [Clause 3](#) have been updated and modified;
- a method to treat a higher number of specimens ($N > 120$) has been introduced for method A: maximum likelihood parameter estimators for single flaw populations;
- in [Annex D](#), example codes have been added for calculating the maximum likelihood parameters of the Weibull distribution with modern analysis software.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Measurements of the strength at failure are taken for one of two reasons: either for a comparison of the relative quality of two materials regarding fracture strength, or the prediction of the probability of failure for a structure of interest. This document permits estimates of the distribution parameters which are needed for either. In addition, this document encourages the integration of mechanical property data and fractographic analysis.

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Fine ceramics (advanced ceramics, advanced technical ceramics) — Weibull statistics for strength data

1 Scope

This document covers the reporting of uniaxial strength data and the estimation of probability distribution parameters for advanced ceramics which fail in a brittle fashion. The failure strength of advanced ceramics is treated as a continuous random variable. Typically, a number of test specimens with well-defined geometry are brought to failure under well-defined isothermal loading conditions. The load at which each specimen fails is recorded. The resulting failure stresses are used to obtain parameter estimates associated with the underlying population distribution.

This document is restricted to the assumption that the distribution underlying the failure strengths is the two-parameter Weibull distribution with size scaling. Furthermore, this document is restricted to test specimens (tensile, flexural, pressurized ring, etc.) that are primarily subjected to uniaxial stress states. [Subclauses 6.4](#) and [6.5](#) outline methods of correcting for bias errors in the estimated Weibull parameters, and to calculate confidence bounds on those estimates from data sets where all failures originate from a single flaw population (i.e. a single failure mode). In samples where failures originate from multiple independent flaw populations (e.g. competing failure modes), the methods outlined in [6.4](#) and [6.5](#) for bias correction and confidence bounds are not applicable.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

NOTE See also Reference [1].

3.1 Defect populations

3.1.1 flaw

inhomogeneity, discontinuity or (defect) feature in a material, which acts as stress concentrator due to a mechanical load and has therefore a certain risk of mechanical failure

Note 1 to entry: The flaw becomes critical if it acts as fracture origin in a failed specimen.

3.1.2

censored data

strength measurements (i.e. a sample) containing suspended observations such as that produced by multiple competing or concurrent flaw populations

Note 1 to entry: Consider a sample where fractography clearly established the existence of three concurrent flaw distributions (although this discussion is applicable to a sample with any number of concurrent flaw distributions). The three concurrent flaw distributions are referred to here as distributions A, B, and C. Based on fractographic analyses, each specimen strength is assigned to a flaw distribution that initiated failure. In estimating parameters that characterize the strength distribution associated with flaw distribution A, all specimens (and not just those that failed from type-A flaws) shall be incorporated in the analysis to ensure efficiency and accuracy of the resulting parameter estimates. The strength of a specimen that failed by a type-B (or type-C) flaw is treated as a *right censored* observation relative to the A flaw distribution. Failure due to a type-B (or type-C) flaw restricts, or censors, the information concerning type-A flaws in a specimen by suspending the test before failure occurs by a type-A flaw^[2]. The strength from the most severe type-A flaw in those specimens that failed from type-B (or type-C) flaws is higher than (and thus to the *right* of) the observed strength. However, no information is provided regarding the magnitude of that difference. Censored data analysis techniques incorporated in this document utilize this incomplete information to provide efficient and relatively unbiased estimates of the distribution parameters.

3.1.3

competing failure modes

distinguishably different types of fracture initiation events that result from concurrent (competing) flaw distributions

3.1.4

compound flaw distribution

any form of multiple flaw distribution that is neither pure concurrent, nor pure exclusive

Note 1 to entry: A simple example is where every specimen contains the flaw distribution A, while some fraction of the specimens also contains a second independent flaw distribution B.

3.1.5

concurrent flaw distribution

competing flaw distribution

type of multiple flaw distribution in a homogeneous material where every specimen of that material contains representative flaws from each independent flaw population

Note 1 to entry: Within a given specimen, all flaw populations are then present concurrently and are competing to each other to cause failure.

3.1.6

exclusive flaw distribution

mixture flaw distribution

type of multiple flaw distribution created by mixing and randomizing specimens from two or more versions of a material where each version contains a different single flaw population

Note 1 to entry: Thus, each specimen contains flaws exclusively from a single distribution, but the total data set reflects more than one type of strength-controlling flaw.

3.1.7

extraneous flaw

strength-controlling flaw observed in some fraction of test specimens that cannot be present in the component being designed

Note 1 to entry: An example is machining flaws in ground bend specimens that will not be present in as-sintered components of the same material.

3.2 Mechanical testing

3.2.1

effective gauge section

that portion of the test specimen geometry included within the limits of integration (volume, area or edge length) of the Weibull distribution function

Note 1 to entry: In tensile specimens, the integration may be restricted to the uniformly stressed central gauge section, or it may be extended to include transition and shank regions.

3.2.2

fractography

analysis and characterization of patterns generated on the fracture surface of a test specimen

Note 1 to entry: Fractography can be used to determine the nature and location of the critical fracture origin causing catastrophic failure in an advanced ceramic test specimen or component.

3.3 Statistical terms

3.3.1

confidence interval

interval within which one would expect to find the true population parameter

Note 1 to entry: Confidence intervals are functionally dependent on the type of estimator utilized and the sample size. The level of expectation is associated with a given confidence level. When confidence bounds are compared to the parameter estimate one can quantify the uncertainty associated with a point estimate of a population parameter.

3.3.2

confidence level

probability that the true population parameter falls within a specified confidence interval

3.3.3

estimator

function for calculating an estimate of a given quantity based on observed data

Note 1 to entry: The resulting value for a given sample may be an estimate of a distribution parameter (a point estimate) associated with the underlying population, e.g. the arithmetic average of a sample is an estimator of the distribution mean.

3.3.4

population

collection of data or items under consideration

3.3.5

probability density function

pdf

function $f(x)$ for the continuous random variable X if

$$f(x) \geq 0 \quad (1)$$

and

$$\int_{-\infty}^{\infty} f(x) dx = 1 \quad (2)$$

Note 1 to entry: The probability that the random variable X assumes a value between a and b is given by

$$Pr(a < X < b) = \int_a^b f(x) dx \quad (3)$$

3.3.6

cumulative distribution function

function $F(x)$ describing the probability that a continuous random variable X takes a value less than or equal to a number x

Note 1 to entry: Therefore, the cumulative distribution function (cdf) is related to the probability density function $f(x)$ by

$$F(x) = Pr(-\infty < X < x) = \int_{-\infty}^x f(x') dx' \tag{4}$$

Differentiating [Formula \(4\)](#) with respect to x shows that the pdf is simple the derivative of the cdf:

$$f(x) = \frac{dF(x)}{dx} \tag{5}$$

Note 2 to entry: According to [3.3.5](#), $F(x)$ is a monotonically increasing function in the range between 0 and 1.

3.3.7

ranking estimator

function that estimates the probability of failure to a particular strength measurement within a ranked sample

3.3.8

sample

collection of measurements or observations taken from a specified population

3.3.9

statistical bias

type of consistent numerical offset in an estimate relative to the true underlying value, inherent to most estimates

3.3.10

unbiased estimator

estimator that has been corrected for statistical bias error

3.4 Weibull distributions

3.4.1

Weibull distribution

continuous distribution function which can be used to describe empirical data from measurements where continuous random variable x has a two-parameter Weibull distribution if the probability density function is given by

$$f(x) = \left(\frac{m}{\beta}\right) \left(\frac{x}{\beta}\right)^{m-1} \exp\left[-\left(\frac{x}{\beta}\right)^m\right] \text{ when } x \geq 0 \tag{6}$$

or

$$f(x) = 0 \text{ when } x < 0 \tag{7}$$

and the cumulative distribution function is given by

$$F(x) = 1 - \exp\left[-\left(\frac{x}{\beta}\right)^m\right] \text{ when } x \geq 0 \tag{8}$$

or

$$F(x) = 0 \text{ when } x < 0 \quad (9)$$

where

m is the Weibull modulus (or the shape parameter) (>0);

β is the Weibull scale parameter (>0).

Note 1 to entry: The random variable representing uniaxial tensile strength of an advanced ceramic will assume only positive values. If the random variable representing uniaxial tensile strength of an advanced ceramic is characterized by [Formulae \(6\) to \(9\)](#), then the probability that this advanced ceramic will fail under an applied uniaxial tensile stress σ is given by the cumulative distribution function.

$$P_f = 1 - \exp \left[- \left(\frac{\sigma}{\sigma_\theta} \right)^m \right] \text{ when } \sigma \geq 0 \quad (10)$$

$$P_f = 0 \text{ when } \sigma < 0 \quad (11)$$

where

P_f is the probability of failure;

σ_θ is the Weibull characteristic strength.

Note 2 to entry: The Weibull characteristic strength is dependent on the uniaxial test specimen (tensile, flexural, or pressurized ring) and will change with specimen geometry. In addition, the Weibull characteristic strength has units of stress, and has to be reported using SI-units of Pa, or adequately in MPa or GPa.

Note 3 to entry: An alternative expression for the probability of failure is given by

$$P_f = 1 - \exp \left[- \frac{1}{V_0} \int_V \left(\frac{\sigma}{\sigma_0} \right)^m dV \right] \text{ when } \sigma > 0 \quad (12)$$

$$P_f = 0 \text{ when } \sigma \leq 0 \quad (13)$$

The integration in the exponential is performed over all tensile regions of the specimen volume (V) if the strength-controlling flaws are randomly distributed through the volume of the material, or over all tensile regions of the specimen area if flaws are restricted to the specimen surface. The integration is sometimes carried out over an effective gauge section instead of over the total volume or area. In [Formula \(12\)](#), σ_0 is the Weibull material scale parameter and can be described as the Weibull characteristic strength of a specimen with unit volume or area loaded in uniform uniaxial tension. For a given specimen geometry, [Formulae \(10\) and \(12\)](#) can be combined, to yield an expression relating σ_0 and σ_θ (this means: $\sigma_\theta V_0^{1/m} = \sigma_0$). Further discussion related to this issue can be found in [Annex A](#).

4 Symbols

A	specimen area
b	gauge section dimension, base of bend test specimen
d	gauge section dimension, depth of bend test specimen
$f(x)$	probability density function

$F(x)$	cumulative distribution function
L	likelihood function
L_i	length of the inner load span for a bend test specimen
L_o	length of the outer load span for a bend test specimen
m	Weibull modulus
\hat{m}	estimate of the Weibull modulus
\hat{m}_U	unbiased estimate of the Weibull modulus
N	number of specimens in a sample
P_f	probability of failure
q	intermediate quantity defined in 6.5.1 , used in calculation of confidence bounds
r	number of specimens that failed from the flaw population for which the Weibull estimators are being calculated
t	intermediate quantity defined by Formula (22) , used in calculation of confidence bounds
UF	unbiasing factor
V	tensile loaded region of specimen volume
V_0	unit size volume
V_{eff}	effective volume
x	realization of a random variable X
X	random variable
β	Weibull scale parameter
σ	uniaxial tensile stress
$\hat{\sigma}$	estimate of mean strength
σ_j	maximum stress in the j th test specimen at failure
σ_0	Weibull material scale parameter (strength relative to unit size) defined in Formula (12)
$\hat{\sigma}_0$	estimate of the Weibull material scale parameter
σ_θ	Weibull characteristic strength (associated with a test specimen) defined in Formula (10)
$\hat{\sigma}_\theta$	estimate of the Weibull characteristic strength

5 Significance and use

5.1 This document enables the experimentalist to estimate Weibull distribution parameters from failure data. These parameters permit a description of the statistical nature of fracture of fine ceramic materials for a variety of purposes, particularly as a measure of reliability as it relates to strength data

utilized for mechanical design purposes. The observed strength values are dependent on specimen size and geometry. Parameter estimates can be computed for a given specimen geometry ($\hat{m}, \hat{\sigma}_\theta$) but it is suggested that the parameter estimates be transformed and reported as material-specific parameters ($\hat{m}, \hat{\sigma}_0$). In addition, different flaw distributions (e.g. failures due to inclusions or machining damage) may be observed, and each will have its own strength distribution parameters. The procedure for transforming parameter estimates for typical specimen geometries and flaw distributions is outlined in [Annex A](#).

5.2 This document provides two approaches, method A and method B, which are appropriate for different purposes.

Method A provides a simple analysis for circumstances in which the nature of strength-defining flaws is either known or assumed to be from a single population. Fractography to identify and group test items with given flaw types is thus not required. This method is suitable for use for simple material screening.

Method B provides an analysis for the general case in which competing flaw populations exist. This method is appropriate for final component design and analysis. The method requires that fractography be undertaken to identify the nature of strength-limiting flaws and assign failure data to given flaw population types.

5.3 In method A, a strength data set can be analysed and values of the Weibull modulus and characteristic strength ($\hat{m}, \hat{\sigma}_\theta$) are produced, together with confidence bounds on these parameters. If necessary, the estimate of the mean strength can be computed. Finally, a graphical representation of the failure data along with a test report can be prepared. It should be noted that the confidence bounds are frequently widely spaced, which indicates that the results of the analysis should not be used to extrapolate far beyond the existing bounds of probability of failure. A necessary assumption for a valid extrapolation (with respect to the tested effective volume V_{eff} and/or small probabilities of failure) is that the flaw populations in all considered strength test pieces are of the same type.

5.4 In method B, begin by performing a fractographic examination of each failed specimen in order to characterize fracture origins. Screen the data associated with each flaw distribution for outliers. If all failures originate from a single flaw distribution compute an unbiased estimate of the Weibull modulus, and compute confidence bounds for both the estimated Weibull modulus and the estimated Weibull characteristic strength. If the failures originate from more than one flaw type, separate the data sets associated with each flaw type, and subject these individually to the censored analysis. Finally, prepare a graphical representation of the failure data along with a test report. When using the results of the analysis for design purposes it should be noted that there is an implicit assumption that the flaw populations in the strength test pieces and the components are of the same types.

6 Method A: maximum likelihood parameter estimators for single flaw populations

6.1 General

This document outlines the application of parameter estimation methods based on the maximum likelihood technique (see also References [13], [14], [20] and [21]). This technique has certain advantages. The parameter estimates obtained using the maximum likelihood technique are unique (for a two-parameter Weibull distribution), and as the size of the sample increases, the estimates statistically approach the true values of the population more efficiently than other parameter estimation techniques.

6.2 Censored data

The application of the techniques presented in this document can be complicated by the presence of test specimens that fail from extraneous flaws, fractures that originate outside the effective gauge section, and unidentified fracture origins. If these complications arise, the strength data from these specimens should generally not be discarded. Strength data from specimens with fracture origins outside the effective gauge section [3] and from specimens with fractures that originate from extraneous flaws should be censored, and the maximum likelihood methods presented in method B (Clause 7) are applicable. It is imperative that the number of unidentified fracture origins, and how they were classified, be stated in the test report. A discussion of the appropriateness of each option can be found in 7.2.2.

Applying the censored analysis implies that it is assumed that the flaw populations are concurrent. This is a choice, which should be indicated in the test report.

6.3 Likelihood functions

The likelihood function for the two-parameter Weibull distribution of a sample with a single flaw population [4] is defined by Formula (14):

$$L = \prod_{i=1}^N \left(\frac{\hat{m}}{\hat{\sigma}_\theta} \right) \left(\frac{\sigma_i}{\hat{\sigma}_\theta} \right)^{\hat{m}-1} \exp \left[- \left(\frac{\sigma_i}{\hat{\sigma}_\theta} \right)^{\hat{m}} \right] \quad (14)$$

NOTE σ_i is the maximum stress in the i th test specimen at failure and N is the number of test specimens in the sample being analysed. The parameter estimates (the Weibull modulus, \hat{m} and the characteristic strength, $\hat{\sigma}_\theta$) are determined by taking the partial derivatives of the logarithm of the likelihood function with respect to \hat{m} and $\hat{\sigma}_\theta$ and equating the resulting expressions to zero.

The system of formulae obtained by differentiating the log likelihood function for a sample with a single flaw population [5] is given by

$$\frac{\sum_{i=1}^N (\sigma_i)^{\hat{m}} \ln(\sigma_i)}{\sum_{i=1}^N (\sigma_i)^{\hat{m}}} - \frac{1}{N} \sum_{i=1}^N \ln(\sigma_i) - \frac{1}{\hat{m}} = 0 \quad (15)$$

and

$$\hat{\sigma}_\theta = \left[\frac{\sum_{i=1}^N (\sigma_i)^{\hat{m}}}{N} \right]^{\frac{1}{\hat{m}}} \quad (16)$$

Formula (15) is solved first for \hat{m} . Subsequently $\hat{\sigma}_\theta$ is computed from Formula (16). Obtaining a closed form solution of Formula (15) for \hat{m} is not possible. This expression shall be solved numerically.

Since the characteristic strength also reflects specimen geometry and stress gradients, this document suggests reporting the estimated Weibull material scale parameter, $\hat{\sigma}_\theta$. Expressions that relate $\hat{\sigma}_\theta$ to the Weibull material scale parameter σ_0 for typical specimen geometries are given in Annex A.

6.4 Bias correction

6.4.1 The procedures described herein, to correct for statistical bias errors and to compute confidence bounds, are appropriate only for data sets where all failures originate from a single population (i.e. an uncensored sample). Procedures for bias correction and confidence bounds in the presence of multiple active flaw populations are not well developed. It is well-known that the maximum likelihood estimators

with respect to the two-parametric Weibull distribution are biased, but consistent (i.e. the shift of expectation values of the estimated Weibull parameters goes to zero with increasing sample size). The statistical bias associated with the estimator $\hat{\sigma}_\theta$ is minimal (<0,3 % for 20 test specimens, as opposed to ≈ 7 % bias for \hat{m} with the same number of specimens). Therefore, this document allows the assumption that $\hat{\sigma}_\theta$ is an unbiased estimator of the true population parameter. The parameter estimate of the Weibull modulus, \hat{m} , generally exhibits statistical bias. The amount of statistical bias depends on the number of specimens in the sample. An unbiased estimate of \hat{m} shall be obtained by multiplying \hat{m} by unbiasing factors^[6]. This procedure is discussed in 6.4.2. Statistical bias associated with the maximum likelihood estimators presented in this document can be reduced by increasing the sample size.

6.4.2 An unbiased estimator produces nearly zero statistical bias between the value of the true parameter and the point estimate. The amount of deviation can be quantified either as a percent difference or with unbiasing factors. In keeping with the accepted practice in the open literature, this document quantifies statistical bias through the use of unbiasing factors, denoted here as UF. Depending on the number of specimens in a given sample, the point estimate of the Weibull modulus, \hat{m} , may exhibit significant statistical bias. An unbiased estimate of the Weibull modulus (denoted as \hat{m}_U) is obtained by multiplying the biased estimate with an appropriate unbiasing factor:

$$\hat{m}_U = \hat{m} \times UF \tag{17}$$

Unbiasing factors for \hat{m} are listed in [Table 1](#). Alternatively, the table values can be approximated by a simple analytical function f_{UF} defined by

$$f_{UF}(N) = 1 - 1,61394 \times N^{-1,04033} \tag{18}$$

This function interpolates the tabulated values in [Table 1](#) with errors smaller than 1 %, but it is also applicable to sample sizes $N > 120$ ^[17].

An example in [Annex B](#) demonstrates both the use of [Table 1](#) and of [Formula \(18\)](#) in correcting a biased estimate of the Weibull modulus.

Table 1 — Unbiasing factor for the maximum likelihood estimate of the Weibull modulus

Number of specimens, <i>N</i>	Unbiasing factor, <i>UF</i>	Number of specimens, <i>N</i>	Unbiasing factor, <i>UF</i>
5	0,700	42	0,968
6	0,752	44	0,970
7	0,792	46	0,971
8	0,820	48	0,972
9	0,842	50	0,973
10	0,859	52	0,974
11	0,872	54	0,975
12	0,883	56	0,976
13	0,893	58	0,977
14	0,901	60	0,978
15	0,908	62	0,979
16	0,914	64	0,980
18	0,923	66	0,980
20	0,931	68	0,981
22	0,938	70	0,981

Table 1 (continued)

Number of specimens, N	Unbiasing factor, UF	Number of specimens, N	Unbiasing factor, UF
24	0,943	72	0,982
26	0,947	74	0,982
28	0,951	76	0,983
30	0,955	78	0,983
32	0,958	80	0,984
34	0,960	85	0,985
36	0,962	90	0,986
38	0,964	100	0,987
40	0,966	120	0,990

6.5 Confidence intervals

6.5.1 Confidence bounds quantify the uncertainty associated with a point estimate of a population parameter. The size of the confidence bounds for maximum likelihood estimates of both Weibull parameters will diminish with increasing sample size. The values used to construct confidence bounds are based on percentile distributions obtained by Monte Carlo simulation; e.g. the 90 % confidence bound on the Weibull modulus is obtained from the 5 and 95 percentile distributions of the ratio of \hat{m} to the true population value m . For a point estimate of the Weibull modulus, the normalized values $q = (\hat{m}/m)$ necessary to construct the 90 % confidence bounds are listed in [Table 2](#). Consequently, the upper and lower confidence bounds for m are given by

$$\hat{m}_{upper} = \hat{m} / q_{0,05} \tag{19}$$

and

$$\hat{m}_{lower} = \hat{m} / q_{0,95} \tag{20}$$

respectively.

The example in [Annex B](#) demonstrates the use of [Table 2](#) in constructing the upper and lower bounds. Note that the statistically biased estimate of the Weibull modulus shall be used here. Again, this procedure is not appropriate for censored statistics.

A convenient way to calculate confidence bounds is the usage of an interpolating function of the form

$$q_p(N) = 1 + \frac{a_{1/2}}{\sqrt{N}} + \frac{a_1}{N} + \frac{a_{3/2}}{\sqrt{N^3}} + \frac{a_2}{N^2} + \frac{a_{5/2}}{\sqrt{N^5}} + \frac{a_3}{N^3} \tag{21}$$

which can also be used for larger samples with $N > 120$. The corresponding coefficients for a_i are given in [Table 3](#). [Formula \(21\)](#) is asymptotically correct for large N and the deviation with respect to the tabulated values in [Table 2](#) is smaller than 0,5 %^[17]. Additionally, the coefficients for calculation of the confidence bounds with respect to 95 % confidence level are listed in [Table 4](#).

6.5.2 Confidence bounds can be constructed for the estimated Weibull characteristic strength. However, the percentile distributions needed to construct the bounds do not involve the same normalized ratios or the same tables as those used for the Weibull modulus. Define the function:

$$t = \hat{m} \ln \left(\frac{\hat{\sigma}_\theta}{\sigma_\theta} \right) \tag{22}$$

The 90 % confidence bound on the characteristic strength is obtained from the 5 and 95 percentile distributions of t , so that the upper and lower confidence bounds are given by:

$$\left(\hat{\sigma}_\theta \right)_{\text{upper}} = \left(\hat{\sigma}_\theta \right) \exp \left(-t_{0,05} / \hat{m} \right) \tag{23}$$

$$\left(\hat{\sigma}_\theta \right)_{\text{lower}} = \left(\hat{\sigma}_\theta \right) \exp \left(-t_{0,95} / \hat{m} \right) \tag{24}$$

For the point estimate of the characteristic strength, these percentile distributions are listed in [Table 5](#). Again an interpolating function for t_p is defined by

$$t_p(N) = \frac{b_{1/2}}{\sqrt{N}} + \frac{b_1}{N} + \frac{b_{3/2}}{\sqrt{N^3}} + \frac{b_2}{N^2} + \frac{b_{5/2}}{\sqrt{N^5}} + \frac{b_3}{N^3} \tag{25}$$

which allows an analytic and accurate calculation of the confidence bounds. In [Table 6](#) and [Table 7](#) the corresponding coefficients b_i are listed with respect to 90 % and 95 % confidence level respectively.

An example in [Annex B](#) demonstrates the use of [Table 5](#) in constructing upper and lower bounds on $\hat{\sigma}_\theta$. Note that the biased estimate of the Weibull modulus (i.e. the result of the maximum likelihood procedure [see [Formula \(15\)](#)]) shall be used here. This procedure is not appropriate for censored statistics. [Formula \(22\)](#) is not applicable for developing confidence bounds on $\hat{\sigma}_\theta$ therefore the confidence bounds on $\hat{\sigma}_\theta$ should not be converted through the use of [Formulae \(10\)](#) and [\(12\)](#).

Table 2 — Normalized upper and lower bounds on the maximum likelihood estimate of the Weibull modulus — 90 % confidence interval

Number of specimens, N	$q_{0,05}$	$q_{0,95}$	Number of specimens, N	$q_{0,05}$	$q_{0,95}$
5	0,683	2,779	42	0,842	1,265
6	0,697	2,436	44	0,845	1,256
7	0,709	2,183	46	0,847	1,249
8	0,720	2,015	48	0,850	1,242
9	0,729	1,896	50	0,852	1,235
10	0,738	1,807	52	0,854	1,229
11	0,745	1,738	54	0,857	1,224
12	0,752	1,682	56	0,859	1,218
13	0,759	1,636	58	0,861	1,213
14	0,764	1,597	60	0,863	1,208
15	0,770	1,564	62	0,864	1,204
16	0,775	1,535	64	0,866	1,200
17	0,779	1,510	66	0,868	1,196
18	0,784	1,487	68	0,869	1,192
19	0,788	1,467	70	0,871	1,188
20	0,791	1,449	72	0,872	1,185
22	0,798	1,418	74	0,874	1,182

Table 2 (continued)

Number of specimens, N	$q_{0,05}$	$q_{0,95}$	Number of specimens, N	$q_{0,05}$	$q_{0,95}$
24	0,805	1,392	76	0,875	1,179
26	0,810	1,370	78	0,876	1,176
28	0,815	1,351	80	0,878	1,173
30	0,820	1,334	85	0,881	1,166
32	0,824	1,319	90	0,883	1,160
34	0,828	1,306	95	0,886	1,155
36	0,832	1,294	100	0,888	1,150
38	0,835	1,283	110	0,893	1,141
40	0,839	1,273	120	0,897	1,133

Table 3 — Coefficients according to Formula (16) for the normalized upper and lower bounds on the maximum likelihood estimate of the Weibull modulus — 90 % confidence interval

	$a_{1/2}$	a_1	$a_{3/2}$	a_2	$a_{5/2}$	a_3
$p = 0,05$	-1,280 61	2,088 03	-2,365 01	-1,941 65	13,623 8	-14,666 1
$p = 0,95$	1,283 79	2,136 0	3,451 5	8,520 81	-19,55 11	65,739 1

Table 4 — Coefficients according to Formula (16) for the normalized upper and lower bounds on the maximum likelihood estimate of the Weibull modulus — 95 % confidence interval

	$a_{1/2}$	a_1	$a_{3/2}$	a_2	$a_{5/2}$	a_3
$p = 0,025$	-1,523 97	2,531 61	-2,673 06	-4,644 68	22,357 7	-22,903 6
$p = 0,975$	1,521 37	2,993 89	-0,318 37	44,728 8	-123,859	202,815

Table 5 — Normalized upper and lower bounds on the function t — 90 % confidence interval

Number of specimens, N	$t_{0,05}$	$t_{0,95}$	Number of specimens, N	$t_{0,05}$	$t_{0,95}$
5	-1,247	1,107	42	-0,280	0,278
6	-1,007	0,939	44	-0,273	0,271
7	-0,874	0,829	46	-0,266	0,264
8	-0,784	0,751	48	-0,260	0,258
9	-0,717	0,691	50	-0,254	0,253
10	-0,665	0,644	52	-0,249	0,247
11	-0,622	0,605	54	-0,244	0,243
12	-0,587	0,572	56	-0,239	0,238
13	-0,557	0,544	58	-0,234	0,233
14	-0,532	0,520	60	-0,230	0,229
15	-0,509	0,499	62	-0,226	0,225
16	-0,489	0,480	64	-0,222	0,221
17	-0,471	0,463	66	-0,218	0,218
18	-0,455	0,447	68	-0,215	0,214
19	-0,441	0,433	70	-0,211	0,211
20	-0,428	0,421	72	-0,208	0,208
22	-0,404	0,398	74	-0,205	0,205
24	-0,384	0,379	76	-0,202	0,202

Table 5 (continued)

Number of specimens, N	$t_{0,05}$	$t_{0,95}$	Number of specimens, N	$t_{0,05}$	$t_{0,95}$
26	-0,367	0,362	78	-0,199	0,199
28	-0,352	0,347	80	-0,197	0,197
30	-0,338	0,334	85	-0,190	0,190
32	-0,326	0,323	90	-0,184	0,185
34	-0,315	0,312	95	-0,179	0,179
36	-0,305	0,302	100	-0,174	0,175
38	-0,296	0,293	110	-0,165	0,166
40	-0,288	0,285	120	-0,158	0,159

Table 6 — Coefficients according to [Formulae \(19\)](#) and [\(20\)](#) for the function t used to calculate the upper and lower bounds on the maximum likelihood estimate of the characteristic strength — 90 % confidence interval

	$b_{1/2}$	b_1	$b_{3/2}$	b_2	$b_{5/2}$	b_3
$p = 0,05$	-1,726 2	-0,187 398	0,059 163	-17,199 8	40,928 9	-59,972 8
$p = 0,95$	1,731 0	0,055 668	2,308 3	1,671 11	-4,038 37	13,695 1

Table 7 — Coefficients according to [Formulae \(19\)](#) and [\(20\)](#) for the function t used to calculate the upper and lower bounds on the maximum likelihood estimate of the characteristic strength — 95 % confidence interval

	$b_{1/2}$	b_1	$b_{3/2}$	b_2	$b_{5/2}$	b_3
$p = 0,025$	-2,059 32	-0,048 120 6	-1,388 13	-19,065 2	51,812 7	-93,808 2
$p = 0,975$	2,063 75	0,122 882	3,496 57	2,904 76	-10,659 3	30,435 5

7 Method B: maximum likelihood parameter estimators for competing flaw populations

7.1 General

This document outlines the application of parameter estimation methods based on the maximum likelihood technique. This technique has certain advantages, especially when parameters are to be determined from censored failure populations. When a sample of test specimens yields two or more distinct flaw distributions, the sample is said to contain censored data, and the associated methods for censored data shall be used. The methods described in this document include censoring techniques that apply to multiple concurrent flaw distributions. However, the techniques for parameter estimation presented in this document are not directly applicable to data sets that contain exclusive or compound multiple flaw distributions^[7].

The estimation techniques for censored data presented herein require positive confirmation of multiple flaw distributions, which necessitates fractographic examination in order to characterize the fracture origin in each specimen. Multiple flaw distributions may be further evidenced by deviation from the linearity of the data from a single Weibull distribution.

For data sets with multiple active flaw distributions where one flaw distribution (identified by fractographic analysis) occurs in a small number of specimens, it is sufficient to report the existence of this flaw distribution (and the number of occurrences), but it is not necessary to estimate Weibull parameters. Estimates of the Weibull parameters for this flaw distribution would be potentially biased with wide confidence bounds (neither of which could be quantified). However, special note should be made in the report if the occurrences of this flaw distribution take place in the upper or lower tail of the sample strength distribution.

7.2 Censored data

7.2.1 The application of the censoring techniques presented in this document can be complicated by the presence of test specimens that fail from extraneous flaws, fractures that originate outside the effective gauge section, and unidentified fracture origins. If these complications arise, the strength data from these specimens should generally not be discarded. Strength data from specimens with fracture origins outside the effective gauge section[3] as well as from specimens with fractures that originate from extraneous flaws should be censored[20][21], and the maximum likelihood methods presented in this document are applicable.

7.2.2 This document recognizes four options the experimentalist can pursue when unidentified fracture origins are encountered during fractographic examinations. Specimens with unidentified fracture origins can be:

- a) assigned a previously identified flaw distribution using inferences based on all available fractographic information;
- b) assigned the same flaw distribution as that of the specimen closest in strength;
- c) assigned a new and as yet unspecified flaw distribution;
- d) be removed from the sample.

7.2.3 It is imperative that the number of unidentified fracture origins, and how they were classified, be stated in the test report. A discussion of the appropriateness of each option appears in [Annex C](#). If the strength data and the resulting parameter estimates are used for component design, the engineer shall consult with the fractographer before and after performing the fractographic examination. Considerable judgement may be needed to identify the correct option. Whenever partial fractographic information is available option a) is strongly recommended, especially if the data are used for component design. Conversely, option d) is not recommended by this document unless there is overwhelming justification.

7.3 Likelihood functions

The likelihood function for the two-parameter Weibull distribution of a censored sample is defined by [Formula \(26\)](#):

$$L = \left\{ \prod_{i=1}^r \left(\frac{\hat{m}}{\hat{\sigma}_\theta} \right) \left(\frac{\sigma_i}{\hat{\sigma}_\theta} \right)^{\hat{m}-1} \exp \left[- \left(\frac{\sigma_i}{\hat{\sigma}_\theta} \right)^{\hat{m}} \right] \right\} \left\{ \prod_{j=r+1}^N \exp \left[- \left(\frac{\sigma_j}{\hat{\sigma}_\theta} \right)^{\hat{m}} \right] \right\} \quad (26)$$

This expression is applied to a sample where two or more active concurrent flaw distributions have been identified from fractographic inspection. For the purpose of the discussion here, the different distributions are identified as flaw types A, B, C, etc. When [Formula \(26\)](#) is used to estimate the parameters associated with the “A” flaw distribution, then r is the number of specimens where type-A flaws were found at the fracture origin, and i is the associated index in the first product. The second product is carried out for all other specimens not failing from type-A flaws (i.e. type-B flaws, type-C flaws, etc.). Therefore, the product is carried out from $(j = r + 1)$ to N (the total number of specimens) where j is the index in the second product. Accordingly, σ_i and σ_j are the maximum stress in the i^{th} and j^{th} test specimen at failure. The parameter estimates (the Weibull modulus, \hat{m} and the characteristic strength, $\hat{\sigma}_\theta$) are determined by taking the partial derivatives of the logarithm of the likelihood function with respect to \hat{m} and $\hat{\sigma}_\theta$ and equating the resulting expressions to zero. Note that $\hat{\sigma}_\theta$ is a function of specimen geometry and the estimate of the Weibull modulus \hat{m} . Expressions that relate $\hat{\sigma}_\theta$ to the Weibull material scale parameter σ_0 for typical specimen geometries are given in [Annex A](#).

The system of formulae obtained by differentiating the log likelihood function for a censored sample^[5] is given by:

$$\frac{\sum_{i=1}^N (\sigma_i)^{\hat{m}} \ln(\sigma_i)}{\sum_{i=1}^N (\sigma_i)^{\hat{m}}} - \frac{1}{r} \sum_{i=1}^r \ln(\sigma_i) - \frac{1}{\hat{m}} = 0 \quad (27)$$

and

$$\hat{\sigma}_\theta = \left[\left(\sum_{i=1}^N (\sigma_i)^{\hat{m}} \right) \frac{1}{r} \right]^{1/\hat{m}} \quad (28)$$

where r is the number of failed specimens from a particular group of a censored sample.

[Formula \(27\)](#) is solved first for \hat{m} . Subsequently $\hat{\sigma}_\theta$ is computed from [Formula \(28\)](#). Obtaining a closed form solution of [Formula \(27\)](#) for \hat{m} is not possible. This expression shall be solved numerically.

8 Procedure

8.1 Outlying observations

Before computing the parameter estimates, the data should be screened for outlying observations (outliers). An outlying observation is one that deviates significantly from other observations in the sample. It should be understood that an apparent outlying observation may be an extreme manifestation of the variability of the strength of an advanced ceramic. If this is the case, the data point should be retained and treated as any other observation in the failure 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 is clearly aware that a gross deviation from the prescribed experimental procedure has occurred, the outlying observation may be discarded, unless the observation can be corrected in a rational manner.

8.2 Fractography

8.2.1 Fractographic examination of each failed specimen is highly recommended in order to characterize the fracture origins. The strength of advanced ceramics is often limited by discrete fracture origins which may be intrinsic or extrinsic to the material. Porosity, agglomerates, inclusions, and atypical large grains are considered intrinsic fracture origins^[10]. Extrinsic fracture origins are typically on the surface of the specimen and are the result of contact stresses, impact events or adverse environment. When the means are available to the experimentalist, fractographic methods should be used to locate, identify, and classify the strength-limiting fracture origin causing catastrophic failure in an advanced ceramic test specimen. Moreover, for the purpose of parameter estimation, each classification of fracture origin shall be identified as a surface fracture origin or a volume fracture origin in order to use the expressions given in [Annex A](#). Thus, there may exist several classifications of fracture origins within the volume (or surface area) of the test specimens in a sample. It should be clearly indicated in the test report if a fractographic analysis is not performed.

8.2.2 Perform a fractographic analysis and label each datum with a symbol identifying the type of fracture origin. This may be a word, an abbreviation, or a different symbol for each type of fracture origin.

8.3 Graphical representation

8.3.1 An objective of this document is the consistent representation of strength data. To this end, the following procedure is the recommended graphical representation of strength data^[22]. Begin by ranking the strength data obtained from laboratory testing in ascending order, and assign to each a ranked probability of failure P_f according to the ranking estimator

$$P_f(\sigma_i) = \frac{i-0,5}{N} \tag{29}$$

or

$$P_f(\sigma_i) = \frac{i-0,3}{N+0,4} \tag{30}$$

where

N is the number of specimens;

i is the ranking number (ascending order).

NOTE [Formula \(30\)](#) is a well-accepted approximation of the medians of uniform order statistics.

Compute the natural logarithm of the i th failure stress, and the natural logarithm of the natural logarithm of $[1/(1 - P_f)]$ (i.e. the double logarithm of the quantity in square brackets), where P_f is associated with the i th failure stress.

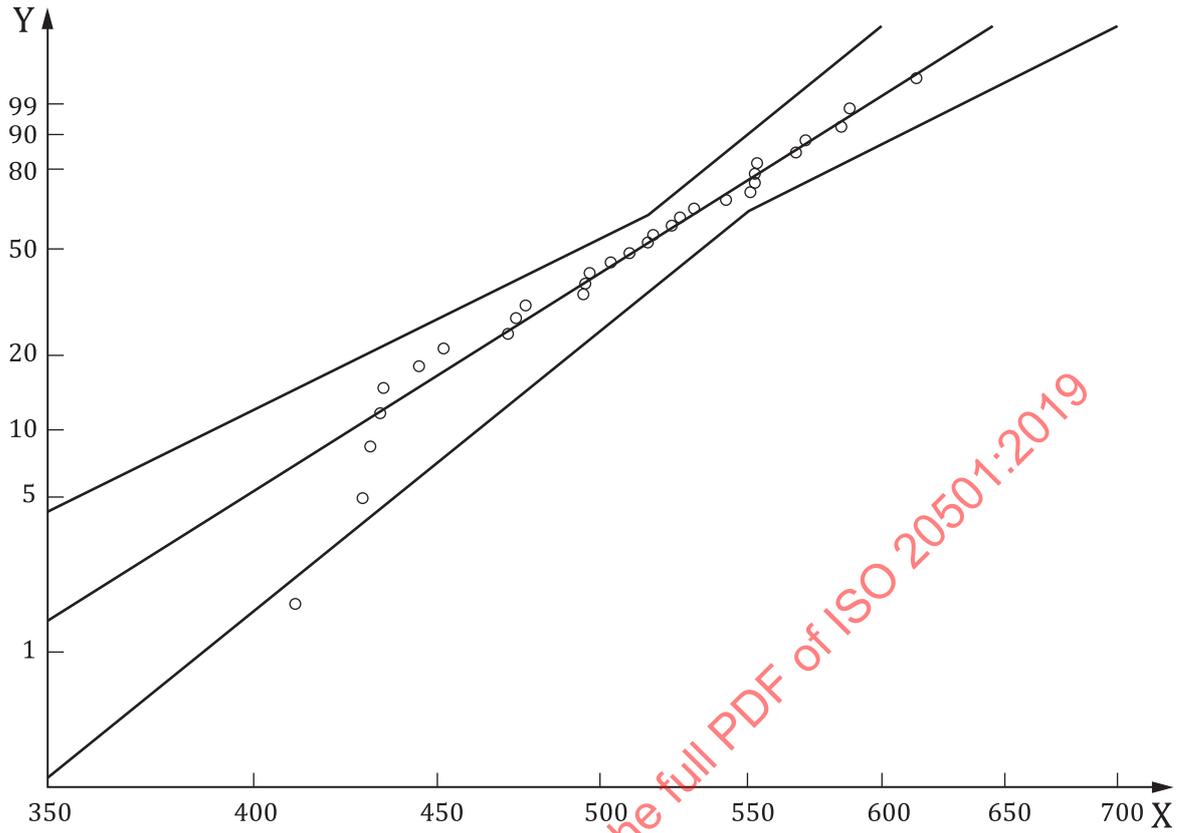
8.3.2 Create a graph representing the data as shown in [Figure 1](#). Plot $\ln\{\ln[1/(1 - P_f)]\}$ as the ordinate, and $\ln(\sigma)$ as the abscissa. A typical ordinate scale assumes values from +2 to -6. This approximately corresponds to a range in probability of failure from 0,25 % to 99,9 %. The ordinate axis shall be labelled as probability of failure P_f , as depicted in [Figure 1](#). Similarly, the abscissa shall be labelled as failure stress (flexural, tensile, etc.), preferably using units of MPa or GPa.

8.3.3 Included in the plot should be a line whose position is fixed by the estimates of the Weibull parameters. The line is defined by [Formula \(31\)](#):

$$P_f = 1 - \exp \left[- \left(\frac{\sigma}{\hat{\sigma}_\theta} \right)^{\hat{m}} \right] \tag{31}$$

The slope of the line, which is the estimate of the Weibull modulus \hat{m} , should be identified, as shown in [Figure 1](#). The estimate of the characteristic strength $\hat{\sigma}_\theta$ should also be identified. This corresponds to a P_f of 63,2 %, or a value of zero for $\ln\{\ln[1/(1 - P_f)]\}$.

8.3.4 This document does not provide a definitive criterion in order to judge the relative fit of the individual data points to a linear two-parameter Weibull curve estimated from the data. Theoretical bounds on the reliability curve are complex and outside the scope of this document. Confidence bounds on the estimate of the Weibull modulus and the Weibull characteristic strength can be used to construct confidence bands in a Weibull plot (see [Figure 1](#)). The bands to the left of the estimated two-parameter Weibull curve are constructed using the lower confidence bound on the Weibull characteristic strength and the upper confidence bound on the Weibull modulus for probability of failures above 63,2 %. Probability of failures below 63,2 % correspond to the lower confidence bound on the Weibull modulus. The bands to the right of the estimated two-parameter Weibull curve are constructed using the upper confidence bound on the Weibull characteristic strength along with the lower confidence bound on the Weibull modulus for probability of failures above 63,2 %. Probabilities of failure below 63,2 % correspond to the upper confidence bound on the Weibull modulus.



Failure stresses, MPa	
411	516
429	518
431	524
434	527
435	532
445	543
452	552
472	553
474	553
477	554
495	568
496	572
497	585
504	588
510	614

Key

X $\ln(\text{failure stress}), \text{MPa}$

Y $\ln(\ln 1/(1-P_f))$ with P_f , probability of failure, %

NOTE Estimated $m = 10,24; \sigma_\theta = 532 \text{ MPa}$.

Figure 1 — Weibull Plot

9 Test report

The test report shall contain the following information:

- a) type of material characterized;
- b) characterization of specimen: geometry, condition of surfaces (e.g. as-sintered, machined surfaces, chamfered edges, etc.)
- c) test procedure, preferably designating an appropriate standard;
- d) number of tested/failed specimens;
- e) flaw type;
- f) flaw populations: single, multiple, assumed concurrent flaw populations;
- g) maximum likelihood estimates of the Weibull parameters: \hat{m} , $\hat{\sigma}_\theta$;
- h) upper and lower confidence bounds with respect to 90 or 95 % confidence level for the Weibull parameters: $[\hat{m}_{\text{lower}}, \hat{m}_{\text{upper}}]$, $[(\hat{\sigma}_\theta)_{\text{lower}}, (\hat{\sigma}_\theta)_{\text{upper}}]$;
- i) unbiasing factor; unbiased Weibull modulus: UF , \hat{m}_U .

Insert a column on the graph (in any convenient location), or alternatively provide a separate table that identifies the individual strength values in ascending order. This will permit other users to perform alternative analyses. In addition, the experimentalist should include a separate sketch of the specimen geometry that includes all pertinent dimensions. An estimate of mean strength can also be depicted in the graph. The estimate of mean strength is calculated by using the arithmetic mean as the estimator:

$$\hat{\mu} = \left(\sum_{i=1}^N \sigma_i \right) \left(\frac{1}{N} \right) \quad (31)$$

NOTE This estimate of the mean strength is not appropriate for samples with multiple failure populations.

Annex A (informative)

Converting to material-specific strength distribution parameters

A.1 [Formula \(A.1\)](#) defines the relationship between the parameters for tensile specimens^[16]:

$$\left(\hat{\sigma}_0\right)_V = (V)^{1/(\hat{m})_V} \left(\hat{\sigma}_\theta\right)_V \quad (\text{A.1})$$

where V is the volume of the uniform gauge section of the tensile specimen, and the fracture origins are spatially distributed strictly within this volume.

The gauge section of a tensile specimen is defined herein as the central region of the test specimen with the smallest constant cross-sectional area. However, the experimentalist may include transition regions and the shank regions of the specimen if the volume (or area) integration defined by [Formula \(10\)](#) is analysed properly. This procedure is discussed in [A.3](#). For a tensile specimen in which fracture origins are spatially distributed strictly at the surface of the specimens tested,

$$\left(\hat{\sigma}_0\right)_A = (A)^{1/(\hat{m})_A} \left(\hat{\sigma}_\theta\right)_A \quad (\text{A.2})$$

where A is the surface area of the uniform gauge section.

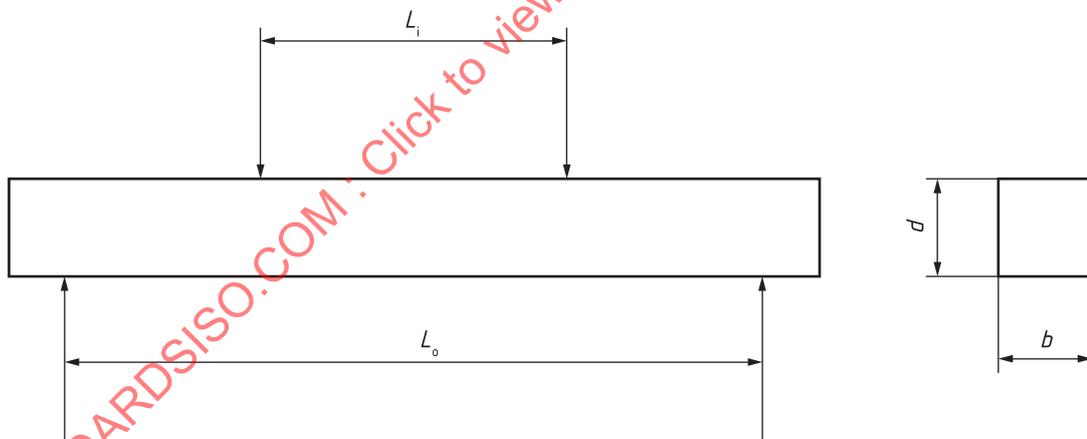


Figure A.1 — Typical bend specimen geometry

A.2 For flexural specimen geometries^[15], the relationships become more complex^{[8][18][19]}. The following relationship is based on the geometry of the flexural specimen shown in [Figure A.1](#). For fracture origins spatially distributed strictly within both the volume of a flexural specimen and the outer load span:

$$\left(\hat{\sigma}_0\right)_V = \left(\hat{\sigma}_\theta\right)_V \left\{ \frac{V \left[\left(\frac{L_i}{L_o} \right) (\hat{m})_V + 1 \right]}{2 \left[(\hat{m})_V + 1 \right]^2} \right\}^{\frac{1}{(\hat{m})_V}} \quad (\text{A.3})$$

where

V is the volume of the gauge section defined by the expression

$$V = bdL_o \tag{A.4}$$

(b and d are dimensions identified in [Figure A.1](#))

L_i is the length of the inner load span;

L_o is the length of the outer load span.

For fracture origins spatially distributed strictly at the surface of a flexural specimen and within the outer load span:

$$(\hat{\sigma}_0)_A = (\hat{\sigma}_\theta)_A \left\{ L_o \left[\frac{d}{\left[(\hat{m})_A + 1 \right]} + b \right] \left[\left(\frac{L_i}{L_o} \right) (\hat{m})_A + 1 \right] \left[\frac{1}{\left[(\hat{m})_A + 1 \right]} \right] \right\}^{\frac{1}{(\hat{m})_A}} \tag{A.5}$$

A.3 Test specimens other than tensile and flexural specimens may be utilized. Relationships between the estimate of the Weibull characteristic strength and the Weibull material scale parameter for any specimen configuration can be derived by equating the expressions defined by [Formulae \(8\)](#) and [\(10\)](#) with the modifications that follow. Begin by replacing σ (an applied uniaxial tensile stress) in [Formula \(8\)](#) with σ_{\max} , which is defined as the maximum tensile stress within the test specimen of interest, then:

$$P_f = 1 - \exp \left[- \left(\frac{\sigma_{\max}}{\sigma_\theta} \right)^m \right] \tag{A.6}$$

Also perform the integration given in [Formula \(10\)](#) such that:

$$P_f = 1 - \exp \left[-kV \left(\frac{\sigma_{\max}}{\sigma_0} \right)^m \right] \tag{A.7}$$

where k is a dimensionless constant that accounts for specimen geometry and stress gradients.

In general, k is a function of the estimated Weibull modulus \hat{m} , and is always less than or equal to unity. The product kV is often referred to as the effective volume (with the designation V_E). The effective volume can be interpreted as the size of an equivalent uniaxial tensile specimen that has the same risk of rupture as the test specimen or component. As the term implies, the product represents the volume of material subject to a uniform uniaxial tensile stress^[9]. Setting [Formulae \(A.6\)](#) and [\(A.7\)](#) equal to one another yields [Formula \(A.8\)](#):

$$(\hat{\sigma}_0)_V = (kV)^{1/(\hat{m})_V} (\hat{\sigma}_\theta)_V \tag{A.8}$$

Thus for an arbitrary test specimen, the experimentalist evaluates the integral identified in [Formula \(10\)](#) for the effective volume, kV , and utilizes [Formula \(A.8\)](#) to obtain the estimated Weibull material scale parameter $\hat{\sigma}_0$. A similar procedure can be adopted when fracture origins are spatially distributed at the surface of the test specimen.

Annex B (informative)

Illustrative examples

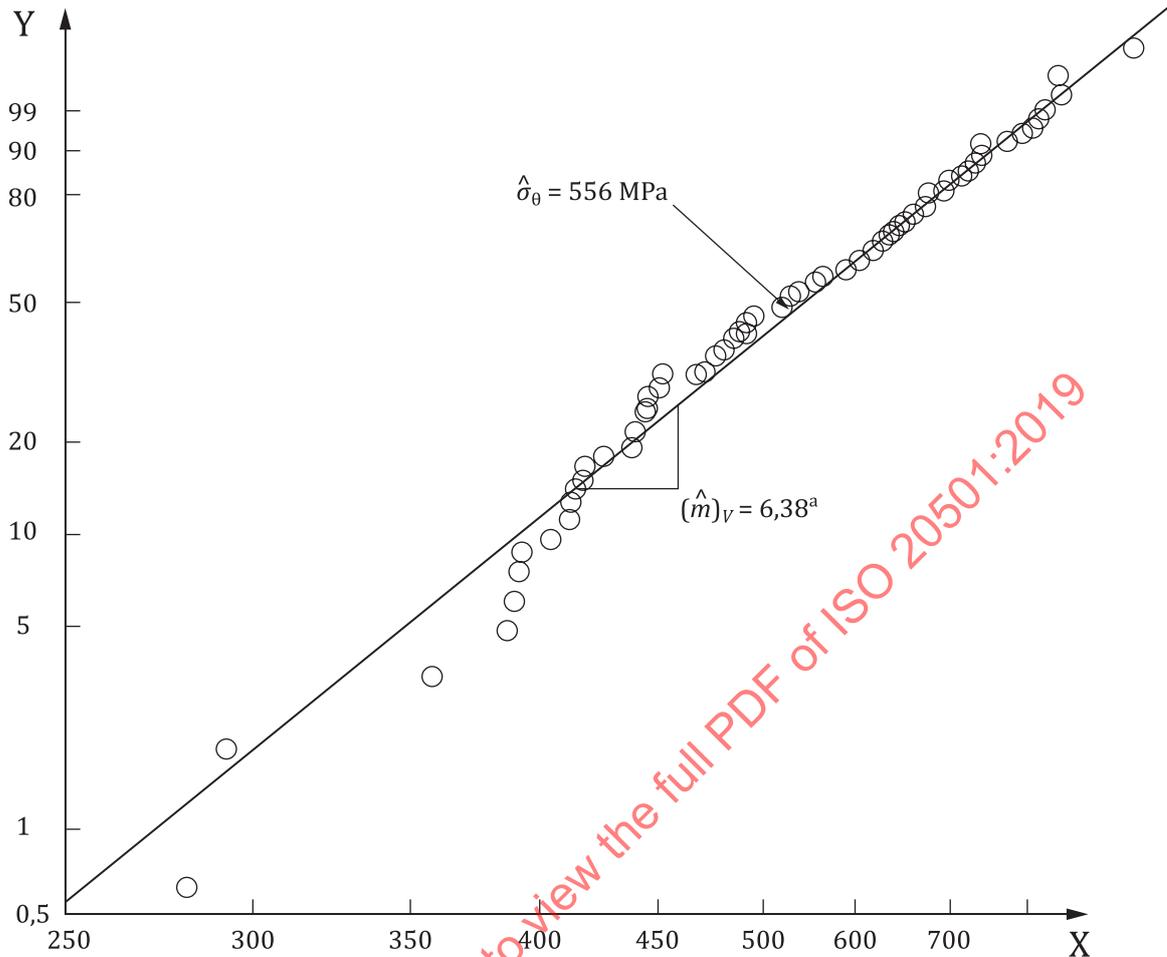
B.1 The first example considers the failure data in [Table B.1](#). The data represent four-point (1/4 point) flexural specimens fabricated from HIP'ed (hot isostatically pressed) silicon carbide.^[11] The solution of [Formula \(15\)](#) requires an iterative numerical scheme and for this data set yields a biased parameter estimate of $\hat{m} = 6,48$. Subsequent solution of [Formula \(16\)](#) yields a value of $\hat{\sigma}_\theta = 556$ MPa. These values for the Weibull parameters were generated by assuming a unimodal failure sample with no censoring (i.e. $r = N$). [Figure B.1](#) depicts the individual failure data and a curve based on the estimated values of the parameters. Next, assuming that the failure origins were surface-distributed and then inserting the estimated value of \hat{m} and $\hat{\sigma}_\theta$ in [Formula \(A.5\)](#) along with the specimen geometry (i.e. $L_o = 40$ mm, $L_i = 20$ mm, $d = 3,5$ mm, and $b = 4,5$ mm) yields $(\hat{\sigma}_0)_A = 360 \text{ MPa} \cdot (m)^{0,309}$. Note that $(\hat{\sigma}_0)_A$ has units of stress \cdot (area) ^{$1/\hat{m}$} ; thus, $0,309 = (2/6,48)$. Alternatively, if one were to assume that the failure origins were volume distributed, then the solution of [Formula \(A.3\)](#) yields $(\hat{\sigma}_0)_V = 37,0 \text{ MPa} \cdot (m)^{0,463}$. Note that $(\hat{\sigma}_0)_V$ has units of stress \cdot (volume) ^{$1/\hat{m}$} ; thus, $0,463 = (3/6,48)$. The different values obtained from assuming surface and volume fracture origins underscore the necessity of conducting a fractographic analysis.

Table B.1 — Unimodal failure stress data for HIP'ed (hot isostatically pressed) silicon carbide — Example 1

Specimen number	Strength, σ_f MPa	Specimen number	Strength, σ_f MPa
1	281	41	516
2	291	42	520
3	358	43	528
4	385	44	531
5	389	45	531
6	391	46	546
7	392	47	549
8	403	48	553
9	412	49	560
10	413	50	562
11	414	51	563
12	418	52	566
13	418	53	566
14	427	54	570
15	438	55	573
16	440	56	575
17	441	57	576
18	442	58	580
19	444	59	583
20	445	60	588

Table B.1 (continued)

Specimen number	Strength, σ_f MPa	Specimen number	Strength, σ_f MPa
21	446	61	589
22	452	62	591
23	452	63	591
24	453	64	593
25	470	65	599
26	474	66	600
27	476	67	610
28	476	68	613
29	479	69	620
30	484	70	620
31	485	71	622
32	486	72	622
33	489	73	640
34	492	74	649
35	493	75	657
36	496	76	660
37	506	77	664
38	512	78	674
39	512	79	674
40	514	80	725

**Key**

X ln(failure stress), MPa

Y probability of failure, P_f

a Unbiased.

Figure B.1 — Failure data in B.1

B.2 The next example considers a sample that exhibits multiple active flaw distributions (see [Table B.2](#)). Each flexural test specimen was subjected to fractographic analysis. The failure origin was identified as either a volume or a surface fracture origin, and parameter estimates were obtained by using [Formulae \(17\)](#) and [\(18\)](#). For the analysis with volume fracture origins, $r = 13$, and the calculations yielded values of $(\hat{m})_V = 6,79$ and $(\hat{\sigma}_\theta)_V = 876$ MPa. For the analysis with surface fracture origins, $r = 66$, and

the calculations yielded values of $(\hat{m})_A = 21,0$ and $(\hat{\sigma}_0)_A = 693$ MPa. For the most part, the data as plotted in [Figure B.2](#) fall near the solid curve, which represents the combined probability of failure^[7]:

$$P_f = 1 - [1 - (P_f)_A][1 - (P_f)_V] \tag{B.1}$$

where $(P_f)_V$ is calculated by using

$$(P_f)_V = 1 - \exp \left\{ - \left[\frac{\sigma}{(\hat{\sigma}_0)_V} \right]^{(\hat{m})_V} \right\} \tag{B.2}$$

and $(P_f)_A$ is calculated by using

$$(P_f)_A = 1 - \exp \left\{ - \left[\frac{\sigma}{(\hat{\sigma}_0)_A} \right]^{(\hat{m})_A} \right\} \tag{B.3}$$

The curve obtained from [Formula \(B.1\)](#) asymptotically approaches the intersecting straight lines that are defined by the estimated parameters and calculated from [Formulae \(B.2\)](#) and [\(B.3\)](#). Inserting the estimated Weibull parameters (obtained from the analysis for volume fracture origins) into [Formula \(A.3\)](#) along with the specimen geometry ($L_o = 40$ mm, $L_i = 20$ mm, $d = 3,5$ mm and $b = 4,5$ mm) yields $(\hat{\sigma}_0)_V = 65,6$ MPa·(m)^{0,442}. Inserting the estimated Weibull parameters (obtained from the analysis for surface fracture origins) into [Formula \(A.5\)](#) yields $(\hat{\sigma}_0)_A = 446$ MPa·(m)^{0,95}.

Table B.2 — Bimodal failure stress data — Example 2

Specimen number, <i>N</i>	Strength, σ_f MPa	Fracture origin type ^a	Specimen number, <i>N</i>	Strength, σ_f MPa	Fracture origin type ^a
1	416	V	41	671	S
2	458	S	42	672	S
3	520	V	43	672	S
4	527	V	44	674	S
5	546	S	45	677	S
6	561	V	46	677	S
7	572	S	47	678	S
8	595	V	48	680	S
9	604	S	49	683	S
10	604	S	50	684	S
11	609	V	51	686	S
12	612	S	52	687	S
13	614	S	53	687	S
14	621	V	54	691	S
15	622	S	55	694	S
16	622	S	56	695	S
17	622	V	57	700	S
18	622	S	58	703	S
19	625	S	59	703	S
20	626	V	60	703	S

^a Volume fracture origin, V; surface flaw origin, S.

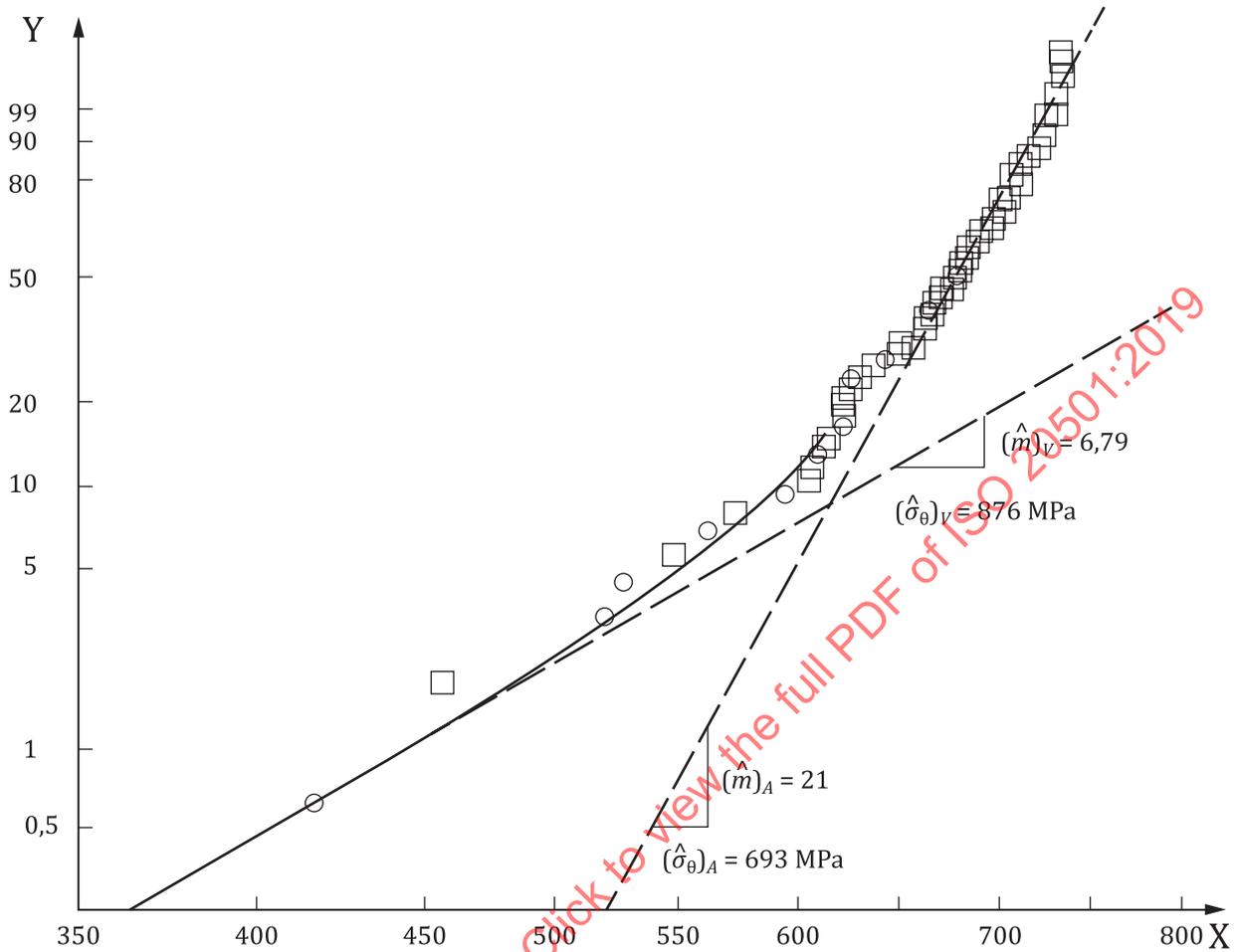
Table B.2 (continued)

Specimen number, <i>N</i>	Strength, σ_f MPa	Fracture origin type ^a	Specimen number, <i>N</i>	Strength, σ_f MPa	Fracture origin type ^a
21	631	S	61	703	S
22	640	S	62	704	S
23	643	V	63	704	S
24	649	S	64	706	S
25	650	S	65	710	S
26	652	V	66	713	S
27	655	S	67	716	S
28	657	S	68	716	S
29	657	V	69	716	S
30	660	S	70	716	S
31	660	S	71	716	S
32	662	V	72	717	S
33	662	S	73	725	S
34	662	S	74	725	S
35	664	S	75	725	S
36	664	S	76	726	S
37	664	S	77	727	S
38	666	S	78	729	S
39	669	S	79	732	S
40	671	S			

^a Volume fracture origin, V; surface flaw origin, S.

B.3 It should be noted in this example that fractography apparently indicated that all volume failures were initiated from a single distribution of volume flaws, and that all surface failures were initiated from a single distribution of surface flaws. Often, fractography will indicate more complex situations such as two independent distributions of volume flaws (e.g. inclusions of foreign material and large voids) in addition to a distribution of surface flaws. Analysis of this type of sample would be very similar to the

analysis discussed above, except that [Formulae \(17\)](#) and [\(18\)](#) would be used three times instead of twice, and the resulting figure would include three straight lines labelled accordingly.



Key

- X ln(failure stress), MPa
- Y ln(ln1/(1-P_f)) with P_f probability of failure, %

Figure B.2 — Failure data from B.2

B.4 As an example of computing unbiased estimates of the Weibull modulus, and bounds on both the Weibull modulus and the Weibull characteristic strength, consider the unimodal failure sample presented in [B.1](#). The sample contained 80 specimens and the biased estimate of the Weibull modulus was determined to be $\hat{m} = 6,48$. The unbiasing factor corresponding to this sample size is $UF = 0,984$, which is obtained from [Table 1](#) (see [6.5.2](#)). Thus, the unbiased estimate of the Weibull modulus is given as

$$\begin{aligned}
 \hat{m}_U &= \hat{m} \times UF && \text{(B.4)} \\
 &= 6,48 \times 0,984 \\
 &= 6,38
 \end{aligned}$$

Using the interpolation [Formula \(18\)](#) leads to a unbiasing factor of $UF = 0,983$, resulting in an unbiased Weibull modulus of 6,37 (the deviation between the table value and the function value is within the given accuracy).

The upper bound for this example is

$$\begin{aligned}\hat{m}_{\text{upper}} &= \hat{m} / q_{0,05} & (B.5) \\ &= 6,48 / 0,878 \\ &= 7,38\end{aligned}$$

where $q_{0,05}$ is obtained from [Table 2](#) for a sample size of 80 failed specimens. The lower bound is

$$\begin{aligned}\hat{m}_{\text{lower}} &= \hat{m} / q_{0,95} & (B.6) \\ &= 6,48 / 1,173 \\ &= 5,52\end{aligned}$$

where $q_{0,95}$ is also obtained from [Table 2](#). Alternatively using the interpolating function [Formula \(21\)](#) with the coefficients given in [Table 3](#), the results 7,37 and 5,51 are obtained for the upper and lower bound of m .

Similarly, the upper bound on $\hat{\sigma}_{\theta}$ is

$$\begin{aligned}(\hat{\sigma}_{\theta})_{\text{upper}} &= (\hat{\sigma}_{\theta}) \exp(-t_{0,05} / \hat{m}) & (B.7) \\ &= (556) \exp(0,197 / 6,48) \\ &= 573 \text{ MPa}\end{aligned}$$

where $t_{0,05}$ is obtained from [Table 5](#) for a sample size of 80 failed specimens. The lower bound on $\hat{\sigma}_{\theta}$ is

$$\begin{aligned}(\hat{\sigma}_{\theta})_{\text{lower}} &= (\hat{\sigma}_{\theta}) \exp(-t_{0,95} / \hat{m}) & (B.8) \\ &= (556) \exp(-0,197 / 6,48) \\ &= 539 \text{ MPa}\end{aligned}$$

where $t_{0,95}$ is also obtained from [Table 5](#). The identical values are obtained by using the analytical approach according to [Formula \(23\)](#) and [Table 6](#).

Annex C (informative)

Test specimens with unidentified fracture origin

C.1 The four options

C.1.1 General

[Subclause 7.2.2](#) described four options, a) to d), that the experimentalist can utilize when unidentified fracture origins are encountered during fractographic examination. [C.1.2](#) to [C.1.5](#) further define the four options, and use examples to illustrate appropriate and inappropriate situations for their use.

C.1.2 Option a)

Option a) involves using all available fractographic information to subjectively assign a specimen with an unidentified origin to a previously identified fracture origin classification. Many specimens with unidentified fracture origins have some fractographic information that was judged to be insufficient for positive identification and classification. (It should be noted that the degree of certainty required for “positive identification” of a fracture-initiating flaw varies from one fractographer to another.) In such cases, option a) permits the experimentalist the use of the incomplete fractographic information to assign the unidentified fracture origin to a previously identified flaw classification. This option is preferred when partial fractographic information is available. As an example, consider a tensile specimen where fractography was inconclusive. Fractographic markings may have indicated that the origin was located at or very near the specimen surface, but the fracture-initiating flaw could not be positively identified. Other specimens from the sample were positively identified as failing from machining flaws. It is recognized that machining damage is often difficult to discern therefore, in this case, it would be appropriate to use option a) and infer that the origin is machining damage. The test report should clearly indicate each specimen where this (or any other) option is used for classifying unidentified specimens. The conclusion of machining damage in this example, however, could be erroneous; e.g. the fracture initiating flaw may have been a “mainstream microstructural feature”^{[3][12]} (which is also typically difficult to resolve and identify) that happened to be located near the specimen surface. The possibility of erroneous classifications such as this are unavoidable in the absence of positive identification of fracture origins.

C.1.3 Option b)

Option b) involves assigning the unidentified fracture origin to that fracture origin classification of the test specimen closest in strength. The specimen closest in strength must have a positively identified fracture origin [not one assigned using options a) to d)]. As an example of use of this option, consider a tensile specimen that shattered upon failure such that the fracture origin was damaged and lost, but fracture was clearly initiated from an internal flaw. Other specimens from the sample included positive identification of inclusions and large pores as two active volume-distributed fracture origin classifications. When the fracture strengths from the total data set were ordered, the specimen closest in strength to the specimen with the unidentified fracture origin was the specimen that failed due to an inclusion. Use of option b) for this test specimen would then allow the unidentified origin to be classified as an inclusion. Justification for option b) arises from the tendency of concurrent (competing) flaw distributions to group together specimens with the same origin classification when the test specimens are listed in order of fracture strength. Therefore, the most likely fracture origin classification of a random unidentified specimen is the classification of the specimen closest in strength. The above example can be modified slightly to illustrate a situation where option b) would be inappropriate. If, the fracture origin classification of the specimen closest in strength was a machining flaw, then option b)

would lead to a conclusion inconsistent with the fractographic observation that failure occurred from an internal flaw. Fractographic evidence should always supersede conclusions from option b).

C.1.4 Option c)

Option c) assumes that the unidentified fracture origins belong to a new, unclassified flaw type and treats these fracture origins as a separate flaw distribution in the censored data analysis. This may occur when the fractographer cannot recognize the flaw type because features of the flaw are particularly subtle and difficult to resolve. In such cases, the fractographer may consistently fail to locate and classify the fracture origin. Examples of flaw types that are difficult to identify include machining damage, zones of atypically high micro porosity, and mainstream microstructural features. Option c) may be appropriate if a set of specimens with unidentified fracture origins have similar and apparently related features. Unfortunately, there are many situations where option c) is incorrect and where use of this option could result in substantial errors in parameter estimates; e.g. consider the case where several unidentified specimens are concentrated in the upper tail (high strength) of the strength distribution. These fracture origins may belong to a classification that has been previously identified, but the smaller flaws at the origins were harder to locate, or possibly the origins were lost due to the greater fragmentation associated with high strength specimens. Use of option c) to treat these high strength specimens as a new flaw classification would create a bias error of unknown magnitude in the parameter estimates of the proper flaw classification.

C.1.5 Option d)

Option d) involves the removal of test specimens with unidentified fracture origins from the sample (i.e. the strengths are removed from the list of observed strengths). This option is rarely appropriate, and is not recommended by this document unless there is clear justification. Option d) is only valid when test specimens with unidentified fracture origins are randomly distributed through the full range of strengths and flaw classifications. There are few plausible physical processes that create such a random selection. An example where option d) is justified is a data set of 50 specimens where the first 10 fractured specimens (in order of testing) were misplaced or destroyed after testing but prior to fractography. The unidentified specimens were therefore created by a process that is random. That is, the 10 strengths are expected to be randomly distributed through the strength distribution of the remaining 40, and the 10 origin classifications are expected to be randomly distributed through the origin types of the remaining 40. (In this example, option b) could also be considered.) Option d) is not appropriate where unidentified fracture origins are a consequence of high-strength test specimens shattering virulently such that the fragment with the origin is lost. This situation occurs with more frequency in the upper tail (high strength) of the strength distribution, and thus the unidentified fracture origins would not occur at random strengths.

C.2 Proper use and implementation of the four options

C.2.1 When partial fractographic information is available, option a) is preferred and should be used to incorporate the information as completely as possible into the assignment of fracture origin classification. Option d) should be used only in unusual situations where a random process for creation of unidentified origins can be justified.

C.2.2 Situations may arise where more than one option will be used within a single data set; e.g. of five specimens with unidentified origins, three might be classified based on partial fractographic information [option a)], while the remaining two, which have no fractographic hints, might then be classified using option b).

C.2.3 When specimens with unidentified fracture origins are contained within a data set, the test report (see [Clause 9](#)) should include a full description of which specimens were unidentified, and which option or options were used to classify the specimens.