Designation: C 1323 – 96 (Reapproved 2001)$^{\epsilon 1}$

Standard Test Method for Ultimate Strength of Advanced Ceramics with Diametrally Compressed C-Ring Specimens at Ambient Temperature[1]

This standard is issued under the fixed designation C 1323; 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.

ϵ^1 NOTE—Equation X1.2 was editorially corrected in April 2007.

1. Scope

1.1 This test method covers the determination of ultimate strength under monotonic loading of advanced ceramics in tubular form at ambient temperatures. Note that ultimate strength as used in this test method refers to the strength obtained under monotonic compressive loading of C-ring specimens where monotonic refers to a continuous nonstop test rate with no reversals from test initiation to final fracture.

1.2 Values expressed in this test method are in accordance with the International System of Units (SI) and Practice E 380.

1.3 *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]

C 1145 Terminology on Advanced Ceramics
C 1161 Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature
C 1239 Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics
E 4 Practices for Force Verification of Testing Machines
E 6 Terminology Relating to Methods of Mechanical Testing
E 337 Test Method for Measured Humidity with Psychrometer (Measurement of Wet- and Dry-Bulb Temperatures)
E 380 Practice for Use of International System of Units (SI) (the Modernized Metric System)

2.2 *Military Standards:*[3]

MIL-HDBK-790 Fractography and Characterization of Fracture Origins in Advanced Structural Ceramics
MIL-STD-1942(A) Flexural Strength of High Performance Ceramics at Ambient Temperature

3. Terminology

3.1 *Definitions:*

3.1.1 *advanced ceramic*—an engineered, high-performance, predominately nonmetallic, inorganic, ceramic material having specific functional qualities. **(C 1145)**

3.1.2 *breaking load*—the load at which fracture occurs. **(E 6)**

3.1.3 *C-ring*—circular test specimen geometry with the mid-section (slot) removed to allow bending displacement (compression or tension). **(E 6)**

3.1.4 *flexural strength*—a measure of the ultimate strength of a specified beam in bending.

3.1.5 *modulus of elasticity*—the ratio of stress to corresponding strain below the proportional limit. **(E 6)**

3.1.6 *slow crack growth*—subcritical crack growth (extension) which may result from, but is not restricted to, such mechanisms as environmentally assisted stress corrosion or diffusive crack growth.

4. Significance and Use

4.1 This test method may be used for material development, material comparison, quality assurance, and characterization. Extreme care should be exercised when generating design data.

4.2 For a C-ring under diametral compression, the maximum tensile stress occurs at the outer surface. Hence, the C-ring specimen loaded in compression will predominately evaluate the strength distribution and flaw population(s) on the external surface of a tubular component. Accordingly, the condition of the inner surface may be of lesser consequence in specimen preparation and testing.

NOTE 1—A C-ring in tension or an O-ring in compression may be used

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[1] This test method is under the jurisdiction of ASTM Committee C28 on Advanced Ceramics and is the direct responsibility of Subcommittee C28.04 on Applications.

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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 Standardization Documents Order Desk, Bldg. 4 Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.

to evaluate the internal surface.

4.3 The flexure stress is computed based on simple curved-beam theory (**1**)[4] with assumptions that the material is isotropic and homogeneous, the moduli of elasticity are identical in compression or tension, and the material is linearly elastic; all homogeneity and isotropy assumptions preclude the use of this standard for continuous fiber reinforced composites. Average grain size(s) shall be no greater than one fiftieth (1⁄50) of the C-ring thickness.

4.4 Because advanced ceramics exhibiting brittle behavior generally fracture catastrophically from a single dominant flaw for a particular tensile stress field, the surface area and volume of material subjected to tensile stresses is a significant factor in determining the ultimate strength. Moreover, because of the statistical distribution of the flaw population(s) in advanced ceramics exhibiting brittle behavior, a sufficient number of specimens at each testing condition is required for statistical analysis and design. This test method provides guidelines for the number of specimens that should be tested for these purposes (see 8.4).

4.5 Because of a multitude of factors related to materials processing and component fabrication, the results of C-ring tests from a particular material or selected portions of a part, or both, may not necessarily represent the strength and deformation properties of the full-size end product or its in-service behavior.

4.6 The ultimate strength of a ceramic material may be influenced by slow crack growth or corrosion, or both, and is therefore, sensitive to the testing mode, testing rate, or environmental influences, or a combination thereof. Testing at sufficiently rapid rates as outlined in this test method may minimize the consequences of subcritical (slow) crack growth or stress corrosion.

4.7 The flexural behavior and strength of an advanced monolithic ceramic are dependent on the material's inherent resistance to fracture, the presence of flaws, or damage accumulation processes, or a combination thereof. Analysis of fracture surfaces and fractography, though beyond the scope of this test method, is highly recommended (further guidance may be obtained from MIL HDBK-790 and Ref (**2**)).

5. Interferences

5.1 Test environment (vacuum, inert gas, ambient air, etc.) including moisture content (that is, relative humidity) may have an influence on the measured ultimate strength. In particular, the behavior of materials susceptible to slow crack-growth fracture will be strongly influenced by test environment and testing rate. Testing to evaluate the maximum inert strength (strength potential) of a material shall therefore be conducted in inert environments or at sufficiently rapid testing rates, or both, so as to minimize slow crack-growth effects. Conversely, testing can be conducted in environments and testing modes and rates representative of service conditions to evaluate material performance under use conditions. When testing in uncontrolled ambient air for the purpose of evaluating maximum inert strength (strength potential), relative humidity and temperature must be monitored and reported. Testing at humidity levels >65 % RH is not recommended and any deviations from this recommendation must be reported.

5.2 C-ring specimens are useful for the determination of ultimate strength of tubular components in the as-received/as-used condition without surface preparations that may distort the strength controlling flaw population(s). Nonetheless, machining damage introduced during specimen preparation can be either a random interfering factor in the determination of the maximum inert strength (strength potential) of pristine material (that is, increase frequency of surface or edge initiated fractures compared to volume initiated fractures), or an inherent part of the strength characteristics being measured. Universal or standardized methods of surface/sample preparation do not exist. Hence, it shall be understood that final machining steps may or may not negate machining damage introduced during the initial machining. Thus, specimen fabrication history may play an important role in the measured strength distributions and shall be reported.

6. Apparatus

6.1 *Loading*—Specimens shall be loaded in any suitable testing machine provided that uniform rates of direct loading can be maintained. The system used to monitor the loading shall be free from any initial lags and will have the capacity to record the maximum load applied to the C-ring specimen during the test. Testing machine accuracy shall be within 1.0 % in accordance with Practices E 4.

6.1.1 This test method permits the use of either fixed loading rams or, when necessary (see 9.3), a self-adjusting fixture such as a universal joint or spherically seated platen may be used in conjunction with the upper loading ram. When fixed loading rams are used, they shall be aligned so that the platen surfaces which come into contact with the specimens are parallel to within 0.015 mm. Alignment of the testing system must be verified at a minimum at the beginning and at the end of a test series. An additional verification of alignment is recommended, although not required, at the middle of the test series.

NOTE 2—A test series is interpreted to mean a discrete group of tests on individual specimens conducted within a discrete period of time on a particular material configuration, test specimen geometry, test conditions, or other uniquely definable qualifier (for example, a test series composed of Material A comprising ten specimens of Geometry B tested at a fixed rate in strain control to final fracture in ambient air).

6.1.2 Materials such as foil or thin rubber sheet shall be used between the loading rams and the specimen for ambient temperature tests to reduce the effects of friction and to redistribute the load. Aluminum oxide (alumina) felt or other high-temperature "cloth" with a high-temperature capability may also be used. The use of a material with a high-temperature capability is recommended to ensure consistency with elevated temperature tests (if planned), provided the high-temperature "cloth" is chemically compatible with the specimen at all testing temperatures.

6.2 The fixture used during the tests shall be stiffer than the specimen to ensure that a majority of the crosshead travel (at least 80 %) is imposed on the C-ring specimen.

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

6.3 *Data Acquisition*—At the minimum, an autographic record of applied load shall be obtained. Either analog chart recorders or digital data acquisition systems can be used for this purpose. Ideally, an analog chart recorder or plotter shall be used in conjunction with a digital data acquisition system to provide an immediate record of the test as a supplement to the digital record. Recording devices shall be accurate to 0.1 % of full scale and shall have a minimum data acquisition rate of 10 Hz with a response of 50 Hz deemed more than sufficient.

7. Hazards

7.1 During the conduct of this test, the possibility of flying fragments of broken test material may be high. Means for containment and retention of these fragments for safety, later fractographic reconstruction, and analysis is highly recommended.

8. Specimen

8.1 *General*—The C-ring geometry is designed to evaluate the ultimate strength of advanced monolithic materials in tubular form in as-received or as-machined form. When possible, the specimen shall reflect the actual size of the component to minimize size scaling effects and to increase the likelihood that the specimen will have the same microstructure and flaw population(s) as the component. Hence, standard specimen dimensions or overall sizes can not be recommended without compromising the original purpose of the test method. Instead, specimens shall be prepared from the stock used for the actual component when possible.

8.1.1 *Specimen Size*—To maintain plane stress conditions (**3,4**) in the specimen while avoiding undue influence from the edges (edge effects), the width of the sample shall be at least one, but no greater than four times the thickness:

$$1 \leq \frac{b}{r_o - r_i} \leq 4 \tag{1}$$

where the dimensional terms b, r_o, and r_i are defined in Fig. 1.

NOTE 3—Experimental or finite-element studies, or both, are recommended to verify the magnitude, distribution, and uniaxiality of the stresses in the actual C-ring used for testing.

8.1.2 The slot height (L) in the C-ring specimen (Fig. 1) shall be at least equal to the width of the specimen to ensure that the slot is significantly greater than the maximum displacement at failure. When thin tubular specimens are studied, a larger slot not to exceed one fourth of the outer circumference may be required.

8.1.3 The parallelism tolerance for the two machined sides of the C-ring specimen is 0.015 mm.

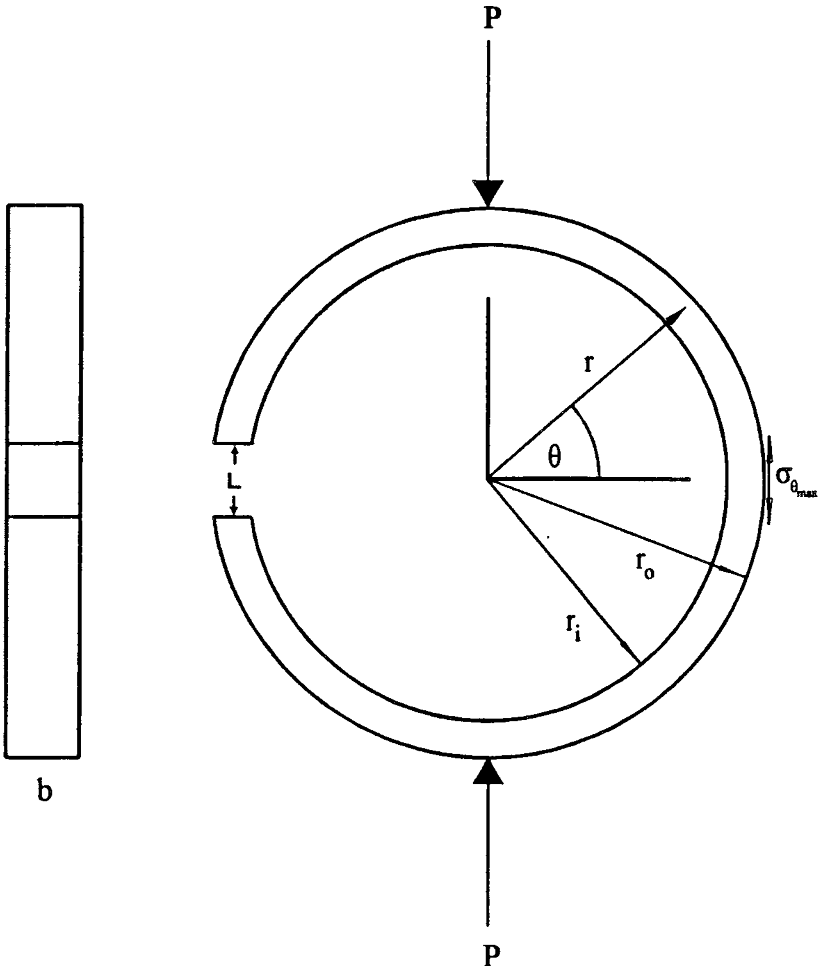

FIG. 1 C-Ring Test Geometry with Defining Geometry and Reference Angle (θ) for the Point of Fracture Initiation on the Circumference

8.2 *Specimen Preparation*—Depending on the intended application of the ultimate strength data, use one of the following three specimen preparation procedures:

8.2.1 *As-Fabricated*—The external and internal surface of the C-ring specimen shall simulate the surface conditions and processing route of an application where no machining is used. No additional machining specifications for these surfaces are relevant. Each side section shall be machined from the tubular stock and lap finished with 15 µm media to remove any large machining defects. All edges shall then be either chamfered at 45° to a distance of 0.15 ± 0.05 mm or rounded to a radius of 0.15 ± 0.05 mm to avoid edge dominated failures ("edge-checking").

NOTE 4—If the C-ring specimen has a nonuniform diameter, the tolerances stated in 8.2.1 may be relaxed; however, the edges shall still be chamfered or rounded.

8.2.2 *Application-Matched Machining*—The C-ring specimen shall have the same surface preparation as that given to the component. When possible, the specimen shall also retain the original radii of the component provided the surface area and volume are sufficient to sample the inherent flaws of the material under study. All other side finishing specifications shall be the same as the as-fabricated specimens. Unless the process is proprietary, the report shall include all details about the stages of material removal, wheel grits, wheel bonding, and the material removal rates for each pass.

8.2.3 *Standard Procedure*—In instances where 8.2.1 through 8.2.2 are not appropriate, 8.2.3 shall apply. This procedure shall be viewed as a baseline; more stringent procedures may be necessary depending on the application(s).

NOTE 5—This procedure is similar to the ones specified in Test Method C 1161 and MIL-STD-1942(A).

8.2.3.1 All grinding or cutting shall be done with ample supply of appropriate filtered coolant to keep the workpiece and grinding wheel constantly flooded and particles flushed. Grinding must be done in at least two stages, ranging from coarse to a finer rate of material removal. All cutting can be done in one stage appropriate for the depth of cut. Unless the process is proprietary, all reports shall be specific about the stages of material removal, wheel grits, wheel bonding, amount of material removed per pass, and type of coolant used.

8.2.3.2 Stock removal rate shall not be greater than 0.03 mm per pass using diamond tools with a grit size range of 320 to 500. No less than 0.06 mm per face shall be removed during the final finishing phase, and a rate of not more than 0.002 mm per pass. Equal stock shall be removed from each side face where applicable.

8.2.3.3 Finer grinding wheels and lower material removal rates shall be used for materials with low fracture toughness values or materials that are susceptible to grinding damage.

8.2.3.4 All edges shall then be either chamfered at 45° to a distance of 0.15 ± 0.05 mm or rounded to a radius of 0.15 ± 0.05 mm to avoid edge dominated failures ("edge-checking").

8.3 *Handling Precaution*—Extreme care shall be used in storage and handling of all finished specimens to avoid the introduction of random and severe flaws from scratches, impacts with containers, or other specimens. In addition, attention shall be given to pre-test storage of specimens in controlled environments or desiccators to avoid unquantifiable environmental degradation of specimens prior to testing.

8.4 *Number of Specimens*—A minimum of ten tests is recommended for the purpose of estimating a mean. A minimum of 30 tests may be necessary if estimates regarding the form of the strength distribution and Weibull (**5**) parameters are desired within the confidence bounds established by Practice C 1239.

9. Procedure

9.1 *Specimen Dimensions*—After machining the C-ring and slot, measure the outer diameter, inner diameter, wall thickness, and width of each machined specimen to within ±0.01 mm or 1 % of the thickness, whichever is greater. Similar accuracy shall be achieved with as-received specimens with the understanding that multiple measurements around the specimen shall be made to make allowance for eccentric or oval sections in as-fired C-rings. A minimum of four (4) measurements at equally spaced intervals with two (2) at the load points are recommended. Divide each measured internal diameter by two to give the local nominal internal radius. Add the local wall thickness to the nominal radius to determine the nominal external radius. For both machined and as-fired C-rings, the wall thickness shall be checked at the actual site of fracture after testing.

9.1.1 Because each specimen's dimensions may vary, all stress and Weibull calculations must incorporate actual sample dimensions.

9.2 Carefully position each specimen in the test fixture to minimize the possibility of damage and to ensure alignment. The specimen shall be directly centered below the axis of the applied loading. Loading points are at 90° and 270° as defined by Fig. 1. Marking the loading points with a pencil, nonreactive ink, or paint (such as "white-out") is advisable.

9.3 Slowly apply the preload to the C-ring specimen. The maximum value of preload stress shall not exceed 25 % of the mean strength of the material under scrutiny. After the preload has been applied, always inspect the line of contact to ensure alignment, continuous contact, and the absence of contaminants. If the specimen is unable to be completely aligned or continuous contact between the platen and C-ring cannot be maintained, a self-adjusting fixture as described in 6.1.1 should be used.

9.4 *Loading Rates*—The crosshead rates are chosen in order that the strain rates experienced by the C-ring specimens are on the order of $1.0 \times 10^{-4}\ \mathrm{s}^{-1}$.

9.4.1 *Strain Rate*—The maximum strain rate for a C-ring loaded in compression is as follows:

$$\dot{\epsilon} = \frac{(r_o - r_i)^2}{6\pi r_a^3}\left[\frac{R(r_o - r_a)}{r_o(r_a - R)}\right]\delta \quad (2)$$

where:

$\dot{\epsilon}$ = strain rate,
b = specimen width,
r_o = outer C-ring radius,
r_i = inner C-ring radius,

δ = crosshead speed, and

the terms R and r_a are defined as:

$$R = \frac{(r_o - r_i)}{ln\left(\frac{r_o}{r_i}\right)} \tag{3}$$

$$r_a = \frac{r_o + r_i}{2} \tag{4}$$

9.4.2 Typical failure times for ceramics range from 3 to 30 s. It is therefore assumed that the loading fixtures are sufficiently rigid and that a majority of the crosshead travel is imposed as strain on the C-ring specimen.

9.5 *Breakload*—Measure the breakload (load at fracture) to an accuracy of ±1.0 %.

9.6 All primary fracture fragments shall be retained to assess the angle (θ) and location (edge, side surface, ID surface, or OD surface) of fracture initiation and for fractographic analysis. Because fractography can be an interpretive analytical method, the guidelines established in military handbook MIL-HDBK-790 are highly recommended for consistency.

9.7 Determine the relative humidity in accordance with Test Method E 337.

9.8 The occasional use of strain-gaged specimens is recommended, and is used to verify the predicted stress state in accordance with 10.1.

10. Calculation

10.1 The following expression shall be used to calculate the maximum tensile stress at fracture and for a comprehensive Weibull analysis (**6**):

$$\sigma_{\theta max} = \frac{PR}{btr_o}\left[\frac{r_o - r_a}{r_a - R}\right] \tag{5}$$

where:

σ_θ = the engineering tangential (hoop) stress

P = the maximum applied compressive load

b = specimen width as shown in ,

t = specimen thickness, $r_o - r_i$, and

all other variables are as previously defined by Eqs 3 and 4 or shown in Fig. 1.

10.1.1 In some cases, Eq 5 may not provide the actual stress acting on the flaw that is the origin of failure. Hence, fractography must be utilized and the fracture stress corrected for subsurface origins.

10.1.2 When the fracture stress for a C-ring specimen loaded in diametral compression is to be calculated for the angle of fracture initiation on the circumference, the general expression for the stress state as a function of the radius, r, and angle, θ, defined in Fig. 1 (**6,7**) is to be used:

$$\sigma_\theta = \frac{PR}{btr}\left[\frac{r - r_a}{r_a - R}\right]cos\,\theta \tag{6}$$

NOTE 6—The values predicted by Eq 6 shall not be used to calculate average strengths.

11. Report

11.1 Report the following minimum information about the test and results:

11.1.1 Test configuration, test equipment description, and specimen dimensions (r_o, r_i, b, t, and L),

11.1.2 All details of machining and surface(s) preparation,

11.1.3 Number of specimens (n) used,

11.1.4 All relevant and available material data including data of manufacturing, billet identification, and manufacturer material designation,

11.1.5 Heat treatment(s) and exposure, if any,

11.1.6 Test environment including humidity (Test Method E 337) and temperature,

11.1.7 Strain rate (stress rate = $\dot{\sigma} = E\,\dot{\epsilon}$) or crosshead speed,

11.1.8 The measured fracture load and calculated fracture stress of each specimen to at least three (3) significant digits,

11.1.9 The angle (in radians) at which the fracture occurred as defined by Fig. 1 to at least two (2) significant digits,

11.1.10 Calculate mean ($\bar{S}$) and standard deviation (SD) using the following relationships:

$$\bar{S} = \frac{\sum_{i=1}^{n} \sigma_{\theta i}}{n} \tag{7}$$

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(\sigma_{\theta i} - \bar{S})^2}{n-1}} \tag{8}$$

11.1.11 Any alterations or deviations, or both, from the procedures described in this test method.

12. Precision and Bias

12.1 Because of the statistical distribution of flaws in ceramics that are the origin of fracture, the fracture strength as measured by the C-ring test is not a deterministic quantity. As shown by a number of analogous studies (**8,9**), Weibull statistics or other probabilistic methods shall be used to address this scatter when encountered. This test method has been devised to maximize precision while minimizing bias relative to the inherent variability of strength of the material.

13. Keywords

13.1 advanced ceramic; C-ring specimen

APPENDIX

(Nonmandatory Information)

X1. WEIBULL EFFECTIVE-AREA AND EFFECTIVE-VOLUME RELATIONSHIPS FOR C-RINGS UNDER DIAMETRAL COMPRESSION

X1.1 The statistical nature of brittle fracture in ceramics often dictates the use of probabilistic fracture mechanics for the prediction of reliability and the assessment of strength properties (additional details concerning the determination of strength distribution parameters are provided in Practice C 1239). This in turn requires the evaluation of the effective-area and effective-volume relationships for the specimen used.

X1.1.1 *Effective Area*—For C-ring specimens, the effective-area KA that calculates the area under tensile stress that is equivalent to a simple tensile specimen with an equivalent risk of failure is defined as (**6**):

$$KA = \int_A \left(\frac{\sigma_\theta}{\sigma_{\theta max}}\right)^m dA = br_o f_1(\theta) + 2r_o^{\,m} f_1(\theta) f_2(r) \qquad \text{(X1.1)}$$

where:

m = the Weibull modulus,

$$f_1(\theta) = 2\int_\theta^{\pi/2} cos^m(\theta)d\theta = \sqrt{\pi}\frac{\Gamma\left(\frac{m+1}{2}\right)}{\Gamma\left(\frac{m}{2}+1\right)} \qquad \text{(X1.2)}$$

Γ = the gamma function, and

$$f_2(r) = \int_{r_o}^{r_a} \left(\frac{r - r_a}{r_o - r_a}\right)^m r^{1-m} dr \qquad \text{(X1.3)}$$

NOTE X1.1—Equation .1 assumes that the surface flaw populations are the same on all surfaces. Hence, fractography should be used to identify all fracture origins.

X1.1.2 *Effective Volume*

For C-ring specimens, the effective volume KV that calculates the volume under tensile stress that is equivalent to a simple tensile specimen with an equivalent risk of failure is defined as (**6**):

$$KV = \int_V \left(\frac{\sigma_\theta}{\sigma_{\theta max}}\right)^m dV = br_o^{\,m} f_1(\theta) f_2(r) \qquad \text{(X1.4)}$$

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