
When considering the resistance of glass to applied loads, whether intentional, accidental, man-made or climatic, it is important to understand the basics of how and why glass fractures. This document aims to give a basic introduction to some contributing factors for glass strength, as well as basic parameters.

## GLASS COMPOSITION

The composition of soda-lime-silicate (SLS) glass is discussed in Document **Glass Fundamentals GF-1A**, and the following information is based on the structure and composition of this glass type. Parameters will differ for aluminosilicate and borosilicate glass types.

## THE THEORETICAL STRENGTH OF GLASS

The theoretical strength of a material can be determined based on the energy required to separate interatomic bonds, and in doing so, create a pair of new surfaces. The following equation, based on the work of Orowan, can be applied to amorphous soda-lime silicate glass;

$$\sigma_{th} = \sqrt{\frac{E \cdot \gamma}{r_0}}$$

| | | |
|---|---|---|
| Where; | $\sigma$ | Strength (GPa) |
| | $E$ | Young's Modulus, 70.0 GPa [1] |
| | $\gamma$ | Young's Bond Fracture Surface Energy 3.5 J/m$^2$ [1] |
| | $r_0$ | Equilibrium Interatomic Spacing, 0.162 nm [2] |

This yields a theoretical strength of approximately 40 GPa.

## THE PRACTICAL STRENGTH OF GLASS

Clearly a value of 40 GPa is an order of magnitude above what would be expected for annealed glass, and so consideration needs to be given to the structure of the material, specifically with regards to the influence of surface flaws.

### CRACK TIPS AND SURFACE FLAWS

Flaws will occur on the surface and edge of glass as a result of interactions with the material during manufacture, handling, processing and in service. The influence of microscale flaws on the stress generated in glass is well documented.

The relationship between the size and shape of a crack and the resultant stress generated at the crack tip was determined by Inglis [3]. The tensile stress at a crack tip can be determined as follows;

$$\sigma_m = 2 \cdot \sigma \sqrt{\frac{a}{r_{ct}}}$$

Where; $a$ Half Crack Length (m)

$r_{ct}$ Crack Tip Radius (m)

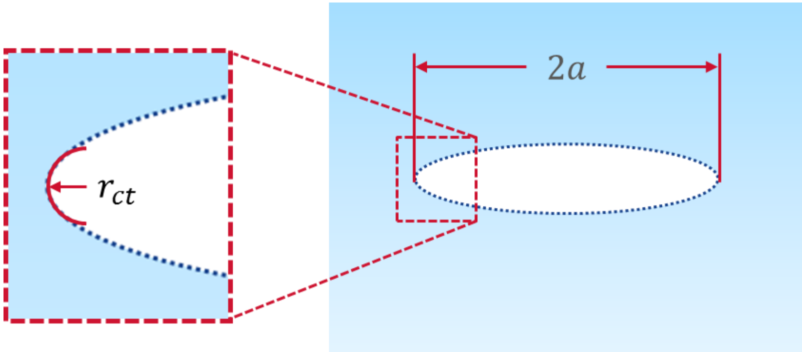



Figure 1 - Schematic of Crack Tip

As an example, a crack 2 mm in length with a crack tip radius of 5 nm, where a surface tensile stress of 50 MPa is being generated, will yield a stress at the crack tip of approximately 45 GPa, which would exceed the theoretical strength of glass.

By combining the equation for theoretical strength and stress at a crack tip, the following equation can be used to determine the practical strength of glass, based on flaw size;

$$\sigma_p = \sqrt{\frac{E \cdot \gamma \cdot r_{ct}}{4 \cdot a \cdot r_0}}$$

This allows the determination of the glass strength as a function of both crack tip radius and crack length, and can be plotted, as follows, to demonstrate the relationship between the two parameters. Essentially, longer and narrower, so sharper, cracks will reduce the strength of the glass by a greater degree.

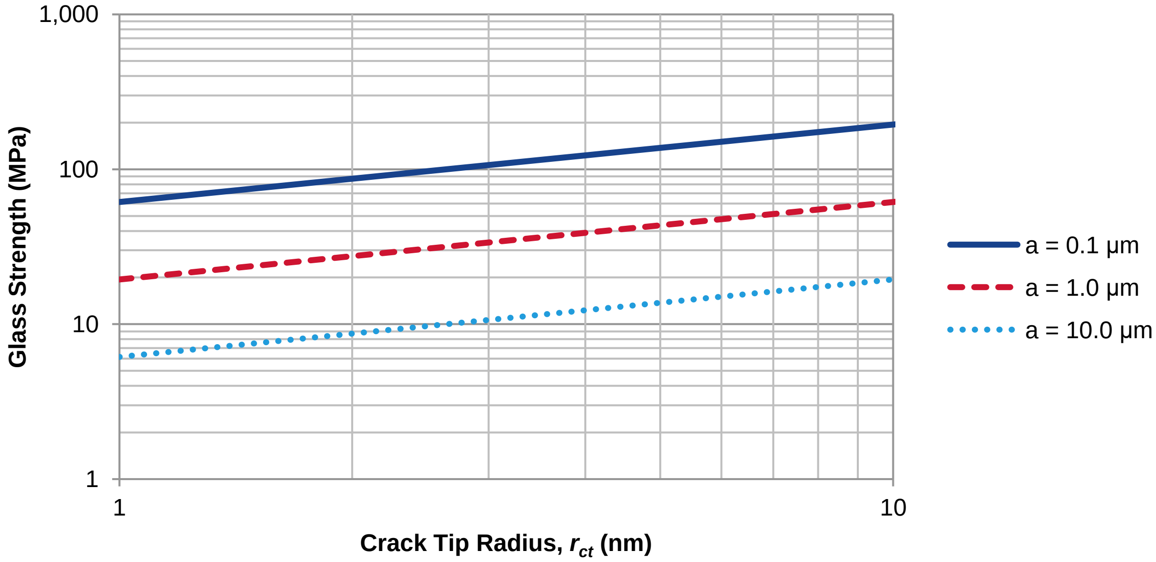



Figure 2 - Glass strength and crack tip radius and length relationship (Inglis)

## GENERALISED DETERMINATION OF STRESS CONCENTRATION

Griffith derived relationships [4] whereby the details of the crack tip weren't required, and for the mode stress intensity factors ($K_I$) for an interior crack is as follows;

$$K_I = \sigma \cdot \sqrt{\pi \cdot a}$$

And for a surface crack;

$$K_I = \sigma \cdot \sqrt{\frac{\pi \cdot a}{2}}$$

Where; $\sigma$ Applied Stress (MPa)

The Griffith equation then allows the critical stress needed for a crack to propagate to be determined, for an interior crack;

$$K_I = \sigma_c \cdot \sqrt{\pi \cdot a} = \sqrt{E \cdot \gamma}$$

Therefore;

$$\sigma_c = \sqrt{\frac{\gamma \cdot E}{\pi \cdot a}}$$

And for a surface crack;

$$K_I = \sigma_c \cdot \sqrt{\frac{\pi \cdot a}{2}} = \sqrt{E \cdot \gamma}$$

Therefore;

$$\sigma_c = \sqrt{\frac{2 \cdot \gamma \cdot E}{\pi \cdot a}}$$

These formulae allow the relationship between flaw size and critical stress to be observed, as below;

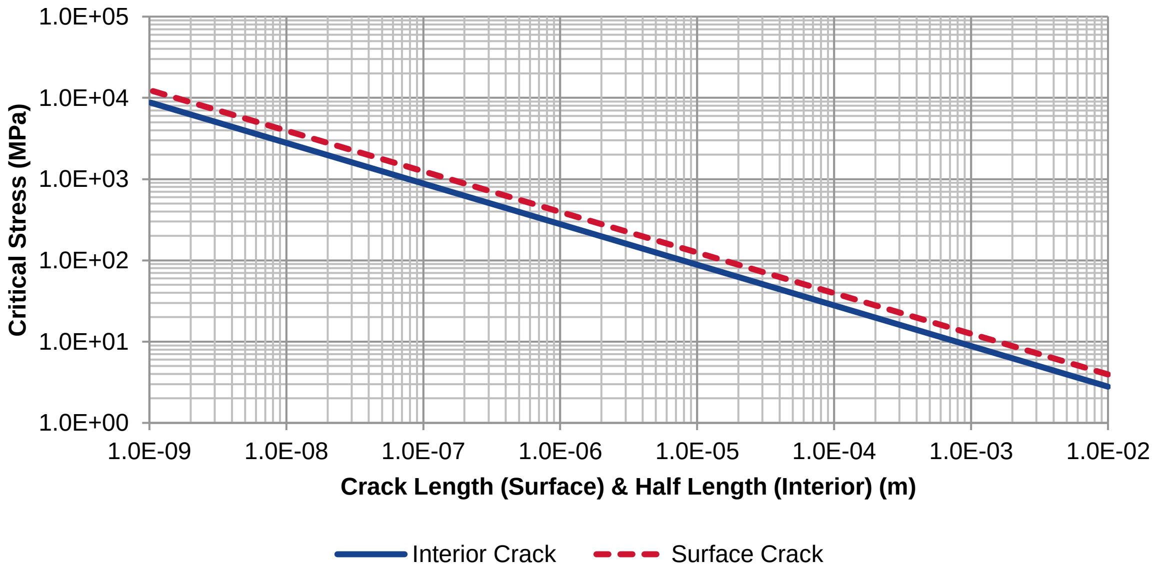



**Figure 3 - Glass strength and crack length relationship (Griffith)**

## THE INFLUENCE OF LOAD DURATION

The duration of a load on glass will have an influence on the strength, and is a result of the reaction of atmospheric moisture with the Si-O network within the glass. Static fatigue was observed by Grenet [5] in 1899, with investigations by others, including Shand [6], showing the trend for increased load duration, with reduced strength, as illustrated with Figure 4.

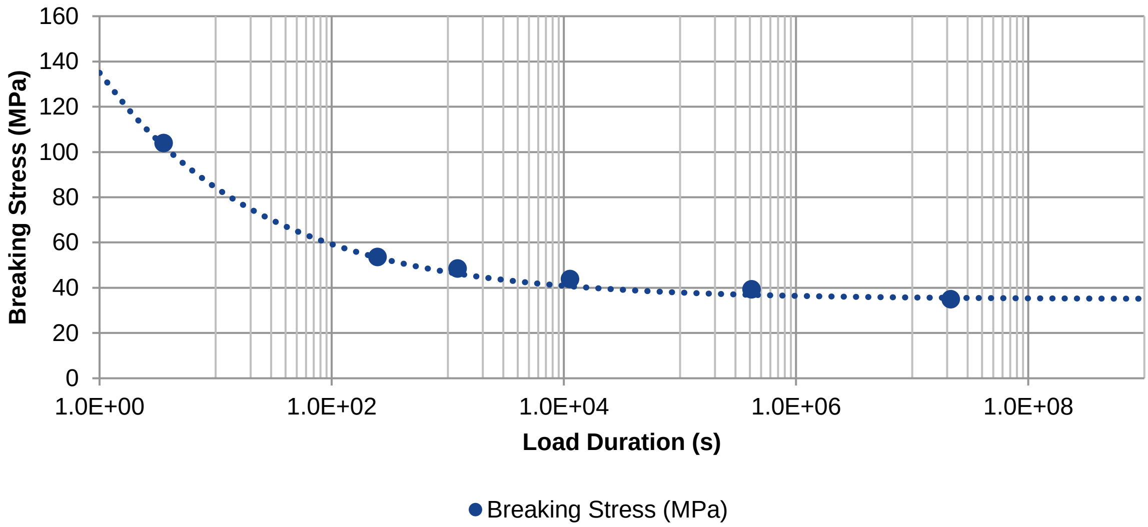


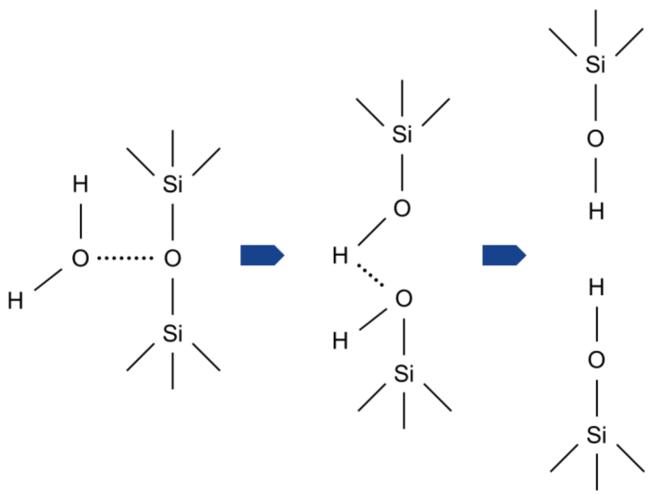

**Figure 4 - Breaking Stress vs. Load Duration, based on Data from Shand [6]**

### REACTIONS AT THE CRACK TIP

As stated, this reduction in strength is due to a chemical reaction occurring at the crack tip, also called a stress-corrosion reaction.

$$\equiv \mathrm{Si} - \mathrm{O} - \mathrm{Si} \equiv + \mathrm{H_2O} \rightarrow 2 \cdot \equiv \mathrm{SiOH}$$

A reaction between $H_2O$ and the Si-O network in a silicate glass leads to the breaking of siloxane bonds of the Si-O network structure. The reaction kinetics will be dependent on the presence of stress, temperature and the concentration of hydroxyl and other ionic species, and has been intensively researched.




### LOAD DURATION IN DESIGN

In order to consider the influence of long terms loads, various design standards utilise a factor for annealed glass types, to modify the strength based on load duration. prEN 16612 for example, uses the following;

$$k_{mod} = 0.663 \cdot t^{-\frac{1}{16}}$$

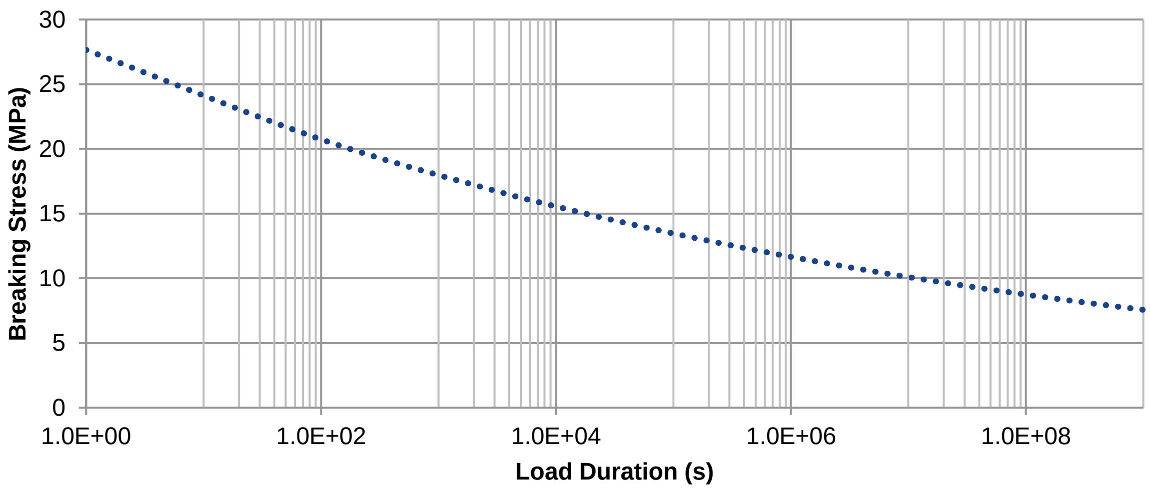



Figure 5 - Breaking Stress vs. Load Duration, based on prEN 16612 $k_{mod}$ Factors

## MEASURING THE STRENGTH OF GLASS

The strength of glass samples can be determined by a 4-point bend test, EN 1288-3 [7], which includes edge effects, or a co-axial double ring test, EN 1288-5 [8], which excludes edge effects. These are the standards referenced by the various product standards for annealed and treated soda-lime-silicate glass types when discussing the characteristic strength.

### CHARACTERISTIC STRENGTH & FRACTILE VALUES

The 5% fractile value of a glass type is typically presented as the characteristic strength. The below table shows the various characteristic strengths for the various SLS glass type;

Table 1 - Glass Strength Values

| Glass Type | | Product Standard | Mechanical Strength (5% Fractile) (N/mm²) |
|---|---|---|---|
| Soda-Lime-Silicate Glass | Float | EN 572-1 [9] | 45 |
| | Patterned/Drawn | | 24 |
| Heat Strengthened Soda-Lime-Silicate Glass | Float | EN 1863-1 [10] | 70 |
| | Enamelled | | 45 |
| | Patterned/Drawn | | 55 |
| Thermally Toughened Soda-Lime-Silicate Glass | Float | EN 14179-1 [11]<br>EN 12150-1 [12] | 120 |
| | Enamelled | | 75 |
| | Patterned/Drawn | | 90 |

The values are derived from test data, typically based on Weibull distributions, as shown below for as-received annealed float glass (Figure 6) and damaged glass (Figure 7) [13].

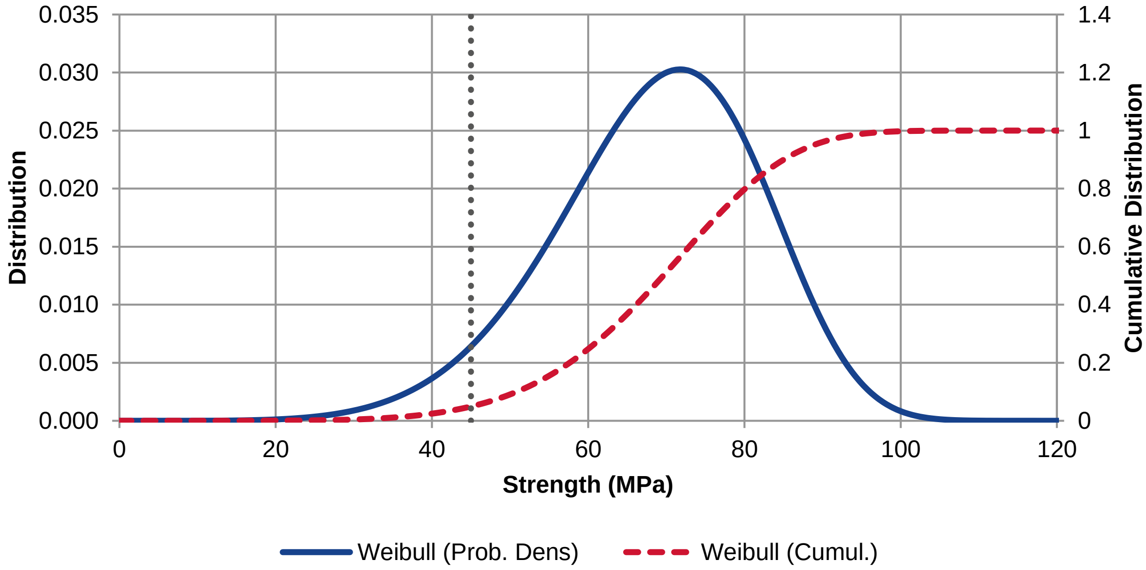



**Figure 6 - Characteristic Inherent Bending Strength, "As-Received" Glass (Weibull Distribution)**

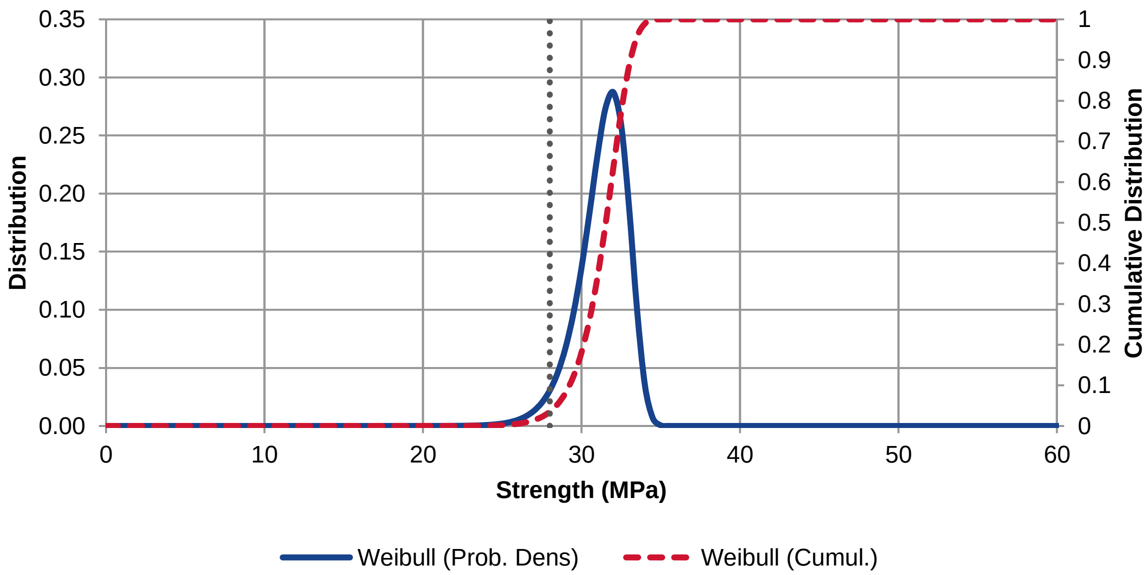



**Figure 7 - Characteristic Inherent Bending Strength, "Damaged" Glass (Weibull Distribution)**

Similar data is available for heat treated glass types, and some example data can be found in work by Mellman and Maultzsch [14] for float glass (Figure 8) and thermally toughened float glass (Figure 9).

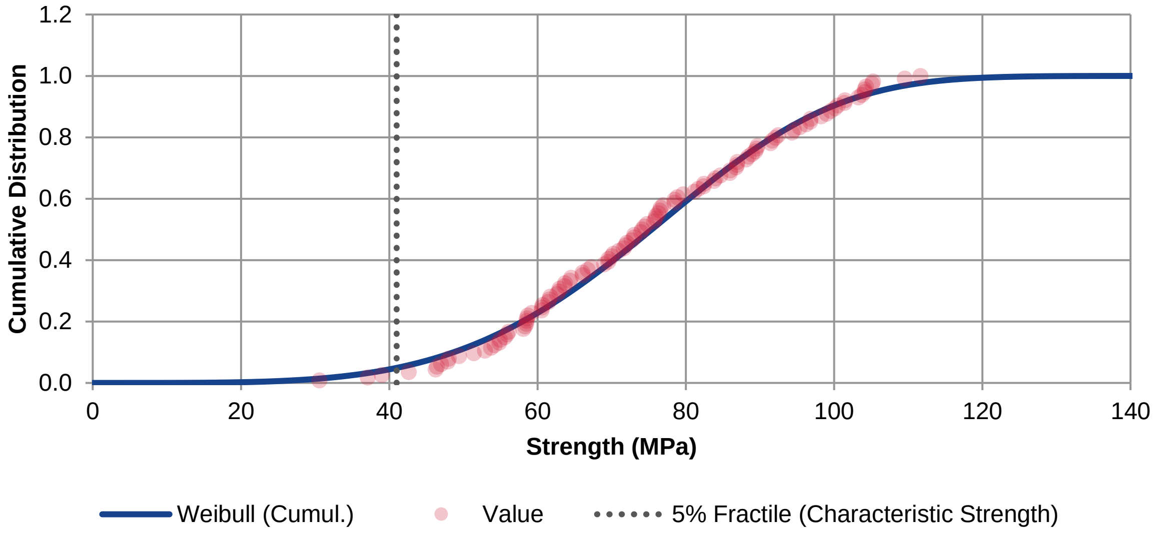



**Figure 8 - Characteristic Inherent Bending Strength, Annealed Float Glass (Weibull Distribution)**

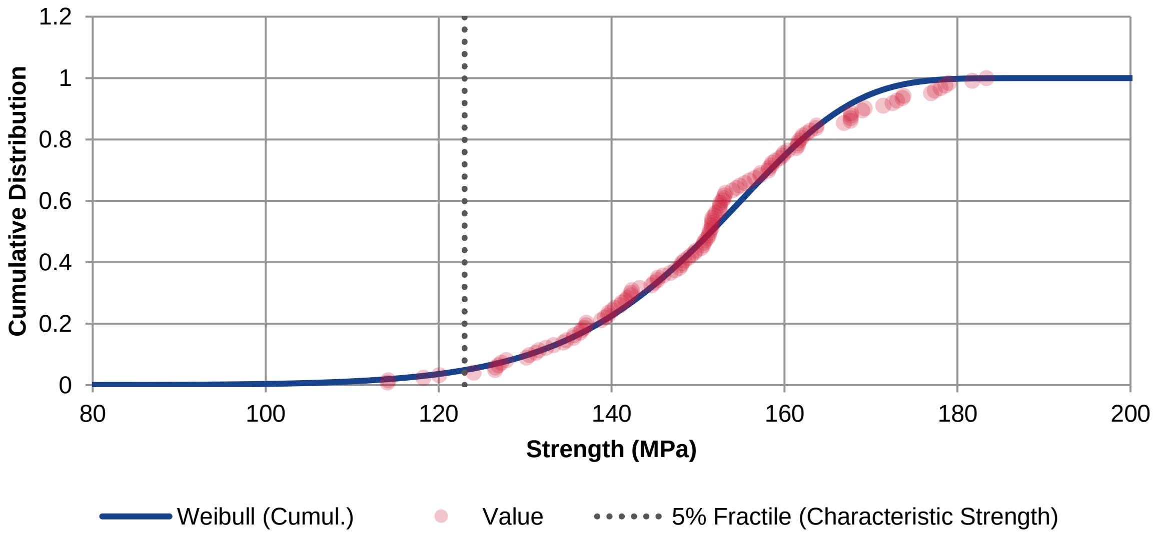



**Figure 9 - Characteristic Inherent Bending Strength, Thermally Toughened Float Glass (Weibull Distribution)**

## APPLICABLE DESIGN VALUES

Whilst the characteristic strength of glass will provide a statistical probability of expected strength, to accommodate uncertainties associated with the expected actions, resistance, and modelling of the loading, safety factors are introduced, either global or partial, depending on the design methodology.

Depending on the method or guidelines followed, the design strength, or permissible stress, of glass can be as low as 7 MPa for long term loads on annealed float glass; The following recommendations for allowable stresses are provided in Structural Use of Glass [13], which defines values based on load type and glass type;

**Table 2 - Glass Design Strength Values (IStructE)**

| Load Type | Load Example | Glass Type Allowable Stress (N/mm²) | |
|---|---|---|---|
| | | Annealed | Thermally Toughened |
| Short Term Body Stress | Wind | 28* | 59 |
| Short Term Edge Stress | Wind | 17.8* | 59 |
| Medium Term | Snow | 10.75 | 22.7 |
| Medium Term | Floors | 8.4 | 35 |
| Long Term | Self-Weight, Water, Shelves | 7 | 35 |

* Valid for annealed glass greater than 10 mm nominal thickness. For 6 mm nominal thickness glass, values may be multiplied by 1.4.

Values are also provided by German guidelines TRLV (Technical Rules for the Use of Line Bedded Glazing) [15] provides the following allowable stress limits;

**Table 3 - Glass Design Strength Values (TRLV)**

| Glass Type | Permissible Stress (N/mm²) | |
|---|---|---|
| | Vertical Glazing | Overhead Glazing |
| Thermally Toughened Float Glass | 50 | 50 |
| Thermally Toughened Patterned Glass | 37 | 37 |
| Enamelled Thermally Toughened Float Glass* | 30 | 30 |
| Heat Strengthened Glass | 29 | 29 |
| Enamelled Heat Strengthened Glass* | 18 | 18 |
| Annealed Float Glass | 18 | 12 |
| Annealed Patterned Glass | 10 | 8 |
| Laminated Annealed Float Glass | 22.5 | 15 (25**) |

* Permissible stress of enamelled surface.

** Allowable stress of lower laminated pane within an IGU in the even the upper pane has failed.

## REFERENCES

[1] F. Wallenberger and P. Bingham, Fiberglass and Glass Technology: Energy Friendly Compositions and Applications, Springer Science & Business Media, 2009.

[2] F. Liebau, Structural Chemistry of Silicates; Structure Bonding and Classification, Springer Science & Business Media, 2012.

[3] C. Inglis, "Stresses in a Plate Due to the Presence of Cracks and Sharp Corners, Transactions of the institute of Naval Architecture," *Engineering,* vol. 95, p. 415, 1913.

[4] A. Griffith, "The Phenomena of Rupture and Flow in Solids," Philisophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character, vol. 221, pp. 163-198, 1921.

[5] L. Grenet, "Mechanical Strength of Glass," *Enc. Industr. Nat. Paris,* vol. 5, no. 4, pp. 838-848, 1899.

[6] E. Shand, "Experimental Study of Fracture of Glass: II, Experimental Data," *Journal of the American Ceramic Society,* vol. 37, no. 12, pp. 559-572, 1954.

[7] European Committee for Standardization, EN 1288-3:2000 - Glass in building. Determination of the bending strength of glass. Test with specimen supported at two points (four point bending), CEN, 2000.

[8] European Committee for Standardization, EN 1288-5:2000 - Glass in building. Determination of the bending strength of glass. Coaxial double ring test on flat specimens with small test surface areas, CEN, 2000.

[9] European Committee for Standardization, EN 572-1:2012 - Glass in building. Basic soda lime silicate glass products. Definitions and general physical and mechanical properties, CEN, 2012.

[10] European Committee for Standardization, EN 1863-1:2011 - Glass in building. Heat strengthened soda lime silicate glass. Definition and description, CEN, 2011.

[11] European Committee for Standardization, EN 14179-1:2016 - Glass in building. Heat-soaked thermally-toughened soda lime silicate safety glass. Definition and description, CEN, 2016.

[12] European Committee for Standardization, EN 12150-1:2015 - Glass in building. Thermally toughened soda lime silicate safety glass. Definition and description, CEN, 2015.

[13] M. Haldimann, A. Luible and M. Overend, *Structural Use of Glass,* IABSE, 2008.

[14] G. Mellman and M. Maultzsch, "Untersuchung zur Ermittlung der Biegefestigkeit von Flachglas für bauliche Anlagen," Federal Institute for Materials Research and Testing, 1989.

[15] Deutsches Institut für Bautechnik, Technische Regeln für die Verwendung von linienförmig gelagerten Verglasungen (TRLV), DIBt, 2006.

[16] British Standards Institute, BS 6180:2011 - Barriers in and about buildings. Code of practice, BSI, 2011.

[17] T. Cottrell, The Strengths of Chemical Bonds, Butterworth Scientific Publications, 1958.