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Review of Glass Testing Data Sets and Design Strength Models

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Abstract

The design strength models in glass standards have evolved through a range of methodologies, each shaped by the assumptions, test methods and data sets available at the time. As there is no ideal model for all situations; new strength prediction models continue to evolve. This paper explores why stress probability integrals are useful for window glass and peak-stress based approaches are more suitable for structural applications, as well as why there is such a range of criteria published. Window glass is generally loaded out-of-plane and is thin relative to the target displacement. The resulting failure criterion is complex because the distribution of 'stressed area' to total area and biaxial vs uniaxial stress is a function of the load, aspect ratio and deflection to thickness ratio. The second order effects result in the system stiffening with increasing load. The maximum stress often occurs on the surface of the panel. By contrast, structural glass applications are generally loaded in-plane, typically slender, with second order effects increasing stress. The maximum stress often occurs at the edge or connection point of the panel. Key considerations include Griffith flaws, Brown's integral, flaw orientation, environmental effects, float glass characteristics, edge processing, and stress distribution patterns. In selecting design strength criterion for the Structural Glass Design Manual, the approaches of ASTM E1300, CEN/TS 19100, AS1288 and AAMA CW-12 were examined and conclusions drawn for the merits and limitations of each approach considered relative to its intended purpose.

Keywords

Structural Glass Design Manual, Failure criteria, Strength distributions, Testing populations, Characteristics glass strength, Surface conditions, Edge working, Peak stress, Probability integrals

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1. Introduction

When selecting design criteria for any material standard, there is always a compromise of sophistication versus simplicity. When selecting a strength model for the Structural Glass Design Manual (SGDM), 3 families of precedent strength models were considered:

- Weibull stress-probability-area integral:
  - ASTM E1300, CAN/CGSB 12.20
- Fixed Principal Tensile Stress:
  - CEN/TS 19100, EN 16612, DIN 18008 (Limit State)
  - AAMA CW- 12 Structural Properties of Glass (typically used with allowable stress methods)
- Variable Principal Tensile Stress:
  - AS1288

Each standard has certain advantages and disadvantages which arise from the derivations and selection of priorities for efficiency versus simplicity.

Within North America, ASTM E1300 and its cousin CAN/CGSB 12.20, are the most widely used standards for window glass design. In the absence of standards for structural glass applications, the stress design criteria therein have been applied to systems which are explicitly excluded from the scopes of the application of these documents. As there have been structural glass projects successfully completed and there is familiarity within North America with this standard by designers and engineers, it is worth understanding the document's history and its merits.

2. Introductory History of Glass Strength Models

Glass has been utilized and admired for hundreds of years, but it is only over the last 100 years or so that we have been able to better understand its unusual engineering properties and make predictive calculations. Some critical discoveries (not an exhaustive list) begin with understanding some of the phenomena associated with fracture mechanics. Beginning in 1899, L. Grenet's work provided us the first recognition that glass is a time-sensitive material. In 1913, Ingles developed equations for stress concentrations at the tips of elliptical holes and notches. Less than a decade later, Griffith (1920) realized that a similar approach could be taken to small flaws in brittle materials. Weibull (1939) created a hypothetical reliability distribution based on the idea of 'weakest link in a chain,' which scaled based on the number of links in the chain. This was found to also have good representation of the scalability of area for surface flaws and volume to volume flaws. Further understanding of rapid unstable brittle fracture was developed by Irwin (1957) with the concept of stress intensity factors and the instantaneous brittle fracture criterion K_{Ic}. Charles (1958) determined that the shape of the crack tip also reduced as a function of the applied tensile stress. Shortly thereafter, Gillman (1960) determined that single crystals had surface energies and the creation of cracks and/or the recoalescence of those cracks had an energy associated with it. Between 1967 and 1970, Wiederhorn (along with several co-authors) published a series of papers describing stable, or subcritical, crack growth which explained the static fatigue time dependency originally documented by Grenet 70 years prior. Brown (1972) developed a stress time history integral that utilized the aggregate subcritical crack growth to explain aggregate load cycle fatigue. In the early 1980's, non-linear behavior and the transition between bending and "sail-like" membrane action was considered by Abiassi (1981), noting that the peak stress is not linearly related to lateral load in thin flat plates. Computational modeling was becoming an effective tool by this time, with computers being able to process numerical models with a speed and accuracy that was previously impractical. Vallabhan's work in 1983 developed a non-linear plate analysis program whereby the non-linear bending to membrane transitions could be investigated with the associated peak stress and stress distributions. By the mid-1980's, Beason and Morgan (1984) (building on Beason's 1980 PhD) combined all of these effects in a unifying glass failure prediction model, which would go on to create the basis of ASTM E1300 and CAN/CGSB 12.20.

2.1. ASTM E1300

At the time ASTM E1300 (E1300) was written in the late 1980's, powerful computers were generally limited to large universities or large engineering companies but were not available with suitable capacity for the typical glass engineer. As such, the format of E1300 was a series of design charts based on pressure and aspect ratio. The charts incorporated the stress integral based on a Weibull material strength model, non-linear behavior of thin plates, time effects and consideration of uniaxial-biaxial stress. The Weibull material parameters were developed from testing and consensus agreement. Importantly, testing included glass that was exposed to the natural environment with what was assumed to be a fully developed flaw distribution of a random nature. Correction factors were provided for load duration and later additional factors were added for laminated glass, insulating glass, and heat-treated glasses.

Prior to ASTM E1300-16, the actual time-stress-area-integral was not included in the publication, but with the widespread availability of powerful personal computers and suitable programs, the formula was included as a discretized version of the following:

$$P_b = 1 - e^{-B} \tag{1}$$

$$B = k \int_0^a \int_0^b \left[c(x,y) * \left(\frac{t_d}{60}\right)^{1/n} * (\sigma_{max}(x,y) - RCSS(x,y) \right]^m dydx \tag{2}$$

$$for\ (\sigma_{max}(x,y) - RCSS(x,y)) \geq 0 \tag{2a}$$

$$c(x,y) = -0.005r_i^6 + 0.022r_i^5 + 0.055r_i^4 + 0.039r_i^3 + 0.031r_i^2 + 0.060r_i + 0.8 \tag{3}$$

$$r_i(x,y) = \frac{\sigma_{min}(x,y) - RCSS(x,y)}{\sigma_{max}(x,y) - RCSS(x,y)} \tag{4}$$

Where:

- P_b = the probability of breakage
- k = (2.86 × 10-53 N-7 m12) or (1.365 × 10-29 in.12 lbf-7),
- m =7, is the Weibull modulus
- t_d = duration of loading (seconds),
- n = 16, is Charles' time dependency parameter
- σ_{max} = maximum principal (tensile) stress at the point (x,y)
- σ_{min} = minimum principal stress at the point ((x,y),
- $RCSS$ = residual compressive surface stress;
- $c(x,y)$ = Biaxial Stress Correction Factor

2.2. Merits and Limitations of E1300

Merits

- Excellent design efficiency for window glass and systems subject to lateral loading.
- Allows for the observation that the origin of fracture is associated with the flaw location interacting with tensile stress and not necessarily the peak stress location.
- A correction factor "c" makes allowance for uniaxial and biaxial stress, which accounts for the random distribution of the flaw orientation relative to the stress field.
- A time correction factor "n" accounts for static load fatigue and equivalent aggregate load (nominally n=16 in ASTM E1300)
- The Weibull Modulus m is surface flaw parameter which is a measure of the variability of the probability of breakage against stress (nominally m = 7 in ASTM E1300)
- A surface parameter $k = 2.86 \times 10^{-53}$ $[N]^{-7}$ $[m]^{12}$ which relates the median strength of a reference area to the median strength – see also below.

Limitations

- ASTM E1300-24 expressly limits its scope to be (emphasis added):
  - "This practice covers procedures to determine the load resistance (LR) of specified glass types, including combinations of glass types used in a sealed insulating glass (IG) unit, exposed to a uniform lateral load of short or long duration, for a specified probability of breakage."
  - "This practice shall **not** apply to other applications including, but not limited to, balustrades, glass floor panels, aquariums, **structural glass members**, and glass shelves."
  - "This practice applies only to monolithic and laminated glass constructions of rectangular shape with continuous lateral support along one, two, three, or four edges."
  - "This practice does **not apply** to any form of wired, patterned, sandblasted, drilled, notched, or grooved glass. This practice does not apply to glass with **surface** or **edge treatments** that reduce the glass strength. NOTE 1—Ceramic enamel is known to affect glass load resistance. Consult the manufacturer for guidance."

This essentially precludes the use of ASTM E1300 for structural applications, which are frequently controlled by in-plane loading and stresses at edges or holes. Throughout the publication of E1300, limiting tensile stresses, based on a lower-bound envelope of common sizes and aspect ratios, were included as an appendix. Perhaps the greatest difference between E1300 and the principal tensile stress standards is the inclusion of a biaxial stress correction factor. (By consensus, m is considered to be 7 in ASTM E1300)

Table 1: Biaxial Stress Correction factor as presented by Beason and Morgan (1984).

Ratio of minimum to maximum principal stress, n	BIAXIAL STRESS CORRECTION FACTOR											
	Integer Values of m Surface Flaw Parameter											
	4 (2)	5 (3)	6 (4)	7 (5)	8 (6)	9 (7)	10 (8)	11 (9)	12 (10)	13 (11)	14 (12)	15 (13)
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.80	0.91	0.91	0.91	0.92	0.92	0.92	0.92	0.93	0.93	0.93	0.93	0.93
0.60	0.84	0.85	0.86	0.86	0.87	0.88	0.89	0.89	0.90	0.90	0.90	0.91
0.40	0.78	0.80	0.82	0.83	0.85	0.86	0.86	0.87	0.88	0.89	0.89	0.90
0.20	0.75	0.78	0.80	0.81	0.83	0.84	0.85	0.86	0.87	0.87	0.88	0.89
0.00	0.72	0.76	0.78	0.80	0.82	0.83	0.84	0.85	0.86	0.87	0.87	0.88
—0.20	0.71	0.74	0.77	0.79	0.81	0.82	0.83	0.84	0.85	0.86	0.87	0.87
—0.40	0.69	0.73	0.76	0.78	0.80	0.81	0.83	0.84	0.85	0.86	0.86	0.87
—0.60	0.68	0.72	0.75	0.77	0.79	0.81	0.82	0.83	0.84	0.85	0.g6	0.87
—0.80	0.67	0.71	0.74	0.77	0.79	0.80	0.82	0.83	0.84	0.85	0.85	0.86
—1.00	0.66	0.70	0.73	0.76	0.78	0.80	0.81	0.82	0.83	0.84	0.85	0.86

The biaxial stress correction factor can be thought of as the distribution of the flaw orientation to the principal tensile stress and is the element most conspicuously absent from the principal tensile stress only approaches. By evaluating both the principal tensile stress and the perpendicular stress at the various locations across thin window glass and integrating the probability, a process that is both sophisticated and complex, E1300 is able to deliver higher efficiency for a specific common application.

2.3. What Stress to Use?

It is important to understand that while glass strength distribution typically follows a Weibull Distribution, ASTM E1300 includes multiple non-linear considerations, hence the outcome is no longer a Weibull Distribution(Blanchet, Norville, and Morse, 2018). Further, the stresses in the appendices of E1300 have a convoluted derivation based on the lower bound of stress-area-probability integral conducted for many sizes and aspect ratios. In fact, many designs that conform with E1300 breach these stress limits.

It is noteworthy that the glass strength model used in E1300 is not based on a single set of test data; rather, it is based on a consensus agreement of appropriate values based in part on prior design experience, and which was further recalibrated with the conversion from 60second loads to 3 second gust as the basis of design loads.

Table 2: Extract from Beason and Morgan (1984) summarizing glass plate failure loads from various sample sets, the first 4 from testing by Beason and Morgan.

TABLE 3.—Comparisons of Failure Loads for Square Glass Plates

Source of glass strength (1)	GLASS PLATE FAILURE LOADS, psf[a]					
	Glass Plate Area Equal to 16 Square Feet[a]		Glass Plate Area Equal to 25 Square Feet[a]		Glass Plate Area Equal to 36 Square Feet[a]	
	Probability of failure equal to 0.008 (2)	Probability of failure equal to 0.500 (3)	Probability of failure equal to 0.008 (4)	Probability of failure equal to 0.500 (5)	Probability of failure equal to 0.008 (6)	Probability of failure equal to 0.500 (7)
GPL[b]	25.5	76.2	17.8	53.7	13.6	39.9
Anton[b]	23.6	86.1	15.9	59.3	11.8	43.5
Dallas[b]	30.3	91.4	21.5	64.1	16.4	47.3
New Float Glass[b]	96.4	192.5	68.9	132.2	51.1	96.2
PPG[c]	53.0	—	37.0	—	27.0	—
L.O.F.[c]	67.0	167.5	43.0	107.5	30.0	75.0

[a]1 psf = 47.9 N/m^2; 1 ft^2 = 0.093 m^2.
[b]Failure loads calculated using the failure prediction model and the corresponding surface flaw parameters.
[c]Failure loads obtained from industry literature (25,31).

Table 3: Surface Flaw Parameters determined by Beason and Morgan and the ASTM E1300 consensus values.

Data Set	m	k
GPL	m=6	k = 4.40 x lO^{-25} in^{10} lb^{-6}
Anton	m=5	k = 9.67 x lO^{-22} in^{10} lb^{-6}
Dallas	m=6	k = 2.09 x lO^{-25} in^{10} lb^{-6}
New Float Glass	m=9	k = 3.02 x lO^{-38} in^{16} lb^{-9}
ASTM E1300	m=7	k = 1.365x10^{-29}in^{12}lbf^{-7}

One of the challenges to the format of the equation in E1300 and Beason and Morgan is the unit format, where *a material property has variable units*. In response to the paper by Beason and Morgan, Walker (1985) proposes using the original Weibull format in terms of m and σ_0 (or S_o, which is customary in Canada) which makes comparison more effective.

2.4. WALKER FORMAT

George Walker (1985), in response to the Beason and Morgan paper, proposes that the format would have more significance if it were more similar to the original Weibull format with

$$B = \int_0^A k\left(\frac{c\,\sigma_{max}}{\sigma_0}\right)^m dA \tag{5}$$

Where c is a function of the biaxial (vs uniaxial) stress; σ_0 corresponds to the median failure stress of a brittle surface of unit area in uniform biaxial tension, i.e., with the principal stresses equal and c = 1; and, m and k are material surface flaw parameters. Walker states there is a direct relationship with the prior definitions of m and k, whereby:

$$\sigma_0 = \left(\frac{0.693}{k}\right)^{1/m} \tag{6}$$

Where σ_0 is the median stress of the Weibull distribution and $-ln(0.5) = 0.693$.

However, this still results in unusual units because B is dimensionless and k must account for the units of the integration, which can be further made intuitive with the following; here the format follows the glass strength model of Weibull with 2 parameters, m and σ_0, and an integration quotient, Q, which is a function of the unit systems.

$$P_b = 1 - e^{-B} \tag{7}$$

$$B = Q\int_0^a \int_0^b \left[c(x,y) * \left(\frac{t_d}{60}\right)^{1/n} * \frac{(\sigma_{max}(x,y) - RCSS(x,y))}{\sigma_0}\right]^m dydx \tag{8}$$

$$for\ (\sigma_{max}(x,y) - RCSS(x,y) \geq 0, and\, c\ and\, r\ as\ above \tag{8a}$$

$$Q_{m^2} = 0.693\ \frac{1}{m^2} \tag{9}$$

Here Q is a quotient selected to be consistent with the dimensional units of the area integration for σ_0 being the median stress for a 1m^2 sample. It should be noted that if converting between unit areas for a given glass, the measure of surface area also needs to be accounted for where:

$$\frac{\sigma_{o1}}{\sigma_{o2}} = \left[\frac{S_{E2}}{S_{E1}}\right]^{1/m} \tag{10}$$

Table 4: Integration Quotient, Q, as function of the reference size of σ_o and the units of integration.

Q	Integration Unit			
Ref. Subject size, per	m^2	ft^2	in^2	mm^2
m^2	**0.693**	0.0644	4.47E-04	6.93E-07
ft^2	7.46	**0.693**	0.004813	7.46E-06
in^2	1,074	99.792	**0.693**	1.07E-03
mm^2	693,000	64,382	447	**0.693**

Now the Beason and Morgan data can be compared using like terms

Table 5: Surface Flaw Parameters per Beason and Morgan and ASTM E1300 expressed as m and σ_0.

Data Set	m	k	σ_0 for ref area 1.0 in^2 (psi)	σ_0 for ref area 1.0 m^2 (MPa)
GPL	m =6	k = 4.40 x IO^{-25} in^{10} lb^{-6}	10,786	21.9
Anton	m =5	k = 9.67 x IO^{-22} in^{10} lb^{-6}	14,827	23.5
Dallas	m =6	k = 2.09 x IO^{-25} in^{10} lb^{-6}	12,211	24.8
New Float Glass	m =9	k = 3.02 x IO^{-38} in^{16} lb^{-9}	14,164	43.2
ASTM E1300	m =7	k = 1.365x10^{-29}in^{12}lbf^{-7}	12,616	30.5

Note that σ_0 is a function of the size of the reference area and units do not directly translate (Eq. 10).

It can be seen that the range of data at the median is highly disparate and from the table, the stress at a probability at 8:1000 capacity also ranges by a factor of 3-4 (Table 2 above) between maximum and minimum (the latter of which is in part due to the non-linear effect outside of the Weibull effects.)

3. Variable Datasets

Further to the work of Beason and Morgan, many other data sets also show a wide variety of outcomes.

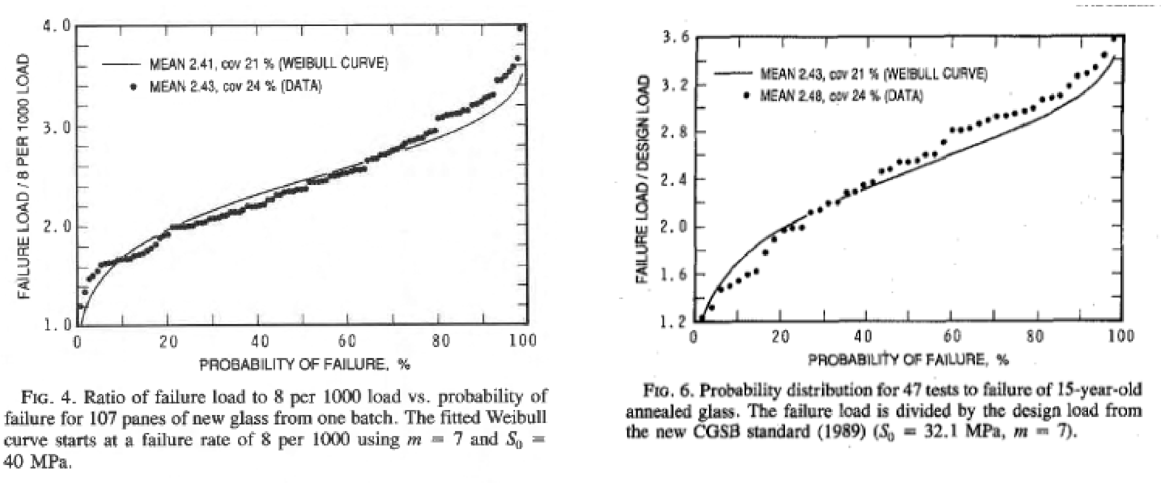

Fig. 1: Dalgleish and Taylor (1990– Ontario Research Foundation). New Glass 1524 x 2438 x 6 mm (left); 15 year old glass 4mm and 1.2 to 1.9m^2 with aspect ratios of 1 to 1.5 (right).

To illustrate the variance that is seen in different data sets, consider data sets from PPG 1957, Libbey Owens Ford 1973, Swedish 1979, Ontario R Foundation 1980, TTU 1983, Beason 1984, EN 1995, Morris 2019, Bowles Sugarman 1962, Libbey-Owens Ford 1973 (plate), Libbey-Owens Ford 1973 (sheet), TTU 1983, Norville 1993, Carre and Daudeville_1999. Individually the graphs look scattered (stress in ksi).

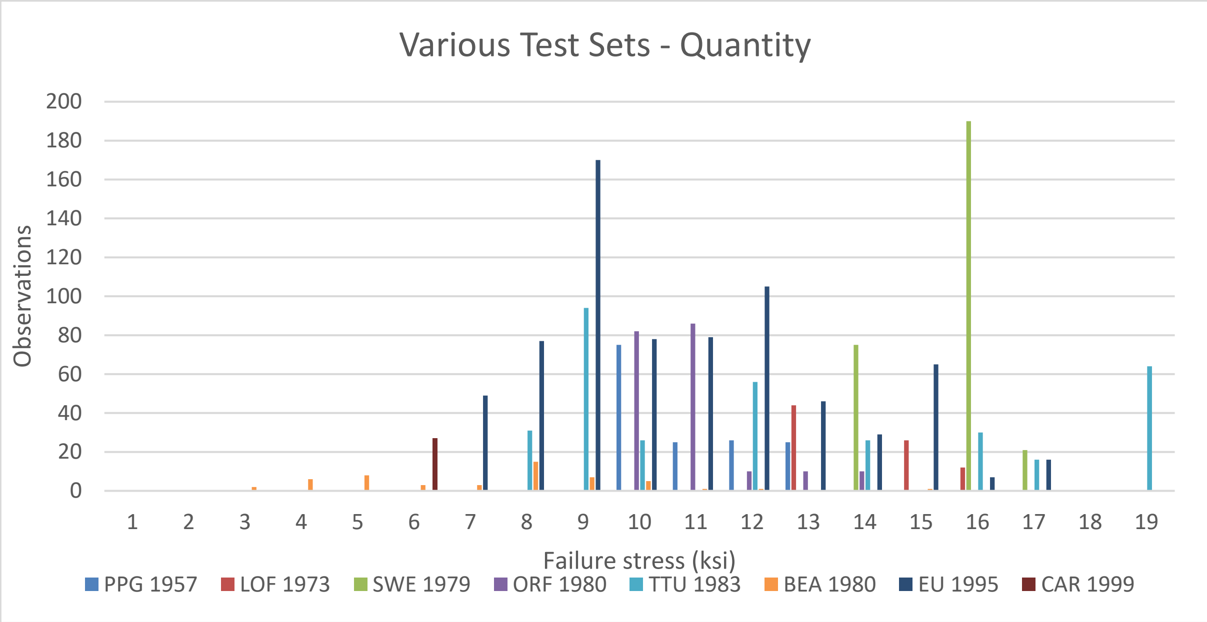

Fig. 2: Summary of available testing result expressed as stress – test quantity (ksi). Source: Structural Glass Design Manual (SGDM-PD2) – Appendix BB (2025).

(Note in the context of single-stress capacity models, area scaling has not been applied.) When the various test sets are totaled, a broader picture emerges:

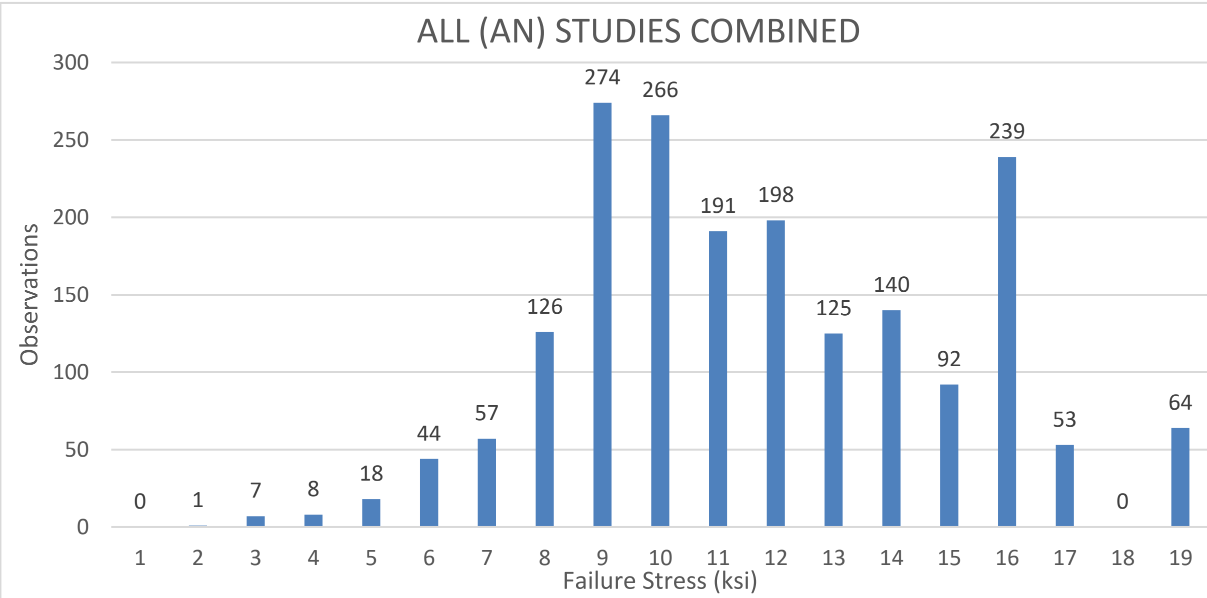

Fig. 3: Combined available testing result expressed as stress – test quantity (ksi). Source: Structural Glass Design Manual (SGDM-PD2)– Appendix BB (2025).

At a purely fracture stress basis, we can see that even with 1903 data points, the difference between various distributions is not great.

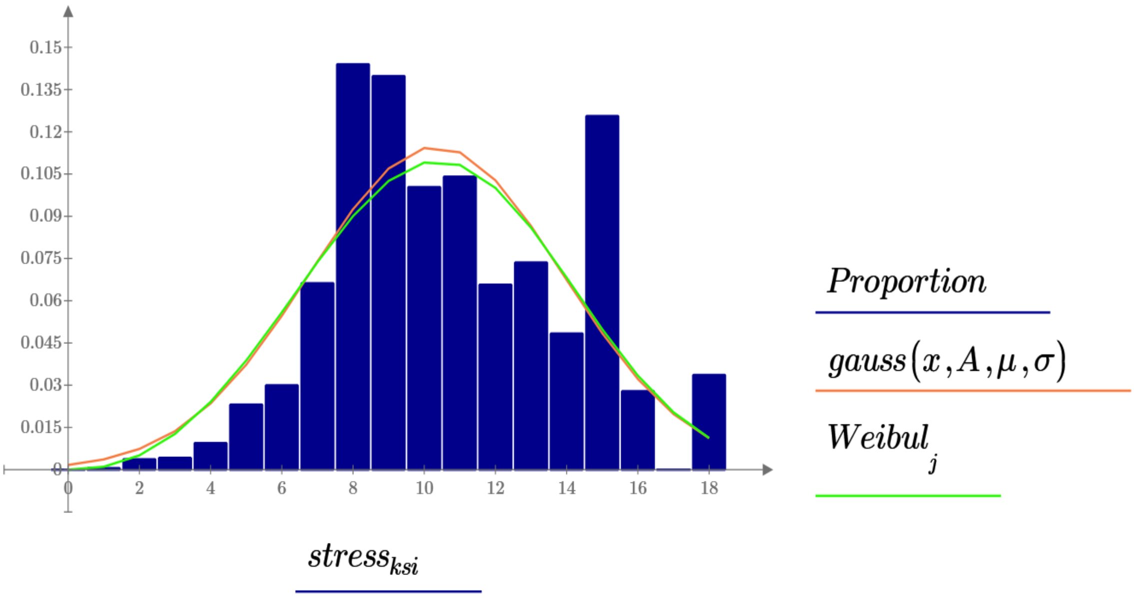

Fig. 4: Comparison of distributions.

One of the big questions for traditional US glass engineers, is 'How can glass, which according to AMMA CW 12-84 with a mean modulus of rupture of 41MPa (5.9 ksi) @60 second load, 49MPa (7.1 ksi) @3 second load have a characteristic stress with a 5% fractile of 45MPa (6.5 ksi)?' The AAMA number is representative of the weathered glass subset only. Taking the AAMA approach for weathered glass, with mean of 45MPa (6.53 ksi) and a Coefficient of Variation of 0.25, the fit to the overall distribution is poor.

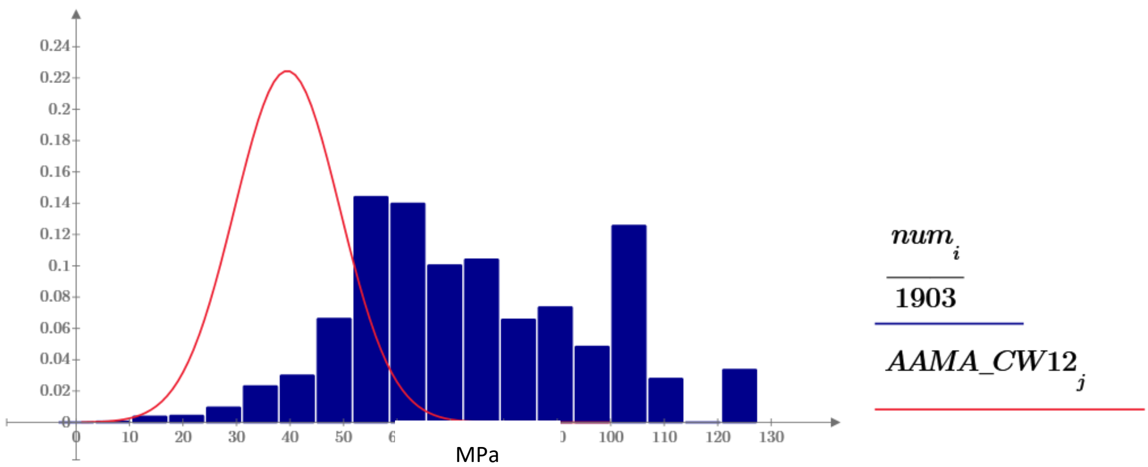

Fig.5: SGDM Figure BB.3 AAMA CW-12-84 probability density curve compared to the combined data sets (MPa)–.

While the AAMA figures are useful for design of glass for in-service conditions, representing the weathered state of glass, the consideration of only part of the distribution has serious implications for the conclusions from testing, thus the full picture must be considered. Conversely the EU standards are based on an extensive review of fresh and abraded glass from 9 manufacturers.

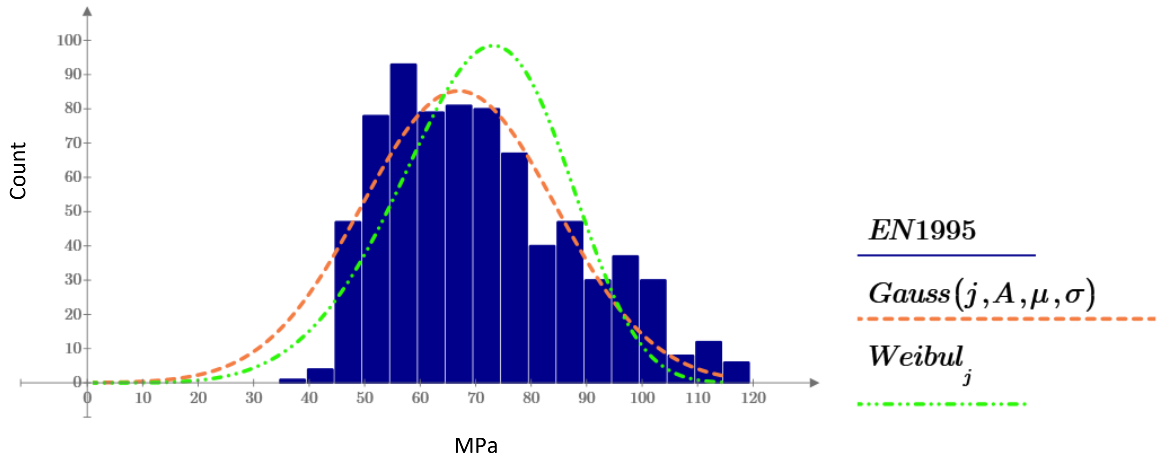

Fig. 6: SGDM BB1. 4: The failure distribution of 'fresh' annealed glass (MPa) from nine different European factories (Structural Use of Glass in Buildings (Second Edition), February 2014 by The Institute of Structural Engineers) with curve fits to Normal (Gaussian) distribution and Weibull Distribution.

The fit to the critical left side of the strength distribution can be explained by the incomplete development of the flaw distribution.

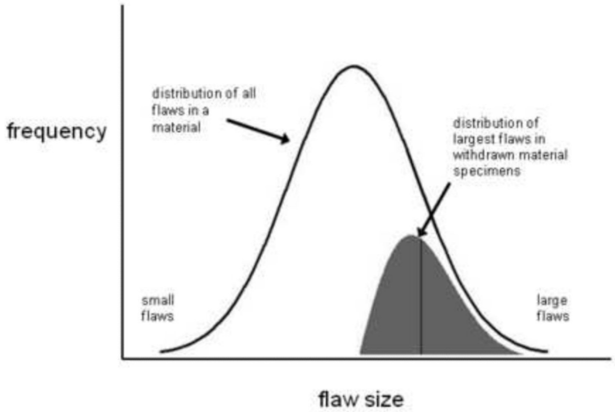

Figure 1.
Total flaw distribution in a material (curved line). Withdrawing multiple test pieces from the total flaw population and collecting the largest flaw from each test piece results in a different distribution of "largest flaws" (shaded area).

Fig. 7: – Extract of extreme flaw distribution from Quin-Quin (2010).

As the flaw population becomes more developed, the tail to the right side becomes more developed and the distribution of the extremes moves further to the right. The strength distribution, which is related inversely to the square root of the flaw by equation 11, will become more developed to the left, which is eloquently explained in Quin and Quin (2010).

$$\sigma_f = \frac{K_{Ic}}{Y\sqrt{c}} \tag{11}$$

Where σ_f is the fracture stress at the origin; $K_{Ic}$is the fracture toughness (or Mode I critical stress intensity factor); Y is the stress intensity shape factor - a dimensionless, material-independent constant, related to the flaw shape, location, orientation and stress configuration; and c is the flaw size.

It is worthwhile noting that both Y and c are distributions. The difference between 'fresh glass' and abraded glass is evident in the testing performed developing the strength model for prEN13474/EN16612. The abraded glass combined with ring-on-ring tests results in a near uniform failure stress (figure 9) at the lower bound of the fresh glass (figures 7 and 8) because of the uniform flaw distribution in a uniform bi-axial stress field which eliminates the distributions of flaw orientation and stress at a location. Perhaps the greatest in-principle difference between EN16612 and CEN/TS 19100, and ASTM E1300 is the incorporation of the biaxial stress correction factor in E1300 which accounts for the distribution of flaw orientation and the variation of both principle stresses on the surface of a window glass loaded out of plane as a function of pressure and location.

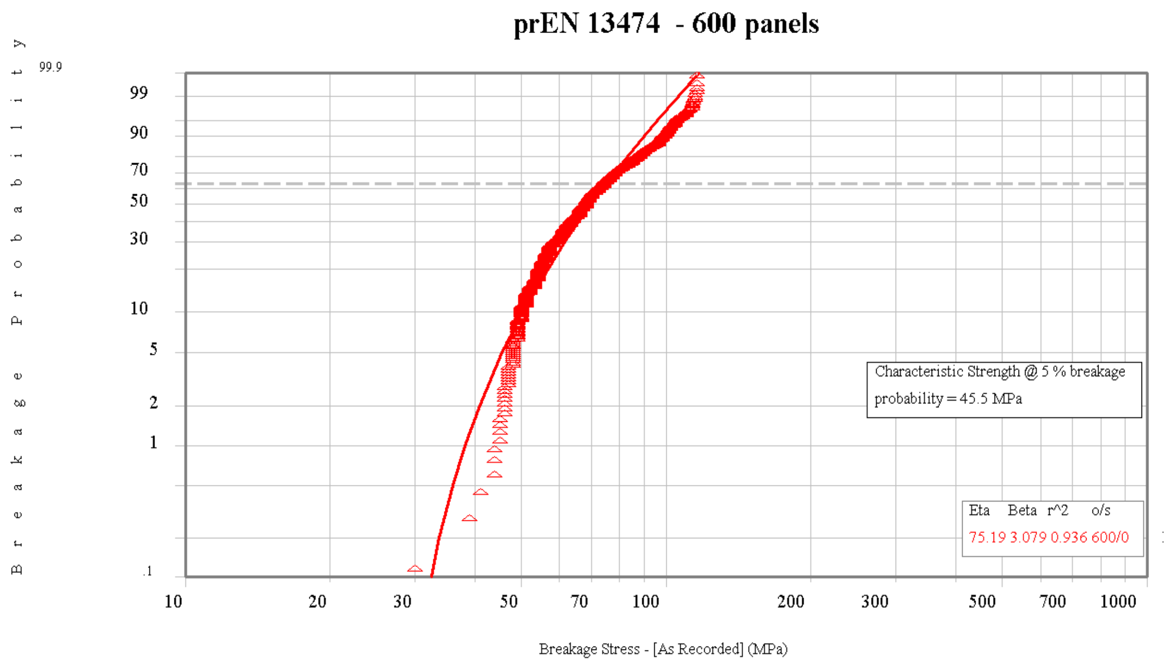

Fig. 8: Weibull distribution – 3 Parameter (Graph courtesy of Dr Leon Jacobs).

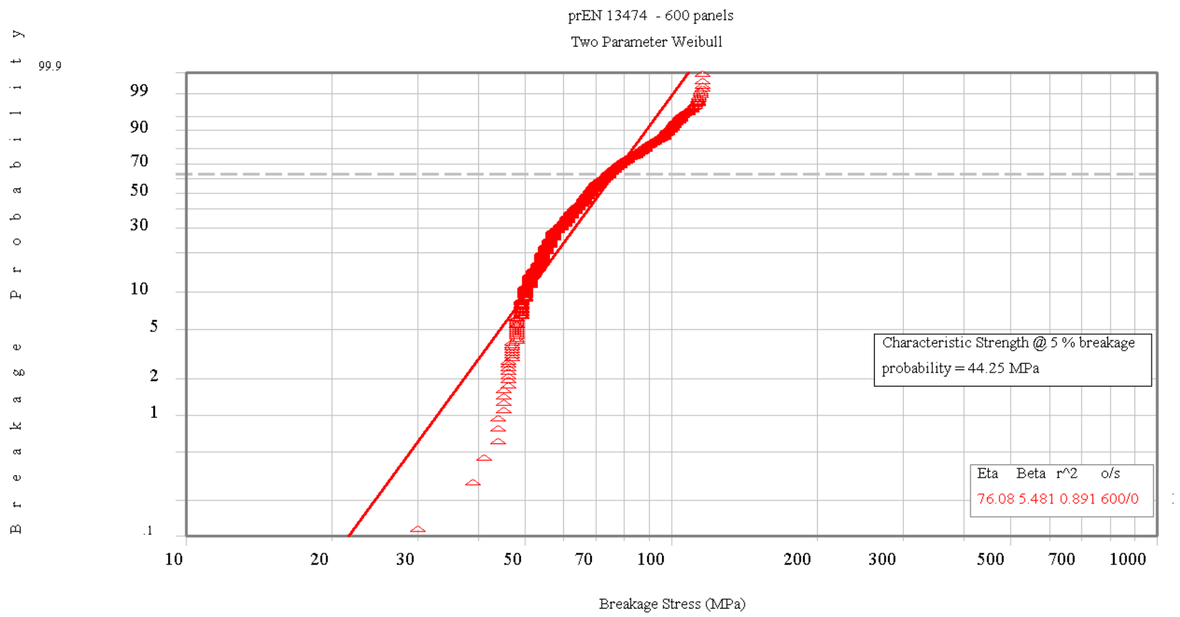

Fig. 9: Weibull distribution – 2 Parameter (Graph courtesy of Dr Leon Jacobs).

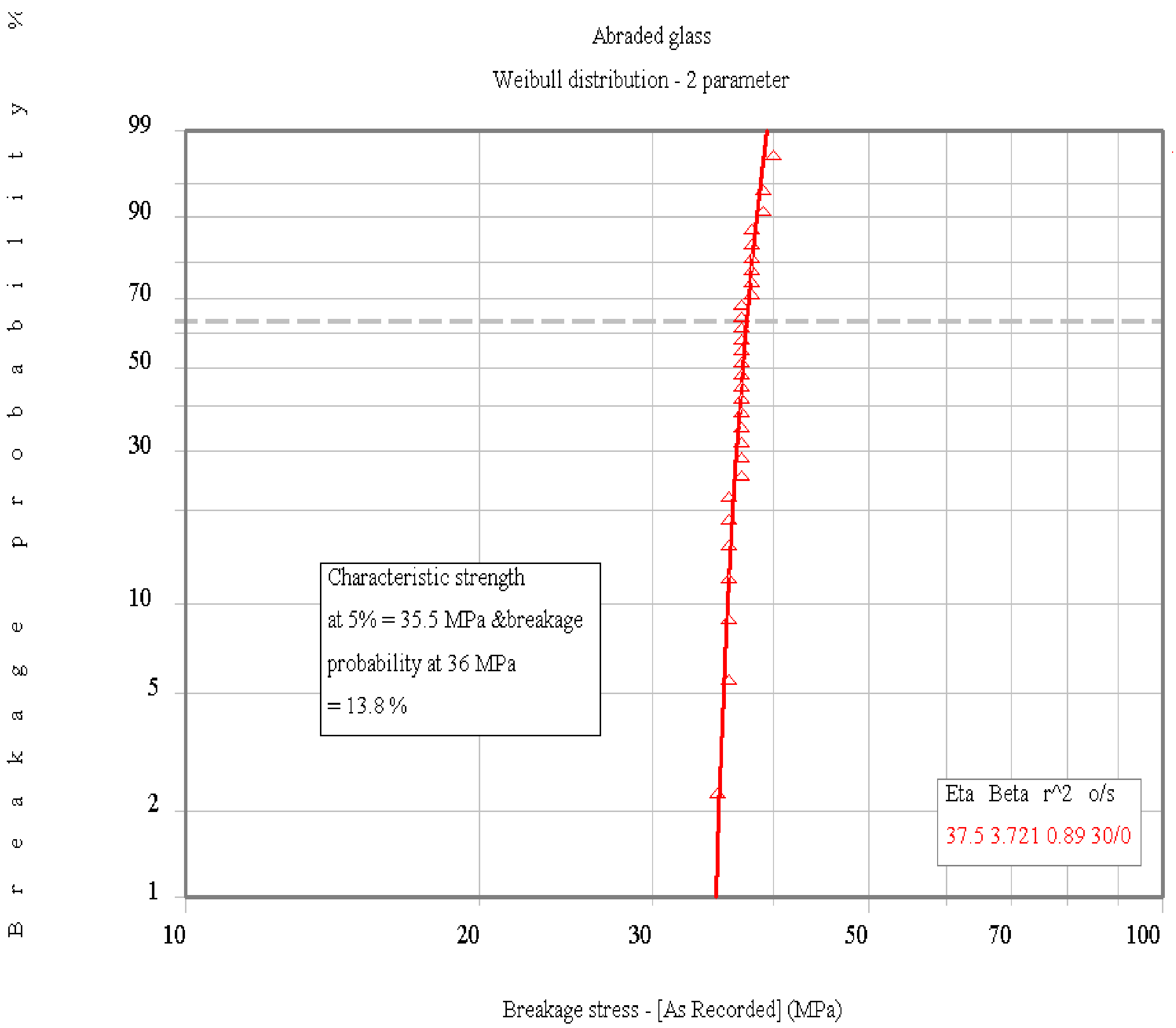

Fig. 10: Weibull Distribution for Abraded Glass – 2 Parameter – note the different x-scale (Graph courtesy of Dr Leon Jacobs).

It can be seen in Figure 9 that the Weibull chart is close to vertical, which would suggest that a singular value is appropriate for design. The form of glass strength in CEN/TS 19100 (which is the same for annealed and has an additive approach for Residual Compressive Surface Strength (RCSS)):

A.3 Bending strength resistance based on nominal product strengths

(1) The design value of the strength of glass is

$$f_{g,d} = k_e \cdot k_{sp} \cdot \lambda_A \cdot \lambda_l \cdot k_{mod} \cdot \frac{f_{g,k}}{\gamma_M} + k_p \cdot k_{e,p} \cdot \frac{f_{b,k} - f_{g,k}}{\gamma_p} \quad (A.1)$$

where

$f_{g,d}$ is total design bending strength

$f_{g,k}$ is characteristic bending strength of annealed glass (see Table 5.2)

$f_{b,k}$ is characteristic value of glass strength after a strengthening treatment (see Table 5.3)

γ_M is material partial factor (see Table 8.1)

γ_p is partial factor for pre-stress on the surface (see Table 8.1)

k_e is edge or hole finishing factor (see Table A.1)

k_{sp} is surface profile factor (see Table A.2)

k_{mod} is modification factor (if annealed glass is used see Table A.3, in all other cases k_{mod} = 1,0)

λ_A see NOTE

λ_l see NOTE

k_p is pre-stressing process factor (see Table A.4)

$k_{e,p}$ is edge or hole pre-stressing factor (see Table A.5)

Fig. 10a: Extract from CEN/TS 19100.

8.2 Partial factors

(1) The partial factor γ_M shall be applied to the characteristic values of the following properties: strength resistance of glass as well as mechanical resistance of glass components and their joints.

(2) The partial factor γ_P shall be applied to the characteristic value of the following property: pre-stress.

NOTE The values for γ_M and γ_P are given in Table 8.1 (NDP) unless the National Annex gives different or more differentiated values.

Table 8.1 (NDP) — Partial factors γ_M and γ_p for glass

Design situations		Class of consequences		
		CC1	CC2	CC3
Persistent & Transient (fundamental combination)	Basic material γ_M	1,6	1,8	2,0
	Surface pre-stress γ_P	1,1	1,2	1,3
Accidental	Basic material γ_M	1,0	1,1	1,2
	Surface pre-stress γ_P	1,0	1,0	1,0

NOTE Annex A or Annex B gives guidance on applying partial factors γ_M and γ_P.

Fig. 10b: Extract from CEN/TS 19100.

It should be noted that the CEN/TS format has a more generalized scope than ASTM E1300 and there are good reasons why both approaches may be appropriate for their respective scopes. There are some considerations of why this 'single value' outcome was arrived at, and why they have suitable simplicity.

3.1. Types of Testing

There are multiple types of testing performed on glasses at both laboratory scale and architectural scale. Some of those used are:

Table 6: Examples of various tests used to determine strength of glass.

Standard	Test Type	Description
EN 1288-2	Coaxial double-ring test (large area)	Flexure test with large stressed area.
EN 1288-3	Four-point bending	Specimen supported at two points, loaded at two points.
EN 1288-4	Channel-shaped glass testing	Special geometry testing for channel glass.
EN 1288-5	Coaxial double-ring test (small area)	Flexure test with small stressed area
ASTM C158	3 point bending ("Modulus of Rupture")	Specimen supported at two points, loaded at one point.
ASTM C158	4 point bending (1/4 points) ("Flexural Strength")	Specimen supported at two points, loaded at two points.
JIS R 3111-3	4- point bend test (1/3 points)	Specimen supported at two points, loaded at two points.
	Pressure Chamber Testing	Testing full-scale samples with pressure.
	Water table testing	Similar to pressure chamber testing but water is less compressible and has less stored energy at fracture.
ASTM C1421	Double cantilever	Small scale laboratory testing to determine K1C
	V-groove	

Each test has its own advantages and disadvantages, so it needs to be understood that the same material may have different results with different methods. For example, as the ring-on-ring test produces a state of biaxial stress, it has the asset that it records the strength of the most significant flaw, regardless of orientation. Conversely, it provides no information about the influence of flaw orientation on the probability of breakage. Similarly testing only 'as delivered glass' and abraded glass may have the effect of creating unnaturally uniform flaw densities with lack of natural variation.

ASTM E1300 incorporates many useful features that follow theoretical fracture mechanics, including additional factors for uniaxial stress vs biaxial stress, load duration, and integration of area. However, while E1300 follows good theoretical logic and is thus scalable; however, it is questionable whether the underlying data is sufficiently accurate to justify the precision of the calculation. Ultimately both systems have errors which are as deterministic through consensus as they are probabilistic.

Whereas ASTM follows a theoretically rigorous process which is scalable delivering efficient designs, it is complex to implement outside of the designated scope of lateral loads on edge supported glass. The CEN process is more general and makes some bounding approximations that allow use of a single principal tensile stress as the controlling factor.

Australian Standard AS1288 takes a compromise approach, where the available design capacity is a function of the thickness of the glass; as the glass gets thicker the available strength is reduced. The logic has a basis on both practical handling and overall risk. Thicker glass tends to be heavier, so may tend to develop deeper flaws in handling; and, thicker glass tends to be used in either larger applications or more structurally critical ones, thus it allows a degree of area scaling while maintaining the simplicity of principal stress analysis.

It is perhaps worth noting that CEN/TS 19100 and AS1288 were both developed after non-linear finite element programs on personal computers became more readily available. Consequently, the non-linear membrane components could be addressed in the analysis rather than in the standardized procedure.

4. Strength Model Simplifications

Whereas CEN/TS 19100, and its uncles DIN 18008 and EN 16612, are based on the simplest single-characteristic-strength model in that it uses a set characteristic principal tensile stress limit that is fixed, and using several modification factors for load duration etc, the standards have sophisticated methods for calculation of isochoric pressure effects in insulating glass units. By comparison, ASTM E1300 has sophisticated methods suitable for window glass yet only a simple glass type factor associated with insulating glass.

Each standard includes areas of sophistication and simplification based on its noted prioritization, and what is deemed to be practical for usage at the time the standard was developed.

5. The Structural Glass Design Manual

The Structural Glass Design Manual (SGDM) gives priority to reliability and robustness of glass design for non-window applications in the context of the design environment in North America to cover scope items excluded from coverage under ASTM E1300. Unlike windows, the system is typically loaded in-plane with linear elastic behavior, the maximum tensile stress location does not move due to the load magnitude, and the critical location is often at an edge or connection. Bukeida et.al. (2004) confirmed that the strength at the edge is strongly a function of the processing methods that are undertaken. Additionally, where the peak stress is at a connection point, it has a relatively small area. In that context there is not sufficient data to have sophisticated strength models to compare with stochastic loads with the aim of extracting maximum efficiency.

In fact, one of the common observation and associated design principles of structural glass is that the loss of strength is due to non-design events, such as rigid body impact and chips, inclusions and other formation defects, or installation deficiencies and damage. As a consequence, loss of strength is typically limited to one ply in a laminated unit and the glass is not under peak load at the time of fracture. Here the mode of behavior, preventing disproportionate collapse under non-design events to which glass is vulnerable, is more important and a greater risk than fracture due to actions exceeding resistance. Given the complexity and subjectivity of system behavior, as well as variability of the available data, a simplified strength model is appropriate.

The strength model used in the Structural Glass Design Manual has many parallels in the development of CEN/TS19100, which should not be surprising as they were developed at a similar time for similar purposes.

As noted above, the Weibull and Normal have a similar form, however Weibull is more convenient for cumulative distribution functions and area scalability. When dealing with structural glass systems with local stress concentrations, the Normal distribution also has merits. The variability of the data between various data sets (and indeed relative to the consensus strength models in standards) is arguably greater than the difference between the Normal and Weibull distributions. As a consequence, normal is used as a convenient basis for example comparisons and small sample testing statistics. In testing, small variations around as tested values will be adequately approximated by the Normal Distribution for full-scale testing of samples with a representative size, even where the underlying strength model has basis in Weibull.

6. Conclusion

Material standards describing the resistance capacity of a system in a particular circumstance must make some simplifications and include a degree of deterministic selection of appropriate limits through a consensus process. Each standard is a function of the information and analysis tools available at the time. It is also strongly influenced by the scope and intent of the standard, with narrower scopes permitting less generalization and more sophistication within the prioritized scope. Although ASTM E1300, CEN/TS 19100, AAMA CW19, AS 1288 and the Structural Glass Design Manual have strength models that appear to be very different, they are all considering the same material from a viewpoint of different sub-sets of data and different priorities of where to simplify and where to maintain sophistication or complexity.

When selecting a strength model for the Structural Glass Design Manual, it was noted that maximum tensile stress with a typically conservative lower bound was appropriate given the degree to which edge strengths are variable. The strength model is substantially consistent with the approach in CEN/TS 19100, which has a similar scope. Instead, priority in the SGDM was given to reliability and robustness, which are documented in detail, because glass is vulnerable to fracture from events at less than design load. By prioritizing the mode of breakage, the risk of disproportionate collapse due to non-design loads is mitigated. As the dynamic impact of sudden stiffness loss should a component of a glass element fail under load, it is important to also target a conservative approach to the design strength, even if the peak stressed area is small, as is achieved by the methods in CEN/TS 19100 and the Structural Glass Design Manual.

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ASTM International – ASTM E1300-24 Standard Practice for Determining Load Resistance of Glass in Buildings

ASTM International - ASTM E2353-21 Standard Test Methods for Performance of Glazing in Permanent Railing Systems, Guards, and Balustrades

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