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Testing of Structural Glass Elements: Background and Methods in the Structural Glass Design Manual

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Abstract

Testing forms an important part of designing structural glass systems. Glass systems lack ductility and are intolerant to incorrect assumptions, so validation testing, even when calculations are well prepared, performs an important role. Design standards with equations for the applicable limit states are available for most structural materials and are the most common approach. “Rational analysis” based on published papers and engineering fundamentals is another approach where there are gaps in the local codes and standards. Another method is “design by testing” which can be a great approach to optimize the design and calibrate the limit state if used correctly. However, as our standards have been advanced to cover more of the limit states with empirical formulas, practicing engineers have had less exposure to “design by testing” and we have seen inconsistencies in the application of this method in practice such as consideration of “validation by testing” to be equivalent to full justification. This paper is intended to walk through the “design by testing” method, highlighting on appropriate references, statistical analysis of the results and the appropriate reliability and safety factors to align with the standardized reliability objectives. The paper will also highlight the difference between “design by testing” and “validation by testing” and discuss the objectives of each approach, how they can be employed in practice, and how they are addressed within the Structural Glass Design Manual.

Keywords

Glass, Design by Testing, Validation by Testing, Glass Strength, Reliability, Statistics

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1. Introduction

Glass is a material that lacks ductility and fails by rapid progression of cracks throughout the entire body initiating from surface flaws. With the failure mechanism governed by fracture mechanics and flaw distribution, the engineered systems can be sensitive to both modelling assumptions and the practical manufacturing, fabrication, and construction techniques utilized to build the system. Furthermore, as glass becomes 'weathered' and it gains additional or larger flaws, there is a question of whether the glass at the time of testing is representative of the glass for the in-service condition. Evidence of the extent of strength shift can be seen even in international standards where standards such as EN16612, CEN/TS 19100, DIN18008 are based on a Characteristic Stress (5% fractile) of 45 MPa (6,526 psi), whereas the AAMA CW-12-84 states an average 60 second modulus of rupture is equal to 41.3 MPa (6,000 psi). How can the average of one set be less than the characteristic of another for the same material? The AAMA source data is based on 'weathered glass' versus the European model which is based on fresh glass source data. When it comes to testing glass, it is improper to discount either of these numbers and it is important to understand their significance when testing glass assemblies and assessing the statistical significance of the results. The weathered portion of the strength distribution is a subset of the total distribution. If testing was analyzed assuming the weathered part was the entire distribution, then testing with 'new glass' would be highly misleading, potentially producing an unexpectedly high capacity. Equally, if it were not recognized that edge preparation and/or weathering affected the glass strength, suitable adjustments to interpretations of the testing results could not be made.

See also separate papers about strength distributions in this conference and in the reference material of The Structural Glass Design Manual.

2. Design by Testing and Validation Testing

Design by testing is an acceptable engineering principal that allows for a certain number of representative test samples to a load higher than the design load, using statistics to predict a valid load resistance within a certain degree of confidence.

Validation Testing assumes that adequate design and calculations have previously been performed on the same material and limit state as a test for design application which usually involves a small sample size (often a single test) to check that the result will be predictable within the bounds of the previous calculation checks and does not miss a lower bound failure mode. These tests do not achieve statistical significance but still serve an important role in understanding the system limit state. Frequently this is referred to as a 'proof test' with a load applied that is 1.5x the ASD (Allowable Stress Design: typically, 1 in 50 year mean return period according to ASCE7-22) level load or in more recent practice, the factored strength limit state load (also known as the LRFD load in US based standards or Strength Limit State and Ultimate Limit State load elsewhere.) Typically, the tests are performed at full-scale with production methods that are representative of the population. A validation test demonstrates that there is not something fundamentally inadequate with the design proposed, but cannot, on its own, be relied upon to determine the adequacy of the system. This type of test includes the factor(s) for the variation in load (demand), but not a variation in the strength of the system (resistance). The reason that validation testing is not definitive is that the probability of selecting a sample from the bottom 5% of the strength population is small i.e. there is a 95% chance that the strength of the sample will be higher than the nominal strength.

For glass, where the variation in strength is potentially significant, the distinction between test types is more significant than for materials with low variation and ductile failure mechanisms that allow load redistribution before failure.

When conducting design by testing, an additional testing factor k_t based on the coefficient of variation of the material and the number of units tested is applied to the applied load or minimum failure load. According to Australian Standard AS1170.0 Appendix B, the k_t value is a testing factor that accounts for variability of the structural units tested and is always greater than 1.0. The principles in Australian Standard AS1170.0 Appendix B have been used as a precedent for the testing section of the Structural Glass Design Manual with the more recent statistical model based on the work of Wang and Pham (2011), which provides a formula to establish the testing capturing the effects of: the coefficient of variation due to materials and fabrication; the target reliability index through percentage failure and Confidence Interval; and the number of tests.

- coefficient of variation (COV, CV or V_{sc}) –
    - The coefficient of variation (CV) is defined as the ratio of the standard deviation σ to the mean μ, $CV = \frac{\sigma}{\mu}$.and is often expressed as a percentage. It shows the extent of variability in relation to the mean of the population.
    - When only a sample of data from a population is available, the population $\widehat{CV}$ can be estimated using the ratio of the sample standard deviation s to the sample mean $\bar{x}$: $\widehat{CV} = \frac{s}{\bar{x}}$, But this estimator, when applied to a small or moderately sized sample, tends to be too low: it is a biased estimator. For normally distributed data, an unbiased estimator for a sample of size n is: $\widehat{CV}^* = (1 + \frac{1}{4n})\widehat{CV}$ (https://en.wikipedia.org/wiki/Coefficient_of_variation) An alternative is to use a confidence interval for COV based on the Chi-squared distribution as described below.
- Confidence Interval - A confidence interval (CI), for example 95% confidence interval, is a range of values, *calculated from sample data*, that is likely to contain the *true population* parameter about 95% of the time if the experiment were repeated many times. It reflects the reliability of the estimation method rather than a direct 95% probability for a single interval. It quantifies uncertainty, with narrower intervals indicating greater precision and wider ones suggesting more variability in the data or smaller sample size and is crucial for assessing statistical significance.
- Reliability index - The reliability index is a statistical measure used to assess the safety and performance of structures under various loads. It quantifies the likelihood that a structure will perform adequately without failure. (ASCE 7-22)

As the number of tests increases, the probability of achieving representative sampling from across the strength distribution increases, and therefore the k_t parameter lowers because the dependability of the overall data increases as the number of test samples increases.

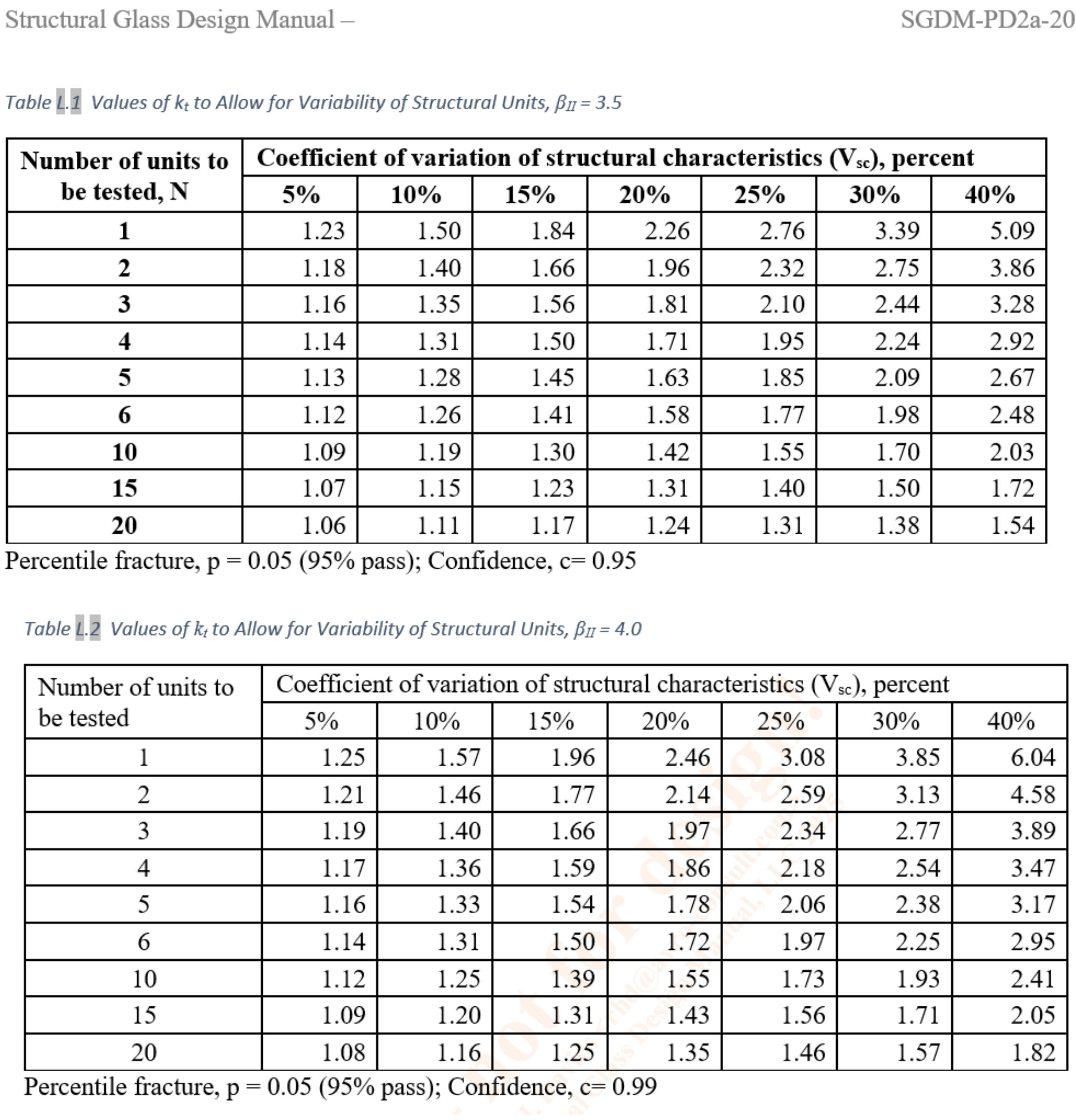

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Table L.1 Values of k_t to Allow for Variability of Structural Units, $\beta_{II} = 3.5$

Number of units to be tested, N	**Coefficient of variation of structural characteristics (V_{sc}), percent**						
	5%	**10%**	**15%**	**20%**	**25%**	**30%**	**40%**
1	1.23	1.50	1.84	2.26	2.76	3.39	5.09
2	1.18	1.40	1.66	1.96	2.32	2.75	3.86
3	1.16	1.35	1.56	1.81	2.10	2.44	3.28
4	1.14	1.31	1.50	1.71	1.95	2.24	2.92
5	1.13	1.28	1.45	1.63	1.85	2.09	2.67
6	1.12	1.26	1.41	1.58	1.77	1.98	2.48
10	1.09	1.19	1.30	1.42	1.55	1.70	2.03
15	1.07	1.15	1.23	1.31	1.40	1.50	1.72
20	1.06	1.11	1.17	1.24	1.31	1.38	1.54

Percentile fracture, p = 0.05 (95% pass); Confidence, c= 0.95

Table L.2 Values of k_t to Allow for Variability of Structural Units, $\beta_{II} = 4.0$

Number of units to be tested	Coefficient of variation of structural characteristics (V_{sc}), percent						
	5%	10%	15%	20%	25%	30%	40%
1	1.25	1.57	1.96	2.46	3.08	3.85	6.04
2	1.21	1.46	1.77	2.14	2.59	3.13	4.58
3	1.19	1.40	1.66	1.97	2.34	2.77	3.89
4	1.17	1.36	1.59	1.86	2.18	2.54	3.47
5	1.16	1.33	1.54	1.78	2.06	2.38	3.17
6	1.14	1.31	1.50	1.72	1.97	2.25	2.95
10	1.12	1.25	1.39	1.55	1.73	1.93	2.41
15	1.09	1.20	1.31	1.43	1.56	1.71	2.05
20	1.08	1.16	1.25	1.35	1.46	1.57	1.82

Percentile fracture, p = 0.05 (95% pass); Confidence, c= 0.99

Fig. 1: Testing factors k_t as presented in the Structural Glass Design Manual.

Alternative values for, V_{sc} <40%, may be determined by the formula

$$k_t = \left[\frac{ln(1-c)}{N*ln(1-p)}\right]^{V_{sc}} \tag{1}$$

Where c is the confidence level.

V_{sc} = *COV = coefficient of variation*

N= number of tests

P= percentile fracture (e.g. 5% fracture)

2.1. Example 1:

For a Fully Tempered (FT) beam acting as secondary element supporting live load only with a live load (L) and an LRFD load factor (LF) of 1.6, where it is anticipated to perform 4 tests. It is assumed that the support system does not increase the variation and V_{sc} = COV of glass. The coefficient of variation for the population of FT glass is assumed to be 10% and the testing is consistent with that assumption.

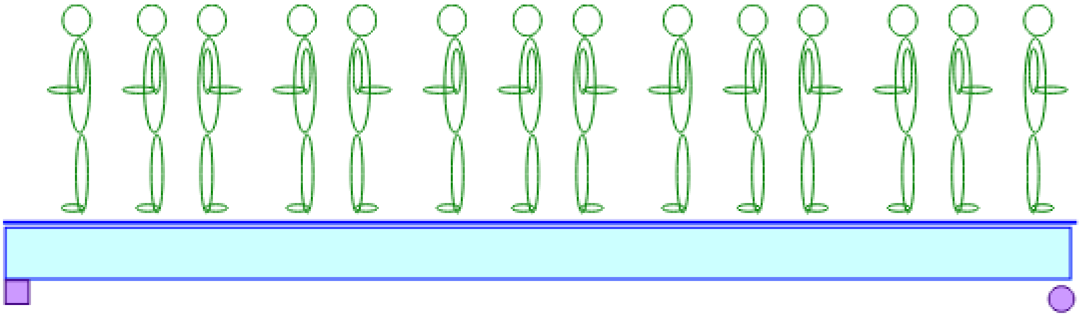


Fig. 2: Schematic of live load on glass beam to be tested.

From Figure B.1 of the Structural Glass Design Manual, Robustness requirement is R-3 and from Table B.8 βII Target Reliability , βII = 3.5.

The testing factor k_t = 1.31

$$Test\ load = L\ x\ LF\ x\ k_t = L\ x\ 1.6\ x\ 1.31 = L\ x\ 2.10$$

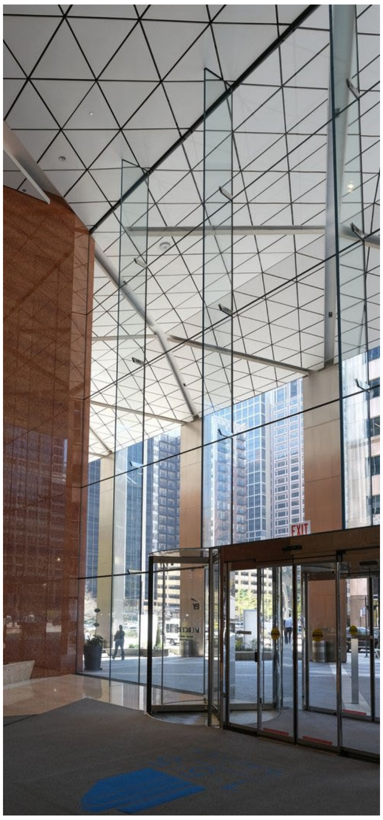


Fig. 3: Example of a wind load bearing glass fin. Photograph by Terrence R. McDonell.

2.2. Example 2a (US):

For an annealed (AN) beam supporting wind load only with a wind load (W) and an LRFD load factor (LF) of 1.0*, where it is anticipated to perform 5 tests. The coefficient of variation for the population of AN glass is assumed to be 25% and the testing is consistent with that assumption.

From Figure B.1, Robustness requirement is R-3 and from Table B.8 βII Target Reliability, βII = 3.5

The testing factor k_t = 1.93

$$Test\ load = W\ x\ LF\ x\ k_t = W\ x\ 1.0\ x\ 1.93 = W\ x\ 1.85$$

* Per ASCE 7 (after 2010 edition) W is an LRFD level load based on indexed return periods, for other loading standards or cades, add factors as required, example below.

2.3. Example 2b (EU/AU):

For an annealed (AN) beam supporting wind load only with a load of W_{ASD} (where W_{ASD} is an ASD level load) and the local Authority Having Jurisdiction has a Strength Limit State load factor (LF) of 1.5**, where it is anticipated to perform 5 tests. The coefficient of variation for the population of AN glass is assumed to be 25% and the testing is consistent with that assumption. From Figure B.1, Robustness requirement is R-3 and from Table B.8 βII Target Reliability , βII = 3.5

The testing factor k_t = 1.85

$$Test\ load = W_{ASD}\ x\ LF\ x\ k_t = W_{ASD}\ x\ 1.5\ x\ 1.85 = W_{ASD}\ x\ 2.78$$

** Wind loading limit state factors vary by jurisdiction and loading standard.

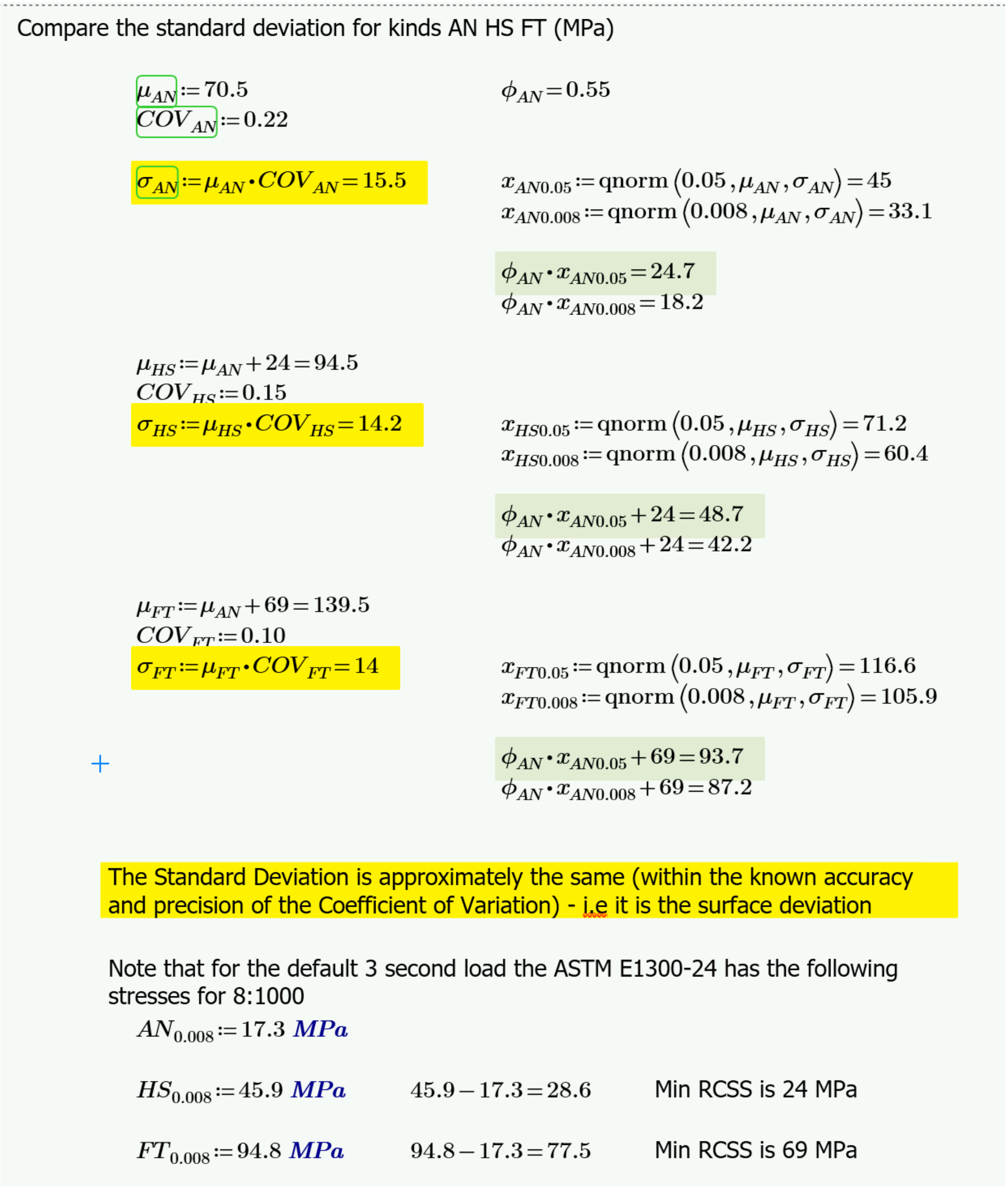
3. Variability of Samples

3.1. Variability of Samples

Typically, the Modulus of Rupture of various glass types are reported as having the following coefficients of variation for float surfaces:

Annealed (AN)	22-25%
Heat Strengthened (HS)	15%
Fully Tempered (FT)	10%

Interestingly, when considering the Residual Compressive Surface Stress (RCSS) and resultant strength of Characteristic + RCSS multiplied by the CoV, they all have similar numbers which can be assumed to be associated with the surface tensile capacity.



Compare the standard deviation for kinds AN HS FT (MPa)

$\mu_{AN} := 70.5$

$COV_{AN} := 0.22$

$\phi_{AN} = 0.55$

$\sigma_{AN} := \mu_{AN} \cdot COV_{AN} = 15.5$

$x_{AN0.05} := \text{qnorm}\left(0.05, \mu_{AN}, \sigma_{AN}\right) = 45$

$x_{AN0.008} := \text{qnorm}\left(0.008, \mu_{AN}, \sigma_{AN}\right) = 33.1$

$\phi_{AN} \cdot x_{AN0.05} = 24.7$

$\phi_{AN} \cdot x_{AN0.008} = 18.2$

$\mu_{HS} := \mu_{AN} + 24 = 94.5$

$COV_{HS} := 0.15$

$\sigma_{HS} := \mu_{HS} \cdot COV_{HS} = 14.2$

$x_{HS0.05} := \text{qnorm}\left(0.05, \mu_{HS}, \sigma_{HS}\right) = 71.2$

$x_{HS0.008} := \text{qnorm}\left(0.008, \mu_{HS}, \sigma_{HS}\right) = 60.4$

$\phi_{AN} \cdot x_{AN0.05} + 24 = 48.7$

$\phi_{AN} \cdot x_{AN0.008} + 24 = 42.2$

$\mu_{FT} := \mu_{AN} + 69 = 139.5$

$COV_{FT} := 0.10$

$\sigma_{FT} := \mu_{FT} \cdot COV_{FT} = 14$

$x_{FT0.05} := \text{qnorm}\left(0.05, \mu_{FT}, \sigma_{FT}\right) = 116.6$

$x_{FT0.008} := \text{qnorm}\left(0.008, \mu_{FT}, \sigma_{FT}\right) = 105.9$

$\phi_{AN} \cdot x_{AN0.05} + 69 = 93.7$

$\phi_{AN} \cdot x_{AN0.008} + 69 = 87.2$

The Standard Deviation is approximately the same (within the known accuracy and precision of the Coefficient of Variation) - i.e it is the surface deviation

Note that for the default 3 second load the ASTM E1300-24 has the following stresses for 8:1000

$AN_{0.008} := 17.3\ \mathbf{MPa}$

$HS_{0.008} := 45.9\ \mathbf{MPa}$ $\quad 45.9 - 17.3 = 28.6$ $\quad$ Min RCSS is 24 MPa

$FT_{0.008} := 94.8\ \mathbf{MPa}$ $\quad 94.8 - 17.3 = 77.5$ $\quad$ Min RCSS is 69 MPa

Fig. 4: Comparison of Coefficient of Variation between types of glass.

3.2. Variability of Manufacture

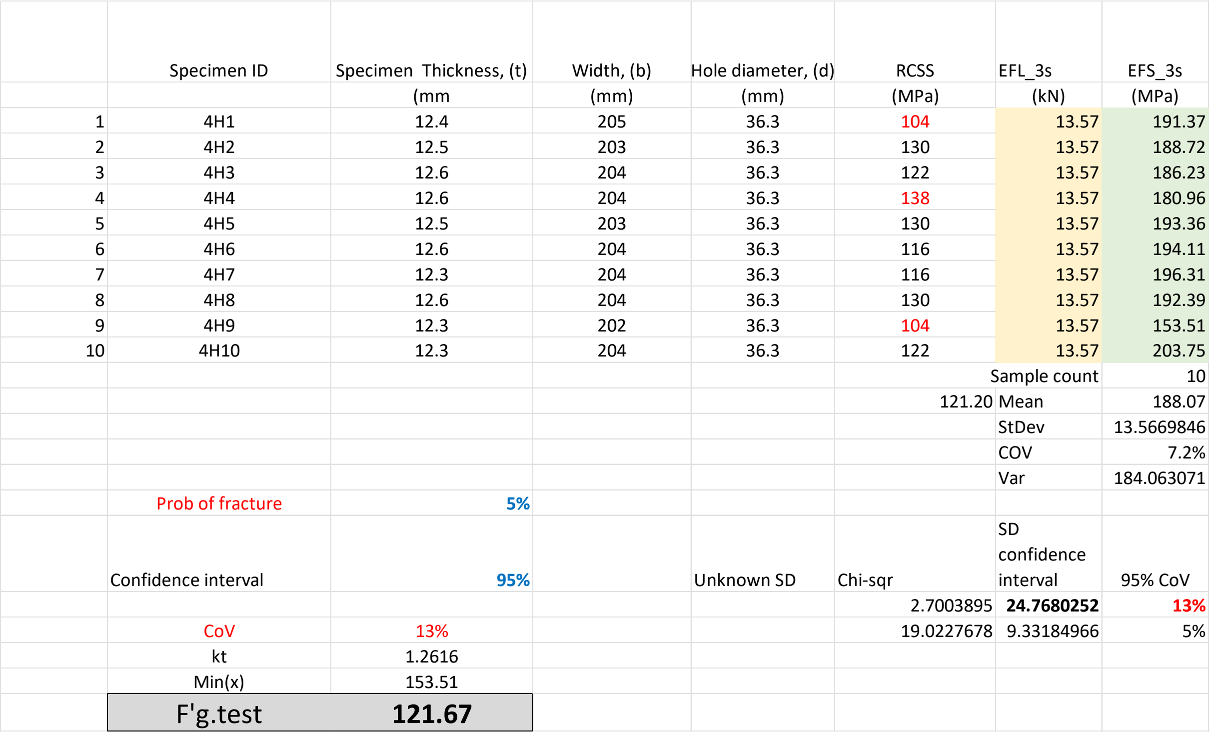
Where the glass has been processed, the variability is also affected, so in some testing the coefficient of variation of the population is itself an unknown and must be approximated from the sample. In this case Chi-squared distribution can be used to evaluate the range which V_{sc} should lie within.

$$Confidence\ Interval = \left[\sqrt{\frac{(n-1).s^2}{\chi^2_{\alpha/2}}}\ ,\ \sqrt{\frac{(n-1).s^2}{\chi^2_{1-\alpha/2}}} \right] \qquad (2)$$

where:

- n **:** sample size
- s**:** sample standard deviation
- χ^2**:** Chi-square critical value with $n-1$ degrees of freedom. (https://www.statology.org/confidence-interval-standard-deviation/)

Table 1: System with unknown coefficient of variation with destructive testing:
in 10 tests, after allowing for corrections in specimen dimensions and production parameters.



	Specimen ID	Specimen Thickness, (t)	Width, (b)	Hole diameter, (d)	RCSS	EFL_3s	EFS_3s
		(mm	(mm)	(mm)	(MPa)	(kN)	(MPa)
1	4H1	12.4	205	36.3	104	13.57	191.37
2	4H2	12.5	203	36.3	130	13.57	188.72
3	4H3	12.6	204	36.3	122	13.57	186.23
4	4H4	12.6	204	36.3	138	13.57	180.96
5	4H5	12.5	203	36.3	130	13.57	193.36
6	4H6	12.6	204	36.3	116	13.57	194.11
7	4H7	12.3	204	36.3	116	13.57	196.31
8	4H8	12.6	204	36.3	130	13.57	192.39
9	4H9	12.3	202	36.3	104	13.57	153.51
10	4H10	12.3	204	36.3	122	13.57	203.75
						Sample count	10
					121.20	Mean	188.07
						StDev	13.5669846
						COV	7.2%
						Var	184.063071
	Prob of fracture	5%					
	Confidence interval	95%		Unknown SD	Chi-sqr	SD confidence interval	95% CoV
					2.7003895	**24.7680252**	**13%**
	CoV	13%			19.0227678	9.33184966	5%
	kt	1.2616					
	Min(x)	153.51					
	F'g.test	**121.67**					

Note that the Chi-squared confidence interval of COV is more conservative than the approximation of $\hat{c}_v^{\,*} = (1 + \frac{1}{4n})\hat{c}_v$ referenced above.

4. Representative samples

As the surface becomes weathered or machined in a manner that introduces flaws (e.g. serrations, grinding marks, or sharks’ teeth produced on the edges), the average and the spread of the distribution both reduce. Edge working quality is particularly critical for structural assemblies because the systems are often loaded in plane or have unsupported edges.

Bukieda et al (2024) found that edge polishing has a direct correlation to edge strength. In general, the effect of edge polishing has been recognized by standards such as ASTM E1300, ASTM 1048, EN1288-3, and AS/NZS 1288 since the work of Walker and Muir (1984). Bukieda et.al. goes further finding that the glass does not just need to look polished at a macro level, it needs to have flaws removed at a micro level and that the polishing process can affect the strength. In the context of testing, this means that by preparing test samples to a level of edge polishing that is less than specified for production it is likely that the results will be more consistent and conservative.

Self-healing in atmospheric conditions is also observed empirically and quantified in Stavrindis (1980). Based on this work it should be noted that samples freshly prepared maybe artificially less strong than is representative of units in service. (See also a separate paper on weathering, self-healing and design flaws at this conference Green et.al (2026).) For this reason testing should not occur immediately after fabrication in annealed glass.

Hot viscous healing is observed in the heat treatment of glass with holes (Schneider and Wörner 2001) with potential mechanisms and influencing factors discussed by Girard et. al. (2011). Where such heat treatment is anticipated in the standard fabrication it is reasonable to have samples prepared by the same process, with corresponding strength increase in surface tensile capacity as well as RCSS for testing, provided the samples are representative.

Particular care is required when testing fully tempered and heat-strengthened glass because the residual compressive surface stress (RCSS) in the samples may vary. Fully tempered glass may be tested vs. its lower bound RCSS in production, or conversely the quality control in production should ensure that the RCSS is greater than in testing. Heat-treated glass is specified in an allowable range therefore the testing regime needs to be representative of a narrow RCSS target range planned within the production. As part of the quality control utilizing a GASP (Grazing Angle Surface Polarimeter) or SCALP (scattered light polariscope) in a manner consistent with ASTM C1048 to verify the target range planned within production. The standard range of RCSS levels can vary and change the testing results significantly. Where possible the testing samples should bound the likely production range of RCSS, including an allowance for production variation. It is also necessary to specify production limits where it is known to be important.

The work of Pisano and Royer (2016) note that where we typically consider the design value for heat-treated glass to be represented by the sum of the characteristic values of annealed glass strength and of the heat-induced surface prestress the statistics, physical mechanisms and spatial variations are not the same or similar. This has a significant influence on the interpretation of the safety of tempered glasses based on test data.

5. Sample Preparation

For structural glass assemblies, the point of highest stress is frequently at a connection, point of application of load or boundary condition, or an edge. Unlike window glass with high deflections (relative to thickness), where the location of maximum stress varies with the amount of load and the degree of membrane stress developed, in structural systems the load may be in-plane with linear elastic load-stress relationships (at least at a macro level). Provided that the edge of the sample is prepared in a way that the testing sample is representative of worst case and a suitable duration has occurred to allow atmospheric self-healing to a typical strength (see separate paper at this conference) then a reasonable degree of consistency can be anticipated.

In other building materials there is often a factor which accounts for the potential of ‘over strength’ of the sample relative to the design strength (or acceptable production lower bound) of the population. In glass the potential for the samples to exceed the strength of the in-service population is also a consideration, in particular for strengthened glass (heat treated or chemically strengthened) the RCSS needs to be no greater in the test sample than it will be in the production items, so that the test is conservative. The data also needs to be normalized if the results are intended to be used for glass from different suppliers.

If appropriate, the surface may need artificial surface flaws and ageing to be representative. However great caution should be used if coefficients of variation derived from the sample set which are less than typical for the kind of glass. As found in the work of Datsiou and Overend (2017a and 2017b) prepared samples can result in a uniform flaw with low variance leading to higher characteristic values. Similarly here great care and justification is required before using coefficients of variation that are less than typical for the kind of glass to avoid using a testing factor k_t which is less than appropriate to determine the usable capacity.

Where possible, care should be taken to be consistent regarding the tin and air side of the glass between sample and production units. Tin can affect the surface behaviour, have a small effect on the surface strength, and be necessary for bonding of ionoplast interlayers.

6. Testing Conditions

For laminated systems, the stiffness is a function of the temperature and load duration, due to the visco-elastic nature of the material. Unless it can be determined that either an upper bound temperature or lower bound temperature is critical by calculations, the testing may need to test at both testing extremes. Further, in rare cases, if there are multiple kinds of glass (AN/HS/FT), asymmetric laminates or combinations of thick and thin glass sheets, the critical stress at intermediate coupling-degrees (temperatures) can be found at an interlayer/glass interface and not the upper or lower surface of the laminate.

Currently the ASTM E2353 test for balustrades allows the tests to be carried out between a temperature range of 15 to 30 degrees C (59F – 86F). The authors recommend using the worst-case temperature for the specific load case/combination for testing and the designer should be careful of features that can increase the surface temperature (tints, films, ceramic frits etc.)

For higher temperatures anticipated over the design lifespan of the element, it may be difficult to achieve these high temperatures in laboratories when utilizing larger load test setups e.g. when testing balustrades with multiple panels. A localized chamber can be set up with sheets of polyvinyl and space heaters but this can be uncomfortable for the workers performing the testing. Infrared heaters have also been used in an open-air environment. With infrared heaters, it is critical to not place the heating device too close to the specimen and allow the heat to build slowly and evenly on the surface to avoid localized hot spots, overheating or thermal stress.

Where the configuration of the system results in cumulative creep over time, such as horizontal systems with dead load across the thickness of the plies, testing in the extreme conditions is recommended. The rate of creep may be accelerated through the use of elevated temperature or a combination of elevated temperature and surcharge loading.

As the strength of glass is time sensitive and the physical behaviour is both time and temperature sensitive, the testing durations need to be selected to be representative of the design load duration and aggregate loading.

Following validation testing, it is important that both the mode of failure and the test value meet or exceed expectations.

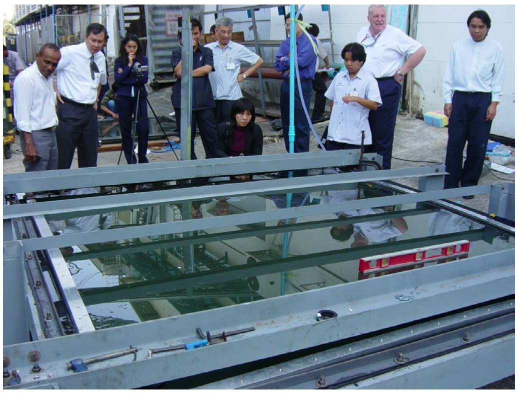


Fig. 5a: Full-scale pressure bed testing.

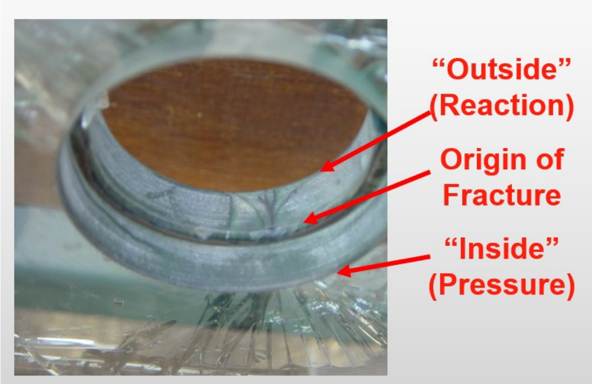


Fig. 5b: Testing resulted in breakage consistently from the center of the laminate due to variable compression across the *thickness* of the interlayer.

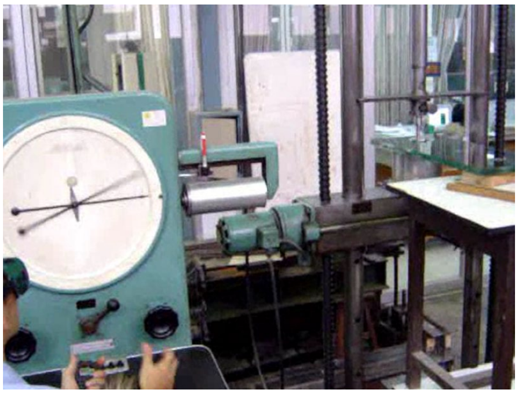


Fig. 5c: Follow up laboratory testing to explain.

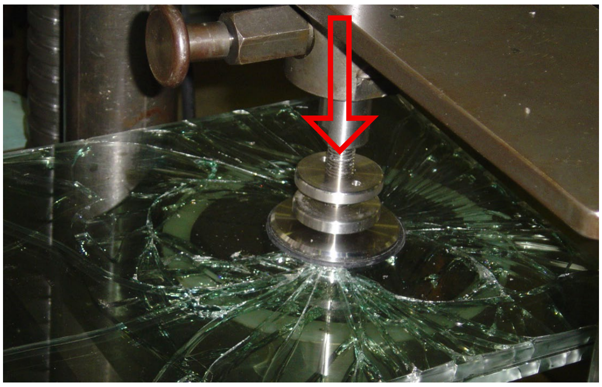


Fig. 5d: Lab sample testing, top ply always broke first.

Fig. 5e: Finished project.

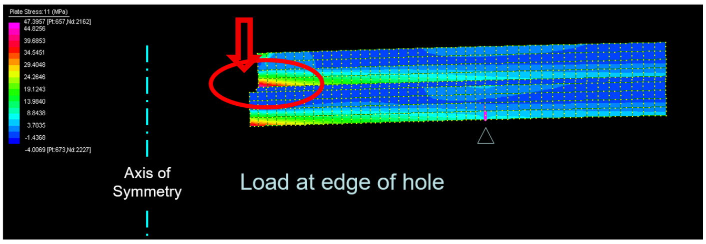


Fig. 5f: Axisymmetric model found that compression of the interlayer across the thickness caused greater curvature at the loaded ply rather than the extreme fiber of the laminate – modeling matched testing—30,000m^2 of Heat-strengthened point fixed glass was successful.

Fig. 5: Suvarnabhumi Bangkok International Airport: Point fixed PVB laminated glass tested at 30ºC for a tropical region.

7. Testing Protocol

The following is a summary of items suggested in the Structural Glass Design Manual (SGDM) to be considered in developing a testing protocol.

- Agree with all parties the objectives of the testing and the anticipated outcomes prior to the test.
- To the greatest extent possible testing conditions should match the design conditions for or make suitable accommodations:
  - Load duration
    - Both glass and interlayers are time sensitive materials.
  - Temperature
    - Laminated panels, insulated glass unit (IGU), spandrel panel, and shadow box systems are temperature sensitive. Consider adding thermal couples to monitor the temperature once the sample is installed until the end of the load test.
  - Strength of sample
    - RCSS
    - Edge preparation
    - Artificial weathering
      - Abrasion
      - Self-healing
      - Heat treatment
  - Scale and size effects
    - Float thickness variation
    - Physical size versus actual
      - Poisons effects at reduced dimension samples
      - Geometric non-linearity
  - Boundary conditions
    - Representative supports
  - Compatibility requirements
    - No change in load path during testing, including during ‘overload’ conditions
  - Residual Displacements
    - Does the designer anticipate that the system will fully recover deflection after testing? When testing to failure provide for safety from fracture and ease of collection of the fractured pieces.
    - Is there indication of permanent deflection in either the (laminated) glass specimen or metal fixtures.
      - *Note: as the Coefficient of Variation (CoV) for glass is greater than metals, the testing factors will be higher than the typical safety factors for metal and suitable allowances may be required in planning the test. (Many tests have been prematurely invalidated by failure of the metal components rather than the glass!)*
  - Where possible, test to failure
    - To determine the actual capacity
    - To determine if the failure mechanism matches the predictions
      - Where required, revise the calculations and/or test to achieve correlation between calculations and testing.

- If possible/necessary, repeat the test to check for consistency of outcomes.
    - By its nature, glass may have unexpected failures due to inclusions, fuses or installation damage, but it is important to both establish what is 'typical behaviour' and design systems in a robust manner because atypical strength may also occur in-service conditions.

8. Importance of Robustness and Residual Capacity

The testing regime is structured relative to design loads, but for glass it is not unusual that significant damage can be caused by events that are less than design loads, such as rigid body impact. Unlike ductile materials, small local events may propagate throughout glass element with complete loss of integrity and capacity. In addition to the external events causing loss of strength, inconsistencies and inclusions within the glass may cause unexpected loss of strength.

Nickel-sulfide (NiS) inclusions are the most widely recognized cause of spontaneous glass breakage, and although heat-soak testing can significantly reduce their occurrence, NiS is not the only potential initiator of failure. Other inclusions, such as cuprous or ferrous inclusions, are much rarer but are not addressed by heat soak testing. Float production defects —such as glass stones, bubbles/seeds reams/fuses, knots and formation defects—also pose risks and should be addressed through robust designs.

While the probability of a single ply containing a 'low strength defect' is very low, the consequences of such a failure in monolithic assemblies are potentially high and the vulnerability of the system is also high. In the assessment of ASCE 76 *Standard for Mitigation of Disproportionate Collapse Potential in Buildings and Other Structures:*

$$Risk = Hazard\ Likelihood \times Vulnerability \times Consequences \tag{3}$$

For robust systems, with laminated plies, the likelihood of more than one ply being affected by an extraordinary defect is many orders of magnitude lower, and the consequences of an extraordinary element failure is unlikely to propagate to all elements (reduced vulnerability) and as a result is also unlikely to cause collapse in a well-designed system. As such robust systems, such as multiply laminated systems, present a much lower risk and are suitable for use in structural systems requiring reliability.

When attempting to use testing as the main design criteria for higher risk categories that require residual load resistance after breakage, testing includes the full limit state strength and also a set of post-damage testing with one (or more) ply(s) broken (e.g. the Structural Glass Design Manual, ASTM E2751, AS1288, CEN/TS 19100). This form of testing is a good means to test the robustness of a system. It should be noted that, where extraordinary damage is not caused by high design loads, the probability of element damage corresponding with peak loads are small and can be treated similarly to companion load combinations. Consequently, the assumption that damaged glass elements will be replaced in a timely manner, which may not be the case, and is a both a consideration in the design and the testing protocol.

9. Informal Testing

Once the formal testing is complete, or visual mockups are finished being viewed there is value in performing ‘unreasonable testing’ to find the limits of behavior of the failed state. Understanding the behavior of the system in extreme conditions is a good way to understand the robustness of the system beyond the target robustness.

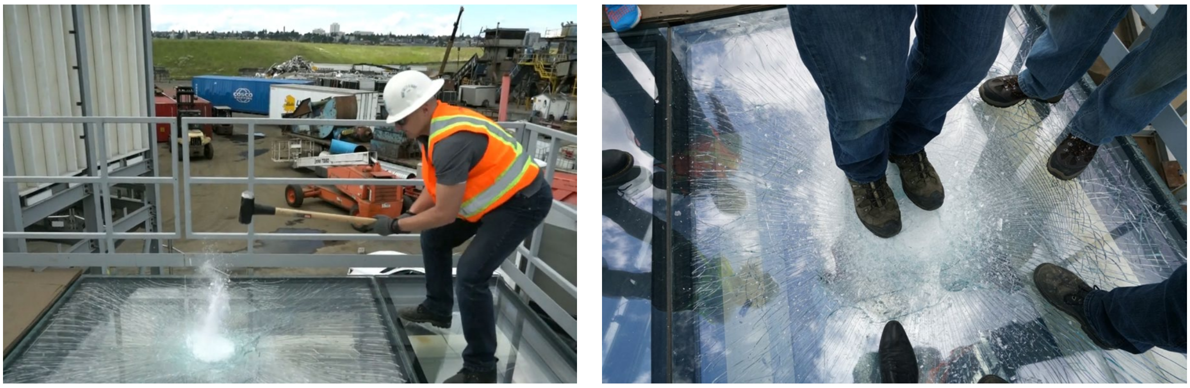


Fig. 6: Destructive testing of visual mockup.

10. Conclusion

Testing glass is important because calculations only check for failure mechanisms anticipated by the engineer/designer. Validation testing that demonstrates the anticipated load capacity and failure mechanism is useful for glass because it lacks the ductility to redistribute load, so is more sensitive and less predictable than other materials. Design by testing is an option for complex systems provided that the sample size is adequate and suitable allowances are made for the load variation, using the strength limit state (LRFD) load, the material variability and the size of the testing sample, which combine in determining an appropriate testing factor. The samples need to be representative, with preparation matching the actual production or a lower bound thereof. Parameters that are particularly sensitive for glass include the fabrication methods, the Residual Compressive Surface Stress, and any edge working/polishing. Testing can be particularly useful for determining behavior and capacity in a partially damaged state.

Fig. 7a: Informal 4-point bending validation test of full-scale art glass panel using copper slag weight in buckets (AN fused art glass||FT||AN fused art glass).

Fig. 7b: Residual capacity after initial fracture (Photos: Kerry Johnson Glass).

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