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Testing of Structural Glass Elements: Calibration to Design

Andrew Crosby [a], **Richard Green** [b], **Terry McDonnell** [c]

a RJC, Canada, acrosby@rjc.ca
b Green Facades, USA, richard@greenfacadesllc.com
c CTL Group, USA, tmcdonnell@ctlgroup.com

Abstract

The engineering of structural systems can be performed by more than one method. Design standards with equations for the applicable limit states are available for most structural materials and remain the most common approach. "Rational analysis" based on published papers and engineering fundamentals is another approach used where there are gaps in the local codes and standards. Another method is "design by testing" which can be an effective 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" leading to inconsistent application, including the misinterpretation of "validation by testing" as equivalent to full design justification. This paper discusses 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 also clarifies the difference between "design by testing" and "validation by testing" and discusses 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

Testing can be used to validate the design or serve as proof of design in lieu of numerical simulation. In validation testing, calculations according to a recognized code or standard are performed for all elements of the structural system. The test in this scenario is used to check the overall behavior and calibrate the numerical simulations to the test to ensure no significant behavior has been overlooked. The test supports the design team but would not be required as part of the engineering proof. In this scenario, greater flexibility may be allowed in selecting the applied test load. Alternatively, in design by testing, the test is intended to be used in lieu of calculations and forms the basis of design for a system or portion thereof. In this scenario, the overall safety factor and reliability index required by design standards and building codes must still be achieved in “design by testing” in lieu of a recognized calculation approach. The number of tests, statistical properties and failure mechanism are important aspects of determining the resulting design value obtained from the tests. Engineers have limited codified references for “design by testing”, and these are often material or element specific (e.g. guards). There is also limited clarity on whether the applicable testing guidance includes a safety factor adequate for design purposes.

This paper explores applicable references for testing and also more generic statistical approaches.

2. Appropriate references

Glass specific structural testing references include ASTM E2353/2358, ASTM E2751, CSA A500-16, and International Building Code (IBC) Chapter 17.

ASTM E2353/2358 is the standard for testing of glass balustrades in North America. It includes code-mandated loading and addresses different glazing applications used in structural guards. ASTM E2353 describes the testing method and ASTM E2358 outlines the performance criteria. While there is a pass/fail criterion at the end of the standard it is not clear how the test should be used in practice in order to achieve the goal of “design by testing”. The scenarios progress from class I – IV and aspects of the applied loading increase however the load factors do not align with the load factors in ASCE-07 nor do the standards include a material safety factor. Without achieving the same reliability index specified in the building code this performance criteria could not be used as “design by testing”. It is also important to indicate what elements are included within the design by testing and what elements will have supporting calculations. For instance, gross member yielding in a ductile element (e.g. steel and aluminum) may have a 0.9 material resistance factor (partial safety) whereas elements with brittle failure or rupture may have material resistance factors between 0.65 and 0.75 (e.g. welds, block shear etc) . The load achieved must be higher if the test is used to validate a brittle failure mode. This is similar for glass applications, where infill non-guard elements could be justified as having lower material resistance factors. The material resistance factors for glass are not well defined in current codes which adds to the complexity engineers face when determining an overall factor of safety.

ASTM E2751 is the standard for the Design and Performance of Supported Glass Walkways. It includes guidance on verification testing (“design by testing”) and is required for the scenario where a 2-ply laminate is used instead of a 3-ply laminate. The testing requires that the worst-case load be taken with the worst ply broken. This is a post-breakage verification check and is considered a rare or extraordinary event. Most codes treat the extraordinary event as the primary “action” and therefore have reduced load factors, or companion factors, for other loads acting at the same time. ASCE-07, National Building Code of Canada (NBCC) and EN 1990 all have reductions in live load in the event of "accidental load". The load factor is 0.5 in ASCE-07 and NBCC commentary and ranges from 0.5 to 0.9 in EN 1990 depending on the occupancy use. The Australian standard AS1170 has a load factor of 1.0 in the accidental load combination. While there is logically a reduction due to the probability of the full live load acting simultaneously with an accidental breakage scenario there are other factors such as potential amplifications due to redistribution or strength loss due to a critical flaw which could justify the use of the 1.0 live load factor. In a rare event it may also be justified that the material resistance factors may be increased due to the probability that accidental breakage occurs on the glass panel with the lowest strength properties of the population. In prEN 19100-1 Design of Glass Structures, the "accidental" load combinations for glass have a partial safety factor of 1.1 (material resistance factor of 0.91) for the annealed strength portion and a partial safety factor of 1.0 for the tempered portion for Consequence Class 2 (CC2 – medium consequence). Given that the safety factors on both sides of the equation are nearly 1.0, a post-breakage test applied with a 1.0 safety factor could be argued to capture the load and material factors. This test does not specify a minimum number of tests and caution should be used to ensure statistical relevancy.

CSA A500-16 is the standard for building guards and deals specifically with glass balustrades. In section 4 it allows for design by calculation (Section 6) or design by testing (Section 5). Section 5 requires a minimum of two tests and notes that the "applied [testing] force shall be that due to the factored loads divided by the appropriate resistance factor" (CSA A500, 2016). While this requirement is clearly laid out in the document, the material factor for glass is not well defined in CGSB 12.20, the referenced withdrawn Canadian standard addressing the strength calculation for structural glass in CSA A500-16.

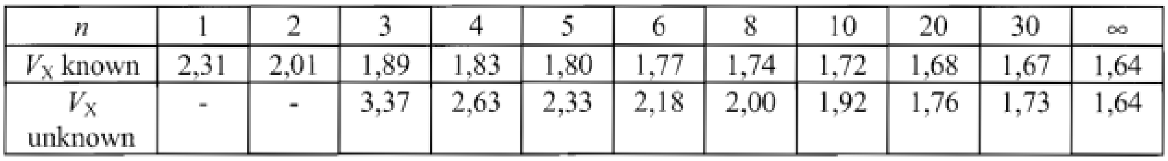
While the above glass specific references are helpful, they do not provide much guidance on the final design values to be used or the overall safety factors.

The IBC Chapter 17 on "Special Inspections and Tests" addresses Preconstruction Load Tests in clause 1709. It notes that when "proposed construction is not capable of being designed by approved engineering analysis [] The building official shall accept certified reports of such tests". It has a specific section on exterior windows, doors and skylights which requires a load factor of 1.5 per AAMA 404 unless noted otherwise. The 1.5 safety factor on the unfactored or allowable stress design (ASD) load for windows, doors and skylights is often referenced in performance mockups for façade systems and serves as the industry standard structural check of the system (AAMA 501 series referencing ASTM E330). Since this safety factor does not account for the load factor and material safety factor that are consistent with the current IBC/ASCE load combinations and reliability index's, the 1.5 should not be used in lieu of structural calculations. The load level in this case is a "proof" test on the system and is meant to calibrate the overall behavior of the façade. The IBC also has a generic section, 1709.9, for scenarios where load test procedures are not specified by another standard. This section requires testing to failure and applying a safety factor of 2.5. There is no minimum number of tests required in this section. Assuming a load factor of 1.6, a 2.5 safety factor would correspond to a material resistance factor of 0.64, consistent with brittle/rupture failure mechanisms of concrete and connections. The 2.5 safety factor is intended for "design by testing" but it is limited by the impacts of number of tests, the limit state considered and the effects of the testing statistics.

EN 1990 Annex D provides a more general rationale for design by testing which aims to be consistent with the reliability index for "design by calculation". The document encourages the use of a characteristic value per D.7.2, combined with code stipulated material safety factors, and also provides guidance for a direct design method per D.7.3 where this is not possible. The characteristic method lognormal distributions and direct design approach are shown below in Eq. 1 and Eq. 2 respectively.

The statistical properties of the tests are incorporated, and the number of tests is included in the approach. The sampling factor, k_t is used in determining the design value and reflects statistical uncertainty consistent with Bayesian principles (i.e. probability based on prior knowledge). The reference tables provide k_t values where there is no prior knowledge about the coefficient of variation and when there is full knowledge of the coefficient of variation called the V_x unknown and V_x known respectively (Figure 1 and 2). The characteristic approach has a 75% confidence level for the fractile value. A 95% confidence interval, commonly used in design of structural elements, in conjunction with a material resistance factor was deemed to be excessively conservative for small sample sizes often used in testing (Gulvanessian et al 2012). A 75% confidence level, therefore, provides a conservative yet practical best-estimate basis for design.

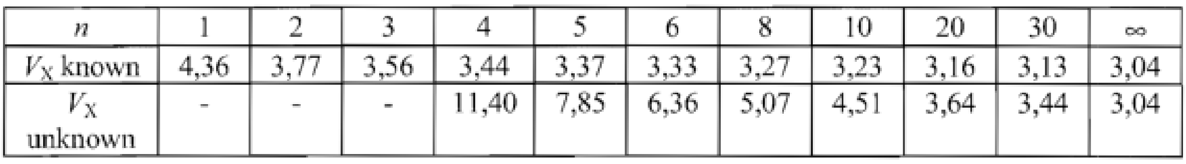
$$X_d = \frac{\eta_d}{\gamma_m} \exp\left[m_y - k_n s_y\right] \tag{1}$$



n	1	2	3	4	5	6	8	10	20	30	∞
V_X known	2,31	2,01	1,89	1,83	1,80	1,77	1,74	1,72	1,68	1,67	1,64
V_X unknown	-	-	3,37	2,63	2,33	2,18	2,00	1,92	1,76	1,73	1,64

Fig. 1: kn values for assessment via the characteristic value (EN 1990 Annex D).

$$X_d = \eta_d m_X \{1 - k_{d,n} V_X\} \tag{2}$$

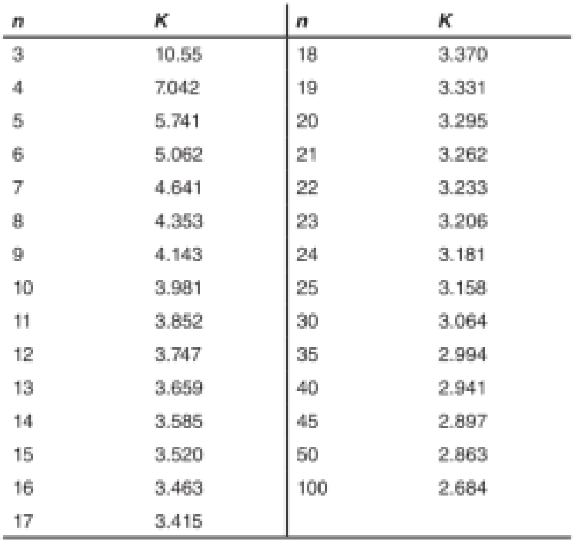


n	1	2	3	4	5	6	8	10	20	30	∞
V_X known	4,36	3,77	3,56	3,44	3,37	3,33	3,27	3,23	3,16	3,13	3,04
V_X unknown	-	-	-	11,40	7,85	6,36	5,07	4,51	3,64	3,44	3,04

Fig. 2: kn values for direct assessment of the design value (EN 1990 Annex D).

The Aluminum Design Manual (ADM) addresses testing in Annex I. Method 1 within this Annex uses a one-sided factor k_t for 99% exceedance with a 95% confidence interval. The method accounts for the number of tests and requires that the material resistance factor is applied to the result. This test is a more conservative approach when compared to the approach shown in the EN 1990 due to the high confidence interval with potentially low number of test samples.

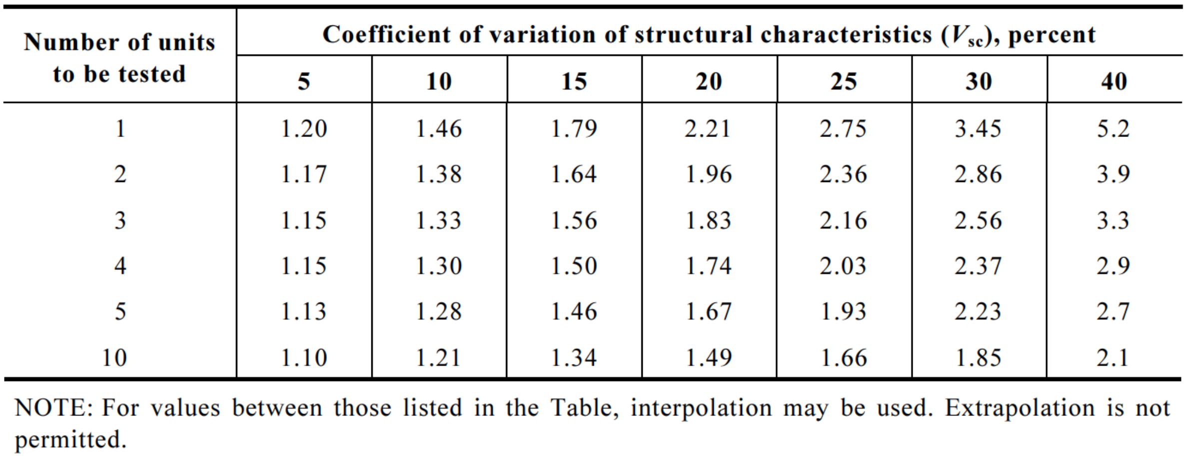
$$R_n = R_{tm} - K\sigma_x \tag{3}$$



n	K	n	K
3	10.55	18	3.370
4	7.042	19	3.331
5	5.741	20	3.295
6	5.062	21	3.262
7	4.641	22	3.233
8	4.353	23	3.206
9	4.143	24	3.181
10	3.981	25	3.158
11	3.852	30	3.064
12	3.747	35	2.994
13	3.659	40	2.941
14	3.585	45	2.897
15	3.520	50	2.863
16	3.463	100	2.684
17	3.415		

Fig. 3: Statistical Coefficient K (ADM 2015).

AS 1170 is the Australian standard for structural design and includes testing guidance based on the minimum test value, the number of tests and the coefficient of variation. It provides a k_t value that is to be used in determining the design value. Like the EN 1990 approach, AS 1170 applies a penalty for small sample sizes to ensure the target reliability index is maintained. However, the AS 1170 Annex B k_t values are based on a Weibull distribution which is right-skewed, but its focus on the "weakest link" makes it an often more conservative statistical model for design than the lognormal distribution.



Number of units to be tested	Coefficient of variation of structural characteristics (V_{sc}), percent						
	5	10	15	20	25	30	40
1	1.20	1.46	1.79	2.21	2.75	3.45	5.2
2	1.17	1.38	1.64	1.96	2.36	2.86	3.9
3	1.15	1.33	1.56	1.83	2.16	2.56	3.3
4	1.15	1.30	1.50	1.74	2.03	2.37	2.9
5	1.13	1.28	1.46	1.67	1.93	2.23	2.7
10	1.10	1.21	1.34	1.49	1.66	1.85	2.1

NOTE: For values between those listed in the Table, interpolation may be used. Extrapolation is not permitted.

Fig. 4: Values of kt for design by testing (AS 1170 Part 0 Annex B).

The Structural Glass Design Manual approach is based on the research from Wang and Pham. The k_t factor accounts for the desired confidence interval and does not require a material resistance factor to be added as it assumes “all sources of uncertainty have been accounted for in the estimate of the coefficient of variation” (Wang and Pham 2011). The paper provides k_t values for both a minimum test value approach and an average test data approach. The minimum test value has been used as a conservative approach. A lognormal data set is used which is generally preferred for structural resistances and material properties particularly where uncertainty arises from multiplicative effects and where negative values are physically impossible (JCSS 2002).

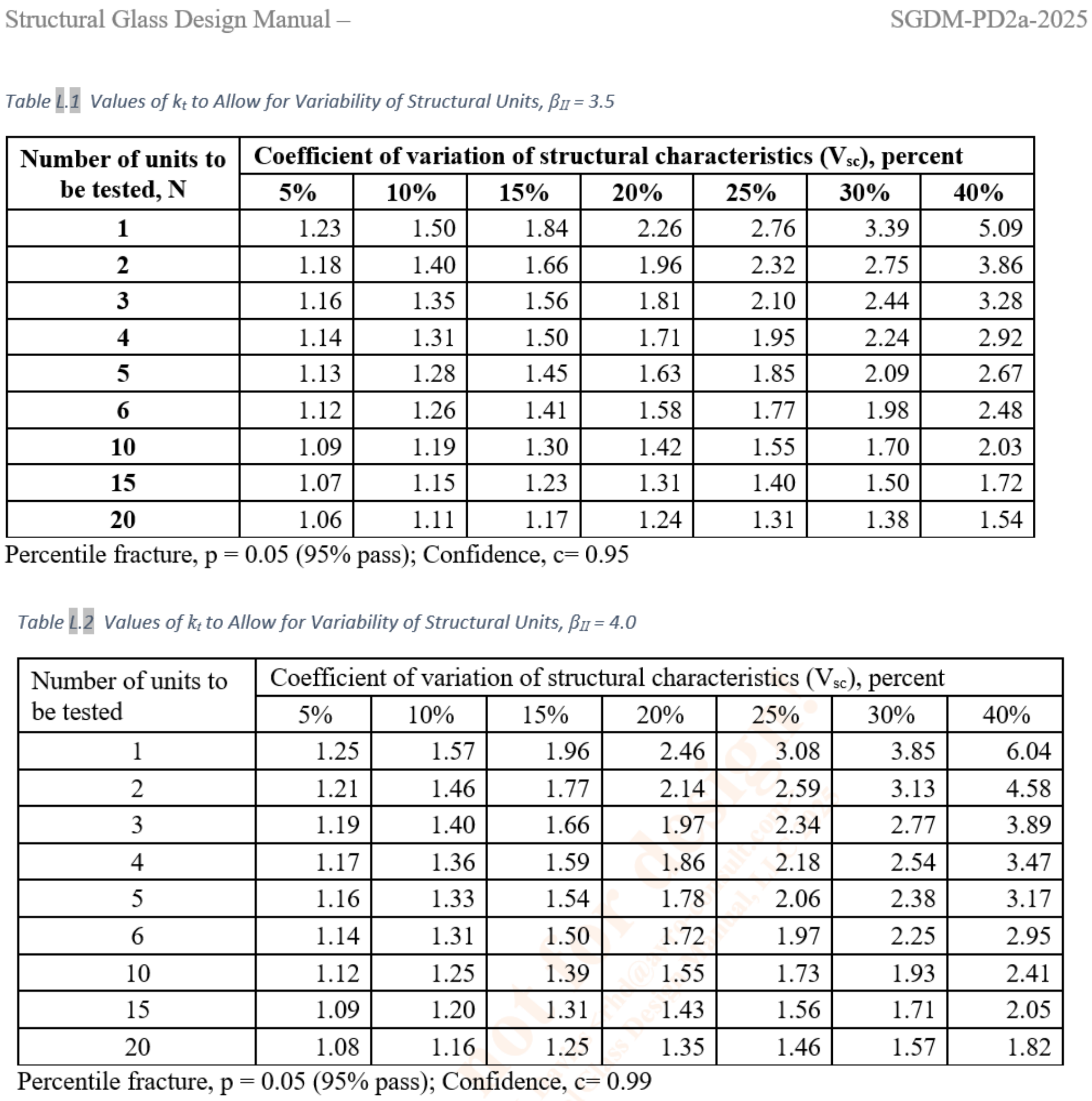


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Table L.1 Values of k_t to Allow for Variability of Structural Units, $\beta_{II} = 3.5$

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. 5: Testing factors kt as presented in the Structural Glass Design Manual.

For the purposes of comparing design values of brittle materials, the Precast Concrete Institute (PCI) test approach in Appendix A and ACI 355.2 Concrete test approach in Appendix A2 were reviewed in addition to the above referenced standards in the method comparison.

3. Method Comparison

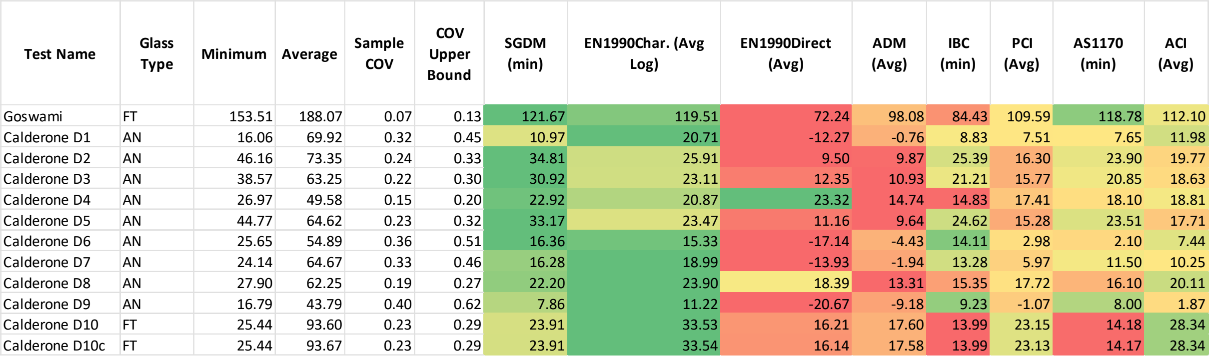
To review the above methods in detail actual glass testing data sets were reviewed with the approaches mentioned above. The data was based on 3-second-equivalent failure stress data from different glass types and the respective design values were determined and compared.

The test data came from Goswami, et al (2023) and from Calderone et. al (1999) and includes results for annealed and fully tempered glass so that glass type and the impact of surface compression could be reviewed.

Since the coefficient of variation was "unknown" for the population, the upper bound coefficient of variation for the population based on the chi-squared method was used. The chi-squared method uses the sample size n, along with the sample mean and standard deviation to create an upper and lower bound estimate. This was required for the SGDM and AS 1170 approach. The EN 1990 direct design approach already included k_t values for unknown COVs. The other approaches did not utilize the population COV.

The test data was organized into a spreadsheet and the general properties of the data were determined; Minimum test value (Min.), Mean test value (Avg.), Standard deviation, Coefficient of variation and variance. The design value was then calculated for each approach and compared in an overall data table.

Each data set shows the test name, glass type along with the minimum test value, average test value, the coefficient of variation and the upper bound for the population coefficient of variation based on the chi-squared method along with the design value for each of the approaches calculated. The results are shown in Figure 6 and can be compared across the row.



Test Name	Glass Type	Minimum	Average	Sample COV	COV Upper Bound	SGDM (min)	EN1990Char. (Avg Log)	EN1990Direct (Avg)	ADM (Avg)	IBC (min)	PCI (Avg)	AS1170 (min)	ACI (Avg)
Goswami	FT	153.51	188.07	0.07	0.13	121.67	119.51	72.24	98.08	84.43	109.59	118.78	112.10
Calderone D1	AN	16.06	69.92	0.32	0.45	10.97	20.71	-12.27	-0.76	8.83	7.51	7.65	11.98
Calderone D2	AN	46.16	73.35	0.24	0.33	34.81	25.91	9.50	9.87	25.39	16.30	23.90	19.77
Calderone D3	AN	38.57	63.25	0.22	0.30	30.92	23.11	12.35	10.93	21.21	15.77	20.85	18.63
Calderone D4	AN	26.97	49.58	0.15	0.20	22.92	20.87	23.32	14.74	14.83	17.41	18.10	18.81
Calderone D5	AN	44.77	64.62	0.23	0.32	33.17	23.47	11.16	9.64	24.62	15.28	23.51	17.71
Calderone D6	AN	25.65	54.89	0.36	0.51	16.36	15.33	-17.14	-4.43	14.11	2.98	2.10	7.44
Calderone D7	AN	24.14	64.67	0.33	0.46	16.28	18.99	-13.93	-1.94	13.28	5.97	11.50	10.25
Calderone D8	AN	27.90	62.25	0.19	0.27	22.20	23.90	18.39	13.31	15.35	17.72	16.10	20.11
Calderone D9	AN	16.79	43.79	0.40	0.62	7.86	11.22	-20.67	-9.18	9.23	-1.07	8.00	1.87
Calderone D10	FT	25.44	93.60	0.23	0.29	23.91	33.53	16.21	17.60	13.99	23.15	14.18	28.34
Calderone D10c	FT	25.44	93.67	0.23	0.29	23.91	33.54	16.14	17.58	13.99	23.13	14.17	28.34

Fig. 6: Summary of methods for determining design stress values from test data.

The results were also graphed in cluster columns to represent the data another way. The data was split into fully tempered and annealed tests in Figures 7 and 8 respectively.

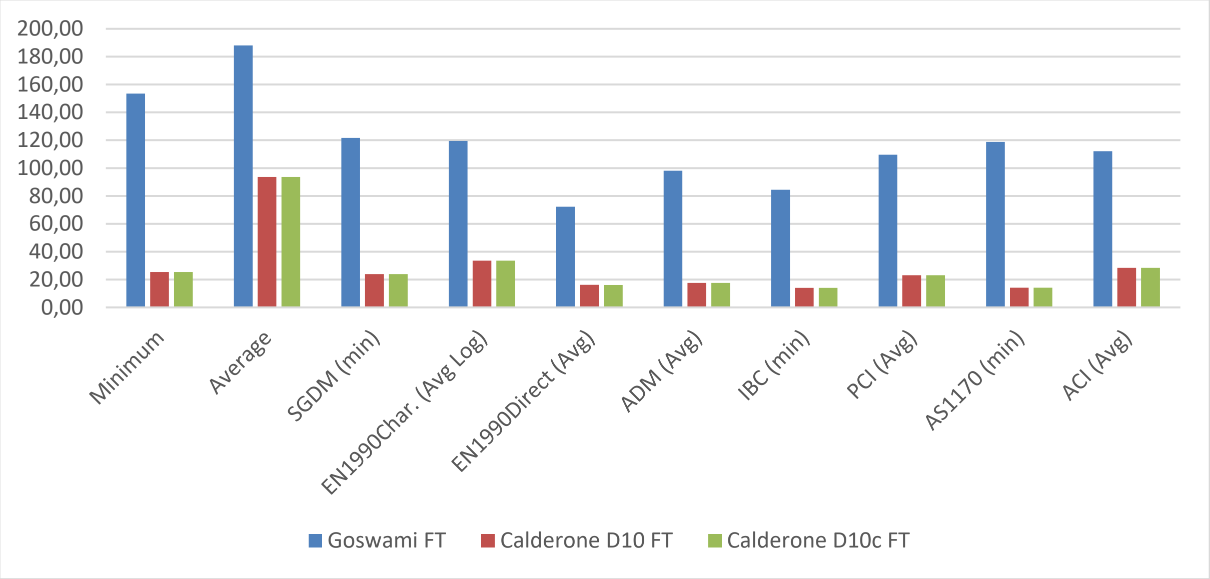


Fig. 7: Summary of methods for determining design stress values from test data (Fully Tempered Data).

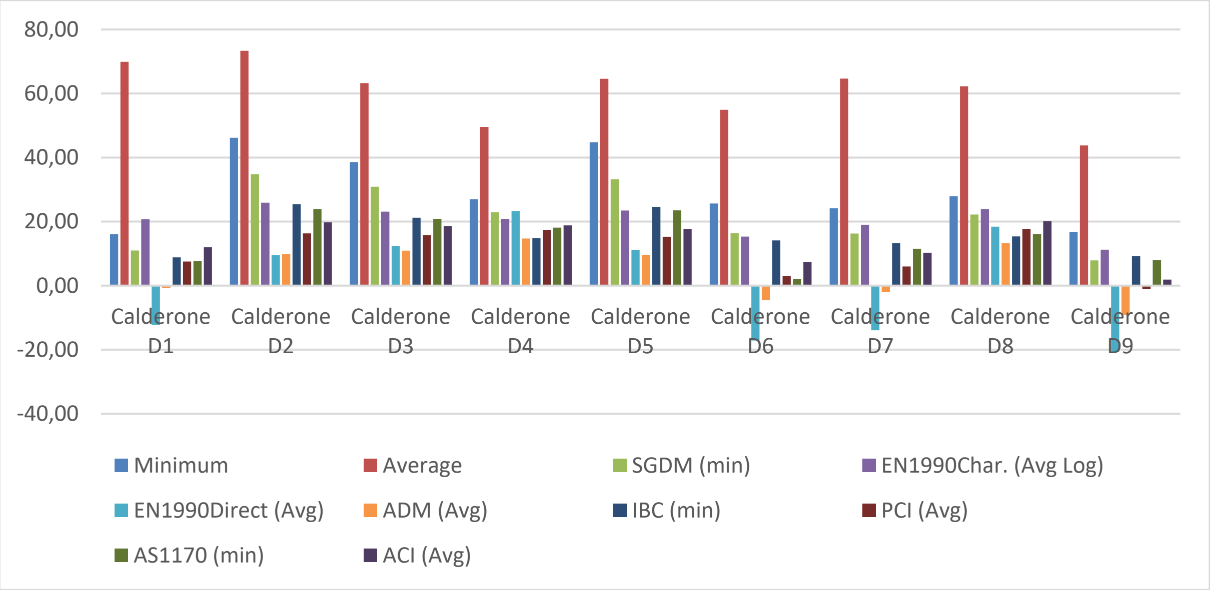


Fig. 8: Summary of methods for determining design stress values from test data (Annealed Data).

4. Conclusions

The results in general show that the EN 1990 Direct method and ADM approach provide the most conservative design values. The EN 1990 direct design method does not have a reference limit state partial safety factor (material resistance factor) which justifies a more conservative design value. The ADM uses a 95% confidence interval and applies a material safety factor which was noted to provide conservative results in the EN 1990 commentary.

Where low outlier data was present, the approaches which relied on the minimum test data were more conservative.

The EN 1990 direct method resulted in negative design values for some scenarios where the coefficient of variation was large and the mean was relatively low.

Similarly, the ADM resulted in negative design values for some scenarios where the standard deviation was high and the mean was relatively low.

The Structural Glass Design Manual and the EN1990 characteristic approach showed reasonable alignment. Since the SGDM uses a minimum value approach the results varied more drastically when there was a low outlier in the data.

The study also appears to provide some validation to the 2.5 overall safety factor approach used in the IBC however it should be noted that all testing data used had a relatively high number of samples. A 2.5 safety factor may be reasonable with at least 20 samples and less than 40% COV, adjusted for the population, however at 3 tests it may not reasonable with a COV greater than 15%.

5. Other considerations

The EN 1990 characteristic approach has a n,d value which is intended to act as a variable addressing uncertainty in the testing. With heat-treated glass such as fully tempered glass, uncertainty needs to be reviewed when considering the surface pre-compression. Glass manufacturers often exceed the minimum surface compressions required for glass types such as heat-strengthened and fully tempered. This needs to be understood when utilizing test data. It needs to be normalized when extrapolating to general conditions and monitored when elevated values are accounted for from sampling testing.

For laminated systems, the stiffness remains 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 through analysis, the testing may need to test at both testing extremes. 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 eg. 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 and overheating.

Testing will remain a vital aspect of structural engineering and supports the development of new structural materials and attachment methods. The guidance provided in the Structural Design Manual is intended to consolidate industry best practices for design and testing to promote excellent structures with a consistent level of robustness and safety.

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