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Weathering vs Self-healing: Development of the Design Flaw and Cumulative Load Duration for Hurricanes

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Abstract

Glass design standards include an allowance for load duration but are silent on the capacity of glass immediately following a near-design-duration load event and the capacity to sustain subsequent loading. They treat loading events as isolated occurrences rather than cumulative phenomena. Typically, wind loads are treated as 3 second load duration, regardless of the type of storm or the associated gust patterns and cumulative duration. For this to be true, the glass must heal somewhat between the loading events, if not to the level of fresh glass, then healing to the level of surface flaw assumed in the design standard. This paper explores the dynamic nature of flaw-development in glass from fresh to weathered states and self-healing from design-duration-loaded state to re-establishment of design level resistance. In prior research these effects have mostly been treated separately; this paper examines both the mechanisms that contribute to "weathering" and "self-healing" of glass, as well as climatic data in the context of cumulative wind load event duration. Particular attention is given to evaluating appropriate load durations for atypical sustained-wind events such as hurricanes, cyclones, and typhoons. This paper reviews prior material from disparate areas and proposes revised design practices for areas prone to hurricane events. It contrasts window glass and structural glass assemblies and the implications for standardization and design of structural glass.

Keywords

Structural Glass Design Manual, Weathering, Self-healing, Design Flaw, Load duration, Independent events, Hurricanes

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1. Introduction

Glass is brittle, with the tensile strength capacity controlled by surface flaws and the growth of those flaws by sub-critical crack growth, while the surface is in tension for loads below the level of fast-fracture. The usable resistance of float glass is load-duration sensitive. Countering the cumulative effect, some degree of self-healing and/or blunting of flaws occurs over time. This paper discusses the various mechanisms for strength loss and strength gain, and relevant timeframes in which they occur.

Generally, the load duration for wind events on glass is regarded as three seconds (3s) regardless of the type of storm encountered. One of the arguments for using a three second wind standard in hurricane regions is that we do not see extensive breakages. However, if window design is typically controlled by displacement, then lack of extensive visible breakage is not necessarily a good litmus of strength limit state. Structural glass assemblies, unlike windows, tend to be stiff and loaded in-plane, with strength controlling the design. For this reason, the load duration of tropical storms needs to be more carefully considered. Windows generate membrane stress and the location of the peak stress varies with the load cycle. In structural glass assemblies, the system tends to be linear elastic, with the peak stress occurring at a constant location. When considering windows as a benchmark, because the location of peak stress changes, this also influences the time-stress-history of the glass at any particular flaw. Structural glass is more likely to experience peak stress at the same flaw repeatedly, so events which have been successfully treated as time-independent in window glass will likely not be so in structural glass.

Furthermore, Australian standards and ASTM disagree on the strength standard for fully tempered glass. Australian standards use a strength factor of 2.5 compared to ASTM's strength factor of 4.0. The Australian rationale for this practice is that if fully tempered glass were treated as having a 4.0 strength factor, the displacement under wind load would become alarming because the glass would be relatively thin. U.S. practice is to allow for higher strength but check for displacement separately; both routes result in similarly sized glass for typically sized windows. It is important to recognize that design controlled by displacement does not mean that the glass is also fully utilized for strength and that acceptable practice for windows may not extrapolate to appropriate practice for structural glass assemblies.

To assess the merits of considering a different wind load duration for hurricanes, other than what has generally been adequate for window glass, in design practice for structural glass assemblies, the mechanisms of "weathering", "self-healing", and storm characteristics are considered. In addition, the consideration of the physical attributes that make strength-controlled design less likely in windows than structural glass assemblies have been reviewed. When considered in combination with time series from hurricanes and evaluated with Brown's integral, a revision to the time duration for glass design, and in particular design of structural glass assemblies, is proposed.

2. Weathering of Glass

"Weathering" of glass, in the context of this paper, is a general term for phenomena that reduce the surface capacity of the material. The term encompasses addition of physical flaws (pitting, scratches), chemical attack, static fatigue (sustained load and sub-critical crack growth), and cyclic loading fatigue (aggregated sub-critical crack growth). The static fatigue of glass was noted as early as 1899 by Grenet and has been well-documented in the intervening century and a half, and well summarized by Meyland, Nielsen, and Kocer (2021) in the graph below.

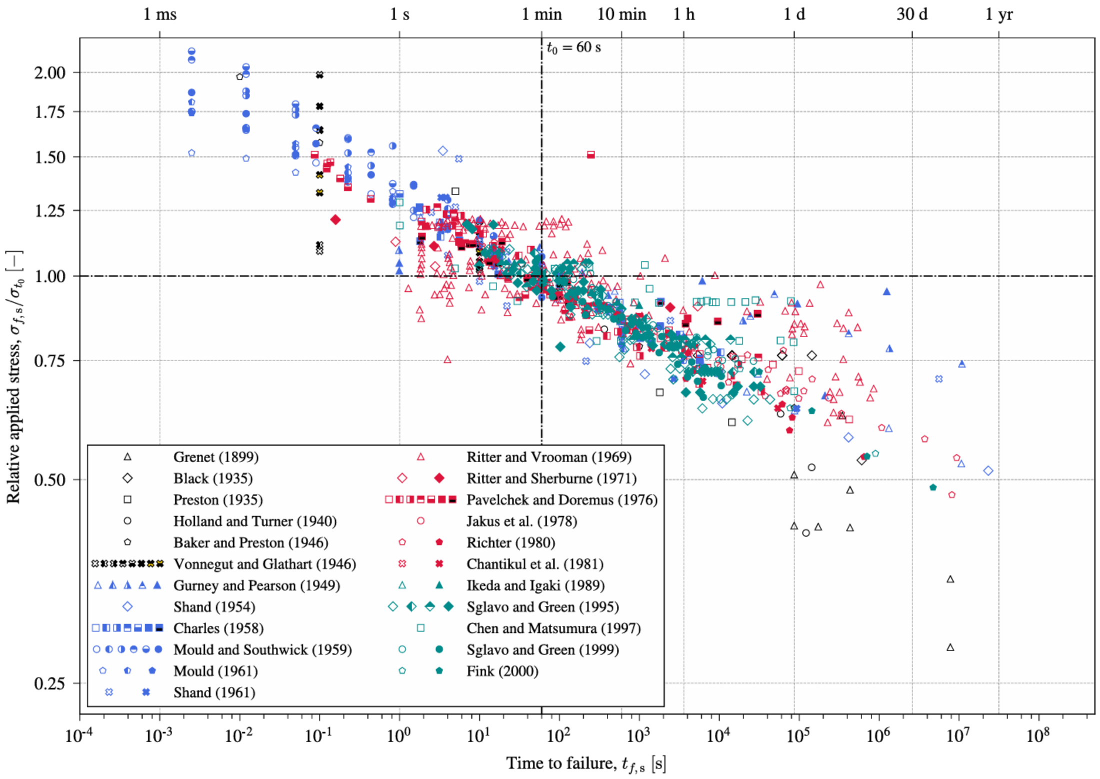
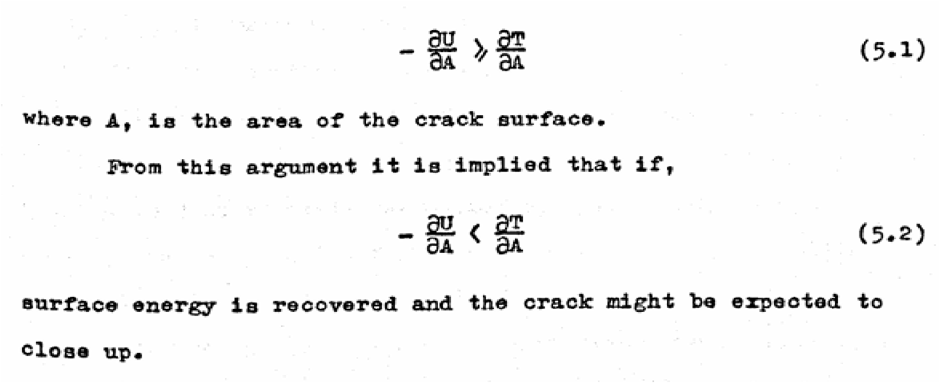


Fig. 10. A re-plot of the reviewed static fatigue data of soda-lime-silica glass, as the relative applied stress (see Sec. 3.1.2) as a function of time to failure.

Fig. 1: Failure stress vs Time to Failure (Meyland et.al. 2021).

In general, the testing for both static and dynamic fatigue has been conducted on fresh glass or freshly initiated flaws rather than weathered or aged flaws. This information is true for flaws that have been newly initiated but may not represent the entire picture for weathered glass and aged flaws.

Crack propagation is the conversion of elastic energy into surface free energy on a fracture surface. Energy balance would suggest that below a certain threshold, surface energy may be recovered into elastic energy and the crack will close (Stavrinidis 1980).



$$-\frac{\partial U}{\partial A} \geqslant \frac{\partial T}{\partial A} \qquad (5.1)$$

where A, is the area of the crack surface.

From this argument it is implied that if,

$$-\frac{\partial U}{\partial A} < \frac{\partial T}{\partial A} \qquad (5.2)$$

surface energy is recovered and the crack might be expected to close up.

Fig. 2: Extract from Stavrinidis 1980.

Note: the equations above are for ideal brittle material, while glass exhibits a degree of plasticity. However, the underlying principle holds true. In practice, the materials’ energy dissipates at or near the advancing crack tip; as such, the amount of released elastic strain must be greater to compensate for dissipation. Crack propagation in semi-brittle materials, as opposed to ideally brittle materials, typically comes with surface irregularities around the crack tip.

When externally applied load is removed, the surface elasticity of the glass tends to pull the crack tip surfaces back into partial contact. Complete re-formation is improbable enough to be presumed functionally infeasible because of reaction with the environment and irregularity in the fracture surface. “...adsorption of environmental species such as O_2, H_2O, or CO_2 onto the fresh fracture surface may inhibit significant bonding between the surfaces: although closed and possibly invisible, such cracks would therefore probably not be load bearing. Nevertheless, in practice…finite load is required to reopen the closed cracks.” (Stavrinidis 1980 pg. 102). As such, self-healing may not reestablish the original structure or strength but still provides an appreciable increase in strength relative to the freshly opened crack-tip.

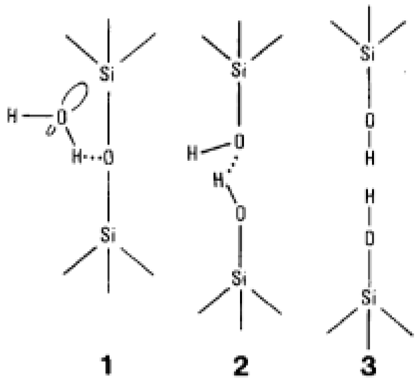


Fig. 3: Representation of proposed reaction between water and strained Si-O-Si bond at crack tip. Reaction steps involve (1) adsorption of water to Si-O bond, (2) concerted reaction involving simultaneous proton and electron transfer, and (3) formation of surface hydroxyl groups. After Michalske and Freiman (1983).

3. Self-healing of glass

“Self-healing” of glass, in the context of this paper, is a general term for any increase in strength state over a period of time in ambient conditions, without external active interventions or actions.

Wiederhorn and Townsend (1970) documented self-healing in their paper *Crack Healing in Glass*. Testing was by applying opening forces to a pre-formed crack.

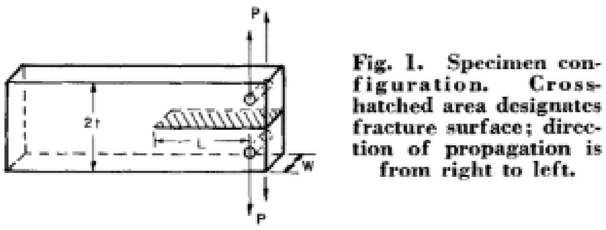


Fig. 1. Specimen configuration. Cross-hatched area designates fracture surface; direction of propagation is from right to left.

Fig. 4: Testing configuration of Wiederhorn and Townsend (1970).

Wiederhorn found that the energy for fracture is calculated from the formula

$$\gamma = \left[6\, P^2 L^2 / E w^2 t^3\right]\left[1 + \frac{1.34t}{L} + 0.45\left(\frac{t}{L}\right)^2\right] \tag{1}$$

where P is the load to induce crack opening, L the apparent crack length, E Young's modulus, and t and w are specimen dimensions. The fracture surface energy, γ, and the critical stress intensity factor, K_{Ic}, are related by the equation for opening mode failure

$$\gamma = K_{IC}/2E \tag{2}$$

Wiederhorn and Townsend state: “Approximately 80% strength was recovered in cracks formed by mechanical shock, whereas approximately 20% was recovered in cracks that closed after being held open to the atmosphere for several minutes…. Crack healing can introduce surface flaws into glass that cannot be detected by current methods of nondestructive testing…. Cracks containing freshly fractured surfaces of the type just described would be expected to heal readily on release of mechanical restraints because the surfaces are very active.... In the present experiments, the high degree of strength recovery of the healed cracks formed by shock treatment probably results from the very active fracture surfaces originally formed. **In the presence of H_2O and O, freshly formed fracture surfaces are not expected to be active, and weak bonds are expected to form on closure**. Water is expected to react with the strained S_i-O bonds in the surface to form S_iOH, thus releasing the elastic energy associated with the strained bonds. In addition, O and H_2O are expected to react with the dangling bonds. The energy of the freshly fractured surfaces will thus be reduced by chemical reaction with the environment, and as a result the energy released during healing will not be as large as that released by fracture surfaces that have not been altered chemically.” (Wiederhorn et al emphasis added) Thus the type of bond reforming is a function of time as the presence of moisture and oxygen can be assumed for architectural applications.

Further, the work of self-healing behavior has been studied in numerous environments and with a variety of mechanisms. Irrespective of the assumed mechanism, the energy to refracture the flaws that have healed after a given duration of time is quantifiable.

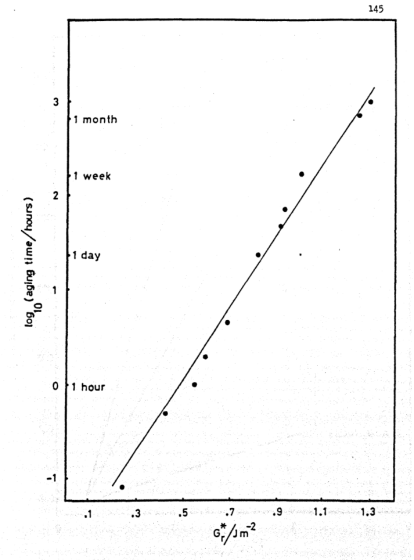


Figure 7.3 Variation of G_r^* with aging time in air in soda-lime-silica glass.

Fig. 5: Variation of Strain Energy Release G_r for repropagation of a closed crack versus Time of Aging in Air (Stavrinidis 1980).

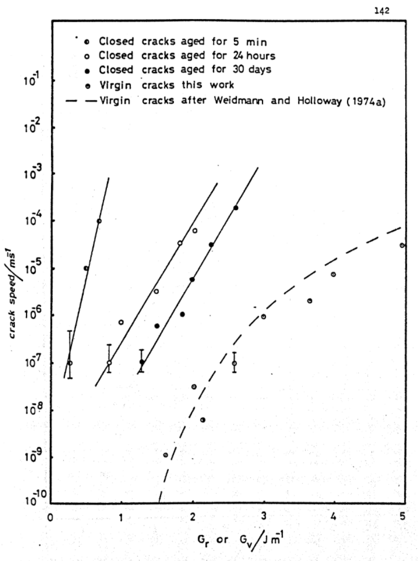


Figure 7.1 Variation of crack speed with G_r and G_v in air, for aged closed cracks and for virgin cracks respectively, in soda-lime-silica glass.

Fig. 6: Variation of Crack Speed with Strain Energy Release (Stavrinidis 1980).

As Stavrinidis notes, "When cracks had been formed or propagated and then given sufficient time to close, they could be heat-treated or tested again without the specimen's history impacting the results. **The only factor that altered the specimen's repropagation behavior was the treatment after crack closure."** (emphasis added) To summarize this concept, if the healing was by corrosion and blunting alone, the flaw would continue to get deeper and the stress intensity would be a function of the total flaw in addition to new growth. In that case, the results would not be repeatable, and for that reason the corrosion-only hypothesis is considered to be unlikely.

Table 1: Values of strain energy release, G_r in Jm^{-2} obtained for repropagation of closed cracks under specified test conditions per Stavrinidis Table 7.1.

Material	Ageing time in air			Medium	
	5 min	7 days	30 days	Water(1)	Dry gas(2)
Float Glass	0.25	1.05	1.25	0.14	1.30
Pyrex Glass	0.25	0.45	0.55	----	1.30
Silica Glass	0.25	----	0.35	----	------

(1) Refers to repropagation tests on closed cracks formed and tested under the same environment

(2) Refers to vacuum (10^{-3} Nm^{-2}), or dried nitrogen, or dried helium gas

Table 2: Values of strain energy release, G_G in J.m^{-2} obtained in crack closure tests$^{(1)}$ under specified environment per Stavrinidis Table 7.2.

Material	Water	Air	Vacuum$^{(2)}$
Float Glass	0.1	0.17	0.1
Pyrex Glass	----	0.15	0.1
Silica Glass	----	0.15	----

(1) The cracks were closing at a very slow rate (approximately 10^{-7} ms^{-1}).

(2) Refers to vacuum (10^{-3} Nm^{-2}), or dried nitrogen, or dried helium gas.

4. Chemistry at the crack tip

Genuine-crack-healing, defined generally as the re-formation of the original material and structure , is unlikely to be entirely responsible for the load-bearing capacities of closed cracks in air. When cracks are formed by slow or rapidly repeated loading in air, prior to healing, the surfaces will be contaminated by gas and/or solution components adsorbed into the crack. Atmospheric contamination thus prevents the chemical re-formation of the original bond structure within the glass.

A traditional view of moisture based self-healing is presented by Beason (1980). He notes that under stress the presence of moisture sharpens the crack tip and, when not stressed, moisture blunts the crack tip by corrosion. This paper does not refute that possibility but rather contends that there is a mechanism that better explains observed phenomena that warrants further exploration.

It is important to note that at the nano scale of crack tips, the interaction of H_2O with the glass is not chemically or physically the same as the interaction with water in the macro condition. “The liquid formed when water vapor is condensed in sub 100 µm capillaries (known as anomalous water…) exerts a vapor pressure lower than that of pure water introduced into a similar capillary in the liquid state.” (Everett et al 1971b)

Liquid water is far too large to fit into these cracks other than when opened under stress. However, water vapor such as would be found in humid air could reasonably be assumed to diffuse more deeply than liquid water. As Wiederhorn and Fuller (1989) (referencing Michalske and Frieman (1983)) note, crack velocity is much more sensitive to the applied stress in acidic solutions than it is in basic solutions. This would imply that, at least under stress, the composition of solutions are affecting the tip of the crack.

Anecdotally, Dr Leon Jacob found microscopic water forming at the crack surface when performing double cantilever testing to determine K_{Ic} values in air with any humidity. This indicates that the hydrophilic nature between glass and water is particularly strong in small gaps, even where the relative humidity (RH) is very low. Additionally, he noted that if glass is not snapped within 10 minutes of scoring the fracture path may not follow the score line, indicating that significant self-healing is occurring in an unstressed state and modest timeframe. Due to the time of self-healing not being immediate, true re-bonding is unlikely, rather a process involving water (vapor) is more probable.

Based on a comprehensive summary by Everett, Haynes, and McElroy (1971a)of more than one hundred papers, “anomalous water” in capillary tubes included a variety of ions that varied based on the capillary source material. This capillary condensation of nanoconfined water is relevant to our purposes for its demonstration that water vapor displays strong reactive capability and high viscosity in actively open surfaces with miniscule gaps. While the incidence of this material was tested across a variety of substances, its consistency in key characteristics and composition suggests that water under these conditions specifically reacts with the Si-O bond in the structure, creating a reactive solution in the capillary. The behaviour of H_2O in crack tips can reasonably be assumed to be similar to that observed in capillaries exhibiting high reactivity with soda-lime glass and may be responsible for the initial load bearing capacity of the closed crack.

Capillary attraction from water in the system cannot fully account for apparent glass healing. Further research in this area suggests that “For surfaces in close proximity (<100 nm), the forces between the surfaces that have been measured with sufficient accuracy for a quantitative analysis are of three types: dispersion forces resulting from induced dipole-dipole interactions between the atoms of the solid; double-layer forces arising from the charges that form on the surface of glass placed in aqueous solutions; and structural or entropic forces that are caused by distortions to the structure of the fluid as the surfaces approach separation of <1 nm.” Wiederhorn and Frieman (1989). Additionally, Stavrinidis’ work found that stress intensity at a crack tip in air is higher than the intensity of a similar crack tip immersed in water, and that Strain Energy Release Gr is strongly dependent on chemical composition of the glass, such that the rate of increase of Gr may be explained in the context of ion exchange between the glass and adsorbed water molecules.

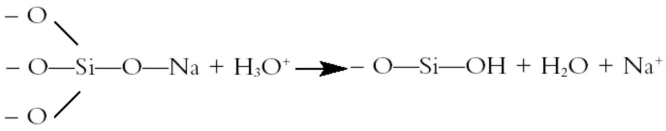


Fig. 7: Alkali metal ions are lost from the surface layer of the glass and replaced by hydrogen ions accompanied by water. Sodium ion migrates into the solution, which becomes progressively more alkaline, in effect becoming a solution of sodium hydroxide. After Griffiths and Feuerbach 2001.

The relatively high sodium content in soda-lime glass would further contribute to the reactivity of silica-water solutions at the crack tip. Indeed, it has been found that glasses with higher sodium contents healed faster. This includes study into a mechanism for crack healing in which the subsurface layer of the glass is attacked by water, which both bonds to electronegative atoms on the surface of the glass and dissociates into the deeper layers. This creates a mobile exchange in which Na^+ moves to the glass surface, which disrupts the structure of the silicon-oxygen network. (Stavrinidis 1980) A hydronium-alkali ion exchange mechanism was also posited by Guin and Wiederhorn (2005) in their analysis of crack-tip topology as an explanation for noted surface displacement near the crack tip. Another of Guin and Wiederhorn’s observations was that a re-opened crack showed an ogee tip rather than a sharp fracture, implying that the glass had healed by filling the flaw, rather than blunting the tip radius, before re-fracturing.

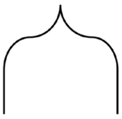


Fig. 8: Ogee Shape

This research suggests that ‘self-healing’ of glass cracks have not actually experienced re-formation of the original glass structure; rather, a secondary substance has been formed in the crack tip. Water seeps into the crack tip, reacts with the fractured face, pulls the crack together, and forms a new substance of the available species with a different amorphous structure to the surrounding glass. This may transition initially from hydrogen bonding to a cationic bridging (with electrolytes causing the silica colloids to coagulate) or siloxane bridging forming a dense silica network. (Michalske, Fuller 1985) The healing in this case begins at the far tip of the crack, propagates outwards and forms a meniscus rather than a flat face. Stavrinidis’ work also noted a marked change in refractive index along healed crack faces. Although his observations were qualitative, they support the theory that the substance in healed cracks is not chemically the same as normal glass. His theory is also supported by others’ contention that “The corrosion rate of glass at a crack tip will depend on the pH of the crack-tip solution and on the concentration of solutes in that solution.” (Guin, Wiederhorn, 2005). A pH dependency further supports the ion exchange theory, especially combined with the physical shape of the re-broken cracks.

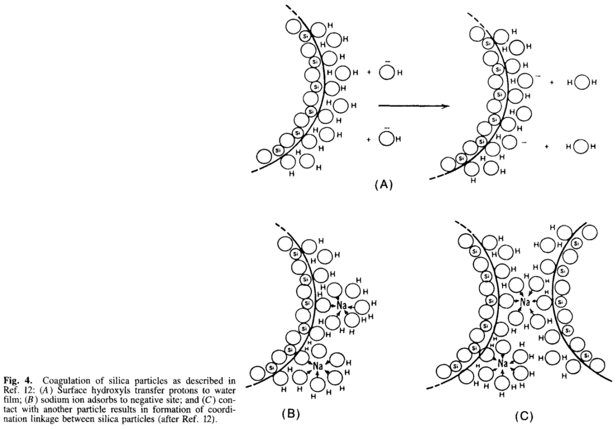


Fig. 4. Coagulation of silica particles as described in Ref. 12: (*A*) Surface hydroxyls transfer protons to water film; (*B*) sodium ion adsorbs to negative site; and (*C*) contact with another particle results in formation of coordination linkage between silica particles (after Ref. 12).

Fig. 9: Coagulation of silica particles as described in Iler (1979): (A) Surface hydroxyls transfer protons to water film; (B) sodium ion adsorbs to negative site; and (C) contact with another particle results in formation of coordination linkage between silica particles – Michalske and Fuller (1985) after Iler (1979).

Stavrinidis goes further, suggesting that removal of the Na from the surface of the glass leaves the silicon also more likely to be available as building blocks for self-healing with a gradual transition from hydrogen bonding to a structure containing a combination of Na^+, Si, OH^- etc. progressively bridging the structure forming primary bonds, but without necessarily forming an amorphous structure identical to the substrate glass.

In this paper it is contended that flaws under storm conditions sub-critical crack-growth in architectural glass would display similar characteristics to the anomalous water formation sites, the humidity from the air reacting with the silicon-oxygen bonds in soda-lime-silicate glass in particular, where the moisture accelerates the flaw growth and more slowly heals the flaw with a new amorphous structure that may differ from the original in its physical properties.

While the true behavior at the crack tip, both in terms of crack growth and mechanism of repair, is still not fully understood, we can reasonably state that with the exception of instantly healed bonds of an uncontaminated surface, in a vacuum or other unnatural conditions, the self-healing process in the presence of moisture is a time-consuming one which requires a significant period between wind gust events for the events to be regarded as non-cumulative.

5. Time effects in weathered glass

Since crack healing does not result in the actual re-formation of the original glass, it would be unreasonable to expect self-healed cracks to necessarily exhibit the same time-dependence of load that virgin glass does. Ignatius Calderone's (1999) data on aged glass breakage stress shows a greatly reduced dependency with respect to time, rather than a decreasing capacity with log-time dependency the way that fresh glass does. This apparently paradoxical finding makes sense if we consider a healed crack to be a somewhat different substance; glass bonds are extremely strong but brittle, so they are governed by fracture mechanics and hence have a time dependency. The newly formed bonds in the healed glass may be of a substance that has weaker bond strength but reduced brittleness, resulting in different time-strength characteristics.

Calderone's work includes a rare data set in which window glass tests were conducted by the same method in full-scale pressure chamber conditions on fresh glass and old glass of similar size and thickness with variable strain rates. The nominal sizes are "fresh" 2000 x 1000 x 6mm and "old" 2045 x 958 x 6mm. Breakage stress has been back-calculated considering the pressure at breakage and breakage location. (Note the old glass was replaced due to exterior etching and testing was performed on the interior surface; breaks from obvious chips due to deglazing were excluded from these results.)

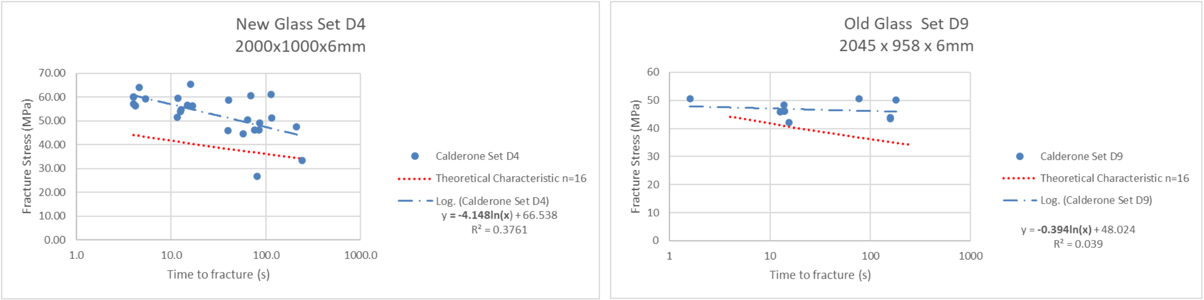


Fig. 10a,b: Comparison of New (left) and Aged (right) Glass, Fracture Stress v Time.

Note that the sample size for the old glass is small and the R^2 parameter is poor, so further work is needed on aged glass before confident conclusions can be made. However, the findings are consistent with the premise that the behaviour of aged glass may be different to what is theoretically anticipated from research on fresh glass, and further research is warranted. (See also 9. future work.)

Fortunately, the design envelope of both fresh glass flaws and healed ones have a similar stress capacity magnitude and the existing equations serve well. In the context of ASTM E1300, where it is assumed that the point of fracture is not at the maximum stress due to the maximum flaw not being at that location, it is worth noting that due to window cleaning and other in-service accumulation of flaws, it is likely that the flaw density becomes more uniform with time but that the flaws may also heal to a less time-sensitive state. In effect, the glass moves towards the state of a *design flaw* and fluctuates around it in a process of weathering and healing. For this reason, the use of principle stress has merit, but random incidence of the fresh flaw cannot be ignored and may indeed be the critical flaw in many cases.

Below are tests on a small sample of weathered glass which indicate that the time related properties of this weathered glass may be different than typically assumed.

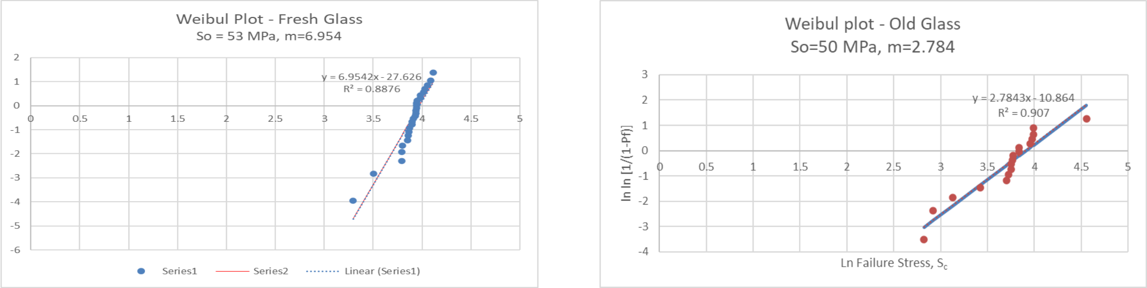


Fig. 11a,b: Comparison of New (left) and Aged (right) Glass – Weibull Plot without time correction.

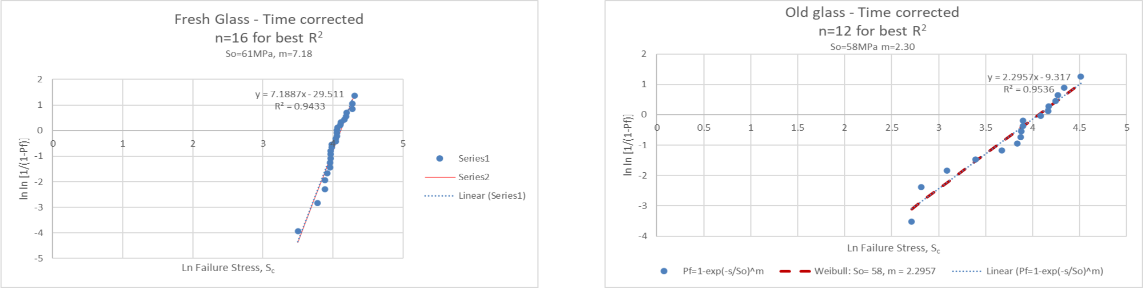


Fig. 12a,b: Comparison of New (left) and Aged (right) Glass – Weibull Plot with time correction “n” optimised for best fit.

6. Event independence – Storm types

With research having established that self-healing in air (by whatever mechanism) is time dependent, it is important to consider the types of loading patterns associated with different storm types, the separation of gusts, and the number of gusts within a period of time. Stavrinidis’ work investigated (see Figure 5) and found that the degree of self-healing in a 6 minute (10^{-1} hours) span is small relative to the self-healing that occurs with time separations of greater than a month. On the basis that design storms with a mean recurrence interval of 50 years are rare relative to the self-healing timeframe of soda-lime glass, it is reasonable to study individual storms.

In thunderstorm events, there tends to be a small number of highly elevated gusts within a generally elevated wind period associated with the storm. There is also a significant time between design level storms.

ASTM E1300-89 was originally based on a 60 second (60s) load duration; it was based on the work of Dalgleish (1980) to accommodate storms of up to 2 hours (CAN/CGSB 12.20-89), but it was generally accepted that this was too conservative. When ASCE 7 wind pressure calculation changed from fastest mile to 3 second gust, the reference time for glass strength was also adjusted to 3 seconds, which empirically brought the probabilistic approach into closer agreement with prior experience. Dalgleish and Irwin have suggested that 10 seconds is more appropriate for thunderstorms. Given that the thunderstorm has relatively few gusts and the difference between 3 seconds and 10 seconds is less than 10 percent in resistance capacity, with calculations based on minimum glass thickness for glass produced in finite thicknesses, the odds of exceedance for window glass in a thunderstorm are extremely low. In general, thunderstorms are sufficiently separated for them to be reasonably treated as independent events.

6.1. Non-cumulative load events – Thunderstorms

Typical thunderstorms have been described in many papers; the following are typical examples. It is worth noting that the time scale is in seconds with overall plot of ~10 mins. The stormfront typically progresses rapidly with winds that are from a constant direction. Design windspeeds are typically of the order of 38 to 41 m/s for areas controlled by thunderstorms.

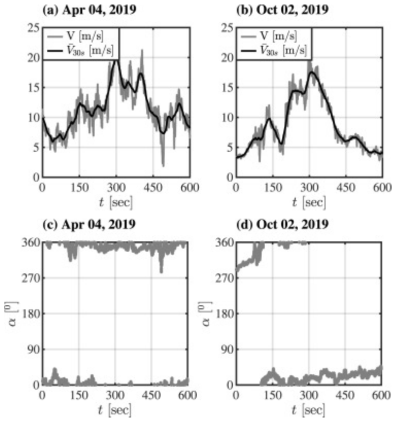


Fig. 13: Full-scale measurements of a thunderstorm, velocity and direction – Mengistu and Repetto (2023).

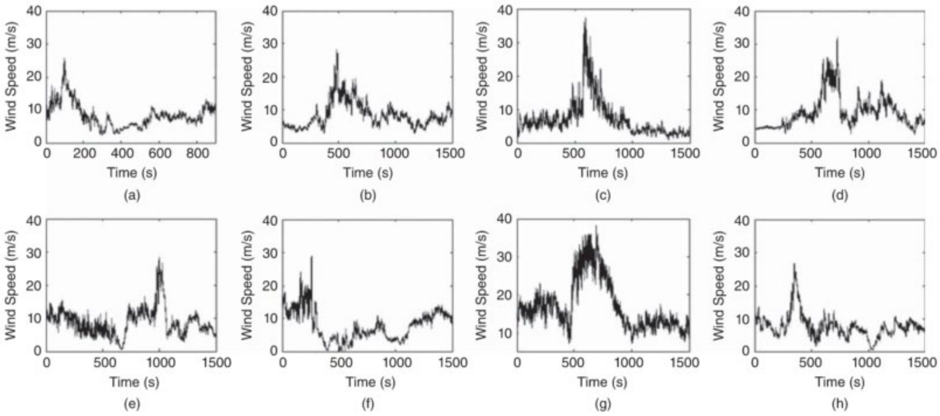


Fig. 14: Time histories of eight thunderstorm events – Simiu and Yeo (2019) after Lombard et.al (2014).

Gavanski and Kopp (2011) found the three-second gust approximation to be adequate for thunderstorms. Thus, for areas outside of hurricane type storms, the three-second approximation is adequate and no change to practice is proposed.

6.2. Cumulative load events - Hurricane

Gavanski and Kopp (2011) used full-scale velocity data from real storm events in combination with wind tunnel pressure coefficients and Brown's integral to evaluate the suitability of three-second equivalent static gust for annealed glass. They concluded that this period is inadequate for storms of hurricane duration. Gavanski suggests that a 90th percentile wind would be an appropriate wind pressure for use with a three-second gust. However, per International Building Code (IBC 2024) the wind load associated with E1300 is an ASD level wind load with a nominal load W_n of $mean$ / 0.78 (Galambos 1981). If it were assumed that the time sensitivity was entirely due to the time sensitivity of glass where a 90th percentile pressure is adequate (albeit potentially conservative in many cases) but a 50th percentile is not, then a load duration of 30 minutes would be necessary for the nominal wind load (see Figure 16).

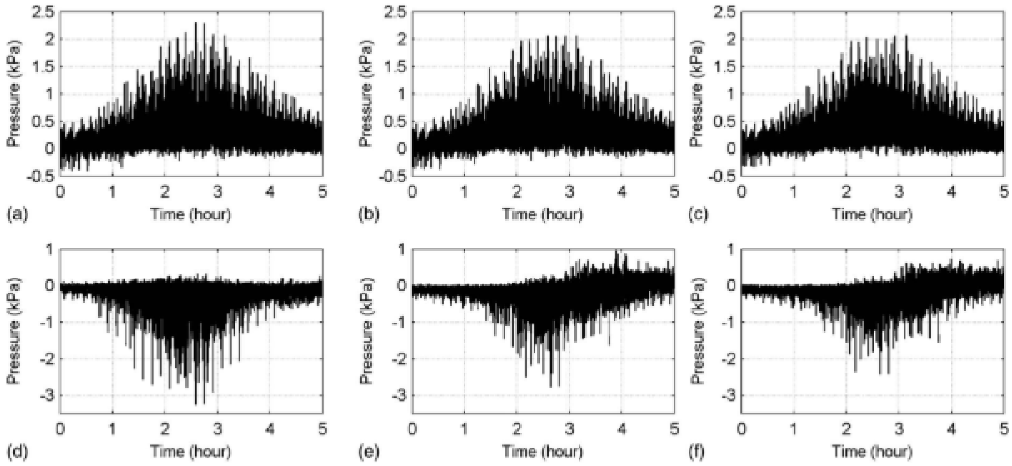
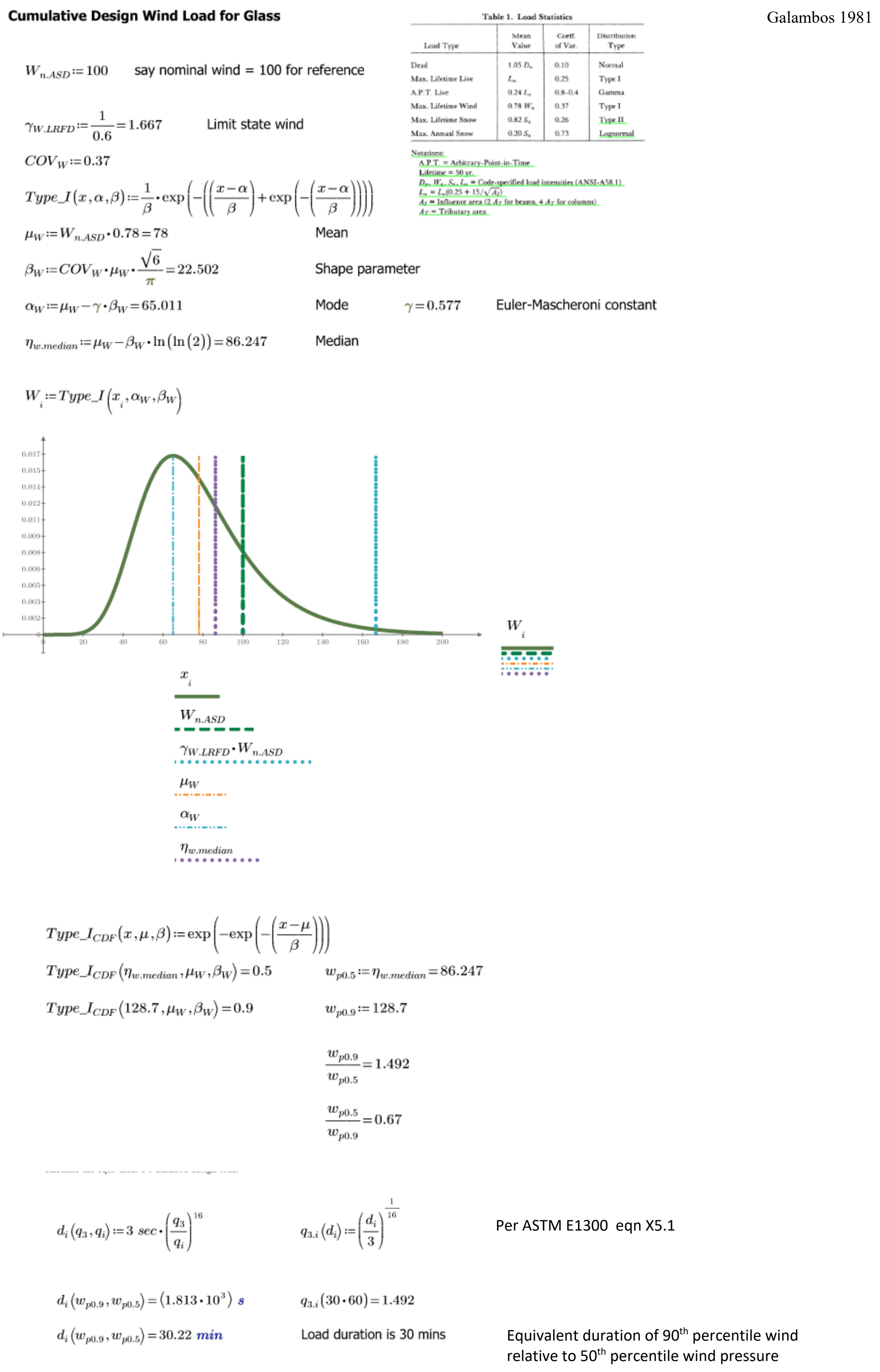


Fig. 3. Design cyclone pressure time series: (a) $A_t = 1.0\ \mathrm{m}^2$, positive; (b) $A_t = 4.1\ \mathrm{m}^2$, positive; (c) $A_t = 9.2\ \mathrm{m}^2$, positive; (d) $A_t = 1.0\ \mathrm{m}^2$, negative; (e) $A_t = 4.1\ \mathrm{m}^2$, negative; (f) $A_t = 9.2\ \mathrm{m}^2$, negative

Fig. 15: Design cyclone pressure series – Gavanski and Kopp (2011).



Cumulative Design Wind Load for Glass

Galambos 1981

Table 1. Load Statistics

Load Type	Mean Value	Coeff. of Var.	Distribution Type
Dead	1.05 D_n	0.10	Normal
Max. Lifetime Live	L_m	0.25	Type I
A.P.T. Live	0.24 L_o	0.8–0.4	Gamma
Max. Lifetime Wind	0.78 W_n	0.37	Type I
Max. Lifetime Snow	0.82 S_n	0.26	Type II
Max. Annual Snow	0.20 S_n	0.73	Lognormal

Notations:
A.P.T. = Arbitrary-Point-in-Time
Lifetime = 50 yr.
D_n, W_n, S_n, L_o = Code-specified load intensities (ANSI-A58.1)
$L_m = L_o(0.25 + 15/\sqrt{A_I})$
A_I = Influence area (2 A_T for beams, 4 A_T for columns)
A_T = Tributary area

$W_{n.ASD} := 100$ say nominal wind = 100 for reference

$\gamma_{W.LRFD} := \frac{1}{0.6} = 1.667$ Limit state wind

$COV_W := 0.37$

$Type\_I(x,\alpha,\beta) := \frac{1}{\beta} \cdot \exp\left(-\left(\left(\frac{x-\alpha}{\beta}\right) + \exp\left(-\left(\frac{x-\alpha}{\beta}\right)\right)\right)\right)$

$\mu_W := W_{n.ASD} \cdot 0.78 = 78$ Mean

$\beta_W := COV_W \cdot \mu_W \cdot \frac{\sqrt{6}}{\pi} = 22.502$ Shape parameter

$\alpha_W := \mu_W - \gamma \cdot \beta_W = 65.011$ Mode $\gamma = 0.577$ Euler-Mascheroni constant

$\eta_{w.median} := \mu_W - \beta_W \cdot \ln(\ln(2)) = 86.247$ Median

$W_i := Type\_I\left(x_i, \alpha_W, \beta_W\right)$

$Type\_I_{CDF}(x,\mu,\beta) := \exp\left(-\exp\left(-\left(\frac{x-\mu}{\beta}\right)\right)\right)$

$Type\_I_{CDF}\left(\eta_{w.median}, \mu_W, \beta_W\right) = 0.5$ $w_{p0.5} := \eta_{w.median} = 86.247$

$Type\_I_{CDF}\left(128.7, \mu_W, \beta_W\right) = 0.9$ $w_{p0.9} := 128.7$

$\frac{w_{p0.9}}{w_{p0.5}} = 1.492$

$\frac{w_{p0.5}}{w_{p0.9}} = 0.67$

$d_i\left(q_3, q_i\right) := 3\ sec \cdot \left(\frac{q_3}{q_i}\right)^{16}$ $q_{3.i}\left(d_i\right) := \left(\frac{d_i}{3}\right)^{\frac{1}{16}}$ Per ASTM E1300 eqn X5.1

$d_i\left(w_{p0.9}, w_{p0.5}\right) = \left(1.813 \cdot 10^3\right)\ s$ $q_{3.i}(30 \cdot 60) = 1.492$

$d_i\left(w_{p0.9}, w_{p0.5}\right) = 30.22\ min$ Load duration is 30 mins

Equivalent duration of 90th percentile wind relative to 50th percentile wind pressure

Fig. 16: Equivalent Load Duration for Structural Glass Design.

Following investigation of glass failures in less than design windspeed conditions, investigators concluded that “Direction and duration of extreme winds, not just velocity, should be considered for the design of large buildings in urban environments. The Integrated Kinetic Energy (IKE) index proposed by Powell and Reinhold [2007] should be considered as a descriptor of damage. Current practice for wind design still results in significant cladding damage.” Vega and Konz (2009 emphasis added)

7. Critical Load Direction

The ASCE 7 calculation of wind load for components and cladding, including architectural glass and their support systems, includes a wind directionality factor kd, with a nominal value of 0.85. This factor accounts for two effects: (1) the reduced probability of maximum winds coming from any given direction; and (2) the reduced probability of the maximum pressure coefficient occurring for any given wind direction. (ASCE 7-22 C26.6) However, in the case of hurricanes, the direction is continually changing throughout the peak duration of winds and the probability of the wind coming from the peak direction is high, hence it is recommended that a factor kd = 1.0 be used for structural glass in hurricane regions.

There is precedent for this design practice in FEMA 543 (2007) which also recommends using k_d =1.0 for critical facilities in hurricane prone regions. (FEMA 543 s.3.3.1.2) Typically structural glass assemblies assume that loss of strength in one ply is due to non-design load circumstances, hence the strategy of one-ply broken is a reasonable approach. It is critical, however, that the loads are conservative because should breakage occur during peak load, the impact of load re-distribution could cause a cascade of breakage with catastrophic collapse. Thus it is reasonable to assume structural glass is a critical structure and the wind may come from the critical direction during the extended peak gust period of a hurricane, and increase the wind load by assuming k_d=1.0.

Using a combination of k_d = 1.0 with a cumulative load duration of 3 to 10 minutes appears to provide a combined increase in reliability consistent with the 90th percentile recommendations of Gavanski and Kopp. The actual load duration is a function of the storm history at the project site combined with the air flow geometry of the project and surroundings. For such details a wind consultant with experience in glass load duration effects is recommended.

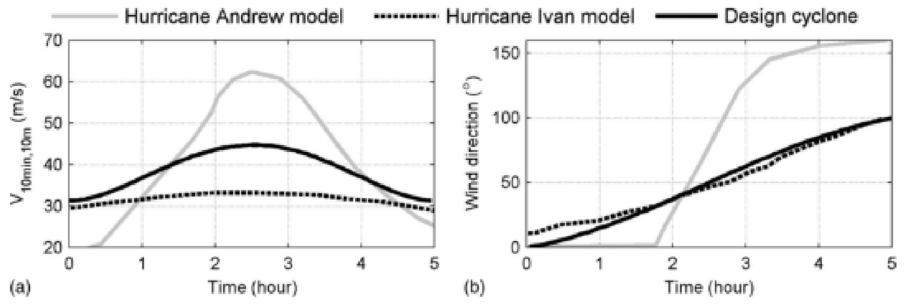


Fig. 1. Variation of (a) 10 min mean wind speed at 10 m height; and (b) wind direction for the design cyclone and Hurricanes Andrew and Ivan

Fig. 17: Hurricane wind intensity and direction from Gavanski and Kopp (2011).

8. Conclusion

Design standards for window glass typically treat wind loads as a three-second gust regardless of the storm type. Experience has shown that this has worked adequately for window glass. There are a number of factors that may be advantageous for window glass, however, that are not applicable for structural glass assemblies. As such, extrapolation of a three-second load duration requires more careful examination before being adopted for structural glass in hurricane prone regions.

Glass also becomes weathered, which weakens it. Weathering occurs from many sources, including physical imposed flaws (ranging from impact to window cleaning), chemical corrosion (including action of water), and sub-critical crack growth (due to load application). Conversely, glass is also known to exhibit self-healing, with the effectiveness and nature of bonds dependent on the environment and the time duration the crack is held apart. While the native Si-O bonds may reform in vacuum or inert environments, in natural environments it is likely that H_2O also participates in both the sub-critical crack growth and self-healing. Several prior papers propose an ion exchange mechanism with rebuilding of the material at the crack tip rather than corrosion blunting at the tip. It is possible that the properties of self-healed cracks are not the same as fresh cracks, but further work is required to substantiate this. It is also possible that the properties are still sufficiently similar to be well approximated within the safety factors of existing design practices.

Prior research has also shown that it takes months to self-heal glass in the presence of moisture. Design level winds driven by thunderstorms typically have an event duration of 6-10 mins with isolated gusts of design wind speed. The design level storms (for ASTM E1300) have a mean recurrence interval of 50 years, hence are typically sufficiently separated to be treated as isolated events. Gavanski and Kopp found the three-second gust approximation to be adequate for such events.

For hurricane events, the storm duration is extended, the peak gusts capable of damage accumulation are more frequent, and the direction varies continuously through a sector. Gavanski assumes no self-healing between gusts, which is consistent with a low degree of self-healing after 6 minutes indicated by Stavrinidis. Gavanski evaluated the pressure-time-stress relationship with Brown’s integral and found that 3 second design duration to be non-conservative for hurricane prone regions.

Because structural glass assemblies are typically controlled by strength and not deflections, the extrapolation of window glass practice, which is typically deflection controlled and seems to perform adequately in hurricanes, is potentially a false positive. Longer cumulative load durations should be allowed for structural glass applications.

In hurricane regions, the wind direction systematically changes within the duration of the storm such that wind from the critical direction is likely, thus the directionality factor should be set to $k_d = 1.0$ for critical cladding components. Because failure of structural glass components may result in a sudden impact associated with redistribution of load (and potentially resulting in sudden progression to collapse), it is recommended that structural glass in hurricane prone zones be treated as critical structures with increased wind load by using $k_d = 1.0$. Such logic is already codified for critical structures in FEMA 543.

Extrapolation of current design practices for window glass which uses three-second load duration in hurricane prone regions, to structural glass assemblies, is considered to be non-conservative. It is proposed that it is more appropriate to use higher wind pressures with $k_d = 1.0$, and a load duration of at least 3 to 10 minutes, as appropriate to account for cumulative loads from hurricane events.

9. Future work

Further work on the time series of aged glass is required, noting that with age the flaw distribution will become more developed and uniform, but that the time series and flaw behaviour may be somewhat different to fresh glass flaws. If there are more prior data-sets available of naturally aged glass with variable stress rates, please advise the author.

The author is currently planning re-glazing of a 27-storey tower, with a potentially abundant supply of 40-year-old naturally aged heat strengthened glass in insulating glass units. Should anyone have the resources or inclination to perform testing on this glass, please contact the author.

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References

ASCE.(2022).“Minimum design loads for buildings and other structures.” ASCE 7-22, Reston, VA.

ASTM. “Standard practice for determining load resistance of glass in buildings.” E1300-24 (2024).

Calderone, I.J., The Equivalent Wind Loading for Window Glass Design. PhD Thesis Monash University (1999)

Canadian General Standard Board (CGSB). (1989). “Structural design of glass for buildings.” CAN/CGSB-12.20-M89, National Standard of Canada, Ottawa, Canada.

Dalgliesh, W.A., 1979: "Assessment of Wind Loads for Glazing Design," Proceedings, IAHR/IUTAM Symposium on Practical Experiences with Flow- Induced Vibrations (September 3-6, 1979), Naudascher, E. and Rockwell, D. (Eds.), Springer-Verlag, Berlin Heidelberg, pp. 696-708.

Datsiou, K.C., Overend, M.: The Strength of Aged Glass. Glass Struct. Eng. (2017) 2:105–120 DOI 10.1007/s40940-017-0045-6

Everett, D.H., Haynes, J.M., McElroy, P.J.: The story of anomalous water. Science Progress Vol. 59, No. 235 pp. 279-308

(1971a),

Everett, D.H., Haynes, J.M., McElroy, P.J.: The thermodynamics of anomalous water solutions I. Vapor pressure and enthalpy of evaporation J. Colloid and Interface Science Pages: 483-488 Volume: Volume 36, Issue 4 https://doi.org/10.1016/0021-9797(71)90382-1 (1971b)

FEMA 543, Risk Management Series Design Guide for Improving Critical Facility Safety from Flooding and High Winds (2007)

Friedman, S., Wiederhorn, S., Mecholsky, J., 2009. Environmentally Enhanced Fracture of Glass: A Historical Perspective. J. Am. Ceram. Soc., 92 [7] 1371–1382 DOI: 10.1111/j.1551-2916.2009.03097.x

Galambos T. V., Load and Resistance Factor Design Engineering Journal / American Institute Of Steel Construction (1981)

Gavanski, E., Kopp, G.A.: Storm and Gust Duration Effects on Design Wind Loads for Glass. ASCE (2011).

Griffith, A.: The Phenomena of Rupture and Flow in Solids. Philosophical Transactions of the Royal Society of London Vol. 221 (1921)

Griffiths, D. R., Feuerbach A. M: The Conservation of Wet Medieval Window Glass: A Test Using An Ethanol And Acetone Mixed Solvent System JAIC 2001, Volume 40, Number 2, Article 4 (pp. 125 to 136)
https://cool.culturalheritage.org/jaic/articles/jaic40-02-004_1.html

Guin, J.P., Wiederhorn, S.: Crack-Tip Structure in Soda–Lime–Silicate Glass. J. Am. Ceram. Soc., 88 [3] 652–659 (2005) DOI: 10.1111/j.1551-2916.2005.00108.x

Iler R. K., The Chemistry of Silica; pp. 373-78. Wiley, New York, 1979.

Lombardo, F.T., Smith, D.A., Schroeder, J.L., and Mehta, K.C. (2014). Journal of Wind Engineering and Industrial Aerodynamics 125: 121–132. http://dx.doi.org/10.1016/j.jweia.2013.12.004.

Meyland, M., Nielsen, J., Kocer, C.: Tensile behaviour of soda-lime-silica glass and the significance of load duration – A literature review. Journal of Building Engineering (2021).

Michalske, T.A., Freiman, S.W.: A Molecular Mechanism for Stress Corrosion in Vitreous Silica. J. Am. Cerum. Soc., 66 [4] 284-88 (1983).

Michalske, T.A, Fuller E.R. Closure and Repropagation of Healed Cracks in Silicate Glass .J. Am. Ceram. Soc., 68 [11] 586-90 (1985)

Powell, M. D. and T. A. Reinhold, Tropical cyclone destructive potential by integrated kinetic energy. Bull. Amer. Meteor. Soc., 87 (2007): 513-526.

Stavrinidis, B, 1980. Fracture and Flow in Glass. PhD Thesis https://keele-repository.worktribe.com/output/414674

Structural Glass Design Manual Eds. Green R.R., Crosby A.D., McDonnell T.R. https://structglass.org/ 2025, 2026

Weibull W. A statistical theory of the strength of materials. Royal Inst for Eng Res, Stockholm. 1939; 151:1–45.

Wiederhorn, S.M., Fett, T., Rizzi, G., Funfschilling, S., Hoffmann, M.J., Guin, J.P.: Effect of Water Penetration on the Strength and Toughness of Silica Glass. J. Am. Ceram. Soc., 94 [S1] S196–S203 (2011) DOI: 10.1111/j.1551-2916.2011.04530.x

Wiederhorn, S.M., Fuller, E.R.: Effect of Surface Forces on Subcritical Crack Growth in Glass. J. Am. Ceram. SOC., 72 121 248-51 (1989)

Wiederhorn, S.M., Townsend, P.R.,1970. Crack Healing in Glass. Institute of Materials Research, National Bureau of Standards, Washington, D. C. 20234

Vega, R. E., & Konz, R. C. (2010). *Cladding performance of high-rise buildings in the Houston CBD during Hurricane Ike*. In Forensic Engineering 2009: Pathology of the Built Environment (Proceedings of the Fifth Congress on Forensic Engineering, November 11–14, 2009, Washington, DC). American Society of Civil Engineers (ASCE)

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