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Silicone Spandrel Glass Coatings: Mitigating Glass Breakage Risk from Thermal and Other Stresses

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Curtain wall design commonly uses insulating glass units for vision and spandrel glazing to provide better visual harmonization of building façade glass. Risks with this design approach include higher thermal stresses, especially when low-emissivity coatings are used on insulating glass units in spandrel areas. Ceramic enamel frit – commonly used to opacify spandrel glass – is known to induce a bending strength reduction of up to 50%. The ability of ceramic enamel frit coated glass to resist thermal stress is similarly reduced. Multiple incidences of thermal stress related fracture have occurred with heat-strengthened, ceramic enamel frit opacified spandrel glass. An increased chance of spontaneous breakage, by nickel sulfide inclusions, may occur if ceramic enamel frit opacified spandrel glass is fully-tempered to withstand the thermal stresses that it is exposed to. Silicone spandrel glass coatings have been examined as a solution to prevent the strength reduction in heat-treated glass when ceramic enamel frit is applied as an opacifier. Four-point bending tests were used to investigate the flexural strength of coated heat-strengthened and fully-tempered glass. Ball drop testing was used to investigate the impact resistance of coated fully-tempered glass. Test data shows silicone coatings have no adverse effect on the flexural strength or impact resistance of the substrate and, in some instances, improve it. Therefore, silicone opacifiers do not reduce the resistance to thermal stress of heat-treated glass. These coatings also provide fallout protection in accordance with ASTM C1048 (ASTM, 2012). This suggests using a silicone opacifier on heat-treated spandrel glass could greatly reduce the risk of fracture resulting from thermally induced tensile stress, flexural stress, and impact related glass breakage in addition to reducing risk of injury from fallout if breakage occurs.

Keywords: Glass Strength, Silicone Coatings, Insulating Glass Units, Glass Weakness, Ceramic Enamel Frit, Architectural Glass, Uniform Lateral Load, Four-point Bending, Ball Drop

1. Introduction

In the world of façade glass, there are two types of glass: vision, and spandrel. Vision glass is transparent to provide viewing areas for occupants and daylight for the interior. Spandrel glass areas, where slab ends, vents, and mechanical elements reside, is opaque. Since the 1990’s, the amount of spandrel glass on a building has fluctuated between 15-30% of a building's total glass area, as dictated by design trends. Recent energy codes, where the baseline building is governed by lower glazing ratios, has resulted in increased spandrel areas of glazed facades. As a sizable area of a building’s exterior, spandrel glass not only contributes to visual appeal, but a building’s energy use since insulating glass (IG) units improve the energy performance of the spandrel area.

Insulating glass units have been used in commercial and residential high-rise construction for many years to increase HVAC energy efficiency, and more recently, in the case of spandrel areas, to provide greater color and visual harmonization between vision and spandrel areas. As vision glass improves – greater light transmission with lower reflectance, plus increased energy performance – with the use of low emissivity (low-e) coatings it can become difficult to visually harmonize façade glass unless the spandrel areas use the same glass configuration.

However, there is a risk associated with using IG units in a closed spandrel area. Most importantly, known to the industry, is thermal stress will increase, particularly in the opacified inboard glass lite. This is primarily due to heat gain that accumulates in the center of the inboard lite as the sun’s rays strike it. The increased heat differential between the inboard glass center and its edges, often exacerbated with the use of low-e coatings or by dark colors in a spandrel cavity (Mognato and Barbieri, 2013), leads to thermal stresses which can result in fracture. The accepted rule is that 0.34 MPa (50 psi) hoop stress is created around the edge of a lite of glass for every 0.56°C (1°F) increase in temperature of the exposed area. Therefore, a center-to-edge temperature difference (ΔT) of 56°C (100°F) will create 34.5 MPa (5,000 psi) thermal stress.

Issues from thermal stress are further aggravated by the use of ceramic enamel frit as a spandrel opacifier. In recent years, there has been increased awareness in the industry that ceramic enamel frit, used as a spandrel coating, lowers the flexural strength of both heat-strengthened (HS) and fully-tempered (FT) glass. The degree of weakening depends on glass coverage, the colors used, and even the formulation of the ceramic enamel frit itself (Maniatis and Elstner, 2016). There are several newly published works that discuss the weakness of various heat-treated (HT) products with an applied ceramic enamel frit opacifier; "full coverage black ceramic enamel…reduced the load resistance (LR) of FT glass and HS glass by approximately factors of 2.0" (Natividad et al., in press) and 37.5% reduction of strength (Krampe, 2014).

In summary: laboratory tests have shown significant flexural strength reductions in both new and artificially weathered glass, in both HS and FT glass, when fully covered with a ceramic enamel frit opacifier. Strength reductions, of approximately 50% to 20% have been measured in mean strength and in the 8 per 1000 probability of breakage strength, respectively. Bergers, et al. (2016) attributed the difference between mean strength values and design strength values to the fact that samples with ceramic enamel frit opacifiers have a much lower coefficient of variation (CoV) than clear samples. A lower CoV signifies the difference between values for design load resistance is less than the differences between mean load resistance.

European product standards EN 12150-1 (2015) & EN 1863-2 (2004) address reductions in flexural strength of HT – HT referring to either HS and/or FT – glasses resulting from the application of ceramic enamel frit. These standards reduce the minimum surface flexural strengths of HT glass from 120 N/mm^2 (17400 psi) to 75 N/mm^2 (10900 psi) and from 70 N/mm^2 (10200 psi) to 45 N/mm^2 (6500 psi) for FT and HS glass with ceramic enamel frit, respectively.

The American standard, ASTM E 1300 "Standard Practice for Determining Load Resistance of Glass in Buildings," uses conservative 2X and 4X multiplying factors for the strength of HS and FT glass, when compared to annealed glass (ASTM, 2016). Since no field-breakage has been reported from flexural stress in enameled HT glass, there has been little immediate incentive to change the published uniform load strength values in ASTM E 1300-16 (2016). Currently, there is no standard available to determine the resistance of glass to thermal loads in insulating glass units.

However, there have been a significant number of thermal stress breakages in HS IG spandrel units with ceramic enamel frit (Barry and Norville, 2015). In all reported cases, the fracture origin is typically located between 13 mm (0.5") to 25 mm (1") in from the cut edge of the glass (Fig. 1). Significantly, the fracture origin has always occurred on the glass surface in contact with the ceramic enamel frit and never on the uncoated glass surface (Fig. 2). This clearly indicates a relatively large reduction of the tensile strength of HS, in-service, glass with an application of ceramic enamel frit.

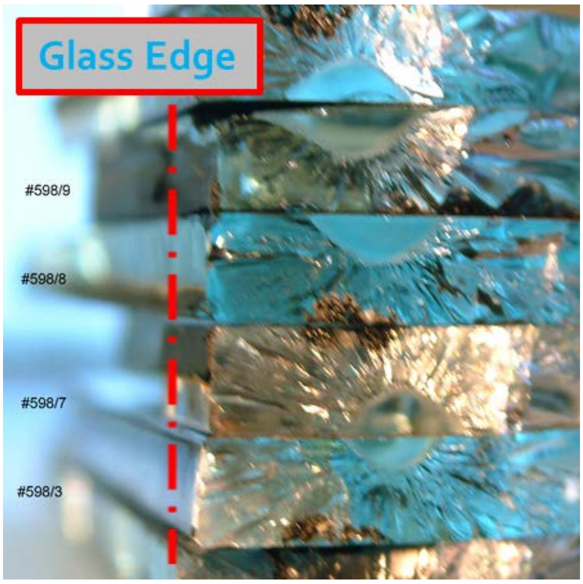

Figure 1. Ceramic enamel frit opacifiers on spandrel glass with the thermal stress fractures beginning away from the glass edge.

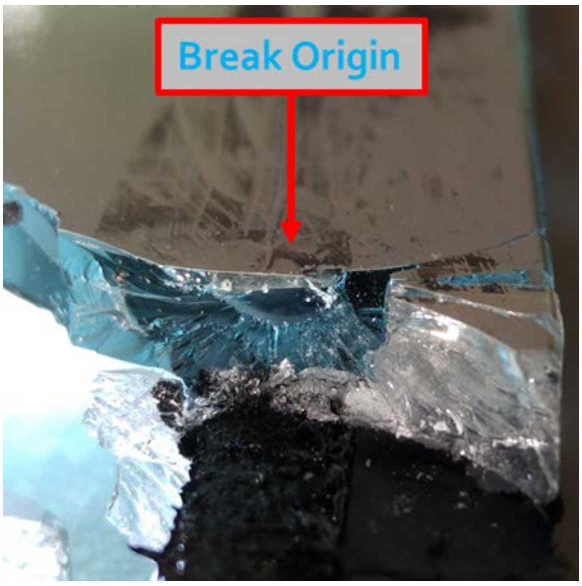

Figure 2. Ceramic enamel frit opacifier on spandrel glass with the thermal stress fracture located where frit material interfaces with glass.

In response to the thermal stress failures in the field, FT glass lites have been used in spandrel areas to mitigate thermally induced breakage. However, this mitigation strategy increases the risk of spontaneous breakage from nickel sulfide inclusions in FT glass, unless the glass is heat soaked, with a consequent cost increase. Also, if a FT inboard lite of an IG unit breaks and goes unnoticed, the LR of the IG unit may decrease to where additional fracture may occur allowing glass shards to fall from the spandrel cavity.

As such, there is an increasing need for a spandrel opacifier that does not weaken the glass, but ideally, increases its strength and offers fallout protection. Silicone coatings were examined as a solution to the strength reduction issue created by applying ceramic enamel frit to HT glass as a spandrel opacifier. Investigations were performed using four-point bending and ball drop test methods.

2. Experiment Methods

2.1 Four-Point Bending Test

Six samples of HS and six samples of FT 102 x 305 x 6 mm (4 x 12 x ¼ in.) flat glass beams were obtained, with each sample comprised of at least 30 specimens (Table 1).

Table 1: Samples tested via four-point bending.

Sample	Sample Size	Glass Type	Coating
1	34	HS	Clear (Uncoated)
2	33	HS	OPACI-COAT-300®
3	30	HS	OPACI-COAT-500®
4	33	FT	Clear (Uncoated)
5	33	FT	OPACI-COAT-300®
6	30	FT	OPACI-COAT-500®

Specimens were coated using OPACI-COAT-300®, a water borne silicone elastomer, or with OPACI-COAT-500®, a 100% solids silicone elastomer. All coatings were applied to the air side of the specimen – the side most commonly coated with opacifiers in spandrel glass fabrication. A total of 193 specimens were tested. All coatings were black. OPACI-COAT-300® was applied via spray gun to 330 µm (13 mils) wet film thickness (WFT). OPACI-COAT-500® was applied via roll coat to 150 µm (6 mils) WFT.

Specimens were tested in four-point bending using an MTS machine to provide load at a uniformly increasing rate as per ASTM C 1161-13 (ASTM, 2013). The MTS machine was certified by the American Association for Laboratory Accreditation (ASLA Cert. No. 11455.01) for the basis of the ISO/IEC 17025 international standards for calibration laboratories. During loading, a data acquisition (DAQ) system captured the load-time history from inception of loading to fracture for each specimen. Traditional beam theory was used to convert load-time histories to stress-time histories. Next, using equation 1 (Beason, 1980), each stress-time history was converted to a three-second equivalent fracture stress (σ_3). Finally, each value of (σ_3), was used to determine values for equivalent fracture load (P_3) from traditional beam theory.

$$\sigma_3 = \left[\frac{\int_0^{t_f}(\sigma(t)-RCSS)^{16}dt}{3\,sec}\right]^{1/16} + RCSS \quad (1)$$

Where,

- σ_3 denotes the 3-second equivalent fracture stress
- t_f denotes the time of fracture
- $\sigma(t)$ denotes stress at time, t
- RCSS denotes the minimum observed residual compressive surface stress in a sample

All specimens were installed in the four-point testing mechanism with the float glass air side (coated side) facing down (Fig. 3). This orientation induces tensile stresses in the float glass air side and compressive stresses in the float glass tin side during testing. Glass will break under tensile stress. This is true whether glass is stressed mechanically or thermally. The loading supports spanned 254 mm (10 in.) where each glass beam specimen was placed center to center (c-c) allowing 63.5 mm (2.5 in.) between each support and loading point. The four-point bending creates uniform stresses between the inside loading supports' 127mm (5 in.) span.

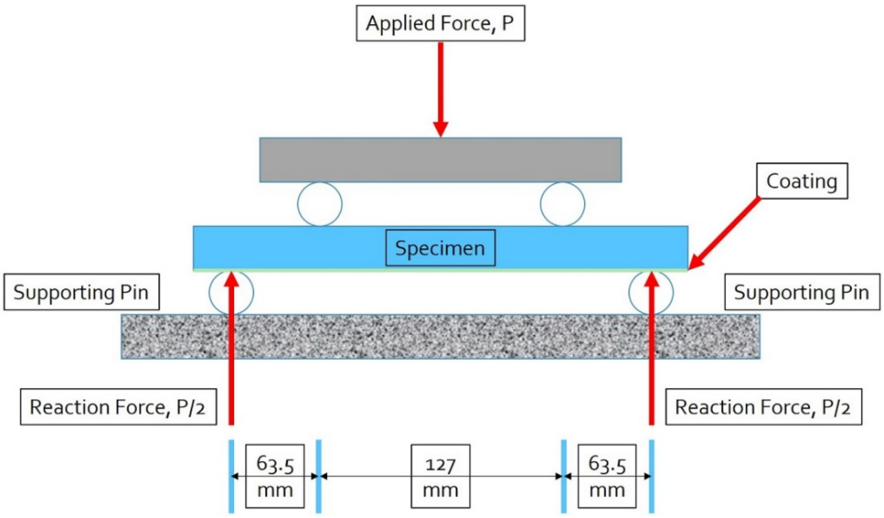

Figure 3. Schematic diagram of four-point bending test.

Once installed each test consisted of loading a beam specimen at a rate of 2.54 mm per min (0.1 inches per min), an equivalent loading rate of 445 N per min (100 lbs per min), while the DAQ system recorded the load and time histories at a sampling rate of 10 Hz. Each test concluded with the fracture of the beam specimen, followed by inspection and measurement.

Using the Maximum Likelihood Estimation (MLE), the σ_3 values were used to fit a three parameter Weibull distribution to obtain cumulative distribution functions (CDFs) for the P_3 using equation 2:

$$P_f = 1 - \exp(-B) \quad (2)$$
$$B = kS_m$$
$$S_m = {\sigma_3}^m A_{surface}$$

Where,

- $\boldsymbol{m}$ and $\boldsymbol{k}$ denote statistical parameters
- $\boldsymbol{B}$ denotes a risk function,
- $\boldsymbol{S_m}$ denotes an equivalent plate area that depends on the magnitude of the tensile stress and the Weibull parameter m
- $\boldsymbol{A_{surface}}$ denotes the surface area

The CDF's allow direct comparison concerning the LR of clear (uncoated) and coated beam specimens of the same glass type. In this work, LR for the glass beams is defined as the constant applied force with 3-second duration that leads to a probability of breakage equal to or less than 8 per 1000. Work by others (Bergers, et al., 2016) has indicated a reasonable correspondence between results from four-point bending tests and full-scale test of rectangular lites.

2.2 Ball Drop Test

Four samples of FT 305 x 305 x 3 mm (12 x 12 x 1/8 in.) flat glass beams were obtained, with each sample comprised of at least 30 specimens (Table 2)

Table 2: Samples tested via ball drop.

Sample	Sample Size	Glass Type	Coating
1	34	FT	Clear (Uncoated)
2	34	FT	OPACI-COAT-300®
3	31	FT	OPACI-COAT-500®
4	33	FT	Ceramic Enamel Frit

Specimens were coated using OPACI-COAT-300®, a water-borne silicone elastomer, OPACI-COAT-500®, a 100% solids silicone elastomer, or with a ceramic enamel frit. All coatings were applied to the air side of the specimen. A total of 132 specimens were tested. All coatings were black. OPACI-COAT-300® was applied via spray gun to 330 μm (13 mils) WFT. OPACI-COAT-500® was applied via roll coat to 150 μm (6 mils) WFT. Ceramic enamel frit was applied via screen print to 38 μm (1.5 mils) WFT.

Specimens were tested in a ball drop impact test frame following the parameters from a GANA Specification (GANA 76-12-10a, 2008), using a 50 mm (2 in.) diameter steel ball with 535 g mass weighing approximately 5.25 N (1.18 lbs).

Samples were loaded into the test frame, float glass air side (coated side) facing down. Impact height was increased until fracture occurred, at which point drop height was recorded and the specimen inspected.

3. Results and Discussion

3.1. Four-Point Bending Test Results

All specimen fracture origins lay between the load points on the beam specimens, that is, within the area of constant bending moment and flexural stress. No fracture origin was located on the edge of a specimen.

Below is a summary of the statistical results for the samples. Researchers used the minimum RCSS for each sample in calculations described (Table 3).

Table 3. Sample statistics displaying mean P_3, standard deviation, coefficient of variation (CoV), and minimal residual compressive surface stress of all samples

Sample	Mean P_3 (kN)	Standard Deviation (kN)	CoV (%)	Minimum RCSS (MPa)
1	2.19	0.23	10.5	50.2
2	2.35	0.16	6.67	52.0
3	2.36	0.17	7.26	52.9
4	2.75	0.15	5.48	104
5	2.74	0.16	5.76	104
6	2.77	0.11	3.81	82.6

The CoVs for samples of HS glass beams coated with OPACI-COAT-300® and OPACI-COAT-500® were relatively small. The small values of CoV led to large and similar values of the statistical parameter $m = 17$ and $m = 18$ for Sample 2 and Sample 3, respectively, which were significantly larger than $m = 10$ for Sample 1. One can make a similar observation concerning values of m and the CoVs for Samples 4, 5, and 6.

Figures 4 and 5 display the empirical values and CDFs for the P_3 values for HS and FT samples respectively while Figures 6 and 7 present the lower portion of the CDFs for HS and FT samples respectively. The solid blue curved lines in each graph represents the strength expected from HT glass when bought from a typical glass fabricator. Orange and red perforated, curved lines in each graph represents HT glass strength when coated with the OPACI-COAT-300®, and OPACI-COAT-500® silicone opacifiers.

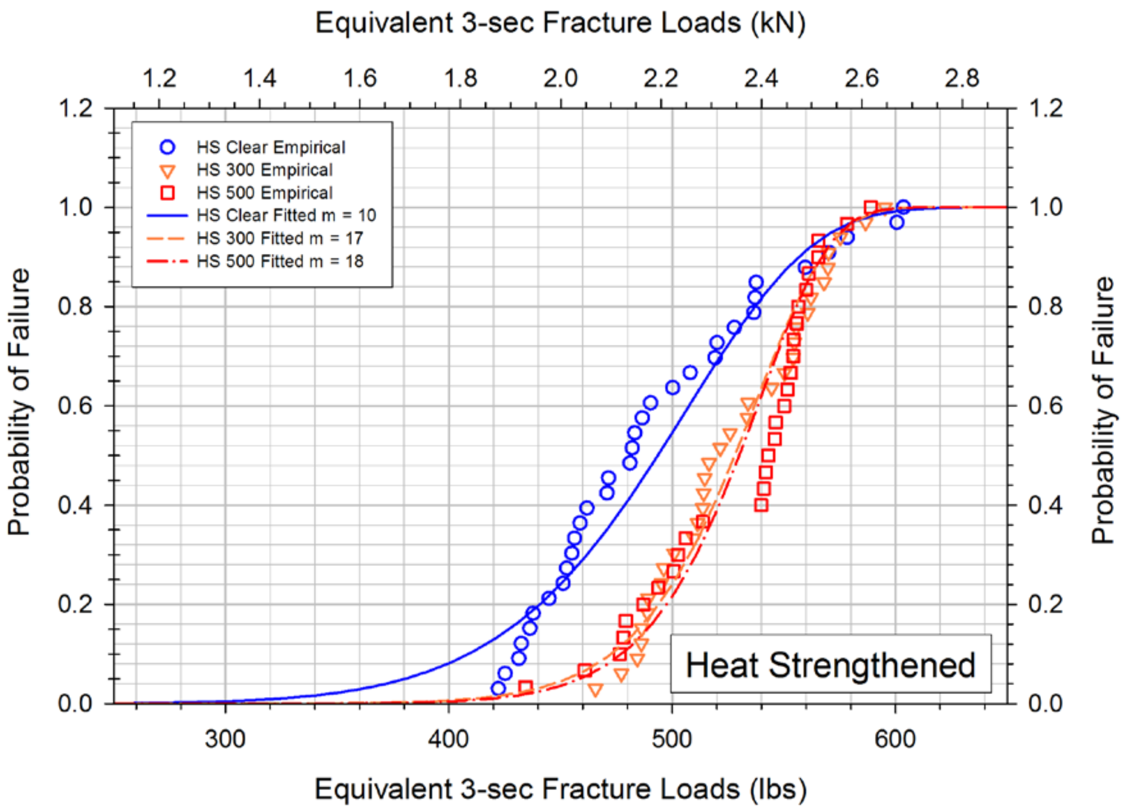

Figure 4. Cumulative distribution function for the probability of failure for clear HS, OPACI-COAT-300®, and OPACI-COAT-500® specimens.

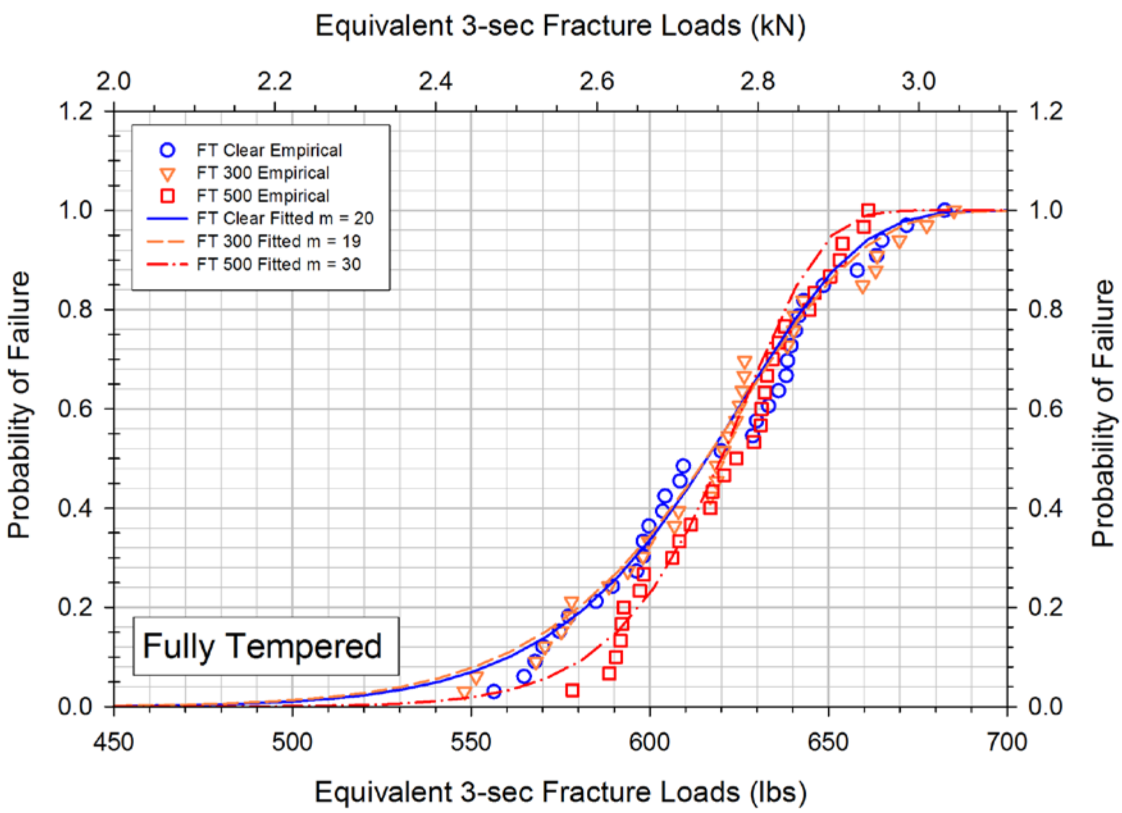

Figure 5. Cumulative distribution function for the probability of failure for clear FT, OPACI-COAT-300®, and OPACI-COAT-500® specimens.

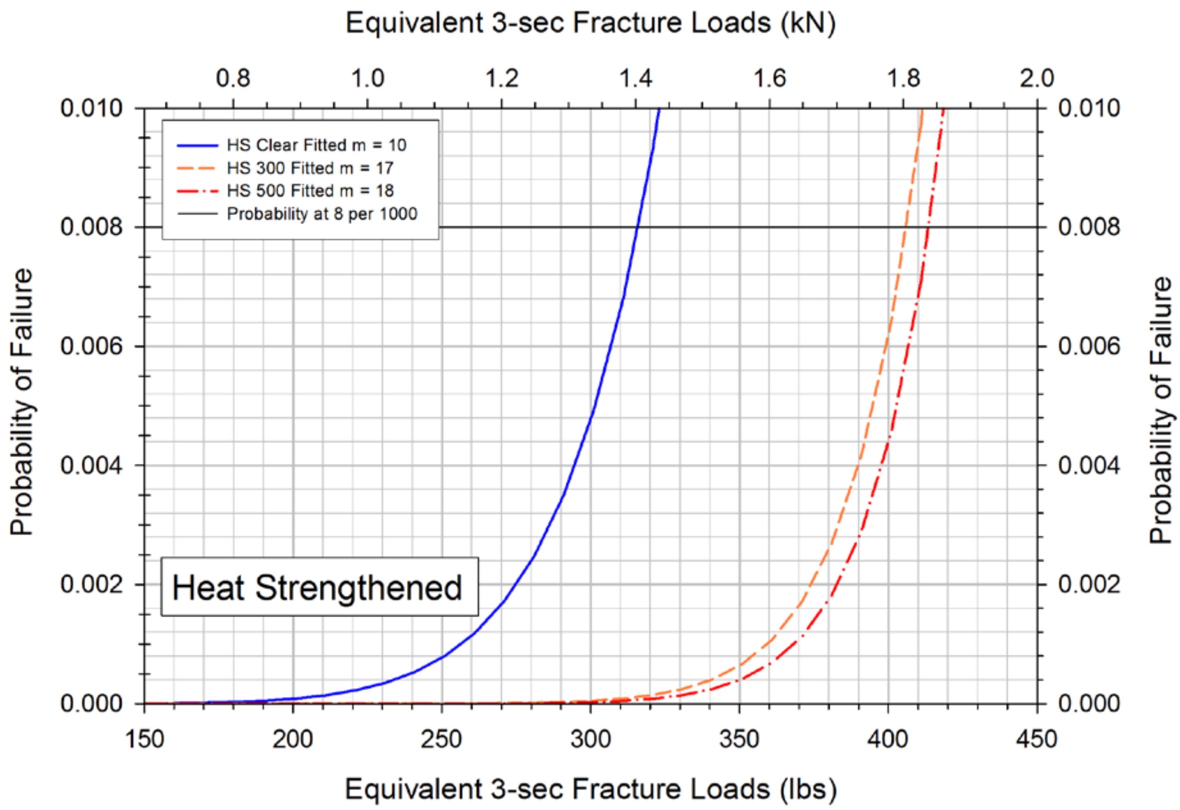

Figure 6. Fitted cumulative distribution function for the probabilities of failure less than or equal to 10 per 1000 for clear HS, OPACI-COAT-300®, and OPACI-COAT-500® specimens.

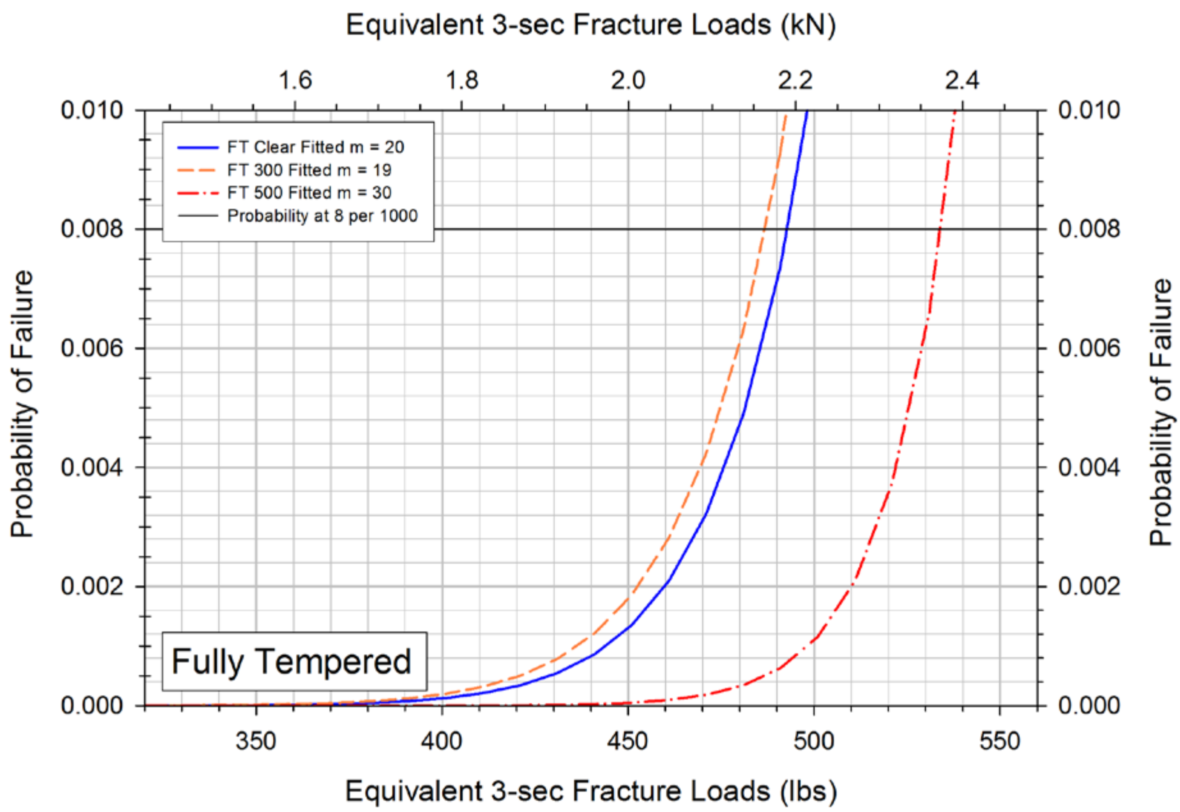

Figure 7. Fitted cumulative distribution function for the probabilities of failure less than or equal to 10 per 1000 for clear FT, OPACI-COAT-300®, and OPACI-COAT-500® specimens.

The cumulative distribution functions in Figures 4 and 6 indicate that both OPACI-COAT-300® and OPACI-COAT-500® increased the strength of HS glass a statistically significant amount. This is demonstrated in mean P_3 values and most prominently at a probability of breakage less than or equal to 8 per 1000. This data is summarized in Table 4.

In Table 4, Samples 2 and 3 are HS glass specimens coated with OPACI-COAT-300®, and OPACI-COAT-500® respectively, while samples 5 and 6 are FT glass specimens coated with OPACI-COAT-300®, and OPACI-COAT-500® respectively.

Table 4. Change in P_3 and load resistance (LR) relative to the associated clear samples.

Sample	Δ P_3 (%)	Δ Load Resistance (LR) (%)
2	7.28	28.50
3	7.66	30.90
5	-0.16	-1.20
6	0.75	8.36

Fully-tempered specimens coated with OPACI-COAT® silicone coatings however do not demonstrate a statistically significant change in either P_3 or load resistance relative to uncoated specimens

3.2. Ball Drop Test Results

Table 5 summarizes the statistical results for the samples while Figure 8 displays the mean fracture height of all samples. Table 6 shows the statistical values associated with mean fracture heights relative to those of uncoated Sample 1. Figure 9 displays the percent change in fracture height of the sample means relative to that of uncoated Sample 1.

Table 5. Sample statistics displaying mean fracture height, standard deviation, and coefficient of variation (CoV) of all samples.

Sample	Mean Fracture Height		Standard Deviation		CoV
	(m)	(ft)	(m)	(ft)	(%)
1	1.42	4.65	0.36	1.17	25.3
2	2.13	7.00	0.72	2.36	33.7
3	2.06	6.76	0.84	2.74	40.6
4	0.44	1.43	0.05	0.17	11.8

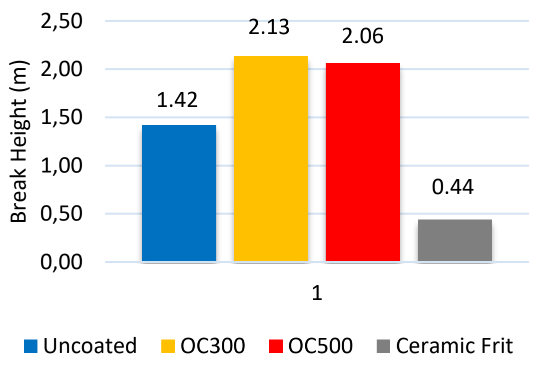

Figure 8. Mean fracture height of coated and uncoated specimens.

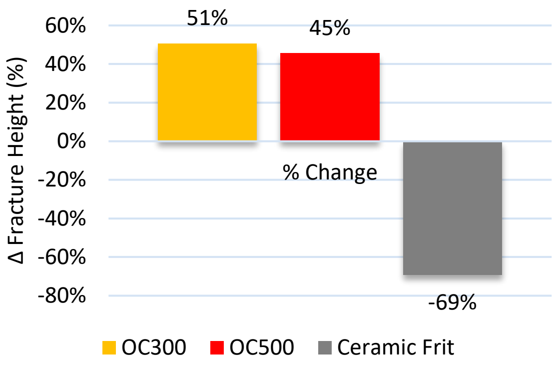

Figure 9. Percent change in fracture height of coated specimens relative to uncoated glass specimens.

Table 6. Sample statistics displaying change in mean fracture height relative to uncoated Sample 1, and associated P-value.

Sample	Δ Height	Δ Height	Δ Height	P-Value
	(m)	(ft)	(%)	
2	0.72	2.35	50.6	$7.9(10^{-5})$
3	0.64	2.11	45.5	$22.2(10^{-3})$
4	-0.98	-3.21	-69.2	$6.1(10^{-14})$

Specimens coated with OPACI-COAT-300® demonstrated a mean increase in fracture height of 0.72 m (2.35 ft.) compared to uncoated glass, while specimens coated with OPACI-COAT-500® displayed a similar mean increase in fracture height of 0.64 m (2.11 ft.). This corresponds to increases of 50.6% and 45.5% respectively. Specimens coated with ceramic enamel frit demonstrated a reduction in break height of 0.98 m (3.2 ft.), or -69.2% compared to uncoated glass.

4. Conclusion and Next Steps

Four-point bending test results indicate OPACI-COAT® silicone coatings have a positive impact on the flexural strength of heat-strengthened glass, and have little to no impact on the strength of fully-tempered glass. Furthermore, ball drop tests displayed a large increase in impact resistance for OPACI-COAT® coated fully-tempered glass. Since four-point bending is generally considered a more precise flexural strength testing methodology those results should be given greater weight.

It is clear silicone opacifiers, such as OPACI-COAT® silicone coatings, certainly do not decrease the load resistance or thermal stress control capability of heat treated glass, unlike ceramic enamel frit. As such, silicone opacifiers should be considered instead of ceramic enamel frit as a spandrel opacifier when glass breakage from thermal or bending induced tensile stresses, or from impact loads, is a concern.

Further testing should be conducted to explore the applications where increased load resistance and/or impact resistance of silicone coated heat-strengthened glass compared to uncoated glass may be important.

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