Evaluating the Performance and Durability of Acrylic Foam Tapes for Structural Glazing Applications

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ABSTRACT

This article presents a simple linear damage accumulation model that may have applicability for predicting damage from sustained winds in double-sided acrylic foam tape used to attach curtain wall glazing panels to buildings.

The goal is to investigate the possible cumulative effects of years of wind-induced stresses that are typically lower than the peak stress expected during a three-second gust, as specified in current design guidelines established by the structural glazing industry and adopted by the manufacturer of these structural glazing tapes.

Using the wind speed histories employed here, the results from this linear damage accumulation model indicate that the sustained non-peak stresses do not induce more damage than the peak stresses, and therefore do not provide clear evidence that the industry-established procedure of peak-stress design is inadequate when applied to 3M VHB™ G23F acrylic foam tape bond. The results do suggest, however, that the accumulation of damage from sustained wind speeds, especially winds from storm events, could present a mode of failure that merits examination along with the more traditional peak wind speed design procedure currently in use by the structural glazing industry and employed by the vendor. This approach may have applications for other time-dependent glazing sealants as well.

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KEYWORDS

Structural glazing tape, acrylic foam tape, wind loading, linear damage accumulation model, stress-rupture master curve, life prediction model.

INTRODUCTION

Any construction material used to attach curtain wall or commercial window glazing panels to buildings must perform multiple functions. It must be strong enough to withstand short, intense wind loads while retaining the compliance to maintain a bond with the glazing panel during differential thermal expansion and contraction. Two materials commonly used for this role are structural silicone sealants and structural glazing tapes, such as the VHB™ Tape line of acrylic foam tapes produced by the 3M Company. Manufacturers of these materials have established design guidelines to account for peak dynamic load resistance and static dead load resistance [1, 2]. This article investigates the implications of sustained, wind-induced stresses that are lower than the established allowable dynamic load. This is important because acrylic foam structural glazing tapes are generally more sensitive to the rate [3] or duration [4] of loading.

Geiss and Brockman [6] performed creep resistance testing on a number of acrylic foam tapes, examining the effect of temperature, humidity, substrate material, and glass bead filler material on time to failure. Heitman [7] performed a study to characterize several types of acrylic foam tapes for long-term shear and tensile creep rupture performance and fully reversed fatigue loading. He found that the compressive portion of the cyclic fatigue load may restore the bond that was damaged during the tension side of the load cycle, and so non-reversing tensile cycling could be a more critical failure mode than the full-reversal mode. The study concluded that the controlling design factor for the tapes tested was sustained creep load endurance limits. Vendor experience suggests that cyclic fatigue is less important for acrylic foam tape durability than sustained loads. Because of this, the cyclic fatigue effects are specifically omitted in the study presented in this article, although they should be addressed for more thorough design considerations.

The majority of previous work on the effects of wind loading has examined statistical methods of predicting peak wind loads [8], or examined the effects of cyclic fatigue loading, as opposed to examining cumulative damage from sustained wind-induced stresses. On the other hand, work has been performed to examine the effects of the accumulation of wind-induced stresses on the glass component of glazing panels. Dalgliesh [9] proposed a method to model storm wind damage to glass glazing panels, in a manner similar to the model presented herein to simulate damage on the glazing sealant or adhesive. He converted the wind-induced stresses to damage on the glazing panel using a glass-specific cumulative damage equation. Holmes [10] also examined glass damage accumulation from wind-induced stresses during a storm event.

Kumar and Stathopoulos [11] discussed modeling of wind pressure fluctuations using various probability distributions, in order to perform a fatigue analysis of roof cladding. Ko and Kim [12] discussed methods of counting fatigue cycles to calculate damage accumulation.

In linear damage accumulation models, damage is assumed to occur independently of the prior loading history or order of the loading events, leading to damage laws that are similar to the Palmgren-Miner linear damage hypothesis, which has been widely used in fatigue studies. Although models exist that are more refined, this approach is used as the basis for this initial study.

The model developed herein incorporates wind loading as a multiple-year series of constant load levels. Each constant load is the average wind-induced stress over a recording period such as ten minutes or one hour. The damage model assumes that after wind-induced damage has accumulated, strength does not recover during periods of zero or compressive loading. Evidence on this is inconclusive, and so the possible effect of healing has been ignored for this conservative analysis. Future experimental effort in this direction would be useful to further the characterization of acrylic foam structural glazing tapes.

Because the wind loading is simplified to a series of static rather than dynamic loads, the model presented here does not examine cumulative damage in the form of fatigue. The effect of fatigue from the dynamic, cyclic nature of wind loading is certainly important for many materials and applications. Cyclic stress effects are neglected in this study in order to focus specifically on the effect of the long-term, sustained aspect of wind loading, which may be a limitation of the acrylic foam tapes [7].

The experimental work performed to determine the relation between an applied stress-rupture stress and time to failure for VHB™ G23F acrylic foam structural glazing tape can be found in [4, 5].

WIND DATA

Representative wind data from two sources were used in this work. The first data were from Fowley Rocks, Florida gathered by the National Data Buoy Center [13], and the second from Chicago, Illinois gathered by a National Weather Service station [14]. The Fowley Rocks data consists of roughly 707,000 data entries averaged over 10-minute intervals for a 15 year period (1991 to 2007, excluding 1994 and 1995), at a height of 44 m (144 ft) above ground elevation. This sampling incorporated the close pass of Hurricane Wilma during October of 2005. The Chicago data consists of roughly 52,000 data entries at 60-minute intervals, measured over six years from 1995 to 2000, and sampled at a height of 44 m (144 ft) above ground elevation. The data includes the average speed and wind direction at one-hour intervals.

The Chicago, IL wind history was selected as a representative example of high, sustained wind speeds at a location in the interior of the U.S. The two Fowley Rocks, FL wind histories were selected to represent coastal wind speeds with and without a near pass by a Category 5 hurricane.

The use of a 10-minute averaging interval versus a 60-minute averaging interval will influence the damage model results, as larger averaging times will tend to smooth out the short-duration peaks in wind speed. As will be shown later in the article, peaks in wind speed may result in significant damage on the structural glazing adhesive. The practical implication of this effect is that the Fowley Rocks data sets, with an averaging interval of 10 minutes, will be somewhat more conservative than the Chicago data set, with an averaging interval of 60 minutes. A more detailed description of the wind data processing can be found in [4] and [5].

WIND SPEED AND ADHESIVE STRESS

To convert wind speeds into stress on a glazing panel, this analysis followed the procedure specified in ASCE 7-05, Minimum Design Loads for Buildings and Other Structures. The detailed procedure to evaluate the wind stress on glazing tape is documented in [4] and [5].

Wind reduces the external pressure (creating suction) on the leeward side of a building, and if a building is enclosed, internal pressure from wind blowing on the windward side of the building contributes to the force pushing the glazing away from the leeward building face.

Following ASCE standard and using the constants recommended by the standard, the wind pressure on glazing panel was evaluated based on the wind speed; this wind pressure was then used to calculate the stress on the structural adhesive holding the glazing panel on to the building. Using the trapezoidal load distribution method recommended in ASTM Standard C1401, the portion of wind pressure on a rectangular glazing panel transferred to the structural adhesive bond along any one of the panel's edges can be evaluated. Specifically, the location of the highest stress on the adhesive or sealant will be at the center of the longer edges of the window or panel, and at that location the stress can be approximated by the following equation:

$$\sigma_{\max} = \frac{p \cdot d}{2 \cdot w} \tag{1}$$

where,

p = Wind pressure,

d = The shorter dimension of the rectangular panel,

w = The width of the structural adhesive.

STRESS-RUPTURE TIME MASTER CURVE

Our previous research [3, 4] has established a power law describing the tensile stress rupture life master curve for VHB™ G23F structural glazing tape bonded to anodized aluminum adherends at a 30°C (86°F) reference temperature:

$$t_f = 0.01724 \cdot \sigma^{-8.078} \tag{2}$$

where,

σ = Tensile stress on the adhesive tape (MPa)

t_f = Time to failure (seconds)

Note that the exponent in this equation indicates the sensitivity of VHB™ Tape's stress-rupture time to variation of applied stress.

Figure 1 shows the tensile stress rupture data measured from 126 specimens and the fitted stress rupture master curve. Each plotted point represents an average of nine replicates. Detailed descriptions of the experimental work and process of constructing the master curve are presented in [3, 4].

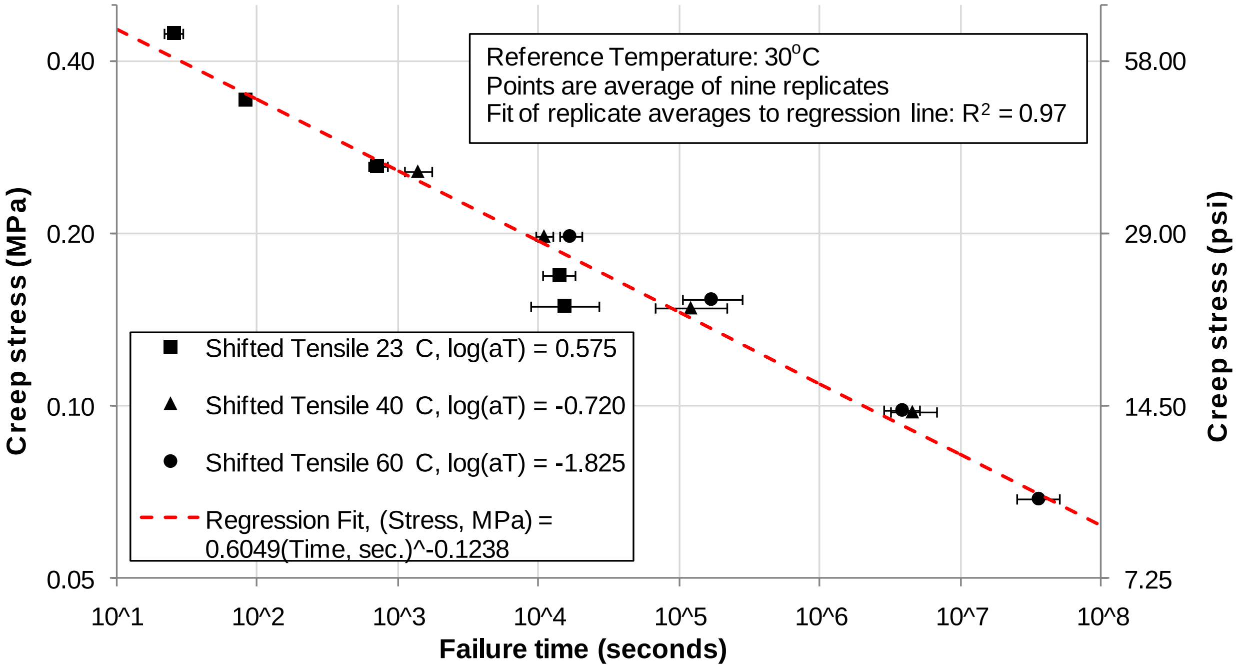

Figure 1 VHB™ Tape's tensile stress rupture time data that included the shifted data to establish a 30°C (86°F) reference temperature master curve; each data point is an average of nine replicates, and error bars represent +/- one standard deviation.

There are three assumptions made when this stress rupture time master curve is applied to predict time to failure for VHB™ Tape used in structural glazing applications.

1. First, to predict the stress rupture time at low stress levels (< 0.07 MPa), the extrapolation of the stress rupture time master curve into the low stress region is assumed to be acceptable.
2. Second, when the stress rupture time master curve is used in a linear damage accumulation model to predict the life of the adhesive tape, any potential recovery of residual strength between loading periods is assumed to be negligible.
3. Finally, during the stress rupture experimental tests, the VHB™ Tape adhesive specimens exhibited an average strain of 700% to 1100% at fracture. A glazing installation generally can only accommodate a much lower tensile strain of the tape (typically under 100%). It is assumed that the stress rupture time of the adhesive tape under a low strain level is equivalent to that measured under a much higher (up to 1100%) strain, and it is

reasonable to assume that this assumption will result in a more conservative prediction of the stress rupture time.

Table 1 provides the predicted time to failure for a given range of constant wind loads. The data in this table were generated using the design parameters of a 1.22 m by 1.83 m (4 ft by 6 ft) glazing panel at 30.5 m (100 ft) elevation from ground, and a VHB™ Tape width of 19.1 mm (0.75 in.) [3, 4].

Table 1 Constant wind speeds and resulting failure times. (shaded cells denote times to fail based on extrapolating stress-rupture data beyond experimentally determined master curve)

Constant wind speed		VHB tape stress		Predicted time to failure		
m / sec	mph	MPa	lb / in^2	Seconds	Days	Years
5	11.2	0.0010	0.14	4.064E+22	4.704E+17	1.289E+15
10	22.4	0.0038	0.56	5.566E+17	6.442E+12	1.765E+10
20	44.7	0.0154	2.23	7.622E+12	8.822E+07	2.417E+05
30	67.1	0.0346	5.02	1.089E+10	1.261E+05	3.454E+02
40	89.5	0.0615	8.92	1.044E+08	1.208E+03	3.310E+00
50	111.8	0.0961	13.94	2.838E+06	3.284E+01	8.998E-02
60	134.2	0.1384	20.07	1.492E+05	1.727E+00	4.731E-03
70	156.6	0.1884	27.32	1.236E+04	1.431E-01	3.920E-04
80	179.0	0.2461	35.68	1.430E+03	1.655E-02	4.533E-05
90	201.3	0.3115	45.16	2.132E+02	2.468E-03	6.761E-06

LINEAR DAMAGE ACCUMULATION MODEL

The linear damage accumulation model represents an extension of the Palmgren-Miner Rule for cumulative fatigue damage to stress-rupture data:

$$D = \frac{L_s}{L_d} \sum_{i=1}^{n} \frac{t_i}{t_{fail,i}} \tag{3}$$

where

L_d = The length of time encompassed by the wind history data file,

L_s = The desired service life,

n = The number of entries in the wind speed data file,

t_i = The time spent during data point i,

$t_{fail,\,i}$ = The stress rupture time due to the average wind-induced stress at data point i.

The model predicts that failure occurs when the damage sums to unity, or $D = 1$. The inclusion of the L_s/L_d ratio is necessary if the wind speed history is not long enough to represent the design life of a glazing installation.

When qequations (1) and (2) are substituted into equation. (3), the accumulative damage can be presented in a general form as:

$$D = \frac{L_s}{L_d}\sum_{i=1}^{n}\frac{t_i}{\left(\dfrac{0.6049}{\Omega\cdot p_i\cdot\dfrac{d}{2w}}\right)^{8.078}}\ , \tag{4}$$

and,

$$p_i = 0.613\cdot K_z\cdot K_{zt}\cdot K_d\cdot I\cdot V_i^2\cdot(GC_p - GC_{pi})\cdot\frac{1}{1000000}\left(\frac{\text{MPa}}{\text{Pa}}\right), \tag{5}$$

where,

D	Fraction of life used, or fraction of damage done by end of service life
L_s	Duration of service life, in years (50 years)
L_d	Duration of wind speed data file, years (15 years for Fowley Rocks, FL and 6 years for Chicago, IL)
n	Number of entries in wind speed data file
i	Designation of individual entry in wind speed data file
t_i	Duration of individual entry, in seconds
Ω	Safety factor
d	Length of shorter dimension of rectangular glazing panel, in mm. (1220 mm)
w	Width of VHB™ Tape, in mm. (19.1 mm)
p_i	Wind pressure on glazing panel for point *i* in wind speed data file, in MPa to match creep rupture terms
V_i	Wind speed from point *i* in the source data file, mph or m/sec – data file should be reduced to encompass a 90° range of wind directions, which represents the worst case, in m/sec.

Terms from ASCE 7-05:

K_z	Velocity pressure exposure coefficient (0.99 for 30.5 m (100 ft) height, exposure B)
K_{zt}	Topographical effect factor (1.0 for no nearby hills or escarpments)

K_d	Directionality factor (1.0; directionality accounted for by sampling 90° direction range of wind speeds)
I	Importance factor (1.0 for office buildings)
GC_p	External pressure coefficient (−1.8 for edge of leeward face of building)
GC_{pi}	Internal pressure coefficient (0.18 for enclosed building)

The values shown in parentheses above are those used in this analysis, and the corresponding results are presented and discussed in the next section.

RESULTS AND DISCUSSION

The predicted damage results for the three wind loading histories are listed in Table 2, where no safety factor is included in the analysis. The analysis is extrapolated to a 50-year service life.

Note that the resulting damage (or the fraction of life used) by the wind-load history is relatively low (Table 2). However, if a safety factor of 5 is employed, the estimated damage would increase significantly, resulting in a much shorter time to failure. Though this is attributed to the sensitivity of VHB™ Tape's stress-rupture time to applied stress as seen in Eq. (2), further investigation into this effect is still needed since this model does not consider any potential recovery of residual strength between loading periods.

Table 2 Predicted Damage with No Safety Factor

Wind history	Fraction of life used (for duration of wind history)		Fraction of life used (extrapolated to 50 year service life)
Chicago, IL [b]	5.65x10^{-12} (6 years)		4.71x10^{-11}
Fowley Rocks, FL [a,c] Hurricane Wilma excluded	5.51x10^{-7} (15 years)		1.84x10^{-6}
Fowley Rocks, FL [a] Hurricane Wilma included	3.09x10^{-4} (15 years)		1.03x10^{-3}
Notes:			
[a] Data sampled on ten minute interval for fifteen years.			
[b] Data sampled on one hour interval for six years.			
[c] This data set excludes Hurricane Wilma by sampling from a direction range that the hurricane did not fall into.			

Figure 3 provides the relation of occurrence frequency of wind speed to the predicted damage using the wind-load history from Fowley Rocks, FL, excluding the winds of Hurricane Wilma.

The fractions of damage as presented in Fig. 3 and Table 2 are normalized by the damage reached by the end of the respective wind histories. In other words, 100% damage in this particular plot and the table does not mean the tape has failed; it simply indicates that all the predicted damage had occurred for the period under examination. These percentage values are presented here because they provide information on the relative importance of various categories of wind speeds.

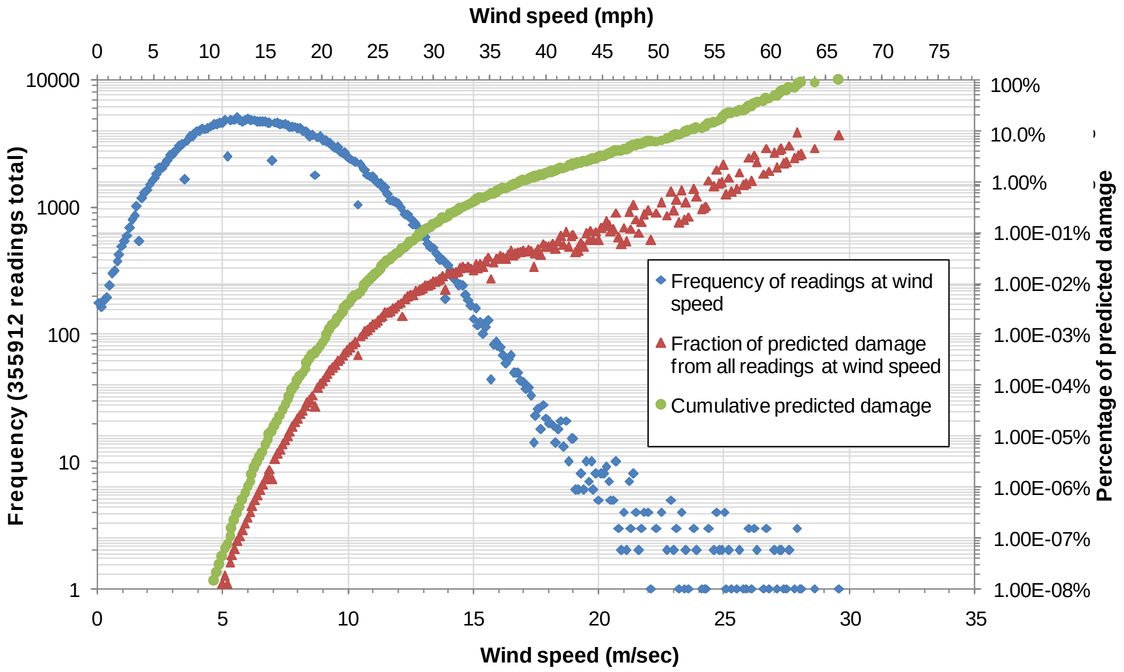

Figure 3 Frequency of readings and percentage of predicted damage from wind speeds at Fowley Rocks, FL, excluding Hurricane Wilma.

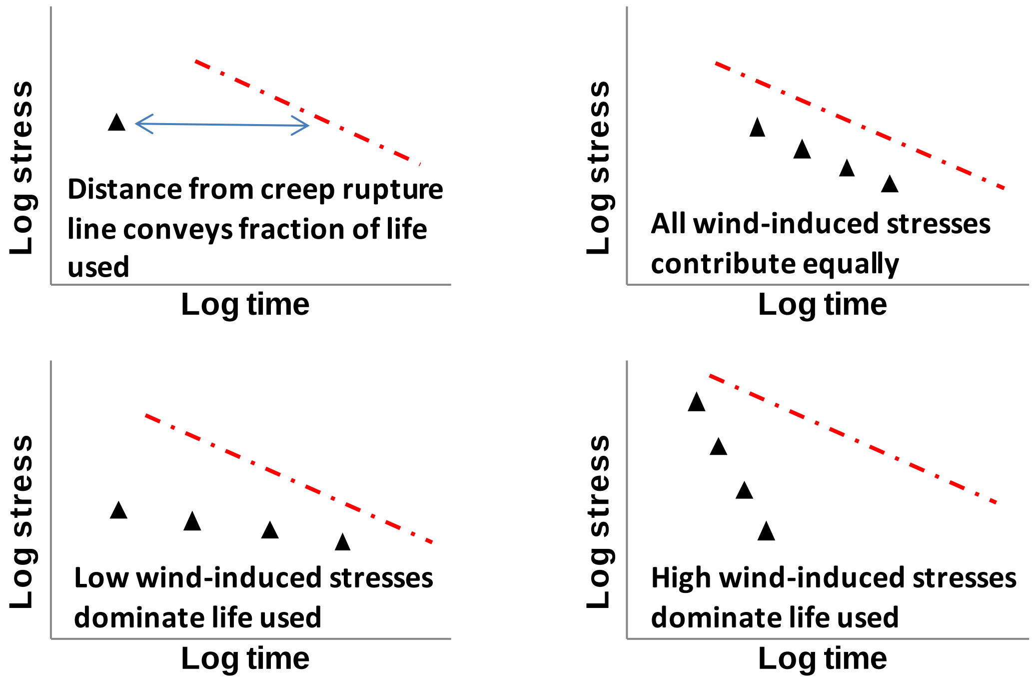

Figure 4 Illustration of comparison between stress-rupture curve and wind-induced stress distribution.

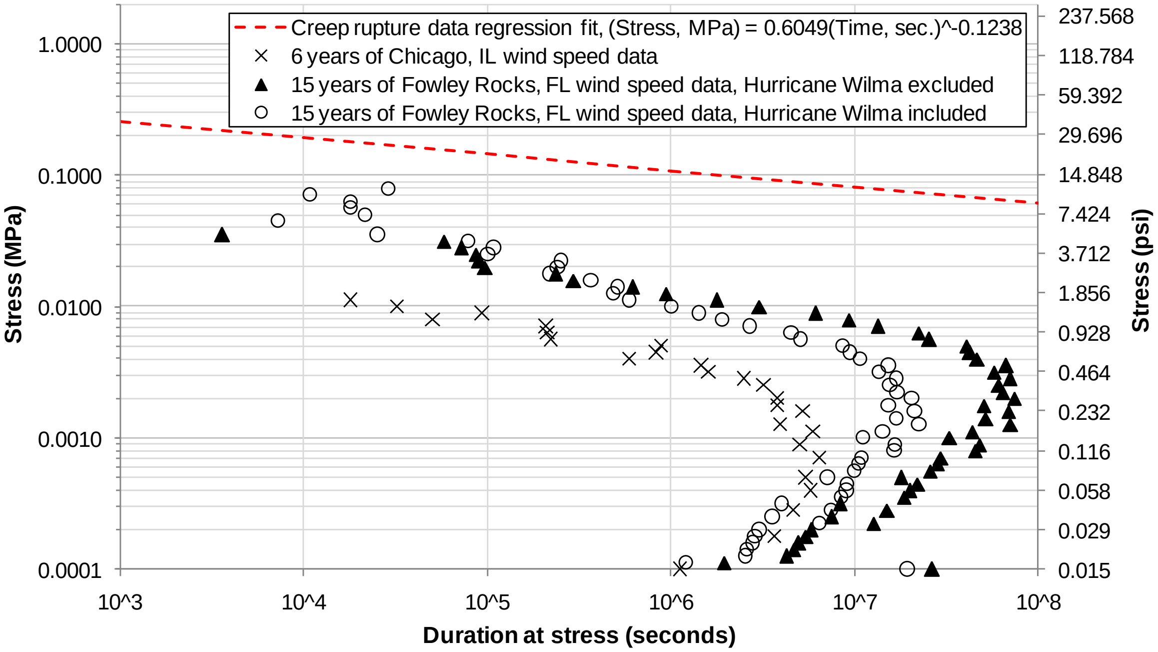

Figure 5 Comparison between stress-rupture time and wind-induced stress distributions.

In Fig. 5, the actual distribution of wind-induced stresses is plotted against the stress-rupture time curve of the VHB™ Tape. It shows that instead of a single peak stress, a relatively wide range of stresses (those above 0.004 MPa) can cause damage, as long as the durations of these stresses are comparable.

This then suggests that when predicting damage in VHB™ Tapes under a wind-load history, it is important that the damage-inducing effects of all these stress levels, not just the peak stress, be considered.

To put these results into perspective, the standard peak load design methodology contains the inherent assumption that 100% of the damage is caused by the highest wind-induced stress and all other lower stresses contribute negligible damage.

Compared to VHB™ Tape, the stress rupture time curves for several structural silicone sealants show that the low level stresses cause a much smaller amount of damage [3, 4] as compared to the high level stress. Accordingly, the performance of structural silicones may be more adequately characterized using the traditional peak stress design procedure.

<u>Design Tape Width and Evaluating Factor of Safety Based on Peak Stress Method</u>

The existing design procedure established by 3M for the resistance of wind loading on glazing with VHB™ Structural Glazing Tape is simple, and follows the allowable strength design methodology (also known as permissible stress).

Using this design method, the peak wind-induced stress, *S*, is specified for a given service period. When using ASCE 7-05 design standard, *S* is the stress resulting from the maximum three-second gust that is expected to occur over a desired service period. Therefore the design criterion is:

$$S \leq S_{allowble}/\Omega \qquad (6)$$

where,

$S_{allowble}$ = Allowable dynamic stress or dynamic strength of the adhesive tape

Ω = Factor of safety.

3M has performed tests to establish an allowable dynamic stress for VHB™ Tapes:

$$S_{allowble} = 85 \text{ kPa } (12 \text{ psi})$$

which was determined with considerations of the typical peak wind gust duration, the size of glazing panels, and geometry of the VHB™ Tape [15].

Using this methodology, the required VHB™ Tape width can be determined for a given wind load and factor of safety. For example, for a 1.22 m by 1.83 m (4 ft by 6 ft) glazing panel with the same ASCE 7-05 parameters used to generate the constants in Eq. (4) and a safety factor of 5, the required VHB™ Tape width is 31.8 mm (1.25 in.) for Fowley Rocks and 12.7 mm (0.50 in.) for Chicago. The three-second peak gust wind speeds used for this calculation are 40 m/sec (90 mph) for Chicago and 65 m/sec (145 mph) for Fowley Rocks (ASCE 7-05).

Determine Factor of Safety Based on Damage from Wind-Load History

To evaluate the factor of safety for a particular adhesive bond design under a particular wind-load history, the following approach is used.

Instead of comparing a peak value of wind stress with adhesive tape design allowable to determine the factor of safety as described above, the total damage by the wind load history and the stress rupture life master curve (Fig. 1) are used to evaluate the factor of safety for a bond design.

The approach employed here is to scale all the stresses in a wind-load history by a factor of safety, Ω, such that the damage, D, induced by this scaled up stress history reaches unity at the end of a specified service life. Using Eq. (4), the factor of safety, Ω, can then be evaluated. The evaluated factors of safety are listed in Table 3. Note that the experimental data that provided the stress rupture life master curve were originally collected using a 19.0 mm (0.75 in.) specimen tape width.

Table 3 Safety Factors Corresponding to 50 Year Service Life

VHB™ Tape width	Safety Factor, Ω		
	Chicago, IL	Fowley Rocks, FL No Hurricane	Fowley Rocks, FL With Hurricane
31.8 mm (1.25 in.)	19.0	8.6	3.9
25.4 mm (1.00 in.)	15.2	6.8*	3.1*
19.1 mm (0.75 in.)	11.4	5.1*	2.3*
12.7 mm (0.50 in.)	7.6	3.4*	1.6*

*Represents tape widths that would not meet industry-accepted design guidelines for this wind exposure.

The safety factor evaluated from the linear damage accumulation model are greater than those evaluated following the peak load design procedure for the wind load histories at Chicago, IL and Fowley Rock, FL without a hurricane event. For the Fowley Rocks wind history that did include a close pass by a hurricane, the safety factor from the linear damage accumulation model was slightly less than that from the established design procedure.

Recall that the purpose of this work is to investigate the possible cumulative effects of years of wind-induced stresses on acrylic foam structural glazing tape that are typically lower than the peak stress expected during a three-second gust. The results presented in Table 3 show that the safety factors predicted here by this analysis are high, hence it is reasonable to suggest that:

1. Substantial wind speeds are responsible for the majority of the damage induced by the wind load, moderate wind speeds are expected to have a negligible effect on damage accumulation.
2. Because of the observation listed above, the results here do not indicate that the practices of "design by peak stress" currently used in the industry and applied by 3M for their acrylic foam structural glazing tapes are likely to result in insufficient adhesive bond design and potential bond failures for the wind scenarios considered here.

These results are believed to be appropriate for the 3M™ VHB™ Structural Glazing Tape system reported herein, but are subject to several assumptions and conditions summarized below:

1. The linear damage accumulation model examined only the sustained aspect of wind loading, such as that provided by average wind speeds over ten minutes or one hour, and not fatigue loading. Furthermore, the model is based on data obtained at standard laboratory conditions, so specific environmental factors were not explored.
2. The reliability index has not been established for the safety factors provided by the model, and so it is not possible at this time to compare the exact probability of failure of the two design methods.
3. The testing that established the stress-rupture strength curve was performed at stresses greater than those usually generated by winds. Therefore, the stress-rupture strength was

extrapolated into the range of low stress levels to allow the stress-rupture time prediction of the adhesive bond under wind load.

4. The linear damage accumulation model assumed no residual strength recovery takes place during the periods of wind load history when the VHB™ Tape experiences low or even compressive stresses.
5. The linear damage accumulation model and stress-rupture prediction equations have not been validated with long-term testing over months or years, nor with forensic investigations of real VHB™ Structural Glazing Tape installations.
6. Although the wind histories examined here were selected to represent locations with high sustained wind speeds generated from elevations 4 times higher than typically measured according to ASCE 7-05, other locations may be of interest in providing sustained, unidirectional wind speeds and storm events.

SUMMARY

A linear cumulative damage model is developed based on experimental data including stress-rupture life and real wind-load histories from two geographic locations.

Using this model, the cumulative effects, in terms of damage, of long term wind-induced stresses on adhesive bond strength in glazing applications are evaluated. Further, the effect of the damage on the adhesive bond durability are assessed by comparing the factors of safety of adhesive bond designs using the industry standard “peak 3-second wind gust stress” design method and the cumulative damage design method present here.

The results indicate that time-dependent materials such as adhesives or sealants used in glazing applications are likely to experience damage from sustained wind loading over the life of an installation. However, the general conclusion suggested by the analysis presented here is that a curtain wall or commercial window glazing system utilizing acrylic foam tapes such as VHB™ Structural Glazing Tape and designed to withstand the traditional single peak wind load is expected to retain its integrity after many years of low and intermediate sustained wind loads.

Finally, although the methodology presented herein could prove useful for estimating durability of other time dependent adhesive and sealants for glazing or other applications, the numerical results and general conclusions could be quite different for these other materials.

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