

# Comparison of traditional and Herculite<sup>®</sup> XP glazing subject to blast loads

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## Abstract

Protection Engineering Consultants (PEC), in cooperation with PPG Industries, Inc., is investigating the performance of a new glass technology for anti-terrorism/force protection (ATFP) applications. This new PPG glass product is significantly stronger than typical fully tempered glass, which is advantageous in impact, ballistic, and blast resistant window design. This paper compares the performance of this new glass technology, known as Herculite<sup>®</sup> XP glazing, to that of traditional (annealed and fully-tempered) glazing subjected to blast loads. The performance of the Herculite<sup>®</sup> XP glazing is based on results from a series of static tests and a large-scale blast test on eight windows. The results of the static and dynamic tests are briefly discussed. A brief discussion is also included on the use of a statistical fracture based glass strength model called the Glass Failure Prediction Model (GFPM) that was used to develop Herculite<sup>®</sup> XP resistance functions employed in single-degree-of-freedom (SDOF) blast response models.

*Keywords: glass technology, blast testing, window design, SDOF analysis.*

## 1 Introduction

Protection Engineering Consultants (PEC) and PPG Industries, Inc. are investigating the performance of Herculite<sup>®</sup> XP glass, a new glass technology that is stronger than typical fully tempered (FT) glass, for anti-terrorism/force protection (ATFP) applications. To evaluate the performance of Herculite<sup>®</sup> XP glazing subjected to blast loads, a single large-scale blast test on eight specimens was conducted at the Air Force Research Laboratory (AFRL) at Tyndall Air



Force Base in Florida. Predictions made with preliminary resistance functions developed using the glass failure prediction model (GFPM) compared well to dynamic test observations. Static tests performed at PEC in Austin, Texas enabled the confirmation of strength values for prediction models. This paper presents a summary of the performance of Herculite® XP glass during each test, an overview of the glass failure prediction model, and comparisons between the performance of Herculite® XP to traditional (annealed and fully-tempered) glazing.

## 2 Resistance function development

Preliminary resistance functions were developed to perform predictions for the large-scale blast test and to provide an initial comparison between annealed, fully-tempered, and Herculite® XP glazing. The resistance functions utilize a rate dependent model to predict glass break response and a theoretical membrane equation based on equations developed by Timoshenko and Woinowsky-Kreiger [7], adjusted with static and dynamic test data to predict post-crack glazing response. Each model and resulting resistance functions are briefly discussed below.

### 2.1 Glass failure prediction model overview

The glass failure prediction model (GFPM) by Beason and Morgan [3] is an unrestricted model that predicts glass break strength and deflection. The GFPM is the basis for ASTM E1300, the North American Standard on glass selection for wind loads, and is based on theoretical development as supported by a review of thousands of test data records for glass break. The GFPM (Beason and Morgan [3]) relates the probability of failure of glass, surface flaw characteristics, and induced stresses by combining a statistical failure theory for brittle materials (Weibull distribution) with results of a geometrically nonlinear plate analysis. The model is specifically applicable to the analysis of rectangular glass to resist uniform lateral pressures (not missile impact) and includes all factors that significantly affect the strength of glass including plate geometry, load duration, probability of failure, and glass surface condition (size and distribution of flaws, age of glass, static strength, etc.). The GFPM (Beason et al. [4]) was used to predict glass resistance, while the predicted deflection was determined with a fit by Dalglish (CGSB, 1989). The GFPM is a rate-based model that truly accounts for glass being a ceramic-type material where strength is not solely based on the static material properties of the base material, but also on the size and distribution of inherent flaws in the material. In addition, the GFPM allows for analysis of new glass and weathered or aged glass within the same model, as well as different types of glass [annealed (AN), heat strengthened (HS), fully-tempered (FT), and higher strengths].

#### 2.1.1 Load duration

The GFPM is a function of load duration, as shown in Figure 1 (for a 31"x60"x1/2" [0.219"x0.060"PVBx0.219"] Herculite® XP with a probability of



failure of 0.5). The GFPM predicts larger resistances for shorter duration loads (i.e., 10 ms) than longer duration loads, which is consistent with dynamic increase factors for other materials. In general, most materials experience an increase in strength under rapidly applied loads because the material cannot respond at the same rate at which the load is applied. GFPM predictions with annealed and fully tempered glass show similar trends; small glass sizes and small load durations predict stronger glass.

### 2.1.2 Probability of failure

Probability of failure (POF) is the number of lites out of 1000 that will fail at the prescribed load. A POF of around 8/1000 (0.008) is typically used for design;

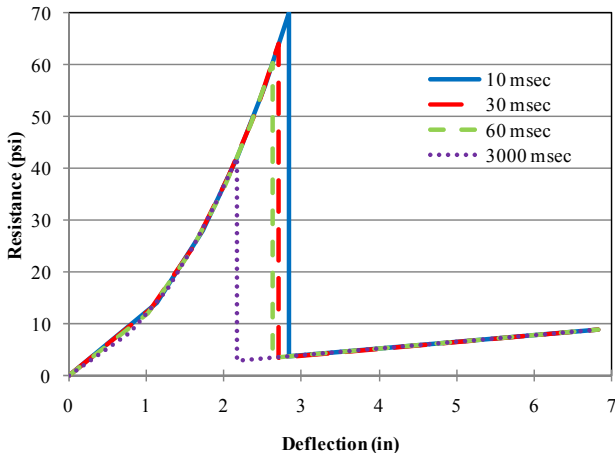


Figure 1: Affect of load duration on GFPM predictions for 31x60x1/2 Herculite® XP glazing (POF = 0.5).

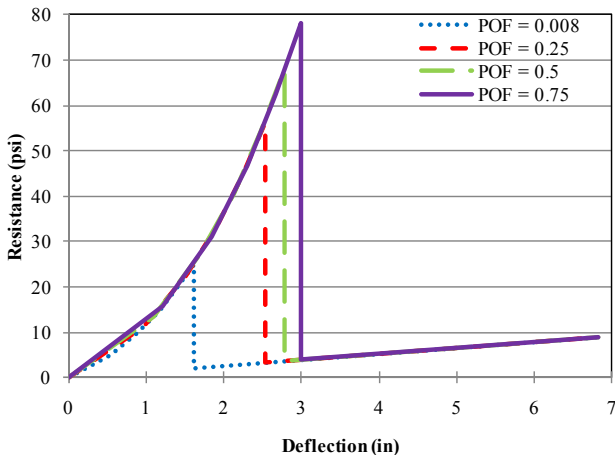


Figure 2: Affect of probability of failure on GFPM predictions for 31x60x1/2 Herculite® XP glazing (15 msec duration).

Table 1: Surface flaw parameters for new glazing.

Glass type	Strength (psi)	$m$	$k$
Annealed	3380	6.94	2.86E-53
Fully tempered	13500	6.54	2.86E-53
Herculite XP	34000	6.4	2.86E-53

while a POF of 0.5 was used to best match blast test data generated using “new” (not weathered or “in-service”) glass. The glass resistance increases as the POF increases (more glass is allowed to fail which is less conservative), as shown in Figure 2. Analysis of test data was performed to select a set of surface flaw parameters for the GFPM that best match the desired POF of 0.5.

### 2.1.3 Surface flaw parameters

GFPM is based on the theory that glass plate failure is a result of interaction of glass surface flaws (which result from the manufacturing process and subsequent exposure) and surface tensile stresses from applied loads. The two surface flaw parameters are  $m$  and  $k$ , which represent the severity and distribution of surface flaws. “Examination of a wide range of theoretically generated glass strength data shows that  $m$  is related to the coefficient of variation of the data. As  $m$  increases, the coefficient of variation decreases. Further, these examinations show that  $k$  is closely related to the mean of the glass strength data.” (Beason et al. [4]) After much debate, ASTM E1300 established the following set of surface flaw parameters to be used for annealed (AN) glass design for normal in-service exposures:  $m = 7$  and  $k = 2.86 \times 10^{-53} \text{ N}^{-7} \text{ m}^{12}$ . The recommended values do a relatively good job predicting the strength of AN glass when keeping in mind the variations due to glass size and load duration discussed above.

During manufacturing of tempered windows (specifically the heat quench process), residual compressive stresses are induced into the exterior surfaces to increase the nominal glass strength. At the same time, the heat quench process reduces the number and size of flaws present in fully-tempered (FT) glass, which adds to the increase in nominal glass strength. The nominal strength increase due to glass type is accounted for in the GFPM by a strength modifier. However, the strength increase resulting from the reduction in flaws should also be accounted for by the adjustment of the surface flaw parameter,  $m$ , for different glass types. Static testing of new annealed, FT and Herculite® XP glazing has allowed the determination of the surface flaw parameter,  $m$ , for a probability of failure of 0.5, as summarized in Table 1. The testing has shown that new tempered glass requires a smaller flaw parameter,  $m$ , than new annealed glass more flaws, lower strength.

## 2.2 Membrane model overview

Membrane models predict post-crack glazing response for laminated windows. The laminate interlayer is very thin relative to the glass material and act as membranes after the glass breaks, preventing window failure until they fail.



Membranes displace significantly before rupture and typically provide very significant additional resistance to the window response. PEC is working on development of an updated theoretical membrane model based on static test data and a strain-adjusted modulus of elasticity. The new model was used for all comparisons in this paper, instead of HazL or WinGARD membrane models.

The slope of the PVB (polyvinyl butyral) interlayer resistance is relatively linear, rather than highly non-linear as calculated by theoretical equations. The modulus of the PVB interlayer was considered to be variable, where it initially included a large contribution from the attached glass just after break, and then reduced to a value nearer the static modulus of the PVB as membrane strain increased.

### 2.3 Resistance functions

The resistance functions utilize the glass failure prediction model to predict glass break and a theoretical membrane equation adjusted with static and dynamic test data to predict post-crack glazing response. The resistance functions were updated after the static and dynamic tests to utilize the observed glass strength and strain rate effects. The modified version of the GFPM was used to evaluate annealed (AN), fully-tempered (FT), and Herculite® XP laminated glazing of varying size and thickness for comparison. Laminated glazing lay-ups included two lites of glass of equal thickness laminated together by a 0.060-in PVB interlayer. A probability of failure of 0.5 and a load duration of 15-msec was used in the GFPM to calculate each resistance function.

Figure 3 illustrates the resistance functions for several annealed, fully-tempered, and Herculite® XP glazings. Note that the slope and peak of the PVB membrane response is constant for similar window geometry (dimensions), while the glass break response highly dependent on the type of glass, window geometry, and thickness. The maximum Herculite® XP glass break resistance is 93% and 58% larger than that of AN or FT, respectively. The glass break deflection for Herculite® XP is also larger than that of AN or FT by 80% and 36%, respectively. The disparities in the point of glass break illustrate the significant increase in strength and energy absorbing capacity (i.e., area under the resistance function) of Herculite® XP glazing over AN and FT. Herculite® XP response up to glass break accounts for 71% of the total area under the resistance function, while FT and AN glass only account for 39% and 4%, respectively, of the total area under the respective resistance functions. Therefore, the response of the PVB is less prominent (however, not insignificant) for higher strength glass. Overall, the contribution of the glass increased by 95% and 45% with the use of Herculite® XP over AN and FT, respectively.

## 3 Static testing of Herculite® XP

To evaluate the performance of Herculite® XP glazing, a series of large-scale static tests were conducted at the PEC Austin office. The objectives of the static tests were to determine strength values for prediction models (specifically, the



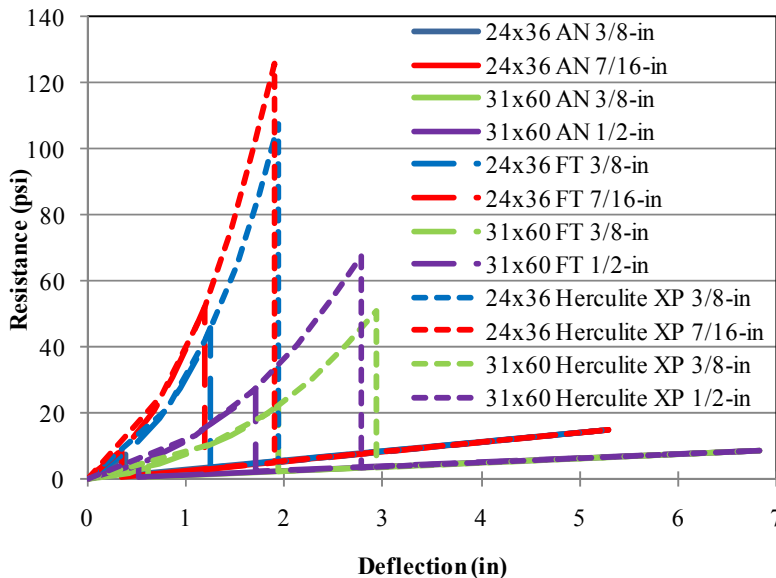


Figure 3: Comparison of resistance functions for various glazing lay-ups.

flaw parameter,  $m$ ) and failure mechanisms of Herculite<sup>®</sup> XP glazing. The two main test variables include glass thickness and window size. The windows were subjected to static water pressure until failure. Post-test the resistance functions (i.e., GFPM) were updated to provide a better predictive design tool using a single-degree-of-freedom (SDOF) analysis.

### 3.1 Test set-up

PEC designed a steel test tank, two steel masks, and aluminium window frames for static window testing, while PPG provided all glass specimens. The tank was filled with water, an incompressible medium, by a pump with a pulse-less flow to steadily load the glass (load-controlled test). Air was bled out during the filling process to reduce the amount of air, a compressible medium, in the tank. The lack of air allowed the more accurate capture of post-break PVB response. Neoprene gaskets were used at the tank/mask and mask/specimen interface to create a water tight seal. Glazing construction of test specimens included monolithic lites of Herculite<sup>®</sup> XP glazing and two lites of Herculite<sup>®</sup> XP glass of equal thickness laminated together by a 0.060-in PVB interlayer. All glass lites were attached to the frame mounts with 1.25-in wide, 3M VHB Structural Glazing (grey) Tape G23F. The window frame mounts were constructed out of aluminium for ease of construction and installation. To reduce frame rotation during testing, shims were used at bolt locations during installation. The strong side of the glass was tested during each test. Silicone was applied to the water face (weak side) of the test specimen to create a water tight seal and minimize leaks. Instrumentation during the test included two linear potentiometers, a pressure gauge, and video camera. Figure 4 illustrates the static test set-up.



Figure 4: Static test set-up.

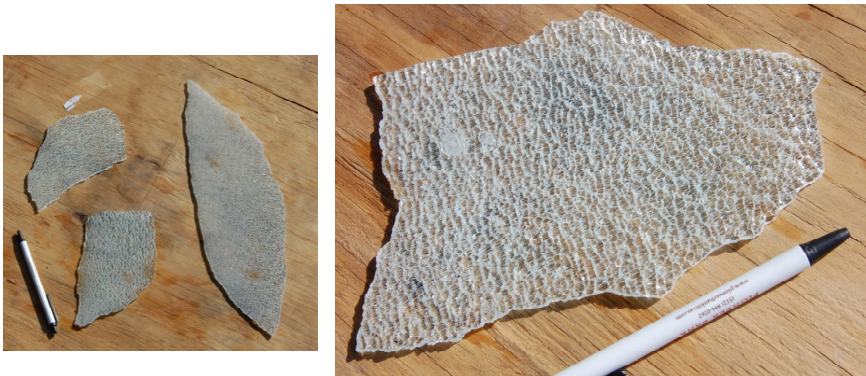


Figure 5: Crack pattern of Herculite® XP glazing.

### 3.2 Test observations

All windows were tested to failure (i.e. first crack for monolithic specimens and PVB failure for laminated specimens). Test observations include extremely small glass fragments for Herculite® XP glazing, as shown in Figure 5. The Herculite® XP glass fragments were smaller and smoother than both AN and FT glass. Small fragments were beneficial during static testing of laminated Herculite® XP glazing because they reduce the chance of a premature PVB tear and failure; instead allowing significant displacement of the membrane to occur up to membrane rupture, as shown in Figure 6.



Figure 6: Significant deflection prior to failure.

### 3.3 Test conclusions

An average surface flaw parameter,  $m$ , of 6.4 was determined from the series of static tests on Herculite® XP glazing. An oval cracking pattern with small fragments was a typical failure mechanism for monolithic Herculite® XP glazing, while significant deflection prior to membrane rupture was noted for laminated Herculite® XP glazing.

## 4 Dynamic testing of Herculite® XP

To further evaluate the performance of Herculite® XP glazing subjected to blast loads, a single large-scale blast test on eight specimens was conducted at the AFRL at Tyndall Air Force Base in Florida. The objectives of the dynamic test were to evaluate the preliminary resistance function and confirm failure mechanisms. The three main test variables include glass thickness, window size, and window frame material. The windows were subjected to a blast load associated with a predetermined charge weight and standoff. Post-test comparisons between measured deflections and deflections predicted by single-degree-of-freedom (SDOF) analyses illustrated the accuracy of the developed resistance functions.

### 4.1 Test set-up

AFRL Tyndall provided a reaction structure consisting of four reinforced concrete culverts and 5-ft wide clearing panels around each exterior edge. PEC designed four culvert fronts and eight window frames to modify the existing reaction structure for window testing, while PPG provided all glass specimens. Glazing construction of all test specimens included two lites of Herculite® XP glass of equal thickness laminated together by a 0.060-in PVB interlayer. Nominal glazing thicknesses are shown in Figure 7 along with the dynamic test



set-up. All glass lites were attached to the frame mounts with 1.25-in wide, 3M VHB Structural Glazing (grey) Tape G23F. The window frame mounts were constructed out of steel and aluminium to represent hard and soft mounts, respectively. Instrumentation during the blast test included pressure gauges, strain gauges, deflection gauges, and high-speed video cameras. Eight reflective pressure gauges were installed on the culvert fronts (two per culvert) to determine the applied blast loads. Four interior pressure gauges (one per culvert) were provided, as well as two free-field pressure gauges for explosive yield validation.

## 4.2 Test observations

The standoff for the charge was selected such that the varying window constructions exhibited a range of responses from no break to near PVB rupture. As predicted, all of the Herculite® XP windows survived the applied blast load, as shown in Figure 8. Four out of the eight windows did not fracture (i.e. no

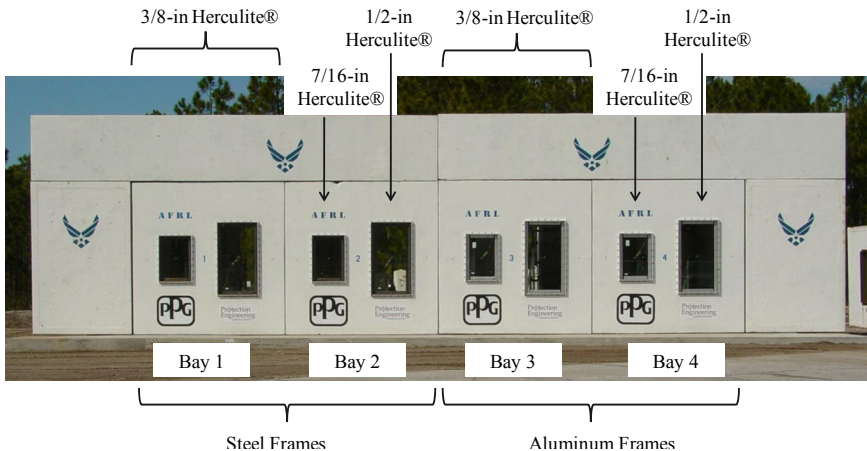


Figure 7: Dynamic test set-up.



Figure 8: Dynamic test observations.

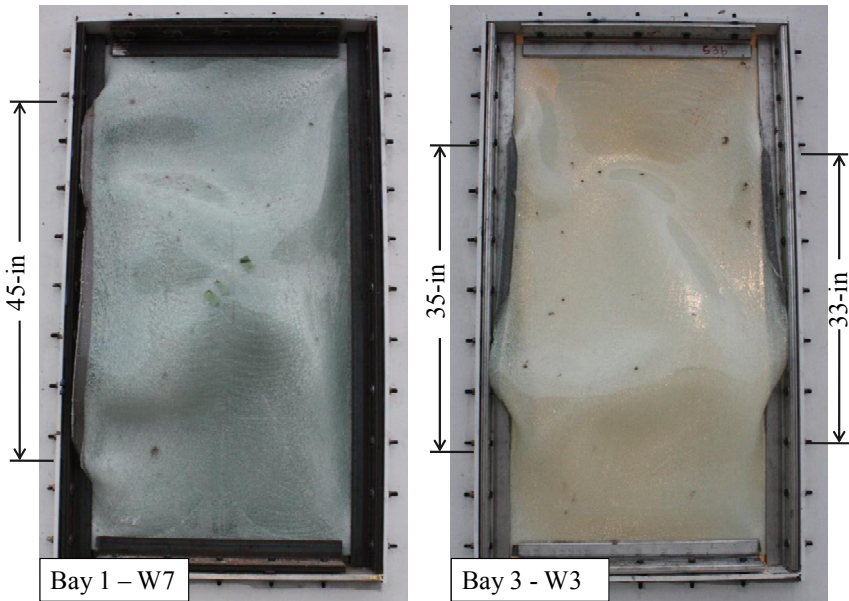


Figure 9: Energy absorption of Herculite® XP laminates.

break). Fracture of the outer lite only was observed for two of the windows (no hazard, according to the UFC 4-010-01 and ASTM 1642-04), while the last two windows experienced fracture of both lites and significant pullout at the frame edges (very low hazard), as shown in Figure 9.

### 4.3 Test conclusions

Overall, the predictions matched test observations extremely well. The large, thin window predictions included glass fracture and significant exercise of the PVB, but not PVB failure, which was observed. The small, thin window predictions were on the verge of first crack; observations show that one window fractured due to a projectile, while the other did not fracture. Therefore, the large-scale blast test results confirmed response predictions made with the GFPM approach and the validity of the approach for future tests and designs.

## 5 Comparison of Herculite® XP and fully-tempered glazing

The static and dynamic tests enabled the characterization of Herculite® XP glazing subjected to blast loads and the development of a predictive design tool for this new technology. The tweaked version of the GFPM was used to evaluate fully-tempered and Herculite® XP laminated glazing of varying size and thickness for comparison. Laminated glazing lay-ups included two lites of glass of equal thickness laminated together by a 0.060-in PVB interlayer. A

probability of failure of 0.5 and a load duration of 15-msec was used in the GFPM to calculate each resistance function (see Figure 3).

To make comparisons, the resistance functions developed with the GFPM were employed in single-degree-of-freedom (SDOF) analysis to evaluate window response. Each window was subjected to the Department of Defense (DoD) charge weight I (CWI) load at various standoffs to reach first crack and PVB failure. Figure 10 illustrates the required standoffs for FT and Herculite® XP glazing of various size and thickness. The standoff associated with first crack for Herculite® XP glazing decreased by 32% on average relative to FT glazing. The results also suggest that standoffs required for PVB failure of Herculite® XP glazing decreased by 27% relative to FT glazing standoffs. In addition, the difference in standoff between first crack and PVB failure increases as the glass strength decreases (12% and 5% for FT and Herculite® XP, respectively). Overall, the results suggest that Herculite® XP glazing requires 27% smaller standoffs than FT glazing for PVB failure.

## 6 Conclusions

The static and dynamic test results confirmed predictions made with the GFPM model which validates the approach for future glazing design. The results also provide data to suggest that standoffs for first crack of fully tempered glass are 32% greater than those for Herculite® XP glazing. Therefore, a stronger glass allows a reduced standoff for the same level of protection which increases the

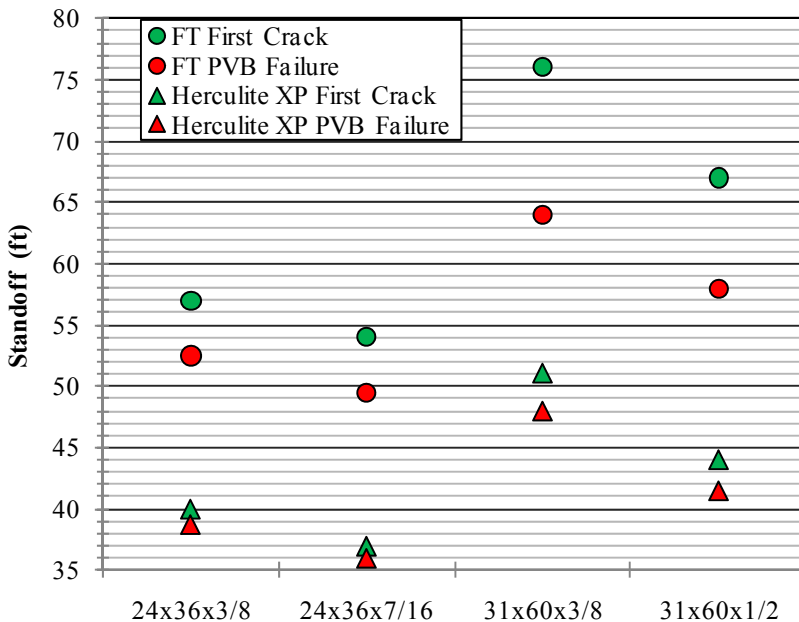


Figure 10: Standoff comparison for glazing lay-ups loaded with DoD CWI.



usable site area and available real estate. If additional standoff is not required, thinner layups with higher strength glass could be used in place of thicker traditional glazing layups to provide a significant cladding weight savings. Extremely small fragmentation was observed during the Herculite® XP testing, which may lead to improved PVB membrane response. Overall, laminated glass layups with higher strength glass (i.e., Herculite® XP) provide a good alternative to existing annealed or conventionally tempered layups.

## 7 Future work

The successful static and dynamic testing of Herculite® XP glazing will be followed by the further development of this new glazing material. The static test data will allow the development of ASTM E 1300 type design guidance for Herculite® XP glazing subjected to wind loads to be used in the GFPM. Impact testing will also be completed in the near future to evaluate the hurricane performance of Herculite® XP glazing. Also, more investigation into the application of Herculite® XP glass in insulated glass units is being pursued.

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