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Behavior of Silicone Sealants in Bomb Blast Mitigating Window Designs

ABSTRACT: The threat of terrorist attack impacts our lives every day. Because this threat is very real, we have seen the use of bomb blast mitigating window designs grow significantly in recent years. Effective bomb blast mitigating window designs allow the window system to withstand a moderate bomb blast without causing significant injury to building occupants from the blast itself or flying glass shards. The occupants are protected because laminated glass, which can withstand the blast, is attached in the framing with a silicone sealant.

The silicone sealant is an important component of the window design along with the glass composition, glass dimensions, the framing, anchoring of the framing, etc. Silicone sealants provide unique benefits to these window designs due to their strength properties and their ability to anchor the laminated glass in the framing during a blast situation. In addition, they provide long-term elasticity, adhesion and durability. The proper use and selection of silicone sealant is critical to the performance of these systems.

In this paper, two commercially available high strength structural silicone sealants which are currently marketed for bomb blast mitigating window designs will be evaluated in high speed tensile testing to simulate loads on the sealant joint during a bomb blast. Sealant joints similar to those used in current bomb blast mitigating window designs will be tested in tension and shear. Results will be analyzed to determine the conditions for optimum sealant joint design.

KEYWORDS: silicone sealants, bomb blast, protective glazing, window design, structural glazing

Introduction

Bomb blast mitigating window designs have increased in usage globally during the past decade as a result of terrorist threat. These designs have been used extensively in new construction for government, institutional and some high profile commercial buildings. Existing window designs which were not originally designed to withstand bomb blast have been retrofitted with specially developed protective films and silicone sealants. The trend is expected to continue through the coming years.

Even though a building uses a bomb blast mitigating window design, there is no guarantee that a building's occupant will be safe. In the event of an attack such as occurred on the 11th of September 2001, a building cannot reasonably be designed to withstand such an impact. Nevertheless, bomb blast mitigating windows were installed on Wedge 1 of the Pentagon in Washington DC just prior to the attack. It was reported by Engineering News Record that over 80 lives were saved because the wall and window system adjacent to the impact remained intact and allowed occupants to escape.

There are many examples in the past of the extensive damage and injury resulting from a bomb blast. One of the major examples occurred in 1995 in Oklahoma City, Oklahoma, USA. One hundred and sixty-eight people were killed and over 500 were injured¹. Many of those injured were in buildings within a one mile (1.6 km.) of the blast. The impact of the blast caused flying shards of glass to fly into the occupied space of the buildings near the blast. By using a bomb blast mitigating window design, potentially many injuries and deaths could have been prevented.

The threat of terrorist attacks is very real today. Although there is no way to make a truly risk free living and working environment, there are certain measures that can be taken to lessen our risk. One of those measures is the use of a window design which has been developed and tested to withstand moderate bomb blast.

This paper will discuss aspect of bomb blast mitigating window designs specifically related to the use of silicone sealants. A silicone sealant is only one component of a window system. The performance of a window system is the result of the interaction of all of the components of the system including design, materials and construction. The information provided in this paper is intended to help the designer of these systems to better understand the characteristics and behaviors of silicone sealants for these designs.

Components of Bomb Blast Mitigating Window Designs

Successful bomb blast mitigating window designs are the result of a good design, the use of proper materials and sound construction. ASTM C1564 Standard Guide for the Use of Silicone Sealant for Protective Glazing Systems which was first published in 2003 discusses considerations for protective glazing designs. As discussed in this standard, a successful window is the result of how the various materials function together.

Performance of the system is very much affected by the framing structure whether steel or aluminum and how much of the impact is absorbed by the structure. Common thought is that a more absorbing structural system is favorable versus a too rigid structure. Ultimately, the performance of the window system is irrelevant if the structure itself cannot adequately withstand the blast impact it is intended to withstand.

The next critical component is how the window system is attached to the structure. The building may use a punched window, ribbon window or a continuous glass curtainwall façade such as a structural glazing system. All of these common façade designs have been used successfully in bomb blast mitigating or protective glazing systems. The common element to all of these successful designs is the use of laminated glass and a silicone sealant.

Laminated glass is a critical component of bomb blast mitigating window designs. The role of laminated glass or safety glass is to absorb the shock of the blast by remain intact. The glass breaks but remains mostly attached to the flexible and strong polymer film in between the panes of glass. This laminate film is commonly polyvinyl butyrol (PVB) although other materials are available. The types of glass, whether heat strengthened, tempered, or annealed glass, the type and thickness of the laminate film, and dimensions of the window are a few of the variables which affect the performance of the glass.

To retrofit existing windows, a clear protective film can be adhesively applied on the inside surface of the glass. This laminate film plays a role similar to the PVB in laminated glass.

Whether laminated glass or a protective film is used, for the glass to remain intact in the window frame, a silicone sealant must be used. A silicone sealant provides the following key benefits to these designs:

- High strength necessary to anchor the laminated glass in the frame during the blast impact
- Long term adhesion to the glass or laminate film
- Durability as demonstrated by its long term performance in structural glazing
- Flexibility allowing differential thermal movement
- Long term weatherseal which is critical to the overall performance of the window system

Some of the common window system designs which use laminated glass and silicone are shown in ASTM C1564. In general, these designs can be divided into the following categories:

1. *Non-Structural Sealant Glazed Joint* - This system has the laminated glass or glass with a protective film captured within a frame. In a conventional window system that is not designed for bomb blast mitigation, gaskets are often used. Gaskets are inadequate to anchor the glass in a frame during a blast impact. During a blast, laminated glass which is sealed only with gaskets would fly intact into the occupied area of the building. A silicone sealant should be used to glaze the glass along the window perimeter and

anchor the laminated glass into the frame. A silicone joint may be installed on the interior or both the interior or exterior surfaces of the glass. A sealant joint installed only on the exterior would be ineffective. A common joint dimension is 6 mm (1/4") by 12 mm (1/2") to 25 mm (1").

2. *Structural Sealant Glazed Joint* – This system always uses a silicone sealant whether designed to mitigate bomb blast or not. For a bomb blast mitigating design, a laminated glass must be used. In these designs, a silicone sealant joint may be applied on the interior surface or both the interior and edge surface of the glass in an L-bead design. A common joint design is 6 mm (1/4") by 12 mm (1/2") to 25 mm (1").
3. *Fillet Joint for a Film Laminate* – This system is typically used to retrofit an existing window system to provide bomb-blast mitigating performance. In these systems, the laminated film is adhesively applied to the interior surface of the glass and a silicone sealant is applied in a triangular fillet bead around the perimeter of the window from the protective laminate film to the frame. It is essential that the silicone sealant joint be of adequate dimension, 12 mm by 12 mm (1/2" by 1/2") and maintains a minimum contact of 12 mm (1/2") to both the laminate film and interior window frame. The sealant joint should not be tooled to a concave shape since this reduces the overall strength of the sealant.

For any of the common window systems described above, it is critical that each system be evaluated and tested individually. General guidelines are just that, general, and should not be assumed to always work for every system. Performance of a system should always be verified through actual testing or similar evaluation means.

Why are Silicone Sealants Appropriate?

Silicone sealant performance has been documented in many publications.^{3, 4, 5}

Silicone sealants bring a history of performance of over 45 years in the construction industry. Silicone sealants are the only materials successfully used for structural glazing and are recognized as such in ASTM C 1401 Guide for Structural Sealant Glazing and ETAG 002 Guideline for European Technical Approval for Structural Sealant Glazing Kits. Silicone Structural Glazing has been performing successfully in North America for over 30 years and in Europe and Asia for over 20 years.

Silicone Chemistry

Silicone chemistry is based on a polydimethylsiloxane (Si-O) polymer backbone that is very stable and resistant to ultraviolet light. Well-formulated silicone sealants have demonstrated physical property stability after thousands of hours of accelerated weathering and years of actual performance in a wide range of environments. The earliest silicone sealants were acetoxycure sealants. These sealants are still common today but rarely used in high performance weatherseal or structural glazing applications. More recent silicone sealants use neutral cure systems such as oxime cure or alkoxy cure chemistry and are the basic silicone chemistries used for high performance applications. Silicone sealant properties can vary considerably depending on the types of polymer, cross linkers, adhesion promoters, fillers, plasticizers and pigments used. One component silicone sealants cure by reaction with moisture in the air. Two component sealants are designed to cure quickly for high productivity. Two component sealants cure by reaction of a base with a curing agent in the presence of moisture. Common to all quality silicone sealants is the inorganic Si-O polymer backbone which provides the long term elastomeric properties of the sealant.

Adhesion Durability to Glass

Silicone and glass have in common that they both originate from the same basic raw material: Sand. This alone does not make a silicone sealant appropriate for use on glass. Not all silicones perform well to glass but many perform very well. A properly formulated and tested silicone sealant may have indefinite long term adhesion to glass. This is not true of organic, non-silicone materials. Because the Si-O bond of a silicone sealant is stronger than the degrading effect of ultraviolet light, a silicone sealant can have outstanding long term adhesion to glass. In structural glazing, the silicone sealant structurally attaches glass to a building without any mechanical support. As evidenced by the performance of structural glazing, a silicone to glass bond is continuously exposed to ultraviolet light, moisture, extreme high and low temperatures, ozone, atmospheric pollutants and continuous thermal loads and

wind loads. A silicone sealant is the only material with a proven track record in structural glazing and this success is based on the proven long term adhesion of a silicone sealant to glass.

Strength and Flexibility

A silicone sealant is like a good parent, strong and flexible. No other material has the unique properties of a silicone sealant. A silicone sealant can be formulated over a broad modulus range, strength range and movement range. Some silicone sealants are designed for high moving expansion joints and strength is not important. Some silicone sealants can provide both good movement properties and good strength properties. Other sealants such as the ones that are appropriate for bomb blast mitigating designs provide very high strength, exceptional tear strength and still maintain an adequate level of flexibility or movement capability. Silicone sealants also have the unique property of maintaining a stable modulus over a broad temperature range. Organic materials inherently stiffen in cold temperatures and soften in hot temperatures. Silicone sealants demonstrate a much more stable modulus character over the normal service temperature of a building.

Unique Requirements of Bomb Blast Mitigating Window Designs

The use of a silicone sealant for a bomb blast mitigating window design is a natural extension of the success of silicone sealants in structural glazing. Nevertheless, there are requirements of a bomb blast mitigating design that are different than structural glazing designs. For one, a bomb blast is a one-time event. It is very unlikely that such designs would be expected to perform more than once.

Bomb blast mitigating window designs are different from window systems designed to withstand hurricanes. Hurricane resistant protective glazing systems are designed to withstand the impact of flying debris and then withstand cyclic wind loads on the shattered laminated glass. There is an element of fatigue resistance that is required of window systems designed to perform in hurricanes.

Additionally, the applied loads on a window system designed to withstand bomb blasts can be very high and very fast. Bomb blast loads on the laminated glass are immediately transferred to the silicone sealant anchoring the laminated glass around the perimeter. Silicone sealants are normally tested at relatively slow strain rates of 50 mm (2") per minute. Strain rates on a sealant joint during a bomb blast are obviously much higher. Strain rates from 1320 to 6000 times faster than standard strain rates were used in the experiment portion of this paper.

Applied loads on the sealant joint in a bomb blast mitigating window design can be very complex and are very different than structural glazing or hurricane resistant window designs. During a bomb blast, the impact forces the laminated glass into the building. This is the opposite of structural glazing where the structural silicone transfers stress from the glass to the framing as the glass is being pulled from the building under negative wind load. For structural glazing, both positive and negative wind loads affect the glass but negative wind loads apply the greatest sealant stress. In bomb blast mitigating window designs, the sealant may be experiencing loads under extension, compression or shear depending on the joint design. In a standard non-structural or structural joint design where sealant is applied in a rectangular joint on the interior surface of the glass, applied loads on the sealant are first in compression, then mostly in shear as the laminate film is pushed into the building, then shear and extension as the laminate rebounds out of the window frame. All of these loads are applied in a matter of milliseconds.

Experiment

To simulate the applied loads on a silicone sealant joint in a bomb blast mitigating window design, two commercially available silicone sealants were selected for evaluation.

Sealant A is a two-component neutral cure (alkoxy) silicone sealant used for structural glazing applications. Sealant A complies with ASTM C1184 Specification for Structural Silicone Sealant and ETAG 002 Guideline for European Technical Approval for Structural Sealant Glazing Kits.

Sealant B is a one-component neutral cure (alkoxy) silicone sealant used for structural glazing applications. Sealant B complies with ASTM C1184 Specification for Structural Silicone Sealant and ETAG 002 Guideline for European Technical Approval for Structural Sealant Glazing Kits.

Sealant samples were fabricated in tensile adhesion joints or H-piece joint as described in ASTM C1135 Test Method for Determining Tensile Adhesion Properties of Structural Sealants or ETAG 002 Guideline for European Technical Approval for Structural Sealant Glazing Kits. Joints samples of the following dimension were evaluated:

- 12 mm x 12 mm (1/2" x 1/2")
- 16 mm x 6 mm (5/8" x 1/4")
- 6 mm x 6 mm (1/4" x 1/4")
- 12 mm x 8 mm (1/2" x 5/16")
- 12 mm x 6 mm (1/2" x 1/4")

Test pieces were 18 mm (3/4") long and 3 to 5 samples of each condition were tested. Samples were tested at the following strain rates:

- .00083 m/s (.033 in/s) – Tension and Shear
- 1.1 m/s (43 in/s) – Tension and Shear
- 2.5 m/s (98 in/s) – Tension
- 5.0 m/s (197 in/s) – Tension

Results

Table 1: Sealant A – Tensile Adhesion Properties

Joint Dimension (mm)	.00083 m/s		1.1 m/s		2.5 m/s		5 m/s	
	Peak Tensile MPa (psi)	Elong. (%)						
12 x 12	0.98 (143)	108	1.56 (227)	237	1.48 (215)	265	1.29 (188)	262
16 x 6	–	–	1.62 (236)	271	1.61 (234)	287	1.25 (182)	361
6 x 6	1.21 (176)	96	2.04 (297)	278	2.05 (298)	403	1.54 (224)	436
12 x 8	–	–	1.68 (244)	265	1.58 (230)	369	1.42 (207)	335
12 x 6	–	–	1.56 (227)	266	1.69 (246)	406	1.43 (208)	403

Table 2: Sealant A – Shear Properties

Joint Dimension (mm)	.00083 m/s		1.1 m/s	
	Peak Shear Strength MPa (psi)	Elongation (%)	Peak Shear Strength MPa (psi)	Elongation (%)
12 x 12	0.68 (99)	40	1.20 (174)	228
16 x 6	-	-	1.63 (237)	318
6 x 6	-	-	1.64 (238)	292
12 x 8	-	-	1.41 (206)	284
12 x 6	-	-	1.74 (253)	339

Table 3: Sealant B – Tensile Adhesion Properties

Joint Dimension (mm)	.00083 m/s		1.1 m/s		2.5 m/s		5 m/s	
	Peak Tensile MPa (psi)	Elong. (%)						
12 x 12	1.17 (170)	290	1.44 (209)	278	1.43 (208)	294	1.47 (214)	386
16 x 6	-	-	1.34 (195)	339	1.45 (211)	377	1.51 (220)	472
6 x 6	-	-	1.47 (214)	318	1.48 (215)	370	1.37 (199)	477
12 x 8	-	-	1.39 (202)	331	1.58 (230)	372	1.65 (240)	323
12 x 6	-	-	-	-	1.49 (217)	443	1.45 (211)	495

Table 4: Sealant B – Shear Properties

Joint Dimension (mm)	.00083 m/s		1.1 m/s	
	Peak Shear Strength MPa (psi)	Elongation (%)	Peak Shear Strength MPa (psi)	Elongation (%)
12 x 12	1.07 (156)	82	1.42 (207)	-
16 x 6	-	-	1.30 (189)	-
6 x 6	-	-	1.69 (246)	-
12 x 8	-	-	1.57 (228)	-
12 x 6	-	-	1.48 (215)	-

Discussion

Results from the high speed testing of these two structural sealants demonstrate the suitability of these materials in this high performance application. In all of the high speed tests, the each sealant maintained a minimum ultimate strength of 1.20 MPa (172 psi). This value is 8.6 times greater than the 0.14 MPa (20 psi) sealant design strength or allowable stress used for structural glazing applications. The silicone sealants were able to maintain their high strength while demonstrating elongation properties of over 228% for all test samples.

These results allow for the variables of joint design to be evaluated more thoroughly:

Glueline Thickness: This value is the distance between the glass and framing system. It is the thickness of the sealant. Typically, reducing the glueline thickness from 12 mm (1/2”) to 6 mm (1/4”) increases the peak strength of the sealant. For Sealant A, reducing the glueline 50 % increased the strength up to 24% depending on the rate of strain. For Sealant B, the decrease in glueline thickness showed little effect on the peak strength. For structural glazing and most standard window designs, a minimum glueline thickness of 6 mm (1/4”) is recommended to allow proper joint fill and to allow for differential thermal movement between the glass and framing.

Bite: This value is the contact area on the glass and frame. It is the depth of the sealant joint. This value is a critical value in structural glazing design. A larger bite can support higher loads than a smaller bite. General industry guidelines require a bite which is always greater than the glueline thickness. For structural glazing designs, the bite is determined by a calculation which considers the design windload and size and type of glass. Further information on appropriate design of joint for structural glazing can be found in ASTM C1401 or ETAG 002.

For Sealant A, increasing the bite from 6 mm (1/4") to 16 mm (5/8) decreases the strength by area of contact by approximately 20%. For Sealant B, the decrease is less than 10%. Please be aware that a larger bite is still higher in strength because the overall contact area has increased. For typical window systems designed for bomb blast mitigation, the bite is typically from 12 mm (1/2") to 25 mm (1"). If a design uses a sealant joint on both the inner and outer surface of the glass, then the strength and performance will be higher.

Tension vs. Shear: In a typical window design, the sealant is applied in a rectangular joint between the frame and the glass. During a bomb blast, most of the applied load on the sealant joint is in shear. From the results provided, there does appear to be a slight decrease in the ultimate strength when tested in shear versus tension, although the decrease does not appear to be more than 10%. For some conditions, the shear strength is greater than the tensile strength. For Sealant B, there does not appear to be a statistical drop off in strength between the two strain types.

A recent bomb blast mitigating window design used an L-bead type joint where the sealant has adhesion on both the edge and back surface of the glass. In this design, the sealant on the edge of the glass is being strained in tension. These systems have successfully passed actual bomb blast testing and can be considered as viable design.

Rate of Strain: This testing clearly shows the effect of high strain rates on the performance of silicone. As you see, ultimate strength uniformly increases at these very high strain rates. The increased strain rate causes the peak tensile strength to increase approximately 50%. This testing allows a design professional to use tensile strength results from standard rates of strain as a conservative estimate of the actual performance of the sealant. Knowing that the actual strength of the sealant will be higher in blast conditions provides an inherent safety factor in the design.

Summary

Bomb blast mitigating window designs are clearly growing in popularity in response to greater terrorist risk since 9/11. These window designs are complex with many variables affecting their performance. One essential component needed to develop a successful bomb blast mitigating window system is the silicone sealant. Only a silicone sealant can reliably meet the demands of these systems: Strength to anchor the laminated glass in the frame, flexibility, long term adhesion and proven structural glazing durability. Testing of silicone sealant in a manner simulating bomb blast conditions shows that their behavior is reliable and in line with the requirement of bomb blast mitigating window designs. Future innovations in design will put even greater demands on silicone sealants. By providing data on the behavior of silicone sealants, a design profession is armed with the information needed to innovate and develop systems which will perform successfully and hopefully save lives.

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