Blast induced glass hazards: a comparison of design approaches and recent research

K. A. Marchand[1], E. J. Conrath[2], D. J. Stevens[1] & S. B. Meyer[3]
[1]*Protection Engineering Consultants, Dripping Springs, Texas, USA*
[2]*US Army Corps of Engineers Omaha District, Protective Design Center, Omaha, NE, USA*
[3]*San Antonio, Texas, USA*

Abstract

The greatest numbers of casualties resulting from terrorist bombings of buildings are generated by failed glass assemblages through shard laceration and glass lite induced blunt trauma. Current test methods for glass assemblies provide procedures for the validation of glazing assembly performance. Likewise, computer algorithms such as the Corps of Engineers' HazL software and GSA's WINGARD software predict structural/mechanical and post-break response remarkably well. Test methods and analytical predictions quantitatively evaluate glass performance but only qualitatively evaluate injury potential, however. Situations often arise where specific performance levels cannot be met, or threats to predict these levels are unknown and investment to achieve reduction in risk must be based on a quantitative assessment of risk. This paper describes the benefits of a combined performance evaluation and risk/injury quantification approach for the design of glass assemblies to mitigate the effects of blast loads.
Keywords: blast modeling, blast-resistant, casualties, glass, glazing, hazard models, injuries, terrorism, counter-terrorism.

1 Introduction

Blast loaded glass induced human injury data collected over the last few years has advanced the state-of-the-art in quantitative human injury prediction. This data has led to the development of models that suggest that established procedures, while having served the community well since their inception in the early 1990s, are generally conservative, but are limited in their ability to predict

WIT Transactions on The Built Environment, Vol 87, © 2006 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/SU060261

specific human injury mechanisms and standoff and load thresholds. Specifically, it will be shown that glass "flight" models that are generally accepted as accurate and conservative may, in fact, be highly (overly) conservative in some regimes and unconservative in others.

This paper is divided into four sections: an introduction and review of the existing glass flight based hazard models used in most current codes and standards, a review of the development and nature of recently generated quantitative human injury data for blast loaded glass, a limited graphical comparison of this combined mechanism approach to defining glass hazards using range-to-effect curves for annealed (AN), fully tempered (FT) and insulated glass units (IGU) and some observations and conclusions.

2 Current glass hazard approaches and glass flight models

Current glass hazard models are based primarily on flight distances predicted after break and detachment from frames, sashes or stops. While some methods (ASTM[1]) attempt to capture some glass shard size data as a part of the evaluation of glazing systems, the "flight" method ignores shard size and mass, or even the effect of contiguous sheets of glass shards (for filmed glass) in terms of specific injury mechanisms. Glass flight in these models is strictly correlated with velocity, with the generally accepted high hazard velocity equal to approximately 9 m/s (30 fps). Debris flight models with representations of hazards at 6 levels of protection are shown in Figure 1. These models are currently accepted by the GSA [2], by the US Department of Defense [3] (DoD) and in Europe (specifically the UK [4]) in slightly varying forms.

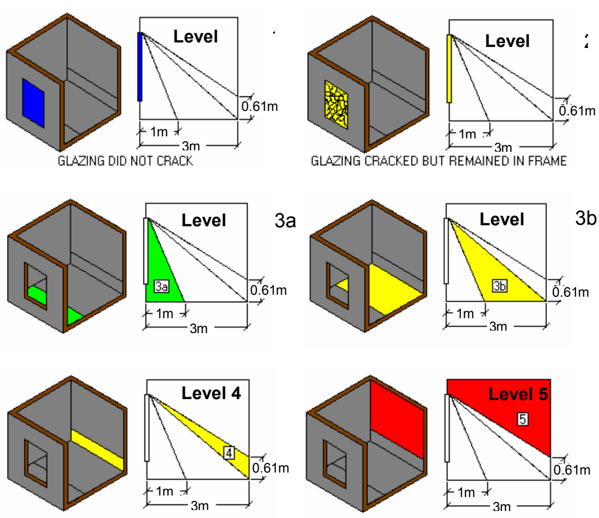

Figure 1: Hazard conditions based on glass shard flight models (general services administration).

The flight distances (generally correlated to hazard level) were developed loosely based on calculations in the UK [5] of the potential for skin penetration at a 0.1 J/mm^2 specific energy threshold. Analysis of relatively large shards (50mm x 50mm x 4mm) suggested that skin penetration could occur at velocities less than 15 m/s for annealed glass, but may not occur until velocities of 60 m/s were reached for "toughened" glass. 9 m/s was suggested as the high hazard level for glass shards, which could be related to approximately 3 m of flight for typical glass installations and spaces. Eye injuries were thought to occur at specific energy levels as low as 0.06 J/mm^2, or, for the same shard, at velocities of approximately 2 m/s. This led to the 1 m flight distance for the low hazard condition in the current standards.

Glass failure loads, deflections and reactions are quite accurately predicted with engineering tools such as GSA's WinGARD [6] and the DoD/COE HazL [7] tools. These models consider glass response up to failure in great detail, including the definition of glass strengths as a function of probability of failure and loading rate, deformation and failure as a function of geometry (span), laminated glass interlayer response, additional capacity provided by retrofits (attached films, etc.), and many other details of the response mechanics of glass. After predicted failure, however, these tools resort to simplified flyout models, imparting either the last calculated velocity prior to failure as an initial flight velocity, or applying residual impulse to the failed glass, and applying "clearing" relationships to decrease further acceleration of the glass after break.

3 Recent developments in glass hazard injury quantification

Over the last 6 years in the US, the DoD and the Technical Support Working Group (TSWG) has sponsored several test and analysis research projects to quantitatively evaluate injury from flying glass. The research focused on three primary injury mechanisms, based on observations from real world events: skin and tissue laceration from glass shards, blunt trauma induced by the impact of large "sheets" of shards held together either by polyester film (fragment retention film) or by the poly vinyl butyral (pvb) interlayer of laminated glass, or blunt trauma induced by the momentum preserved in the "cloud" of shards released from a failed glass lite.

Glass shard hazard research has been accomplished for the most part by Applied Research Associates in San Antonio under sponsorship of the TSWG [8]. ARA conducted 90 some tests of annealed, tempered and insulated glass (symmetric annealed units). The experiments were conducted to measure glass shard geometrical properties as a function of load intensity and glass lite geometry (window size). Four glass types were tested in the ARA experiments: monolithic annealed glass (AN), fully tempered glass (FT), insulated glass units (IGU), and laminated glass. Sizes considered included 0.61 m (2 ft) by 1.22 m (4 ft) and 1.22 m (4 ft) by 1.52 m (5 ft) windows with various thicknesses and load (blast) levels for each thickness. High-speed digital cameras were used to capture size, shape, and shard velocity and the data was reduced with image processing software.

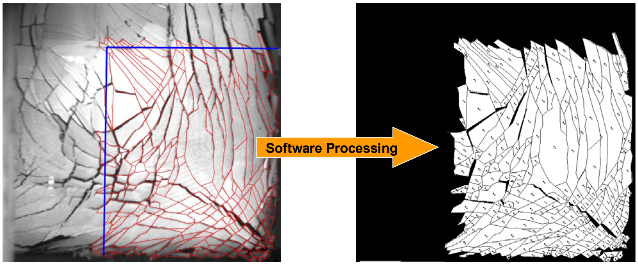

Figure 2: Glass shard imaging, digital processing and identification from ARA experiments [8].

Digital imaging software was used to identify and "tag" shards for later statistical analysis after shards were manually traced on the high speed images. Figure 2 illustrates the shard identification and collection procedure.

The voluminous data collected during the tests and analysis facilitated the development of statistical models for numbers of shards and shard translational velocity and the development of a shard matrix prediction tool called the Shard Fly-Out Model (SFOM). Shard matrices generated by the SFOM are used as input to the Multi-Hit Glass Penetration (MHGP) code also developed by ARA [9]. The MHGP model is an extension of work originally funded by the TSWG to adapt the Army's ORCA (Operational Readiness and Casualty Analysis) code to handle glass shard penetration [10]. ORCA includes a numerical representation of the human body that allows various insults to be evaluated along casualty measure parameters using AIS scores to determine overall ISS (injury severity score). The MHGP code was validated with both ballistic gelatin tests and tests of glass shards fired into human cadaver tissue.

SFOM produces a shard matrix with specified shard size, shape and mass, translational velocity, rotational velocity and lateral velocity (spreading) for each shard. This matrix or cloud is then "flown" into a human body form positioned in the field of flight of the glass, and impacts are predicted. Once shard impacts are determined for the body position in the model, tissue penetration and wound track is calculated in the ORCA model. AIS scores are then assigned, and overall body ISS is determined from the three highest AIS scores. Table 1 presents a table of ISS descriptions and scores prepared in support of the development of BICADS (Building Injury Calculator and DatabaseS) [11].

The TSWG also directed an effort to evaluate the blunt trauma hazards of glass through evaluation of data generated in anthropomorphic dummies (ATD's) subjected to filmed, unfilmed and laminated glass [12] impacts. Realistic office scenarios and geometries were used to permit the generation of all associated debris from the large, free-air explosions. Windows with and without film were tested. The head injury criteria or HIC [13] was used in preliminary development of lethality models for glass induced blunt trauma. Figure 3 shows high speed photographic frames from the filmed tests.

Analytic models were developed for both unfilmed glass shard "clouds" and filmed glass sheets that predicted head injury AIS scores based on glass momentum. This useful criteria suggests that head trauma, and, hence, glass induced blunt trauma is a simple function of applied blast impulse. The information and algorithms developed in the research were incorporated into HULC (HUman Lethality Code).

Table 1: Injury severity scores and descriptions from BICADS [11].

BICADS Injury Level	Description	Range of ISS[1] Scores	Example of Injuries	Typical Worst AIS[2] Score
No Calculated Injury	Typically no medical treatment required	0	No injury Minor bruises Minor cots Small foreign object in eyes Hearing loss	0
Minor to Moderate Injury (Level 1)	Injuries can be treated with medical aid, hospitalization not required	1 to 4	Lacerations to face and body from glass fragments Cuts or abrasions to the eye Contusions and abrasions	1
Serious Non-Life Threatening Injury (Level 2)	Injuries require greater degree of medical aid and hospitalization, but not immediately life-threatening	5 to 10	Bone fractures Large numbers of lacerations Artery or tendon lacerations Concussions	2
Serious Life-Threatening Injury (Level 3)	Severe injuries, immediate medical attention required, high likelihood of survival with prompt medical treatment	11 to 24	Very severe lacerations with significant blood loss Severe open bone fractures Crush injuries Skull fractures	3 to 4
Fatal/Severe Injury (Level 4)	Very severe injury, likelihood of fatality	>=25	Multiple very serious injuries Primarily fatalities	5 to 6

Note 1: ISS (Injury Severity Scores) are a composite injury score based on worst AIS scores assigned to the three most severely injured body regions, out of six body regions, ranging from 1-75.
Note 2: AIS (Abbreviated Injury Scores) are individual injury scores ranging from 1-6, where 1 id minor, 2 is moderate, 3 is serious, 4 is severe, 5 is critical and 6 is fatal.

(a) t=50 ms. (b) t=82 ms.

(c) t=102 ms. (d) t=126 ms.

Figure 3: Series of high speed images from filmed glass blunt trauma tests [12].

Another set of recently compiled data is the BICADS model and databases [11]. Wilfred Baker Engineering and Dr. Chuck Oswald used the previously mentioned glass blunt trauma data along with data from the Oklahoma City bombing, the Khobar Towers bombing, WWII "Blitz" data and data from drop tests of ATD's to develop building induced injury predictions in the BICADS model. These data are used in the comparisons described in the next section of this paper.

4 Comparisons of "design" approaches, hazard approaches and data from "real" events

In the analysis conducted for this paper, and as presented in the figures that follow, comparisons of "flight" model hazard predictions with shard penetration, shard blunt trauma and filmed glass blunt trauma are presented. HazL was used to generate range-to-effect data for AN, FT and IGU glass in two configurations and two sizes. "Flight" models in HazL were used to predict hazards, and the SFOM/MHGP implementation in HazL was used to predict shard penetration ISS's. Blunt trauma hazards were predicted using the momentum (impulse) model developed by K&C and implemented in BICADS. Data from the OKC and Khobar bombings are included for comparison. That data is somewhat independent of glass type, but provides useful comparison for hazard regimes.

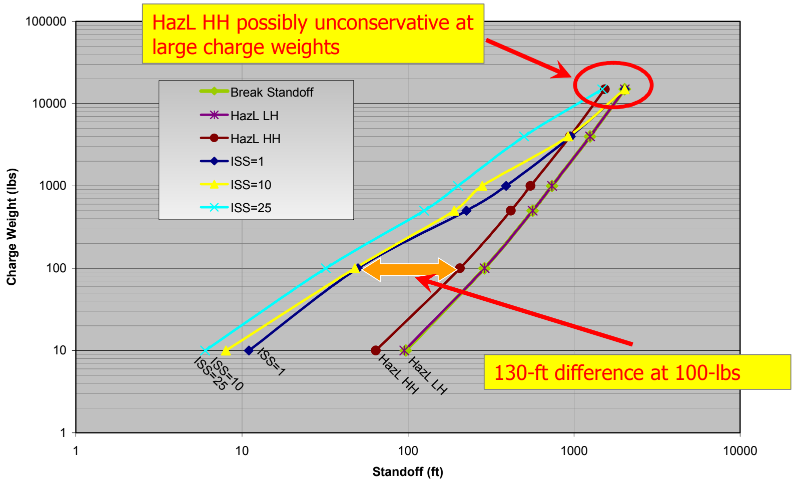

Figure 4: Comparisons of HazL rte versus SFOM ISS scores for 0.61 m x 0.91 (2 ft x 3 ft) 4.8 mm (0.1875 in) annealed glass; no retrofits.

Figures 4-7 present comparisons of the hazard mechanisms and their treatment by the "flight", shard penetration, and blunt trauma models. Figure 4 shows HazL predicted range-to-effect (rte) curves for 0.61 m x 0.91 m (2 ft x 3 ft), 4.8 mm (0.1875 in) annealed glass. The HazL "break" curve is essentially equal to the low hazard (1 m flight, 2 m/s) curve for this configuration. Figure 4 also shows the ISS predictions for shard penetration (SFOM/MHGP models). The figure illustrates the dramatic difference between the "flight" model and the shard model at the lower charge weights. Velocities here are similar in the two models, but at the smaller charge weights, pressures are higher, numbers of shards predicted by the SFOM model are thus larger and fragment masses are smaller, resulting in less energy available for skin/tissue penetration. The flight model only considers velocity for flight, thus predicted ranges are larger. At the very large charges, the HazL high hazard curve might be unconservative. This is probably due to lower pressures in this regime resulting in larger shards in the SFOM model, resulting in higher injury scores in the MHGP model, as well as underprediction of final velocity.

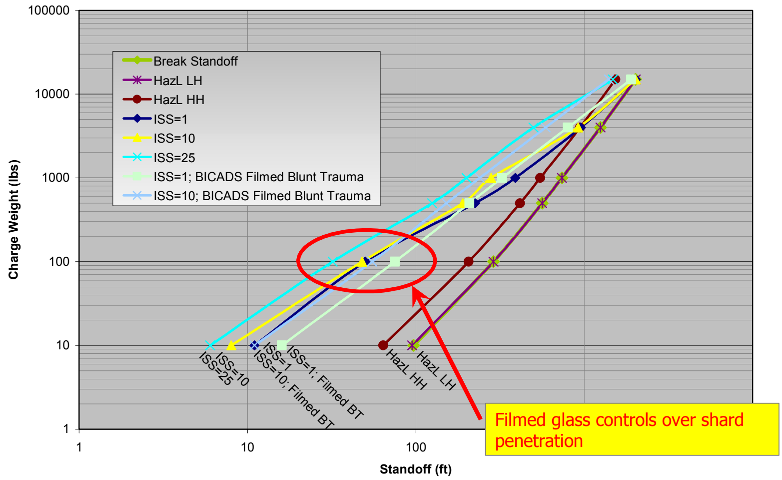

Figure 5: Comparisons of HazL rte versus SFOM ISS scores for 0.61 m x 0.91 (2 ft x 3 ft) 4.8 mm (0.1875 in) annealed glass; polyester film applied.

It should be noted that the difference between the "flight" models and the injury score models can mean significant differences in standoff for a given hazard level. In this case, the difference for a 220 kg (100 lb) charge is 39.6 m (130 ft), a 175% difference.

Blunt trauma thresholds are added to the data of Figure 4 in Figure 5 for the same glass configuration but with film added. For this small glass configuration, the blunt trauma threshold (range) is larger, meaning it controls in terms of ISS score. Similar analysis for larger AN lites (1.22 m x 1.52 m (4 ft x 5 ft)) did not show this trend. Shard blunt trauma thresholds are added in Figure 6. Here, as in all other cases evaluated, shard blunt trauma was not the controlling injury mechanism. Finally, the OKC and Khobar injury data are added and shown in Figure 7. The data was extracted from the BICADS versions of these databases, where actual ISS's were assigned based on the injuries reported and at the standoffs where they occurred for the two events (hence, just the two charge weights). The data suggests that all of the predictions are reasonable (and somewhat conservative).

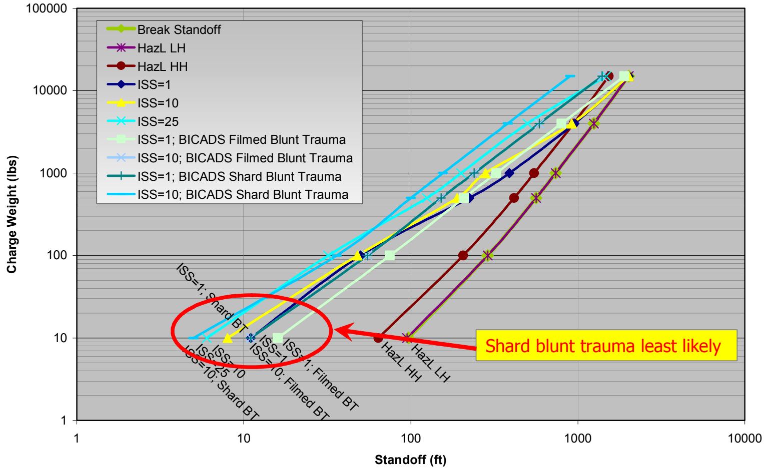

Figure 6: Comparisons of HazL rte versus SFOM ISS scores for 0.61 m x 0.91 (2 ft x 3 ft) 4.8 mm (0.1875 in) annealed glass; shard blunt trauma compared to polyester film and no retrofit.

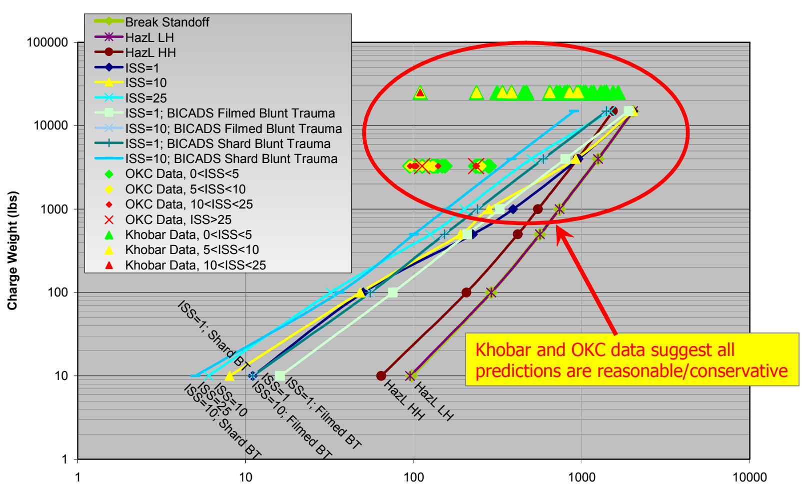

Figure 7: Comparisons of HazL rte versus SFOM ISS scores for 0.61 m x 0.91 (2 ft x 3 ft) 4.8 mm (0.1875 in) annealed glass; comparison to OKC and Khobar Data.

Similar comparisons were made for larger (1.22 m x 1.52 m (4 ft x 5 ft)) fully tempered glass and small (0.61 m x 0.91 (2 ft x 3 ft)) 4.8 mm (0.1875 in) symmetric IGU. For the larger tempered glass, the "flight" models (HazL) were shown to be unconservative at charge weights as low as 2200 kg (1000 lbs.). These analyses also showed that filmed glass does not control in terms of hazard and shard blunt trauma is least likely to be a controlling injury mechanism.

In the small IGU analyses it was discovered that large charge predictions are conservative with respect to the shard penetration ISS predictions, filmed hazards occur at approximately the same ranges as shard penetration, and shard blunt trauma is not a controlling mechanism.

5 Conclusions and recommendations

Observations and conclusions drawn from the analysis presented in this paper suggest that existing glass hazard "flight" models are generally very conservative with respect to actual event and quantitative human injury test data. Additionally, the reviewed data suggest that appropriate ranges/regimes where film is beneficial or, conversely, more hazardous may be defined. Finally, it is recommended that the data and models introduced and manipulated herein should be used to update or replace existing "flight" only models such that standoff advantages can be realized.

References

[1] Standard Test Method for Glazing and Glazing Systems Subject to Airblast Loadings, F1642-04, ASTM International, 2004.

[2] ISC Security Design Criteria for New Federal Office Buildings and Major Modernization Projects, The Interagency Security Committee, U.S. General Services Administration, For Official Use Only, 2001.

[3] DoD Minimum Antiterrorism Standards for Buildings, Unified Facilities Criteria (UFC) 4-010-01, U.S. Department of Defense, October 2003.

[4] "PDSB Notes on Design for Glazing Protection, Current UK Design Philosophy," Police Scientific Development Branch, Home Office, April 2004.

[5] "Velocity of Glass to Cause Injury," Johnson. N.F., notes and calculations, April 1993.

[6] Window Glazing Analysis Response and Design (WinGARD), Version 4.1, General Services Administration, December 2003.

[7] Window Fragment Hazard Level Analysis, HazL, Version 1.2, U.S. Army Corps of Engineers, April 2004.

[8] Stevens, D.J., Meyer, S.B., Barsotti, M.A., Becvar, K.E., and Marchand, K.A., "Glass Debris Visualization, Analysis and Prediction," Final Technical Report, Prepared for the Technical Support Working Group, Contract No. N39998-99-C-0671, Applied Research Associates, December 2002.

[9] Young, L.A., et al, “Extension of the Glass Penetration Model to Provide Multi-Hit Capability,” Final Technical Report, Prepared for the Technical Support Working Group, Contract No. N41756-01-C-7448, Applied Research Associates, December 2002.

[10] Young, L.A., Needham, C.A., and Doolittle, C., “Human Injury Modeling for Physical Security Assessments,” Final Report, Prepared for the Technical Support Working Group, Contract OST N39998-99-C-0671, Applied Research Associates, April 2000.

[11] Oswald, C.J. and Alaoui, S.S., “Methodology Report for BICADS Computer Program,” Prepared for the Technical Support Working Group, Contract N39998-00-C-0658, Wilfred Baker Engineering, October 2003.

[12] Bogosian, D.D., Avanessian, H.D., Fu, S., and Ward, P., “Assessment of Human Injury Data from Cubicle Experiments,” Volume 1: Technical Report, Prepared for the Technical Support Working Group, Karagozian and Case, July 2003.

[13] Mentzer, S.G., “Efficient Computation of Head Injury Criterion (HIC) Values”, Final

[14] Report DOT-HS-806-681, November 1984.