STATE OF THE ART OF BLAST RESISTANT WINDOWS

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Over the past decade a reliable, but possibly conservative, practice has evolved for the design of blast resistant window systems. Herein, the procedure for glazing design is first summarized. This is then comprehensively compared to the results of various prototype tests. Next, the failure criteria for the glass component of the system is critically considered. Finally, the practice for window frame design is examined with a view toward reliable economies.

INTRODUCTION

Over the last 10 years, a design methodology has been formulated, developed and tested for the design of blast resistant glazing. Design procedures have been specifically developed for thermally tempered glass, semi-tempered glass, polycarbonate, laminated tempered, laminated semi-tempered, and annealed laminated glass. A procedure for analyzing monolithic annealed (regular plate or float glass) has also been established (none of the authors recommend annealed or wire glass for blast resistant design). This approach has been subjected to peer review and published in the Department of Defense *Structures to Resist the Effects ofAccidental Explosions*, Army TM5-1300, Navy NAVFAC P-397, and Air Force AFR 88-22, the Naval Physical Security Equipment Manual and the Corps of Engineers Security Engineering Manual Handbook. The approach has also been adopted for design by the United States Department of State and other governmental agencies. The theoretical approach used to develop the design curves, tables, and formulas has also been incorporated into many computer programs. Gerald Meyers developed and wrote TM, PE, PR, EMB, WINDOW, BWORK, BLASTOP, and GLASSTOP. Donald Baldwin has incorporated much of the theory into WINDX, GPLAC, WINLAC, SAFEVUE, MAXLITE, VUELITE and MAXVUE. A brief description of these codes is given in Appendix A. For the convenience of the reader as well as the designer of blast resistant glazing, Table I lists and summarizes the many design computer programs written by Gerald Meyers and Donald Baldwin, their latest version, applicability and capability.

A frame design methodology was also developed and validated in blast tests. Since an inadequate frame will defeat the purpose of a blast resistant design, all truly adequate blast resistant glazing design procedures must address frame design. Also, validation testing of the design procedure must be done in actual frames connected in a realistic way to the structure.

As many professionals in the blast design field are not aware of the large body of testing that supports the adequacy and conservatism of the design procedure, the purpose of this paper is to present for the first time all this test data in one place. Sixty-three successful full-scale blast

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tests to date by different researchers support the conservatism of the design theory. No windows failed at design loads except one laminated tempered glass pane that may have had a pinched gasket. The authors also want to refute any claims that there is only one particular glazing material suitable and adequate for blast resistant design. The test data will show that thermally tempered glass, laminated tempered glass, and polycarbonate are all adequate for blast resistant design. The authors also believe that laminated annealed glass, laminated semi-tempered glass, and acrylics (such as Plexiglass) can be used and will remain structurally intact when subjected to blast if designed to fundamental engineering principles of structural dynamics. The ultimate purpose of this paper is to hopefully suggest a knowledgeable opinion as to where blast resistant glazing research and policy should develop in the future.

GLAZING DESIGN PROCEDURE

The design approach (discussed in detail in References i through 9) utilizes a conventional single degree of freedom vibration approach to analyze dynamic response under blast load. Considering that blast loads can only be predicted to within 20 percent and that it is impossible to accurately model as-built edge framing conditions, this was considered a reasonable and appropriate level of sophistication. Numerical integration of the differential equations of motion is used to determine maximum center deflection under blast loads. The glazing pane is analyzed as a non-linear plate using relationships developed by D. Moore of the Jet Propulsion Laboratory (Reference 10) and confirmed by tests (Reference 2). These relationships, developed by finite element solution, determine maximum stress in the plate for a given deflecting pane size and length-to-width ratio. The maximum stress is then correlated to a chosen probability of failure for design. A viscous damping coefficient of only 2 percent is assumed for design. Actual values observed in tests appear to be considerably higher.

The blast load is typically modeled as an instantaneously applied positive overpressure with a linear decay to zero pressure. The blast load is equated through the principal of equivalent impulse to a pressure time history, that is a right triangle with linear pressure decay. This approach assumes more impulse early-on, timewise, in the structural response and is conservative as it overpredicts center deflection, stress, and ultimately probability of failure. The smaller negative pressure that often follows the positive pressure is ignored in the interest of conservative design. A preliminary design theory for blast resistant frames is also presented.

GLAZING FAILURE CRITERIA

Recently, design theories have been proposed based upon a philosophy of "safe" post failure behavior. Some of the proposals incorporate using the negative pressure that arrives later in the pressure time history to suck out failed glass fragments, cause failed panes to fall outward, or to prevent incipient failure from becoming a catastrophic failure. Other theories purport to limit the velocity of glass fragments below a safe threshold. However, to truly safely use airblast forces to control either the structural response or fragmentation from a failed window, the post-failure behavior models must deal with the following air-blast issues.

Many explosives are not chemically balanced with respect to oxygen. This means that once detonation occurs, the fireball which contains the products of combustion will continue to react as it consumes oxygen from the atmosphere. This will generate a longer positive pressure duration than that assumed from the standard air-blast curves. Many common explosives actually exploit this effect by using aluminum powder to increase the positive duration as this increases the pushing power of the explosive. Ammonia nitrate based explosives strongly exhibit this tendency. Since ideal pressure-time histories used in analysis of explosives often employed in validation testing may not exhibit this longer positive pressure kick, a design theory that does not accommodate non-ideal explosive behavior may prove to be unconservative. In the physical security setting, this problem may be particularly aggravated as many explosives used by terrorists are non-ideal.

Site geometry may also discount the benefit of using negative pressure in design. Positive pressure will reflect from surrounding buildings, walls, or hills and provide positive overpressure later in the pressure time history and structural response. While this effect is often dealt with by doubling charge weight, the reflected positive contribution will arrive later due to its increased travel time. Obstructions, slope, hills and even large vegetation can also cause blast waves to act in a non-ideal manner with complex pressure time histories. Both pressure and duration may vary significantly from the ideal. If a blast resistant window is designed just to or just beyond the point of incipient failure from the positive pressure duration, the second positive pressure duration may have the effect of failing the glazing and/or propelling glass fragments into inhabited spaces.

Another potential problem for post-failure behavior is consensus on what constitutes safe glass fragments. Discussions with experts in the field, including Dr. Royce Fletcher (Lovelace Institute and Los Alamos), indicate that there is no safe glass fragment. Many of the researchers of blast accidents concerning glass failure have also noted that glass fragments often go for eyes and critical throat areas much as tornadoes go for mobile home parks.

For all these reasons, the authors all strongly believe that no design theories based upon controlling ejection of glazing material should be incorporated into blast resistant glazing design. If post elastic or post failure response can be justified by theory and validation tests, then it may represent a legitimate basis for design. Therefore, laminated glass may delaminate and even crack or polycarbonate can permanently deform as it takes advantage of its ductility as long as the pane remains within the frame with a measurable and reliable level of structural strength.

BLAST LOAD TESTS

Blast load tests on thermally tempered glass windows were conducted during January 1986 by the Naval Civil Engineering Laboratory (NCEL) at the LSI (Albuquerque) shocktube of Los Alamos National Laboratory (Ref 1). This shocktube is known in the field as the Lovelace Shocktube. The shocktube is 300 feet long with a diameter of 10 feet at its endplate where test windows were mounted in a stiff frame. Strands of primacord were detonated in the narrow front section of the tube to generate long-duration blast overpressures. All blast positive pressure durations were at least 150 msec long. Additionally, overpressure levels held constant at close to maximum peak pressure for 30 to 50 msec before decay. This had the effect of being a more conservative loading than blast loadings anticipated in the field or modeled in the design criteria. Thirty-six blast tests were conducted.

Window frames were fabricated to the design theory from either off-the-shelf skylight members or from reinforced, but standard, storefront frame members.

Shocktube Tests of Monolithic Tempered Glass

Twenty-eight blast tests were conducted on 18 monolithic (non-laminated) thermally tempered glass specimens. Eight blast tests were also conducted on five laminated thermally tempered glass specimens. Table 2 summarizes the blast test results and provides comparison with predicted blast load capacity at the test blast load duration of 150 msec.

Key parameters of the eight combinations of blast-resistant windows tested are reported in Table 2. When a surviving window was retested at a higher blast overpressure, column 1 of Table 2 records the retest as the original test number but with a sequential letter added. For example, test 14d is the fourth test of specimen 14 (a rectangular 54 x 36 x 3/8-inch laminated tempered glass specimen in a frame fabricated from storefront window glazing sections).

With the exception of tests 10 through 12, all the blast overpressures were calibrated upward to account for the fact that new and thicker glass than minimum was tested. To be conservative, all the design criteria and computer programs assume old and environmentally degraded glass and, unless specified, assume the minimum possible thickness per nominal thickness.

All the monolithic tempered glass survived its design blast load, which is correlated with an acceptable probability of failure of one per thousand. At least one sample in each window type was also tested at a higher blast overpressure predicted to cause a 50 percent rate of failure. This sequential blast testing of glass yields conservative test results as it is believed that repeat blast loading weakens glass by expanding surface flaws in the glazing. Only the BMS window assembly (test 20b) failed glazing (two of four panes) at this higher-than-design blast load.

Finally, one specimen per window type was tested at a blast overpressure predicted to cause a 99 percent failure rate. Glass failure occurred in the single-pane window types AW, AS, BW, and BS. In the four-pane window assembly, BMW (test 19), all four panes failed. Three of the four panes failed on the BMS window assembly (test 22).

In summary, none of the monolithic panes failed at design overpressures. Considerably less than 50 percent of the panes failed at higher than design overpressures predicted to induce a 50 percent probability of failure. Finally, all the window assemblies exposed to blast overpressures which correlated with a 99 percent probability of failure actually did suffer pane failure. In reviewing these results many years after the tests, it seems that a reasonable level of validation was established. If future work shows that a thinner pane can be used, this will only have a minimal effect upon real world design. This is because the economics of decreasing one nominal size in glazing is small. Greater economics can be obtained by concentrating on frame design. Possible avenues of approach are discussed in the last section of this paper.

Shocktube Tests of Laminated Tempered Glass

Eight blast load tests were also conducted on laminated thermally tempered glass windows. Laminated glass was tested as it affords the opportunity to assemble glazing thick enough to resist the high blast overpressures often encountered in physical security design. All the laminated glass tested was 54 by 36 by 3/8 inches (nominal). Architectural grade polyvinyl butyral (PVB), 60 mils (0.060 inch) thick, was used as the interlaminar material. The glass was provided by a leading manufacturer of PVB. The first laminated tempered glass specimen (test 13) blew out at a blast overpressure close to the design blast capacity of an equally dimensioned new monolithic glass pane. However, it is believed that the soft and narrow glazing tape that served as the gasket might have crept out of place before testing. If this did occur, the glass pane was not fully supported during the blast tests. All subsequent tests involved a retightening of the glazing retaining plate prior to testing. No failure occurred in any of the remaining seven blast tests with laminated glass, even though test 14d was at a blast overpressure associated with a 99 percent probability of failure.

While initial deflection and stress measurements indicate that the high strain rates associated with blast loading induced monolithic action, blast testing occurred between temperatures of 40 and 70^0F. Laminated glass may only develop less than 100 percent of its monolithic static strength at possible service temperatures between 100^0F and 170^0F.

Further validation of the blast overpressure capacity listed in the design criteria can be obtained by comparison with blast test data conducted by the Army (Ref. 11). Table 3 summarizes the blast tests and presents the predicted blast load capacity of the test specimen pane for the actual blast load durations. Again, the blast capacity design predictions appear to be reasonably conservative. The only exceptions are in tests where frame failure occurred in unstrengthened frames.

Arena Tests of Polvcarbonate and Laminated Tempered Glass

The following blasts on polycarbonate were conducted during 1987 and 1988 by the Waterway Experiment Station of the Corps of Engineers (Ref. 11). Five samples of 60 x 17 x 1.75 inch polycarbonate with thin sacrificial sheets of glass on its outer edges were used. Each sample was fabricated by a different manufacturer. A large hemispherical charge was detonated with a measure peak reflected pressure of 96 to 100 psi with a positive duration of 8 msec. The panes were mounted in an enclosed box so no wrap around pressure would leak behind the glazing and decrease net loading. The calculated blast capacity of the panes was calculated by the BLASTOP computer program to be 105 psi. All the panes survived.

Five other samples of Lexan SP1250 polycarbonate were tested during 1988 by the Department of State at Ft. Polk, Louisiana (Ref. 12). The peak maximum pressure was between 57.4 and 49 psi with a positive duration of 15.7 msec. Two of the samples were old Lexan polycarbonate (1.25 inch thick normal) obtained from gas stations in Los Angeles. Table 4 summarizes the test. All panes survived. The 26 x 26 x 1.3 inch panes survived at design load. The larger 36 x 36 x 1.3 inch and 40 x 40 x 1.3 inch survived at loads considerably above design capacity. As with the tempered glass tests, the procedure is conservative in not only predicting survival, but with respect to overpredicting maximum center deflection which defines maximum stress and probability of failure. The old and possibly degraded polycarbonate behaved similarly to the new polycarbonate.

Polycarbonate tests were also conducted by the Naval Civil Engineering Laboratory and the U.S. Army Waterway Experiment Station during August 1991. Table 5 summarizes the three arena blast tests on ¾ inch (19 mm) thick polycarbonate. All the panes survived an overpressure of 14.6 psi with an effective positive duration of 15 msec. The 37 x 37 x ¾ survived above its design load. Center deflections are reported in column three. All overpredict center deflection, which is conservative for design. No reported deflection measurements were made on the support frames and as window frames were mounted in outer frames which were attached to the concrete test structure, the measured center deflections may be overstated to an unspecified amount. This is also the case in the subsequent laminated glass tests. The last column reports the design blast capacity obtained by using the BLASTOP computer code for the 15 msec overpressure duration. None of the tests tested polycarbonate past its yield point into the ductile response regime. Preliminary analysis by Meyers with a research computer program that analyzes ductility indicates that blast capacity may increase 40% if 10% ductility is used. The 10% design value is considerably below the available ductility in most polycarbonate, but may represent a conservative value for deterioration from long-term ultraviolet exposure and aging.

The same test also tested 3 laminated tempered glass panes (Ref. 13). The tests are summarized in Table 6. As the tests occurred during August at Ft. Polk, Louisiana and photographic lights applied heat to the laminated glass, it can be assumed that the panes were warm. While no temperature readings were recorded, it is reasonable to believe that the panes were above 100^0F. It has been theorized by many experts and exhibited by test (Ref. 14) that laminated glass may behave differently at higher temperatures induced by solar radiation. This may be because that the PVB may not be able to transmit 100% of the shear between adjoining layers of glass. All the panes survived the blast load which was measured at 13.5 psi with an effective duration of 15 msec. Both Gerald Meyers and Donald Baldwin reduce the static design load of laminated glass to 75% of its original to account for heat effects which may cause laminated glass not to act monolithically. This ratio was advocated by many building codes and a leading manufacturer of PVB. As this will tend to model laminated as less stiff and with a longer natural period of vibration, the blast capacity may not be reduced by 25% when the calculations of structural dynamics are performed. It is important to note that efficient and economical designs can easily be obtained using this design assumption. In this test, a blast capacity was demonstrated for laminated glass at a 13.5 psi blast load with a positive duration of 15 msec. This is a very reasonable level of design. Also the 33 x 33 inch and 37 x 37 inch survived considerably above the blast load. Calculations with the 75% strength factor underpredicted center deflections. The authors are not entirely sure if this is a result of not having the differential deflection obtained between the inner frame and the glazing. As the glazing is thick and short-spanned with small deflections, small movements, bending or rocking in the frame, gasket, or shims, can have a very significant impact on the final deflection. A review of blast tests (references 3 and 5) where deflection in frames under blast load was recorded indicates that deflections of 0. 1 to 0.2 inches may be reasonable under the 13.5 psi blast load. BLASTOP was also modified to run with a 50% reduction factor off monolithic strength. These center deflections are relatively close to measured. The sixth column of Table 6 reports predicted deflections if the glazing performed as a series of stacked plates. The ratio of these center deflections to the measured center deflection exceeded the typical 20 to 25% overprediction of deflections that are relatively common to the analytical method. It can be concluded that the laminated glass did not act as a stacked plate, but instead behaved as a quasi-monolithic plate with a reduction factor that is yet to be determined.

More research and testing is required on the behavior of laminated glass and PVB at high temperatures before a final design criteria for laminated glass is adopted. The last column of Table 6 reports the design capacity obtained by using the BLASTOP computer code at the 15 msec overpressure duration.

FRAME DESIGN

Considerable future economy can be achieved by removing some of the conservation in the current design procedures (References 1-9) on frame design.

In current practice, the frames for blast resistant windows are designed so that they exceed the resistance of the glazing material they encompass. This follows the fundamental tenant to engineer any connection to be stronger than the elements which it joins. A typical section through a blast resistant window frame is illustrated in Figure 1. The glazing material is held in an inner frame by gaskets. This factory-fabricated frame consists of an angle and a tubular stop. It is in turn installed with bolts and shims to an outer frame or embed. This embed is anchored to the structural wall during construction in the field.

A conservative design is achieved through stringent limits on deflection and comfortable factors of safety on material strengths. Specifically, frame deflections are usually limited to 1/230 of the span for thermally tempered glazing and to 1/100 for glazing systems containing polycarbonate. Stresses in the frame material, which is usually mild steel, are limited to fy/1.65 where fy is the yield stress. Fastener stresses are in turn held to f~2.0. For the anchorage of the outer frame, factors of safety of 2 and 4 are used for headed studs and expansion bolts respectively.

In checking these limits, the stress induced in the frame by the blast is computed in one of three ways. Most commonly and conservatively, these correspond to the full static capacity of the glazing. A small deflection approximation for normally loaded plates has proven to be useful in this case. Alternately, the frames are sometimes designed for the dynamic edge shear from the glazing. The single degree of freedom reactions due to the blast and the inertial loads give the stresses in this option. In cases of complex geometry, a dynamic finite element analysis is occasionally required to estimate the stresses in the frame.

While the foregoing practice achieves adequate frames for blast resistant windows, a number of opportunities exist for economy in the structural design. The first is a wider use of dynamic analysis for the frame members. This generally results in lower induced stresses than the static analysis for the full capacity of the glazing. In addition, an examination of the overall reliability achieved using the deflection limits and the material factors of safety may be in order. This examination is expected to lead to smaller sections for the members of the frame. Further, some allowance for inelastic response should be considered. While this must provide for the control of deflections, similar allowances have proven attractive in a wide variety of blast design problems.

Other opportunities for savings are present in the architectural aspects of blast resistant window design. Firstly, the selection of the smallest possible window size consistent with form and function is normally useful. Long, narrow windows (length to width ratios greater than three) often afford economy of design by carrying the load across the small span. Parametric studies indicate that this affords the greatest viewing area for the thinnest cross-section of glazing. Also, the adoption of a uniform size in a particular project permits economies of scale in fabrication and installation. Further, in cases of low blast loading, the required resistance may be achieved with aluminum frame members which can be extruded with a cost savings compared to the fabrication of an equivalent mild steel product.

RECOMMENDATIONS FOR FUTURE RESEARCH

The authors believe that the following areas offer the greatest benefit to cost return in future work on blast resistant glazing:

Polycarbonate

Polycarbonate should be further tested into its ductile range. A safe point of usable ductility should be established to account for losses due to aging or ultraviolet exposure.

Laminated Glazing

More research on the actual performance of laminated glass at high service temperatures Is required. As it is likely that laminated glazing is not performing monolithically at common high service temperatures, an adjustment will be required for conservative design. Very possibly, a reduction to 50% of monolithic strength or a stacked plate model should be adopted. Very possibly, a design theory by Beason and Magro will prove useful in designing laminated glass.

Frames

As few glazing researchers actually build or modify buildings, there is a tendency to be myopic about second order considerations concerning pane thickness and behavior. In reality, a onenominal size increase in pane thickness very seldom has economic significance. However, cost is involved in obtaining the existing frames which are in all probability overconservative. Research and development should focus on more economical frame designs.

Air-Gap Glazing Systems

It is recommended that a simple but effective analytical model be developed and tested to predict the blast performance of air-gap glazing systems. There are many such systems in use today in conventional structures, however existing analytical models do not directly address them except in a very conservative manner. There is some evidence, based on explosive tests of security glazing systems, that properly designed air-gap glazing systems do in fact have greater blast resistance than equivalent stacked plate window assemblies.

Post Failure Prediction

The authors suggest that testing and analytical work should be performed to determine the post failure performance of laminated glazing. In particular, quantitative data needs to be developed concerning the ability of different interlayer materials to safely retain failed glazing in the window frame as well as the ability of different edge engagement techniques and framing system designs to withstand the increased edge loads that occur under these circumstances.

New Techniques for Im~rovin~ the Blast Performance of Existing Window Svstem Installations

Few building owners can afford the high cost of complete retrofit of existing glazing systems that could be subjected to blast overpressure threats, whether intentional or accidental. Therefore, a very real need exists to develop cost effective ways to both increase the effective blast resistance of existing window glazing systems as well as find new methods of protecting in-place window systems from blast overpressure effects while at the same time preserving as much as possible the architectural benefits of the window systems.

Design Awareness

In conventional buildings, the window systems are nearly always designed as a purely architectural feature. As a consequence, thought to protecting or designing window systems from intentional or accidental blast pressure effects is furthest from the mind of the designer. Since later retrofit to provide life safety protection for building occupants is very costly, if at all possible, a concerted effort is needed to educate both building owners and their design architects of the issues and problems involved as well as acquaint them with the existing design and analytical tools at their disposal.

FIGURE 1. GENERIC BLAST WINDOW GLAZING AND FRAME DETAIL

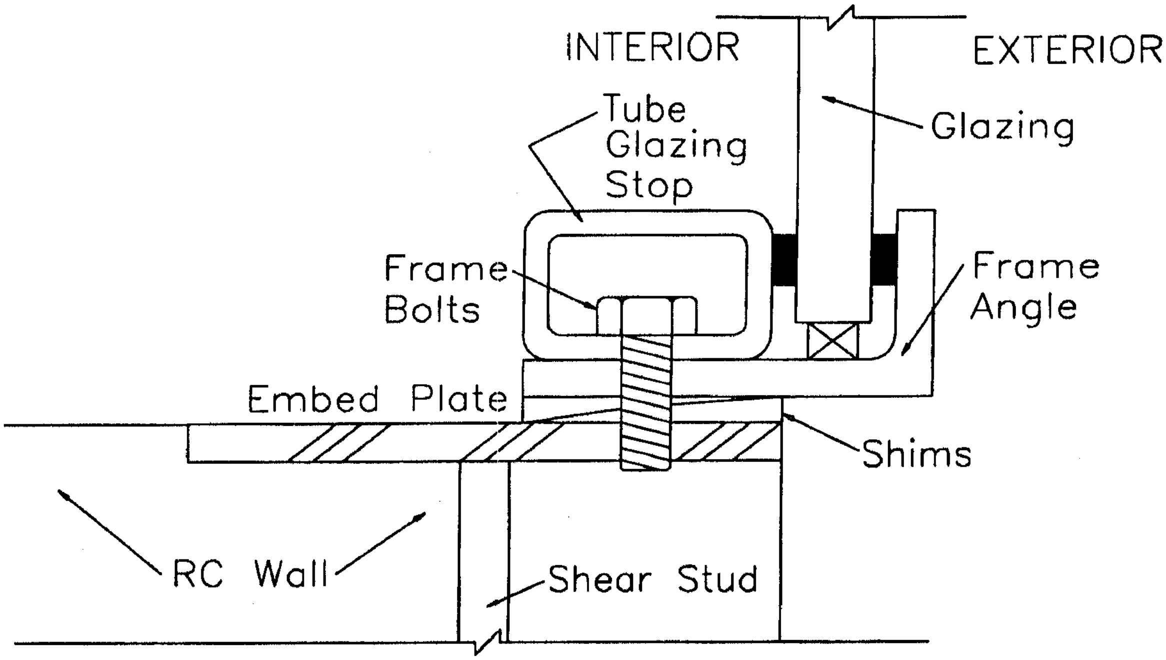

Figure 1. Generic Blast Window Glazing and Frame Detail

Table 1. Computer Programs for Blast Resistant Glazing Based Upon Design Methodology in References 1 through 9

Program Name	Latest Version (August 1994)	Capability/Methodology
Principal Author: Gerald Meyers		
TE	1985	Developed design charts for blast resistant glass as printed in TM5-1300. Calculates peak positive pressure for specified risk probability of survival for different durations, of blast Fortran compiler needed to run.
PE	1986	Developed design charts for blast resistant polycarbonate as printed in Reference 5 and 9.
PR	1887	Similar to TE, Fortran compiler needed to run. Developed design tables to specify thickness, bite, frame loading for a large family of charge weights and standoff distances. Needs Fortran compiler to run.
EMB	1988	Calculates response of blast resistant glazing (glass, laminated glass, polycarbonate) under blast loading.
WINDOW	1989	Interactive version of EMB. Predicts probability of failure for tempered glass. Input is glass dimensions, peak overpressure and positive duration. Incorporated into GPLAC by Don Baldwin. Name incorporated by Microsoft.
GMW3	1989	Collaborative effort between Meyers and Baldwin. Adds graphical output (Dave Hyde's WES Graphics to output).
BWORK	1991	Upgrade of WINDOW. Predicts probability of failure for thermally tempered glass, heat treated (semi-tempered glass), annealed, laminated tempered glass, and polycarbonate. Estimates probability of failure for a specific blast load.
BLASTOP	1994 Version 1.4	Upgrades BWORK. Blast load can be entered with pressure or duration, charge weight or distance or peak pressure and impulse. Will predict rank probability of failure under blast load. Code accepts data in English (U.S.) and metric units.

Table 1. Computer Programs for Blast Resistant Glazing Based Upon Design Methodology in References 1 through 9

Table 1. Computer Programs for Blast Resistant Glazing Based Upon Design Methodology in References 1 through 9 (Continued)

Program Name	**Latest Version (August 1994)**	**Capability/Methodology**
GLASSTOP	1994 (expected December)	Upgraded BLASTOP. Can run repeated blast loads. Will permit blast load to be entered as a pressure time history. Program may include negative pressure routine for analysis.
Principal Author: Donald Baldwin		
WINDX	1988 Version 1.0b	Computes blast capacity of thick, nonlinear laminated thermally-tempered glass. Does not model membrane behavior. Program is interactive.
GPLAC	1989 Version 1.3c	Analyzes glass and polycarbonate composite glazing, considers non-linear response. The interactive program plots and prints graphical output. Same mathematical logic as WINDOW.
WINLAC	1990 Version 2.2	Design and evaluate complex laminated plates. Can analyze a system up to 15 different materials. Interactive, menu-driven with graphical output. Can calculate maximum charge that a glazing system can withstand at a specified distance. Version 3.0 under development.
SWAC	1992 Version 1.1	Rewrite of WINLAC. Accepts metric input. Allows 3-D location of charge in lieu of maximum pressure duration. Code is very user friendly.
SAFEVUE	1993 Version 1.2	Developed for Department of Energy. Useful for viewports and safety shields. Expands SWAC to accommodate 99 types of explosives and geometric configurations. Accommodates pressure-time loadings. On-line documentations. Non-linear version under development.
MAXLITE	1993 Version 1.0	Produces design charts for planning.
Vuelite/MAXVUE	1994 Version 1.0	This program pair uses WINLAC logic to expand MAXLITE.

Table 1. Computer Programs for Blast Resistant Glazing Based Upon Design Methodology in References 1 through 9 (Continued)

Table 2. Measured and Predicted Blast Capacity of Thermally Tempered Glass

Test No.	Window Type [a]	Pane Dimension (in)	Nominal Pane Thickness (in)	Design Blast Load [b] (psi)	Test Blast Load (psi)	Comments
1a	AW	36 x 36	1/4	1.43	1.48	No failure
1b	AW	36 x 36	1/4	1.43	2.14	No failure
2a	AW	36 x 36	1/4	1.43	1.51	No failure
2b	AW	36 x 36	1/4	1.43	4.06	Pane blown out
3	AW	36 x 36	1/4	1.43	4.07	Pane blown out
4a	AS	36 x 36	1/4	1.43	1.65	No failure
4b	AS	36 x 36	1/4	1.43	1.94	No failure
5	AS	36 x 36	1/4	1.43	1.51	No failure
6a	AS	36 x 36	1/4	1.43	2.75	No failure
6b	AS	36 x 36	1/4	1.43	3.39	No failure
7a	BW	54 x 36	3/8	2.84	3.51	No failure
7b	BW	54 x 36	3/8	2.84	4.28	No failure
8	BW	54 x 36	3/8	2.84	3.62	No failure
9	BW	54 x 36	3/8	2.84	6.34	Pane blown out

Table 2.

Measured and Predicted Blast Capacity of Thermally Tempered Glass

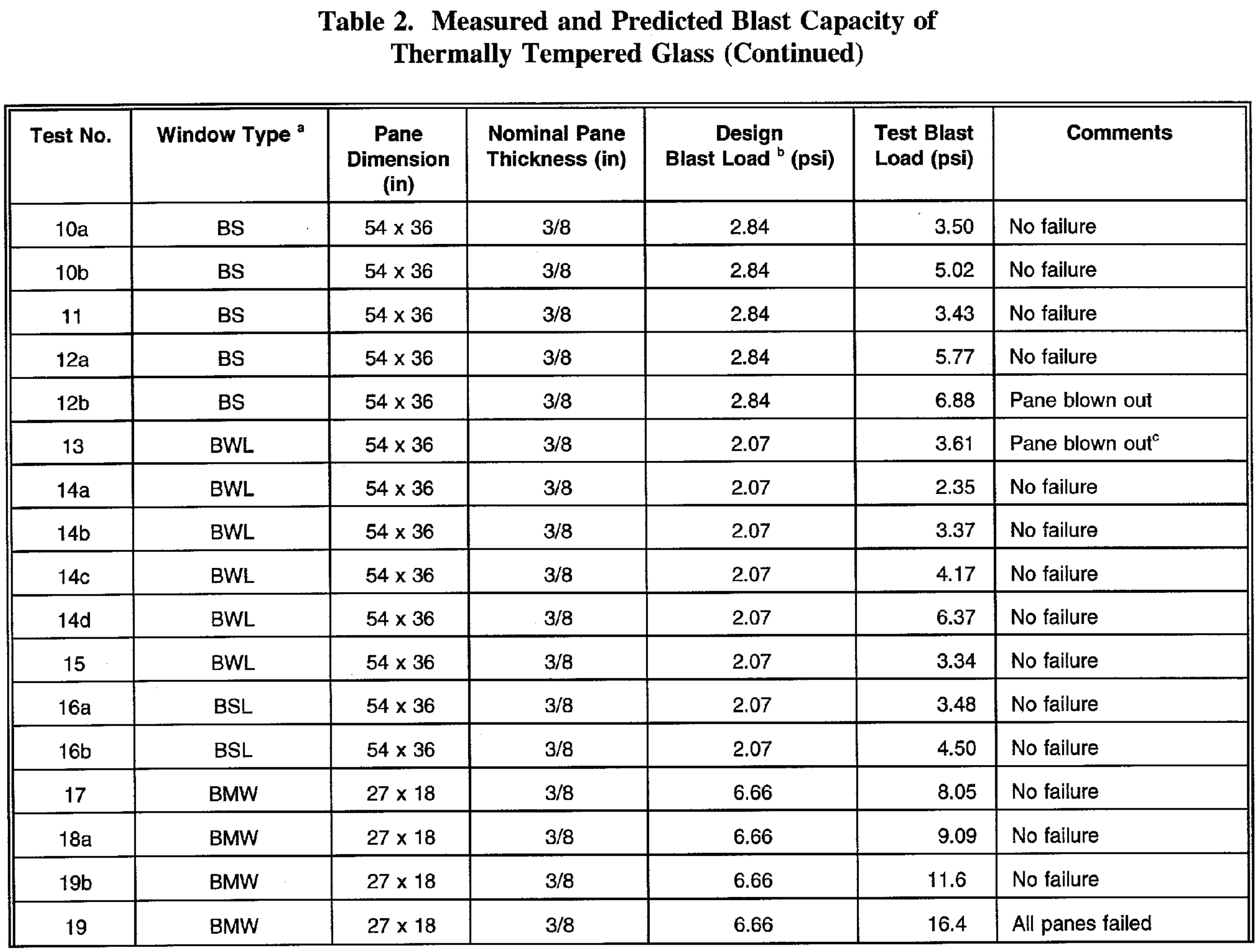

Table 2. Measured and Predicted Blast Capacity of Thermally Tempered Glass (Continued)

Test No.	Window Type [a]	Pane Dimension (in)	Nominal Pane Thickness (in)	Design Blast Load [b] (psi)	Test Blast Load (psi)	Comments
10a	BS	54 x 36	3/8	2.84	3.50	No failure
10b	BS	54 x 36	3/8	2.84	5.02	No failure
11	BS	54 x 36	3/8	2.84	3.43	No failure
12a	BS	54 x 36	3/8	2.84	5.77	No failure
12b	BS	54 x 36	3/8	2.84	6.88	Pane blown out
13	BWL	54 x 36	3/8	2.07	3.61	Pane blown out[c]
14a	BWL	54 x 36	3/8	2.07	2.35	No failure
14b	BWL	54 x 36	3/8	2.07	3.37	No failure
14c	BWL	54 x 36	3/8	2.07	4.17	No failure
14d	BWL	54 x 36	3/8	2.07	6.37	No failure
15	BWL	54 x 36	3/8	2.07	3.34	No failure
16a	BSL	54 x 36	3/8	2.07	3.48	No failure
16b	BSL	54 x 36	3/8	2.07	4.50	No failure
17	BMW	27 x 18	3/8	6.66	8.05	No failure
18a	BMW	27 x 18	3/8	6.66	9.09	No failure
19b	BMW	27 x 18	3/8	6.66	11.6	No failure
19	BMW	27 x 18	3/8	6.66	16.4	All panes failed

Table 2.

Measured and Predicted Blast Capacity of Thermally Tempered Glass (Continued)

Table 2. Measured and Predicted Blast Capacity of Thermally Tempered Glass (Continued)

Test No.	Window Type [a]	Pane Dimension (in)	Nominal Pane Thickness (in)	Design Blast Load [b] (psi)	Test Blast Load (psi)	Comments
20a	BMS	27 X 18	3/8	6.66	8.91	No failure
20b	BMS	27 X 18	3/8	6.66	13.2	2 panes failed
21a	BMS	27 X 18	3/8	6.66	7.33	No failure
21b	BMS	27 x 18	3/8	6.66	9.52	No failure
22	BMS	27 x 18	3/8	6.66	20.0	3 of 4 panes failed

[a] Window type symbol identification:
A = square window
B = rectangular window
L = laminated tempered glass
M = mullion in window frame
S = frame fabricated from skylight member
W = frame fabricated from storefront window members

[b] All design blast loads are calculated at an effective blast duration, T = 150 ms. All actual blast durations ranged between 150 and 180 ms. Laminated glass (window types BWL and BWS) blast capacities are based upon the resistance function reduced to 75% of its monolithic value.

[c] It is expected that contact between the laminated glass and gasket was lost on this specimen during installation.

Table 2.
Measured and Predicted Blast Capacity of Thermally Tempered Glass (Continued)

Table 3. Measured and Predicted Blast Capacities of Windows Subjected to Blast Loads

Window					Blast Parameters[a]		NCEL Design Prediction		Comments
a (in.)	b (in.)	a/b	t (in.)	Glass Type	B (psi)	T (msec)	B (psi)	T (msec)	
43.25	28.375	1.52	1/4	tempered	4.4	45	1.75	45	ARRADCOM dynamic test no. 5, Series I. Glass survived. (Ref. 15)
62.75	47.00	1.34	1/4	tempered	4.4	45	0.91	45	ARRADCOM dynamic test no. 5, Series I. Glass survived.
62.75	47.00	1.34	1/4	tempered	4.4	45	0.91	45	ARRADCOM dynamic test no. 5, Series I. Glass failed.
43.25	28.375	1.52	1/4	tempered	4.4	45	1.75	45	ARRADCOM dynamic test no. 5, Series I. Glass survived.
43.25	28.375	1.52	3/8	tempered	4.4	45	3.45	45	ARRADCOM dynamic test no. 5, Series I. Glass survived.
62.75	47.00	1.34	1/4	tempered	4.4	45	0.91	45	ARRADCOM dynamic test no. 5, Series I. Glass survived.
62.75	47.00	1.34	3/8	tempered	4.4	45	1.96	45	ARRADCOM dynamic test no. 5, Series I. Glass survived.
43.25	28.375	1.52	1/4	tempered	1.0	48	1.75	48	ARRADCOM test no. 1, Series II. Tempered glass in aluminum frame survived.
43.25	28.375	1.52	1/4	tempered	1.2	50	1.75	50	ARRADCOM test no. 2, Series II. Glass failure occurred due to frame distortion.
43.25	28.375	1.52	1/4	tempered	2.3	50	1.75	50	ARRADCOM test no. 3, Series II. Glass survived in strengthened frame.
43.25	28.375	1.52	1/4	tempered	3.1	50	1.75	50	ARRADCOM test no. 4, Series II. Glass fails due to frame distortion.

[a] Blast parameters are expressed in peak positive overpressure and duration of positive pressure.

Table 3.
Measured and Predicted Blast Capacities of Windows Subjected to Blast

Table 4. U.S. Department of State
Blast Tests on Lexan SP1250 Polycarbonate
Nominal Thickness = 1¼ inch
(both new and old)

Size (in.)	Age of Polycarbonate	Blast Load (psi) at Positive Pressure	Design Capacity at Pressure Duration of 15.7 msec	Measured Center Deflection (in.)	BLASTOP Estimated Center Deflection (in.)
26 x 26 x 1¼	New	57.4	56.3	1.32	1.95
26 x 26 x 1¼	Old	57.4	56.3	1.32	1.95
36 x 36 x 1¼	New	49.2	35.4	3.1	3.84
36 x 36 x 1¼	Old	49.2	35.4	3.1	3.84
40 x 40 x 1¼	New	57.4	31.5	4.0	5.03

All glazing survived.

Table 4. U.S. Department of State
Blast Tests on Lexan 5P1250 Polycarbonate
Nominal Thickness = l¼ inch
(both new and old)

Table 5. Naval Civil Engineering Laboratory
U.S. Army Waterway Experiment Station
Joint Polycarbonate Blast Tests in August 1991
(Measured peak blast pressure is 14.6 psi
with a positive duration of 15 msec.)

Size (in.)[1]*	Peak Deflection (in.)[2]	Predicted Deflection by BLASTOP (in.)	Estimated Blast Capacity by BLASTOP (psi)
23 x 23 x 3/4	.85 - .88* 1.17 - 1.04	1.33	27.4
33 x 33 x 3/4	2.67 - 3.06 2.24 - 2.37	2.98	15.7
37 x 37 x 3/4	2.87 - 2.79	3.72	13.3

* Reported Gauge Problem

[1] Actual pane sizes are estimated from drawings.
[2] Frame deflections are unknown.

TABLE 5. NAVAL CIVIL ENGINEERING LABORATORY
U.S. ARMY WATERWAY EXPERIMENT STATION
JOINT POLYCARBONATE BLAST TEST IN AUGUST 1991
(MEASURE PEAK BLAST PRESSURE IS 14.6 PSI
WITH A POSITIVE DURATION OF 15 MSEC.)

Table 6. Naval Civil Engineering Laboratory
U.S. Army Waterway Experiment Station
Joint Blast Tests on Laminated Tempered Glass in August 1991
(Maximum pressure is 13.5 psi at an effective
positive duration of 15.2 msec)

Size (in.)[1]	Deflection Measured (in.)[2]	BLASTOP Estimated Center Deflection (75% Monolithic Strength) (in.)	BLASTOP Estimated Center Deflection (50% Monolithic Strength) (in.)	BLASTOP Estimated Center Deflection (Stacked Plates)	Blast Capacity by BLASTOP (75% Monolithic Strength) (psi)
23 x 23 x 3/4	.06 - .17 .18 - .19	.10	.15	.27	24.9
33 x 33 x 3/4	.52 - .54 .56 - .60	.36	.53	.78	12.7
37 x 37 x 3/4	.68 - .69	.55	.73	1.01	10.5

* All panes survived

[1] Actual pane sizes are estimated from drawings.
[2] Frame deflections are unknown.

Table 6. Naval Civil Engineering Laboratory
U.S. Army Waterway Experiment Station
Joint Blast Tests on Laminated Tempered Glass in August 1991
(Maximum pressure is 13.5 psi at an effective
positive duration of 15.2 msec)

REFERENCES

l. Naval Civil Engineering Laboratory, User Data Package for Blast Resistant Windows, 7M 51-86-13, by Gerald E. Meyers, Port Hueneme, CA, June 1986.

2. Naval Civil Engineering Laboratory, Test Data Report on Static Load Testing of Monolithic and Laminated Thermally Tempered Glass Windows, TM 51-86-23, by Gerald E. Meyers and Harry R. Laatz, Port Hueneme, CA, September 1986.

3. Naval Civil Engineering Laboratory, Test Data Report on Blast Load Testing of Monolithic Laminated Thermally Tempered Glass Windows, TM 51-86-24, by Gerald E. Meyers and Harry R. Laatz, Port Hueneme, CA, September 1986.

4. Naval Civil Engineering Laboratory, Design Guidelines and Criteria for Security of Future U.S. Embassy Buildings Against Terrorist Bombings, by W. Keenan, J. Tanereto, G. Meyers, P. Waser and M. Beyer, Port Hueneme, CA, June 1986.

5. Naval Civil Engineering Laboratory, Interim Military Handbook for Security Glazing, TM 51-87-15, by G.E. Meyers and R.P. Becker, Port Hueneme, CA, September 1977.

6. G.E. Meyers. "Design criteria and acceptance test specification for blast resistant thermally tempered glass glazing," Department of Defense Explosive Safety Seminar, Anaheim, CA, August 1987.

7. G.E. Meyers, "Blast Resistant Polycarbonate Windows," Department of Defense 23rd Explosive Safety Seminar, Atlanta, GA, August 1987.

8. Naval Facilities Engineering Command. MIL-HDBK-1013/1: Design guidelines for physical security of fixed land-based facilities, Alexandria, VA, June 1987.

9. U.S. Army Corps of Engineers. Security Engineering Manual, Omaha, NE, August 1987.

10. Jet Propulsion Laboratory. FSA Task Report No. 5101-291: Thickness sizing of glass plates subjected to pressure loads, by J.M. Moore, Pasadena, CA, August 1982.

11. U.S. Department of State, Bureau of Diplomatic Security, Design of Structures to Resist Terrorist Attack, Report 2, Full-Scale Perimeter Wall and Window Test, October 1987, Washington, DC.

12. U.S. Department of State, Bureau of Diplomatic Security, Design of Structures to Resist Terrorist Attack, Report 5, Embassy Window and Door Blast Standards Verification Program, October 1989, Washington, DC.

13. Corps of Engineers, Waterways Experiment Station, Airblast Testing of Blast Resistant Window

Systems, Technical Report, SL-92-8, April 1992, Vicksburg, MS.

14. Naval Civil Engineering Laboratory, Measured Shear Properties of Polyvinyl Butyral Laminate, TN-I 780, by G. Warren and M. Millew, January 1988, Port Hueneme, CA.

15. U.S. Army Armament Research and Development Command, Blast Capacity Evaluation of Glass Windows and Aluminum Window Frames, ARLCO-CR-78016, by S. Weissman, N. Dobbs, W. Stea, and P. Price, June 1978, Dover, NJ.

APPENDIX A: COMPUTER PROGRAMS DEVELOPED BY DONALD BALDWIN

The following eight window glazing system design computer programs have been developed by Don Baldwin for use on PC's using the Intel 286/386/486/Pentium family of microprocessors. Except for WINDX, all of the other programs listed make use of variations of Dave Hyde's HGRAPH graphics library routines for providing graphical output.

WINDX (Version 1.0b)

WINDX was developed for use by the U.S. Department of State, Office of Foreign Buildings Operations (DoS/FBO) in 1988. The code implements the "thick" plate dynamic analysis procedure outlined in the Naval Civil Engineering Laboratory (NCEL) Report TM 51-86-13. The primary purpose of the code is to design laminated fully thermally tempered window lites in accordance with DoS/FBO criteria for new embassies. WINDX sizes balanced laminated glazing composed of multiple layers, all of the same type of glass. The program does not accommodate "thin" lites that develop membrane action. WINDX uses dynamic load factors to determine the dynamic capacity of the glazing system.

GPLAC (Version 1.3c)

GPLAC was developed in 1989 for the U.S. Department of State, FBO as the successor to WINDX. It implements a non-linear adaptation of the stacked plate dynamic analysis procedure, formulated by Gerald Meyers at NCEL in 1985. The code uses the work of D.M. Moore, DoE/JPL (1980) to develop a non-linear resistance function for each different type of glazing material used in a two-plate laminated glazing system, e.g., chemically strengthened glass and polycarbonate. The primary purpose of GPLAC is to design and/or evaluate the blast performance of glass-polycarbonate laminated security windows for new embassies. GPLAC accommodates lites that develop membrane action, and performs a dynamic single-degree-of-freedom (SDOF) analysis of the composite glazing system.

WINLAC (Version 2.2)

WINLAC was also developed for the U.S. Department of State, FBO in 1990 as a much more generalized window design program than either of its predecessors. It implements the standard DoS/FBO computational procedure for the design and evaluation of both monolithic and complex laminated windows formulated by Gerald Meyers at NCEL in 1985. The procedure builds a composite, "linearized" resistance function for a given laminated lite, based on the work of D.M. Moore, DoE/JPL, and then performs a SDOF dynamic analysis of the composite system. WINLAC is similar to GPLAC but allows analysis of stacked plate systems composed of up to 15 different materials. The code is user friendly and has been adopted by DoS/FBO as its standard design and evaluation procedure for blast resistant windows for new embassies. Currently the WINLAC program is undergoing a major revision (Version 3.0) that will be available later in 1994. This new version will accommodate specification of the threat by weight and type of high explosive material, detonated at a specific location as well as allow the user to find the maximum charge weight that the glazing system can withstand at a specific range. Version 3.0 will be pick-menu driven, have on-line user documentation, and will accommodate both English and metric output as well as input.

MAXLITE (Version 1.0)

MAXLITE was developed in 1993 for the U.S. Department of State, FBO. The code provides FBO's design engineers with a means of quickly generating preliminary glazing design charts for use by architects and facility planners in sizing monolithic TTG window lites for new embassies. The program's basic computational logic is the same as that of WINLAC to assure consistent results during both planning and design phase of embassy window systems. MAXLffE produces a set of design plots of maximum lite size as a function of standoff distance. The code is very user friendly and handles both input and output in metric and English system units.

VUELITEMIAXVUE (Version 1.0)

The VUELITE/MAXVUE program pair is currently under independent development. The programs employ the same basic computational logic as WINLAC, and work together to provide a capability similar to that of MAXLITE. However, their ability to accommodate any type of glazing material make them far more flexible than MAXLffE. VUELITE is used to generate binary formatted graphics files of maximum glazing size as a function of aspect ratio, type and thickness of glazing material, explosive charge weight, and standoff distance. MAXVUE is the viewer program used by architects and designers to view the VUELITE-generated data in the form of simple, easy to read graphic plots when designing or evaluating a glazing system concept. Both codes are very user friendly, and when completed will accommodate multi-material laminated glazing systems. Currently VUELITE employs the linearized Moore static resistance function model. But in the future, both the Beason Glass Failure Prediction Model and a non-linear version of the Moore procedure will be incorporated into the program.

SWAC (Version 1. 1)

SWAC, which is based in-part on WINLAC, was developed independently in 1992. It also implements the DoS/FBO standard procedure used in WINLAC but has in addition a variety of expanded capabilities applicable to the design and evaluation of explosive view ports and safety shields. The program allows the user to specify an explosive charge type and 3-D location inlieu of a blast pressure and duration. SWAC has an improved iterative scheme for determining the maximum capacity of a given glazing system, particularly one that is subject to very small charge sizes at very close ranges. Like WINLAC, the code is very user friendly and has both improved input error detection and mixed metric and/or English system input as well as an improved output display control scheme.

SAFEVUE (Version 1.2)

SAFEVUE was developed in 1993 specifically for the U.S. Department of Energy (PANTEX), for the design and evaluation of both windows and explosive view ports in DoE facilities. The code is a specially tailored version of SWAC designed to implement DoE-specific requirements.

- Accommodate up to 99 different types of explosive material (including the 24 materials cited in the DOE/TIC-I 1268 TNT Equivalences Table).

- Includes scaling functions for 89 of the 94 different explosive material types and configurations from TM5-1300 (Figs. 2-18 through 2-91).

- Accommodates discrete pressure-time loading histories consisting of up to 100 data pairs (e.g., INBLAST output).
- Uses improved numerical integration routines to compute maximum capacity as a function of charge type and weight.
- Expanded and improved input and output displays with on-line user documentation.

Currently, an effort is underway to perform a series of major modifications to SAFEVUE (Version 2.0) which will incorporate the Beason Glazing Failure Prediction Model, Magro variable load-mass factors, and non-linear Moore and Vallabhan-based resistance function generators into the program.