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COMPUTER SOFTWARE FOR THE DESIGN OF BLAST RESISTANT WINDOW RETENTION ANCHORS

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Abstract: Broken glass fragments and flying shards are a significant source of secondary injuries caused by window failure during accidental explosions and terrorist attacks. A comprehensive review of available design procedures used in the construction industry for window retention anchors, as well as related design standards, indicated that most of the previous research and development concentrated on the protective glazing of windows, rather than the anchorage of windows to substrates. This paper introduces BRADS (Blast Resistant Window Anchor Design Software), a computer program for the analysis and design of anchoring systems used in blast-resistant window glazing. The software is intended to aid engineers, architects, and manufacturers enhance the resilience of critical infrastructure against explosive events. The tool may be used to design new glazing anchorages or assess the vulnerability of existing anchors. The innovative design algorithm incorporated in the software can compute the required configuration of window retention anchors based on the major parameters known to influence anchorage capacity, including: substrate deformability, glazing response, window aspect ratio, frame rigidity, the distribution of dynamic reactions, combined stresses, and anchorage boundary conditions. The algorithm, developed and validated by the authors, satisfies the requirements of the new national standard on blast-resistant window retention anchors, CSA S852. The results generated by BRADS were compared against experimental data obtained from shock wave testing of blast-resistant window systems using the University of Ottawa Shock Tube and the University of Kentucky Blast Simulator. The comparison indicated that BRADS can predict the magnitude and distribution of anchor forces of the tested windows with a level of accuracy suitable for the purposes of design and assessment.

1 INTRODUCTION

New materials, construction technologies, and test methods have been developed to address the increased security of structures threatened by terrorist bombing and accidental explosions. A considerable effort has been directed toward increasing the level of protection of windows as secondary blast injuries caused by flying debris, such as glass shards, account for much of the trauma resulting from explosive events (Fryberg, 2002). Examples of technologies which are commonly used to improve the level of protection of blast resistant glazing include the use of anti-shatter security film, laminated glass, cable catch systems, and blast curtains. However, the ability of these systems to fulfill their intended function depends on a continuous load path to transfer applied forces through to the supporting structure. For the case of windows subjected to blast loads, this necessitates continuity of the glazing, frame, anchorage, and substrate.

CSA S852 (CSA, 2018) is a recently developed Canadian standard for the design of blast-resistant window anchor systems. The standard provides guidance for determining the required number, size, and spacing of window retention anchors to ensure sufficient safety against premature anchorage failure. The scope includes blast-resistant punched windows having single pane, multi-pane insulated glass (IG), and laminated or filmed windows. The provisions address different types of substrates and window frame types. It provides detailed design procedures based on two approaches; (i) equivalent static force approach and (ii) dynamic two-degree-of-freedom (TDOF) analysis.

Computer software BRADS (Jacques, 2017) – Blast Resistant Anchor Design Software – has been developed to conduct analysis and design of anchoring systems used in blast-resistant punched windows in accordance with the provisions of CSA S852 (CSA, 2018). The tool was developed to facilitate the design of new window anchorages, or to assess the vulnerability of existing anchors by engineers, security personnel, and manufacturers. This program can account for the major parameters known to influence the performance of anchors in blast resistant windows, including substrate flexibility, glazing response, aspect ratio, window frame rigidity, dynamic reactions, anchor fixity, and combined stresses. This paper is intended to provide an overview of the software and illustrate its capabilities. In addition, experimental data from blast testing of windows is compared against results generated by the software with the purpose of demonstrating its suitability for design and assessment.

2 KEY ELEMENTS OF THE DESIGN SOFTWARE

The design software BRADS was developed to satisfy the Tier II: Dynamic Analysis Procedure permitted by CSA S852 (CSA, 2018) for design of blast-resistant window anchorages. The following discussion provides a general overview of the key elements of the design software. The reader is directed to the references by Jacques and Saatcioglu (2018) and Jacques (2017) for more in-depth discussion.

2.1 Behaviour of Windows Subjected to Blast Loads

The load-deformation characteristics of typical blast-resistant glazed and laminated windows are idealized in Figure 1. These types of windows typically exhibit two phases of response: elastic window response until the glass breaks (known as the “pre-break phase”), and tension membrane response of the broken window (known as the “post-break phase”). However, post-break response is only possible if laminated or glazed windows are sufficiently fastened to the window frame to develop tension membrane forces in the protective film or interlayer.

For a glass window, glazed by a protective film or laminated with an interlayer, the initial pre-break stiffness can be computed using the elastic modulus of glass, the moment of inertia of glass and the appropriate support conditions. The window during the pre-break phase develops small deflections, resulting in anchor shear forces in the direction of blast loading and associated bending moments due to the eccentricity of shear forces relative to the critical anchor section at or near the substrate interface. The mass of the window during the pre-break phase is generally assumed to be the total mass of the window.

Upon failure of glass, the resistance drops, and the protective film or interlayer starts dominating response. This is the post-break phase within which the film or interlayer initially behaves elastically, followed by yielding, exhibiting elasto-plastic response. The effect of broken glass pieces on strength and stiffness can be ignored at this stage, though their contribution to mass must be accounted for. The mass of the window in the post-break phase can be taken as the mass of the protective film or interlayer, and any residual glass pieces still bonded to these elements after glass breakage. As displacements increase, the window develops membrane forces under the action of axial stretching of the protective film or interlayer. The window retention anchors during this phase are subjected to a combination of shear force, axial tension force and bending moment. For anchor design, it is important to check the anchor capacity against two sets of design forces; shear force and bending moment resulting from the pre-break phase; and shear force, axial tension and bending moment resulting from the post-break phase.

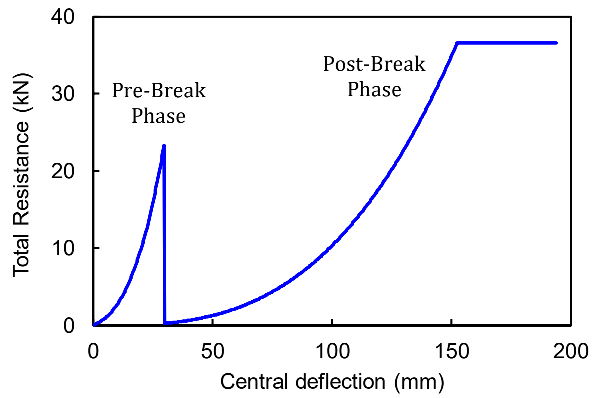
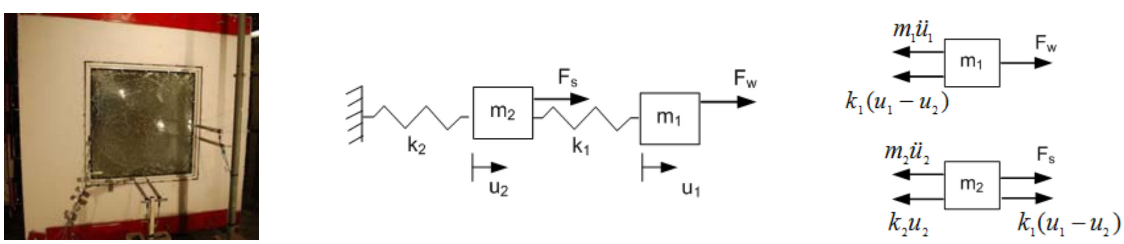


Figure 1: Typical load-deflection curve for a window exhibiting flexural and tension membrane response in the pre- and post-break stages of response, respectively.

2.2 Two-degree-of-freedom (TDOF) Dynamic Analysis

The design of blast-resistant window retention anchors requires the consideration of the effect of dynamic blast loads on the dynamic response of the window-substrate assembly. Exact analytical solutions through Finite Element Analysis, involving the modelling of each component of a window system for two-way plate behaviour can be rather complex and time consuming. This complication cannot be justified for most window anchor designs. The process can be simplified without significantly affecting the accuracy of design. This implies that the complex multiple-degree of freedom analysis of a multi-pane window with insulating air gaps and surface-mounted protective films or interlaminates, developing two-way plate action with distributed mass, interacting with the flexibility of window frames and window substrates in the elastic and plastic range of deformations, can be reduced to a single-degree-of-freedom (SDOF) system, or a two-degree-of-freedom system (TDOF).

The dynamic response of a window mounted into a flexible substrate can be accurately modelled as a TDOF system. A suitable TDOF mass-spring system is illustrated in Figure 2. The equivalent concentrated mass of the substrate is represented by m_2, while the window mass is represented by m_1. The window has an equivalent stiffness k_1 which can be defined from the its resistance function (i.e., Figure 1). The substrate may be assumed to be rigidly supported by the attached structural elements with substrate stiffness represented by spring constant k_2. The entire window-substrate assembly is subjected to a uniform blast pressure with triangular impulsive forcing function $P_r(t)$ with a maximum reflected pressure P_r and positive phase duration t_d. The blast pressure $P_r(t)$ acts on the net area of the window A_w and substrate A_s to develop equivalent time-varying forcing functions F_w and F_S applied to the window and substrate mass-spring systems, respectively. The central deflection of the window is denoted by u_1 and the mid-height deflection of the substrate is denoted by u_2, with respective accelerations of $\ddot{u}_1$and $\ddot{u}_2$.



(a) Window-substrate assembly (b) Idealized TDOF system (c) Free-body diagrams

Figure 2: Two-degree-of-freedom (TDOF) idealization of a typical window-substrate assembly.

The following expressions show the equations of motion for a TDOF system without damping, which can best be solved by a numerical procedure:

[1] $m_1\ddot{u}_1 + k_1u_1 - k_1u_2 = F_w$

[2] $m_2\ddot{u}_2 - k_1u_1 + (k_1 + k_2)u_2 = F_s$

The numerical solution employed to solve the TDOF equation of motion should be able to account for variable mass and stiffness of the window system due to pre-break and post-break inelastic response, and potential nonlinearity of the substrate during blast-induced deformations. Once a solution to the TDOF system has been obtained, the dynamic support reactions of the window system can be established using appropriate expressions (i.e., Biggs, 1964, or Morrison, 2007). These support reactions provide design shear forces for the window retention anchors.

2.3 Anchorage Design

Anchorage design conducted in accordance with CSA S852 (CSA, 2018) is the process of selecting the type, size, spacing, and material properties of the fasteners based on a determination of the glazing and frame reactions. The design process also includes ensuring the anchorage has sufficient strength to resist disengagement from the substrate, and that the substrate is designed to resist local failure near the anchor. Given that there are a myriad of different proprietary window retention anchors available on the market, CSA S852 (CSA, 2018) provides explicit guidance on selecting and proportioning fasteners, while ensuring sufficient anchorage strength developed in the fasteners within the substrate. This is achieved in accordance with the manufacturer's product specifications.

The anchor design procedure adopted in CS S852 (CSA, 2018) is based on the von Mises stress condition for plane stresses given in Eq. [3]:

[3] $$\frac{f_{dy}}{\sqrt{\sigma_n^2 + 3\tau_{max}^2}} \geq 1.0$$

where f_{dy} is the dynamic material strength of the fastener, σ_n is the maximum factored normal stress in the anchor at the critical section, and τ_{max} is the maximum factored shear stress in the anchor. Note that Eq. [3] conservatively assumes that the maximum normal and shear stresses at the critical section act simultaneously.

The factored normal stress σ_n and maximum factored shear stress τ_{max} can be calculated following:

[4] $$\sigma_n = \phi\left(\frac{F_T}{A} + \frac{M}{Z}\right)$$

[5] $$\tau_{max} = \phi\left(\frac{4F_V}{3A}\right)$$

where ϕ is the safety factor required for design by CSA S852 (CSA, 2018), A is the anchor cross-sectional area, Z is the plastic section modulus of the anchor, and F_V, F_T, and M are the design shear, tension, and moment in the anchor at the critical section. As will be subsequently discussed, the design moment M is computed by considering the eccentricity of F_V and F_T relative to the critical section, while also accounting for the effect of boundary conditions of the anchor.

3 DESIGN SOFTWARE OVERVIEW

The software uses a database for window resistance curves and other dynamic properties. While the database includes the data for typical windows commonly used in practice, it can also be used for other types and sizes of windows. This requires the addition of new information to the database. User friendly "Add New Window" function enables the user to enter this information to the database. This gives the user the flexibility to expand the window types available for design. The user can extend the functionality of the software by importing the dynamic properties for any window obtained from specialized window analysis software, such as Wingard (ARA, 2005), SBEDS-W (US Army Corps of Engineers, 2012), finite element analysis, or from experimental tests.

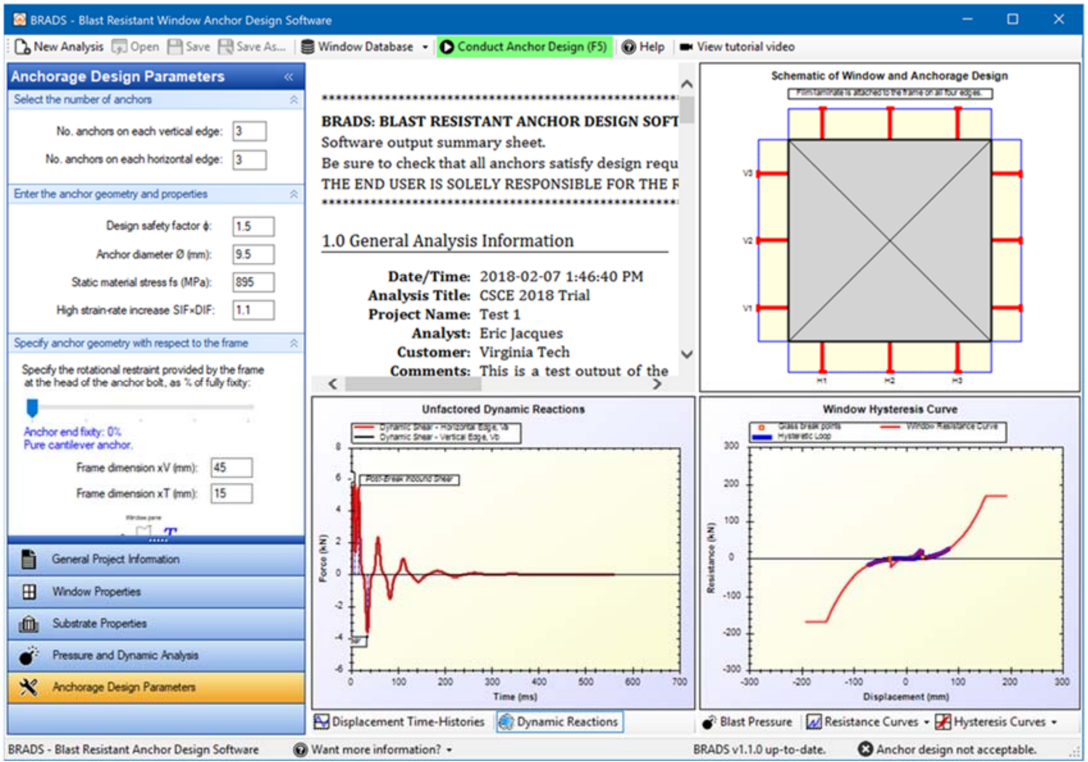


Figure 3: Screen capture of the BRADS analysis output screen.

3.1 Input Data

The graphical user interface (GUI) is structured to accept user input information under five main headings, each relevant to a specific aspect of window anchorage design. These headings are:

1. General Project Information to define and catalog project-specific information, such as the project title, analyst, customer name, and any comments related to the analysis.

2. Window Properties to select a window stored in the database to analyze. Windows are categorized according to their construction type, the configuration of the film/laminate edge attachment, and dimensions (Height × Width). Windows having their film or laminate properly attached to an edge will be designed to resist tensile forces due to membrane action during the post-break phase. The user may specify whether the membrane material is attached on all four sides, the vertical edges, the horizontal edges, or no attachment. The “no attachment” option would be used to analyze windows with daylight application of security film.

3. Substrate Properties to define the geometric and material properties of the mass-spring-damper element representing the substrate. The substrates may be modelled as either elastic or inelastic systems depending on anticipated behaviour. The user can select one of three pre-defined substrates for concrete, masonry, or steel structures. For concrete and masonry substrates, the lumped mass system is assumed to remain perfectly elastic and is constructed based on the equivalent SDOF model for one- and two-way members from UFC 03-340-02 (DoD, 2008). The steel substrate is assumed to be perfectly rigid, thus reducing the TDOF system to a SDOF system composed solely of the window. The software also provides the ability for the user to define a custom nonlinear mass-spring-damper for the substrate. The nonlinear substrate is represented by an inelastic resistance function with degrading stiffness characteristics defined by the yield displacement and yield resistance with elastic and inelastic load-mass transformation factors applied to a lumped substrate mass. The Clough degrading stiffness hysteretic model (Clough, 1966) is used to account for the effect of hysteresis on substrate response.

4. Pressure and Dynamic Analysis allows the user to define the design basis threat (DBT) used in anchorage design and control pertinent parameters of the dynamic analysis solver. The DBT can consist of either: (i) a triangular pressure-time history; (ii) an exponential decay pressure history calculated using the Kinergy-Bulmash polynomials (Kinergy and Bulmash, 1984); or, (iii) as a series of data points imported by the user. The user can also modify the default time-step (0.1 ms) and maximum analysis termination time (5000 ms). The TDOF analysis is programmed to terminate if: (i) the predicted window displacement exceeds the ultimate displacement defined in the window response function (indicating a blow-out failure of the window); (ii) a stable equilibrium of the window is achieved; or, (iii) the TDOF analysis run time exceeds the user-specified termination time.

5. Anchorage Design Parameters: The final input heading is used to establish the design parameters for selecting and proportioning fasteners to satisfy anchor design following CSA S852 (CSA, 2018).
   1. Number of anchors: The number of anchors on each of the vertical and horizontal window frame edges are specified by the user. The software uses this information to calculate anchor spacing.
   2. Anchor properties: The diameter Φ of a circular anchor is specified by the user to compute the cross-sectional area A and plastic section modulus Z used in anchorage design.
   3. Safety factor: CSA S850 (CSA, 2017) and CSA S852 (CSA, 2018) both require a balanced design approach where the window retention anchors are required to be stronger than the window by a factor of 1.5, known as the safety factor ϕ. The shear and tension forces acting on the anchors are multiplied by ϕ to obtain the factored design forces. The default value of ϕ (1.5) may be modified as necessary.
   4. Material properties: The static material stress f_y used in design should be determined from the manufacturer's specifications. The dynamic material stress f_{dy} defines the strength of the anchorage at high strain rates. It is taken as the product of $f_y \times SIF \times DIF$, where SIF is the strength increase factor accounting for additional strength present in the material that is typically neglected under normal loading conditions, and DIF accounts for the apparent increase in material strength under dynamic loads. A default value of 1.1 is used for the product ($SIF \times DIF$) in the software.
   5. Frame geometry and anchor boundary conditions: The construction of the frame and the anchor boundary conditions are critical for design. The design shear F_V and tension F_T for each anchor are calculated from the tributary area under the edge distribution. Figure 4 (a) shows the assumed point of application of F_V and F_T at the location where the window bites into the glazing stop. This defines the eccentricities of shear force x_V and tension force x_T, respectively, relative to the critical section.

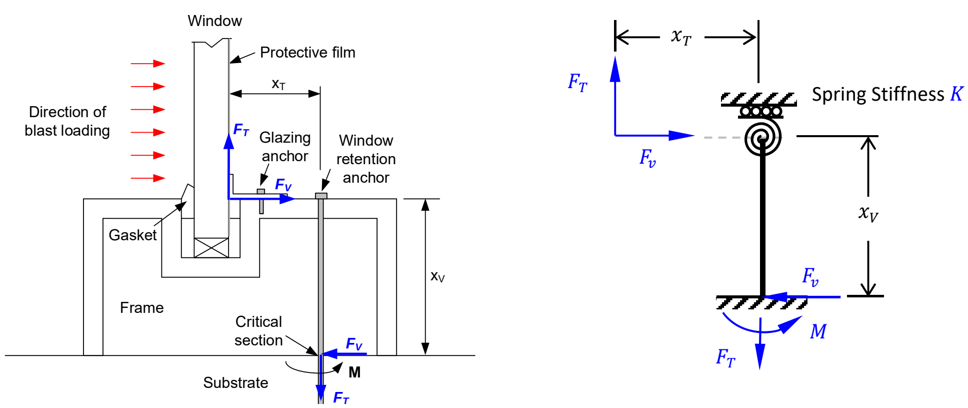


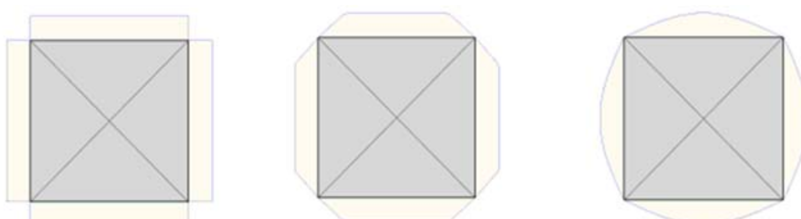
Figure 4: Definition of anchor force eccentricities.

6. The software assumes that the critical section for anchorage design is at the location of the anchor-substrate interface. Anchors are assumed to be fully fixed at the substrate, while the fixity of the anchor head depends on the construction of the frame. The anchor is assumed to behave as a

cantilever when the frame is not able to provide support along the length of the anchor. When the restraint provided by the frame is sufficient to prevent the anchor head from rotating, the anchor behaves as a cantilever with the rotation fixed and translation free at the anchor head. However, the true level of fixity is likely to fall somewhere between these two extremes. Therefore, the software computes the internal forces at the critical section assuming the case of a cantilever with a rotational spring located at the free end, as shown in Figure 4 (b). By varying the relative stiffness K of the spring, the tension F_T, shear F_V, and moment M at the critical section are found from first principles.

7. *Flexural and torsional frame rigidity*: It is well known that the torsional and flexural rigidity of the window frame influences the magnitude of the window deflection and distribution of edge reactions (Morison, 2007). More rigid steel frames tend to produce a more uniform distribution of anchorage forces, while more flexible extruded aluminum frames develop higher anchorage forces near the centre of the frame. The software accounts for the effects of frame rigidity through the empirical edge distributions illustrated in Figure 5. Rigid, semi-rigid, and flexible frames were observed to promote a uniform, trapezoidal, and sinusoidal distribution of edge forces, respectively. The design shear F_V and tension F_T for each anchor is then proportioned from the total shear and tension acting on a window edge based on its tributary area with respect to the distributions illustrated in Figure 5.

8. The potential for reverse corner reactions, known to develop in fully anchored windows subjected to blast loads (Morison, 2007; Department of Defense, 2008), are ignored by the software as their magnitude is negligible compared with the total force developed on an edge.



(a) Rigid frame (b) Semi-rigid frame (c) Flexible frame

Figure 5: Effect of frame rigidity on distribution of anchorage forces.

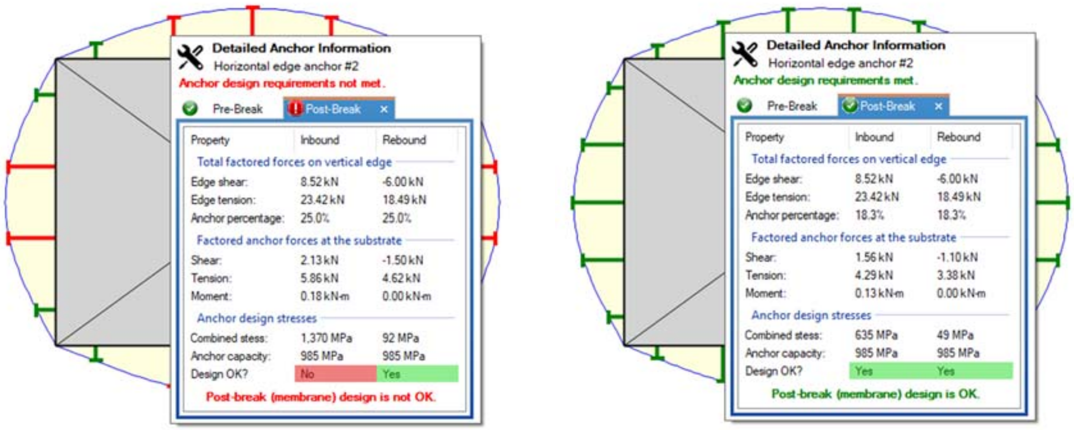
3.2 Analysis Output

The software automatically validates the program inputs once the user has selected a window to analyze, defined the properties of the substrate, established a DBT, and specified the anchorage parameters. If no errors are detected, the software then conducts the anchorage design beginning with the TDOF dynamic analysis to construct the dynamic window reaction time-history. The peak pre-break and post-break reactions are then identified from the dynamic reaction time-history for inbound and rebound response to account for the potential for load reversal during rebound response. The results of this stage of calculations are output to the screen as illustrated in the screen capture shown in Figure 3.

3.3 Design Output

After the software has conducted the TDOF analysis, the capacity of the anchors is verified for pre-break and post-break demands during the inbound and rebound phases. The dynamic reactions are distributed to the anchors in proportion to their tributary areas under the frame rigidity distribution (as shown in Figure 5). These forces are then factored and used to evaluate the anchorage for combined stresses indicated in Eq. [3]. The results of the design calculation are output as illustrated in Figure 6. If the required capacity is higher than the applied design forces, then a green anchor symbol is displayed at the specific location for which the design calculations are done. Otherwise a red anchor symbol is displayed. The user can click on an individual anchor to obtain more detailed information on the applied forces, stresses, and capacities. The user may also vary the anchor size, material, strength, number of anchors, and other design parameters to iteratively obtain an anchorage configuration which satisfies CSA S852

(CSA, 2018) design requirements. This approach provides the designer with complete control of the design process.



(a) Unsatisfactory anchor design (b) Satisfactory anchor design

Figure 6: Screen capture of the BRADS anchorage design popup window.

4 EXAMPLES OF ANCHORAGE DESIGN USING BRADS

4.1 University of Ottawa Shock Tube Tests

The University of Ottawa Shock Tube (Lloyd et al., 2011) was used to test blast-resistant window systems subjected to shock wave loading (Alameer, et al., 2017a, 2017b). The samples were composed of 25.4 mm thick IG windows with 6 mm annealed glass panes mounted into light aluminum frames. Various thicknesses of security film, anchored to the frame with structural silicone or mechanical attachment, were used to retrofit the windows for improved blast resistance. The punched window samples were installed into structural steel, reinforced concrete, block masonry, and stone masonry substrates using dia. 9.5 mm high-strength (Grade 8) window anchors. The spacing and arrangement of anchors varied depending on the substrate and the applied pressure intensity. Strain gauges were placed on the anchors such that the strain profile in the bolt could be decomposed into flexural and axial strain components, from which moments, shear forces, and tension forces could be computed. In the interest of brevity, the results of test C11, conducted on a reinforced concrete substrate, will be examined here. However, the reader is directed to Alameer, et al. (2017a, 2017b) for more information on the experiments and test results.

Test C11 was conducted on a 1676 mm × 560 mm window (aspect ratio of 3.0) retrofitted with 0.36 mm polyester film mechanically attached to the frame on all four sides. The window anchor configuration consisted of four anchors on each of the vertical edges and three along each horizontal edge, for a total of fourteen anchors. The eccentricities of the anchors, measured prior to testing, were found to be $x_V \approx 45\ mm$ and $x_T \approx 15\ mm$. The reinforced concrete substrate was 150 mm thick ($f'_c = 30\ MPa$) with a clear span of 2232 mm and width of 2440 mm. The doubly reinforced cross-section had 12 – 10M rebars on each face distributed around the centrally-located window opening. The anchor bolts were fastened into drop-in anchors that were drilled into the concrete opening. Test C11 was subjected to an applied pressure-time history with $P_r = 27.5\ kPa$ and $I_r = 207\ kPa \cdot ms$. This pressure-impulse combination did not cause any damage to the glass, which remained uncracked, or to the framing system. Inspection of the anchor bolts indicated they remained elastic. Experimental anchorage forces F_V and F_T, shown in Table 1, were computed by decomposing strain gauge readings for three fasteners located in the middle and near the corner on the vertical edge, and located in the corner on the horizontal edge.

BRADS was used to predict the experimental anchorage forces shown in Table 1. The dynamic properties of the window were evaluated using other specialized software (ARA, 2005) and imported into BRADS. The forces were predicted using $\phi = 1.0$, semi-rigid frames, and assuming a level of fixity of 25%

at the free end on the anchorage. The Lumped Inelasticity Approach (Jacques et al., 2015; Jacques, 2014) was used to compute the dynamic properties of the substrate using a bi-linear resistance function, giving a yield deflection of 11.1 mm, yield resistance of 268 kN, effective loaded area of 4.5 m^2, mass of 1510 kg, and damping equal to 5% of critical. Table 1 shows that the experimental anchor forces on the vertical edge were predicted with a reasonable level of accuracy, while the software under-predicted F_V and F_T on the horizontal edge. One possible explanation for this discrepancy was a misalignment of the strain gauges on the anchor which might not have been properly oriented in the plane of bending. As a result, strain readings did not accurately record the influence of applied anchor forces. When the anchorage design procedure was re-run using a safety factor $\phi = 1.5$, a total of fourteen 12.7 mm diameter Grade 5 fasteners (five on the vertical edge, and two on the horizontal edge) would be required to satisfy the design requirements of CSA S852 (CSA, 2018).

Table 1: Comparison of anchorage forces on concrete substrates for test C11 (Alameer et al., 2017a).

Anchor Location	**Experiment**		**Predicted**	
	F_V **(kN)**	F_T **(kN)**	F_V **(kN)**	F_T **(kN)**
Middle anchor on vertical edge	3.7	4.5	2.7	5.8
Corner anchor on vertical edge	2.5	4.4	1.8	3.9
Corner anchor on horizontal edge	3.1	3.2	0.6	1.3

4.2 University of Kentucky Shock Tube Tests

Explosive-driven shock tube trials were conducted at the University of Kentucky on 1680 mm × 1220 mm laminated glass windows (Wedding, 2010). The objective of the study was to record the reaction forces and displacements of blast-resistant windows subjected to explosive loading. The windows were composed of a 1.5 mm Uvekol A interlayer sandwiched between two 3 mm thick heat strengthened glass panes and wet glazed to the surrounding extruded aluminum frame. These were anchored to a rigid structural steel substrate at a total of 26 locations around the perimeter, with 8 anchors on each of the vertical edges and 5 anchors on the horizontal edges. The magnitude and distribution of dynamic window reaction shear forces were measured using force sensors installed at the locations of the anchor points. Dynamic tension reaction forces, generated due to membrane action of the laminate, were not reported.

The majority of the tests conducted by Wedding (2010) were for identical windows subjected to an average positive pressure-impulse of $34.0\ kPa$ and $112.1\ kPa \cdot ms$, respectively, and negative pressure-impulse of $-6.1\ kPa$ and $-18.6\ kPa \cdot ms$, respectively. Table 2 summarizes the experimental edge shears, alongside corresponding edge shears predicted using BRADS. The dynamic properties of the window (resistance, mass, damping, etc.) were evaluated using other software (ARA, 2005) and imported into BRADS for analysis. The substrate was set as rigid and a trapezoidal distribution of edge forces was selected based on the reported distribution of forces. In general, the experimental and predicted design shear forces are comparable, although the predicted quantitates are markedly conservative. This is attributed to inaccuracies in constructing the window resistance curve based on the assumption that the Uvekol A interlayer is equivalent to PVB [an assumption made by Wedding (2010) and adopted in this study]. Nonetheless, the predicted shear is sufficiently conservative for the purposes of design.

Table 2: Comparison of experimental and predicted edge forces for tests conducted by Wedding (2010).

Quantity	**Experiment**	**Predicted**
Total peak dynamic shear (kN)	35.0	44.0
Long edge, average shear reaction (kN)	10.9	12.9
Short edge, average shear reaction (kN)	6.6	9.1

SUMMARY

A design procedure was developed for the analysis and design of anchoring systems used in blast-resistant punched windows. The procedure satisfies the requirements of CSA S852 (CSA, 2018) for the design of blast-resistant window anchor systems following a dynamic analysis methodology. The design procedure was implemented into a computer program to compute the required configuration of window retention anchors based on the major parameters known to influence anchorage capacity, including: substrate deformability, glazing response, window aspect ratio, frame rigidity, the distribution of dynamic reactions, combined stresses, and anchorage boundary conditions. The computed performance of anchors was verified extensively against data obtained from shock tube testing of blast-resistant punched windows installed into steel, concrete, block masonry, and stone masonry substrates. The comparison indicated that the design procedure can predict the magnitude and distribution of anchor forces of the tested windows with a level of accuracy suitable for the purposes of design and assessment. Although the design procedure does not explicitly assess the capacity of the fastener to resist disengagement from the substrate, the anchorage forces output by the tool may be used for this calculation.

Acknowledgements

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