**An analytical approach for quantification of glazing hazard in buildings subject to external explosive blasts**

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This paper describes a conservative analytical approach for quantification of glazing hazard in terms of number of casualties among building occupiers from flying glass fragments produced by shattered windows due to external explosive blast. Three main stages are discussed in the proposed analytical approach: modelling nonlinear transient-dynamic response of monolithic windows subjected to conventional explosions, conservative estimation of glass fragment trajectories influenced by additional aerodynamic forces due to vented blast pressures and estimation of casualties. Four injury severity levels are considered, ranging from minor cuts and bruises to multiple serious injuries with significant blood loss. The total kinetic energy of fragments at impact on occupiers is estimated and used to predict the severity level of injuries, with calculation based on available injury data from archive events. Comparison studies presented in this paper highlight the lack of robustness of existing methods towards quantification of glazing hazard due to explosive blasts. The proposed analytical method will be of direct importance to both engineers and practitioners involved with planning glazing retrofits for existing buildings and identifying cost-effective combinations of protection measures for new buildings.

Keywords**:** blast loads; facade; damage assessment; glazing, extreme loads, casualties

1. **Introduction**

A series of accidental explosions and terrorist attacks begun by the mid-1950s and intensified in the subsequent decades highlighted the vulnerability of building occupiers to glass fragment related injuries. Experience from such events led to the conclusion by many researchers ([Mallonee et al., 1996](#_ENREF_13); [Thompson, Brown, Mallonee, & Sunshine, 2004](#_ENREF_23)) that secondary blast injuries from flying debris (mostly glass fragments) would account for most of injuries to survivors. Examples for such events include the accidental explosion in the Texas City in 1947, bombings at the embassies in Kenya and Tanzania in 1998, attack to the Khobar Towers in Saudi Arabia in 1996, bombing in the Oklahoma City in 1995 and at present, frequent explosive attacks in volatile regions of the world. Of over 5000 personnel injured in the bombings at the United State embassies in Kenya and Tanzanian, many suffered injuries due to broken glass ([Abdallah, Heinzen, & Burnham, 2007](#_ENREF_1)). Investigations ([Thompson et al., 2004](#_ENREF_23)) conducted following the attack of the Khobar Towers revealed that glass was the primary cause for 60% of individual injuries and 88% of persons surveyed reported that glass was responsible for one or more of their injuries. The Oklahoma City bombing remains as one of the deadliest explosions in the history of explosive attacks to civilian buildings. Among survivors (592/759, 78%), the most common cause of injuries was flying glass fragments ([Mallonee et al., 1996](#_ENREF_13)).

Most of the residential and light-commercial buildings in regions of the world at high risk to explosive attacks have no recognisable protection measures to mitigate glazing-related injuries to building occupiers. Identifying the strengthening level required for such buildings is the first step towards targeting glazing retrofits. This may prevent decisions that lead to refurbishment of whole façades, which may not be economically viable. Furthermore, protective design of building envelopes requires reliable predictions of the extent of glazing damage over entire building facades. In this perspective, methods and tools that can reliably quantify the extent of glazing hazard in buildings will be of direct importance, particularly for comparisons of the effectiveness of different combinations of protection measures towards mitigating fragment-related casualties following explosive blast. Despite the requirement for reliable and robust techniques, currently there is a lack of such comprehensive methods for reliably quantifying glazing hazard, with estimations based on fragment kinematics and occupant orientations and distributions inside buildings.

Both occupant distribution and the extent of glazing hazard are influenced by the internal building layout (open-plan or closed-plan). For example, in open-plan areas, many occupants may be vulnerable to fragment strikes from more than one window; increasing the exposure of occupants to serious injuries. As a consequence, despite existing method’s ability of taking account of factors such as fragment mass, occupant orientation and multiple strikes of shards in glazing hazard assessments ([Meyer, Little, & Conrath, 2004](#_ENREF_15)), these methods remain not straightforward. In addition, any individual analysis case using current methods considers only one occupant at risk from fragment-related injuries from a single window. This requires lengthy repetitious analyses when the extent and distribution of glazing hazard over entire building envelopes is of interest. Glazing hazard assessments over entire building envelopes are of significant importance for glazing retrofits and protective design of buildings.

The analytical method described in this paper addresses the drawbacks associated with existing methods in modelling glazing systems and quantifying fragment-related hazards. Section 2 of the paper describes the method adopted for conservatively quantifying the overall glazing hazard following explosive events. Verification studies covering numerical modelling of transient dynamic response of window panes, estimation of fragment trajectories and casualty estimation are presented in Section 3. Section 4 discusses a case study conducted using the proposed method and compares numerical results with alternative predictions using available techniques. Conclusions are given in Section 5.

1. **Methodology**

The proposed method consists of three main stages: modelling nonlinear response of windows subjected to time-varying pressure loads, prediction of fragment trajectories taking account of additional aerodynamic forces due to vented blast pressures and estimation of casualties.

* 1. ***Modelling window response***

Following estimation of blast load parameters based on the slant range *S*, and oblique angle *θ*, corresponding to window locations [see Figure 1(a)], transient dynamic response of each window pane was modelled using an equivalent single-degree-of-freedom (sdof) system as shown in Figure 1(b), where *F(t)* is the equivalent force, *R(t)* is the resistance of the equivalent sdof system and *X(t)* is the central displacement of the window pane. The applicability of sdof equivalent methods for modelling response of structural and non-structural members (mostly glazing systems) is widely accepted ([Li & Meng, 2002](#_ENREF_12); [Smith & Hetherington, 1994](#_ENREF_21); [US Army, 2008](#_ENREF_26)) because of its simplicity and the proven level of accuracy achievable in practice. With regard to sdof structural idealizations, one method for describing the equivalent resistance *R(t),* is to consider each glass pane as an elastic plate with a linear stiffness ([Netherton & Stewart, 2009](#_ENREF_18); [William, 2010](#_ENREF_28)) and a linear load-mass transformation factor ([Biggs, 1964](#_ENREF_3); [US Army, 2008](#_ENREF_26)). However, linear stiffness leads to a lower bound resistance, causing an upper bound maximum deflection of window panes. In this research, a more realistic computational behaviour of windows was achieved using non-linear resistance properties ([Moore, 1980](#_ENREF_16); [Morison, 2007](#_ENREF_17)), taking account of the effect of membrane stresses at large deflections, and nonlinear load-mass transformation factors ([Morison, 2007](#_ENREF_17)). The sdof analysis method adopted in this research successfully employed nonlinear resistance properties and load-mass transformation factors developed by Morison in 2007 ([Morison, 2007](#_ENREF_17)).

During numerical integration, modulus of rupture of glass *σfail*, was compared with maximum tensile stress *σmax*, at each time increment to identify glazing failure. Parameters estimated from sdof modelling include: (i)- time at window failure *tfail*, (ii)- maximum failure deflection *Ymax,c*,and (iii)- initial fragment velocity *Vmax,c*, at the centre of the window pane [see Figure 1(c)]. The distribution of initial fragment velocity *Vmax,* across the window surface was established using *Vmax,c* and the double curvature deflected shape of the pane because velocity at an arbitrary point is the first derivative of displacement *Y*, with respect to time *t*, (*dY/dt*). Figures 2(a)-2(d) illustrate the numerical procedure utilized for estimating initial fragment velocities (*Vx,Vy and Vz*) at an arbitrary point *A*. Parameters *a* and *b* are height and width of the window respectively. *Ra* and *Rb* are radii of curvatures of the deflected shape. *β* and *γ* are the angles describing the point A on the window pane with respect to the centre of curvature. Angles β and γ are smaller than 80 for typical annealed and toughened window glass panes. Equations (1) - (3) describe the initial velocity components of fragments at the point A.

Vx = (Vmax)cosβ.cosγ (1)

Vy = (Vmax)sinβ.cosγ (2)

Vz=Vmax[cosβ.sinγ + sinβ.sinγ] (3)

* 1. *Post-fracture behaviour of fragments*

Monolithic windows (annealed and toughened) compared to blast resistant glazing systems such as laminated glass do not absorb blast energy to a large extent prior to failure. Annealed and toughened glass windows fail rapidly and pressure venting takes place simultaneously with disengagement of glass fragments from windows. Following disengagement, fragments become entrained and interact with the air. In general, the speed of shock waves travelling in air is greater than that of glass fragments. This leads to additional aerodynamic forces acting together with gravity *g*, and accelerates fragments in both horizontal and vertical directions. The skin friction and drag forces acting on objects in moving air depend upon the drag coefficient *Cd*, resultant air particle velocity *Vt*, and air density *ρt*, ([Batchelor, 1967](#_ENREF_2)). One method for estimating air particle velocity and air density histories behind vented shock fronts is to model the breakage of windows and subsequent blast venting phenomenon from first principles utilizing a hydrocode employing a coupled fluid-structure interaction modelling technique [e.g. the Euler-Lagrangian method ([Century Dynamics, 2011](#_ENREF_5))]. However, this proves to be unrealistic in this study due to the sheer scale of the problem. In solution, a simple and conservative method was introduced to estimate the physical properties at and behind vented shock fronts following window failure. This conservative method consists of 8 steps:

(1)Estimation of blast wave properties at window failure using equivalent sdof analysis [see Figure 3(a)].

(2)Calculation of scaled distance *Znew* (*R/W1/3*) corresponding to peak pressure *Pmax,* at window failure [Figure 3(b)].

(3) Calculation of scaled impulse *K* (*I/W1/3*) corresponding to scaled distance *Znew*.

(4)Estimation of new charge mass *Wnew*, that provides an impulse equal to the total impulse *Ir*, corresponding to blast duration from *tfail* to *Td*.

**(5)**Back calculation of new stand-off distance *Rnew*, using the modified values of *Znew* and *Wnew*.

**(6)**Definition of the coordinates of a 3-dimensional space behind each window, within which the aerodynamic effect was considered to influence fragment trajectories. The 3-dimensional space was an idealized volume of air as illustrated in Figure 4. Calculations of aerodynamic forces (described in section 3) indicated that these forces occur, in the space immediately behind broken windows, within a short period of time compared to time durations of fragment trajectories. These forces rapidly become insignificant as vented shock fronts travel past fragments. In conclusion, boundaries of an idealized volume of air as shown in Figure 4 would cover all critical trajectory points of high velocity fragments for estimating aerodynamic forces.

(7)Establishment of the global coordinates (*X, Y* and *Z*) corresponding to fragment location behind broken windows at time *t*, and estimation of air particle velocity components (*Vxt, Vyt* and *Vzt*) and air density *ρt*, at the fragment location using shock arrival time *tbw*, fragment’s flight time *tf*, and durations of air particle- and air density-time histories (*tv,air* and *td,air*) at the corresponding fragment location. As highlighted earlier, the aerodynamic effect on fragments diminishes rapidly due to significant difference in velocities between fragments and surrounding air particles. Within this short period, the pressure was considered to vent smoothly through openings. This assumption reduced numerical accuracy due to two factors: (i)- Room-fill: blast wave propagation into the space behind the broken window,(ii)- Rarefaction of reflected pressures along the window perimeter. However, results of a number of comparative studies conducted utilizing fully-coupled CFD simulations indicated that conservative estimations for air particle velocity and air density histories at arbitrary locations within the idealized space (Figure 4) can be obtained by modifying time histories of blast wave parameters (see section 3). In this paper, calculations of air particle velocities behind vented shock fronts were based on Brode’s results ([Brode, 1955](#_ENREF_4)) derived from numerical analyses of spherical blast waves, with a ground reflection factor of 1.8 ([Mays & Smith, 1995](#_ENREF_14)) to take accounts for blast wave reflections at the ground surface. Air density histories were considered to be directly dependent on the pressure, and was estimated using the method provided in the design manual “*Protective Construction Design Manual, Air-Blast Effects*” by the US Air Force Engineers ([USAFE, 1983](#_ENREF_27)).

**(8)**Estimation of X-, Y- and Z-components of additional aerodynamic forces (*Fxt, Fyt, Fzt*) acting on fragments. System of differential equations of motion were constructed for each fragment using initial velocity components (*Vx, Vy, Vz*) and additional forces as shown in Figure 5. The Runge-Kutta numerical integration method was employed in the solution strategy, in which fragment trajectories with velocity components (*Vxft, Vyft, Vzft*) at each time step (at each predefined fragment location) were obtained.

In order to mathematically describe fragment trajectories, drag coefficient *Cd*, mass *mf*, and frontal area *Af,t*,of each fragment were required to be predefined. The drag coefficient Cd depends on the fragment shape and takes account of both skin friction and drag. Deterministic approaches for defining Cd have become significantly difficult and unreliable because of significant uncertainties associated with glass breakage and the shape of glass fragments ([Netherton & Stewart, 2009](#_ENREF_18)). In solution, probability-based techniques are widely adopted. Such techniques allow mathematical representation of complex fragment behaviour to be described in a simple and conservative manner. With regard to breakage of glazing systems, toughened glass tend to produce cuboid fragments, whereas annealed glass produce glass shards with large aspect ratios ([Cormie & Sukhram, 2007](#_ENREF_7)). The drag coefficient associated with cuboid or square shaped fragments and fragments with large aspect ratios is approximately 1.05 and 2.05 respectively ([Fox & McDonald, 1985](#_ENREF_9)). In several investigations assessing the biological meaning (degree of fragment penetration in flesh) of physical data obtained from blast tests, drag coefficient for glass fragments was shown to be either unity or 1.17([Fletcher, Richmond, & Yelverton, 1980](#_ENREF_8)). In addition, in probabilistic analyses ([Netherton & Stewart, 2009](#_ENREF_18)) conducted to establish risk contours on glazing facades following external explosive blasts, Cd for annealed and toughened glass fragments were taken as 1.72 and 1.38 respectively. These data compare well with the typical range of Cd (1.05-2.05) recommended for cuboid fragments and fragments with large aspect ratios. Based on these data, Cd in this research was set to be uniformly distributed in between 1.15 and 2.0 for annealed glass and in between 1.05 and 1.35 for toughened glass.

Frontal area *Af,t*, of a fragment is the area that is perpendicular to the direction of airflow. The frontal area differs between annealed and toughened glass. A mean frontal area for each fragment is more realistic in numerical analyses because of unpredictable tumbling behaviour of fragments in air. This complex behaviour of fragments in air cannot be easily described in mathematical terms. In this paper, a simplistic model based on a square fragment and the mean of the three orthogonal areas of the square fragment was developed to describe the mean frontal area against fragment mass (see Table 1). Alternative formulae were also developed for a rectangular fragment with a 4:1aspect ratio and for an elongated triangular fragment with a 2:1 aspect ratio (last two columns of Table 1). The square fragment provided a lower bound average area for fragments. For toughened glass, where fragments and clumps are fairly compact, the mean of the first two (5th and 6th columns of Table 1) provide a conservative estimate of the mean frontal area. For annealed glass, where fragments are often elongated and triangular, the mean frontal area is slightly larger than the value estimated using the formula developed for a triangular fragment with a 2:1 aspect ratio. Therefore, simplistic models for estimating the mean fragment area *Amean*, for toughened and annealed glass were written as given in equations (4) and (5) respectively:

(4)

(5)

Where, *Afrontal* is the surface area of the fragment.

The fragmentation behaviour of annealed glass is different from that of toughened glass. Fracture planes in annealed glass are less rectilinear. As a consequence, annealed glass tends to produce a significant number of lethal jagged shards. Conversely, when toughened glass breaks, the majority of fragments tend to be dice-like fragments due to stress gradients introduced across the pane’s thickness by controlled thermal or chemical treatments. These small cubes are less likely to cause injury because such lightweight fragments (typically < 4.25 grams with no sharp edges) tend to bounce off the skin without causing lacerations ([Clark, Yudenfriend, & Redner, 2000](#_ENREF_6)). Fracture of toughened glass also produce clusters of fragments, sometimes weighting even up to 60grams, causing injuries ([Clark et al., 2000](#_ENREF_6)). In experimental investigations ([Clark et al., 2000](#_ENREF_6)) conducted using toughened glass panes tested at different levels of thermal strengthening, it was shown that both mean and standard deviation of fragment mass distributions can be conservatively considered as 10grams. In contrast, a mean fragment mass of 28grams for both annealed and toughened glass has been suggested and utilized in assessing the vulnerability of monolithic glazing systems due to blast loading ([Netherton & Stewart, 2009](#_ENREF_18); [Stewart & Netherton, 2008](#_ENREF_22)). A mean fragment mass of 28grams, in the absence of sufficient test data, is a reasonable engineering judgment for annealed glass; however it would overestimate the fragment size for toughened glass leading to inaccurate modelling of fragment mass distributions.

In this research, mean fragment mass for annealed and toughened glass were taken as 30grams and 10grams respectively, with any fragment weighting less than 4grams was neglected in estimating injuries. These figures compare well with the aforementioned test results and engineering judgements. The distribution of fragment mass is noncentral with respect to mean mass. The majority would be smaller fragments weighting less than or around the mean mass, with less frequent occurrences of either glass shards or clusters. This asymmetric nature of fragment mass distributions was described utilizing a beta distribution ([Peacock, Forbes, Evans, & Hastings, 2011](#_ENREF_20)) as given in equations (6) and (7):

(6)

(7)

Where, *PDF* is the probability density function. *α* and *β* are shape parameters. The parameter α was set to 2. A numerical analysis was conducted to select an appropriate value for β. If β was less than 6, annealed shards weighting greater than 100grams were absent from the calculations. In the present method, β was set to 8 such that fragment mass distributions can include both majority small fragments as well as minority large shards and clusters which can be even 5-6 times heavier than the mean fragment size.

* 1. ***Casualty estimation***

This analytical method predicts injury severity based on the Total Kinetic Energy (TKE) of glass fragments that strike on a human body. Four Injury Severity Levels (ISL) (see Table 2), which have been developed based on the most prevalent injuries observed among building occupiers in historic events ([Meyer et al., 2004](#_ENREF_15)), were utilized. A trial and error back analysis was conducted utilizing available glazing-related casualty data ([Mallonee et al., 1996](#_ENREF_13); [Norville, Harvill, Conrath, Shariat, & Mallonee, 1999](#_ENREF_19); [Thompson et al., 2004](#_ENREF_23)), injury level and glazing hazard classifications ([Home Office Scientific Development Branch [HOSDB], 1997](#_ENREF_11); [Meyer et al., 2004](#_ENREF_15)) and simple glazing hazard prediction tools ([US Army, 2004](#_ENREF_25)) to identify the probability of each injury severity level based on the TKE. Table 2 provides the estimated probability distribution of injury severity levels under each category of TKE. If TKE is greater than 90 joules, corresponding percentage probability (λ1, λ2 and λ3) of ISL 4, ISL3 and ISL2 was found to agree following relationships:

(8)

(9)

(10)

The population density was defined as the number of occupiers per room for closed-plan and the number of occupiers per floor for open-plan internal architectural forms. The position of each occupier was randomly defined using X- and Y-coordinates (see Figure 6), with X as the shortest distance from the exterior wall to the occupant position and Y for open-plan architectural forms was the distance from the left side edge of the facade to the occupant position. For closed-plan buildings, Y was defined as the distance from the left side partition wall to the occupant position. Four types of occupant orientations were used: standing face-on, seated face-on, standing side-on and seated side-on. For example, Figure 6 shows the idealised area for an occupant in the standing face-on orientation. Fragments passing through the idealised area were identified based on the calculated fragment trajectories in section 2.2. The total kinetic energy of all such fragments was estimated using mass and resultant velocity components of each fragment when the fragment intersects the idealised area. The TKE was subsequently related to the injury severity level. Each analysis case comprised 50 independent solutions with randomly defined input parameters at each solution stage. Numerical predictions (casualty distributions) were obtained with 95% confidence.

1. **Validation of the proposed method**

The validation process consists of three steps: (i)- equivalent sdof systems used to model window response were compared with transient nonlinear finite element analyses to identify a suitable combination of equivalent stiffness and load-mass transformation factor *KLM*; (ii)- the proposed method for conservatively estimating blast wave parameters following window failure was compared with coupled (Euler-Lagrange) CFD simulations to demonstrate its validity towards estimating aerodynamic forces acting on fragments; (iii)- finally, an overall assessment of the proposed method was conducted by comparing estimated casualties with alternative casualty estimations.

* 1. ***Validation of window response modelling***

Two linear and nonlinear finite element analyses were conducted for a simply supported square glass pane (1.5m×1.5m×8mm). Modulus of rupture, density, poisson’s ratio and Young’s modulus of glass were 180MPa, 2489kg/m3, 0.21, and 70GPa respectively. The overpressure-time history defined in the study consisted of a peak overpressure of 50kPa, which was considered to decay exponentially to zero over a period of 10.6ms. FE models were uniformly meshed utilizing square thin-shell elements and a flower force technique was employed to apply pressure on the window pane. The follower force technique takes account of the change in direction of the pressure load in global coordinates when the window moves and distorts with time. In this manner, pressure was applied gradually throughout the deformation, and the pressure will still be acting perpendicular to the surface at large deformations. Three alternative sdof simulations, in which the elastic stiffness factor remained unchanged with a different KLM factor in each simulation, were conducted. The Navier solution for all-round simply supported plates ([Timoshenko, 1940](#_ENREF_24)) was employed to calculate the equivalent elastic stiffness factor. KLM factors developed by Biggs ([Biggs, 1964](#_ENREF_3)) and Morison ([Morison, 2007](#_ENREF_17)), and provided in the design manual “*Structures to Resist the Effects of Accidental Explosions, UFC3-340-02*” ([US Army, 2008](#_ENREF_26)) were used in the alternative sdof models.

Figure 7 shows central deformation-time histories of the window pane obtained from linear FE and sdof simulations. Central deformation *d*, is given as ratios of the pane thickness *h*, and time *t*, is given as ratios of the natural period of vibration of the pane *T*. Figure 8 shows central deformation-time histories obtained from nonlinear analyses, with geometric nonlinearity (the effect of membrane forces at large deformations) is introduced. A noticeable difference in the amplitude was evident between linear (52.94mm) and nonlinear (39.7mm) deformation histories because the nonlinear models were observed to have a higher stiffness than the linear models at large deformations due to the effect of membrane forces. Nonlinear sdof analyses conducted utilizing Moore’s nonlinear resistance ([Moore, 1980](#_ENREF_16)) and a small deflection transformation factor developed by Biggs ([Biggs, 1964](#_ENREF_3)) featured a slightly longer response time than that obtained from the transient FE analysis. When the same nonlinear resistance with large deflection factors developed by Morison ([Morison, 2007](#_ENREF_17)) was employed, the timing of transient response was improved and the sdof simulations provided the best timing fit to the response history predicted from the nonlinear FE analysis.

* 1. ***Validation of the estimation of blast wave parameters***

This study considers a two-storey building in a blast environment following an explosion occurring on a road as shown in Figure 9(a). The building façade comprised two rectangular annealed glass windows (1.8m×1.4m×8mm). Modulus of rupture of glass was 80MPa. In CFD simulations, only half of the scaled (1:20) building was modelled [see Figure 9(b) for scaled dimensions of the building]. Figure 10(a) shows a scaled model of the building constructed in Autodyn. Floor plates and walls of the building were assumed to be rigid. Windows were modelled as thin shell structures assuming a biaxial state of stress; no wave propagation across the shell thickness. The air was defined as a subgrid of Eulerian cells. The shell grid moved and deformed with the window, whilst Eulerian cells were fixed in space with the physical airflow occurring through the grid ([Century Dynamics, 2011](#_ENREF_5)). The interaction between Eulerian and shell grids was fully coupled. The artificially thickened shell grid overlapped the Eulerian grid and provided constraints to the flow of material in the Eulerian grid. At the Euler-shell interface, the shell grid remained as a geometric flow boundary to the Euler grid, whilst the Euler grid acted a pressure boundary to the shell grid. As the shell grid moved and distorted, it covered and uncovered the fixed Euler cells permitting an accurate fluid-structure interaction prior to window failure governed by the state of principle stresses in shell elements. Figures 10(b) and 10(c) show blast wave propagation and interaction with the building covering window failure and subsequent pressure venting into the living space.

Blast wave parameters including air particle velocity and air density histories behind the vented shock front were recorded at gauge locations. Table 3 provides X-, Y- and Z-coordinates of the gauge locations. Figure 11 compares X directional particle velocity-time histories estimated from both methods. In Figure 11, particle velocity is given as ratios of the speed of sound in free air *C0*, against scaled time. Autodyn predictions indicated an increase in particle velocities following shock arrival due to the effect of rarefaction waves. The effect of rarefaction waves on the properties of vented blast waves was not taken into account in the approximate method. As a consequence, the approximate method led to underestimations in particle velocities. The strategy employed to overcome this problem was to modify the decay factor *b*, of the modified Friedlander’s equation ([Friedlander, 1939](#_ENREF_10)) which was used to describe particle velocity-time histories. The third curve in each plot (curve labelled as “*Modified decay*”) was constructed utilizing the same peak particle velocity and duration, but with a modified decay factor. It was found that if the decay factor remained equal to 1 or in between 0 and 1, the accuracy of particle velocity calculations improved significantly leading to conservative estimations. However, noticeable discrepancies were identified at locations further away from the window line; particularly at upper floors (e.g. at gauge point 12) because blast wave parameters beyond a certain distance from the window line were noticeably influenced by rarefaction waves formed at all edges of the opening.

Calculations of additional aerodynamic forces indicated that fragments arriving at relatively long distances from the opening were less affected by additional accelerations because of significant difference in the speed between shock fronts and fragment velocities. Even the sum of the shock arrival time and particle velocity duration at distant locations was less than the time that fragments required to reach the corresponding location. In conclusion, when fragments reached distant locations, particle velocities had significantly diminished causing either minor accelerations or decelerations on fragments. Table 4 shows the approximate horizontal distance *Sx*,from the bottom window line, at which horizontal accelerations on a centrally-ejected fragment (*30g*) became insignificant.

The effect of additional horizontal acceleration on hazardous nature of fragments can be further demonstrated by comparing fragment velocities at an arbitrary point. Figure 12 shows percentage increments in the impact velocity and kinetic energy of a fragment (*30g*) at an arbitrary plane located at a distance of 2m from the window line. At scaled distances greater than approximately 2.5m/kg1/3, aerodynamic forces were barely influential. Conversely, at scaled distances less than 1.5m/kg1/3, additional forces increased the impact velocity and total kinetic energy by approximately 8% and 15% respectively. However, at small scaled distances, initial fragment velocities even without the influence of aerodynamic forces comfortably exceeded the high hazard velocity threshold provided in the “*UK Glazing Hazard Guide-Charts”* ([Home Office Scientific Development Branch [HOSDB], 1997](#_ENREF_11)).

Figure 13 compares air density histories at gauge locations. Air density is given as ratios of the density of free air *ρ0*, against scaled time. The approximate method overestimated the air density at low pressure conditions towards the tail end of vented blast waves. These overestimations led to conservative numerical predictions as the aerodynamic effect on fragments was directly proportional to air density (see Figure 5). In conclusion, the implementation of the approximate method for modelling the effect of aerodynamic forces was a success. Although the predictions failed to precisely reproduce the complex time histories of blast wave parameters obtained from coupled CFD simulations, the approximate method led to safe conservative estimations validating its application in this practice.

* 1. *Comparison of casualties*

In order to demonstrate the reliability of the developed method towards estimating casualties, the technique was applied to an annealed glazing façade of a 10- storey building consisting of 9 structural bays. The floor height, bay width and room depth of the building were 3.5m, 3m and 4m respectively. Windows were 1.5m×1.5m in surface area and 8mm in thickness. Modulus of rupture of glass was 80MPa and the other properties of glass were previously described in section 3.1. Blast scenario was defined at 30kgs of TNT equivalence detonated at a stand-off distance of 30m. Injury Severity Levels of 32 occupiers positioned in 16 randomly selected rooms (two occupiers per room) immediately behind the façade were estimated. Table 5 provides details of room location, occupier details and blast scenario for each room. For comparison purpose, the Injury Severity Level for each occupier was alternatively estimated by utilizing the computer tool “*Window Fragment Hazard Level Analysis-HAZL*” ([US Army, 2004](#_ENREF_25)) developed by the US Army Engineer Research and Development Centre. Tables 6 and 7 compare the injury severity level of each occupier and the total casualty distribution among all occupiers respectively. The estimated total casualties in all injury levels compare well with corresponding casualty estimations from the HAZL algorithm (see Table 7). In contrast, comparisons conducted by independently considering each injury level indicated that the predications obtained from the proposed analytical tool are divergent from HAZL’s predictions. However, with a modified injury classification; minor injuries (ISL0+ISL1), moderate injuries (ISL2+ISL3) and severe injuries (ISL4), the numerical predictions were shown to be consistent between the two methods (see Table 7). This highlights the reliability of the proposed method towards quantifying the extent of glazing hazard following external explosive blasts.

1. Application of the proposed method

Two buildings, one with open-plan and the other with closed-plan internal building layouts were considered. The façade height, façade width and the floor height were 30m, 24m and 3m respectively. The horizontal window spacing, room depth and the population density (per room) for the closed-plan building were 3m, 4m and 2 respectively. For the open-plan building, windows were initially spaced at 3m horizontally, which was subsequently reduced to 2m to represent a more realistic open-plan façade arrangement. The population density for the open-plan building was set to 16 occupiers per floor; consistent with the total population distribution (per floor) in the closed-plan building to allow casualty comparisons between the two building forms. Windows were 1.2m×0.9m in surface area and 8mm in thickness. Façade systems comprised either annealed or toughened glass windows, with Young’s modulus, poisson’s ratio and density of glass were respectively taken as 70GPa, 0.21 and 2489kg/m3. Based on test results and comprehensive studies on published data, the design glass breakage tensile stress has been estimated by the Home Office Scientific Development Branch (HOSDB, 1997) as 80MPa for annealed glass, and 180MPa for toughened glass. In this study, these glass breakage tensile stresses were utilized as the modulus of rupture of glass for annealed and toughened glass. In overall, this study considered 6 façade arrangements: two closed-plans (annealed and toughened glass) and four open-plans (each window spacing considered with annealed and toughened glass). The blast scenarios were defined at 40kgs of TNT equivalence detonated at stand-off distances varying from 100m to 10m at 10m intervals. Figure 14 compares estimated cumulative casualties for each building layout against stand-off distance. Table 8 provides 95% confidence interval for the estimated casualties in each ISL. For comparison purpose, Table 8 also provides estimated percentages of the damaged façade area corresponding to each glazing hazard classification level provided in the UK Glazing Hazard Guide-Charts.

At stand-off distances greater than or equal to 70m, even annealed facades in all building configurations were hazardless. At 70m stand-off, the strength of blast outputs were sufficient to cause failure of most of the annealed windows; however, the kinematics of fragments were barely influential causing a post-fracture behaviour dominated by the Minimal hazard level. Fragments under minimal hazard conditions are thought to be almost hazardless because such glass fragments are confined within a maximum distance of 1m from the window line (Home Office Scientific Development Branch [HOSDB], 1997). Notable reductions in the damaged façade area and in total casualties were evident when annealed glass was replaced with toughened glass; toughened glass windows were hazardless at any stand-off distances greater than 30m. At the close-in range, toughened facades, in overall, were more effective in mitigating glazing hazard than annealed facades, reducing casualties by 20% at 10m stand-off and by 60% at 20m stand-off.

Had the population density and the horizontal window spacing (3m) remained unchanged between closed-plan and open-plan building arrangements, the open-plan arrangement reduced the total number of casualties by approximately 12%, whilst the damaged area of the façade under each hazard classification level was identical in both building layouts. This was mainly due to different population distributions in the two cases. A horizontal window spacing of 3m was unrealistically large for the open-plan building and removing internal partition walls led to a more widely-spread occupant distribution, with a reduced threat in living areas between adjacent windows. With the reduced horizontal window spacing (2m) for the open-plan building, the total number of casualties increased by approximately 19% for the annealed facade and by approximately 22% for the toughened facade.

For annealed glazing facades considered with closed-plan or open-plan building form, the extent of glazing hazard estimated according to the UK Glazing Hazard classification remained unchanged at the “*Low Hazard level*” for stand-off distances between 60m and 40m, and at the “*High Hazard level*” for stand-off distances below 20m (see Table 8). This infers the extent of glazing hazard remains unaffected with reducing stand-off distance from 60m to 40m or from 20m inwards. In contrast to this observation, casualty estimations given in Table 8 indicate that the number of casualties corresponding to each ISL continually increases with decreasing stand-off distance from 100m to 10m.The UK Glazing Hazard classification is sorely based on results of a limited number of blast trials combined with some degree of mathematical interpretations. This classification considers only fragment distribution behind broken windows with no particular considerations of fragment-human interaction and fragment kinematics at different magnitudes of blast outputs. In consequence, the lack of robustness towards the definitions of hazard levels in the UK Glazing Hazard Guide, in some circumstances, can lead to underestimations in the overall extent of glazing hazard; a high hazard level can be unrealistically considered as one of the low hazard levels because of sole dependency of the classification on fragment drop zones. In this perspective, the analytical technique discussed in this paper would be of direct importance to personnel involved with protective design of buildings.

1. Conclusions

The proposed glazing hazard assessment method has proven to be a powerful tool for quantifying the extent of glazing hazard in buildings with different internal architectural forms. The fragment fly-out model incorporated in the casualty estimation method led to conservative estimations of fragment trajectories following window failure. At scaled distances greater than approximately 2.5m/kg1/3, the effect of additional aerodynamic forces acting on glass fragments due to vented blast pressures was negligible. Conversely, the aerodynamic effect was found to noticeably influence fragment kinematics at scaled distances smaller than 1.5m/kg1/3, however; at such small scaled distances, even fragment initial velocities (at window failure) can be greater than the velocity threshold for serious injuries. With regard to current glazing hazard classifications, the UK approach lacks robust definitions of hazard levels: no accounts for a realistic post-fracture behaviour and interaction of fragments with building occupiers. This can underestimate the overall extent of glazing hazard eventually causing inadequate recommendations towards glazing retrofits and protective design of new building envelopes. In overall, estimations of casualties using the proposed multi-hit glass injury assessment approach would have economical benefits by being able to quantify the overall extent of glazing hazard in a more robust manner than conventional methods.

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