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Explicit dynamic modelling of architectural glazing subject to blast loading

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The response of an architectural glazing panel to dynamic loading, such as that from explosions, is analysed using an explicit dynamic finite element algorithm coded into a computer program. This software allows for the simulation of various glazing types, and is capable of predicting displacements and stresses up to cracking of the glass and the hazard level experienced by occupants. A variety of support conditions are available, along with several methods of specifying the blast load. Details and challenges of the numerical algorithm and coding are presented, together with the verification procedure that was performed through comparisons with results from analyses using general-purpose finite element programs and from available literature. In parallel, experimentation was performed to determine the dynamic mechanical properties of glass by testing the material in a Split Hopkinson Pressure Bar.

Keywords: Glazing, blast load, finite element, dynamic loading, dynamic material properties

1. Introduction

Recent world events have focused attention on the vulnerability of buildings to explosions occurring in their vicinity. The shock wave generated by an explosion is liable to induce a significant load on a building façade which is considered particularly susceptible to damage as it is often partially or fully constructed from glass. In order to prevent broken glass fragments from being thrust inside, where they are known to cause injury, structural designers have devised a number of solutions which can be implemented in both new and existing buildings. However, all tools currently used to determine the response of a glazing panel to a given blast load are thought to be either too complex, and thus impractical for most structural engineers, or too simplistic in their assessment of the mechanisms involved and, hence, likely not accurate. Therefore, there is a need for a better, yet easy-to-use tool for the purpose of designing blast-resistant building façades which can be employed with confidence by any practitioner of protective design having the basic knowledge of blast loads and their effects on structures. Furthermore, accurate prediction of glazing behaviour subject to dynamic loading requires that the properties of glass under high strain rates be known.

2. Background

2.1. Blast loads and blast effects

An explosion is a release of energy by way of an exothermic chemical reaction which generates a pressure wave of finite amplitude in the air surrounding the explosion site [1]. The magnitude of the 'air shock' undergoes exponential decay as it moves away from the explosion source and all surfaces in the path of the shock front will experience a load in the form of a pressure: the blast load [2]. The area underneath the pressure-time curve is the 'impulse', a measure of the energy contained within the blast load [3]. Since the façade is the first component to experience the load, it is responsible for transferring the energy from the blast wave to the building. If a segment of cladding is compromised, the pressure from the blast enters the building, together with the cladding fragments, where it can cause further damage and injury [1]. For these reasons, glass cladding, or architectural glazing, must be designed so that it can absorb energy from a blast wave whilst remaining intact or failing in a safe manner.

2.2. Material Properties

<u>Glass:</u> The brittle nature of glass is a result of its irregular, non-crystalline molecular structure which makes it impossible for the material to yield before failing. Therefore, it is usually observed to fail at stresses several orders of magnitude lower than its theoretical strength [4]. This is thought to be caused by the presence of microscopic flaws on the glass surface which result from manufacturing, handling and weathering. The presence of these flaws, as well as other factors which affect strength, including load duration and humidity, are accounted for in the 'Glass Failure Prediction Model' (GFPM) [5]. This theory uses experimentally-derived constants in combination with glass pane stresses calculated using numerical modelling to determine the probability of failure in a pane under an out-of-plane load. In practice, glass strength can be increased up to five times by creating a compressive residual stress on its surface by tempering [6].

<u>Interlayer:</u> As with all visco-elastic materials, the mechanical properties of the interlayer used in laminated glass are highly dependent on loading rate and temperature [7]. Consequently, at high strain rates or low temperatures the interlayer behaves in a glass-like manner whilst at high temperature and low strain rates it acts in a rubbery fashion [8]. At constant temperatures, over small periods of time, and at low strains the interlayer can be treated as a linear elastic material with a Poisson's ratio approaching 0.5 and the stiffness determined from the 'short time' shear modulus using solid mechanics equations [9].

2.3. Physical blast effects on glazing

The behaviour of both monolithic and laminated panes of glass under a load applied in the direction perpendicular to their plane is most often described using plate theory, because the thickness of the pane is much smaller than its other two dimensions [10]. Since it is generally accepted that panes of glass can deflect several times their thickness before failing, it is necessary to account for the influence of membrane stresses by employing large deflection ('Von Karman') theory [11].

The behaviour of glazing under blast loads has received a relatively significant amount of attention. Of particular relevance is a venture which employed the GFPM and was aimed at gauging the effect of changing several parameters on the probability of failure

[12]. Using a Finite Element model, the authors discovered that, under blast loading, laminated panes exhibited monolithic behaviour as the interlayer did not have enough time to undergo relaxation [13]. In addition to the glazing panels themselves, the behaviour of supporting elements has received limited treatment as is demonstrated by an investigation into the response of a curtain wall to a low level blast [14], [15]. In this work, the authors showed numerically that principal stresses in glazing panels are greatly reduced in a curtain wall configuration because of the elasticity of the supporting structure.

2.4. Performance Specifications

A particular glazing configuration is typically judged by how far fragments of broken glass fragments are projected into a standard cubicle as a result of a blast. The most prevalent amongst these are the General Standards Administration (GSA) performance specifications which form part of the blast-resistant glazing test standard [16]. Levels 1 and 2 correspond to the glazing remaining intact or failing in a safe manner, whilst levels 3, 4 and 5 represent increasingly unsafe failure modes in which fragments penetrate into the occupied space.

2.5. Existing analysis and design tools for glazing

The single degree of freedom (SDOF) method has been a prominent analysis procedure in the world of blast-resistant design, and has been adapted for use in several computer programs [16], [17]. Whilst convenient and easy to use, such programs, and the SDOF method in general, employ a simplistic model of glazing response. On the other hand, the Finite Element (FE) method has become increasingly widespread in the design of glazing subject to blast loads but it is often too involved for routine design work and is, therefore, typically used only to model complex situations and for research purposes [12], [13], [14], [15]. There are also procedures used for design of windows subject to static and wind loading that can be adapted, with limitation, to determine rather conservatively, the adequacy of a window subject to a particular blast [18].

3. Model of Architectural Glazing

3.1. Finite element model

Modelling the pane of glass as a plate essentially reduces a three dimensional problem to two dimensional elasticity. Although both thin and thick plate theories are acceptable for the range of thicknesses typically seen in glass panes, the latter is simpler in its finite element implementation [19]. Therefore, thick or “Mindlin” plate theory will be assumed to apply. This means that, whilst generally insignificant, transverse shear stresses will be considered in the analysis.

The finite element used in the model is a four-noded isoparametric quadrilateral with five degrees of freedom per node [20]. The formulation of the element was accomplished by first relating the value of a degree of freedom at any point on the plate to the displacements at the nodes of the element on which the point lies using shape function polynomials. This definition of displacement is then substituted into the strain displacement relations to obtain a relationship between strains at any point in the plate and nodal displacements. The product of the previous step, the stain matrix, is then combined with the constitutive matrix and integrated over the area of the element to obtain the stiffness matrix. This is done numerically using 2 x 2 Gauss quadrature with the additional step of "mapping" local coordinates, in terms of which the shape functions are defined, into global coordinates, with respect to which the integration is carried out. It should be noted that 1 x 1 integration is used for the shear stress terms to avoid shear locking. This phenomenon occurs when shear deformable elements, such as the one being used here, are employed in simulation of thin plates which typically exhibit minimal amounts of deformation due to transverse shearing [21]. The final element stiffness matrix has dimensions of 20 x 20. Assembly of the global stiffness matrix is carried out by placing the stiffness coefficients from the element stiffness matrices in the appropriate locations in the global stiffness matrix. Furthermore, geometric nonlinearity was considered through the inclusion of nonlinear terms in the element formulation, resulting in the formation of a geometric stiffness matrix.

The most accurate representation of mass in an object being analyzed is achieved by employing what is known as a "consistent mass matrix". This is computed through numerical integration of the mass over the area of an element by way of the shape functions [22]. Unfortunately, this procedure produces a sparsely populated matrix which is inconvenient for explicit analysis since it requires a matrix inversion to obtain the acceleration vector. In order to circumvent matrix inversion it is necessary that the mass matrix only contain non-zero entries on the diagonal. Such a matrix often referred to as a "lumped mass" or "real mass" matrix can be found by employing the Lobbato integration rule during element mass matrix formulation [22]. This modification allows for much faster computation of results with minimal effect on accuracy.

The model uses the equivalent single layer approach which, using the properties of the individual layers, leads to the creation of a single homogenous isotropic material constitutive matrix used in the analysis. The multi-layered plate can then be treated as a single layered plate with complex constitutive behaviour in which a linear strain profile is maintained through the thickness [21]. Although this method is computationally simple, since nodes must only be placed at the midplane, it prevents determination of interlaminar stresses in laminated glass. However, under blast loading conditions, a laminated pane exhibits monolithic behaviour due to the rapid rate of loading. Therefore, a perfect bond is assumed to exist between the interlayer and glass layers resulting in a linear strain profile through the thickness of the pane during loading.

3.2. Loading and support conditions

The glazing panel is loaded by applying a force to the nodes on the outside of the exterior pane in the direction perpendicular to the panel. The magnitude of the load is determined from the blast pressure felt by the glazing at each time step. The pressure is assumed to act uniformly over the entire face of the panel since blast waves can be assumed planar when considering a small portion of a loaded façade a long distance away from the explosion. The maximum pressure, impulse and positive phase duration of the load are based on the charge weight and standoff distance and determined with the aid of the available design charts [17]. The load is idealized to the shape of a triangle which maintains the true peak pressure and impulse but uses an equivalent duration. Alternatively, pressure-time values can be entered, or the peak pressure and impulse specified directly. Whichever type of entry, the pressure felt by the glazing is converted to a nodal force and applied to each node using the vector of nodal forces.

The model allows for the simulation of several framing arrangements by assigning a specific stiffness to each of the five degrees of freedom present at every node. This can be used to model glazing held in place by structural silicone which allows a panel a limited amount of movement at the supports.

In the event that elastic supports are used to model structurally glazed systems, as opposed to the ideal case of perfectly fixed or free conditions, it is necessary to define the stiffness of the supports in all axis directions. Although the complex nature of the material prevents the derivation of an exact value for the stiffness, there are guidelines which can be used [23], [14].

3.3. Material properties

Glass is known to behave elastically until failure and is, therefore, treated as such in the model. Since the stiffness, density and Poisson's ratio of the material can vary, these parameters can be specified by the user. Failure of the glass occurs when either the maximum principal stress, or the probability of failure reach a preset threshold, the latter as defined by the GFPM. The model allows for the use of either annealed, heat treated or fully tempered glass. Recommended values for material elastic constants are also provided to facilitate the modelling process [24]. These are presented in Table 1.

The interlayer material is treated as linear elastic, as it know to behave in this manner when subjected to the strain rates experienced under blast loading. A value of 330MPa is chosen for the shear modulus as suggested elsewhere. Table 1 also illustrates the properties used for the PVB interlayer prior to glass failure [13].

Table 1: Typical material properties.

	E	υ	ρ
	MPa		kg/m^3
Glass	72000	0.22	2500
Interlayer (PVB)	330	0.5	1100

3.4. Solution for displacements

Due to the transient nature of the blast loading, a dynamic analysis to evaluate the response of the model is performed. This requires that the displacements be solved for at multiple time steps whilst the glazing is subject to the blast load which also varies with time. An accurate time integration scheme is accomplished through linearization of the equation of motion by solving it at discrete times. A variation of the Newmark-Beta method was selected for the task as it has been proven to be effective when implemented in conjunction with the finite element method [19]. This algorithm is used in a manner that allows for explicit solution of the unknowns at a given time step using only known values from the previous time step. This is in contrast with an implicit solution in which unknowns from multiple time steps are solved for, necessitating a matrix inversion. In addition to solving for displacements and stresses, the model allows for the determination of dynamic reaction forces which can be applied afterwards to the supporting structure. The effect of geometric nonlinearity is accounted for through the reformulation of the geometric stiffness matrix at every time step using displacement results. Modelling of the response for insulated glazing units (IGUs) necessitates that the airspace in between the panes of glass be treated as a sealed volume which, upon deflection of the outer pane, transfers the pressure from the blast load to the inner pane through an increase in pressure.

3.5. Glass failure prediction model

The GFPM is used to determine the probability that a pane of glass will fail under a given load. If selected by the user, it is invoked at each time step after calculation of maximum and minimum principal stresses for each element.

3.6. Fragment projection

The hazard level is determined by the distance of fragment projection. The fragments are thrust forward by the remainder of the blast load and have an initial displacement, velocity and acceleration equal to the final value of these parameters registered for the centre node of the now broken pane of glass. The initial conditions and instant force are used to determine the trajectory of the fragments by means of elementary physics equations but the presence of a variable applied force in the form of the blast load necessitates that the problem be integrated over time. The analysis completes when the fragments strike either the floor or the back wall of the standard GSA cubicle, and the hazard condition is determined based on the landing location of the fragments (Figure 1).

4. Model Validation

The accuracy of the model was first verified through a series of static trials as these allowed for a more direct comparison between results from the model and those from the literature. The results of these tests are available elsewhere [25], [28].

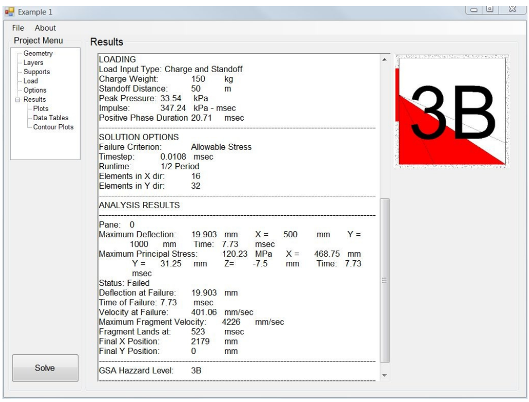
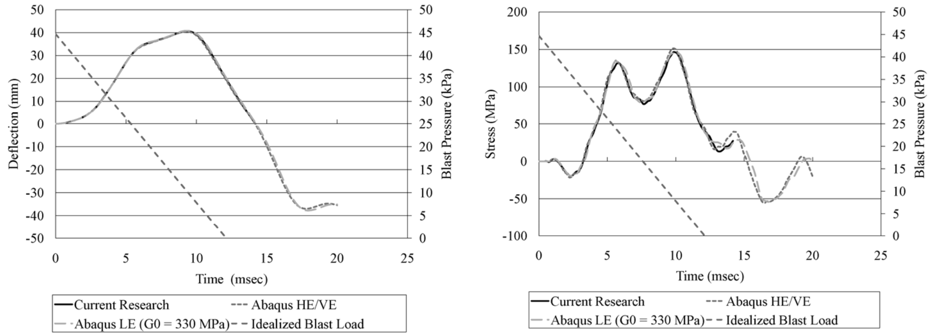


Figure 1: Output window indicating the hazard level.

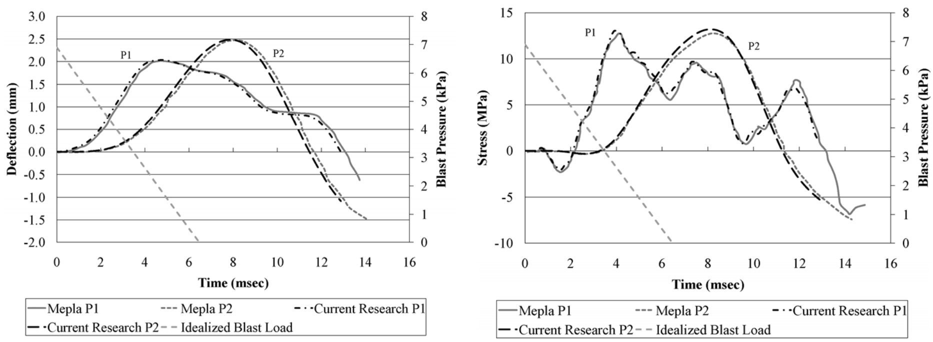
Dynamic validation was then undertaken with the aid of a study regarding the response of laminated and monolithic glazing to blast loading [13]. The elastic properties of the interlayer material were determined from the short time shear modulus. To validate this assumption, the same pane of laminated glass was modeled in a commercially available finite element program using a hyperelastic/viscoelastic material definition for the interlayer. The results, shown in Figure 2, suggest that, under the high strain rates considered in the research, the viscoelastic response of the interlayer is minimal.



(a) Central deflection (b) Maximum principal stress

Figure 2: Behaviour of laminated pane under 44.7 kPa/271 kPa-msec blast load.

Validation of the insulated glazing response was accomplished through comparisons with results from the finite element analysis program SJ Mepla [26]. This software, designed specifically for linear analysis of glazing, was used to analyze a square double-glazed unit subjected to a blast load of pressure equal to 6.6 kPa and an impulse of 22.3 kPa-msec. The stress results from the trials, which are shown in Figure 3, demonstrate the similarity in the behaviour predicted by the two simulations. Therefore, it can be concluded that the model is also capable of accurately portraying the behaviour of IGUs.



(a) Central deflection (b) Maximum principal stress

Figure 3: Behaviour of the two panes of an IGU under 6.9 kPa/22.3 kPa-msec blast load.

Finally, a study was undertaken with the goal of determining the accuracy of the model at predicting the behaviour of an elastically supported pane of glass. This was done through a comparison with results from an investigation into the response of curtain walls to low level blast loading [15]. Both simply-supported and silicone-supported panes were subjected to a 23.4 kPa peak pressure triangular blast load which decayed to zero in four seconds. The plot illustrated in Figure 4 demonstrates the effect of the silicone support which reduces the maximum stress experienced by the pane, thus confirming the findings of the referenced study. A complete account of the validation efforts undertaken can be found in the literature [25], [27].

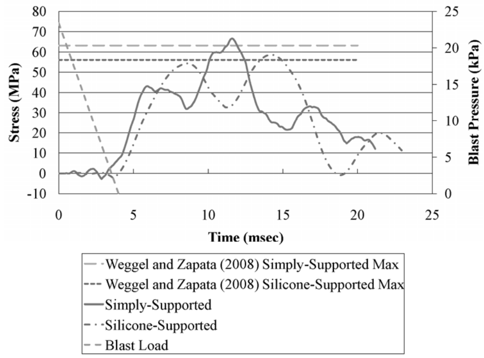


Figure 4: Max. principal stress for simply- and silicone-supported pane under 23.4 kPa/46.8 kPa-msec blast load.

5. Dynamic Material Testing

5.1. Split Hopkinson Pressure Bar Test (SHPB)

Testing using the SHPB is the most common method of determining the dynamic mechanical properties of materials [28]. The apparatus for the modern version of the test is presented schematically in Figure 5. The cylindrical specimen is placed between the two long bars with its longitudinal axis either parallel or perpendicular to the longitudinal axis of the bars. The former is used in the compressive test, whilst the latter arrangement is used during the tensile test.

Testing involves accelerating the striker, from the gun towards the incident bar. At impact, a compressive stress pulse is created within the bar, which travels through the sample to the transmission bar. The strain gauges monitor the bars' strain histories, which can be used to obtain the stress-strain curve of the sample in compression. During the tension test, a tensile stress is induced along the line parallel to direction of stress wave propagation that causes the sample to split open in tension, allowing for the calculation of the failure stress. The test can stimulate strain rates in excess of 10^4 s^{-1}, which are similar to those experienced in most impact and blast loading applications.

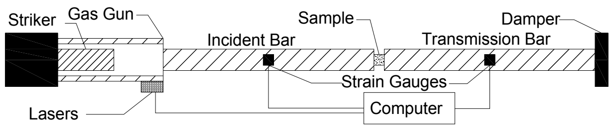


Figure 5: Split Hopkinson Pressure Bar test setup.

5.2. Testing programme

In order to improve the numerical model being developed, an experimental programme was undertaken to determine the mechanical properties of glass under dynamic loads. This consisted of testing annealed soda lime float glass specimens in both compression and tension using the SHPB apparatus. In addition, static compression and tension tests were carried out for comparison purposes. All samples were cored out of the same pane of glass. The compression specimens were chosen to have a diameter roughly equal to their height whilst the tension samples had a diameter to height ratio of two. In order to achieve several different strain rates three different striker velocities were used in the compressive tests whilst two were employed during the tensile trials. Because of the expected high scatter of data, several samples were tested in each of the four experiments in order to obtain results representative of the actual material properties. Upon completion of the tests, the results were evaluated by comparing both average values as well as the magnitude of the scatter in strength values.

5.3. Results

The static strengths of glass in tension and compression, determined through experimentation to be 41 MPa and 859 MPa respectively, are thought to be consistent with data found in the literature [27]. The mean dynamic tensile strengths of the material were determined to be 66.0 MPa and 67.8 MPa, translating in to an increase of approximately 60% over the corresponding static value. The lack of difference in average strength between the two series may be explained by the relative similarity in strain rates which resulted from the 69 and 103 kPa gun pressures used to accelerate the striker. The mean strengths for the three dynamic compressive tests were 533 MPa, 690 MPa and 917 MPa (Figure 6). The results of the dynamic compressive test showed that the strength of the material increases with strain rate. However, it was also discovered that some dynamic tests yielded lower results than the average static value. This suggests that the dynamic compressive samples may have failed in a manner other than crushing of the entire cross section.

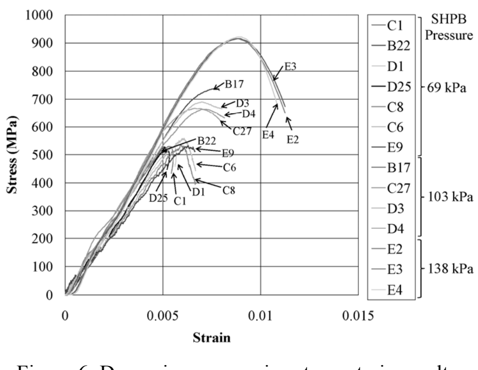


Figure 6: Dynamic compressive stress strain results.

6. Conclusion

The developed finite element model is proven to be successful at simulating the behaviour of monolithic, laminated and insulated architectural glazing panels subjected to a blast load, under a variety of support conditions. The computer program is designed to make the modelling process relatively straightforward by ‘hiding’ many of its aspects from the end user whilst also providing them with several customizable input parameters. The flexibility of the finite element model, combined with the modular construction of the program, allows for future expansion of capabilities. Furthermore, the laboratory tests completed as part of the current project were deemed to be generally successful at determining the dynamic properties of glass. It was found that strain rate tends indeed to have an effect on the strength of this material in both tension and compression.

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