An Energy-Based Approach in Predicting Failure of the Glazing Systems Subjected to Blast Loads

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***Abstract*-In an air blast, building windows break into high-velocity flying shards (annealed glass windows) or fragments (fully tempered windows) that are a primary source of injury to the buildings occupants. In order to successfully design these glazing systems against air blast loading, there should be a balance between the safety and security of the window panel and considerations for the physical appearance and cost-effectiveness, based on the proposed level of security and previous lessons learned. Better understanding of the glazing systems' failure due to the blast load characteristics is an important step forward in mitigating injuries. In this paper, glass failure dynamics is studied using energy methods and brittle failure theories combined with finite element simulations and techniques. Because both methods take into account glass panel characteristics and blast load intensities, employing explicit nonlinear finite element methods with analytical energy methods to model the brittle failure of the conventional building glazing systems is the superior strategy. The results of this study will be beneficial in development of more comprehensive blast-resistance design guidelines and a glazing injury model that will enhance the security of the buildings and improve the safety of the occupants during an air blast.**

Keywords- Energy Methods; Glazing Systems; Manmade Hazards; Finite Element Analysis; Safety Assessment

I. INTRODUCTION

During an air blast, extreme loading on glazing systems results in glass panels shattering into smaller pieces that fly at very high velocities. Due to the high-impact, low-frequency nature of the blast waves and potential risk to the occupants, strict design criteria should be put in place for designing the building envelope and structural glazing technologies. In this study, the blast pulse is assumed to have a triangular shape in which the overpressure rises instantaneously to its peak value (peak pressure) and has a linear decay back to zero (atmospheric pressure) in a very short period of time (milliseconds).

Annealed glass shards and fully tempered glass fragments are the primary source of injuries to building residents during an explosion. Trawinsky et al. [1] showed that more than 80% of human casualties during an air blast event are associated with the failure of window glass panels or curtain walls. When subjected to blast overpressure, window glass panels break into numerous flying shards or fragments that fly into the residential spaces at high velocities. Norville et al. [2] stated that, in the 1995 Oklahoma City terrorist attacks, 198 people in buildings within a radius of 970m suffered from direct glass-related injuries caused by the flying glass shards.

Given the fact that predicting crack initiation times and historical glass failure times is a complex process, current methodologies in this field are mainly based on the Griffith Theory of Brittle Failure that recalls fracture mechanics principles and energy methods. However, in this paper, complex finite element techniques are also introduced and used to obtain crack propagation time histories across the proposed window panels and therefore to compare crack initiation times and blast-related damage assessment to conventional glazing systems. The results of this investigation and similar initiatives will eventually help develop more comprehensive design guidelines and flying glass injury models that enable safety engineering professionals to make appropriate structural and architectural choices to address the threats facing occupants during an air blast.

II. THE GRIFFITH THEORY OF BRITTLE FAILURE

Griffith (1920) developed the first analysis of the fracture mechanics of sharply discontinuous fragments. According to the work undertaken by Barsom and Rolfe [3], failure analysis is performed based on the assumption that incipient fractures in ideally-brittle material (e.g. glass panels) occur when the magnitude of elastic energy supplied at the crack tip during an incremental increase in crack length is equal to or greater than the magnitude of elastic energy existing initially at the crack tip during an incremental increase in crack length. Griffith [4] formulated his brittle fracture theory based on six essential assumptions that were later revisited by Sanford [5]. These assumptions are: (1) All materials contain a population of fine cracks: that is the reason why real materials show lower strength in their tensile properties than those expected from near-perfect materials; (2) Some of the existing fine cracks are oriented in the most unfavorable direction relative to the applied loads so they have the maximum stress concentration factor; (3) At one of these existing cracks, the theoretical strength is reached at the crack tip and the crack grows; (4) The source of the energy for crack propagation is the released strain energy as

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the crack extends, and since strain energy decreases as the crack extends, this energy becomes available to the crack and is consumed for its propagation; (5) The growth of the crack will result in an increase in surface energy due to the formation of new surfaces; and (6) The crack growth process continues as long as the rate of released strain energy exceeds the required surface energy to form new surfaces. Fig. 1 shows an infinite glass plate of unit thickness (t = 1) that contains a through-thickness crack and is subjected to uniform tensile stress, σ, applied at an infinitely far distance from the crack. Damage accumulation factors, glass age, and the shape and location of non-homogeneity and imperfections across the panel can negatively affect the failure stress of the glass.

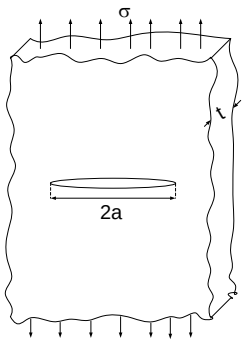

Fig. 1 Through-thickness crack in a unit thickness plate with uniform stresses applied at infinity

Wei and Dharani [6] stated that the total potential energy of the system, *U*, is obtained by Eq. (1):

$$U = U_0 - U_a + U_\gamma \tag{1}$$

where (U_0) is the initial elastic energy of the uncracked glass panel; (Ua) is the decrease in elastic energy caused by the introduction of the crack in the glass panel, and ($U\gamma$) is the increase in elastic surface energy due to the formation of the cracked surfaces.

Due to loading, annealed glass or laminated glass panels of any size and thickness with any boundary condition that are subjected to an air blast store a certain amount of elastic strain energy. Therefore, according to Sanford [5], such systems that are currently out of equilibrium have to release the stored energy to return to the equilibrium state. The release of the stored energy can be manifested in the formation of new cracks or the propagation of already-existing cracks. The elastic surface energy ($U\gamma$) is the product of the unit elastic surface energy of the material (γs) and the new surface area of the crack. Fig. 2 shows a glass panel with (a x b) dimensions that are assumed to be broken into rectangular-shape fragments with area of $\Delta A = \Delta a$ x Δb, and which are bounded by cracks in their four sides; the free body diagram of this fragment subjected to the tensile stresses. Due to the symmetry in loading and geometry, only a quarter of the modeled simply supported window panels are illustrated in Fig. 2.

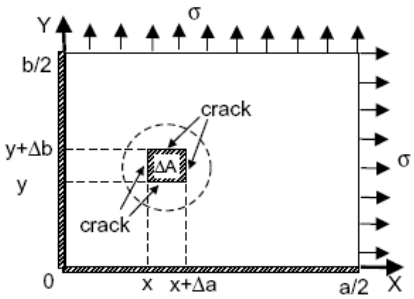

Fig. 2 Glass shard fragment with cracks in all four sides on a glass panel

The surface energy of the glass fragment element can be obtained by Eq. (2):

$$U_\gamma = 2(\Delta a + \Delta b) h_g \gamma_s \tag{2}$$

where γ_s is the surface energy coefficient of the soda-lime glass and h_g stands for the fragment element thickness, which is usually equal to the glass panel thickness.

According to Wiederhorn's research [7], the values of the surface energy for glass (γ_s) range from 3.5 to 5.3 J/m^2, depending on the chemical composition of the glass and the temperature of the test, based on experiments and the theoretical strength of

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glass. According to research conducted by Mlakar in 1999 [8], the surface energy coefficient for soda-lime glass in a static state, the same kind of glass used in this study, is $\gamma_s = 3.9\, J/m^2$.

The strain energy that is consumed by the breakage of the glass window is equal to the energy inherent in the two or more new surfaces that are created when the cracks form. Eq. (3) gives the strain energy of an isolated glass fragment:

$$U_a = \frac{1}{2}\iiint_V (\sigma_x \varepsilon_x + \sigma_y \varepsilon_y + \tau_{xy}\gamma_{xy})dV = \frac{1}{2E_g}\int_x^{x+\Delta a}\int_y^{y+\Delta b}\int_{h_p/2}^{h_g+h_p/2}\left[(\sigma_x)^2 + (\sigma_y)^2 + 2(1+\nu_g)(\tau_{xy})^2\right]dzdydx \tag{3}$$

where h_p is the polyvinyl butyral (PVB) interlayer thickness; E_g is the glass modulus of elasticity, and ν_g is Poisson's ratio for the glass.

Wei and Dharani [6] assumed that the shape and size of the glass fragments are related to the geometry of the glass panel. According to this assumption, the flying glass shards will be rectangular for a rectangular glass panel and will have the same aspect ratio of the original panel. Therefore, ideally, the window panel will break into *m* x *m* equally-shaped and sized fragments [6]. According to research results published in [6] and [3], the required surface energy to break the glass panel into these unique *m* x *m* fragments is obtained by Eq. (4):

$$U_\gamma = 2(a+b)(m-1)h_g\gamma_s \tag{4}$$

and the elastic strain energy for the glass ply is further elaborated in Eq. (5):

$$U_a = \frac{1}{2E_g}\int_{-a/2}^{a/2}\int_{-b/2}^{b/2}\int_{h_p/2}^{h_g+h_p/2}\left[(\sigma_x)^2 + (\sigma_y)^2 + 2(1+\nu_g)(\tau_{xy})^2\right]dzdydx \tag{5}$$

The American Society for Testing and Materials (ASTM F1642-04) standards [9] defines glass fragments as any particle with a *united dimension* of 2.5 cm (1") or greater. The united dimension of a glass particle is the summation of the glass fragment length, width, and thickness. According to the ASTM F1642-04 standards [9], smaller particles are only considered glazing dust.

Depending on the energy equilibrium state at each time increment through the explicit finite element timeframe advancements, the glass panel will crack if the released strain energy takes a greater value than the formed surface energy. Hence, according to Wei and Dharani [6], the precondition for the formation of cracks in the panel or for crack propagation occurs when *free energy*—defined as the difference between surface energy and released strain energy—becomes negative:

$$\textit{Free Energy} = (\textit{Surface Energy}) - (\textit{Elastic Strain Energy}) = U_\gamma - U_a \tag{6}$$

Therefore, the sufficient requirement for crack formation and propagation across the glass panel is:

$$U_\gamma - U_a \le 0 \Rightarrow U_\gamma \le U_a \tag{7}$$

The "*Damage Initiation Index*" (DI) is defined as the elastic strain energy (U_a) over the surface energy (U_γ), and it involved dividing both sides of the above inequality by the surface energy (U_γ). If this ratio is greater than 1.00, the released strain energy for crack propagation supersedes the stored surface energy inside the panel, which is in favor of further crack propagation across the panel, or it is an indicator of crack initiation across the glass panel (DI = Ua / Uγ > 1). Similarly, if the ratio is less than 1.00 (*DI < 1*), there will be no cracks initiated or propagated in the glass while *DI = 1* is the borderline limit for crack initiation across the window panel. In order to better visualize the oscillatory nature of this parameter about zero and understand fracture occurrence, the Damage Initiation Index (*DI*) is modified to (DI - 1). With this slight modification, if ($DI - 1$>0), cracks are expected to form or propagate in the glass panels.

III. INTRODUCTION OF THE ENERGY EQUATIONS FOR THE MODELS

The following are technical terms associated with the use of energy methods that obtain the size and number of glass fragments as well as the corresponding glass panel damage factors.

The internal energy of the whole model is defined as the sum of the stored recoverable strain energy plus the artificial strain energy, which is the energy associated with constraints used to remove the singular modes. There are no plastic dissipation or creep effects in the models used in this study; therefore, the internal energy of the models is the sum of the stored and artificial strain energies.

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The total energy balance of the glass panel is a constant value at each time increment that consists of the total internal strain energy, plus the kinetic energy, minus the total work of the external forces on the panel. There are other negligible terms of viscous dissipation energy and frictional dissipation energy that also need to be added to the total energy balance [10].

This study assumes that the total internal energy (*IE*) at time frame (*t*) equals its value at time frame (*t-1*) minus the sum of stored recoverable strain energy (*SE*) at time (*t*) plus the surface energy values at each time frame (*t*), as illustrated in Eq. (8):

$$(IE)_t = (IE)_{t-1} - (SE)_t + (Surface\ Energy)_t \tag{8}$$

Since the initial internal energy of crack formation before cracking occurs is zero, we can obtain the time history of the surface energy given the time histories of the internal energy and the strain energy balances.

IV. MODEL CHARACTERISTICS AND MATERIAL PROPERTIES

Given the fact that predicting glass failure patterns, crack propagation paths, and the number of these glass fragments and their velocities and flying distances are very complex, the current blast-resistant glazing guidelines mostly utilize either empirical formulations or simplified numerical simulations. The empirical formula, however, is mainly based on field observations and simplified approaches and makes major assumptions, such as the initial fragment size values.

In this paper, simply-supported annealed glass (AG) and fully-tempered (FT) glass window panels with three different sizes are modeled and analyzed as follows: (1) Small window panels of 50 cm x 75 cm (20" x 30"); (2) Medium window panels of 80 cm x 100 cm (32" x 40"), and (3) Large window panels of 100 cm x 135 cm (40" x 54").

Due to the high velocity of the air blast wave (normally in milliseconds), building occupants have little time to prepare for the arrival of the wave. Each window panel size is studied under three different air blast loadings: (i) Small intensity blasts from 100 lbs of TNT; (ii) Medium intensity blasts from 1000 lbs of TNT, and (iii) High intensity air blasts from 5000 lbs of TNT. The stand-off distance, at which the explosives are detonated, is set at 100 ft (30.5 meters) for all three explosive weights. According to the Defense Threat Reduction Agency Manuals, this is the stand-off distance that will cause severe wounds and the maximum amount of casualties by flying glass shards. However, due to the extremely high blast overpressure in the case of 5000 lbs of TNT at 100 ft, the failure mode of the proposed glazing systems will mainly be dominated by the intensity of the load rather than the effects of the glazing systems' aspect ratios.

Given the weight of the explosive (*W*) and the stand-off distances (*R*) for each blast loading intensity, the blast load characteristics including the Peak pressure (P_r), Reflected impulse (i_r) and the Load duration (t_0) are summarized in Table 1 using the "A.T. Blast" software [11].

TABLE 1 BLAST LOADING CHARACTERISTICS

W (Kg)	R (m)	i_r (Pa . ms)	P_r (Pa)	t_0 (msec)
45.0	30.5	2.50×10^5	3.98×10^4	12.55
453.5	30.5	1.25×10^6	1.65×10^5	15.12
2268.0	30.5	3.99×10^6	6.80×10^5	11.75

Annealed Glass (AG) is the most common type of glass in conventional construction and building envelope systems. It fractures in irregular patterns (with aspect ratios that can reach as high as 10), which leads to sharp glass shards that cause injuries to building occupants [12]. Fully Tempered (FT) glass is made by controlling uniform heating and rapid cooling of annealed glass (AG). However, FT panels have more hardening and approximately four times the strength of annealed glass. They have a different shattering pattern: they break into numerous smaller fragments [13].

In this paper, the window panel is modeled using two types of glazing materials: Annealed Glass (AG) with 6.0 mm (1/4") thickness and Fully Tempered (FT) glass with 7.5 mm (0.3") thickness. The models' material properties are summarized in Table 2.

TABLE 2 GLAZING MATERIAL PROPERTIES

Glazing Material	Elastic Modulus (GPa)	Poisson's Ratio	Density (kg/m^3)	Fracture Strength (MPa)
Annealed Glass	69	0.22	2491.19	27.58
Fully Tempered Glass	69	0.22	2491.19	110.32

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V. PROPERTIES OF THE MESH AND THE EXPLICIT FINITE ELEMENT ANALYSIS

Belytscheko et al. [14] illustrated that the tangent stiffness matrix is not required for explicit dynamic methods. These methods are used to model and solve problems involving air blasts, considering the high-speed short-duration nature of such loads in congruence with a stability limit (defined as a small time increment that is independent of the type and duration of the loading) [15]. As shown in Eq. (9), the stability limit solely depends on the model's highest natural frequency model ($\omega_{\max}$) and the fraction of critical damping ($\xi_{\max}$) in the mode with the highest frequency [10]:

$$\Delta t_{stability} \leq \frac{2}{\omega_{\max}}\left(\sqrt{1+\xi_{\max}{}^{2}}-\xi_{\max}\right) \tag{9}$$

A more conservative and practical method to calculate the stability limit of the explicit analysis is based on the smallest element length in the mesh (L_{min}) and the dilatational wave speed of the material (c_d):

$$\Delta t_{stability} \approx \frac{L_{\min}}{c_d} \tag{10}$$

According to Belytscheko et al. [14], larger element sizes will increase the stability limit. However, Ataei and Anderson [16] demonstrated that because finer mesh sizes are often necessary to obtain more accurate analysis results, the best approach is to have a fine mesh that is as uniform as possible to obtain the highest possible stability limit.

In this paper, a very fine 4-noded square shell elements mesh is employed to model the entire window panel as one single 3-dimensional deformable shell across the thickness. The studied small window panel (50 cm x 75 cm) has a total of 3750 elements. However, through several mesh refinement iterations to achieve higher precision in modeling glass failure analysis, the number of elements was increased to 15,000. The total number of elements in the medium window panel (80 cm x 100 cm) is 8000 elements, which further refined to 14,250 elements for further computational precision. The total number of elements for the studied large window panel (100 cm x 135 cm) is 13,500 elements.

According to finite element analysis principles for dynamic problems, acceleration at the beginning of the current time increment (t) is calculated as:

$$\ddot{u}]_{(t)} = (M)^{-1}.(P-I)]_{(t)} \tag{11}$$

Where (M) is the Mass Matrix; (P) is the external applied forces, and (I) is the internal element forces. Since the acceleration values of any node are determined solely by its mass and the net force acting on the node, this method makes the nodal computations very inexpensive.

Acceleration is integrated through time by applying the central difference rule to calculate the change in velocity. To determine the velocities at the middle of the current increment, the calculated change in velocity is added to the velocity from the middle of the previous infinitesimal time increment, as per Eq. (12):

$$\dot{u}]_{(t+\frac{\Delta t}{2})} = \dot{u}]_{(t-\frac{\Delta t}{2})} + \frac{\left(\Delta t]_{(t+\Delta t)} + \Delta t]_{(t)}\right)}{2}\ddot{u}]_{(t)} \tag{12}$$

The velocities are therefore integrated through time and added to the displacements at the beginning of the increment to find the displacements at the end of each time increment:

$$u]_{(t+\Delta t)} = u]_{(t)} + \Delta t]_{(t+\Delta t)}\,\dot{u}]_{(t+\frac{\Delta t}{2})} \tag{13}$$

Once the incremental strain rate ($\dot{\varepsilon}$) and the element strain increments ($d\varepsilon$) are calculated and the element stiffness relationships are applied, the element stresses (σ) are computed to be used in the assembly and computation of the internal forces matrix at each time increment.

VI. BRITTLE FAILURE FINITE ELEMENT ANALYSIS OF THE GLAZING SYSTEMS

To study the behavior of the modeled glazing systems that are subjected to the air blast intensities, an infinitesimal time increment of 0.0125 milliseconds (*0.0000125 sec*) is adopted to advance the state of the modeled geometry in dynamic explicit analysis. During the FE analysis, the elements that reach their local failure criteria (i.e. stress, strain, or crack-tip displacement)

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are removed from both the panel mesh and geometry before the re-meshing of the new geometry and the advancement the model to the next timeframe.

Glass panels demonstrate linear elastic behavior until the brittle failure point is reached. Therefore, the maximum (normal) stress criterion is used to identify glazing system failure. This criterion states that failure occurs when the maximum principle stresses in the two-dimensional coordinate system (σ_1, σ_2) reach either the uniaxial tension (σ_t) or the compression strength (σ_c) values of the glass. For the cracking and failure analysis, the fracture patterns of the studied glazing systems are modeled with the "*BRITTLE FAILURE" feature in ABAQUS.

The ASTM standards (ASTM E2461) [17] and Canadian standards (CAN/CGSB-12.20-M89) [18] limit the allowable maximum fracture stress for annealed glass to 25 MPa (3.63 ksi) in the center of the panel and 20 MPa (2.90 ksi) along the edges. Glass deflection is limited to the least of either span length divided by 175 or to 3/4" (whichever is less). Moreover, the shock tube experiments performed by Kumar and Shukla [19] propose an allowable strain of 0.01% for annealed glass panels before fracture, as well as a maximum deflection of only 2 mm (0.079") prior to shattering.

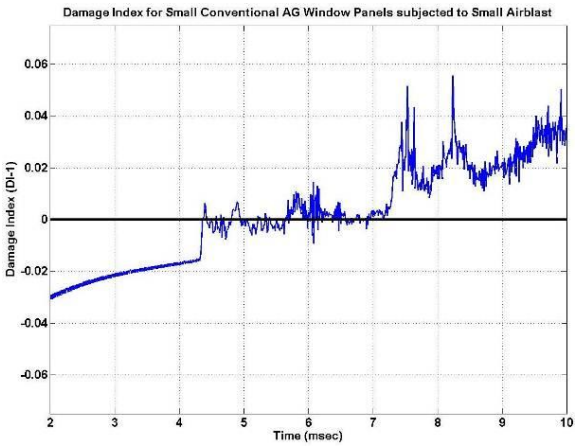
In the element deletion method, the stress values across the panel at each time frame are a true representation of the real stress state in the glass panel: As more elements reach their failure and are removed from the geometry, this computational technique takes into account the stress concentrations at the crack tips as well as the real stress wave distribution paths across the panel. Moreover, the failure times in the element deletion technique allows for the tracing of pre and post-crack behavior with greater accuracy and confidence.

VII. ANALYSIS AND THE DAMAGE INDEX TIME HISTORIES

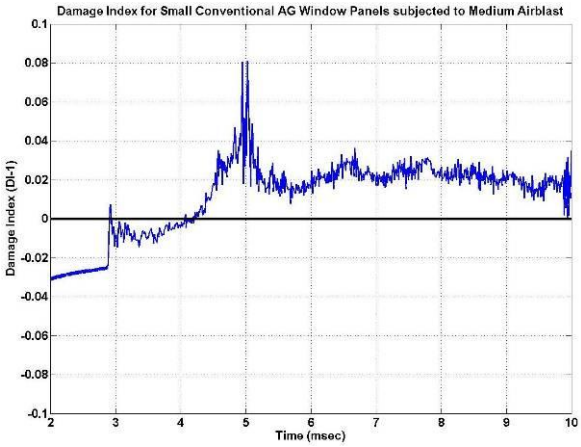
The results of analytical calculations based on the energy methods indicate that annealed glass panels will crack and fail when subjected to all proposed loading cases. However, fully tempered glass will crack and fail when subjected to the medium and high intensity air blasts. The Damage Index calculations indicate that when laminated glass panels are subjected to high-intensity air blasts, the formation and propagation of cracks in the panels will be inevitable. These panels, however, show better resistance towards small and medium intensity loads, compared to both annealed and fully tempered glass panels. Finite element simulations verify these conclusions.

Based on the described energy model for glass fragments, the glass debris size and shape will depend on window type and composition. Given the rectangular mesh that is used to model window panels, it is likely that more square-type glass fragments will occur in fully tempered and laminated panels based on Griffith's model and the developed Damage Indices. Since this analysis is based on the concept of surface energy, the size of the fragments will depend on glass panel characteristics (window sizes, boundary conditions, thickness and panel composition) as well as blast loading intensities (weight of the explosives and the stand-off distances). For lower blast pressures, fewer shards larger in size will be generated. However, for higher blast pressures, there will be more numerous but smaller fragments. These fragments, due to their lower mass and higher kinetic energy, will fly in the air with higher translational velocities to farther distances.

The Damage Index time histories for different glazing systems are presented in Figs. 3 to 9.



(a)



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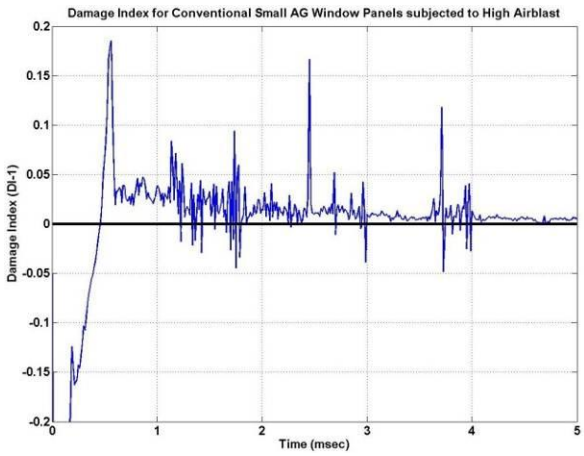
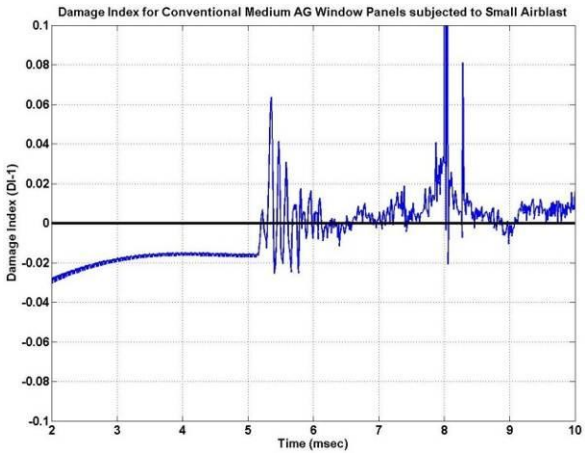
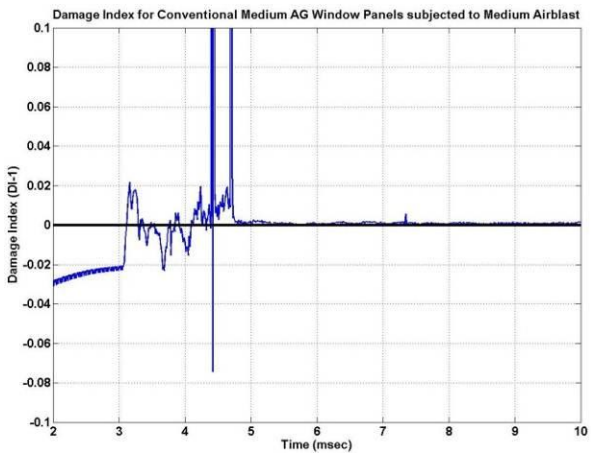


(c)

Fig. 3 Damage Index time histories for small simply supported annealed glass window subjected to: (a) small-intensity air blast, (b) medium-intensity air blast, and (c) large intensity air blast



(a)



(b)

Fig. 4 Damage Index time histories for medium simply supported annealed glass window subjected to: (a) small-intensity air blast, (b) medium-intensity air blast

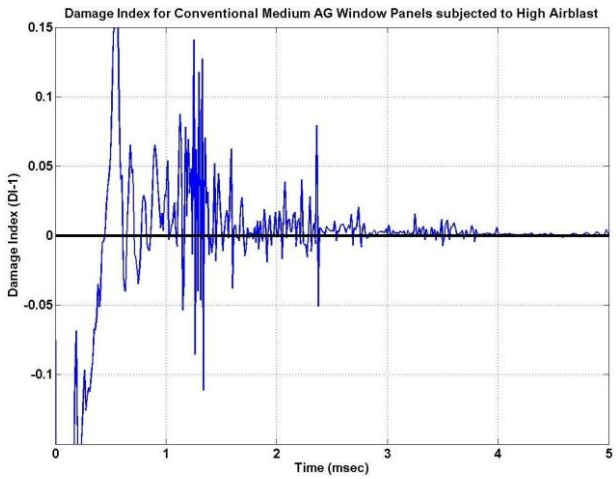


Fig. 5 Damage Index time histories for medium simply supported annealed glass window subjected to high-intensity air blast

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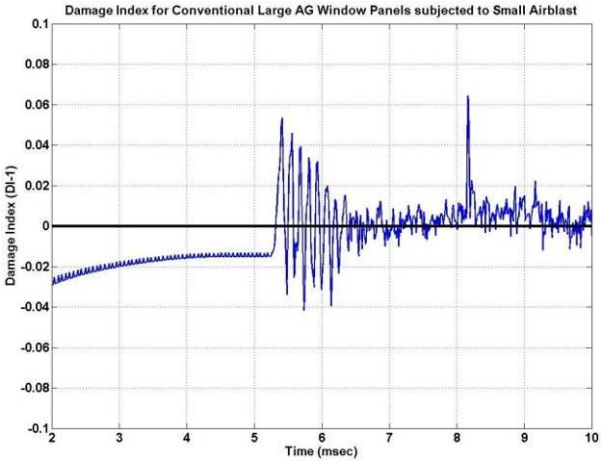
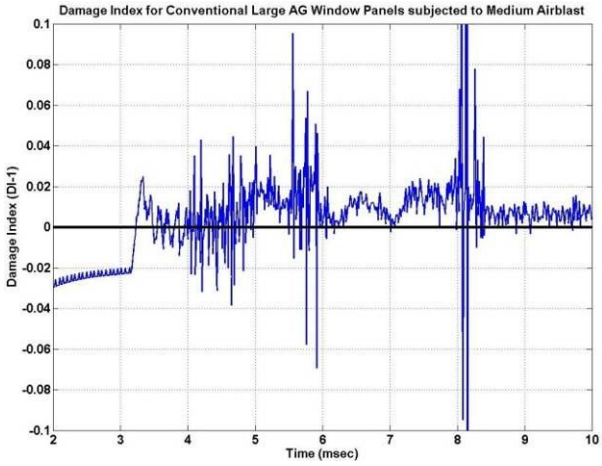


(a)



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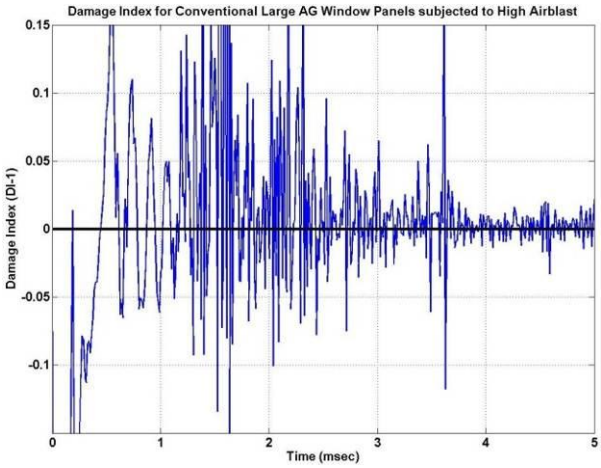
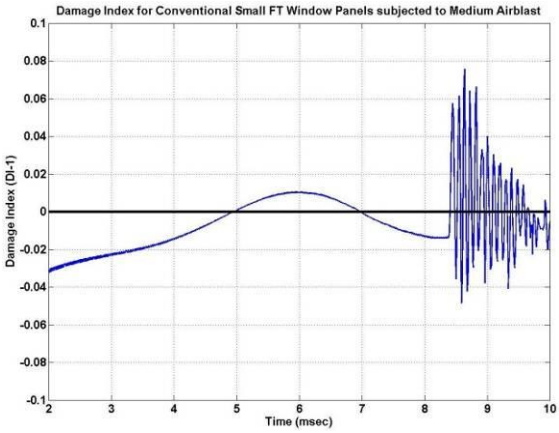
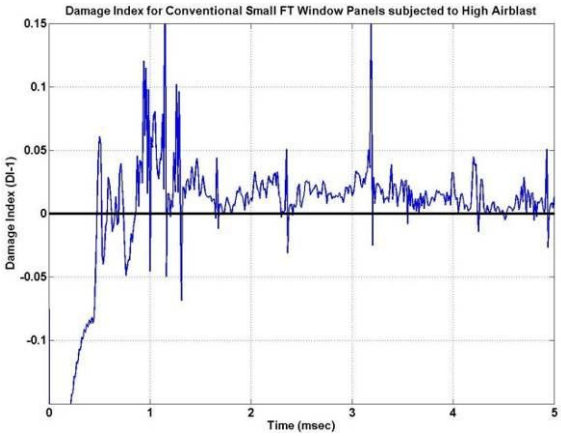


(c)

Fig. 6 Damage Index time history for large simply supported annealed glass window subjected to: (a) small-intensity air blast, (b) medium-intensity air blast, and (c) high-intensity air blast



(a)



(b)

Fig. 7 Damage Index time history for small simply supported fully tempered glass window subjected to: (a) medium-intensity air blast, (b) high-intensity air blast

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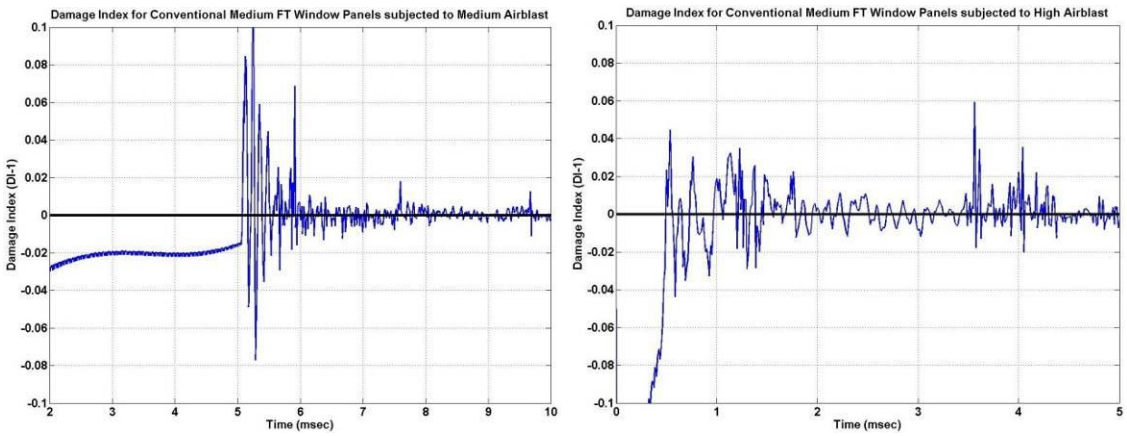
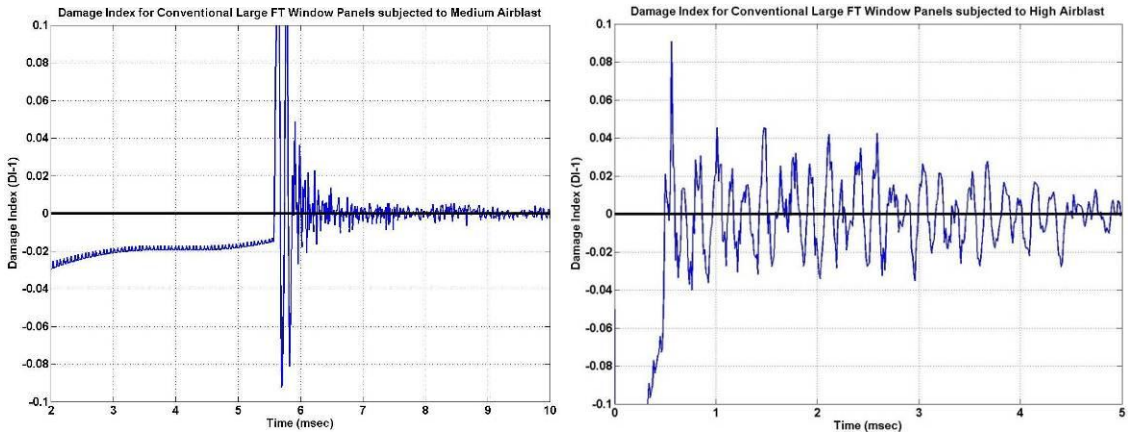


(a) **(b)**

Fig. 8 Damage Index time history for medium simply supported fully tempered glass window subjected to: (a) medium-intensity air blast, (b) high-intensity air blast



(a) **(b)**

Fig. 9 Damage Index time history for large simply supported fully tempered glass window subjected to: (a) medium-intensity air blast, (b) high-intensity air blast

Tables 3 and 4 summarize the result of the Damage Index (*DI-1*) calculation for annealed glass and fully tempered glass panels, for all the three window sizes with simply supported boundary conditions and for all the blast loading intensities. These results will be further compared and verified by finite element simulations.

The calculation of glass fragment (or shards) flying velocities by analytical solutions and the use of energy methods takes into account all characteristics of the glazing system as well as blast load intensities. It accounts for window panel sizes (small, medium or large), glazing system technology (annealed glass or fully tempered), window framing condition (simply-supported), as well as blast load characteristics (small-intensity, medium-intensity or high-intensity air blasts). Definition using the Damage Index, predicts more accurately whether failure will occur in the window panel and when the first cracks will appear across the window panel surface when subjected to all proposed loading cases.

As seen in Tables 3 and 4 (below), the results of energy-method calculation are in good agreement with those of the finite element simulation. Both methods confirm the initial predictions of panel failure through the yield-line analysis application.

FT glass cracks and fails only when subjected to medium and high intensity air blasts. These panels do not break when subjected to small intensity air blast. Compared to the annealed glass panels, they show better resistance towards higher intensity loads with regards to crack initiation times. Based on the described energy model for glass fragments, it can be argued that glass debris size and shape depend on window type and composition, given that the rectangular mesh is initially used to model the window panels. The size of the fragments and the flying velocities will depend on glass panel characteristics (window sizes, boundary conditions, thickness and panel composition) as well as blast loading properties (weight of the explosive charges and the stand-off distances). For lower blast pressures, fewer shards larger in size will be generated. However, for higher blast overpressures, there will be more numerous but smaller fragments.

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TABLE 3 CRACK INITIATION TIMES (FIRST CRACK) FOR SIMPLY SUPPORTED ANNEALED GLASS WINDOW BASED ON THE ENERGY METHODS AND FINITE ELEMENT SIMULATION

		45 Kg TNT at 30.5 m			453 Kg TNT at 30.5 m			2268 Kg TNT at 30.5 m		
		Finite Element Simulation	Energy Methods	Error (%)	Finite Element Simulation	Energy Methods	Error (%)	Finite Element Simulation	Energy Methods	Error (%)
Simply-Supported Conventional AG Window Panels Crack Initiation Times (*msec*)	Small AG Panels (75 cm x 50 cm)	4.400	4.376	0.5	2.938	2.913	0.9	0.588	0.463	21.3
	Medium AG Panels (100 cm x 80 cm)	5.213	5.213	0.0	3.189	3.125	2.0	0.425	0.450	5.9
	Large AG Panels (135 cm x 100 cm)	5.338	5.325	0.2	3.300	3.239	1.8	0.600	0.450	25.0

TABLE 4 CRACK INITIATION TIMES (FIRST CRACK) FOR SIMPLY SUPPORTED FULLY TEMPERED WINDOW PANELS BASED ON THE ENERGY METHODS AND FINITE ELEMENT SIMULATION

		45 Kg TNT at 30.5 m			453 Kg TNT at 30.5 m			2268 Kg TNT at 30.5 m		
		Finite Element Simulation	Energy Methods	Error (%)	Finite Element Simulation	Energy Methods	Error (%)	Finite Element Simulation	Energy Methods	Error (%)
Simply-Supported Conventional FT Window Panels Crack Initiation Times (*msec*)	Small FT Panels (75 cm x 50 cm)	No Breaking		-	8.425	8.888	5.5	0.550	0.488	11.3
	Medium FT Panels (100 cm x 80 cm)	No Breaking		-	5.088	5.088	0.0	0.600	0.500	16.7
	Large FT Panels (135 cm x 100 cm)	No Breaking		-	5.588	5.588	0.0	0.625	0.500	20.0

VIII. SUMMARY AND CONCLUSION

Mitigating injuries from flying glass debris from air blast loading requires that the glass panel responses to blast loading intensities be investigated. During an air blast event, glass panels break into numerous fragments or shards with high velocities that shatter inside the residential and office spaces. These glass particles account for many injuries to building occupants, varying from minor cuts to severe laceration wounds, trauma, or in many cases to death. Therefore, analysis of flying glass dynamics is an important step forward in improving safety.

This paper used analytical calculations based on the Griffith Brittle Failure Theory and the Energy Methods to estimate whether a glass panel subjected to an air blast fails and when the first crack starts propagating across the panel, in order to obtain crack initiation times and compare them with numerical simulation results.

The numerical solutions and analytical methods take into account glass panel characteristics. This renders results that better represent glazing system parameters, an advantage that is often overlooked when using simplified methods or empirical approaches for glass fragment velocity and hazard assessment calculations.

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