# The Influence of Structural Arrangement on Long-duration Blast Response of Annealed Glazing

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# Abstract

This paper investigates the influence of structural arrangement on long-duration blast loaded annealed glazing via variable thickness, area, aspect ratio and edge support conditions. Initially, the findings of eighteen full-scale air-blast trials employing 33 annealed glazing panels are reported where it is demonstrated that fracture mode and fragmentation are a strong function of edge supports. Rigidly clamped edges are shown to induce localised stress transmission, producing significant cracking and small fragments. In contrast, elastic edges are shown to produce large, angular fragments, demonstrating the importance of accurately modelling edge conditions when analysing fragment hazard. Quantification of peak centre panel deflection and breakage time is then presented where variable results indicate the influence of edge supports and aspect ratio to be dependent on proximity to the threshold area as a function of glazing thickness. An initial Applied Element Method (AEM) analysis is then employed to model the influence of structural arrangement on long-duration blast-loaded annealed glazing. AEM models are shown to reasonably predict glazing fragmentation behaviour, breakage time and peak panel deflection at the moment of breakage. Thus indicating AEM's potential suitability to provide a predictive capacity for annealed glazing response during long-duration blast.

**Keywords:** long-duration blast, explosion, glazing, edge supports, applied element method, hazard

# Notations

A: Length of representative area, m

D: Distance between springs, m

E: Young’s modulus, Pa

G: Shear modulus, Pa

$k_{normal}$: Virtual spring normal stiffness

$k_{shear}$: Virtual spring shear stiffness

n: Sample size

P-I: Pressure-impulse

s: Standard deviation

t: T-score

T: Element thickness, m

$t_a$: Time of blast arrival, ms

ρ: Density, kg/$m^3$

$\sigma_{\bar{X}}$: Standard error

$\bar{X}$: Mean

## 1.0 Introduction

Long-duration blasts can be characterised by positive phase durations in excess of 100ms with recent examples including the ‘Buncefield Disaster’ (2005) and the West, Texas (2013) fertiliser plant explosion. These events generate substantial impulse and dynamic pressures which significantly exceed shorter duration blasts with equal static overpressure. Thus producing catastrophic levels of global structural distortion and widespread damage for structural elements such as annealed glazing panels. Fragments are also propelled significant distances downstream as demonstrated by long-duration nuclear events in Japan. Glazing injuries were reported at 3.2km in Hiroshima and 3.8km in Nagasaki [1], equivalent to a sixteen times increase in damage radius versus significant structural damage. Cheap and readily available, reports suggest annealed glazing accounted for ~90% of UK building glass towards the end of 20th century [2]. As a chemically amorphous material it cannot undergo plastic deformation, resulting in sudden failure under tension. While theoretical strength estimates reach 18GPa [3], actual strength is significantly reduced with an upper limit imposed by micro flaws which are randomly distributed throughout the surface. In the case of planar blast loading, glazing panels are subjected to membrane stresses which induce initial cracking at a critical flaw.

As a result of its prevalence and significant hazard potential there has been considerable research into blast effects on glazing. While much of this has emphasised shorter duration events, Iverson [4] analysed annealed ‘float’ and ‘sheet’ glazing response to long-duration nuclear blast while evaluating fallout structure performance. Three full-scale air-blast events subjected various test structures to ~13kPa peak static overpressure. Results showed ~100% breakage for 3-8mm thick glazing at face-on and side-on positions with ~50% failure reported for rear panels.

Sizable frame distortions were observed with heavier 8mm glazing, indicating the potential for edge support conditions to introduce localised glazing stresses and therefore influence breakage probability. A similar study conducted by Fletcher et al. [1] subjected 52 annealed glazing panels of 3-6mm thickness to blast loads from two high-explosive long-duration blast trials. Glazing response was analysed as a function of varying stand-off, framing and aspect ratio. With limited measurement capabilities, analysis was constrained to the binary condition of breakage versus survival. Observations did however indicate that breakage probability was a function of glazing area, thickness, edge supports, angle to the blast wave and additional stresses introduced during installation.

A large series of short duration blast trials conducted over the period 1982-1997 utilised test cubicles to subject annealed glazing panels of varying thickness to a range of blast loads [2]. These results formed the damage and hazard assessment tool, The UK Glazing Hazard Guide [5]. Constant damage boundaries were plotted as hyperbolas on ISO damage curves or (P-I) charts as shown in Figure 1. Horizontal pressure and vertical impulse asymptotes represent minimum damage conditions, thus enabling estimated pressure and impulse combinations to predict glazing breakage and an implied fragment hazard level using the diagram in Figure 2. This hazard tool addressed ~30 glazing configurations with variable thickness at two standard sizes (1.55m x1.25m & 0.55m x 1.25m). There is however no provision for variable edge supports, additional aspect ratios, glazing areas or structural geometry diversity which can introduce non-negligible blast clearing effects.

Much of contemporary research has focussed on blast mitigation strategies via laminated glazing coupled with structural silicone. Studies by Yarosh et al. [6] and Hautekeer et al. [7] examined the performance of structural silicone at high-speed tensile loads where results demonstrated ultimate tensile strength increases of up to 60%. Weggel and Zapata [8] and Seica et al. [9] analytically investigated edge support influence on laminated glazing via FE modelling and silicone supports were found to reduce glazing modal frequencies when compared with simply supported models. Edge supports were found to produce negligible differences in peak deflection amplitude, but principal glazing stress reductions of up to 40% were reported for structural silicone [8]. An analytical study by Larcher et al. [10] investigated the influence of edge conditions on laminated glazing response. FE modelling results showed a ~12% decrease in deflection for elastic (rubber gasket) supports versus rigid and crack patterns were found to be a function of edge fixing. Amadio and Bedon [11] utilised FE analyses to investigate the advantages of flexible viscoelastic spider supports in cable-supported laminated façades versus rigid spider connections. Results exhibited a principal glazing stress reduction of up to 45% for viscoelastic supports with minimal differences reported for peak displacement values. Experimental analysis conducted by Zhang and Hao [12] compared laminated glazing response to short-duration blast loading with rigid edge conditions and a novel sliding boundary arrangement. Post-trial analysis indicated minimal interlayer tearing for the panel with the sliding boundary versus the rigid arrangement, demonstrating a significant reduction in glazing hazard.

At present, there are no experimental studies which systematically investigate and quantify the influence of edge supports, glazing thickness, area and aspect ratio on annealed glazing response to long-duration blast loading. This paper attempts to redress this by reporting experimental findings from a series of 18 full-scale long-duration blast trials. These were conducted at the UK national blast test facility, the Air Blast Tunnel (ABT) at MOD Shoeburyness. This is one of a small number of facilities in existence able to produce full-scale long-duration blast waves associated with multiple tonnes of explosive material via 0.5-4kg of TNT equivalence, thus representing a cost-effective solution. Initial attention focusses on characterising the variability of the experimental blast environment. The influence of edge support conditions is then discussed with a focus on variable fragmentation modes and the implications for hazard. Variations in peak centre panel deflection and breakage time will then be reported as a function of the aforementioned experimental parameters. Thus providing essential glazing response data which can be used to benchmark computational models. The final part of this study attempts to model glazing response through a series of Applied Element Method (AEM) simulations. The AEM analysis aims to investigate the suitability of this new technique to provide future predictive capacity for annealed glazing breakage due to long-duration blast.

## 1.1 The Applied Element Method (AEM)

A relatively new computational structural dynamics technique, AEM and specifically the Extreme Loading for Structures (ELS) solver [13] utilises a ‘virtually discretized’ continuum material approach with a force-displacement methodology. Fast solution times coupled with complex capabilities enables ELS to model each phase of glazing response during blast including initial deflection, fracture and discrete fragment translations via continuum separation. ELS utilises an explicit AEM solver with a Lagrangian reference frame to analyse virtually ‘de-coupled’ continua and associated force-displacement calculations. Virtual discretization of the material continuum enables simulation of elastic and non-linear behaviour including ‘virtual element’ separation into rigid-body elements. These are connected via zero length matrix springs as shown in Figure 3. Virtual matrix springs represent the sum of three components, enabling stress and strain calculations in six degrees of freedom where normal and shear spring stiffness properties are determined via equations 1-2. Each matrix spring set accounts for a partial element volume as determined by spring quantity, enabling spring deformations to fully represent virtual element behaviour. This includes distortions, bypassing the limitations of a rigid-body methodology. AEM produces local stiffness matrices per set of springs before summing to determine a global element matrix. Trivial matrix manipulation finally enables displacement determination. AEM's virtually discretized continuum model contrasts with the widely-used Finite Element Method's (FEM) constant material continuum with nodal connectivity.

$$k_{normal} = \frac{E \times D \times T}{A} \tag{1}$$

$$k_{shear} = \frac{G \times D \times T}{A} \tag{2}$$

Automatic element separation and continuum fracture are modelled via the material law and a non-dimensional strain parameter. Specifically, glazing breakage is determined via modulus of rupture and a constitutive separation strain value where exceedence permits spring removal, enabling fragmentation and fragment flight. Angular fracture modes are modelled via Delaunay triangulation during the spatial discretization phase as shown in Figure 4. Unique subdivision of the total area into polygon seed regions defines a Voronoi diagram. Each region represents a spatial area closer to its seed than any other and neighbouring seeds are connected across region boundaries to produce a Delaunay diagram and thus triangulated discretization. This is analogous to discrete Kirchhoff triangular elements available with finite element modellers such as Europlexus as utilised by Larcher et al. [10].

ELS currently utilises a linear elastic and homogenous glazing material model which limits the randomisation of initial fracture location. Parametric variation can however be utilised to vary breakage strength. The accuracy and stability of the explicit solver is a function of the solution interval which is determined by the loading regime. Impulsive blast loading requires microsecond intervals over the relatively short loading duration. Simulation accuracy is also a function of spatial discretization coarseness and to a lesser degree, virtual spring quantity. Meguro and Tagel-Din [14] conducted a set of 2D analyses while developing AEM to determine zero translational displacement error with varied spring quantity. Rotational motion errors were however reported in the range of 1-25% as a function of spring quantity. Further analyses showed error amplification to be linked to large element sizes relative to the total structure geometry. Reduced element geometries eliminated this rotational error irrespective of spring quantity, demonstrating that solution accuracy is a strong function of element size only.

## 2. Experimental Procedure

Eighteen full-scale, long-duration blast trials employing 33 annealed glazing panels were conducted in the Air Blast Tunnel (ABT) at MOD Shoeburyness in the UK as detailed in Table 1. These aimed to characterise glazing fracture mode, deflection and breakage time as a function of glazing thickness, area, aspect ratio and edge support conditions. A series of shorter duration blast trials previously conducted by Johns and Clubley [15] identified 14kPa peak static free-field overpressure to represent the breakage threshold for 8mm annealed glazing, corroborating with The UK Glazing Hazard Guide [5]. Each of this study’s trials was subsequently designed to utilise constant ~14kPa peak static free-field overpressure and ~110ms positive phase duration with an acceptability level of +/- 10%. The ABT as shown in Figure 5 is an explosively driven shock-tube facility which can simulate long-duration blast events via planar shock waves [16]. By utilising 0.55kg of helically wound Cordtex (PETN), the ABT was able to generate the design blast environment. Thus simulating an air-blast with TNT equivalence of 15 tonnes at 250m stand-off when calculated via the Kingery predictive polynomials [17].

To investigate the influence of edge supports on glazing response, two conditions were imposed in each trial, namely ‘rigid’ and ‘elastic’ as detailed in Figures 6-7 and Tables 2-3. These were designed to represent quantifiable conditions at opposing ends of a rigidity spectrum. Rigid supports were modelled via two-way spanning steel clamp restraints which were uniformly torqued to 4Nm. Compressible gaskets were utilised at frame-to-glass interfaces to limit the likelihood of surface defects inducing cracking during installation. Steel thicknesses of 8-10mm were selected to adequately resist design stress from a 14kPa uniformly distributed load. Elastic edge conditions were modelled via two-way spanning, rear-face structural glazing silicone joints. The two-part structural glazing product Dow Corning 993 was selected with dimensions designed to resist cohesive and adhesive failure modes under load as detailed in Table 3. Peel adhesion tests were performed at 48 hour intervals after silicone application where results demonstrated 100% cohesive failure, indicating adequate adhesion to the steel frame members. Total and net exposed glazing areas (i.e. blast-loaded surface minus edge restraint) were maintained as constant parameters for both edge conditions and aspect ratios as detailed in Table 2.

Trials 1-12 focussed on 4mm and 8mm thicknesses with ‘threshold breakage’ dimensions as shown in Table 2. Prior to conducting the blast trials, threshold dimensions were numerically predicted via preliminary AEM models that extend the experimentally benchmarked solutions presented by Johns and Clubley [15]. These simulations indicated a breakage limit in the form of a minimum required area as a function of glazing thickness, assuming constant material parameters and blast environment. The influence of aspect ratio on response was also examined experimentally as AEM analyses indicated possible breakage variability in the region of 1:1.75 with constant threshold area and blast. As shown in Table 1, eight unique testing arrangements were repeated in triplicate for these twelve trials to accommodate potential response variability associated with proximity to the breakage threshold. Thus providing valuable data for statistical variance relating to each of the measured glazing response characteristics.  A further six trials (13-18) aimed to examine the relationship between threshold dimensions and glazing thickness as shown in Table 2. This was achieved by utilising 4mm glazing with panel dimensions equal to the threshold criteria utilised for 8mm glazing in trials 7-12. Three unique arrangements were employed for these six trials with each repeated three times, allowing for response variability and providing redundancy as detailed in Table 1. This also enabled quantification of statistical variance for each of the glazing response characteristics.

Rapidly de-mountable and modular glazing sub-frames were fixed to a bespoke, armoured twin test cubicle structure as shown in Figure 8. These mountings were uniformly torqued to 40Nm at test cubicle interfaces to form a rigid continuum. The test cubicle structure itself was positioned within the 10.2m diameter ABT test section and constructed by linking two shipping containers via interior steel sections and 20mm steel plate on each exterior surface. Frontal surfaces were retrofitted with 30mm steel plate and H-section stiffeners to limit the likelihood of flexural deformation interfering with glazing response. The structure was positioned with a normal orientation to the approaching blast wave before being secured to the ground surface to prevent downstream translation. Utilising this twin cubicle arrangement enabled each trial to compare the influence of edge supports upon glazing response for panels of equal thickness, area and aspect ratio.

Blast environment data was captured by instrumenting the 10.2m ABT section with Endevco 8510C static overpressure gauges as shown in Figure 9. Thus enabling the measurement of peak pressures, specific impulse and positive phase durations for the static and dynamic free-field environments. Reflected static overpressure was measured for each glazing panel via Kistler 603B1 pressure transducers fixed to the test structure front surface. The validity of this approach was demonstrated by Johns and Clubley [15] in a series of shorter duration high explosive blast trials where reflected glazing panel pressure was shown to correlate with measurements from test cubicle front surfaces. Characterisation of the reflected blast environment enabled the measurement of cumulative specific impulse up to the moment of breakage, subsequently representing applied breakage impulse. Each of the aforementioned pressure devices was calibrated to enable time sequencing with the ABT electrical detonation trigger, thus defining accurate blast arrival.

Ten high-speed Phantom v7.3 cameras were deployed at 2000fps with 800x600 resolution to capture glazing panel response during loading as shown in Figure 9. LEDs positioned within the test structure were utilised to signal blast arrival via pressure-triggered illumination. Thus enabling semi-qualitative analysis of glazing panel breakage times as determined by initial panel fracture and qualitative examination of panel fragmentation modes. Test structure side-perspectives were aligned with central glazing panel axes to minimise the influence of parallax error on displacement measurements for breakage deflection and fragment flight distances.

‘Mirrored’ camera views also enabled displacement variability calculations while providing redundancy. Distance markers were positioned throughout the test cubicles to provide fragment reference points within high-speed footage as shown by the multi-coloured balls in Figure 10a. Monochrome deflection gauges were also fixed to the rear of each glazing panel as shown in Figure 10b. By providing a known reference distance, these gauges facilitated calibration of Phantom video files for a relative quantity of pixels to enable measurements to be made from high-speed footage.

## 3. Numerical Procedure

Numerical modelling of the long-duration blast response of annealed glazing was conducted with the AEM explicit solver, Extreme Loading for Structures (ELS) [13]. Dynamic blast load application was configured via experimental reflected pressure-time data and AEM models were produced for individual test cubicles with glazing panels mounted to the front surface as shown in Figure 11. Annealed glazing is often modelled as linear elastic up to failure and this paper utilised manufacturer supplied static-load material parameters to define the material law as detailed in Table 4. The accuracy of this approach was demonstrated by Johns and Clubley [15] when experimentally benchmarking AEM models of annealed glazing response to shorter duration blast loading. Glazing breakage which is represented by element separation was configured via the fracture toughness parameter of separation strain as shown in Table 4. This was previously established through a trial and error comparison against high-speed video data for glazing response [15]. Future research will aim to investigate the relationship between load-duration dependency and separation strain.

Delaunay triangulated spatial discretization was employed to simulate angular fracture indicative of annealed glazing. Glazing panel models were constructed with 1 element in x-y and y-z planes and a variable number in the x-z plane. 4mm glazing models with 0.25m$^2$ frontal area utilised 750 x-z plane elements versus 1500 elements for each of the 8mm and 4mm glazing models with 0.89m$^2$ frontal area. These produced lower bound fragments between 0.03% and 0.06% of total window mass, enabling element geometries to limit rotational inaccuracies as indicated in the literature [14]. Rigid edge supports were modelled via two-way spanning framing members with fully restricted degrees of freedom as shown in Figure 12a. Elastic edge supports were modelled via two-way spanning structural silicone adhesive as shown in Figure 12b. The silicone was modelled with the Dow Corning 993 material parameters detailed in Table 5. The relatively low Young's modulus in Table 5 demonstrates high ductility and as such this material was designed as an ELS tension model. These neglect shear strength due to predominant tensile forces, thus preventing cohesive failure via material continuum separation. Each of the AEM simulations was conducted using a dedicated dual quad core Intel i7-2600 3.4GHz system with 16GB RAM. Solution intervals were selected as 100µs for models with 0.5s durations which produced mean solver times ranging from 21-28 minutes.

# 4. Results and Discussion

## 4.1 ABT blast environment

Examination of Table 6 shows mean values of 13.8kPa peak overpressure and 108.6ms for the positive phase were recorded by the free-field gauge abt1-ps, representing good agreement with the design blast environment of 14kPa with 110ms duration. Standard deviation values of 4% and 1% of the mean for pressure and duration respectively indicates a well-replicated blast environment across trials 1-18. This is further indicated by a standard deviation of 3% of the mean for specific free-field blast impulse. Low levels of variability therefore demonstrates that these results have met the acceptability criteria of +/- 10% to provide a relatively constant blast wave throughout the series.

Figures 13a-f provide time histories for reflected overpressure with associated specific impulse for each test cubicle in trials 1-18. Table 6 also details reflected overpressure measurements at glazing locations tc1-pr and tc2-pr. Mean values of 30.5kPa and 30.9kPa were recorded respectively to produce a minor 1.3% relative difference. Mean reflected impulse and positive phase duration measurements were found to differ by 30.9kPa-ms and 0.3ms respectively for these gauges, representing minimal relative differences of 3.4% and 0.26%. Thus suggesting blast wave uniformity across the cross sectional area of the 10.2m diameter ABT section for each of the eighteen trials. Standard deviation values ≤4% of the mean for each of the reflected blast parameters also demonstrates that these results have met the acceptability criteria of +/- 10%, further indicating blast wave repeatability across the series.

### 4.2 Edge support influence on glazing response

Qualitative analysis of glazing fracture for rigid edge supports revealed significant cracking of the glazing material as shown in Figures 14a-b and 14e-f. Indicating that rigidly clamped steel-glass interfaces induced a localised impulsive stress transmission through the amorphous glazing interlayers, producing a greater proportion of small fragments. In contrast, elastically supported panels were found to induce a radial fracture pattern with a greater number of large, angular shards as shown in Figures 14c-d and 14g-h. This represents the failure mode most often associated with annealed glazing [18]. With vastly different fragment masses and geometries, it is evident that edge support conditions may greatly influence potential human hazard or risk during a blast. As a result, smaller fragments associated with rigid edge supports may be propelled greater distances versus larger, heavier shards from elastic supports. Similarly, it can be shown that the impulse imparted by in-flight fragments upon an interacting surface will vary proportionally with fragment mass, adding further complexity to an appraisal of hazard during blast.

## 4.3 Parameter influence on glazing response

### 4.3.1 Deflection

Table 7 details mean values of peak centre panel deflection up to the point of breakage for each of the eleven unique arrangements. Examination of 4mm glazing with 0.25m$^2$ frontal area showed a constant 10mm peak deflection with zero observable difference for varied edge supports or aspect ratio. The Phantom v7.3 cameras utilised to measure panel response were however limited to +/- 1.0mm degree of accuracy, introducing +/- 10% uncertainty to these measurements. This also limited calculations for standard error and 50% confidence interval bounds as shown by zero values in Table 7.

Peak deflection measurements for 8mm glazing with 0.89m$^2$ frontal area showed greater variability with a range of 11-18mm. The rigidly supported 1:1.7 arrangement was found to produce a 50% confidence interval of +/- 1.5mm, equivalent to +/- 9.3% of peak deflection. Confidence intervals were produced using a statistical T-distribution as a result of the relatively modest sample size of three trials per unique structural arrangement. These were calculated with the standard error of the mean as shown in equation 3. The Influence of high-speed video accuracy was partially reduced for 8mm glazing with a range of 5.6-9.1% of mean peak deflection, details of which are given in Table 7.

$$\pm\, t(\sigma_{\bar{X}}) = \pm\, t\, \left(\frac{s}{\sqrt{n}}\right) \tag{3}$$

Analysis of the 8mm results revealed maximum peak deflection values of 18mm and 15mm with rigid supports at 1:1 and 1:1.7 aspect ratios as illustrated in Figure 15. These values were found to reduce by 5mm and 4mm respectively when introducing elastic edge supports, representing 28% and 27% decreases. Rectangular aspect ratios of 1:1.7 were also found to decrease peak deflection by 3mm and 2mm versus 1:1 arrangements for constantly rigid and elastic supports respectively, representing reductions of 17% and 15%. The combination of 1:1.7 aspect ratio and elastic supports produced the largest decrease in mean peak deflection of 7mm or 39% versus the rigid 1:1 arrangement.

Peak deflection for 4mm glazing with 0.89m$^2$ area showed greater variability than the 0.25m$^2$ results with measurements in the range of 18-21mm. The rigidly supported 1:1 arrangement was found to produce a sizable 50% confidence interval of +/- 3.4mm, representing +/- 32.3% of peak deflection. High-speed video measurement uncertainty was partially reduced versus the 0.25m$^2$ results with a range of 4.7-5.6% of mean peak deflection as shown in Table 7.

As expected, Table 7 shows larger deflection values for 4mm glazing with 0.89m$^2$ area versus equivalent arrangements with 0.25m$^2$ area. Table 7 also demonstrates larger deflections for 4mm at 0.89m$^2$ versus 8mm with equal frontal area and equivalent structural arrangement. Further examination of 4mm at 0.89m$^2$ indicates a maximum peak deflection of 21mm for elastic supports at 1:1, representing a 17% increase versus the rigid panel at 1:1 and inverse behaviour to the 8mm glazing results. Mean peak deflection for 4mm at 0.89m$^2$ was found to decrease by 2mm at 1:1.7 aspect ratio compared to the 1:1 panel with constant elastic edge supports, representing a 10% decrease and similar behaviour to 8mm glazing. The combination of rigid supports and 1:1 aspect ratio produced the lowest mean peak deflection value of 18mm for 4mm glazing at 0.89m$^2$. This contrasts with the 8mm results where the smallest deflection was recorded for the elastically supported 1:1.7 panel. It is evident from Figure 15 that 4mm glazing results with 0.89m$^2$ area do not correlate with the static results seen with the 0.25m$^2$ panel area. It is also clear that the oscillatory 4mm results do not correlate with the decreasing trend identified for 8mm glazing with equal 0.89m$^2$ frontal area. Larger confidence interval bounds also suggest a greater likelihood of deflection variability with 4mm glazing at 0.89m$^2$ versus 8mm glazing and the 0.25m$^2$ results.

### 4.3.2 Breakage Time

Table 8 details mean values of breakage time for the eleven unique arrangements. Initial inspection revealed shorter times for 4mm glazing with 0.25m$^2$ area versus 8mm with 0.89m$^2$ area for each equivalent arrangement. Examination of the 4mm results at 0.25m$^2$ shows a range of 2.2-3.1ms, the maximum of which was recorded for the elastically supported 1:1 panel and the minimum for the rigid panel at 1:1.75. Standard errors were produced in the range of 0-0.50ms with the largest value calculated for the elastically supported 1:1.75 panel. High-speed video accuracy of +/- 0.25ms was found to represent 8.1-11% of mean breakage time as detailed in Table 8.

It is evident from Table 8 that elastic supports produced a 0.6ms increase in breakage time versus rigid at 1:1 and a 0.3ms increase versus rigid at 1:1.75, representing 24% and 14% rises respectively. Inversely, aspect ratios of 1:1.75 were found to decrease mean breakage times by 0.3ms and 0.6ms versus 1:1 arrangements for rigid and elastic supports, producing 12% and 19% reductions respectively. These opposing behaviours are demonstrated in Figure 16 where the combination of elastic supports and 1:1.75 aspect ratio produced zero change in mean breakage time when compared with the rigidly supported panel at 1:1. Thus inferring a cancellation effect of these two structural arrangement parameters.

Breakage time measurements for 8mm glazing with 0.89m$^2$ frontal area represent a range of 3.5-4.9ms with the minimum recorded for the elastic panel at 1:1.7 and the maximum for the rigid panel at 1:1. This panel also produced the widest 50% confidence interval bounds of +/- 0.45ms, representing +/- 9.1% of mean breakage time. Longer breakage times than 4mm glazing with 0.25m$^2$ area was found to reduce the influence of high-speed video accuracy to 5.1-7.1% of mean breakage time. Examination of Figure 16 illustrates similar decreasing behaviour to that identified with peak deflection results in Figure 15. This is also evident in Table 8 with a 1.1ms decrease in breakage time for elastic supports versus rigid at 1:1 and a 0.7ms decrease versus rigid at 1:1.7, representing reductions of 22% and 17% respectively. Aspect ratios of 1:1.7 were also found to reduce mean breakage times by 0.7ms and 0.3ms versus 1:1 panels with rigid and elastic supports, representing 14% and 8% decreases respectively. The grouping of elastic supports and 1:1.7 aspect ratio produced the largest decrease in mean breakage time with a 1.4ms or 29% reduction versus the rigid panel at 1:1.

Examination of mean breakage time results for 4mm glazing with 0.89m$^2$ area revealed a maximum recorded value of 3.8ms for the elastically supported 1:1 panel and a minimum of 3.3ms for the elastic panel at 1:1.7. Standard errors were calculated in the range of 0.17-0.58ms with the largest being produced for the rigidly supported panel at 1:1.

Further analysis revealed longer breakage times for 4mm glazing at 0.89m$^2$ versus equivalent arrangements with 0.25m$^2$ frontal area. In contrast, shorter mean breakage times were recorded versus 8mm with equal 0.89m$^2$ area for the 1:1 rigid and 1:1.7 elastic arrangements. Examination of 4mm at 0.89m$^2$ indicates a maximum breakage time of 3.8ms for elastic supports at 1:1. This is equivalent to a 0.5ms or 9% increase versus the rigid panel at 1:1, correlating with 4mm results at 0.25m$^2$ area but representing inverse behaviour to 8mm glazing results for these arrangements. Mean breakage time was found to decrease by 0.5ms for the elastically supported 1:1.7 panel compared to the elastic 1:1 panel for 4mm at 0.89m$^2$, representing a 13% decrease. Thus matching the response of both 8mm glazing at 0.89m$^2$ area and 4mm glazing at 0.25m$^2$ area. The combination of elastic supports and 1:1.7 aspect ratio produced the shortest mean breakage time of 3.3ms for 4mm glazing at 0.89m$^2$ area, representing similar behaviour to 8mm glazing with equal area.

Examination of Figure 16 demonstrates decreased breakage time with rectangular aspect ratio and elastic supports for 8mm glazing, illustrating the same decreasing behaviour identified for peak deflection. Inversely, 4mm glazing at 0.25m$^2$ area exhibits an oscillatory, counter-balance in breakage time, contrasting with static peak deflection results. 4mm glazing at 0.89m$^2$ area follows the same partial upward trend seen with the 0.25m$^2$ panel area for 1:1 arrangements, indicating inverse behaviour to 8mm glazing with equal 0.89m$^2$ frontal area.

### 4.4 Numerical results

Using the numerical procedure described above, a series of AEM simulations were undertaken to model the long-duration blast response of annealed glazing. Peak centre panel deflection was selected as the first metric for base-lining AEM results as shown in Table 9 where experimental measurements are compared to those obtained numerically. Initial inspection of 4mm glazing with 0.25m$^2$ frontal area indicates zero difference for the 1:1 panels and 10% lower AEM deflection for the 1:1.75

arrangements. Thus representing reasonable accuracy for the AEM predictions considering +/- 10% uncertainty introduced by the Phantom v7.3 cameras utilised to measure experimental deflection.

Analysis of 8mm glazing at 0.89m$^2$ area shows correlation between numerical predictions and the experimentally identified decreasing trend. This is visible in Figure 17 where it can also be seen that three of four AEM results are within standard error bounds. Further examination of Table 9 shows AEM predictions for 1:1 arrangements and the rigidly supported 1:1.7 panel to be within +/- 8% of experimental values. With a +2mm difference, AEM deflection for elastic supports at 1:1.7 represents an 18% increase of the mean experimental value, slightly exceeding the standard error range. The combination of elastic edge supports and 1:1.7 aspect ratio produced the largest decrease in predicted peak deflection, agreeing with the experimentally observed response. AEM deflections for rigidly supported panels at 1:1 and 1:1.7 were also reduced with elastic supports, correlating with experimental behaviour. Predicted deflections for 1:1 panels with constant rigid and elastic edge supports were also decreased with 1:1.7 aspect ratio, further matching the experimental response.

Examination of 4mm glazing at 0.89m$^2$ showed AEM predictions to correlate with the experimental trend as illustrated in Figure 17. Further inspection of Table 9 shows the AEM prediction for rigid supports at 1:1 to be 7% lower than experimental deflection and within standard error bounds. With differences of -3mm, AEM deflections for 1:1 rigid and 1:1.7 elastic panels slightly exceed standard error bounds. These predicted values do however exceed those for equivalent arrangements with 8mm glazing at equal area and 4mm glazing at 0.25m$^2$, correlating with experimental results. The combination of elastic edge supports and 1:1 aspect ratio was found to produce the largest predicted breakage deflection, matching the experimental response. Similarly, AEM deflection for the 1:1 panel with elastic edge conditions was found to reduce with 1:1.7 aspect ratio, agreeing with the experimental data.

Table 10 compares mean experimental breakage times to numerical predictions. Examination of 4mm glazing at 0.25m$^2$ shows AEM to be within +/- 13% of experimental values with differences in the range of +/- 0.4ms. A minor 0.1ms difference between predictions for 1:1 rigid and 1:1.75 elastic arrangements correlates with experimental behaviour as shown in Figure 18. AEM breakage time for the rigidly supported 1:1 panel was found to reduce with 1:1.7 aspect ratio, matching the experimental response. The rigid arrangement at 1:1.7 also produced the shortest breakage interval, further agreeing with experimentally observed behaviour. Predicted breakage time for the elastically supported 1:1 panel was found to increase by 0.1ms with 1:1.75 aspect ratio, contrasting with experimental response where a decrease was observed. Examination of Figure 18 shows the AEM results to partially correlate with the counter-balance trend identified experimentally. Further inspection shows AEM breakage time for elastic supports at 1:1.75 to lie within standard bounds with the other predictions slightly exceeding standard error ranges.

Analysis of 8mm glazing at 0.89m$^2$ showed AEM predictions to correlate with the experimentally identified decreasing trend as shown in Figure 18. Further examination of Table 10 shows predictions to be within 13% of the experimental values. AEM breakage time for the 1:1 rigid arrangement can be seen to lie within standard error bounds while the other predictions slightly exceed standard error ranges. The combination of elastic edge supports and 1:1.7 aspect ratio produced the largest decrease in AEM breakage time, correlating with experimental results. Breakage time predictions for rigidly supported panels at 1:1 and 1:1.7 were also reduced with elastic supports, further agreeing with experimentally observed response. AEM breakage times for 1:1 panels with constant rigid and elastic edge conditions were found to decrease with 1:1.7 aspect ratio, matching the experimental data.

Examination of AEM breakage times for 4mm glazing at 0.89m$^2$ showed correlation with the experimental trend as shown in Figure 18. Table 10 shows predictions to be 11-17% shorter than mean experimental breakage times with differences in the range of 0.3-0.6ms. Table 10 also shows an increase in predicted breakage time for the elastically supported 1:1 panel versus rigid edge supports, matching the experimental response. The combination of elastic edge supports and 1:1 aspect ratio also produced the longest AEM breakage time, correlating with experimental results. Predicted breakage time for the 1:1 panel with elastic edge supports was found to shorten with 1:1.7 aspect ratio, further matching the experimental behaviour. The grouping of elastic supports and 1:1.7 aspect ratio also produced the shortest predicted breakage time, agreeing with the experimentally observed response. Examination of Figure 18 shows the AEM breakage time for rigid supports at 1:1 to be within standard error bounds with the other predictions slightly exceeding standard error ranges. Figure 18 also shows predictions for 1:1 rigid and 1:1.7 elastic arrangements to be shorter than equivalent arrangements with 8mm glazing at 0.89m$^2$ area, correlating with experimental results.

Examples of numerically predicted fragmentation modes are illustrated in Figure 19 for 8mm glazing. Figure 19a compares the influence of rigid and elastic edge conditions on AEM models of 1:1 glazing panels. It is evident from both the side and front perspectives that rigid edge conditions produced greater breakup and smaller fragments than elastic arrangements. Similarly, Figure 19b compares the influence of edge conditions on fragmentation for AEM models of 1:1.7 panels where it can also be seen that rigid edge supports induced greater panel breakup and a reduction in fragment size versus elastic supports. These results indicate reasonable qualitative correlation with high-speed video observations of experimental response where rigid supports were found to produce a greater proportion of small fragments versus elastic panels which led to larger shards. Future work will attempt to develop AEM models of glazing fragmentation to provide predictive capacity for glazing hazard during long-duration blast.

## 5. Conclusions

This paper has investigated the response of annealed glazing panels to long-duration blast loading. Initial analyses demonstrated the ABT blast environment to possess low variability over the series of eighteen trials with minimal variation reported for free-field and reflected blast overpressure results. Glazing fragmentation was qualitatively determined to be a strong function of edge conditions with rigidly clamped edges found to induce localised impulsive stress transmission, leading to significant cracking throughout the material and a high proportion of small fragments. In contrast, elastically supported panels were shown to produce large, angular shards in radial breakage patterns. Significant variability of fragment masses and geometries demonstrates the important influence of edge support conditions in terms of fragment hazard during a blast event.

As expected, experimental analysis of peak centre panel deflection revealed larger values for 4mm glazing with 0.89m$^2$ area versus equivalent arrangements at 0.25m$^2$. Oscillatory results were found for 4mm at 0.89m$^2$ as a function of both edge supports and aspect ratio which contrasts with the static results for 4mm glazing at 0.25m$^2$. 8mm glazing with 0.89m$^2$ frontal area demonstrated a decrease in mean deflection with elastic edge supports and rectangular aspect ratio with the largest reduction produced by the elastic panel at 1:1.7 versus the rigid arrangement at 1:1. Interestingly, larger deflections were reported for 4mm at 0.89m$^2$ versus 8mm glazing with equal area and arrangement. Sizably larger confidence intervals for 4mm glazing at 0.89m$^2$ area versus 8mm at 0.89m$^2$ and 4mm at 0.25m$^2$ area does however indicate a greater likelihood of deflection variability.

Experimental analysis of breakage times for 4mm glazing at 0.25m$^2$ area revealed a counter-balance with the combination of elastic supports and 1:1.75 aspect ratio producing zero change versus the rigid panel at 1:1. In contrast, the introduction of elastic edge supports and rectangular aspect ratio both produced reductions in breakage time for 8mm glazing at 0.89m$^2$, correlating with the decreases observed for peak deflection. Unsurprisingly, 4mm and 8mm glazing at 0.89m$^2$ produced longer breakage times than 4mm at 0.25m$^2$ for each equivalent arrangement. Interestingly, 4mm glazing at 0.89m$^2$ produced shorter breakage times than 8mm glazing with equal area for two of the three equivalent arrangements despite larger peak deflections. 4mm glazing at 0.89m$^2$ also produced a partial upward trend for the 1:1 arrangements, matching that seen with 4mm glazing at 0.25m$^2$. Thus representing the inverse to the decreasing behaviour found with 8mm at 0.89m$^2$ area. Importantly, examination of breakage time results for each of the three panel thickness and area combinations revealed maximum differences in the range of 14-29% as a function of edge supports and aspect ratio, demonstrating a significant variation in the impulse required to induce panel breakage.

The experimental evidence presented suggests the influence of edge supports and aspect ratio on glazing panel response to be dependent upon the combination of panel area and thickness. This is clearly demonstrated by contrasting response data for 8mm and 4mm glazing arrangements with equal 0.89m$^2$ area and 4mm glazing at 0.25m$^2$ and 0.89m$^2$. In each case, the latter was designed to exceed its predicted breakage threshold and the former to be within close vicinity to its threshold. The response variability reported herein therefore indicates that edge support and aspect ratio influence may be dependent upon immediacy to a notional breakage threshold as determined by panel area for a particular thickness. An additional six trials will aim to extend this investigation in the future by further examining the relationship between threshold dimensions and glazing thickness. This will be achieved by employing 6mm glazing with panel dimensions equal to those utilised for 8mm glazing in this study.

The final part of this study attempted to model long-duration blast response of annealed glazing through a series of Applied Element Method (AEM) simulations. The numerical prediction of peak deflection up to breakage yielded a maximum difference of 18% versus mean experimental values with the mean difference representing 11% for the eleven unique arrangements. AEM predictions of peak deflection were also shown to produce reasonable correlation with experimental trends. Similar levels of agreement were demonstrated for numerical breakage times with a maximum difference of 17% and a mean difference of 11%. AEM predictions were also found to show correlation with experimentally observed trends for breakage time. The reported comparisons have therefore demonstrated a reasonable level of agreement with experimental measurements. Future work will seek to experimentally benchmark a larger series of AEM models of annealed glazing response to long-duration blast with the aim of providing a predictive tool for glazing breakage.

Analysis of AEM fragmentation predictions demonstrated greater panel breakup for rigid edge conditions versus larger fragments for elastically supported arrangements. These results demonstrate reasonable qualitative agreement with experimental observations whilst supporting the experimental conclusion that fragmentation is a function of edge supports. Future work will seek to further investigate AEM models of glazing fragmentation to assess the viability of its predictive capacity for glazing hazard during long-duration blast.

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