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EXPERIMENTAL TESTING OF STRUCTURAL ARRANGEMENT ON WINDOW RESPONSE TO LONG-DURATION BLAST

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ABSTRACT

In an explosion, window failure can occur at large standoff distances resulting in a significant hazard radius. Up to 80% of injuries in an urban blast are estimated to be caused by glass failure and subsequent fragmentation. Annealed glass, found in many older buildings, shatters instantly into angular shards lacerating the skin on impact and causing significant injury. Large explosions produce long-duration blast environments in the far-field. These events are high-energy and produce impulses which can cause window failure several kilometres away from the detonation. Data from long-duration blasts indicate window failure is highly dependent on glazing aspect ratio, area and other structural support parameters. In this paper, influence of glazing aspect ratio, support conditions, material strength and the blast environment on window failure was experimentally investigated. Twenty full-scale experiments quantified parameter influence on glazing response to long-duration blast. Importantly, experimental repeats exhibited notable data spread demonstrating that glazing response should be quantified primarily by probability of failure and not deterministic methods characteristic of current custom and practice. Repeat reference data sets are of considerable scientific value to both practitioners and researchers particularly in this difficult field of engineering where access to suitable test facilities remain limited.

Keywords: Blast, long-duration, glass failure, support strength

Word count: 5321 main text, No of figures: 16, No of tables: 7

1 INTRODUCTION

On 19th April 1995, between 1800kg and 2300kg of ammonium nitrate and fuel oil mixture (ANFO) detonated outside the Alfred P. Murrah Federal building, Oklahoma. Window failure occurred further than 1.6km away from the detonation. A large proportion of windows in the area were manufactured using monolithic annealed glass. This shattered instantaneously into angular shards that lacerated skin on impact, causing significant injury. Such shards were thrown further than 3m into buildings close to the explosion, a dangerous and potentially life-threatening hazard. 167 deaths and 592 injuries were recorded, 39% of injuries were glass related. Victims generally suffered multiple soft tissue injuries like lacerations, contusions and abrasions [1]. Trawinski et al. [2] estimated up to 80% of injuries in an urban blast are due to glass failure. In 1998, studies by Claber [3] showed approximately 90% of UK buildings contained some annealed glazing. While modern facades generally utilise toughened, heat-strengthened or laminated glass, monolithic annealed glass remains common particularly in older buildings and represents a high hazard should an explosion occur. The widespread prevalence of annealed glazing internationally and the commensurate threat to infrastructure due to high-energy blast and fragmentation effects was recently demonstrated in Beirut (4th August 2020) by the severity of glazing damage recorded at considerable range from the point of large yield detonation (estimated 0.50-1.12kt TNT eq. [4]).

In an explosion, product gases under high pressure and temperature, rapidly expand, forcing surrounding ambient air outwards inducing a blast wave, shown in Figure 1 as an idealised shock. The pressure increase from ambient conditions is termed overpressure. Large explosions like the Oklahoma event, produce a long-duration blast wave in the far-field typically defined by a positive phase duration

greater than 40ms. This blast environment produces large impulses causing window failure several kilometres away despite low overpressure presenting a significant hazard radius. In August 2015, an estimated 800 tons of ammonium nitrate detonated in Tianjin, China [5] causing critical damage to windows five and a half kilometres away [6]. Window damage to a residential building in close proximity to the detonation is shown in Figure 2 [7]. It can be readily assumed that all windows received the same blast pressure due to the explosion magnitude. Furthermore, it is also a reasonable assumption that the glass was the same age, thickness, had the same framing and was monolithic annealed. Despite these common characteristics some glass failed and some survived. Analysis indicates a higher proportion of smaller windows survived compared to larger windows, indicating the influence of area on window survival. From the same imagery it was determined that higher aspect ratio glazing had a higher failure probability than square glazing of a similar area. Material strength which can vary by more than $\pm 25\%$ [8] (dynamic design strength of annealed glass subjected to blast loads is 80MPa [9]), was the likely cause of inconsistent failure of windows with the same dimensions. The image of damage caused by the Tianjin explosion indicates window response to blast loading can be highly variable, dependent on material strength and key structural parameters particularly glazing area and aspect ratio.

Importantly, very little long-duration blast testing has been conducted to determine glazing response to highly dynamic loading. Several tests were undertaken between 1950 and 1980, but data collected were limited to qualitative descriptions. Many windows consisted of a sash and muntin construction and no dimensions were quoted. In 1951, a building with 3mm and 6mm toughened glass windows was subjected to an estimated free-field overpressure of 14kPa. The majority of 3mm thick glass on the front of the building failed however all 6mm thick glass located on the building front

remained undamaged. All 3mm thick windows on the sides of the building were broken, despite only being subjected to the free-field overpressure. Frames containing thicker glass were more heavily damaged which was attributed to a longer break time, resulting in a higher load transferral to the frame [10]. In 1955, three houses were subjected to P_s 12kPa [11]. No information on glazing dimensions was provided. In all three houses, glass in the front windows was destroyed. Most side windows were blown in and glass in the rear windows “suffered some damage”.

In the 1973 Eskimo II trials [13], 26 windows with varying structural parameters were subjected to three different long-duration blast environments. Glazing aspect ratio ranged from 1:1 to 1:2.1 and area varied between 0.54m² and 2.8m². The 2-3mm thick annealed glass was supported using a range of different conditions. All ten windows subjected to P_s 3.7kPa and impulse of 292kPa.ms failed (impulse estimated assuming idealised triangular blast wave). Seven of the eight windows subjected to P_s 2.8kPa and impulse 252kPa.ms failed. In comparison all eight windows subjected to P_s 1.5kPa and impulse 152kPa.ms survived. Despite a large variation in structural parameters like aspect ratio and glazing area, the blast environment appeared to govern window failure or survival.

Modern long-duration blast trials require use of specialist facilities such as the air blast tunnel (ABT) at MOD Shoeburyness, UK (Figure 3)[14]. The ABT is one of a small number of facilities worldwide capable of testing full-scale structural response to long-duration blast waves. In a series of full-scale experimental trials, Johns and Clubley[15,16] varied glazing thickness, exposed area, aspect ratio and support conditions, concluding that influence of support conditions and aspect ratio was dependent on area, thickness and proximity to the glazing failure threshold. Elastically

framed windows recorded a lower probability of failure compared to rigid framing which Johns argued was a result of stress reduction due to elastic framing. It was concluded that glazing response to long-duration blast was dependent on framing conditions, glazing area, thickness and aspect ratio.

More recent experimental research into glazing response to blast loading has mainly focussed on short-duration blasts and the use of laminated glass to mitigate risks due to blast loading. Due to the high cost involved, many researchers complete a limited series of explosive trials with few to no repeats and often only as a curtailed benchmark for computationally biased and abstract analysis. Highly variable material strength, which is extremely difficult to model numerically, means rigorous experimental testing is necessary to understand the complexities of glazing response to blast loading. Nawar et al.[17] performed three long-duration shock tube tests on laminated glazing to benchmark an FEA numerical study. Results indicated that a thinner interlayer deflected further under blast loading and is more susceptible to tearing. Heat-strengthened glass plies resulted in reduced deflection indicating a stiffer arrangement when compared to annealed glass plies in the same laminate configuration. Hooper et al.[18] completed four full-scale short-duration blast tests on laminated glass and compared results to an FEA study. Analysis of digital image correlation (DIC) data indicated that the deflected panel shape had a flat central region with little deformation and areas of high deformation near panel edges. Deflection was not symmetrical, a larger deflection often occurred at the bottom outer corner of the panel. In three full-scale shock tube tests on laminated windows, Lusk et al.[19] determined that glazing thickness influenced displacement, with thicker windows displacing less than thinner glass exposed to the same blast environment. Chen et al.[20] completed nine full-scale blast tests on four-point supported laminated glazing assemblies, finding that

increasing window thickness from 8mm to 10mm decreased peak displacement by approximately 20%. Wei et al.[21,22] used FEA (LS-DYNA) to simulate in isolation the behaviour of old, new laminated and monolithic glazing subjected to a short-duration blast. It was found probability of failure was higher for older glass compared to new glass panel structures. Increasing glass thickness and decreasing area both decreased probability of failure. For new annealed glass, an aspect ratio of 1:1.4 provided the greatest blast resistance and a window of 1:2.8 aspect ratio the least. Zhang et al. [23] discussed the importance of research into the blast performance of monolithic glass windows due to the “ubiquitous use in structural facades and windows for decades”. The authors conducted full-scale arena tests of monolithic tempered glass panels, recording panel deformation and fracture characteristics when subjected to blast loading. Test results were compared to ASTM and UFC standards, and the authors concluded that the standards may not provide accurate estimations of toughened glass performance, especially in an impulsive (long-duration) blast environment.

This paper builds directly upon Johns’ important research[15,16] quantifying influence of structural parameters on glazing response to long-duration blast loading. Monolithic annealed, 4mm thick glass represents the UK minimum window specification and therefore and importantly, the worst-case damage in a blast event. This thickness was implemented in all trials. Influence of glazing aspect ratio, support conditions and peak overpressure was investigated in an extensive ABT trial schedule over two phases. The effect of each parameter on glazing response was analysed and ranked to determine its significance in governing commensurate failure.

2 EXPERIMENTAL SET-UP AND INSTRUMENTATION

Two identical glass samples were tested for each explosive trial, with 40 windows in total tested over 20 trials (Table 1). In all trials, 4mm thick annealed glass with area 0.89m^2 was used. In Phase 1, four aspect ratios were tested, 1:1, 1:1.3, 1:1.7 and 1:2, with four repeats for each arrangement. Only rigid support conditions were tested and a blast environment with peak free-field pressure (P_s) 14kPa implemented. In Phase 2 24 glass samples were tested at two lower blast environments, P_s 5kPa and 10kPa. Aspect ratios 1:1, 1:1.3 and 1:2 with both rigid and elastic support conditions were tested.

Steel test cubicles used successfully in Johns' experimental trials[15], were installed in the 10.2m diameter section of the ABT, normal to the blast wave (Figure 4). Modular housings enabled frames to be constructed separately then fitted to test cubicles facilitating a quick turnaround allowing two blast trials per day. All sub-frame assemblies were rigidly connected to the test cubicle using bolts torqued to 40Nm. The rigid frame (Figure 5a) was designed to represent a perfectly rigid support condition. Glass was restrained by steel frames bolted together against 7mm spacers to ensure uniform restraint. Thick foam of 3mm thickness compressed to 1.5mm, was adhered to both sides of the glass to prevent stress concentrations due to uneven frame surfaces. Elastic framing implemented structural sealant Sika SG500 to enable out-of-plane glass rotation representing pinned support conditions (Figure 5b). A full pressure history was recorded using three Endevco 8510-50 static pressure gauges and two Endevco 8515C-50 reflected gauges (gauge locations shown in Figure 6). Reflected pressure (P_r) gauges were attached to the test cubicle front surface in line with window centres. All pressure gauges were analysed at a 1MHz sample rate. Two high-speed cameras in each test container captured glazing response. Phantom 2512

cameras (C1 and C2) recorded crack location and break time. Phantom V711 cameras C3 and C4 tracked deflection gauge movement enabling measurement of central deflection (shown respectively in Figure 7). All cameras utilised frame rates of 75,000 frames per second (fps). All instrumentation was triggered by fibre optic at driver detonation to ensure a common time scale.

3 RESULTS & DISCUSSION: REFERENCE BLAST ENVIRONMENT

Overpressure, P_s and free-field impulse, (I_s) were recorded 3m upstream of the test cubicles. Excellent consistency was observed in the trial series for both pressure and impulse, specifically in the initial part of the blast wave. Slight variations in impulse in the later part of the overpressure history was attributed to gauge noise or flow field turbulence behind the blast wave front. Free-field pressure and impulse histories for trials at 14kPa, 10kPa and 5kPa P_s are shown for reference in Figure 8. Values of P_s , I_s and positive phase duration (t_d) for each trial are detailed in Table 2. Good agreement and high levels of consistency were observed for all blast parameters. Maximum repeatability was recorded for P_s 14kPa trials with mean P_s 13.4 ± 0.1 kPa, t_d 100 ± 1 ms and I_s 690 ± 7 kPa.ms. P_s 5kPa trials exhibited reduced consistency in P_s compared to 14kPa trials (6.3 ± 0.3 kPa) but recorded t_d (48 ± 1 ms) and I_s values were highly consistent (223 ± 4 kPa.ms). This increased P_s variation (standard deviation of 5%) can be attributed to blast wave perturbations due to turbulence at low pressures.

Shock wave reflections produced by the test containers within the contained environment of the ABT led to increased measurements of free-field pressure and impulse. An initial rise observed after the peak pressure was a function of changing light levels in the ABT due to dust translation and overall Endevco 8510-50 gauge sensitivity, which are sensitive instrumentation with respect to intense light and heat.

This behaviour has been observed in multiple ABT trials dependent on the power envelope and environmental conditions. A second observable free field peak was caused by air particles reflecting off the container front surface and travelling upstream. Further subsequent peaks in the free-field pressure history can be attributed to characteristics of the ABT and driver charge design. The ABT diameter does not increase linearly but in three stages, shown in Figure 3. These large-scale shock tube regions cause decreases in air density and pressure causing peaks and troughs in the pressure trace while reshaping the wave towards an intended near planar Mach front. Any final peaks in the pressure history at comparative late times can be attributed to shock reflections from the rarefaction wave eliminator (RWE) travelling back upstream. Reflected overpressure histories for all trials (shown in Figure 8) demonstrated good consistency between trials and for both test cubicles, indicating a uniform pressure wave. Reflected peak overpressure (P_r) and reflected impulse (I_r) for each trial are detailed for reference in Table 3.

Mean reflected pressure, P_r values for 14kPa, 10kPa and 5kPa blast environments were 27.2 ± 0.9 kPa, 20.1 ± 1.0 kPa and 12.4 ± 0.7 kPa respectively. The largest standard deviation was 6% of the mean for the low power, low pressure 5kPa blast environment; arguably the most difficult and challenging environment for the ABT to reliably recreate. Total reflected impulse was equally consistent with a maximum standard deviation 2%. The peak value was recorded from the average overpressure in the first 0.5ms, removing gauge noise. An increase in reflected overpressure between 0.5ms and 1.5ms after blast wave arrival was due to pressure build up and reflections within steelwork on the front of test containers. It cannot be assumed the glass experienced the same reflections; consequently, the initial peak was used to characterise the reflected blast wave.

4 RESULTS & DISCUSSION: GLAZING RESPONSE

In this section the effect of aspect ratio, support conditions and peak overpressure on window failure is analysed and quantified. Three long-duration blast environments were defined in the ABT environment substantiation and will be subsequently referred to in terms of P_r (see Table 4). Three samples remained unbroken for reflected pressures of 12kPa. All windows subjected to higher peak pressures failed. Out of those that survived, two comprised elastic frames and one rigid while each window retained a different aspect ratio; 1:1, 1:1.3 and 1:2. In this section glazing arrangements are referred to in the following format [P_r , aspect ratio, support conditions] e.g. [27kPa, 1:1, rigid].

Two break parameters quantified glazing failure overall: central deflection at failure and reflected impulse received at break. Glass failure was defined by cracking identified using front-facing camera imagery. Time to failure was calculated as the difference between time of blast arrival (measured from P_r gauges) and time of glazing failure (from front-facing camera). Reflected impulse was measured at break time from P_r gauges. Glass panel deflection was measured by tracking a scaled gauge with a high-speed camera. Measurement errors for break time, failure impulse and failure displacement were $\pm 0.01\text{ms}$, $\pm 0.2\text{kPa.ms}$ and $\pm 1\text{mm}$ respectively. Failure impulse errors were negligible. The failure displacement error was more significant ($\pm 1\text{mm}$) with typical measurements between 10mm and 30mm. This error was due to camera image pixilation and could not be improved without compromising the high frame rate which was required for a precise break time measurement. This error was insignificant when compared to any possible variation in results due to material variability.

4.1 PEAK OVERPRESSURE

Glass panel assemblies with aspect ratio 1:1.7 were disregarded from this analysis as they were only used in higher pressure, P_r 27kPa trials. All break parameters are plotted against P_r in Figure 9 to provide an overview of data spread and general trends. For failure deflection, results spread for each reflected pressure was greater (approx. 20mm) and demonstrated consistency between blast environments. Results spread indicated deflection dependency on other parameters (aspect ratio, support conditions and material strength). This trend was independent of P_r across all blast environments tested. An increase in deflection by 5-10mm occurred over a P_r 8kPa increase. Impulse spread was constant (approx. 60kPa.ms) for all blast environments. Impulse at failure increased significantly with P_r , indicating a dependency on P_r .

Influence of the blast environment was quantified by categorising the data into six key structural arrangements, shown in Table 5. Mean parameters were normalised against a result for P_r 12kPa using equation 1 and were plotted in Figure 10. Standard deviation calculations were omitted for single data points.

$$\text{Normalised break parameter} = \frac{\bar{x}_{P_r}}{\bar{x}_{P_r=12kPa}} \quad [1]$$

The largest normalised displacement increase shown was for aspect ratio 1:1. A 72% displacement increase was recorded for [1:1, elastic] between reflected pressures, P_r 12kPa and 20kPa. No significant change was measured for [1:1, rigid] between P_r 12kPa and 20kPa but an increase of 202% was recorded for P_r increased to 27kPa. P_r exhibited a smaller effect on displacement for all other arrangements. The largest displacement increase was +34% for [1:1.3, elastic] between P_r 12kPa and 20kPa. All other normalised displacements were less than 1.20 and shown

insignificant with respect to standard deviations calculated for each arrangement. No significant trend was determined for these arrangements. Change in displacement was attributed to material variation that was not fully removed from the mean due to the small number of repeats.

All normalised failure impulses increased as P_r increased. The largest normalised impulse was for aspect ratio 1:1. Elastically supported glass exhibited a larger normalised impulse for aspect ratios 1:1 and 1:1.3 but smaller for 1:2 when compared to rigid framing. All normalised impulses except [1:2, elastic] were larger than 1.20 implying trends were significant compared to standard deviations. Failure impulse increased with reflected pressure, P_r for all arrangements but normalised values were smaller than observed for deflection. The spread of results was small compared to displacement indicating failure impulse was governed by P_r and structural parameters had less effect. An increased response of windows with aspect ratio 1:1 can be attributed to the symmetrical 2-way spanning arrangement that resulted from a large span. This span governed a reduced window stiffness while more susceptible to increasing rate of impulse due to P_r producing a higher rate of deflection.

4.2 ASPECT RATIO

Four aspect ratios from 1:1 to 1:2 was investigated in blast environment P_r of 27kPa, three were used in trials with P_r of 20kPa and 12kPa. Aspect ratio 1:1.7 was not used in these trials. Elastic and rigid support conditions were investigated in trials with blast environment P_r of 20kPa and 12kPa, only rigid supports were implemented in P_r of 27kPa trials. Mean break parameters and corresponding standard deviations for each arrangement are outlined for reference in Table 6. Mean values were normalised against the 1:1 value to determine the effect of aspect ratio.

Individual displacement results and the arrangement mean are plotted in Figure 11. For all arrangements aspect ratio 1:1.3 exhibited the largest displacement. For [27kPa, rigid] displacement in aspect ratios 1:1 and 1:1.3 was considerably higher than 1:1.7 and 1:2. Different behaviour was observed in glass subjected to P_r 20kPa and 12kPa, displacement for aspect ratio 1:1.3 was greater than 1:1 and 1:2. This trend was exaggerated at P_r 12kPa than P_r 20kPa indicating aspect ratio had a larger effect on displacement at lower overpressures. Aspect ratio exhibited a reduced effect on displacement of elastically supported windows and this effect decreased at lower overpressures. Displacement spread for each arrangement was considerable, the largest standard deviation was 11mm for [27kPa, 1:2, rigid]. For some structural arrangements especially at P_r 27kPa, the spread was larger than the observed trend. More displacement data from additional blast trials would be required to determine categorically if observed trends were due to aspect ratio or spread of results.

Aspect ratio trends overall were quantified by normalising failure displacements against a reference 1:1 result (see Figure 11). Arrangement [27kPa, rigid] recorded a 15% increase in displacement from 1:1 to 1:1.3 but reduced displacements for aspect ratios 1:1.7 and 1:2 (39% and 27% reduction from 1:1 result respectively). Normalised displacements for rigid framing were small compared to those from other blast environments. In comparison normalised deflections for [20kPa, 1:1.3, rigid] and [12kPa, 1:1.3, rigid] were 2.96 and 3.15 respectively. Normalised displacement for [1:1.3, rigid] arrangements increased as P_r decreased whereas, a reduction was evident for elastically window supports, with a maximum of 1.31 for [12kPa, 1:1.3, elastic]. Failure impulse trends were similar to that for deflection (Figure 12). A decrease in impulse as reflected pressure, P_r decreased was observed. In general, the largest break impulse was recorded for aspect ratio 1:1.3. Results for aspect ratios

1:1 and 1:2 were similar at lower peak overpressures (P_r 20kPa and 12kPa). For rigidly framed windows the response to aspect ratio 1:1.3 increased as P_r decreased. Normalised break impulses were lower than normalised deflections, but similar trends were observed. The maximum normalised impulse was 1.67 for [12kPa, 1:1.3, rigid] compared to 3.15 for displacement indicating less significance for aspect ratio with respect to failure impulse. For all rigid support arrangements, maximum normalised impulse was recorded for aspect ratio 1:1.3 and increased as P_r decreased. The largest normalised result for [27kPa, rigid] was 1.12 suggesting the trend was insignificant compared to standard deviations for this arrangement.

For failure displacement and impulse combined, aspect ratio influence was dependent on support conditions. Aspect ratio exhibited a greater effect on break parameters from rigid support arrays compared to elastic samples. Aspect ratio showed little effect on deflection of rigidly supported glass subjected to P_r 27kPa. A decrease in displacement with aspect ratio increase from 1:1.3 to 1:2 can be attributed to a decrease in the shortest glass dimension producing a stiffer one-way spanning arrangement. Aspect ratio 1:1 also exhibited a reduced displacement due to its stiffer two-way spanning installation. Smaller normalised deflections recorded in the P_r 27kPa blast environment can be explained by the higher blast pressure punching through the glass. At reduced overpressures, glazing panels were able to deflect and broke due to deflection, allowing aspect ratio to affect glazing behaviour to a higher extent. Elastically supported windows showed smaller normalised deflections indicating aspect ratio was less influential. This can be explained by reduced glass stresses due to elastic framing allowing early rotation, reducing the effect of aspect ratio compared to a clamped rigid frame. The same trends were observed for failure impulse indicating break parameters were closely linked. Aspect ratio 1:1.3 recorded

the largest normalised impulse for all rigid frames. This trend increased in magnitude as P_r decreased indicating aspect ratio was more significant at lower P_r values. Importantly, at lower pressures glazing deflection occurred over a longer time resulting in a larger commensurate influence on structural failure parameters e.g. aspect ratio.

4.3 SUPPORT CONDITIONS

Rigid and elastic framing conditions were implemented for 20kPa P_r and 12kPa P_r blast environments. Only rigid supports were implemented in P_r 27kPa trials therefore results were disregarded from this section. All results are plotted against support conditions, shown in Figure 13. Importantly, two out of six (33%) elastically supported windows survived when subjected to P_r 12kPa. Only one rigidly supported sample (17%) survived in the same blast environment. Conversely, all samples failed when subjected to P_r 20kPa. A small increase in failure displacement was observed for elastically supported glass compared to rigid framing. For both support conditions results spread was shown to be high, 3mm to 29mm for rigid supports and 8mm to 27mm for elastic supports. Impulse variance for elastic frames was smaller than rigid supports, indicating rigid framing introduced more inconsistency. This outcome could be attributed to irregular stress concentrations in the glass caused by an uneven frame surface despite ensuring a smooth finish and applying foam tape to protect the glass. There was no significant difference between elastic and rigid mean results for break parameters indicating support conditions had little effect on the mean probability of glass failure.

Mean rigid and elastic results from each arrangement are compared for reference in Table 7. Mean break parameters for both framing options were normalised against rigid results and plotted in Figure 13. The largest normalised response was for displacement which was 3.23 for [20kPa, 1:1]. Arrangement [12kPa,

1:1] also recorded a large normalised displacement of 1.81. Results from all other arrangements were significantly smaller. Normalised displacements were greater than one-quarter of the six arrangements, indicating larger observed displacements for elastic frames. Normalised responses for failure impulse were lower than displacement but exhibited a similar key trend. The largest observed was 1.30 for [20kPa, 1:1] and the smallest was 0.85 for arrangement [12kPa, 1:1.3]. Results from remaining arrangements ranged between 0.95 and 1.00, recording no significant change in impulse between the two support conditions.

Support conditions influenced failure displacement more than blast impulse. Elastic framing gave rise to the largest increase in deflection for arrangements with aspect ratio 1:1. Response was greater for reflected pressures, P_r 20kPa than 12kPa. Normalised deflection remained low for all other aspect ratios, between 0.75 and 1.18 with an even number of results above and below 1.00 indicating support conditions had little influence on outcome. Failure impulse followed the same trends identified for deflection, windows with aspect ratio 1:1 recorded the largest normalised impulse.

4.4 STRUCTURAL PARAMETER SIGNIFICANCE

The significance of each structural parameter was determined from the magnitude of the range identified. Range was defined as the difference between maximum and minimum mean values for an arrangement (see Figure 14). In this example the effect of aspect ratio on failure displacement was quantified for arrangement [27kPa, rigid]. The largest mean value was 25mm and the smallest 14mm, producing a spread of 11mm. This displacement range due to material variability was plotted for all arrangements with the maximum value coloured black (Figure 15). Each displacement range for aspect ratio was plotted in Figures 15 & 15c. The largest value was highlighted in red. The process was repeated for support

conditions and P_r . Mean values reduced spread of results due to material variability. The significance of this intrinsic variability was determined by finding the spread (e.g. displacement range) between experimental repeats of the same arrangement, shown in red in Figure 15a. Maximum and mean values for each structural parameter were compared in part (d) of the figure to determine the most significant parameter. The process was repeated for failure impulse (Figure 16). Four repeats were completed for all arrangements subjected to P_r 27kPa but only two repeats for alternative blast environments. One window remained unbroken from arrangements [12kPa, 1:1, elastic], [12kPa, 1:1.3, rigid] and [12kPa, 1:2, elastic] resulting in zero material variation range.

The largest displacement spread due to material variability was 26mm for [27kPa, 1:1, rigid]. For rigid support conditions all blast environments were considered, elastic framing was only tested in blast environments P_r 20kPa and 12kPa (Figure 15b). The largest displacement spread was 15mm for [1:1, rigid]. Displacement range for elastic supports was smaller than rigid which was attributed to elastic supports not being tested at P_r 27kPa. Displacement variation decreased as aspect ratio increased for both support conditions, implying P_r had a reduced impact on displacement at higher aspect ratios. The largest displacement range for aspect ratio was 16mm for [12kPa, rigid]. Rigidly supported glass exhibited larger displacement ranges than equivalent elastic arrangements indicating aspect ratio exhibited a greater effect on rigid framing. Aspect ratio and displacement spread increased as P_r conversely decreased indicating higher sensitivity to aspect ratio at lower overpressures for rigid supports. Importantly, elastic framing recorded the opposite effect; displacement variation reduced as P_r decreased. Displacement spread for support conditions was significantly lower than aspect ratio or P_r . The maximum was 16mm for [20kPa, 1:1].

Maximum and mean displacement ranges for each parameter are shown in Figure 15e. Little difference between maximum deflection ranges was observed. Material variation exhibited a higher maximum variation (26mm). Considering mean values, aspect ratio had the largest influence on displacement (11mm), compared to material variability (9mm), P_r (7mm) and support conditions (6mm). Over all arrangements experimentally tested, aspect ratio was shown to be the most significant parameter when considering glazing displacement at failure. Effect of material variation was also commensurately significant.

The largest failure impulse range due to material variation was 53kPa.ms for [27kPa, 1:1, rigid] (Figure 16a). The largest impulse spread due to P_r was 88kPa.ms for [1:1, rigid] (Figure 16b). All impulse ranges for rigid supports were larger than equivalent elastic samples. It should be noted that elastic supports were not used in trials with P_r 27kPa. Impulse variation for elastic frames decreased as aspect ratio increased indicating P_r was less significant at higher aspect ratios for elastic support conditions. A similar trend was not observed for rigid supports. Break impulse ranges due to aspect ratio were much smaller than those due to P_r . The largest spread was 38kPa.ms for [12kPa, rigid]. For rigid framing, break impulse variation increased as P_r decreased. This indicated increased aspect ratio significance at lower P_r values. The opposite effect was recorded for elastic framing, impulse ranges decreased with P_r increase. Break impulse ranges for support conditions were much smaller than other parameters (maximum 26kPa.ms for [20kPa, 1:1]).

Support conditions gave rise to lower sensitivity with respect to glazing aspect ratios. Results showed that support framing effects were independent of aspect ratio for P_r 12kPa. Reflected overpressure was consistently the parameter with the largest

effect on break impulse (maximum spread 88kPa.ms and mean range 52kPa.ms).
Material variability produced the second largest variance but a smaller overall mean.

5 CONCLUSIONS

In total, 40 window structures were tested in 20 individual air blast trials. Importantly, the blast environment in the ABT was shown to be highly consistent across all trials with the largest total reflected impulse standard deviation at just 2% of the mean. Reflected overpressure histories exhibited good consistency between trials, providing reliable loading and accurate impulse measurements, an important and key consideration with respect to repeats and scientific rigour. Three out of twelve windows subjected to peak reflected overpressure of 12kPa survived, all other windows failed. There was no trend in window survival, indicating material variation was the root cause. It was concluded that a pressure, P_r of 12kPa was close to the survival threshold for 4mm thick annealed glass with area 0.89m². It was determined that failure displacement was dependent on aspect ratio and material variability whereas failure impulse was governed by the blast environment. Experimental observation showed support conditions had minimal effect on failure behaviour.

Trends within break parameter ranges indicated all components were interlinked and glazing behaviour was dependent on a complex non-deterministic combination. Importantly, experimental repeats in this paper exhibit notable data spread, demonstrating that glazing response is highly variable therefore repeat data are critical. Where budget constraints prevent repeat data, consideration should be given to the representativeness of test data and benchmarking of further research should be undertaken with caution. Reliance upon legacy pressure-impulse diagrams or methods should be re-examined as a priority; particularly given their deterministic

approach and poor scope for parameter inclusion e.g. geometric size, supports or material variability. Repeat (reference) data sets in this paper provide considerable scientific value to both practitioners and researchers particularly in this costly and difficult field of engineering where access to suitable test facilities remain limited.

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8 TABLES

Table 1. Dynamic trials specification

Phase	Trial	Design P_s	Aspect Ratio	Glass Dimensions	Support	No.
	No.	(kPa)		[x:y] (mm)	Conditions	Windows in Trial
1	1	14	1:1	[945:945]	Rigid	2
	2	14	1:1.3	[827:1075]	Rigid	2
	3	14	1:1.7	[725:1230]	Rigid	2
	4	14	1:2	[667:1334]	Rigid	2
	5	14	1:1	[945:945]	Rigid	2
	6	14	1:1.3	[827:1075]	Rigid	2
	7	14	1:1.7	[725:1230]	Rigid	2
	8	14	1:2	[667:1334]	Rigid	2
2	9	10	1:1	[945:945]	Rigid	2
	10	10	1:1	[945:945]	Elastic	2
	11	10	1:1.3	[827:1075]	Rigid	2
	12	10	1:1.3	[827:1075]	Elastic	2
	13	10	1:2	[667:1334]	Rigid	2
	14	10	1:2	[667:1334]	Elastic	2
	15	5	1:1	[945:945]	Rigid	2
	16	5	1:1	[945:945]	Elastic	2
	17	5	1:1.3	[827:1075]	Rigid	2
	18	5	1:1.3	[827:1075]	Elastic	2
	19	5	1:2	[667:1334]	Rigid	2
	20	5	1:2	[667:1334]	Elastic	2

539 **Table 2.** Free-field blast parameters for all trials.

Design P_s	Trial No.	1	2	3	4	5	6	7	8	$\bar{x}$	σ
14kPa	P_s (kPa)	13.4	13.3	13.5	13.5	13.4	13.5	13.5	13.1	13.4	0.1
	t_d (ms)	101	102	100	99	100	99	101	100	100	1
	I_s (kPa.ms)	701	693	681	691	681	694	697	683	690	7
Design P_s	Trial No.	9	10	11	12	13	14			$\bar{x}$	σ
10kPa	P_s (kPa)	10.4	10.3	10.2	10.3	9.9	9.7			10.1	0.2
	t_d (ms)	74	74	73	74	74	75			74	1
	I_s (kPa.ms)	452	443	442	443	439	431			442	6
Design P_s	Trial No.	15	16	17	18	19	20			$\bar{x}$	σ
5kPa	P_s (kPa)	6.1	6.0	6.1	6.6	6.0	6.7			6.3	0.3
	t_d (ms)	49	48	48	49	49	47			48	1
	I_s (kPa.ms)	222	217	220	226	228	223			223	4

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Table 3. Reflected blast parameters for all trials.

Design P _s 14kPa											
Trial No.	Cubicle	1	2	3	4	5	6	7	8	$\bar{x}$	σ
P _r (kPa)	A	26.1	25.9	26.7	26.6	26.3	26.7	27.5	26.1	27.2	0.9
	B	26.8	26.9	28.2	28.6	27.7	28.7	28.8	27.5		
I _r (kPa.ms)	A	734	738	716	725	715	729	728	717	724	8
	B	734	735	715	723	712	726	727	716		
Design P _s 10kPa											
Trial No.	Cubicle	9	10	11	12	13	14			$\bar{x}$	σ
P _r (kPa)	A	20.5	20.4	20.2	20.3	18.9	18.0			20.1	1.0
	B	21.2	21.2	20.7	20.9	19.4	19.2				
I _r (kPa.ms)	A	450	441	439	440	437	429			435	7
	B	441	432	431	434	427	423				
Design P _s 5kPa											
Trial No.	Cubicle	15	16	17	18	19	20			$\bar{x}$	σ
P _r (kPa)	A	12.4	12.0	11.9	13.1	11.4	13.5			12.4	0.7
	B	12.1	11.9	11.8	13.5	11.7	13.5				
I _r (kPa.ms)	A	222	212	215	225	228	220			219	5
	B	220	213	212	220	226	217				

545 **Table 4.** P_r values quoted in reference to blast environments for all glazing analyses.

Design P_s (kPa)	5	10	14
Mean P_r (kPa)	12	20	27

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Table 5. Summary: break parameters as a function of P_r .

Aspect Ratio	Support Condition	P_r (kPa)	Failure Displacement (mm)			Failure Impulse (kPa.ms)		
			$\bar{x}$	σ	Norm	$\bar{x}$	σ	Norm
1:1	Rigid	12	7	4	1.00	57	10	1.00
1:1	Rigid	20	7	0	0.97	90	9	1.57
1:1	Rigid	27	22	9	1.00	145	19	2.54
1:1	Elastic	12	13	-	1.00	67	-	1.00
1:1	Elastic	20	23	1	1.72	116	9	1.73
1:1.3	Rigid	12	23	-	1.00	95	-	1.00
1:1.3	Rigid	20	21	8	0.91	118	22	1.24
1:1.3	Rigid	27	25	3	1.10	153	6	1.61
1:1.3	Elastic	12	17	1	1.00	81	5	1.00
1:1.3	Elastic	20	23	4	1.34	115	7	1.41
1:2	Rigid	12	14	11	1.00	64	22	1.00
1:2	Rigid	20	15	4	1.05	96	6	1.50
1:2	Rigid	27	16	4	1.16	132	13	2.07
1:2	Elastic	12	16	-	1.00	78	-	1.00
1:2	Elastic	20	13	5	0.82	92	16	1.17

Norm - Break parameter normalised against result for 12kPa.

Dash indicates no standard deviation due to sample size of one.

552 **Table 6. Summary: break parameters as a function of aspect ratio.**

Support Condition	P_r (kPa)	Aspect Ratio	Failure Displacement (mm)			Failure Impulse (kPa.ms)		
			$\bar{x}$	σ	Norm	$\bar{x}$	σ	Norm
Rigid	27	1	22	9	1.00	145	19	1.00
Rigid	27	1.3	25	3	1.15	153	6	1.06
Rigid	27	1.7	14	6	0.61	128	11	0.88
Rigid	27	2	16	4	0.73	132	13	0.91
Rigid	20	1	7	0	1.00	90	9	1.00
Rigid	20	1.3	21	8	2.96	118	22	1.31
Rigid	20	2	15	4	2.06	96	6	1.07
Rigid	12	1	7	4	1.00	57	10	1.00
Rigid	12	1.3	23	-	3.15	95	-	1.67
Rigid	12	2	14	11	1.90	64	22	1.11
Elastic	20	1	23	1	1.00	116	9	1.00
Elastic	20	1.3	23	4	1.01	115	7	0.99
Elastic	20	2	13	5	0.59	92	16	0.79
Elastic	12	1	13	-	1.00	67	-	1.00
Elastic	12	1.3	17	1	1.31	81	5	1.21
Elastic	12	2	16	-	1.24	78	-	1.16

553 Norm - Break parameter normalised against result for 1:1.

554 Dash indicates no standard deviation due to sample size of one.

555

Table 7. Summary: break parameters as a function of support conditions.

P_r (kPa)	Aspect Ratio	Support Condition	Failure Displacement (mm)			Failure Impulse (kPa.ms)		
			$\bar{x}$	σ	Norm	$\bar{x}$	σ	Norm
12	1	Rigid	7	4	1.00	57	10	1.00
		Elastic	13	-	1.81	67	-	1.18
12	1.3	Rigid	23	-	1.00	95	-	1.00
		Elastic	17	1	0.75	81	5	0.85
12	2	Rigid	14	11	1.00	64	22	1.00
		Elastic	16	-	1.18	78	-	1.23
20	1	Rigid	7	0	1.00	90	9	1.00
		Elastic	23	1	3.23	116	9	1.30
20	1.3	Rigid	21	8	1.00	118	22	1.00
		Elastic	23	4	1.10	115	7	0.97
20	2	Rigid	15	4	1.00	96	6	1.00
		Elastic	13	5	0.92	92	16	0.96

Norm - Results normalised against rigid framing.

Dash indicates no standard deviation due to sample size of one.