Experimentally Investigating Annealed Glazing Response to Long-Duration Blast

***Robert V Johns**
BEng(Hons) MSc PhD

* Corresponding author, Post-Graduate Researcher, Faculty of Engineering and the Environment
University of Southampton, SO17 1BJ, United Kingdom
Email: R.Johns@soton.ac.uk Tel. +44 (0)2380 592862

Simon K Clubley
BEng(Hons) MBA PhD EurIng CEng MICE MinstP MBCS CITP

Senior Lecturer in Civil Engineering, Faculty of Engineering and the Environment
University of Southampton, SO17 1BJ, United Kingdom

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Abstract

This paper examines the response of annealed glazing panels when subject to long-duration blast loading. In particular, this study will quantify glazing response metrics whilst varying glazing thickness, glazing area, aspect ratio and edge conditions. With positive phases exceeding 100ms, long-duration blasts result in significant specific impulse and dynamic pressures. The transient dynamic response of annealed glazing during these events is a complex function of the structural arrangement, material properties and explosive proximity.

Twelve full-scale air-blast trials utilising a heavily armoured test structure subjected 24 glazing panels to ~14kPa free-field overpressure and ~110ms positive phase duration. Results are reported, where it is shown that elastic edge supports can prevent glazing breakage versus rigidly clamped arrangements when suitable panel dimensions are employed. Fragmentation modes are also demonstrated to be a function of edge conditions with elastically supported panels producing large, angular fragments. In contrast, rigid arrangements are shown to induce localised impulsive stress transmission at clamped edges, leading to significant cracking and small fragments. Substantially different fragment masses and geometries demonstrate the need to accurately quantify edge supports when appraising fragment hazard. Quantification of peak panel deflection, breakage time and applied breakage impulse is then presented where results indicate the influence of edge supports and aspect ratio on glazing response to be dependent on proximity to the threshold area for a particular thickness.

Keywords: long-duration blast; explosion; dynamic response; glazing; annealed glass; edge supports; aspect ratio;

Introduction

As a result of positive phase durations greater than 100ms, long-duration blasts such as the chemical explosions at the Port of Tianjin, China (2015) produce substantial blast impulse and significant kinetic mobilisation of air behind the blast known as dynamic pressure. Annealed glazing panels incur widespread damage during these events with fragments propelled sizable distances downstream. Indeed, nuclear events in Japan during World War II resulted in glazing injuries at approximately 4km radial distances (Fletcher et al, 1980). Due to its low-cost, annealed glass represented approximately 90% of building glass within the UK at the close of the millennium (Claber, 1998). Due to its amorphous microstructure, annealed glazing suffers brittle failure when micro flaws initiate crack propagation during flexure. With respect to uniform blast loading, membrane stresses interrogate the panel for critical flaws.

As a result of its widespread utilisation, blast effects on annealed glazing have been the subject of much research. Iverson (Iverson, 1968) analysed the performance of annealed glazing within fallout structures during long-duration nuclear blast loading. Employing annealed ‘float’ glass and ‘blown’ sheet glass, three events subjected an array of test structures to free-field overpressures of ~13kPa. Post-trial analyses revealed breakage in each face-on and side-on panel for 100% for 3-8mm thick glazing whilst rear-facing panels were subject to breakage levels of approximately 50%. Edge support conditions were suggested to influence breakage probability for heavier 8mm glazing as frame distortions may have introduced local glazing stresses. Analysis by Fletcher (Fletcher et al, 1980) focussed on 3-6mm thick annealed glazing with varying stand-off, aspect ratio and framing. Two large-scale TNT blast trials were subsequently conducted to assess the response of 52 glazing panels to long-duration blast loading. Limited testing capabilities of the time constrained results analysis to the binary state of breakage versus survival. The likelihood of breakage was however found to be a mixed function of thickness, glazing area, edge supports, glazing type, stresses introduced during installation and the incident angle to the blast.

Modern research has focussed on the prevention of glazing breakage during blast via laminated glass with high performance silicone sealants. Yarosh (Yarosh et al, 2005) and Hautekeer (Hautekeer et al, 2001) analysed the adequacy of structural silicone to resist tensile loads with an impulsive rise time. The results of which were found to demonstrate increases in ultimate tensile strength of 50% and 60% in the respective studies. Weggel and Zapata (Weggel and Zapata, 2008) and Seica (Seica et al, 2011) investigated the effect of varied edge supports on laminated glass via FEA. These studies found that silicone supports introduced lower frequencies of vibration within the glazing panels versus simply supported alternatives, resulting in the redistribution of vibrational energy. While negligible changes in deflection amplitude were reported, principal glazing stresses were found to reduce significantly with structural silicone. Indeed, Weggel and Zapata (Weggel and Zapata, 2008) indicated a 40% reduction versus simply supported arrangements. An FEA investigation by Larcher (Larcher et al, 2012) into the influence of edge supports on blast-loaded laminated glass revealed a deflection decrease of approximately 12% for panels supported by rubber gaskets compared to those within rigidly clamped frames. FE analyses by Amadio and Bedon (Amadio and Bedon, 2012) exhibited a reduction in principal glazing stress by up to 45% in laminated façades when comparing viscoelastic spider supports versus rigid alternatives. Minimal differences were reported when comparing peak displacements.

To date, there have not been any studies which aim to experimentally quantify the effect of edge supports, panel area, panel thickness and aspect ratio on the response of annealed glass during long-duration blast. This study aims to address this via 12 blast trials conducted at full-scale within the Air Blast Tunnel (ABT) at MOD Shoeburyness. This is one of only a small number of facilities capable of simulating long-duration blasts events at full-scale with a maximum TNT requirement of 4kg, thus representing an affordable methodology. Initially, this study focusses on experimental data from the blast environment before characterising the effect edge conditions on the binary state of breakage. A brief discussion is subsequently presented on the role of edge conditions in producing variable fragment hazard. The final element of this study quantifies peak panel deflection, breakage time and applied breakage impulse as a function of the glazing arrangement parameters discussed above with associated statistical uncertainty.

Experimental Procedure

A total of 12 full-scale trials with 24 panels of annealed glazing were carried out within the Air Blast Tunnel (ABT) at MOD Shoeburyness in the UK, details of which are given in table 1. These aimed to examine the binary state of breakage, fracture modes, peak panel deflection, break time and the required impulse for breakage as a function of glazing panel area, thickness, edge supports and panel aspect ratio. A series of previously conducted shorter duration blast trials revealed 14kPa free-field overpressure to represent the threshold of breakage for 8mm annealed glazing. This study subsequently aimed to utilise a constant free-field overpressure of 14kPa with a positive phase duration of 110ms with +/- 10% acceptability criteria. The ABT as shown in figure 1 is an explosively driven shock-tube which can simulate planar shock waves (Adams et al, 2012) indicative of long-duration blasts. By utilising 0.55kg of PETN, the ABT was able to generate the required air-blast with a TNT equivalence of 15,000kg at a 250m radial distance.

To investigate the effect of edge supports, elastic and rigid conditions were utilised in each trial to represent opposing ends of a stiffness spectrum as shown in figures 2-3 and tables 2-3. Rigid conditions were simulated via steel clamps with a two-way span, uniform torque setting of 4Nm and compressible gaskets to prevent cracking during installation. Elastic conditions were implemented via Dow Corning 993 structural silicone joints on the rear face of the glazing panels with a two-way span and the material properties in table 4. Sealant dimensions were designed to prevent adhesive and cohesive failure modes under load as shown in table 3. Sufficient silicone curing was determined via peel tests which were performed 48 hours after application. These demonstrated cohesive failure of the silicone when peeled, thereby inferring adequate adhesion between the glazing and steel frames. Further examination of table 2 shows that the values for total glazing area and exposed glazing area (restraint coverage subtracted from total area) were maintained as constant when directly comparing panels with rigid and elastic supports.

Trials 1-12 examined 4mm and 8mm thick annealed glazing with the material properties shown in table 4 and the dimensions detailed in table 2. Glazing dimensions were chosen to represent the threshold of breakage for each panel thickness as derived from computational predictions produced with the Applied Element Method (AEM). These extended the benchmarked solutions of Johns and Clubley (Johns and Clubley, 2015), yielding values for the minimum area required to induce glazing breakage for a particular thickness within a constant blast. AEM predictions also inferred breakage variability with aspect ratios approaching 1:1.75. As a result, trials 1-12 also examined the effect of aspect ratio when maintaining the threshold breakage area described above. Further examination of table 1 shows that trials 1-12 implemented eight glazing arrangements with three repeats per arrangement. These repeats provided an allowance for glazing response variability whilst also enabling statistical variances to be determined for each of the response metrics.

The construction of a heavily armoured test structure was essential to the completion of this test programme as shown in figure 4. This structure implemented modular glazing frames which were torqued to 40Nm when connected to the test structure’s front face. This structure was manufactured from two ISO containers which were retrofitted with 20mm steel plate on the side and top surfaces. The front faces utilised 30mm steel to provide additional resistance to flexure in conjunction with a series of steel stiffening columns. The completed structure was fixed to the ground to prevent any unwanted translation during the blast trials. The implementation of a twin container arrangement enabled each trial to directly compare rigid and elastic edge conditions as shown in table 1.

Characterisation of the ABT’s blast environment was accomplished by utilising the instrumentation detailed in figure 5 wherein Endevco 8510C gauges were implemented to measure free-field blast parameters. Reflected blast parameters were measured via Kistler 603B1 transducers which were positioned at the front surface of the test structure. This methodology was previously verified by a study produced by Johns and Clubley (Johns and Clubley, 2015) wherein reflected pressures measured at a glazing panel surface were shown to closely match measurements from the front surface of the test cubicle. Cumulative impulse applied to each glazing panel before breakage could therefore be determined from the reflected pressure data files, yielding applied breakage impulse for each broken panel.

High-speed footage of glazing response was captured via Phantom v7.3 cameras as shown in figure 5. This enabled response to be monitored at 2000fps via ten individual camera positions. The implementation of LEDs within each ISO container was essential to the identification of blast arrival. This was accomplished by setting an illumination trigger to occur when the reflected pressure gauges encountered the blast wave. This methodology enabled breakage times to be determined by the visual inspection of initial panel fracture. Each of the Phantom cameras positioned with a side-view were aligned with the central axes of the glazing panels to reduce parallax error when making displacement measurements from the Phantom data files. Figure 6a shows the distance markers utilised within the ISO containers to provide fixed reference points within the Phantom data files. Figure 6b graphically demonstrates the calibration procedure for the Phantom data files within which a fixed distance is related to quantity of pixels. This was accomplished via deflection markers adhered to the rear panel surfaces, thereby enabling the measurement of panel displacement.

Results and Discussion

Experimental blast environment

Examination of table 5 shows that the gauge abt1-ps recorded mean values of 13.9kPa for free-field overpressure and 108.3ms for the positive phase over the series, indicating that the mean results closely match the design requirement of 14kPa with 100ms duration. Calculations for the standard deviation of pressure and positive phase resulted in values of 4.5% and 0.68% of the mean respectively, thereby demonstrating a well-replicated blast across trials 1-12. Consequently, these low levels of statistical variability indicate that the free-field environment met the previously defined acceptability criteria of +/- 10%.

Figures 7a-d provide reflected pressure time histories with associated impulse captured at both of the reflected pressure gauges on the front of the test structure surface across trials 1-12. Table 5 also details reflected overpressure measurements from these gauges with mean values of 30.6kPa and 31.1kPa representing a negligible difference of 1.6%. Mean values for reflected impulse and positive phase duration were also found to differ by minor values of 2.6% and 0.34% respectively. These results therefore indicate that the blast waves produced within the ABT exhibited a level of uniformity which is consistent with a planar wave for each trial. Indeed, with standard deviations <5% of the mean for the reflected parameters discussed above it can be shown that these results lay within the +/- 10% acceptability criteria for trials 1-12.

Effect of edge conditions on response

Table 6 summarises glazing response for each of the twelve trials where it can be seen that breakage was observed for 22 of 24 glazing panels. 100% failure of 8mm glazing indicates a smaller threshold area for the experimental blast environment than predicted with provisional AEM models. By exceeding the threshold area for 8mm panels it is likely that the probability of a large number of micro-flaws and hence the likelihood of breakage was increased. Two cases of 4mm glazing survival were however recorded from trials 1 and 6 with elastic edge conditions at aspect ratios of 1:1 and 1:1.75. These results infer relatively accurate 4mm threshold area predictions from preliminary AEM models for the experimental blast scenario. Video 1 is supplied for real-time viewing of glazing response in these trials. This evidence suggests elastic framing may have reduced principal tensile stress experienced by the panels, preventing fracture and failure. While the influence of naturally variable glazing strength is not currently quantifiable due to the inability to non-destructively establish each panel’s tensile limit, it must not be discounted. As a result, it is also possible that each of the unbroken panels may have possessed a lower quantity of micro flaws. Flaw geometries may have also differed, limiting the ability for micro-cracks to exceed the critical dimensions required to induce fracture and breakage.

Table 7 demonstrates zero difference in measured glazing deflection for both unbroken 4mm elastic arrangements versus their rigid counterparts. The Phantom cameras used to monitor glazing response were restricted to +/- 1.0mm degree of accuracy, introducing a measurement uncertainty equivalent to +/- 10% of deflection for the 4mm glazing trials. Further inspection of table 7 shows a 1ms increase in peak deflection time for the panel with elastic edge supports and 1:1 aspect ratio compared with the rigidly supported panel from trial 1, producing a 35.3% increase in applied impulse for peak deflection. In contrast, zero difference was observed between elastic and rigid edge conditions at 1:1.75 from trial 6, resulting in a minor 4% difference in applied impulse.

Inspection of broken glazing panels clearly revealed breakage mode to be determined by the edge supports in all cases for 4mm and 8mm glazing. This was confirmed by high-speed video observations within which rigid arrangements were found to result in the transmission of a local impulsive stress wave at the clamped edges throughout the interlayers of the glazing material as seen in figure 8a. This generated significant cracking throughout the thickness of the material, leading to smaller shards. In contrast, the elastic edge conditions were found to produce a larger radial fragments at breakage as shown in figure 8b, thereby resulting in a typical failure mode for annealed glass. With considerable differences in fragment mass and shape, it is clear that edge supports may represent an important factor when determining human risk during a blast event in addition to blast magnitude, cumulative impulse delivered to the fragments and internal room layout.

Influence of parameters on response

Glazing deflection

Table 8 details mean values of peak deflection at the centre of the glazing panel up until breakage for each of the eight unique arrangements. Measurements were made via Phantom data files where 4mm glazing panels were found to show 10mm peak deflection with no measurable change for varied aspect ratio or edge conditions. It is possible therefore that the +/- 1.0mm accuracy of the Phantom v7.3 cameras prevented the detection of deflection differences. As a result, it was not possible to calculate the standard error or 50% confidence interval bounds as shown in table 7.

8mm glazing showed greater variability for peak deflection with measurements in the range of 11-18mm. The largest 50% confidence interval range of +/- 9.3% of peak deflection was calculated for the panel with rigid edge conditions and 1:1.7 aspect ratio as shown in figure 9a. Each of the confidence intervals within this study were calculated with the standard error of the mean and a statistical T-distribution score as seen in equation 1.

$$\pm\, t(\sigma_{\bar{X}}) = \pm\, t\, \left(\frac{s}{\sqrt{n}}\right) \tag{1}$$

Further examination of the 8mm results indicates maximum deflections of 18mm and 15mm with rigid edge supports at aspect ratios of 1:1 and 1:1.7 respectively. Interestingly, reductions of 28% and 27% respectively were found with elastic edge conditions. Reductions in deflection were also found with 1:1.7 aspect ratios as demonstrated by a 17% decrease versus 1:1 for constant rigid supports and 15% reduction versus 1:1 for constant elastic conditions. These decreasing trends are clearly visible in figure 9a. The combination of 1:1.7 aspect ratio and elastic edge conditions resulted in the greatest reduction with a 39% smaller deflection value versus the 1:1 aspect ratio panel with rigid edges.

Breakage Time

Table 9 summarises measurements for mean breakage time for each of the eight unique arrangements where it can be seen that 4mm glazing resulted in shorter breakage times than 8mm glazing in each equivalent instance. Closer analysis of the 4mm results shows a maximum time for the elastic edge conditions with 1:1 aspect ratio and a minimum for the rigid supports with 1:1.75 aspect ratio. These results enabled standard error calculations with the largest value being found for the 1:1.75 aspect ratio with elastic supports. With an accuracy level of +/- 0.25ms, the Phantom measurement error represents 8.1-11% of the mean break time for 4mm glazing as shown in table 8.

Interestingly, table 9 indicates that the elastically supported 4mm glazing panel produced a 24% increase in break time compared with rigid supports at 1:1 aspect ratio and a 14% gain when compared with rigid edges at 1:1.75 aspect ratio. Conversely, the 1:1.75 aspect ratio was found to reduce the break time by 12% and 19% when compared with 1:1 aspect ratios for rigid and elastic supports. These opposite trends are clearly visible in figure 9b where the net effect of elastic edge conditions and an aspect ratio of 1:1.75 produced no change in the mean break time compared with the 1:1 panel with rigid edges, thereby indicating that these two parameters nullified each other.

Analysis of the break times for 8mm glazing shows the panel at 1:1.7 aspect ratio with elastic supports produced the smallest time whereas the panel with 1:1 aspect ratio and rigid supports produced the largest time. This panel also yielded the largest 50% confidence interval of +/- 9.1% of the mean time. Figure 9b reveals a similar decreasing trend to that seen with deflection for 8mm glazing in figure 9a. This is visible in table 9 with a break time decrease of 22% for the panel with 1:1 aspect ratio and elastic edges compared with the rigid alternative. Similarly, a 17% is visible for the panel with elastic edges and 1:1.7 aspect ratio when compared to the rigid counterpart. Aspect ratios of 1:1.7 were also found to decrease break times by 14% and 8% for rigid and elastic edge conditions when compared to 1:1 aspect ratios. The net effect of elastic edge conditions and 1:1.7 aspect ratio yielded the greatest decrease in break time with a 29% reduction versus the 1:1 aspect ratio with rigid edges.

Applied Breakage Impulse

Table 10 details mean values of applied breakage impulse for each arrangement. Initial analysis revealed lower figures for 4mm versus 8mm glazing for each arrangement, logically correlating with the lower breakage times in table 9. Inspection of the 4mm results shows a range of 62.6-86.8kPa-ms with the maximum recorded for the 1:1.75 aspect ratio with elastic supports and the minimum for the 1:1 panel with rigid edges. Standard error calculations were found to represent a range of 1.88-11.6kPa-ms with the value found for the1:1.75 aspect ratio with elastic edge conditions.

Further examination of table 10 shows that elastic edges resulted in 37% and 15% gains in applied breakage impulse for 4mm glazing at 1:1 and 1:1.75 aspect ratios. A 21% increase was also found when comparing rigid edges with 1:1.75 aspect ratios versus those with 1:1 aspect ratio. Variability in aspect ratio with elastic edges was found to produce a negligible 1% difference. This result may have been influenced by a standard error value of 13.4% for the 1:1.75 aspect ratio with elastic edges. The greatest increase in breakage impulse was observed to be 39% for elastic panel with 1:1.75 aspect ratio and elastic supports versus the panel with 1:1 aspect ratio and rigid supports, which is marginally larger than the 37% increase recorded for elastic supports at 1:1.

Inspection of the 8mm results for applied break impulse showed the panel with 1:1 aspect ratio and rigid edges to produce the largest value of 148.7kPa-ms whilst the panel with 1:1.7 aspect ratio and elastic supports produced the smallest at 109.0kPa-ms. Standard errors were calculated to be 1.70-22.6kPa-ms, the largest of which was found for the 1:1 panel with rigid conditions. Further examination of table 10 revealed that elastic edge conditions produced a 15% decrease in breakage impulse for 8mm glazing at 1:1 and a 12% reduction at 1:1.7. Breakage impulse reductions of 17% and 14% for elastic and rigid supports were found with 1:1.7 aspect ratios versus those with 1:1 aspect ratios. The net effect of 1:1.7 aspect ratio and elastic edges resulted in the largest decrease in break impulse with a 27% reduction compared to the panel with 1:1 aspect ratio and rigid edges.

Figure 9c demonstrates a reduction in break impulse with the 1:1.7 aspect ratios and elastic edges for 8mm glazing, thereby demonstrating a similar decreasing trend as seen with deflection and break time. In contrast, 4mm glazing indicates an increase in breakage impulse for these scenarios. Interestingly, this represents vastly different behaviour to the static results for peak deflection and oscillatory data for breakage time with 4mm glazing.

Conclusions

This paper has experimentally investigated and quantified a number of glazing response metrics for annealed glazing panels when subjected to transient long-duration blast loads. The experimental blast environment was found to possess minimal variability for both free-field and reflected blast results across the series of twelve trials. The influence of edge support conditions upon the binary condition of breakage was shown to be variable. Survival of two elastically supported 4mm panels at 1:1 and 1:1.75 aspect ratios inferred a potential reduction in principal tensile stresses. 100% breakage observed for 8mm glazing suggests that this thickness requires a smaller panel area for threshold conditions in the experimental blast scenario.

Glazing panel fragmentation was determined to be directly linked to edge support conditions with elastic supports yielding large, radial breakage patterns. In contrast, rigid supports resulted in the transmission of impulsive stress waves at the clamped edges, leading to a significant cracking and smaller fragments. Significant variability in fragment mass and shape indicates the importance in quantifying edge conditions when seeking to appraise glazing hazard to humans during a blast scenario.

The quantification of peak glazing deflection indicated lower values for 4mm glazing versus 8mm with the former showing zero measurable difference when varying aspect ratio or edge supports. In contrast, 8mm glazing results were found to reduce as a function of these parameters with the lowest value reported for the elastic panel at 1:1.7 aspect ratio.

Breakage time analysis revealed lower values for 4mm versus 8mm with each equivalent arrangement. Each of the two thicknesses demonstrated break time reductions for 1:1.7 aspect ratios versus 1:1 aspect ratios with constant support conditions. 4mm glazing results were found to increase with elastic conditions versus rigid with constant aspect ratio while 8mm glazing demonstrated reductions in these scenarios. The largest 8mm breakage time decrease was recorded for 1:1.7 elastic versus 1:1 rigid. Inversely, 4mm results showed zero change for this scenario, indicating that a counter balance of these two parameters may have produced a cancellation effect.

Examination of applied breakage impulse data revealed lower values for 4mm versus 8mm, correlating with breakage time results. Aspect ratios of 1:1.7 and elastic edge conditions were found to increase breakage impulse for 4mm glazing while the inverse was found for 8mm glazing in these scenarios. These 8mm results represent a similar decreasing trend to that found with peak deflection and break time.

The evidence presented suggests that aspect ratio and edge conditions exhibit an influence on glazing response which is dependent on immediacy to the threshold breakage area for a particular glazing thickness. Thereby indicating that the variable trends identified within the 4mm data may be due to the immediacy of the panel area to the theoretical threshold, as demonstrated by the survival of two elastically supported panels. In contrast, the constant trend identified for 8mm glazing may be a result of the panel areas exceeding the threshold for this thickness as inferred by 100% observed breakage. A further twelve trials will seek aim to investigate this at a future date by analysing the relationship between threshold dimensions and glazing thickness. These will employ 4mm and 6mm glazing with the glazing dimensions utilised within this study for 8mm glazing panels.

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Notation

The following symbols are used in this paper:

E = Young’s modulus, Pa

G = Shear modulus, Pa

N = Sample size

S = Standard deviation

T = T-score

P = Density, kg/m^3

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

$\bar{X}$ = Mean