# Quantifying the Influence of Aspect Ratio on Window Failure when Subject to Long-duration Blast Loading

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## Abstract

Windows differ vastly in size and shape, even for a single building. Analysis of post-explosion photographs shows that aspect ratio can have a significant effect on the survival of a window. While new constructions use laminated glass to mitigate damage, many older buildings still contain more fragile annealed glass. In the United Kingdom, 4mm-thick annealed glass represents the minimum specification for windows and therefore the worst damage case. This paper reports on the effect of window aspect ratio on the failure characteristics of annealed glass subjected to long-duration planar blast waves. Long-duration blasts are typically defined by a positive phase duration greater than 100ms, observed in the far field of large explosions which produce large impulses. The air blast tunnel (ABT) at MOD Shoeburyness is a unique testing facility capable of simulating pressure regimes observed in long-duration blast events. In a series of eight full-scale trials in the ABT, sixteen 4mm-thick annealed glass windows were examined. Four different aspect ratios, from 1:1 to 1:2, were considered. High-speed photography captured glass response while fibre-optic controlled instrumentation recorded full incident and reflected pressure histories. Results from the experimental study demonstrate that aspect ratio significantly influences the break time and crack propagation in glass panels.

*Keywords:* Long-duration blast loading; Aspect ratio; Annealed glass

## INTRODUCTION

Glass windows are the most vulnerable components of a building and, when exposed to blast loading, produce the largest damage radius. Trawinski estimated that when a blast occurs in an urban environment, 80% of injuries are due to glass failure[1]. While new constructions implement safer laminated glazing, many older building contain annealed glass. At failure, these windows shatter into angular shards that lacerate the skin on impact, causing significant injury. Annealed, 4mm thick glass represents the minimum specification for glazing in the UK and therefore the worst case scenario in terms of damage and injury.

In August 2015, detonation of an estimated 800 tons of ammonium nitrate occurred in Tianjin, China producing two explosions of 15 tons and 430 tons TNT equivalence[2]. Over 17,000 households sustained damage to windows up to five and a half kilometres away from the point of detonation. “Severe damage” resulted in buildings up to two kilometres away[3]. A residential building which incurred partial window failure is shown in Figure 1. It can be assumed that all windows experienced the same blast environment yet only some have failed, implying structural parameters such as glass area and aspect ratio influenced survival. Analysis identified windows with smaller areas and lower aspect ratios as having a higher probability of survival.

A large explosion, such as the Tianjin event, produces a long-duration blast wave in the far-field. This blast environment, which is typically defined by a positive phase duration greater than 100ms, produces large impulses that cause window failure several kilometres away, despite its low overpressure. The air blast tunnel (ABT) at MOD Shoeburyness is capable of replicating this blast environment, allowing full-scale experimental trials to be undertaken (Figure 2)[4]. The 200m long explosively-driven shock tube was constructed in 1964 and has been used in a number of experiments investigating structural response to long-duration blast loading[5]–[7].

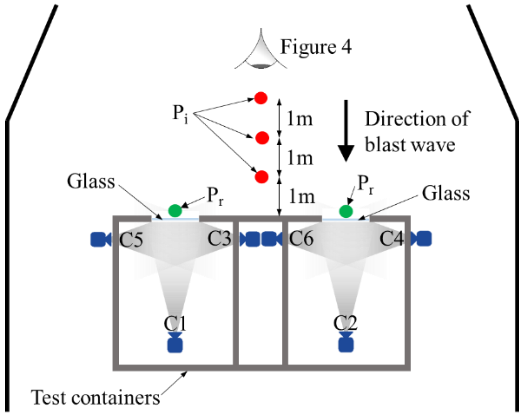
**Figure 1.** Damage to windows in a residential block near to the Tianjin explosion[8].

**Figure 2.** The air blast tunnel (ABT) at MOD Shoeburyness, UK [4].

## EXPERIMENTAL SET-UP

Two reinforced steel containers, constructed by Spurpark Ltd., were installed in the 10.2m diameter testing section of the ABT, normal to the blast wave. Modular sub-frames containing glass samples were attached to the front of these containers. Each window was subjected to a blast wave with peak free-field static overpressure of 14kPa and positive duration of 100ms. Testing containers were sealed to prevent equalisation behind the glass before failure.

A full pressure history of each trial was recorded using incident and reflected overpressure gauges (locations shown in Figure 3). Three Endevco 8510-50 static gauges were located at 1m intervals upstream of the test cubicles and an Endevco 8510C-50 reflected pressure gauge was adhered to the front of each cubicle, in line with the vertical centreline of the glass. These gauges are labelled in Figure 4. High-speed photography captured glazing response to the blast wave, including break time, deflection at failure and crack patterns. Camera positions are labelled in Figure 3 and Figure 4. Crack patterns were recorded by cameras C1 and C2. These were Phantom 2512 models with a frame rate of 75,000 frames per second (fps). An overall view of glass deflection was provided by Phantom V3.3 cameras at locations C3 and C4. These ran with a frame rate of 5,000fps. Cameras C5 and C6 (Phantom V711 with frame rate 75,000fps) tracked movement of the deflection gauge, allowing central glass deflection to be recorded over time. The deflection gauge is shown in Figure 5.



**Gauges:**
$P_i$ – Incident overpressure (Endevco 8510-50)
$P_r$ – Reflected overpressure (Endevco 8510C-50)

**Cameras:**
C1, C2 – Phantom 2512 (75,000fps)
C3, C4 – Phantom V3.3 (5,000fps)
C5,C6 – Phantom V711 (75,000fps)

**Figure 3.** Plan of experimental set-up in the ABT.

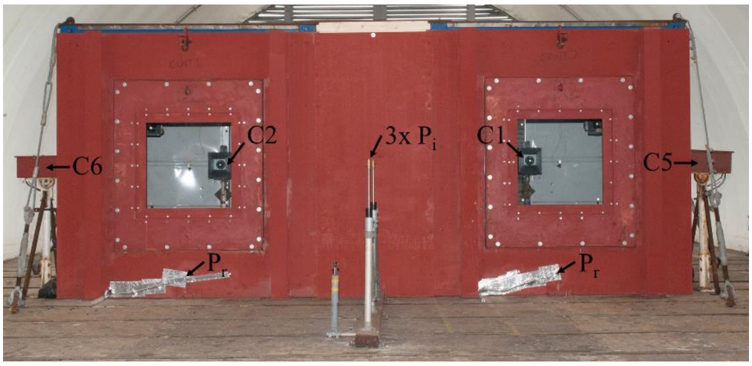


**Figure 4.** Elevation of test cubicles with instrumentation labelled.

**Figure 5.** Deflection gauge used to track central deflection.

In this experimental series, eight trials were conducted with 16 pieces of glass. Four glass aspect ratios were investigated; 1:1, 1:1.3, 1:1.7 and 1:2. For each aspect ratio, four glass samples were used. Identical glass samples were tested in each trial. All glass was annealed and had a total area of 0.89m$^2$ and thickness of 4mm. Glass was restrained by a steel frame bolted against spacers to ensure even stress distribution. This represented "rigid" support conditions. Frame layout and corresponding dimensions for each aspect ratio are presented in Figure 6 and Table 1.

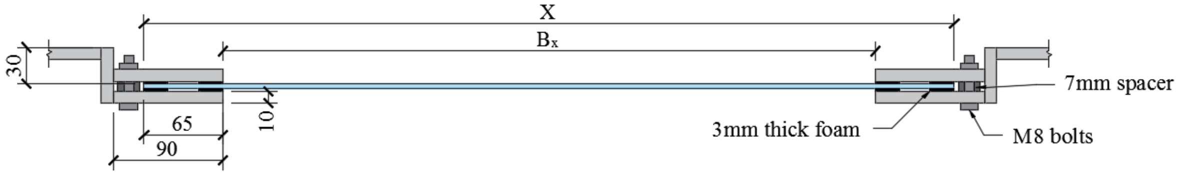


**Figure 6.** Horizontal section through frame, dimensions listed in Table 1.

**Table 1.** Frame and glazing dimensions for each trial as detailed in Figure 6.

| Trial No. | 1-2 | 3-4 | 5-6 | 7-8 |
|---|---|---|---|---|
| Aspect Ratio | 1:1 | 1:1.3 | 1:1.7 | 1:2 |
| Area (m$^2$) | 0.89 | 0.89 | 0.89 | 0.89 |
| X (mm) | 945 | 827 | 725 | 667 |
| Y (mm) | 945 | 1075 | 1230 | 1334 |
| $B_x$ (mm) | 815 | 697 | 595 | 537 |
| $B_y$ (mm) | 815 | 945 | 1100 | 1204 |

## EXPERIMENTAL RESULTS AND ANALYSIS

### Blast Environment

Mean peak free-field static overpressure, recorded 3m upstream of testing cubicles, was 13.4±0.1kPa over the eight trials. Total free-field impulse during the positive phase and positive phase duration were equally consistent, 690±7kPa.ms and 100±1ms respectively. A full pressure and impulse history from this gauge is shown in Figure 7. Very high consistency is observed across all trials, especially in the first 50ms after blast arrival. Slight discrepancies appear towards the end of the positive phase which could be attributed to turbulence behind the blast wave front. The initial rise in overpressure after blast wave arrival was a function of changing light levels on the gauge and has been observed in multiple trials. Large reflections caused by the testing cubicles produced the subsequent peaks in overpressure. This prevented a full free-field pressure history being recorded and an overestimation of total impulse. While a true free-field pressure history was not achieved, consistency between trials was demonstrated.

Reflected overpressure was used to analyse the blast environment that glass samples were subjected to. Very good agreement was observed for both test cubicles across all trials (Figure 8). Mean peak reflected overpressure was 38.8±1.3kPa and mean total reflected impulse was 724±8kPa.ms. All glass samples failed within 4ms of blast wave arrival. Reflected overpressure was approximately constant until after glass failure had occurred.

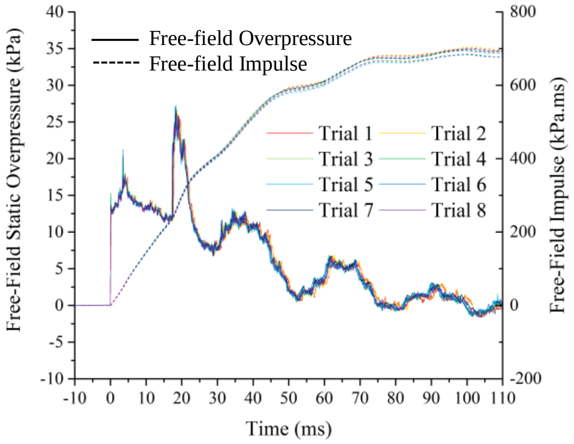


**Figure 7.** Free-field static overpressure and impulse 3m upstream of test cubicles.

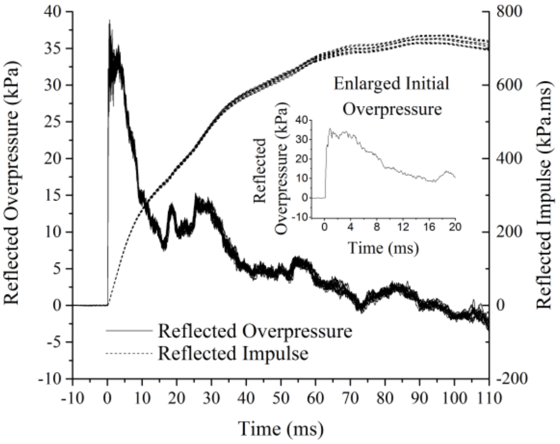
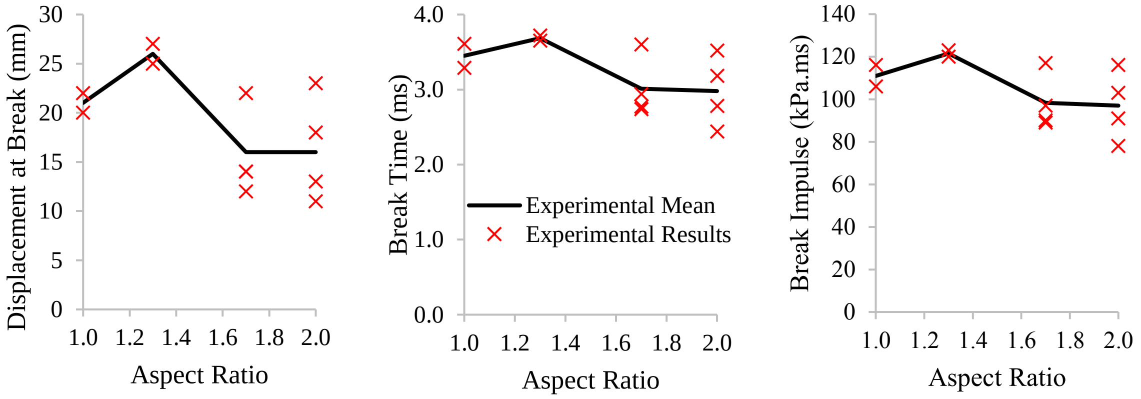


**Figure 8.** Reflected overpressure and impulse for both test cubicles from all trials.

### Break Parameters

Central defection at failure, time to break after blast wave arrival and reflected impulse at break were recorded from camera and gauge data. Deflection was measured using deflection gauges (Figure 5) and cameras C5 and C6. Break time was recorded using cameras C1 and C2 and impulse was calculated from Figure 8 based on break time. Results for each parameter are outlined in Figure 9 and Table 2. Break parameters from Trials 1 and 2 were not recorded due to a gauge fault. This resulted in only two samples for aspect ratios 1:1 and 1:1.3. Mean and individual results are plotted in Figure 9 and 90% confidence intervals were calculated for each parameter and are detailed in Table 2.



**a.** Maximum displacement at time of initial crack.

**b.** Glass failure time.

**c.** Impulse received at time of initial crack.

**Figure 9.** Individual and mean break parameters plotted against aspect ratio.

**Table 2:** Mean break parameters for each aspect ratio with calculated 90% confidence intervals.

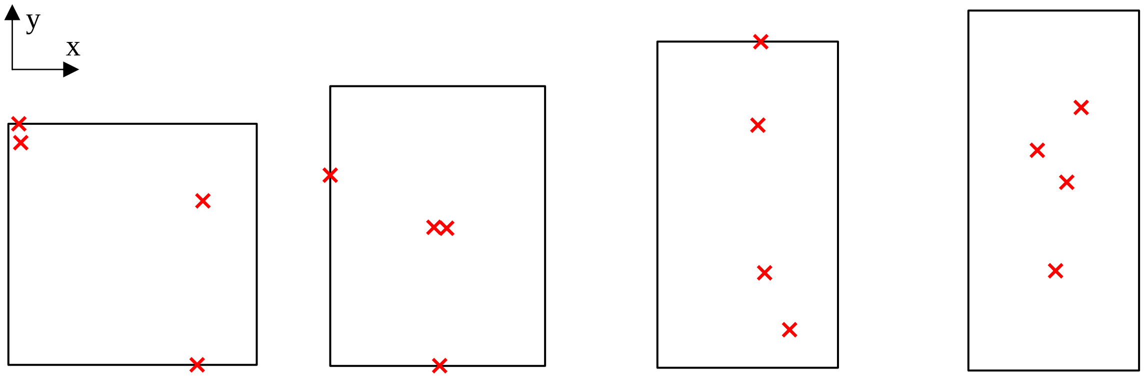
| | | Aspect Ratio | | | |
|---|---|---|---|---|---|
| | | 1:1 | 1:1.3 | 1:1.7 | 1:2 |
| Displacement at Failure (mm) | Mean<br>90% CI | 21<br>±6 | 26<br>±6 | 16<br>±5 | 16<br>±6 |
| Break Time (ms) | Mean<br>90% CI | 3.45<br>±1.0 | 3.69<br>±0.22 | 3.01<br>±0.47 | 2.98<br>±0.55 |
| Impulse at Failure (kPa.ms) | Mean<br>90% CI | 111<br>±32 | 122<br>±9 | 98<br>±15 | 97<br>±19 |

When plotted against aspect ratio, all break parameters followed a similar trend with a peak at 1:1.3 and minimum values for aspect ratios 1:1.7 and 1:2. While break time and impulse are inherently linked, this indicates that displacement at break and failure time are also closely related. The trend is most significant for displacement. A decrease in mean displacement at failure of 38% was recorded between 1:1.3 and 1:1.7 compared to decreases of 18% and 20% for mean break time and mean impulse respectively.

High variability was observed between glass samples of the same aspect ratio. This can be seen in the individual results plotted in Figure 9 and the calculated 90% confidence interval. Variation in results is due to high intrinsic variability of the glass itself. This is caused by the random size and location of the Griffith Flaw[9] in samples. In some cases the 90% confidence interval calculated was larger than the observed trend and more repeats are required to determine if the relationship with aspect ratio is significant when compared to variation in glass strength. Experimental errors such as camera rate and pixel size introduced errors of 0.01ms for break time and 0.5mm for central deflection. These errors are minimal compared to glass strength variation.

## Crack Patterns

Location of initial failure in the glass and crack pattern was highly variable between samples as it was dependent on the location of the Griffith Flaw. Initiation points for each glass sample are shown in Figure 10. These were measured from video footage with maximum error of 6mm. While there is a large variation in crack locations, there is a clear difference between lower aspect ratios 1:1 and 1:1.3, where crack location is random, and higher aspect ratios 1:1.7 and 1:2 where all cracks initiated along the vertical centreline of the glass. This change in crack location could indicate a transition from two-way spanning conditions to one-way spanning where the glass is governed only by the shortest dimension. A transition in spanning conditions could be the cause of the decreased displacement at break for higher aspect ratios. These crack patterns and break parameters will provide a benchmark for future computational modelling of glass subjected to long-duration blast.



**a.** Aspect ratio 1:1. **b.** Aspect ratio 1:1.3. **c.** Aspect ratio 1:1.7. **d.** Aspect ratio 1:2.

**Figure 10.** Initial crack locations from each glass sample.

## DISCUSSION

A decrease in displacement at failure, break time and impulse was observed between aspect ratios 1:1.3 and 1:2. This could be attributed to one-way spanning conditions, governed by length of the shortest span. As aspect ratio increased, the shortest side decreased causing an increase in stiffness. This caused a decrease in deflection at failure and an earlier break time. Aspect ratio 1:1 broke with a lower displacement than 1:1.3 despite having longer dimensions. This could be due to two-way spanning conditions increasing stiffness in the glass. While this theory is supported by crack location at high aspect ratios, 1:1.3 demonstrated highly variable cracking, similar to 1:1 indicating two-way spanning. This aspect ratio is at the transition between spanning conditions, producing an increase in resistance to blast pressure due to a large span but additional stiffness from two-way spanning.

Intrinsic variability in the glass was high leading to large confidence intervals being calculated. However break parameters, especially displacement, varied considerably with aspect ratio, indicating that aspect ratio influences failure. More trials are required, especially at lower aspect ratios, to determine if the mean values calculated are representative and confirm that aspect ratio is a significant factor in window failure. All glass samples were subjected to a peak free-field overpressure of 13.4kPa and broke within 4ms. This blast environment was significantly above the threshold of glass failure meaning that structural parameters such as aspect ratio were insignificant compared to the blast. Despite this, a trend between break parameters and aspect ratio was clear. Future trials, with lower overpressures, will investigate the significance of aspect ratio nearer to the threshold of window failure.

## CONCLUSIONS

Aspect ratio 1:1.3 exhibited the highest resistance to long-duration blast loading with peak overpressure 13.4kPa. A decrease in displacement and time of break was observed for higher aspect ratios which could be due to additional stiffness as a result of one-way spanning conditions and a span decrease. 1:1 windows were also stiffer than 1:1.3 due to two-way spanning conditions. More data is required to confirm this trend due to large variability in results between repeats. This was attributed to variation in glass strength.

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## REFERENCES

[1] E. Trawinski, J. W. Fisher, and R. J. Dinan, “AFRL-ML-TY-TP-2005-4508 Full Scale Testing of Polymer Reinforced Blast Resistant Windows,” Air Force Research Laboratory Report, Florida, USA, 2004.

[2] G. Fu, J. Wang, and Y. Mingwei, “Anatomy of Tianjin Port Fire and Explosion: Process and Causes,” *Process Saf. Prog.*, vol. 35, no. 3, pp. 216–220, 2016.

[3] S. L. Mcgarry, S. Balsari, S. Muqueeth, and J. Leaning, “Preventing the Preventable: The 2015 Tianjin Explosions,” Cambridge, MA, 2017.

[4] S. K. Clubley, “Non-linear long duration blast loading of cylindrical shell structures,” *Eng. Struct.*, vol. 59, pp. 113–126, 2014.

[5] R. Johns and S. K. Clubley, “Experimentally investigating annealed glazing response to long-duration blast,” *J. Struct. Eng.*, 2016.

[6] R. Johns and S. K. Clubley, “The influence of structural arrangement on long-duration blast response of annealed glazing,” *Int. J. Solids Struct.*, vol. 97–98, 2016.

[7] J. Denny and S. K. Clubley, “Multi-axis long-duration blast interaction with I-shape steel sections,” in *MABS 2016; 24th International Symposium on the Military Aspects of Blast and Shock*, 2016.

[8] BBC News, “China explosions: What we know about what happened in Tianjin,” 2015. [Online]. Available: http://www.bbc.co.uk/news/world-asia-china-33844084. [Accessed: 02-Feb-2016].

[9] A. A. Griffith, “The Phenomena of Rupture and Flow in Solids,” *Philos. Trans. R. Soc. London. Ser. A, Contain. Pap. a Math. or Phys. Character*, vol. 221, no. 582–593, pp. 163–198, 1921.