ALTERNATIVE METHODS OF DATA CAPTURE FOR GLASS SUBJECTED TO LONG-DURATION BLAST LOADING

S. Monk, *University of Southampton, UK*
S. K. Clubley, *University of Southampton, UK*

ABSTRACT

The air blast tunnel (ABT) at MoD Shoeburyness is a unique testing facility capable of simulating pressure regimes recorded in long-duration blast events. Long-duration blasts are typically defined by a positive phase duration greater than 100ms, observed in the far field of large explosions. Due to its highly brittle nature, glass panels require high-speed data capture to provide reliable engineering information about their response to blast loading. The harsh environment of the ABT makes accurate collection of this data very difficult. Current methods of data capture depend on interpretation of high-speed video footage, the accuracy of which is severely affected by shock wave induced camera shake. In a series of five companion static loading tests, two different methods of recording glass failure time were trialled; a circuit of conductive paint on the surface of the glass and a series of piezo transducers to record the acoustic profile at breakage. High-speed photography provided an independent correlation. Experimental results demonstrate that piezo transducers are a low-cost and comparatively accurate method of determining the time of glass failure and crack location in a static testing environment. In February 2017, a series of eight full-scale trials in the ABT demonstrated that piezo transducers were capable of replicating these results in a long-duration blast environment.

1. INTRODUCTION

The air blast tunnel (ABT) at MOD Shoeburyness, UK, was constructed in 1964 and is one of a small number of facilities in the world which are capable of testing full-scale structural response to long-duration blast waves (Figure 1)[1]. Long-duration blasts are typically defined by a positive phase duration greater than 100ms, observed in the far field of large explosions. The 200m long explosively driven shock tube has been used for a number of glass related trials in the past[2]–[4], however the harsh environment makes collecting precise data very challenging. Currently, data capture relies on high-speed photography, however this is susceptible to camera shake, reducing accuracy of the results.

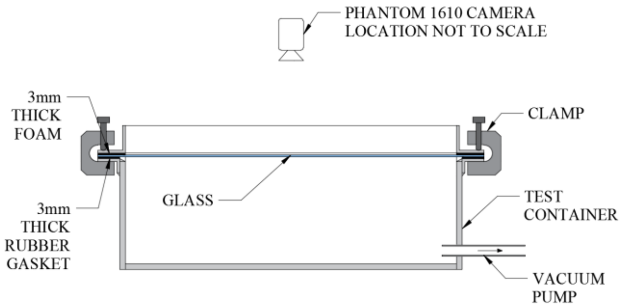
Figure 1. The air blast tunnel (ABT) at MoD Shoeburyness, UK [1].

In this paper, two methods of determining time of glass failure and location of the crack origin are trialled, initially in laboratory conditions and then in the ABT. Break circuits, used by Spiller et al.[5], consist of a 'wire' painted onto the surface of the glass using conductive paint. The circuit then breaks with the glass. Piezoelectric (piezo) transducers convert vibrations, such as the sound of glass breaking, into electrical potential. Difference in time of arrival of the signals between piezo transducers allows the location of the crack to be determined.

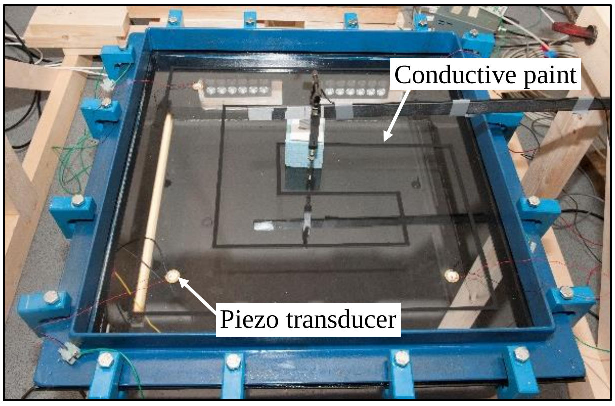
2. STATIC TESTING

2.1 EXPERIMENTAL SET-UP

Five tests in the laboratories at MOD Shoeburyness were undertaken in January 2017 to assess piezo transducers and break circuits under static loading conditions. Each specimen of glass was tested to failure by a vacuum chamber (Figure 2) within which the pressure was reduced linearly at a rate of $0.44kPas^{-1}$. The static testing rig, designed and constructed by the Foulness Trials Group of Spurpark Ltd, consisted of a 10mm thick airtight steel container which supported the framed glass specimen. 700mm x 700mm x 4mm thick basic annealed glass was used in all tests. The aperture of the frame was 620mm x 620mm and the glass was restrained in the frame by four clamps on each edge, providing rigid support conditions.



(a) Schematic of full experimental set-up for static testing.



(b) Static testing box with instrumentation for Test 2.

Figure 2. Static testing set-up.

2.2 INSTRUMENTATION

Instrumentation used in each test is shown in Figure 3. Test 1 validated that piezo transducers and conductive paint were capable of recording break time. Piezo transducer locations were not measured and a single strip of conductive paint was applied. In Test 2, four piezo transducers were located 100mm from the edges of the glass, in each corner. A geometric pattern of conductive paint was produced on the glass to ensure the crack met the circuit quickly (Figures 2b and 3). In Tests 3 to 5, repeatability of piezo transducers in recording the break time and location was examined. Four piezo transducers were applied to the glass, one in each corner, 50mm from the edges. No conductive paint was used.

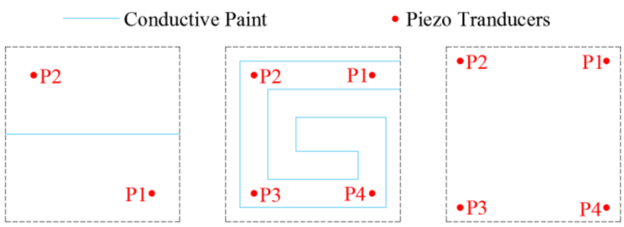


Figure 3. Instrumentation layout on surface of the glass for each test.

The Murata 7BB piezo transducers used were 20mm in diameter and were fixed to the glass using Loctite 496 superglue. The difference in time of arrival method was used iteratively with the minimum sum-of-squares of errors to find crack location. Sound velocity was calculated using the same method. A carbon-based conductive paint was used for the break circuits and was applied as a 5mm thick line. The signal from the piezo transducers and conductive paint was sampled at a rate of 1MHz. A Phantom 1610 camera with a frame rate of 52kHz provided an independent data set for comparison.

2.3 EXPERIMENTAL RESULTS

The initial crack location was calculated for Tests 2 to 5 (Figure 4). This was not possible for Test 1 as only two piezo transducers were used. Good agreement was observed between the piezo transducers and camera with an average difference of 42mm over four tests, and a maximum of 61mm in Test 3. The calculated speed of sound in the glass was 6.0±1.5kms^{-1}.

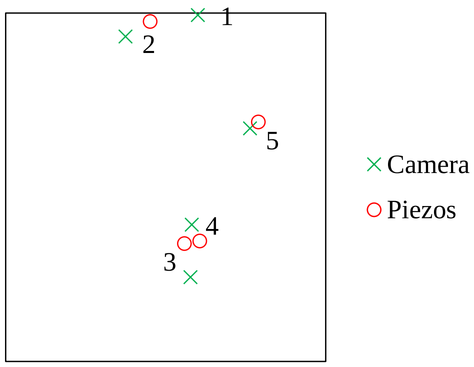
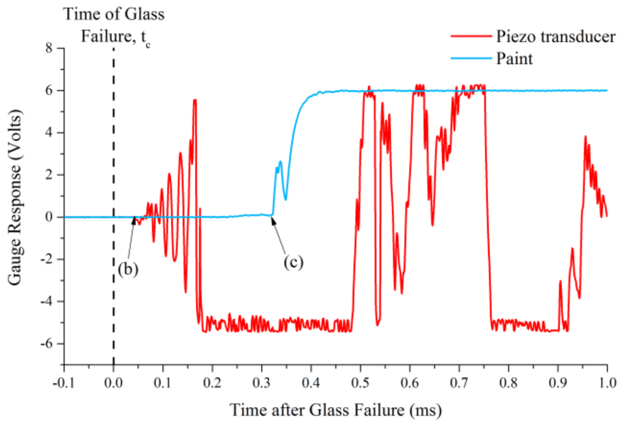
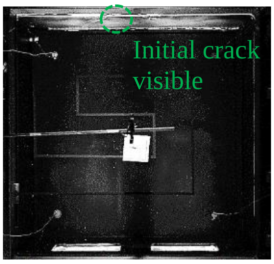


Figure 4. Initial crack locations for each test from the camera and piezo transducers.

Different triggers were used for the camera and gauges, therefore the camera could not be used to compare break times. Piezo transducers accurately located the origin of the cracks in each test, therefore the calculated crack time was reliable. In Test 2, the piezo transducer delay was 0.035ms. Multiple piezo transducers allowed the break time to be calculated, negating this error. In comparison the conductive paint exhibited a delay of 0.312ms (Figure 5a). Figure 5b and Figure 5c show cracking in the glass after these delays. At the time of the piezo transducer response, very slight cracking can be seen. Significant fracturing had occurred before the paint responded, despite cracks crossing several parts of the circuit.



(a) Gauge signal after glass failure for test 2.



(b) Time of piezo transducer response ($t = t_c + 0.038$ ms).

(c) Time of conductive paint response ($t = t_c + 0.304$ ms).

Figure 5. Delay in gauge response time after glass failure for piezo transducers and conductive paint in test 2.

2.4 DISCUSSION

It was not possible to determine the location of the crack origin using break circuits. When compared to piezo transducers, conductive paint exhibited a response delay of 0.3ms, despite cracks propagating across several parts of the circuit. With break times of approximately 3ms in the ABT, this corresponds to an error of 10% in break time. This delay can be attributed to high resistivity of carbon-based paint. Break circuits required significant preparation time to paint the geometric pattern and allow the paint to dry.

Piezo transducers were able to accurately calculate the location of the crack origin with an average error of 5% of the glass dimensions despite large variation in calculated sound velocity (standard deviation was 24% of the mean). The piezo transducers used had a diameter of 20mm but were assumed to be a point in the calculations which introduced a 10mm error in the crack locations calculated. Due to the crack locations being calculated accurately, the break time of the glass could be determined with confidence. Piezo transducers were easy to use in a time-sensitive trial schedule due to their short preparation time. It was concluded that piezo transducers were the most effective break detection method for use in the ABT.

3. DYNAMIC TESTING

3.1 EXPERIMENTAL SET-UP

Four glass samples with piezo transducers attached were subjected to a blast wave in the ABT with peak overpressure of 14kPa and positive phase duration of 100ms. Two steel test cubicles, designed and constructed by Foulness Trials Group of Spurpark Ltd[2], were fitted in the 10.2m diameter section of the ABT normal to the blast wave (see Figures 6 and 7). 667mm x 1334mm x 4mm annealed glass was supported by a steel frame with an aperture of 1207mm x 537mm. The frame provided rigid support conditions and was fixed by bolts tightened against spacers (Figure 8).

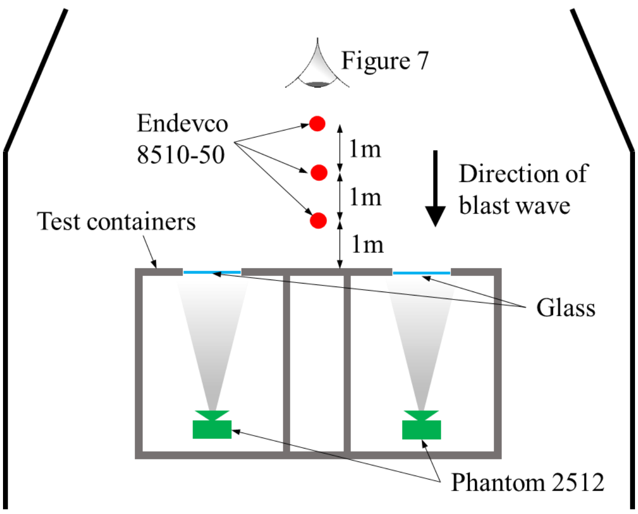


Figure 6. Plan of experimental set-up in the ABT.

Figure 7. Front elevation of test cubicles in ABT.

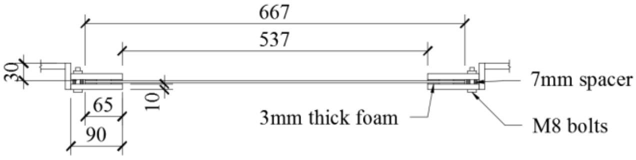


Figure 8. Horizontal section through glass frame.

3.2 INTRUMENTATION

A full free-field pressure history was recorded for each trial using a series of Endevco 8510-50 gauges (shown in Figures 6 and 7). Phantom 2512 cameras, with a frame rate of 75kHz, recorded crack location and break time of the glass. Five 20mm diameter piezo transducers, with a sample rate of 1MHz, were adhered to the rear side of each window (see Figure 9). All instrumentation was triggered at the time of driver detonation to ensure a common time scale.

Figure 9. Piezo transducer numbering.

3.3 EXPERIMENTAL RESULTS

Over the two trials a mean peak overpressure of 13.3kPa was recorded with mean positive phase duration of 100ms (Table 1). While slightly lower than specified, a high level of consistency across the trials was observed with a standard deviation of 0.2kPa. Positive phase duration and maximum impulse demonstrated similar consistency.

Table 1. Blast environment from each trial.

Trial	1	2	Mean
Peak Overpressure (kPa)	13.5	13.1	13.3
Positive Phase Duration (ms)	99	100	100
Maximum Impulse (kPa.ms)	691	683	687

Amplitude sensitivity of the piezo transducers was reduced by a factor of 1000 from the static results to ensure full response was captured (Figure 10). Glass failure was identified by a discontinuity in gauge signal followed by high frequency response. These break times were used to calculate the crack origin for each sample (Figure 11). Very good agreement was seen between the camera and piezo transducers for all tests. The mean difference was 14mm and the maximum was 26mm in sample 2 (see Table 2).

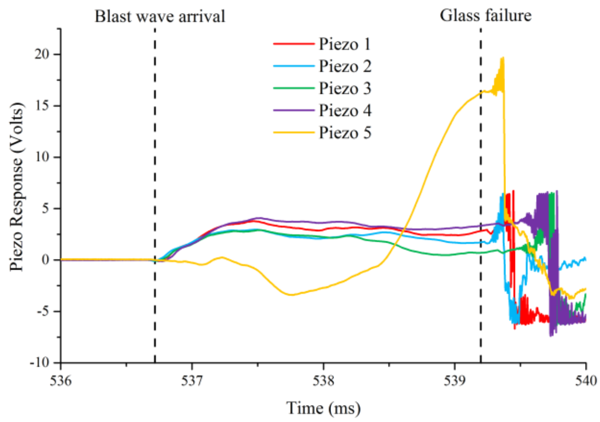


Figure 10. Piezo transducer response for glass sample four.

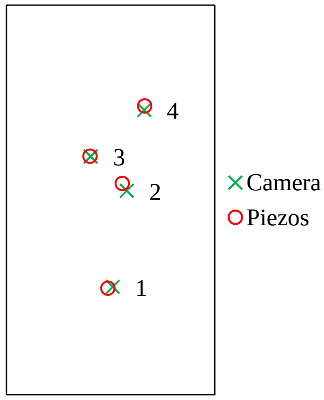


Figure 11. Crack location from camera and piezo transducers.

Table 2. Difference between crack locations from cameras and piezo transducers for each trial.

	1	2	3	4	Mean
Difference (mm)	13	26	3	13	14

Time of glass failure was recorded by cameras and calculated from piezo transducer response. The mean difference in break time between the two methods across four samples was 0.00±0.10ms, this error represents 3% of the mean break time (2.98ms) recorded for the glass panels tested. Calculated sound velocity was 6.0±0.8km/s.

3.4 DISCUSSION

Piezo transducers measured crack locations with high accuracy. The accuracy was greater in the dynamic tests, which could be attributed to the full response being recorded after reduction in sensitivity of the piezo transducers. Spread in calculated sound velocity was low compared to static testing, indicating an improvement in method reliability. Glass break time recorded by piezo transducers was very accurate when compared to the cameras showing that this method is capable of meeting both objectives in the ABT.

4. CONCLUSIONS

Both in the laboratory and the ABT, piezo transducers were capable of measuring both glass failure time and location of the crack origin with very high accuracy. This technique will be used in future experimental work in the ABT.

ACKNOWLEDGEMENTS

The authors would like to express gratitude to the UK Ministry of Defence for allowing use of the blast testing facilities at MOD Shoeburyness. All data obtained whilst using these facilities remains the property of the UK MOD. The permission to utilize these results within this paper is gratefully acknowledged. The authors wish to thank AWE plc for financial support.

REFERENCES

[1] S. K. Clubley, “Non-linear long duration blast loading of cylindrical shell structures,” *Eng. Struct.*, vol. 59, pp. 113–126, 2014.
[2] R. Johns and S. K. Clubley, “Experimentally investigating annealed glazing response to long-duration blast,” *J. Struct. Eng.*, 2016.
[3] 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.
[4] R. Johns and S. K. Clubley, “Post-fracture response of blast loaded monolithic glass,” *Proc. ICE - Struct. Build.*, vol. 168, no. SB1, 2015.
[5] K. Spiller, J. A. Packer, M. V. Seica, and D. Z. Yankelevsky, “Prediction of annealed glass window response to blast loading,” *Int. J. Impact Eng.*, vol. 88, pp. 189–200, 2016.