

Investigating the Origin of Breakage of Panes Subjected to Blast Loading by Acoustic Emission Testing

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The Fraunhofer EMI shock-tube facility “Blast-STAR” is used to simulate blast loadings from high explosive detonations similar to realistic conditions. Mainly tests on explosion-resistant safety glazing and façades are carried out. Due to the extreme conditions during the test, it is not trivial to accurately analyze the specimen reaction and in particular to determine the start of breakage of the glass pane. Usually high-speed footage is used for this purpose. Since the size of tested elements is increasing, the determination of place and time of breakage becomes more challenging. Monk and Clubley successfully used piezo transducers in an alternative approach to measure the shock wave originating from glass breakage for detecting the point of initial cracking. They used long-duration blasts, characterized by small peak pressures and a long positive phase duration. In contrast, the blast waves generated with the “Blast-STAR” are characterized by higher peak pressures and a considerable shorter positive phase. The presented work examines the applicability of the approach for the “Blast-STAR” experiments and the accuracy compared to video recordings. Within the paper five shock tube tests are described and evaluated. The results and the experimental set-up are discussed and an outlook for further research is given.

Keywords: Shock-tube, Blast wave, Glazing, Initial cracking, Acoustic emission testing

1. General

The Blast-STAR (Blast Security Test and Research Facility) shock tube at the Fraunhofer EMI site in Efringen-Kirchen can be used to generate realistic blast waves comparable to highly explosive blasting events (Klomfass et al. (2012)). Standard blast tests on blast resistant safety glazing are carried out according to the criteria of DIN EN 13541 (2012) and ISO 16934 (2007). The European standard DIN EN 13123-1 (2001) specifies criteria for a classification of blast resistance that windows, doors and shutters must meet. The details of the test procedure are described in DIN EN 13124-1 (2001). The blast waves generated by the shock tube according to these standards correspond to those of detonations in the range of 100 kg to 2500 kg TNT in the distances 35 m to 50 m. A view of the shock tube can be seen in Figure 1.

DIN EN 13541 (2012) defines four levels for the classification of pressure wave resistance of glass panes. Each stage is characterized by a reflected overpressure, a positive impulse and a positive pressure duration. Table 1 describes the different stages and the associated characteristics of the pressure wave.

Due to the extreme conditions during the test, it is challenging to accurately record the element reaction over time. In the case of glass panes and glazed elements, the breakage of the glazing is of particular interest. High-speed video systems are usually used to investigate this. However, the resolution is limited. A sufficiently exact determination of the time and the place of origin of the glass breakage may still be practicable with small dimensions of the pane. The trend, however, is towards storey-high dimensions of the tested sizes of the panes and facade elements. Thus, the optical detection of fracture initiation becomes difficult with large elements and is ambiguous.

Alternatively, methods of fractography could be used (Woodtli (2003)). However, only the place and not the time can be determined with this method and the application is time consuming. A third method is the use of piezo transducers glued onto the glazing, that record the acoustic profile during the test. In order to detect the initial cracking it was successfully tested by Monk and Clubley (2017). This method is also known as acoustic emission testing. They investigated the crack formation in glass panes during breakage both under a statically applied load and under a dynamic load in the form of a shock wave generated by an explosion-driven shock tube. Alter et al. (2015) also used acoustic emission testing for investigation of the initial crack formation. They tested laminated glass under quasi-static and impact loading and double-checked their results by a three-dimensional high-speed digital image correlation measurement. The place of initial cracking could be reliably determined in a few seconds after the breakage.



Fig. 1 Blast-star shock tube at the Fraunhofer EMI site in Efringen-Kirchen.

Table 1: Pressure wave parameters and classification according to DIN EN 13541 (2012).

Classification code	Properties of the plane blast wave		
	Maximum overpressure of the reflected blast wave p_r [kPa]	Positive specific impulse i_+ [kPa·ms]	Duration of the overpressure phase t_+ [ms]
ER1	$50 \leq p_r < 100$	$370 \leq i_+ < 900$	≥ 20
ER2	$100 \leq p_r < 150$	$900 \leq i_+ < 1500$	≥ 20
ER3	$150 \leq p_r < 200$	$1500 \leq i_+ < 2200$	≥ 20
ER4	$200 \leq p_r < 250$	$2200 \leq i_+ < 3200$	≥ 20

The pressure waves generated by Monk and Clubley for their dynamic tests were characterized by low peak overpressures and a very long positive pressure duration. The peak overpressure was 14 kPa and the positive pressure duration 100 ms. Such values are characteristic for very large charge quantities of high explosives at large distances. In contrast, the pressure waves generated by the “Blast-STAR” are characterized by significantly higher peak pressures of 50 kPa to 200 kPa with shorter positive pressure durations ranging from 20 ms to 45 ms (see also table 1). Due to the clearly different characteristics of the pressure waves, the transferability of the results from Monk and Clubley to the Blast STAR is open. Two questions arise:

- Can the approach using piezo transducers also be applied at the “Blast-STAR”?
- If so, with what accuracy regarding detection of breakage origin and time can be realized?

In order to answer these questions glass panes were equipped with transducers and tested at the “Blast-STAR”.

2. Experimental analysis

2.1. Description specimen and test setup

A total of four identical glass panes were available for the experimental investigations. The total thickness of the glass cross-section was 15.52 mm including two layers of float glass plus integrated PVB layers. The panes each had a width of 1100 mm and a height of 900 mm. The tests were carried out according to DIN EN 13541 (2012).

2.2. Measurement technique

The reflected transient pressure was measured. A high-speed camera filmed the outer side respectively the protected side of the pane during the test. The image resolution was 1024 x 800 pixels and 9300 frames per second. This results

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in a spatial resolution of $1100 \text{ mm} / 1024 = 1.07 \text{ mm}$ in width and $900 \text{ mm} / 800 = 1.13 \text{ mm}$ in height and a temporal resolution of 0.108 ms per frame.

Four piezo transducers of the type Murats 7BB were glued onto the pane to enable the measurement of sound waves in the element. The same type of sensors had been used by Monk and Clubley (2017). The initial arrangement can be seen in Figure 2 (left). After breakage in test BS 405 all sensors fall off. It turned out, that the sensors were located on the fracture lines, which is supposed to favour the detachment (Figure 3). For all subsequent tests, the position was changed to configuration 2 (Figure 2, right). Besides the four piezo transducers a further sensor "Vallen" was added with the intent to measure the impulse response of the window panes in advance. The frequency spectrum of the vibration responses was investigated by performing a fast Fourier transformation (FFT). The distributions of the frequencies and their magnitude deviated significantly for the measured impulse responses. No further analysis of the measured signals was performed. The Vallen sensor was used as a backup in the case a piezo transducer failed during the test. This was the case for test BS 407.

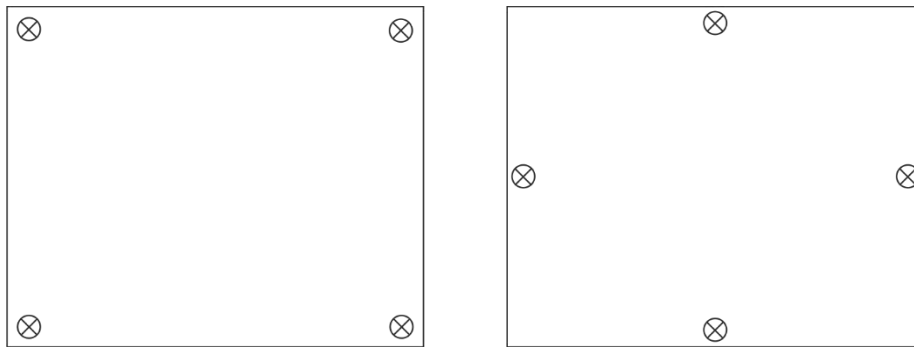


Fig. 2 Used configurations of sensors for vibration measurement: Configuration 1 used for BS 404 and BS 405 tests (left); Configuration 2 used for BS 406 to BS 408 tests (right).

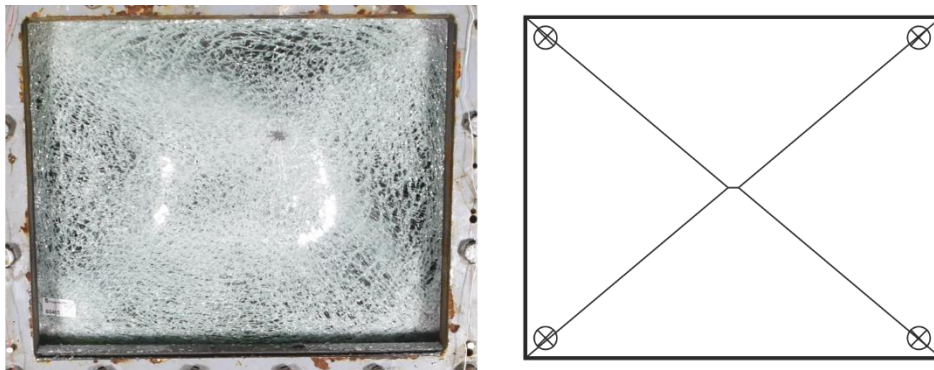


Fig. 3 Fracture pattern of glass pane 1 in BS 405 test (left); position sensors in relation to theoretical position of fracture lines (right).

2.3. Execution of the tests and observations

The first glass pane was exposed to a blast load equivalent to ER1. The glass pane did not break and so the load was increased to a level of ER2. All panes failed at this load level. In total five tests were performed. The characteristics of the generated blast waves are summarized in table 2.

Table 2: Parameters of the pressure waves.

Number Experiment	BS 404	BS 405	BS 406	BS 407	BS 408
Number of glass pane	1	1	2	3	4
Reflected pressure p_r [kPa]	59	109	110	102	106
Positive impulse i_+ [kPa·ms]	442	955	986	966	967
Positive pressure duration t_+ [ms]	20	26	25	26	26
Result according to DIN EN 13541	ER1 (NS)	Failure	Failure	Failure	Failure

3. Evaluation and results

3.1. Detection of initial cracking with high-speed video recordings

The protected side of each test was observed with a high-speed camera. The location and time of the initial crack were determined by analyzing the single video frames step by step. The fast propagation of the cracks from the point of origin and the fine branching made the evaluation very challenging with the existing temporal resolution of 0.108 ms per frame. As an example of the origin and progression of the cracking, some images from the BS 408 experiment are shown in Figure 4 and Figure 5. The location of the initial crack at the time $t = 1.72$ ms could be well identified (Figure 4, left). At $t = 1.828$ ms the crack progressed with a strong branching (Figure 4, right). At $t = 1.935$ ms, the crack development reached the sensors (Figure 5, left). Following further fragmentation of the pane occurred. The state of the pane approx. one millisecond after the determined first crack at time $t = 2.796$ ms is shown in Figure 5 (right). The determination of the coordinates of the initial crack for test BS 408 is shown in Figure 6. The visually determined locations of the initial crack for BS 405 to BS 408 are summarized in Table 3.

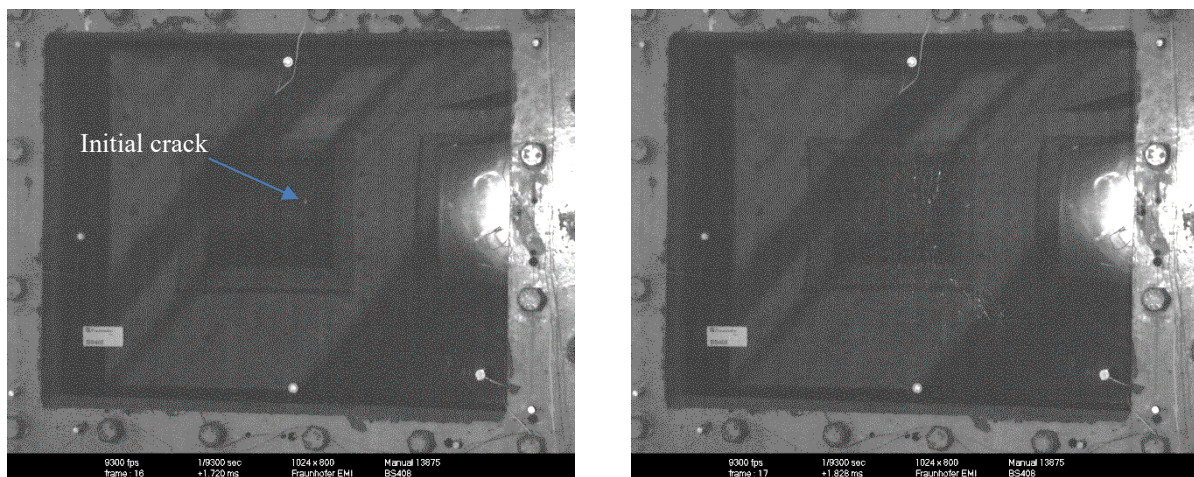


Fig. 4 Crack development during test BS 408: Start at $t = 1.720$ ms (left); progressive crack pattern at $t = 1.828$ ms (right).

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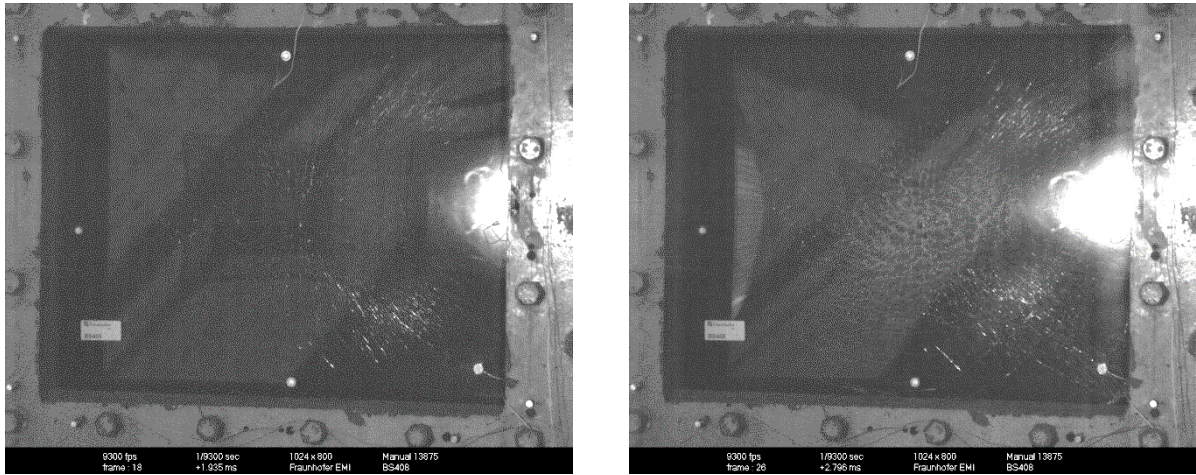


Fig. 5 Crack development during BS 408 test: cracks reach sensors at $t = 1.935$ ms (left); crack pattern approx. 1 ms after breakage at $t = 2.796$ ms (right).



Fig. 6 Visually determined location of initial crack formation using high-speed video recordings (BS 408).

Table 3: Summary of the coordinates of the visually determined locations of crack initiation of tests BS 405 to BS 408. The origin is the lower left corner of the disk.

Experiment number	BS 405	BS 406	BS 407	BS 408
x-coordinate	58.9 cm	79.6 cm	80.0 cm	52.2 cm
y-coordinate	49.8 cm	13.0 cm	4.1 cm	40.3 cm

3.2. Localization of the initial cracking with acoustic emission testing

It is assumed, that the initial crack starts in one single point and the measured signal at the piezo transducers consists of two parts. The first component is the vibration response of the pane to the blast wave. It is supposed that the response spectrum is dominated by low frequencies. The second part results from the fracture of the glass. The crack generates a shock wave that propagates in all directions at the speed of sound of the glass. The frequency spectrum of this part is dominated by high-frequency components. The shock wave initiated by the crack should have a significantly higher velocity than the progression of the crack. Further shock waves are generated by the progression of the crack, but they will not pass the primary shock wave of the initial crack.

To identify the characteristics of the arrival of the signal of initial cracking, the signals of the piezo transducers of tests BS 404 and BS 405 are compared in Figure 7. The signals of BS 404 (Figure 7, left), where no breakage happened,

are continuous after the arrival of the shock wave at $t = 0$ ms. The begin of the signal of BS 405 (Figure 7, right) is qualitatively the same as BS 404 and only the amplitude differs by the factor 2. This is plausible since the peak pressure of BS 405 is approximately twice that of BS 404. The amplitude of BS 405 is so strong that it reaches the sensor's measurement limit of 50 volts. From a certain point onwards, there is a kink in the oscillation signals, indicating the arrival of the blast wave. Monk and Clubley also identified the discontinuity as the arrival point of the shock wave of the initial cracking. In some of the tests, the discontinuities could be identified clearly within the signals but sometimes the signals were too ambiguous. By filtering the measurement signals with a high pass filter of 2000 Hz the identification was improved. Figure 8 (left) shows a section of the filtered signal of the BS 405 experiment around the time of arrival of the shock wave from the glass breakage. In Figure 8 (right) the arrival times of the shock wave at the transducers are marked within the vibration history.

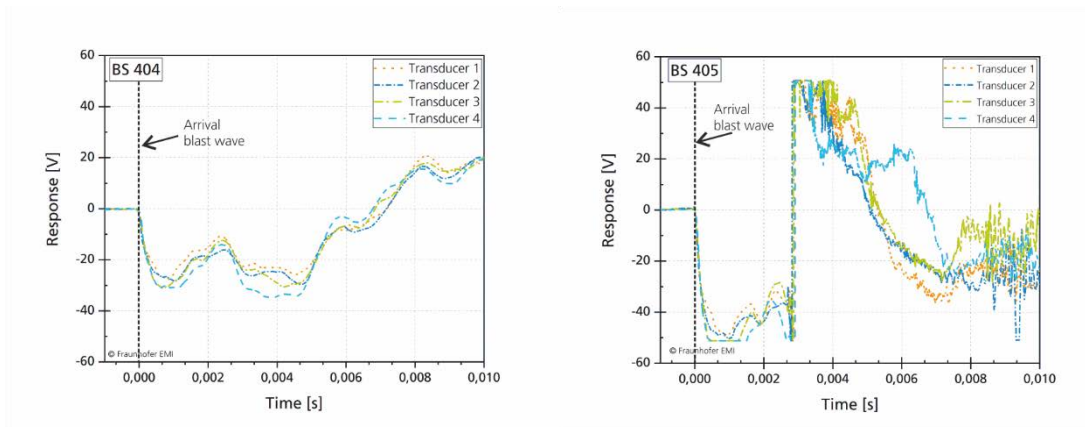


Fig. 7 Comparison of measured oscillations at sensors 1 to 4 from 1 ms before arrival of the pressure wave up to $t = 10$ ms for test BS 404 (left) and BS 405 (right).

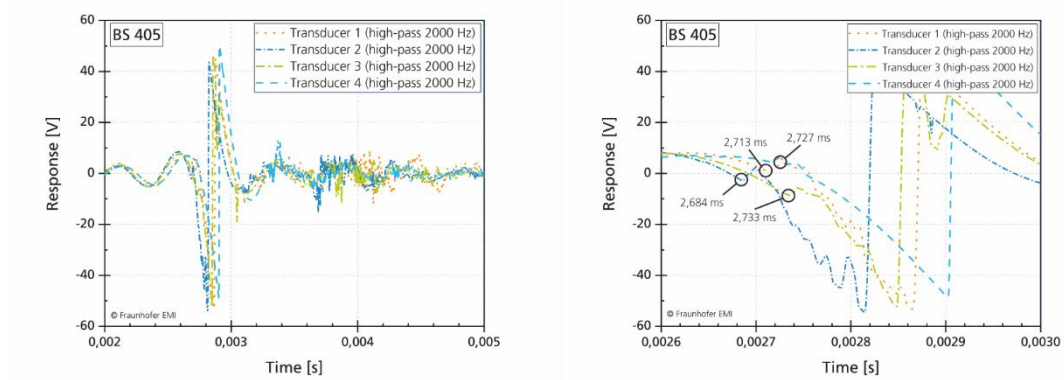


Fig. 8 Filtering of the measured signal for better identification (BS 405): Signal curve after filtering with a 2000 Hz high-pass filter (left); section of the measurement range with identified discontinuities in the measurement signal (right).

With this method the arrival time of the shock wave at the piezo transducers for all tests were determined. They are listed in Table 5 together with the position of the piezo transducers. The origin of the coordinate system is the lower left corner of the glass pane. For test BS 407 the measurement for transducer 3 failed. As substitute, the signal of the Vallen sensor was used for the evaluation. The identification of the discontinuities at the other transducers of experiment BS 407 was also not clear. Compared to the other tests the evaluated result differs considerably.

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Table 4: Summary of coordinates of transducer positions and arrival time of the shock wave of initial cracking (BS 405 to BS 408). Coordinate origin is the lower left corner of the pane.

Experiment number	BS 405			BS 406			BS 407			BS 408		
Transducer number	x_i [cm]	y_i [cm]	t_i [ms]	x_i [cm]	y_i [cm]	t_i [ms]	x_i [cm]	y_i [cm]	t_i [ms]	x_i [cm]	y_i [cm]	t_i [ms]
1	5.7	71.0	2.713	48.1	75.5	0.871	49.2	74.9	2.303	47.9	72.3	1.767
2	92.7	72.5	2.684	95.7	38.5	0.642	95.9	41.9	2.151	95.5	41.2	1.792
3	8.3	6.4	2.733	50.0	5.5	0.752	89.6 ¹⁾	6.4 ¹⁾	2.039 ¹⁾	50.0	5.1	1.769
4	91.2	7.9	2.727	5.4	38.4	0.971	3.6	36.3	2.373	3.7	35.6	1.794

1) Due to failure of sensor 3 the Vallen sensor was chosen instead.

The equations for determining the location and time of the initial crack formation by use of the arrival times at the piezo transducers are derived in the following. In Figure 9 a generic sketch with the definitions is given. The location of the initial crack is determined with the two coordinates x_0 and y_0 . Their values are unknown. Also unknown is the starting time of the cracking, which is denoted with t_0 . The speed of sound in the glass is denoted with v . This value is unknown and was not determined in advance. In total, the four variables x_0 , y_0 , t_0 and v are used to describe the location and time of the initial crack. Four conditions or independent measured values are necessary to formulate sufficient equations in order to determine the unknown variables. For this reason four transducers are needed.

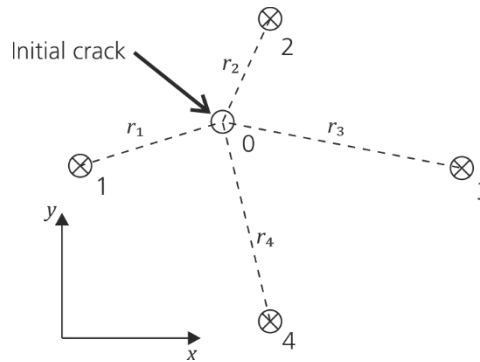


Fig. 9 Situation of initial cracking, related measurement and used definitions.

The positions of the n piezo transducers are known and described by a pair of coordinates x_n and y_n ($n \in 1..4$). The distances r_n of the measuring sensors to the crack origin can be determined by

$$\begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \begin{bmatrix} \sqrt{(x_0 - x_1)^2 + (y_0 - y_1)^2} \\ \sqrt{(x_0 - x_2)^2 + (y_0 - y_2)^2} \\ \sqrt{(x_0 - x_3)^2 + (y_0 - y_3)^2} \\ \sqrt{(x_0 - x_4)^2 + (y_0 - y_4)^2} \end{bmatrix} \quad (1)$$

The arrival time t_n of the breakage was derived from the course of the measurement signals. With the still unknown sound velocity and the time of the first crack formation t_0 , the distances r_n can also be expressed with the equations

$$\begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = v \cdot \begin{bmatrix} t_1 - t_0 \\ t_2 - t_0 \\ t_3 - t_0 \\ t_4 - t_0 \end{bmatrix} \quad (2)$$

By equating (1) and (2) you get

$$v \cdot \begin{bmatrix} t_1 - t_0 \\ t_2 - t_0 \\ t_3 - t_0 \\ t_4 - t_0 \end{bmatrix} = \begin{bmatrix} \sqrt{(x_0 - x_1)^2 + (y_0 - y_1)^2} \\ \sqrt{(x_0 - x_2)^2 + (y_0 - y_2)^2} \\ \sqrt{(x_0 - x_3)^2 + (y_0 - y_3)^2} \\ \sqrt{(x_0 - x_4)^2 + (y_0 - y_4)^2} \end{bmatrix} \quad (3)$$

Now four equations are available for the four unknown variables x_0 , y_0 , t_0 and v . By solving the system of equations (3) they can be clearly determined. With the observed arrival times of the shock wave of the initial crack at the transducers the position of the initial crack, the time t_0 and the sound velocity v were determined for all experiments. The results are summarised in Table 5. The calculated result of the sound velocity of 432 m/s for the glass of test BS 407 is significantly lower than of the other tests. It is therefore questionable whether the determination of the arrival times in the BS 407 test was correct.

Table 5: Summary of location and time of the initial crack and sound speed (BS405 to BS408) determined by acoustic emission testing. Point of origin is the lower left corner of the glass pane.

Experiment number	BS 405	BS 406	BS 407 ¹⁾	BS 408
x_0	54.2 cm	84.1 cm	(55.6 cm)	50.4 cm
y_0	45.3 cm	24.8 cm	(25.1 cm)	39.2 cm
sound speed v	2654 m/s	1929 m/s	(432 m/s)	4943 m/s
time initial crack t_0	2.506 ms	0.549 ms	(1.141 ms)	1.670 ms

¹⁾ Results are questionable due to failure of one piezo transducer and substitution with Vallon sensor.

3.3. Comparison of the results

In Figure 10 the positions of initial cracking determined by acoustic emission testing were compared with the optically determined locations. The distances, which are the deviations between optically determined and the locations determined from the measured data, are summarised in Table 6. The average deviation was 7.1 cm. Test BS 407 was excluded from the calculation of the average value, due to the questionable result and uncertainty of the determined arrival times. The time was not compared, since the temporal resolution of the video recording with 0.108 ms per frame is considered to be too coarse.

The positions of the initial crack determined with both methods are close to each other. Due to the low temporal resolution of the high-speed recording, the optical evaluation is afflicted with a certain uncertainty and therefore the suitability as an optimal reference for the acoustic emission testing is limited. The question of the achievable accuracy using the piezo transducers remains open. However, it can be concluded from the similarity of the results that the use of piezo transducers leads to plausible results. The question whether acoustic emission testing using piezo transducers is suitable for using with the Blast-STAR shock tube can therefore be answered in the affirmative. In addition, the use of piezo transducers is characterized by low costs. The price for the acquisition of a sensor was around ninety euro cents.

Table 6: Deviation of location of the initial crack from optical determination and acoustic emission testing.

Experiment number	BS 405	BS 406	BS 407	BS 408	Average value
Deviation [cm]	6.5	12.6	(32.2) ¹⁾	2.1	7.1

¹⁾ not included in the averaging.

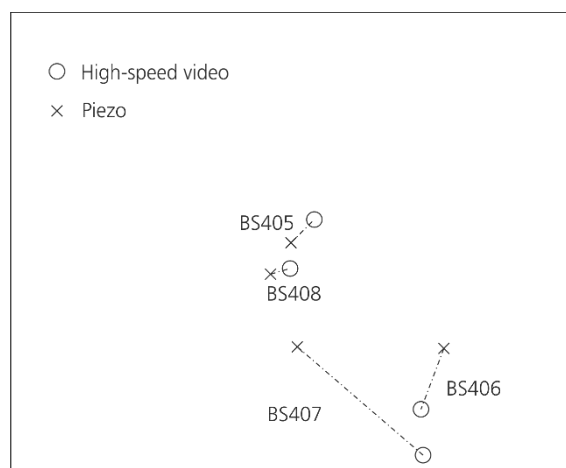


Fig. 10 Location of initial crack: Comparison of the optical determined location and location determined with acoustic emission testing (tests BS405 to BS408).

4. Summary and discussion

When testing glass panes by shock tube loading, the location and time of crack formation during breakage is of particular interest. This is usually done with high-speed footage at the EMI “BLAST STAR”. The use of piezo electric transducers in order to perform an acoustic emission analysis was successfully investigated as a cost-effective alternative for determining the place and time of initial breakage. A test campaign with five tests on four glass panes was performed. It was possible to determine the position and the time of the initial crack. However, the manual determination of the arrival time of the shock wave caused by the glass breakage was time consuming.

For further tests the capacity of the piezo transducers should be increased, since the load was too high for the measuring range. In order to determine the accuracy of this method, it was intended to use high-speed video recording as a reference. Due to the very high propagation speed of the cracks in relation to the temporal resolution of the video recording, the evaluation of the recording was subject to an uncertainty itself and so it was no perfect reference, yet. For a clear statement about the accuracy of the method further tests with a significantly higher temporal resolution of the high-speed video recording is necessary. However, it can be stated that the results of the optical determination and the results of the acoustic emission testing are similar. The influence of the PVB layer of the laminated glazing on the sound velocity of the panes is also unknown. Alter et al. (2015) did not notice any influence. However, for further investigations the sound velocity of the glass pane should be determined in advance. The execution of static tests on the panes is also recommended to check the applicability of the piezo transducers.

5. References

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