Localization of Initial Cracks in Laminated Glass Using Acoustic Emission Analysis – Part I

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Abstract. Laminated glass is experimentally investigated by bending tests with four-point supported glass panes. The objective of the study is to identify the origin of initial cracks during testing in order to develop a physically based model for finite element (FE) simulations of laminated glass under impact load. Tests and FE simulations of windscreens and plane glass plates are carried out and the results are compared in terms of elastic behaviour, maximum load at failure, post breakage behaviour, and the fracture pattern. The localization of the initial cracks is based on the acoustic emission analysis (AE analysis).

1 Introduction

Laminated glass is build of two or more plates of glass together with a polyvinyl butyral (PVB) interlayer. In this context the interlayer fix the broken splinters and fragments of glass to avoid injuries of pedestrians and occupants in the case of car accidents. After cracking, laminated glass is still able to transmit loads because of the interlayer. To simulate this effect using finite elements, reliable and physically based material models are needed in an engineering environment. In an on-going project with focus on pedestrian protection, head impact tests on windscreens were done and simulated with the explicit solver LS-DYNA. The objective of the project is to develop a computational modelling technique, which is capable to predict structural components made from laminated glass under impact load [1-3]. This includes the behaviour before and after damage as well as an approximation for crack propagation. In particular the simulation predicts the location of the initial crack. Thus the windscreens and the flat glass plates are mounted on four pins with a distance of 1000 mm x 700 mm. An impactor, representing a human head is crushed on the glass powered by a pneumatic cylinder [4]. The windshields are tested in concave and in convex position. During the tests the acceleration, the displacement of the impactor, the deflection of the glass plates, and the force between both are measured. In order to validate the accuracy of a standard FE model for head impact tests on windshields AE measurements were carried out to localize the initial crack using six AE sensors.

2 Experimental Procedure

2.1 Experimental Set-up

Windshields of cars were tested under static loading conditions. For these tests twelve panes were available. Left-hand side of Figure 1 presents the testing frame utilized for quasi-static testing. This consists of a desk-like welded steel construction with pyramidal set-up, which holds the loading pin including a pneumatic cylinder of SMC, Type C92LA. This cylinder of 100 mm inner diameter can be pneumatically filled with pressurized air up to 10 bar. The maximal stroke is 400 mm. This cylinder has a special locking unit, which is applied for locking the piston in arbitrary position. Locking and loosening is pneumatically actuated. All these components are vertically aligned. In order to transfer the load to the windshield a head impactor (right-hand side of Figure 1) was pushed against the glass powered by the pneumatic piston rod. The windshield was put on the four support pins in such a way that the windshield's central point was positioned under the loading pin. The support pins carry on their upper ends half-spheres out of Teflon with a diameter of 36 mm. The cylinder is operated in such a way that the piston before test was locked at about 3/4 of the maximal stroke. After filling the upper cylinder chamber with air of about 6 bar pressure and loosening the piston, the piston rod accelerates up to a constant velocity of about 10 m/s.

The force was measured using a very precise load transducer of HBM, Type S9, load capacity 5 kN, class 0.05 (measuring errors smaller than 0.05 percent of load capacity). The displacement of the impactor was measured using a potentiometric displacement sensor of Buster, Type 8719. For the direct measurement of the acceleration during the impact of the impactor, an acceleration sensor type of Kistler 8702B500 was used. In addition, the course of the experiment was analysed with a high-resolution high-speed camera ARAMIS the GOM mbH for optical 3D deformation analysis. To investigate the influence of the weight of the windshield, the complete experimental set-up was placed on its side so that the impactor hits the vertical positioned windshield in the horizontal direction.

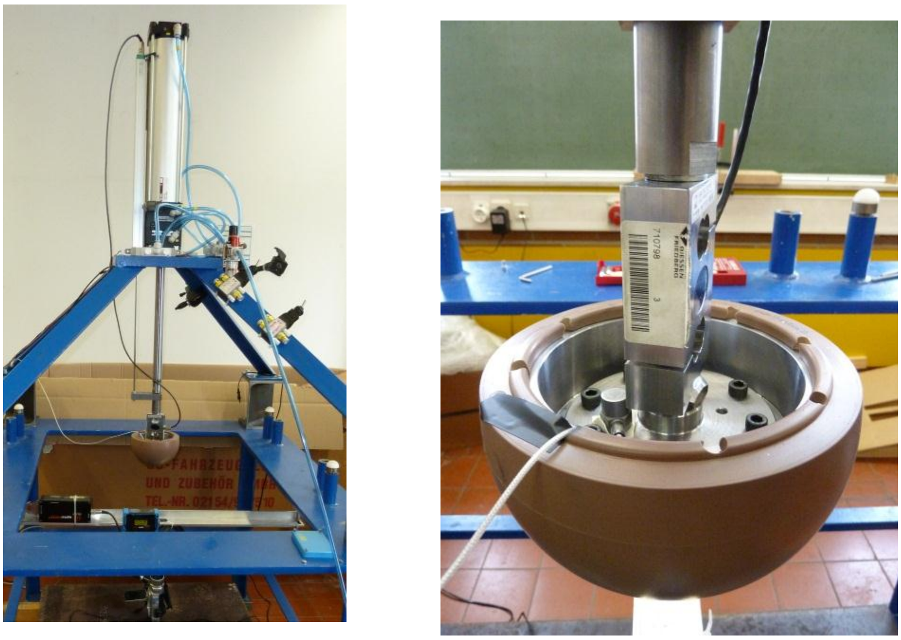

Figure 1. Photography of the experimental set-up with the testing frame (left-hand side) and the head impactor (right-hand side).

In cases where the optical identification of the fracture origins in glass is difficult, e.g. in case of heavy fragmentation, an alternative method of fracture localization is valuable. For this purpose AE measurements were performed [5]. The AE method utilizes elastic waves, which were emitted during fracture formation to localize the fracture origin. For the AE measurements the eight channels AMSY 6 system of Vallen was used.

2.2 Wave Velocity Measurement

For the localization of AE sources the wave velocity in the material must be known. Therefore two sensors (type Vallen VS 900-M) are fixed on the material and an acoustic signal is generated on a defined position with an exactly known distance to the sensors.

The easiest way to figure out the wave velocity is the "pulsing-function" of the AE system. After fixing transmitter and receiver in a known distance on surface of the glass plate, the AE system generates high-voltage wideband pulses. Using the time difference *dt* between transmitter and receiver the AE System is able to compute the wave velocity $v = s/dt$. Hereby v is the calculated wave velocity, s the distance between the sensors and $dt = t1-t0$ the time difference (see Figure 2).

Figure 2. Schematic of experimental set-up to determine the elastic wave velocity.

In order to determine the influence of the intermediate thin film wave propagation measurements were performed in such a way that a receiver was applied on the upper surface of the glass plate in distance of s = 770 mm to the transmitter. The transmitter was mounted on the upper and lower surface of the glass plate, respectively. A high-voltage wideband pulse like a step function was applied to the transmitter.

Left-hand side of Figure 3 shows the wideband transmitted signal (top) and the detected signals at the upper (middle) und the lower (bottom) surface of the glass plate, respectively, and the corresponding frequency spectra (right-hand side of Figure 3). The signals have a complex waveform, resulting from the superposition of many reflected waves at different angles. There are several types of waves (plate modes) excited with varies wave velocities (so-called dispersion). The mean velocity of the first mode (corresponds to the fastest extensional S_0 wave) is about 5.2 mm/s, which is slightly below the speed of the longitudinal wave in glass of about 5.5 mm/s.

Figure 3 clearly shows that the signal waveforms and frequency spectra are very similar. An influence of the intermediate film to the wave propagation, and thus the location accuracy can be excluded. It is not possible to distinguish whether crack propagation starts from the lower or upper glass plate.

2.3 Localization Test

Another possibility to generate an acoustic emission source is the breakage of a lead of a pencil at the glass plate like shown in Figure 4. This artificial source generation is also known as Hsu-Nielson source [6]. The so-called pen test simulating a vertical single force drop generates a signal like a step function with a rise time less than 1 *µsec.*

The breakage of the brittle lead pencil under an angle of 30° at the top of the glass plate causes a small elastic deformation of the surface and the surface relaxes immediately, which induces an elastic wave into the plate. Here it is necessary to use three or more sensors for a planar localization of the artificial AE source. The time differences of the signals are needed to calculate the location of the source.

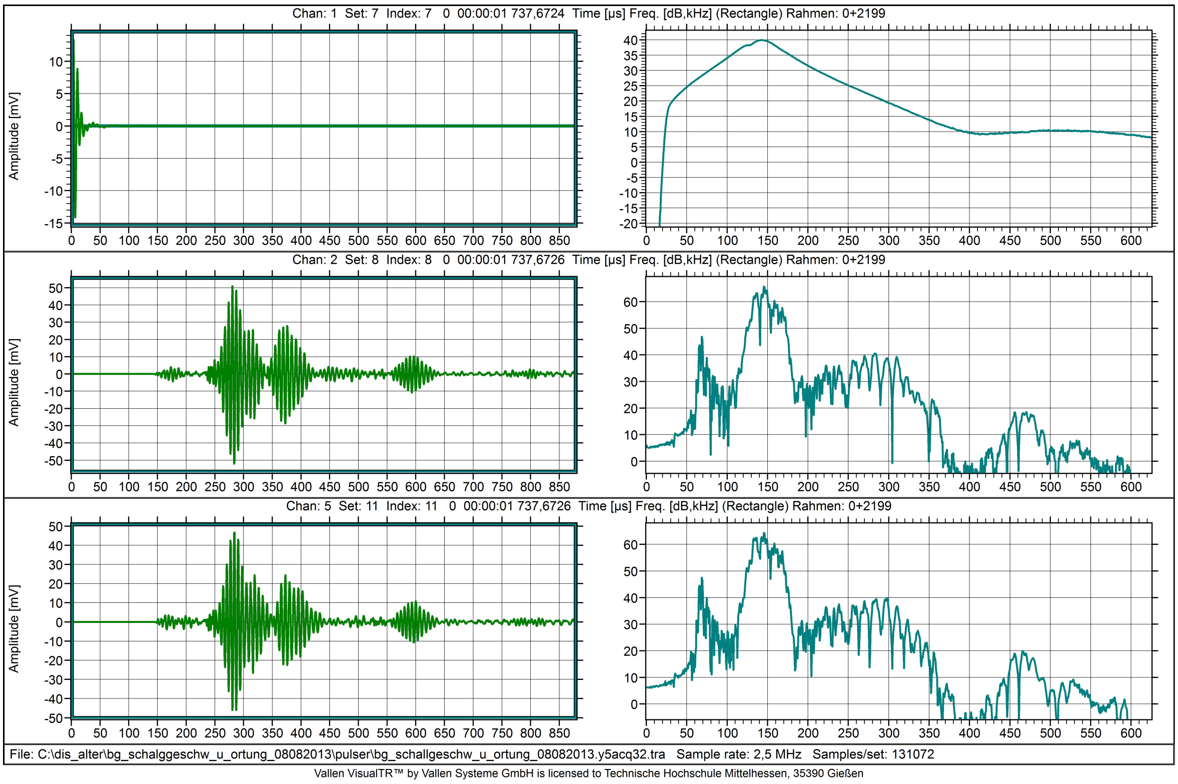

Figure 3. Measured waveforms (left-hand side) at the upper (middle) und the lower (bottom) surface of the glass plate and the corresponding frequency spectra (right-hand side).

In Figure 4 the signals detected at four sensors are plotted. The arrival times of the first onsets are used to calculate the time differences between each hit sensor. Within these time differences the localization software generates a hyperbola between each sensor (see Figure 5). The point of intersection of these hyperbolas is the localized position of the artificial source. Figure 5 shows the accuracy of the used localization algorithm. The set-up for measuring AE was as mentioned before. The acoustic wave velocity used for localization was 5.2 mm/s. The mean deviation between the AE source location and "true" Hsu-Nielson source origin is below 3 mm.

2.4 Test Results

In the following, only the results of one experiment in convex position (impact of outside the car) and in horizontal direction of loading are described (without the influence of self-weight). The force-deflection diagram (Figure 6) of this test shows an approximately linear increase of the force versus deflection. The maximal force of the windshield is about 1500 N and the deflection at fracture of 34 mm. After fracturing the windshield shows a residual force of about 400 N.

Figure 7 displays the waveforms of the six AE sensors, which were fixed at the upper surface of the windshield. The sequence of the signals corresponds to the sequence of the measured time onsets. It can be seen that all signals show clearly discernible onsets, which could automatically determined using a threshold of 40 dB. The many later onsets of bursts were originated from the formation of the crack meshwork in the glass panel during the very fast crack propagation.

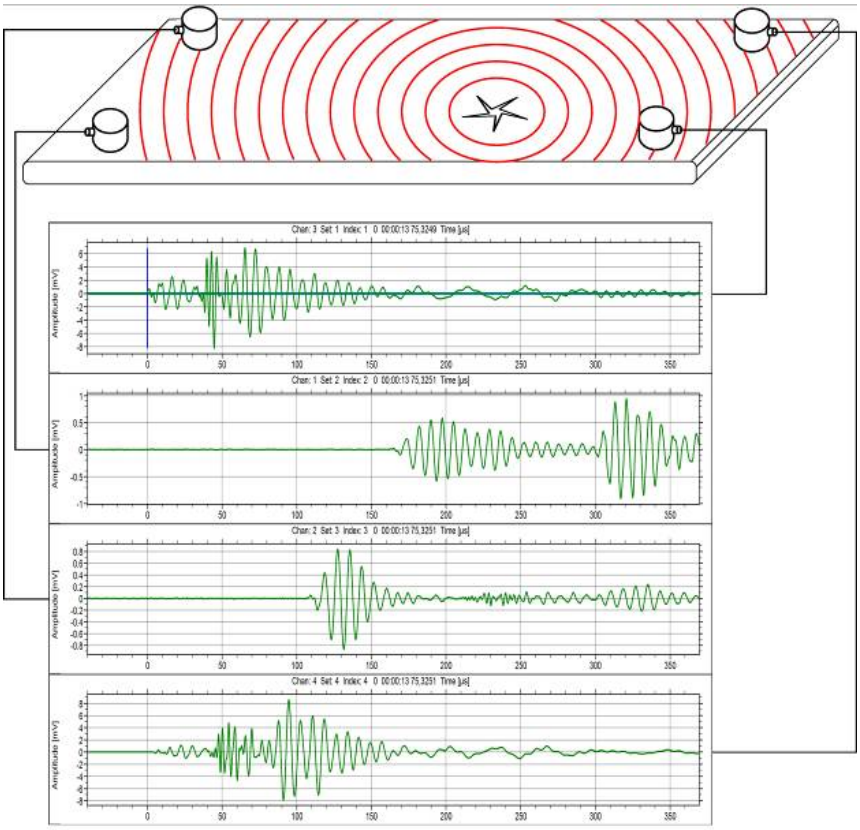

Figure 4. Measured AE signals of an artificial AE source using four sensors at the glass plate. Using the time differences between the first hit sensor and the others it is possible to locate the AE source.

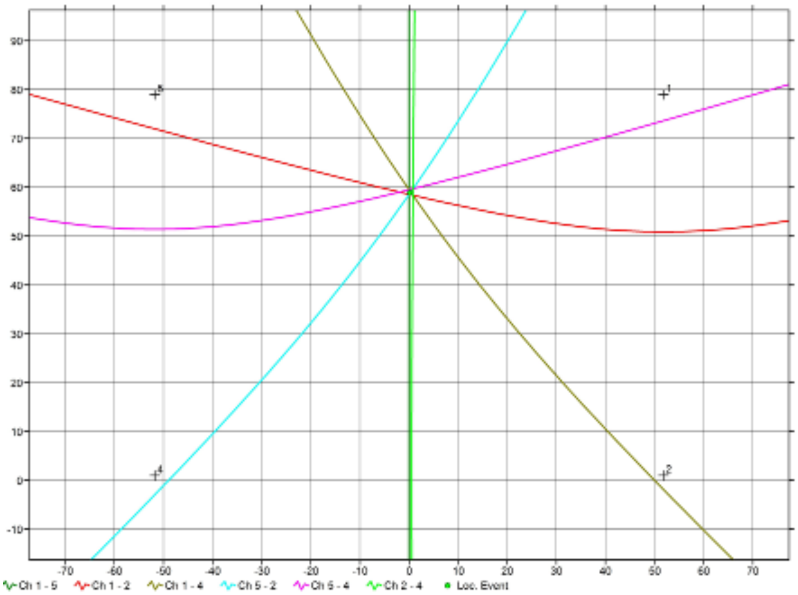

Figure 5. Localization of the Hsu-Nielson source on a flat plate using four AE sensors. The parabolas are calculated by differences in the time due of the signal. The small crosses are indicating the position of the four AE sensors. The grid lines represent a 10-mm spacing.

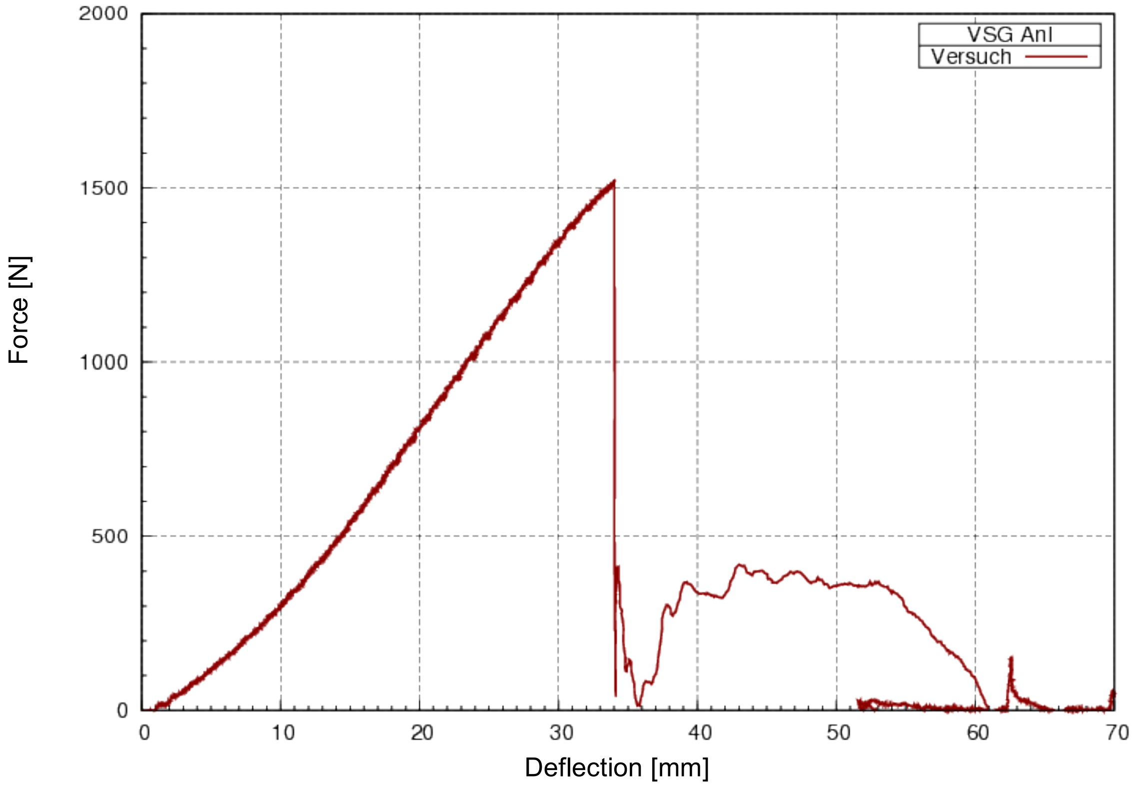

Figure 6. Force versus deflection of a static windshield test in convex position.

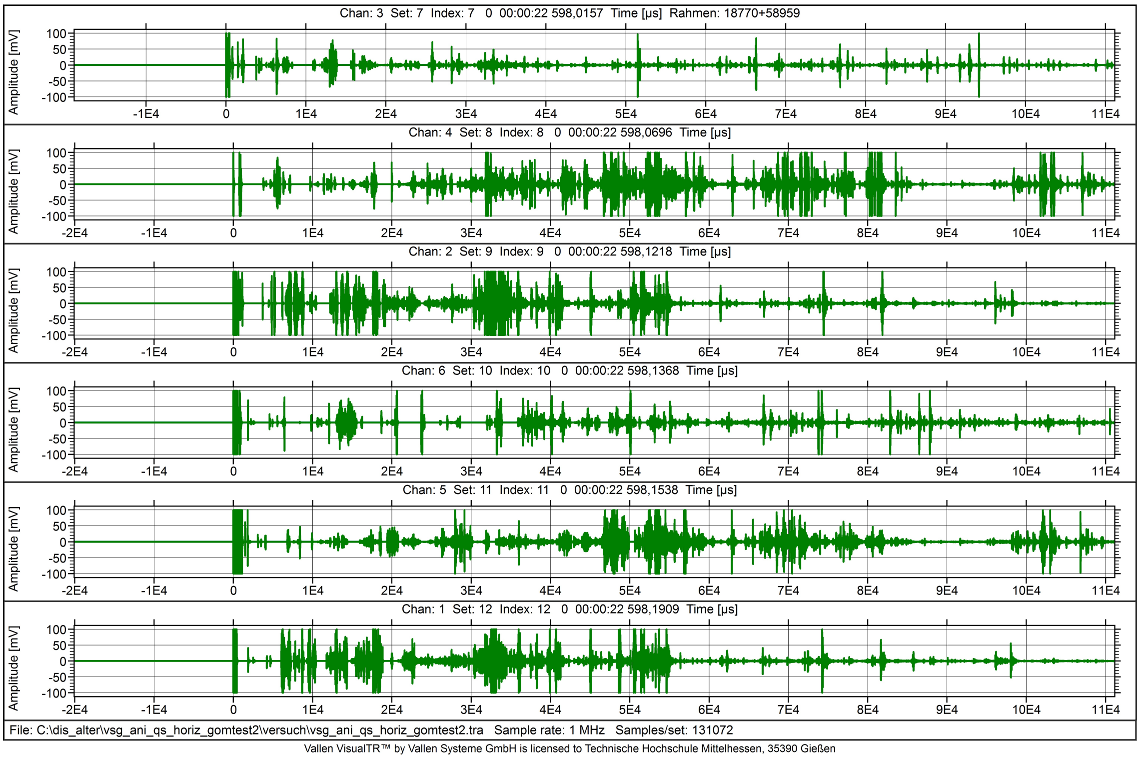

Figure 7. Measured AE signals at the upper surface of the AE sensors.

Figures 8 and 9 show the projection on the x-y plane with marked contour of the windshield (Figure 9). The numbers indicate the positions of the six AE sensors at the edge of the windshield. The location of the AE event is marked by a green dot. The intersection of the hyperbolas is at the bottom of the windshield at coordinates x = -13.55 cm and y = -7.02 cm, which corresponds to the location of the AE event. The origin of the coordinate system is on the vertical line of symmetry 10 cm from the lower edge of the glass pane. According to the AE measurements the crack starts at the lower edge of the pane.

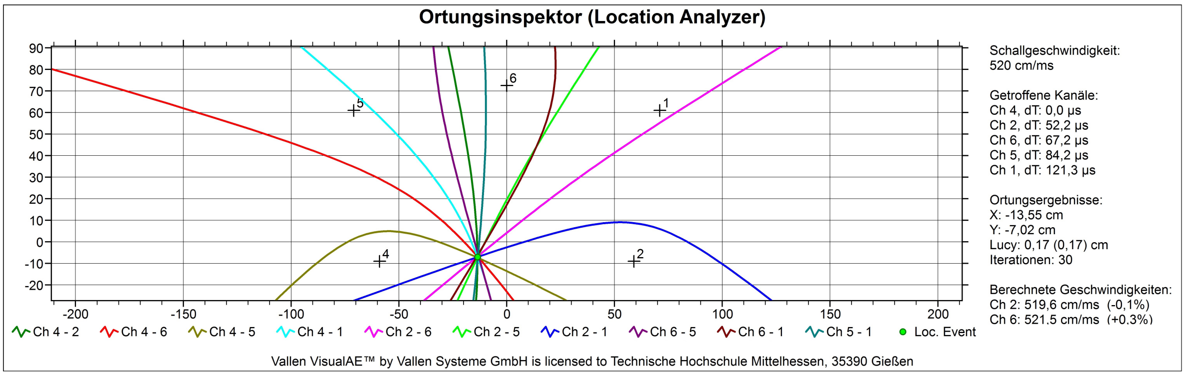

Figure 8. Projection onto the x-y plane with location of AE event at the intersection of the hyperbolas.

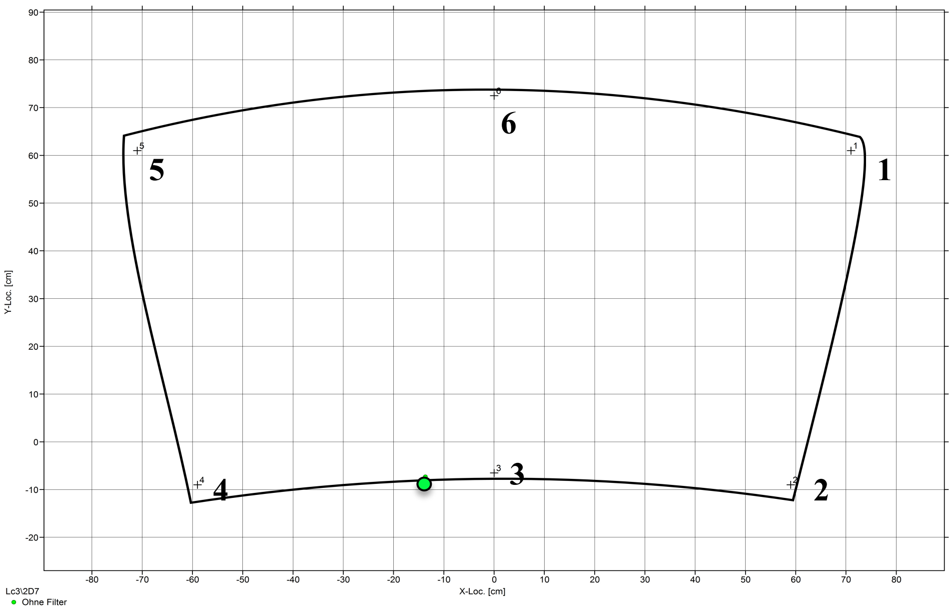

Figure 9. Projection onto the x-y plane with contour of the windshield, the location of AE event (green dot), and the position of the AE sensors (numbers).

2.4 Verification of AE Results Using Optical Measurement Technique

Displacement and strain measurements were carried out with the optical measuring system ARAMIS during the experiment to verify the detection results of the AE measurements. The advantage of this measuring system compared to e.g. measurements with strain gauges is that a large component can be measured without contact and with a high temporal and spatial resolution. Figure 10 shows at the left-hand side the projection onto the x-y plane with the position of the AE sensors (compare with Figure 9), the contour of the disk, the location of the AE event, which corresponds to the initial crack (green dot), and the calculated strain using ARAMIS.

The right-hand side of Figure 10 shows a photograph of a detail of the windshield after the experiment. The location of the initial crack is obtained via the optically determined maximum strain, which is collared in the figure. In the red-collared area the elongation at fracture of glass is exceeded. Starting from this point the crack propagates in direction of the centre of the pane (blue arrow in the right-hand side of Figure 10) where the actual impact has occurred. The results of the two measurement methods agree very well with the real location of the initial crack. Although the crack is located at the edge of sensor array the location accuracy is in the range of a few millimetres.

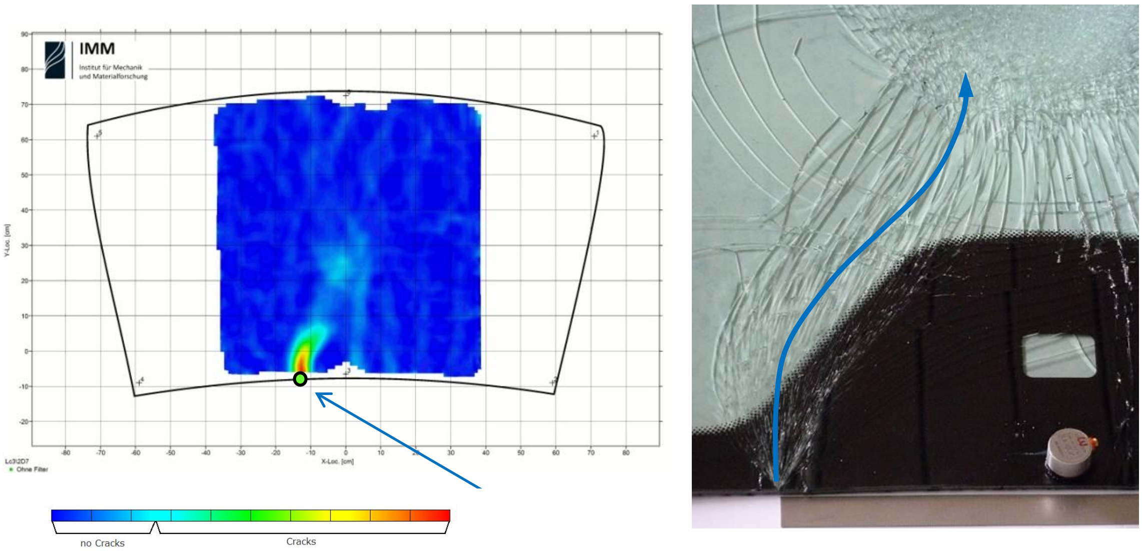

Figure 10. Left-hand side: Projection onto the x-y plane with calculated strain (left-hand side), contour of the windshield, and the location of AE event (green dot). Right-hand side: Photography of a detail of the windshield after the test. The blue arrow indicates the initial crack location and the direction of crack propagation.

3 Conclusion

In this article acoustic emission measurements were carried out to locate the initial crack in laminated safety glass under quasi-static load. The localization results were compared with an optical measurement method. The crack started from the edge of the windshield and propagates in the direction of the centre of the windshield to the point of the impact. In the edge region the strength is much lower than in the interior of the plane. This fact can be explained that grinding of the edges creates small microcracks, which lead to a decrease of the strength. In accordance with DIN 18008-1 it can be assumed that under tensile load the strength decreases up to 20 percent.

In conclusion AE is a helpful tool for the localization of the initial cracks in windshields under impact load. In particular, the initial crack represents an important parameter for validation and verification of finite element models. A comparison in terms of force versus deflection shows that the behaviour of laminated glass up to failure is sufficiently reproduced. Further investigations must be performed for the simulation of the post breakage behaviour. Therefore high speed testing of the PVB interlayer and the usage of an adequate material model are also topics of further investigations.

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