Integration of photogrammetry and acoustic emission analysis for assessing concrete structures during loading tests

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ABSTRACT

This paper focuses on space- and time-resolved crack detection in concrete structures by combining photogrammetric techniques with acoustic emission analysis. For the photogrammetric measurements, the surface of reinforced concrete members is textured with a random pattern. A consumer-grade digital camera is used to observe the region of interest during the loading tests. In a sequence of images, cracks are visualized by detecting discrepancies in local displacement vector fields, which are obtained from matching algorithms applied to consecutive images. Critical areas of concrete samples are additionally equipped with several acoustic emission sensors to monitor the crack formation and propagation by acoustic emission analysis. The parameter-based method is used to record specific parameters in real time and enables the distinction between bending or shear cracks depending on the signal energy and duration. During the loading tests, information about the crack prolongation is used to derive the time of transition from stable to unstable phase. The acoustically detected shear cracks are monitored in the images to track growth and to stop the experiment before a critical bearing status is reached. Thus, shear cracks can be localized temporally and locally on the surface and inside the structure.

In a next step, the detected cracks have to be checked for certain properties providing information about the condition of the structure. Indicators with high level significance referring to structures with no or low advance notice of failure constitute a focal point of further research.

Keywords: crack detection, image sequence analysis, concrete structure, shear crack, acoustic emission analysis

1. INTRODUCTION

Loading tests of concrete structures are often used in civil engineering to prove the load bearing capacity of structural elements in cases where a numerical assessment is not possible or requires enormous effort. In many cases, the load bearing capacity can be estimated realistically and capacity reserves can be developed, thus making complex strengthening or even reconstruction unnecessary. The planning, realization, and evaluation of the experimental investigation are based on the guideline of the German Committee of Reinforced Concrete (DAfStb) [6]. According to a determined scheme, different load stages are used to achieve the target load, though, the ultimate load should not be exceeded. The target load is defined as the maximum load which has to be proven for the future use of the structure. The German Committee of Reinforced Concrete describes basic criteria which announce the achievement of the target load. These principles are special deformation criteria like concrete or steel strains, crack widths, and deflections which cause the early abort of the experimental investigation. Especially the behavior of constructions with no or little ductility is difficult to evaluate because of their low advance notice of failure; hence, these constructions are today still excluded from the experimental assessment of load bearing capacity. This applies, for instances, to structural concrete members without shear reinforcement like slabs, beams, or frames. In this context the term “advance notice” refers to the determination of the ultimate test load, the exceeding of which causes irreversible damages of the tested structure [5]. The idea of instrumental load test monitoring by modern measurement methods is the detection and assessment of the smallest structural changes in the tested member in order to release an immediate warning and to stop the experiment. This way, intolerable damages or even the complete destruction of the structure during the load test can be avoided with sufficient certainty. The combination of complementary monitoring techniques enables a significant improvement of the information quality during the load test, so that the real time evaluation of the measurement results may allow for the definition of objective criteria for the ultimate test load.

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This paper provides an approach of crack detection and evaluation combining two dimensional image sequence analysis and acoustic emission analysis. The first chapter refers to parameters which indicate shear failure and describes the applied methodology to monitor these possible indicators. In addition, the use of photogrammetric and acoustic crack detection is described and justified; thereby, current research and the state of the art are included. The chapter “Data” introduces the breadboard of the conducted shear loading tests. Following, the results of these experiments are presented and discussed. In conclusion, the approach of crack detection and analysis is evaluated and a short outlook is given.

2. METHODOLOGY

2.1 Shear cracks and potential indicators

The shear bearing capacity of concrete structures has already been the subject of many investigations and even today there is no reasonable mechanical model available to precisely describe the shear bearing behavior. Especially for concrete structures without shear reinforcement, different models are used to determine the load bearing capacity. In particular, geometric parameters like the height of components or the distance between load and support affect the type of failure seriously. The risk of shear failure depends on the geometrical constraints to avoid bending failure. For detailed descriptions of shear failure and for a more exhaustive review, reference is made to [14], [19] and [22].

In summary, the load bearing capacity during shear loading strongly depends on the local crack formation; thus, a crucial aspect for the assessment of the load bearing capacity is the observation of the crack initiation and the crack development. The following measurement parameters have been identified as possible indicators (see also Figure 1):

- Critical shear crack width
- Critical inclination of the crack
- Time of crack initiation and crack growth rate (stable versus unstable crack growth)

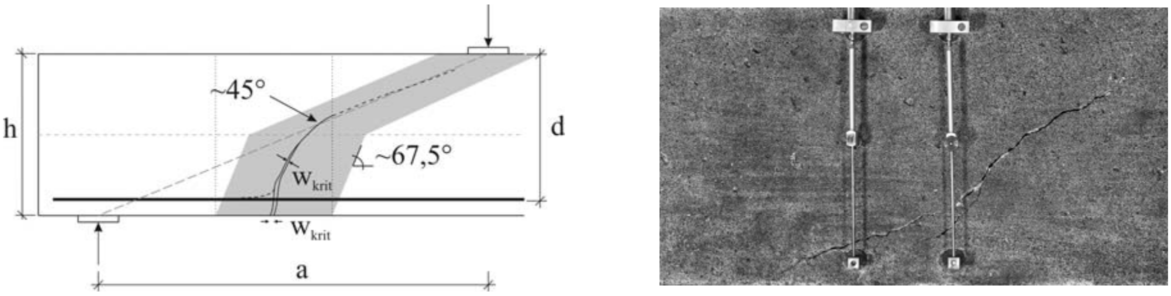

Figure 1. Possible indicators of a shear failure (left) and the formation of a shear crack during experimental tests (right).

2.2 Image sequences analysis

The photogrammetric detection of distortions or cracks is based on the image sequence analysis of one or more cameras. The tracking and comparison of homologous points in temporally successive images enable the measurement and analysis of material deformations. The application of two or more cameras allows the three dimensional evaluation of an observed scene and was described in [3], [18] and [24]. The profit of information by using a second or third camera is associated with the increasing costs of the equipment and the time of analysis. As long as deformations are expected exclusively in two directions, the employment of only one camera provides a potential opportunity of crack detection. The orthogonal and invariant orientation of the camera according to the surface allows the extraction of the deformation directly from the changes of image coordinates, depending on the scale. Furthermore, the evaluation of an image sequence using relative differences to determine deformations removes systematic errors like image distortion in case of small point displacements. A review of two dimensional displacement and strain measurement techniques including an error analysis is given in [21]. An approach to equalize movements in depth direction using telecentric lenses was discussed in [23]. Main disadvantages of this technique are the inflexibility caused by the physical size and weight and the purchase costs. In this research project, the shear failure of reinforced concrete members is to be investigated by detecting the two dimensional crack formation and prolongation; therefore, a single camera system is used.

Tracking algorithms are reliant on some type of texture to trace homogenous points. In principle, two possibilities are distinguished to structure the object surface; first, the application of coded or encoded marker targets and, second, markerless techniques based on the use of artificial or natural pattern. The employment of targets allows their accurate matching, but the resolution of the deformation depends on the distances between the applied marker targets. The enhancement of the resolution in two coordinate directions and the effort of the target application are related quadratically. Investigations of crack detection during load tests of concrete structures using a pattern of discrete target points were described in detail in [4] and [12]; based on the evaluation of the displacements of colorized targets, Barazzetti explained the measurement of deformations in [2]. The use of markerless methods decreases significantly the expenditure of time for the preparation of the tested surface and increases the practical suitability. A three dimensional approach of crack detection and analysis based on artificial surface texture was presented in [10]; the deformation measurement using two and three dimensional image based algorithms was compared in [1]. Correlation methods, for instance the simple cross correlation, are often used for generating a displacement vector field or strain field by tracking homologous points; however, effects of rotation, scale, shear, or illumination during the deformation process cannot be considered. More effective approaches provide adaptive correlation methods or the least-square-matching (LSM) [8]. Results of matching methods can be improved by using interest operators; these algorithms detect features or points of interest which have a high degree of uniqueness in their neighborhood. A comparison of three interest operators and their dependency of contrast enhancement were discussed in [13]. Further operators were comparatively evaluated in [7]; [11] demonstrated a high stability under changes in scale and view applying the approach of Harris.

The conceived concept of crack detection for the investigation of the shear failure with low advance notice is based on the deformation measurement of smallest surface elements. Feature points, detected by the Harris operator, are combined to a dense triangle mesh (Delaunay triangulation). Homogenous triangle corners are tracked in a series of consecutive images by least-square-matching with high accuracy. At the beginning of the experiment, each triangle holds a specific surface area. The evaluation of homogenous triangles of an image series allows the determination of the incremental or absolute surface change compared to the initial state. This enables the localization of strain maxima on the surface. Figure 2 shows a camera image with superposed triangle mesh and its enlargement. The gray coded view of the change of each surface area visualizes zonal deformations and therewith cracks.

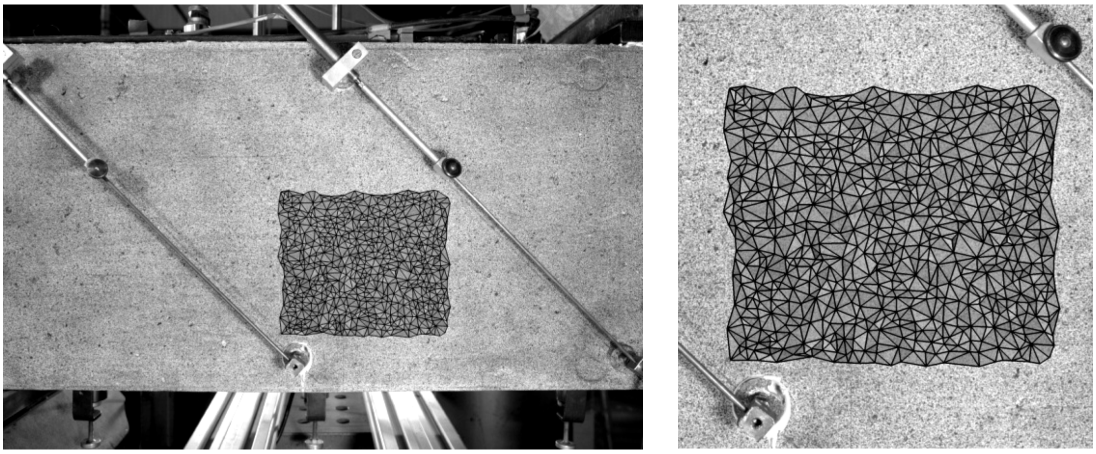

Figure 2. Camera image with superimposed triangle mesh: original size (left); enlarged (right).

2.3 Acoustic emission analysis

Low strains already cause the development of micro cracks in reinforced concrete structures, which grow with increasing loads and become visible on the surface. Due to the compatibility conditions, the component deforms with increasing loads; however, the dislocation is connected with a progressive crack prolongation, which is localized at the crack tip, and is generated by plastic deformations in a special area (crack process zone). One part of the released energy is used to create new surfaces and the other part emits acoustically in the shape of elastic waves, which spread throughout the whole body from the origin of damage. Using piezoelectric sensors the waves are detected on the surface of the concrete body, transformed into voltage signals, and reinforced by a preamplifier. The recorded data can be analyzed either parameter based (qualitatively) or signal based (quantitatively). The parameter based evaluation identifies and saves individual characteristic features instead of the overall signal, which enables real-time application. For the crack detection on concrete structures, indicators like the signal energy, duration, amplitude, and energy rate, as well as the number of incoming signals (hit rate) have been proven for a good characterization of fracture processes [16]. The pronounced micro cracking is a characteristic behavior of reinforced concrete, which explains the high activities of acoustic emissions during the load tests. Focusing on the process of cracking, the development from numerous micro cracks to a visible macro crack is particularly useful and signalizes the moment of transition from individual events to the continuous acoustic emission. The concentration of occurring micro cracks leads to an increase of signals and causes the superposition of them. Therefore, the number of signals decreases again, though the activity of acoustic emissions rises; signals with long duration and high energy are emitted. Figure 3 shows the described detection of shear failure adopting the acoustic emission analysis in dependency of duration and time. Further information about the acoustic emission analysis of concrete structures is given in general in [17] and referenced to shear failure in [15].

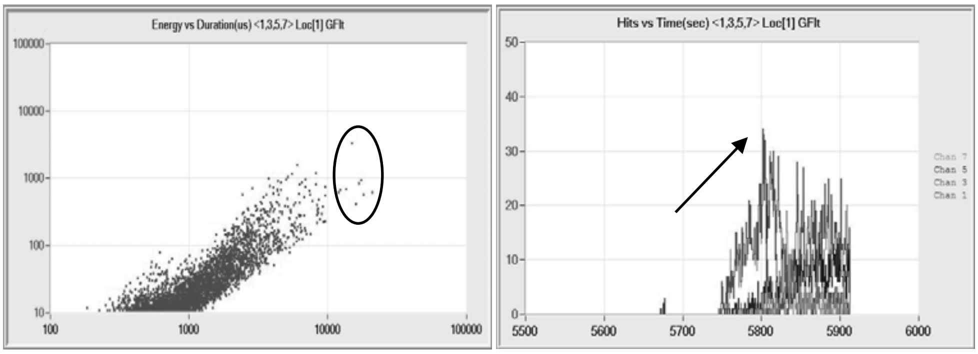

Figure 3. Acoustic emission analysis of a shear failure: Energy vs. Duration (left); Hits vs. Time (right) [20].

3. DATA

One of the main objectives of the research project is the investigation of reinforced concrete structures where the risk of shear failure exists due to the low shear reinforcement. Within the scope of this study a series of shear loading tests have been carried out where the photogrammetric analysis, acoustic emission analysis, and conventional measuring techniques have been used in combination.

Four test beams have been dimensioned in such a way that, on the one hand, the risk of bending failure could be eliminated and, on the other hand, the probability of shear failure has been maximized. Therefore, the beams have been provided with strong flexural reinforcement and, additionally, the shear failure has been forced by choosing a shear slenderness which supplies the highest probability of shear cracking [14]. Figure 4 shows the schematic drawing of the reinforced test beams and the loading arrangement of one side. The precise position of the shear failure could be defined by applying stirrup reinforcement in the middle and at the end of the beam. During the tests, the object was loaded and relieved cyclically. After reaching the target load, the load was increased to failure.

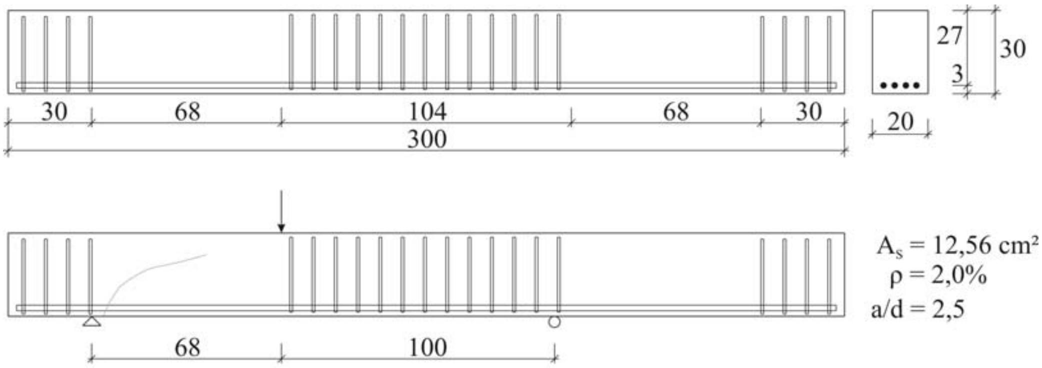

Figure 4. Reinforcement and experimental setup.

Figure 5 shows the applied measuring systems. Besides the eight acoustic emission sensors, various strain gauges and displacement transducers have been used. A better distinction between bending and shear cracks has been reached by dividing the acoustic emission sensors into two groups. In addition, the concept of “first hit sensor” has been applied, thereby, each acoustic signal has only been recorded and evaluated by the sensor located nearest to the source of signal. The regions of interest have been prepared by applying a surface texture for the image sequence analysis, in this case a chalk coating and a graphite powder spray pattern. The high contrast texture is required for good matching results and does not affect the development of cracks. For image acquisition two Nikon D700’s equipped with Nikkor 50 mm lenses have been employed on the front and back side of the tested beam. Taking images every two seconds, the deformation process could be captured with a sufficient temporal resolution. The image roughly covers an area of 45 x 70 cm; the resolution in the object space is given with approximately 0.16 mm per pixel.

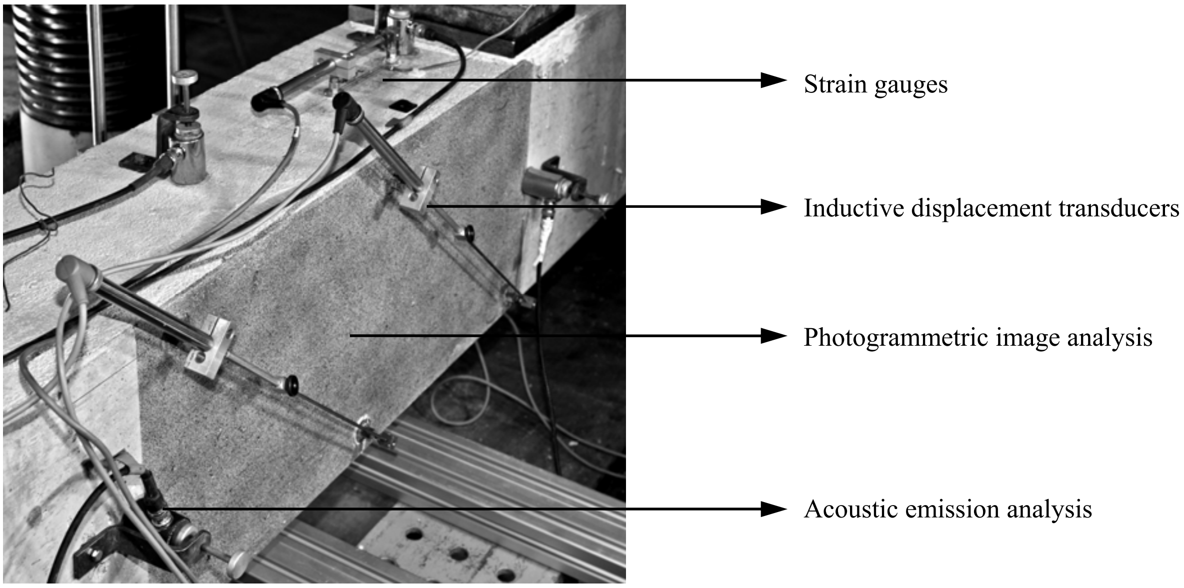

Figure 5. Test beam equipped with different measurement technologies.

4. RESULTS

Described in [9] and [21], the strain measurement accuracy of two dimensional image sequence analysis depends, first, on the quality of the loading and image system and, second, on errors of the correlation principle. Therefore, the breadboard construction and the camera installation have been designed extremely rigid to prevent any movement; thus, out-of-plane displacements have been considered negligible. Using the least-square-matching method, a high accuracy of the point detection has been provided. In addition, the utilization of an interest operator has enhanced the results of the matching process; the mean value of the standard deviation of each parameter of the LSM has been reduced by up to 5 % adopting the Harris operator instead of a regular grid of 30 x 30 pixels. The low increase of performance is caused by the well applied random pattern and the homogenous illumination of the concrete beam and, thus, the image quality in general.

After the evaluation of the image sequences and the acoustic emission signals, the results have been synchronized with the measurements of the strain gauges and the displacement transducers. Figure 6 represents the comparison of two different load stages at the time T1 = 5625 s and T2 = 5633 s. The upper left part of the figure shows the surface stretch of the tested beam at the first indication of a slight crack formation, yet a statement about the type of crack is not possible. The diagram at the upper right corner of the figure combines the measured data of a strain gauge, attached on the upper side (compression zone) of the concrete beam, and the hit rate of all acoustic emission sensors at the time T1 = 5625 s, highlighted with a dotted vertical line. The last load stage and the following increase of load is clearly visible observing the displacement-time graph of the strain gauge. Despite the rising load of the concrete beam, the strain gauge receives first compressive strain and changes at T_3 = 5647 s to tensile strain. This behavior indicates a changing load bearing behavior and probably the exceeding of the ultimate load. At the time T1 a continuous pressure load is shown, which does not allow any conclusion on macro crack formation. The acoustic emission sensors detect an increasing hit rate, an indication of a shear crack. The next time stage displays a clear crack, visible in the camera data as the region with a high surface stretch. The outstanding rise of the surface stretch of connected triangle elements and their distinctive shape allows the crack detection inside the region of interest and the identification as a shear crack. Any information about the crack width is not derivable. The acoustic emission analysis records the highest hit rate at the critical sensor and the load transition to the bearing. In contrast, the strain gauge still displays an increasing load, which does not verify any crack formation. The transition from the stable to the unstable phase has still not been reached. A possible explanation for the late notice of the shear crack using the strain gauge is the friction on the crack edges at small crack widths and the ability to transmit residual tensile strains across the crack. This phenomenon provides the absorption of the applied loading and leads to the delayed detection of the crack. The visual crack detection is possible at the time T4 ≈ 5700 s, more than 30 s after the first photogrammetric recognition.

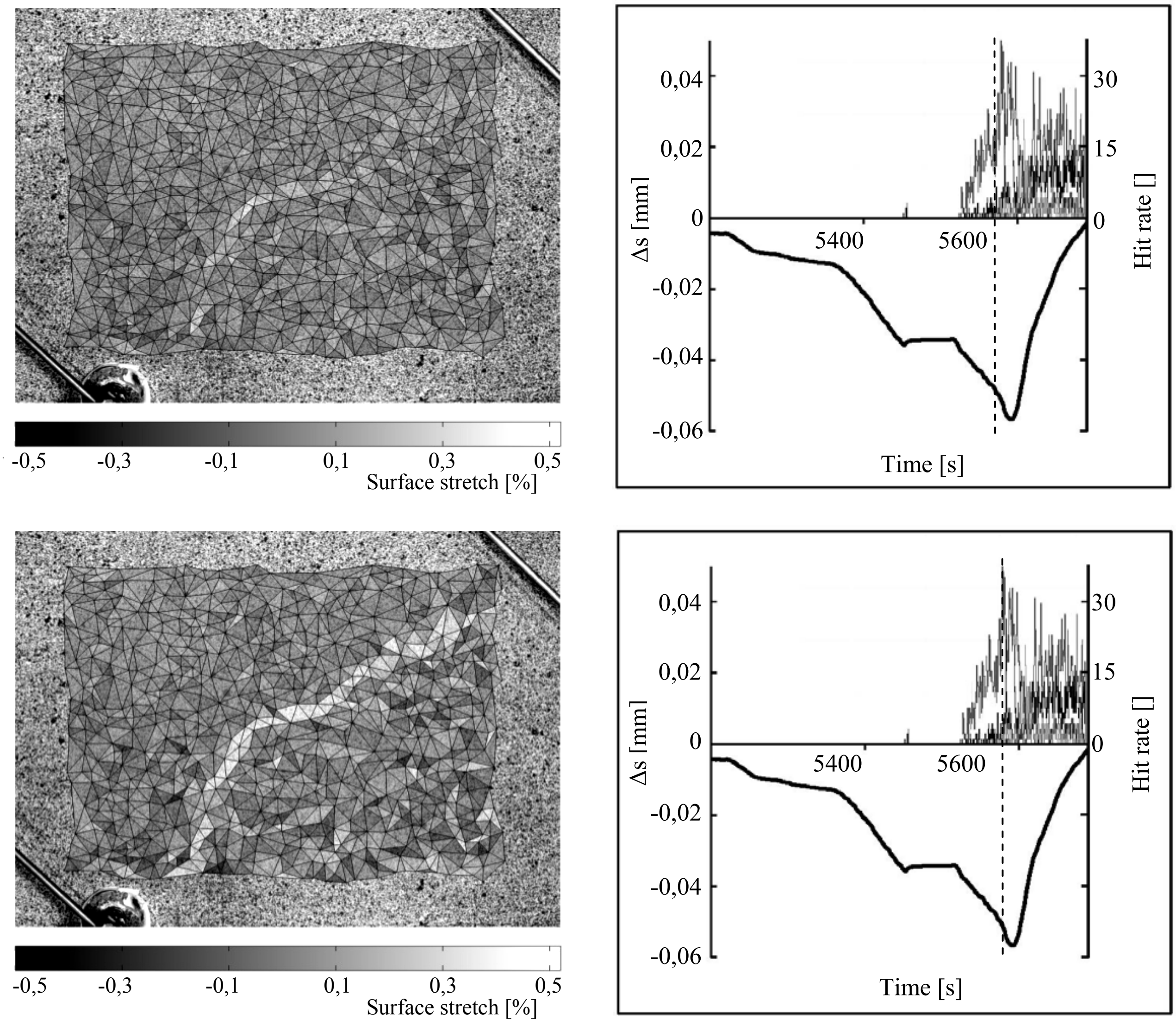

Figure 6. Comparison of the determined surface stretch and the synchronized values of a strain gauge and the acoustic emission sensors (from left to right) at the time T_1 = 5625 s and T_2 = 5633 s (from top to bottom).

5. CONCLUSION

The presented image based approach provides a suitable and robust possibility of detecting cracks using the analysis of surface stretch of small surface elements. In combination with the acoustic emission analysis the time of shear crack formation can be detected and classified much faster than using strain gauges and inductive transducers. The reason for this is the extensive measurement technique in combination with small surface elements. In contrast, the large base length of an inductive transducer leads to a smoothing of the measured deformation and therewith eliminates any form of micro cracking. The early crack detection and classification improves the monitoring possibilities of concrete members with little or no notice of failure.

At the present time the approach does not cover the measurement or analysis of absolute crack widths or deformations. Furthermore, the impact of out-of-plane displacements has to be investigated under real conditions. A possibility to detect movements between the image system and the concrete member could be the assessment of the aspect ratio of the triangle sites of each triangle within the image sequence. Discontinuities have to be recognized as global deformations and possibly compensated for during the process of crack detection.

The next steps of the research work will include the development and implementation of suitable crack analyzing methods, as well as the improvement of system speed. Particular focus is being put on the evaluation of the transmission between stable and unstable crack growth and the determination of indicators with high level significance referring to structures with no or low advance notice of failure.

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