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Prediction of Micro-Cracks in Steel Structures Subjected to Fatigue by Means of Acoustic Emission

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Abstract
This paper presents the development of a monitoring system using acoustic emission (AE) analysis for the prediction of micro- and initial cracks in fatigue-stressed steel structures such as bridges, cranes, offshore, or industrial constructions. Initial experimentation suggests a relationship between microscopically observed crack length and AE intensity, further data is required to establish a definitive correlation. As part of an ongoing research project, AE measurement techniques and evaluation are to be further developed to create a monitoring concept for micro-crack prediction in more complex fatigue-stressed steel components. The focus of this research is not on the localization and detection of crack growth or structural changes but on micro-crack detection using AE. Existing acoustic emission analysis systems can thus be extended to measure and detect micro-cracks for the earliest possible identification of damage events. This paper describes the first results of the innovative research idea.

Keywords Non-destructive testing · Acoustic emission · Fatigue testing · Structural health monitoring · Measurement technique

1 Introduction

The need for renovation of bridges in the German trunk road network has been increasing continuously for years [1–3]. Almost half of the bridges of the federal government are warned of a serious neglect of maintenance measures and are now in need of repair [3].

There is a lack of simple, innovative economic and reliable monitoring systems that can be used to collect the necessary data for assessing damage and loss of load-bearing capacity or fatigue resistance, initially on structures, which require urgent repair. An innovative monitoring system, utilizing real-time data collection and predictive algorithms, could also be used to predict initial cracks in new structures so that major damage does not occur in the first place.

When a component is mechanically, chemically, or thermally stressed and crack initiation occurs, energy is released. Some energy is released as acoustic emission in the form of transient elastic stress waves. These waves can be recorded and by special piezoelectric sensors, providing a signal that can be analysed. Acoustic emission analysis (AE analysis) is a non-destructive measurement method that can be used to detect, track and evaluate cracks, wear and corrosion in real time and even from a great distance. The aim of AE is, in this instance, not to precisely locate the origin of the acoustic emission [4], but rather to detect changes in the component's structure, e.g. as a result of loads, crack initiation or growth, crack surface friction or structural changes, can be measured. The measurement methods are divided into qualitative and quantitative acoustic emission analyses. With quantitative AE, the entire waveform is registered, which means that the AE can also be evaluated afterwards and distinguished from sources of interference. With qualitative AE, only a very simplified image of the waveform is stored, making it more difficult to analyse in retrospect. However, it is possible to register a large number of acoustic emission signals [5]. Deformation and crack growth are among the source mechanisms for the formation of AE. A major

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advantage of acoustic emission testing is that it targets the mechanisms acting at the microscopic level [6]. However, the extraction of features from AE data can lead to a loss of certain information, which is why the AE technique has recently been combined with a deep learning approach [7]. Another study uses acoustic emission (AE) technology to monitor the tensile testing of stainless steel weld specimens and analyses and compares the mechanical properties of the welds and base materials as well as the differences in AE properties during crack propagation [8].

Acoustic emission analysis thus belongs to the passive non-destructive testing methods and is even able to precisely investigate components that are in use. Due to these capabilities, AE is ideal for monitoring critical infrastructure like bridges and storage tanks, particularly in detecting crack formation [9]. At RWTH Aachen University, significant work has been conducted in recent years in the field of fatigue to improve current regulations and common designs [10, 11] or to develop new ones [12, 13]. In initial investigations, AE is now being used to monitor the initial crack formation in steel during the fatigue process. In future, more detailed investigations within the scope of the German research project AKUSTAHL [14], aims to further advance AE measurement techniques and evaluation for micro-crack prediction in fatigue-stressed, more complex steel components. AE could hence be used in an innovative measurement system to immediately predict and detect cracks in fatigue-stressed structures. This paper describes the first results of the innovative research idea.

1.1 General

Structure monitoring is used to monitor constructions and verify whether individual components (of the bridges) or the structure`s behaviour correspond to the planned function and the calculated load bearing capacity. In this way, comprehensive monitoring provides transparency about the functionality of engineering structures including real-world variables that may not be accurately represented in modelling, such as material degradation or unexpected loading. Therefore, in steel construction, the primary focus is on detecting cracks.

Steel failure under fatigue loading can be divided into three phases (Fig. 1). The first phase is crack initiation and micro-crack growth (crack initiation). Then the crack enlarges under cyclic loading (stable crack propagation) and ends with residual fracture (unstable crack growth).

According to Radaj [15] and Chaboche [16], the microscopic (initial) damage is characterised by the formation of microcracks or microvoids over a length of 0.1–1.0 mm, from where it turns into a macrocrack. It has been shown that only 10% of the number of cycles up to a crack of 1 mm can be attributed to physical crack formation, while 90% of the cycles can be attributed to crack propagation [17].

The proportion of the crack initiation phase essentially depends on the specimen surface, whether one speaks of physical or technical crack initiation, whether the specimen is notched and whether short or long-term strengths with compressive or tensile mean stresses are analysed.

The occurrence of first cracks in the crack initiation phase or micro-crack growth phase in particular has not yet been measurable; first cracks usually only become visible and measurable in the macro-crack growth phase. This is where the research approach comes in.

A material subjected to local irreversible changes can emit and propagate waves. This phenomenon is known as acoustic emission (AE) [18].

When a sufficiently large load is applied to a structure, it can lead to plastic deformation. This relative movement of the atoms within a material structure releases energy that propagates through the material in the form of various elastic body waves [19]. These elastic body waves can be measured with a piezoelectric transducer or AE sensor and recorded in the form of a time series. Analysis of this time series can provide information about the nature of the fault or discontinuity in the material.

Acoustic emission measurements have been used in Great Britain since 2006 to monitor the condition of bridge structures; the largest monitoring system in the world was installed on the San Francisco Oakland Bay Bridge (640 sensors, company MISTRAS), which has a localisation accuracy of a few centimetres and can detect cracks 2.5 mm long [20]. For this technique, sensors in the range of 20 kHz to 400 kHz are used, which can localise the source of the signal (e.g. cracks) from the transit time difference of the signals. In contrast, the focus of the proposed research project is not on the localisation and detection of crack growth or structural changes, but on micro-crack detection using AE.

Since there are already application-ready systems for the detection of relatively large cracks, reference is made here to the current state of standardisation for acoustic emission analysis [21]. Relevant standards are DIN EN 13,554 [22], DIN EN 14,584 [23]. However, the initial or micro-crack formation examined here is not taken into account there.

1.2 Mode of Operation

AE analysis belongs to the non-destructive inspection methods and is even able to check components that are in use. This makes it appropriate for monitoring bridges or tanks. General principles of AE testing are given in European standardisation [22, 23].

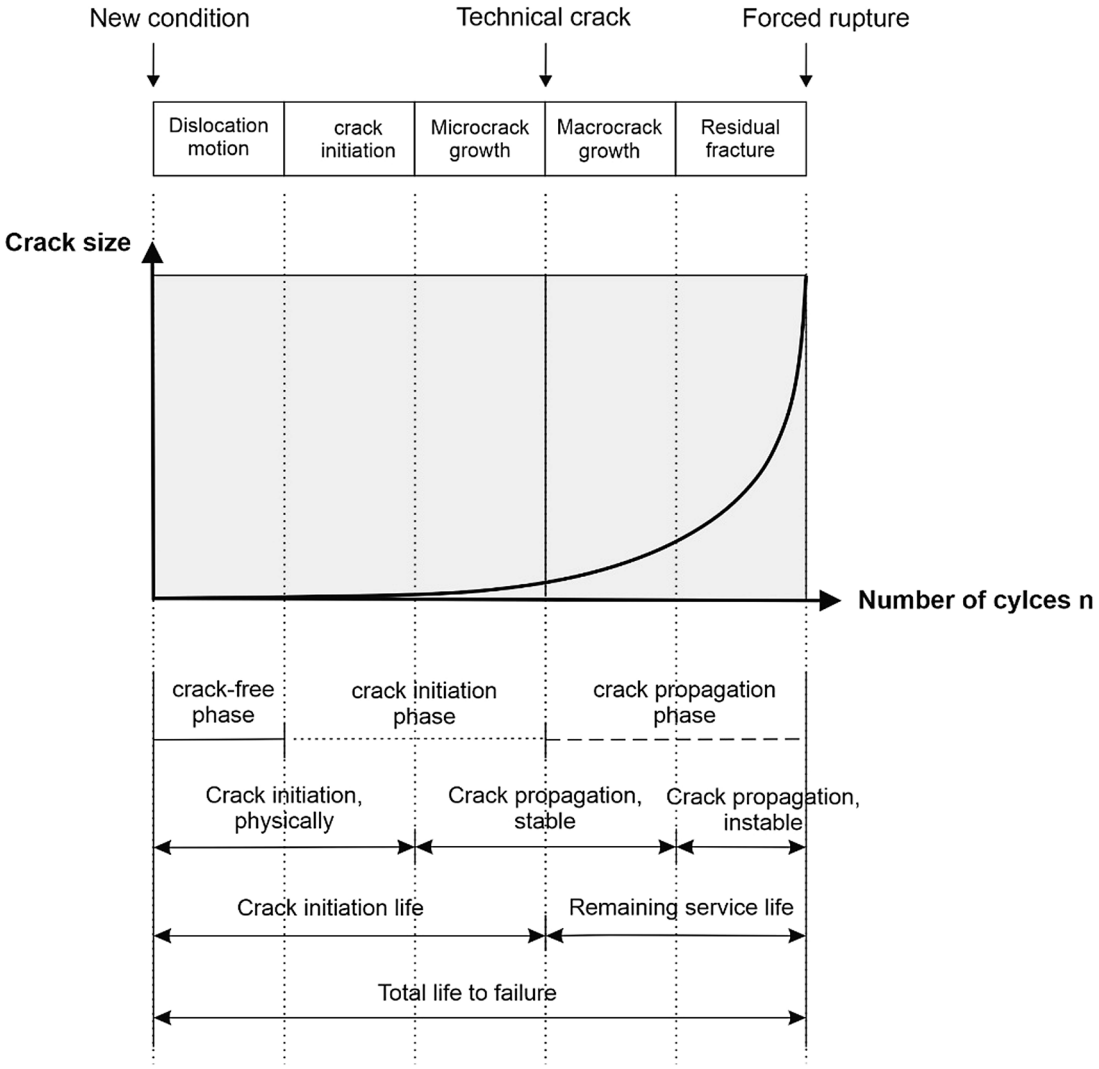


Fig. 1 Crack growth phases in accordance with [15]

With AE analysis it is possible to detect active corrosion, propagation of cracks, fibre fractures and fatigue [9]. However, these can only be detected if they are actively taking place during the test. Existing damage that is no longer changing can therefore not be detected. It is a passive detection method that records the dynamic response of the material to the applied load or the environment factors.

Companies offer equipment for AE analyses for sale [24] and also carry out AE analyses themselves on bridges, tanks, turbines, transformers and pressure vessels [9]. The German testing service provider TÜV also offers AE analyses for the monitoring of tanks [25]. When monitoring tanks, sensors are attached to the outer wall. The aim is to detect active corrosion, whereby leaks can also be determined. The advantage of this method is that the tanks do not have to be emptied for the examination [25]. There are regulations for AE in the detection of corrosion within metallic surrounding filled with liquid [26] and for inspection and testing of unfired pressure vessels [27], for example.

The advantages of AE measurements have long been known in the oil/petrochemical industries and are also increasingly being acknowledged in the construction industry. AE analyses enable continuous 24/7 monitoring of entire bridge structures. Applications with AE measurements enable continuous remote monitoring and alarm output via e-mail and SMS [28]. Studies on monitoring AE on motorway bridges have shown that AE monitoring is a powerful tool for detecting damage on motorway bridges and steel structures as well as for the continuous monitoring of defects. A global monitoring system has been developed as a method to identify damaged structures [29].

However, the existing systems in practice do not have the accuracy to detect micro-cracks smaller than 1 mm. At the RWTH Aachen, research is being conducted on a system that is able to map and detect the formation of fine cracks.

1.3 Practical Applications

In principle, AE analysis enables the testing of materials capable of generating AE with sufficiently high amplitude. The base material, steel, falls within the application range of this method, as the formation of cracks, crack growth or crack surface friction as well as plastic deformations form a good basis for corresponding detection [22]. There are only a few limitations in the technical implementation of AE that prevent the identification of structural component damage. These include interference noise such as internal machinery or operating noise and external noise caused by utilization. Despite these minor limitations, the test method described can be applied in a wide variety of applications and components.

The testing of pressure vessels, pipes and pipelines represents a large area of application-related analyses of AE. The tests are already regulated by standards in certain countries, ensuring that the individual, cyclical or permanent testing program follows a clear procedure [23]. Structures under dynamic influences are particularly susceptible to fatigue damage, which can cause temporary or even permanent failure of the structure and lead to enormous economic damage and downtime. Wind turbines, which are subjected to high dynamic loads, are particularly vulnerable to fatigue damage. The wind turbines consist of the tower, nacelle and rotor blades, all of which can be tested using AE monitoring. While the inspection of the tower and nacelle tends to detect cracks and damage in the steel or possibly in the concrete, the inspection of the rotor blades, which are currently being monitored more frequently, is mainly concerned with detecting delamination of the composite layers [30]. Monitoring the tower structures of wind turbines allows the early detection of cracks and their propagation.

Similarly, bridges are structures subject to significant dynamic loads. Due to their infrastructural and therefore social significance, the stability of bridges is of enormous importance. The monitoring of bridges is regulated by standards in most European countries. While AE inspection is not yet state of the art, there are a few examples demonstrating its successful application to various structures and components. The choice of components to be monitored is relatively extensive as long as the materials used are in accordance with e.g. DIN EN 13,554 [22]. For example, components of reinforced concrete composite bridges or pure steel bridges can be monitored, such as cables and hangers, prestressed tendons, girder grids or deck plates.

A successful application of AE was carried out on the bridge at Altstädter railroad station in Brandenburg, Germany. The tendons used in this bridge were of particular importance. During intensive inspections of the structure, several wire fractures caused by material embrittlement were detected in the tendons. For the period of about one year until the deconstruction of the bridge, it had to be possible to precisely detect and locate further wire breaks for safety reasons. Measurements of artificially induced wire breaks served as a reference for further acoustic monitoring of the tendons. Locating algorithms were used to reliably analyse all further damage developments just in time [31].

The monitoring of fatigue damage using AE was carried out at the Alexandra Bridge in Ottawa. Cracks were detected on eyebars, which were subsequently monitored using acoustic sensors. Acute crack growth could not be documented. However, it was still possible to assess the condition of damaged components using acoustic measurements. Classical assessment methods were successfully supported and safety aspects were strengthened [32].

The monitoring of complex structures using AE is also feasible, as Li et al. [33] were able to show. They investigated crack monitoring on orthotropic deck plates specifically focusing on the Maanshan Yangtze River Bridge. Although they were unable to detect or even actively introduce cracks on this bridge, the fracture of brittle graphite mines on the steel surface triggers acoustic signals similar to those of fatigue fractures in the material. Due to the complexity of the structure and disturbing noises, a classic evaluation of the results is hardly feasible, which is why the development of neural networks was necessary to analyse the sensor results. However, the final evaluation illustrates the superiority of the method compared with classic localization methods for complex structures under difficult boundary conditions [33].

The examples demonstrate a wide range of AE analysis applications. Nevertheless, the larger and more complex the monitored structures become, the more difficult it is to evaluate sensor results. additionally, external noise can further complicate the analysis. In some areas, AE can already be used extensively for condition monitoring. Complex geometric structures, e.g. at joints or connections in steel or bridge construction with varying stiffnesses or difficult boundary conditions such as coatings or rough surfaces should, however, also be the subject of future research with regard to AE in order to expand the range of applications.

1.4 Experimental Applications

Crack detection is crucial in experimental fatigue studies. In addition to fracture and loss of stiffness, the initiation of a crack is an important possible failure criterion for concluding a fatigue test. The detection of a crack can be done via the local strain change in the test section, if strain gauges are applied at the relevant points, see e.g [13, 34]. Alternatively, magnetic particle inspection or dye penetrant inspection can be used at regular intervals during the test to

detect external cracks, but this is a more extensive active inspection method. Internal cracks can be detected to some extent by ultrasonic testing, but also only as a snapshot. As a passive measuring system, a potential measurement can be carried out in addition to the elongation measurement, in which a change in the resistance of a sample is registered.

The AE is a powerful tool for early detection and measurement of crack initiation including first cracks and micro-cracks, in components.

2 Experimental Investigations Applying AE Measurement for Micro-Crack Detection

2.1 General

The crack nucleation process in a component causes a release of energy. Some of this energy manifests in the form of elastic body waves, that propagate through the component and can be measured with an AE sensor resulting in a time series. The formation and growth of cracks in different materials can be measured passively.

Previous studies [35–37] have demonstrated that the analysis of AE parameters can provide useful information about the occurrence of an impending failure of a structure. An event measured from a transient signal with an identifiable beginning and end is called a "burst" [6]. An increase in AE bursts at different stress levels, which is an indicator of nucleation and micro-crack growth.

In first investigations at the RWTH Aachen, AE was recently used to monitor the formation of cracks in steel during the fatigue process in component tests. Similar investigations were carried out in [37], combining AE measurements and accompanying light microscopy images on CT specimens to detect crack initiation. Here, it has already been established that both the signal duration and amplitude as well as the signal frequency allow clear indications of initial crack formation and a linear correlation between microscopically observed crack length and AE intensity can be established. In future, more detailed investigations as part of a newly initiated German research project [14] aim to further develop AE measurement techniques and evaluation in order to create a monitoring concept for micro-crack prediction in more complex fatigue-stressed steel components.

For the acquisition of the AE signals, an AE measurement chain from the company Vallen was used, consisting of a sensor, a decoupling box and a preamplifier. A VS-370 A1 was used as the AE sensor, in contact to the surface of the probes, with sufficient force applied by a magnet holder. For better transmission of the AE signals, 2 ml of a copper paste was injected between the sensor and the probe as a coupling agent before the sensor was applied. The AEP3N preamplifier and associated decoupling box were attached to an analog-to-digital converter (ADC) and connected to a laptop by a cable. During the testing process, the raw files were stored in the laptop. Before the measurements, the coupling of the sensor was checked. For this purpose, 5 Hsu-Nielsen tests were performed. The amplitude of the peaks was not allowed to deviate more than 3dB from the previous Hsu-Nielsen tests. Otherwise, the placement of the sensor had to be adjusted until a uniform coupling was achieved.

2.2 Static Tests on High-Strength Bolted Joints

As part of the AiF/FOSTA research project "P1458 - Optimization of arbitrary steel construction geometries under any load conditions with the aid of damage mechanics" [38], large-scale tests on bolted connections in high-strength steels were investigated in collaboration with the Institute for Steel Construction and the Institute for Ferrous Metallurgy. Due to the large load capacities, a horizontal 12 MN 4-column testing machine was used, and the test was conducted under displacement control at 2 mm/min.

The specimen consisted of an inner plate on each side made of S690QL with a thickness of $t = 40$ mm. Two outer plates were then fastened on one side using six M33 bolts. while a pin with a diameter of $d_0 = 70$ mm was used on the other side. The specimens were designed so that failure would occur in the outer plates at the pin area. The edge and hole distances were chosen as $e_1 = 1.2 \cdot d_0$ and $e_2 = 1.55 \cdot d_0$ to ensure bearing failure.

The steel strains in the area of the 70 mm bolt connections were measured using four strain gauges (SG) positioned approximately at 90° around the pin. Additionally, an AE sensor was applied (Fig. 2).

The global force-deformation behaviour of the bolted connection under static load exhibited the expected curve (Fig. 3). Examining the strain measurements around the bolt, the opposing strain gauges (SG-1 and SG-4 in the tension area) and (SG-2 in the compression area behind the bolt and SG-3 in the neutral area) exhibit a similar pattern (Fig. 3 below). Initially, significant strains develop in the tension area (SG-1 and SG-4), which gradually decrease there (at approximately 25 mm) and shift to the compression area (SG-2) with increasing load.

The AE measurement also indicates that the crest factor shows initial significant deflections in the early yielding phase (up to 10 mm) and then, shortly before specimen failure, a high signal density emerges, indicating massive crack formation due to sliding processes in the steel base material (dislocation dynamics). Even after reaching the maximum load (beyond 25 mm), distinct signal fluctuations were observed.

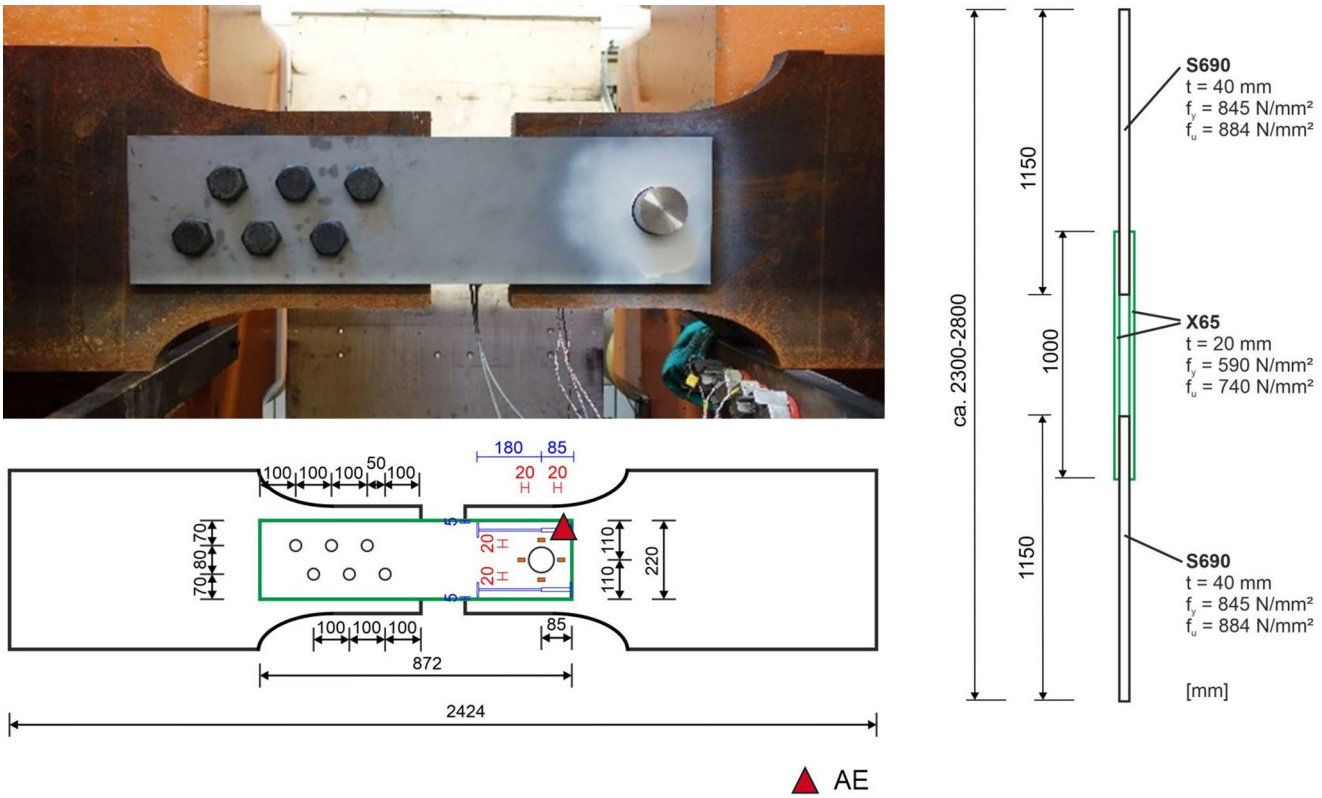


Fig. 2 Installed specimen (left) and schematic drawing (right), see also [38]

2.3 Static Tests of Bonded Strengthening with Steel Patches

As part of the AiF/FOSTA project "Stresspatches P1296 – Strengthening due to bonding technology of fatigue damages for designs used in steel construction" [39], static and fatigue tests were conducted at the RWTH Aachen University on bonded steel patches on component shoulder specimens (dog bone tests). These specimens featured a centrally located repaired crack, which was covered with a steel patch (Fig. 4). The aim of the project was to determine the technical feasibility of this reinforcement method, as well as to verify the static load-bearing capacity and fatigue behaviour of such bonded steel patches, and to establish S-N curves for the bonded steel patches. For this purpose, large-scale steel shoulder specimens with a crack or notch were used; this crack was then repaired, and the repaired area was covered with one or two steel patches. The adhesives used, adhesive layer thicknesses, and dimensions of the steel patches were varied. A two-component epoxy resin adhesive was used, which cures at room temperature.

The measurement technology consisted of displacement transducers to determine slip (relative deformation) in the adhesive joint, laser displacement sensors perpendicular to the test plane to determine deflection of both the steel patch and the steel specimen, as well as strain gauges (SG) to measure strains on both the steel specimen and the steel patch. Additionally, two AE sensors were installed to detect crack initiation.

The static tests were performed under displacement control at a rate of 1 mm/min until fracture. The fatigue tests were conducted with a stress ratio of $R=0.1$ and test frequencies ranging from 2 to 3 Hz, with a sampling rate of 50 Hz. The depicted test setup shows the steel dog bone specimen with a single-sided bonded steel patch; an AE sensor was placed on the backside of the steel specimen near the repaired crack. The AE measurement by the Institute for Advanced Mining Technologies (AMT) was carried out continuously during testing at a sampling rate of 1 MHz.

One objective of the research project is to (further) develop a feature that indicates the formation of cracks by combining various factors related to the main component's frequency and energy. The initial tests have shown promising results for Crest-Factor (CF). However, more data are required, and several combinations of features need to be tested to ensure an appropriate feature to indicate the formation of cracks.

At the beginning of the fatigue test, some CF deflections with low values are observed, which are associated with elastic-plastic transformation (dislocation dynamics and sliding processes in the metal grids) and mechanical noise (Fig. 5). Between 5,000 and 18,000 cycles, numerous CF

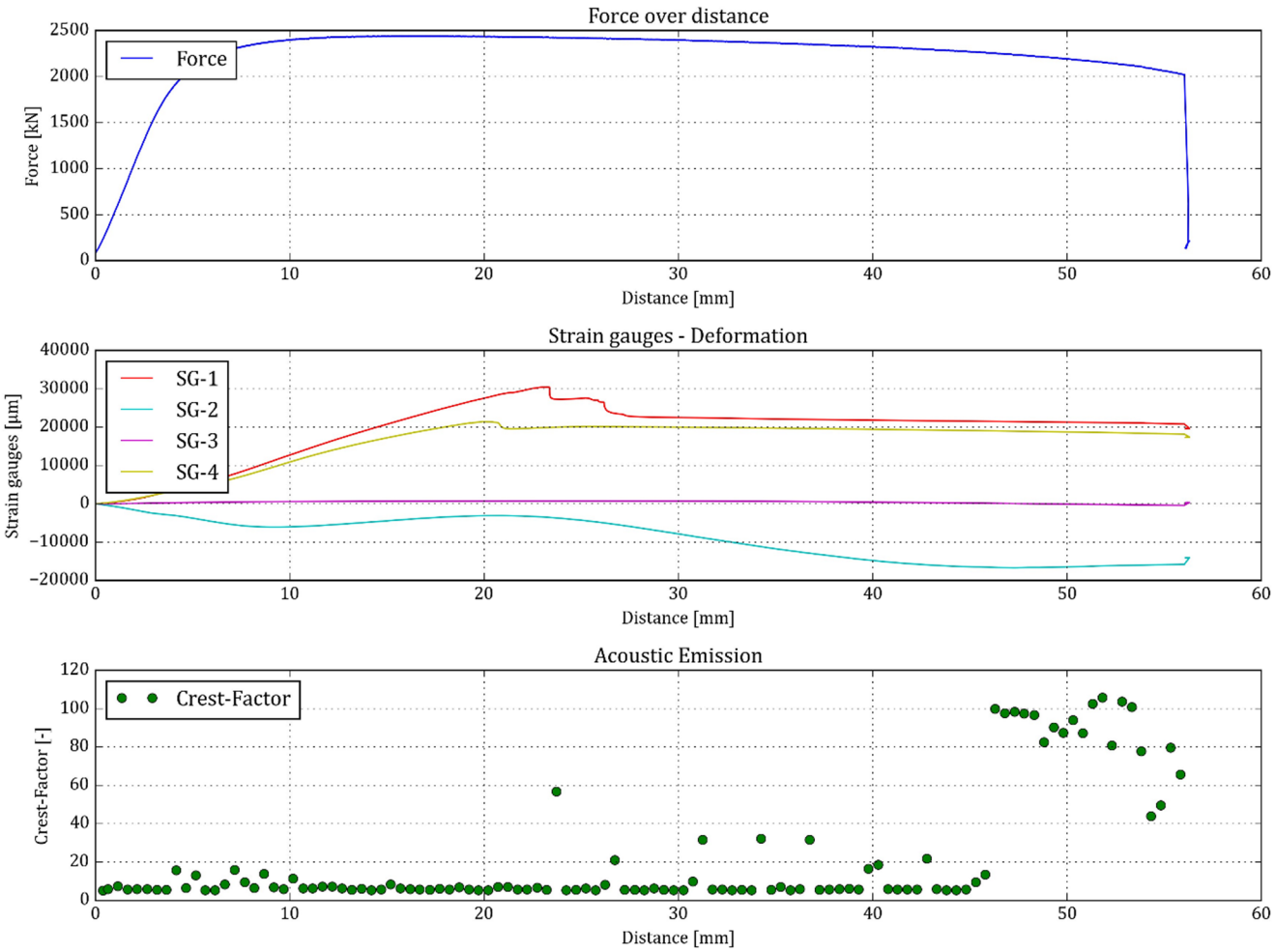


Fig. 3 Strain behaviour of the bolted specimen and corresponding AE signals during the test

deflections occur, indicating the formation of micro-cracks. The high CF values between 20,000 and 30,000 cycles may result from the growth and coalescence of micro-cracks. The highest CF value after the start of the test occurs at around 29,000 cycles, which can be attributed to the formation of macro-fatigue cracks.

From 25,000 cycles onwards, a strong accumulation of CF deflections with higher values is noticeable along with a transition in the SG curve (ARe), which is associated with unstable crack growth and final failure of the specimen.

2.4 Fatigue Tests on Cruciform Joints with Weld Imperfections

As part of the AiF/DASt/FOSTA project "EVOKERB – Evolution detail catalogue for economically optimised steel structures" [40–45], fatigue tests were carried out at RWTH Aachen University on cruciform joints with different weld designs accompanied by AE measurements. The aim of the experimental investigations was the analysis of weld imperfection influences on the fatigue resistance of typical steel details. The cruciform joints have been tested under tension at different stress ranges with a stress ratio of $R = 0.1$. The stress-controlled load frequency was set to 2 to 3 Hz. (1 cycle per second). Figure 6 illustrates the experimental setup of the specimen. Different measuring instruments including strain gauges (SG), wire displacement transducer (WDT), and displacement measurement of the test cylinder were applied to the specimens. The measuring of these sensors recorded 100 cycles at intervals of 1000 cycles with a recording frequency of 60 Hz [43]. One AE sensor was attached via magnets at the upper and lower end of the specimen. The AE measurement was performed at 2 MHz and continuously recorded an acoustic signal for each sensor.

Figure 7 shows the course of the strain difference (determined via strain gauges) parallel to the occurrence of the crest-factor (CF, measured by AE sensors AE1 and AE2) during a fatigue test. The first occurrences of the CF can already be seen at the beginning of the test, with a clear

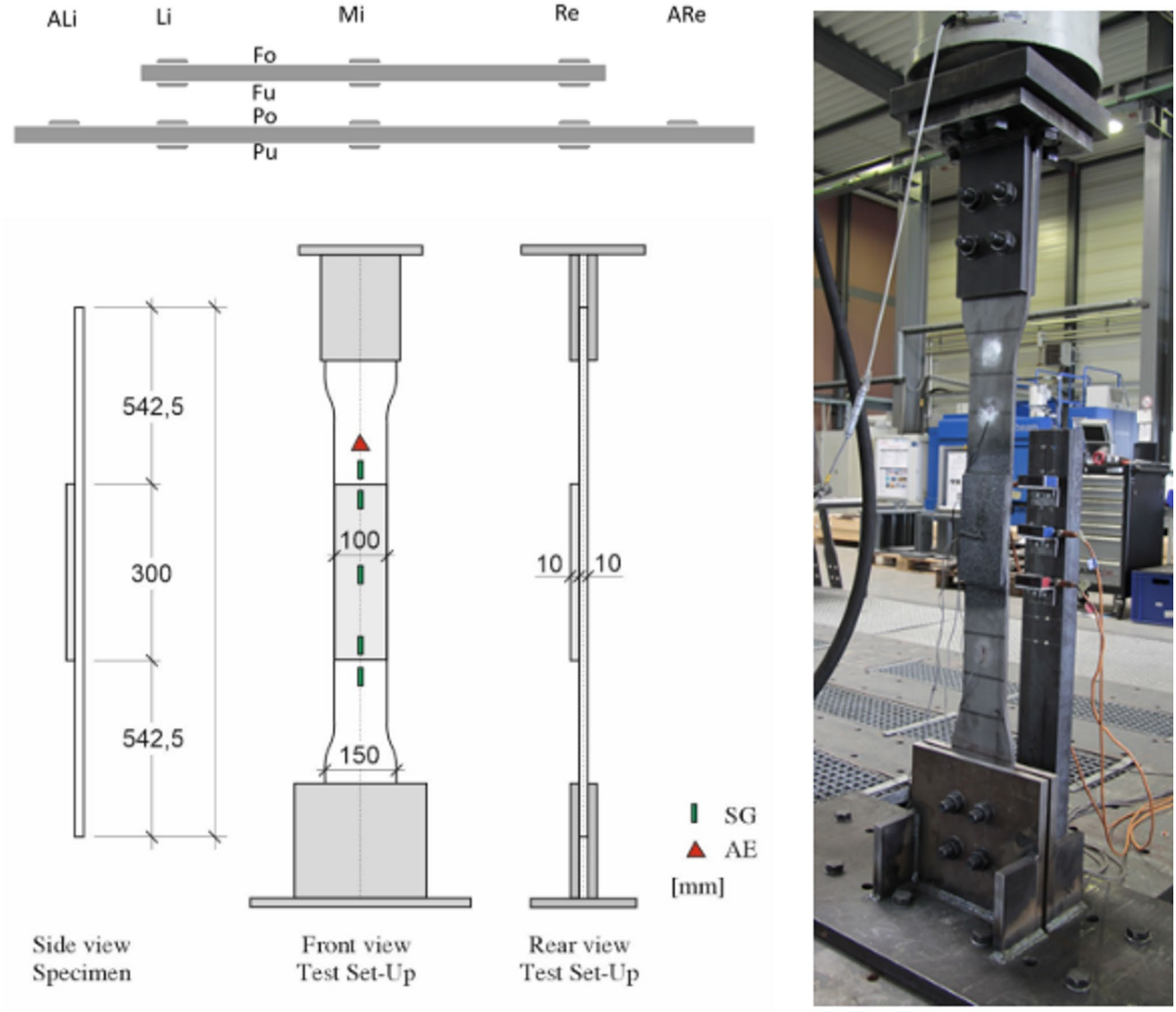


Fig. 4 Measurement technique of component test with bonded steel patch reinforcements: **a**) Technical drawing and **b**) Photo, see also [39]

accumulation just before the end of the test. The first CF deflections could already give indications of micro-crack formation at the weld toe of the cruciform joint.

Towards the end of the fatigue test, from about 120,000 cycles, the strain difference increases progressively. Also, the CF signals occur more frequently. In the final phase of crack growth at the weld toe of the cruciform joint around 160,000 cycles, the strain differences increase extremely on the front side, while they decrease sharply on the back side (where the crack is located). At the same time, there can be seen an enormous amount of CF accumulation. Thus, it can be stated that crack growth, which is accompanied by increasing strain difference, is also associated with an accumulation of CF deflections. This finding lays the foundation for a correlation of CF signals and crack growth, which will be further explored in the future.

In our experiments the CF was calculated from AE bursts captured with a sampling rate of 1 MHz (in the fatigue tests) and 2 MHz (in the cruciform tests). The CF was determined as the ratio of the maximum absolute amplitude to the root mean square (RMS) value within each detected AE burst. A burst was defined as a segment of the signal exceeding a predefined amplitude threshold and bounded by a quiet zone. Before CF extraction, the raw AE signals were band-pass filtered (typically 20–400 kHz) to suppress mechanical noise and environmental interference. No denoising or RMS smoothing was applied after filtering. The use of consistent segmentation and preprocessing ensures comparability of CF values across specimens. However, it is acknowledged

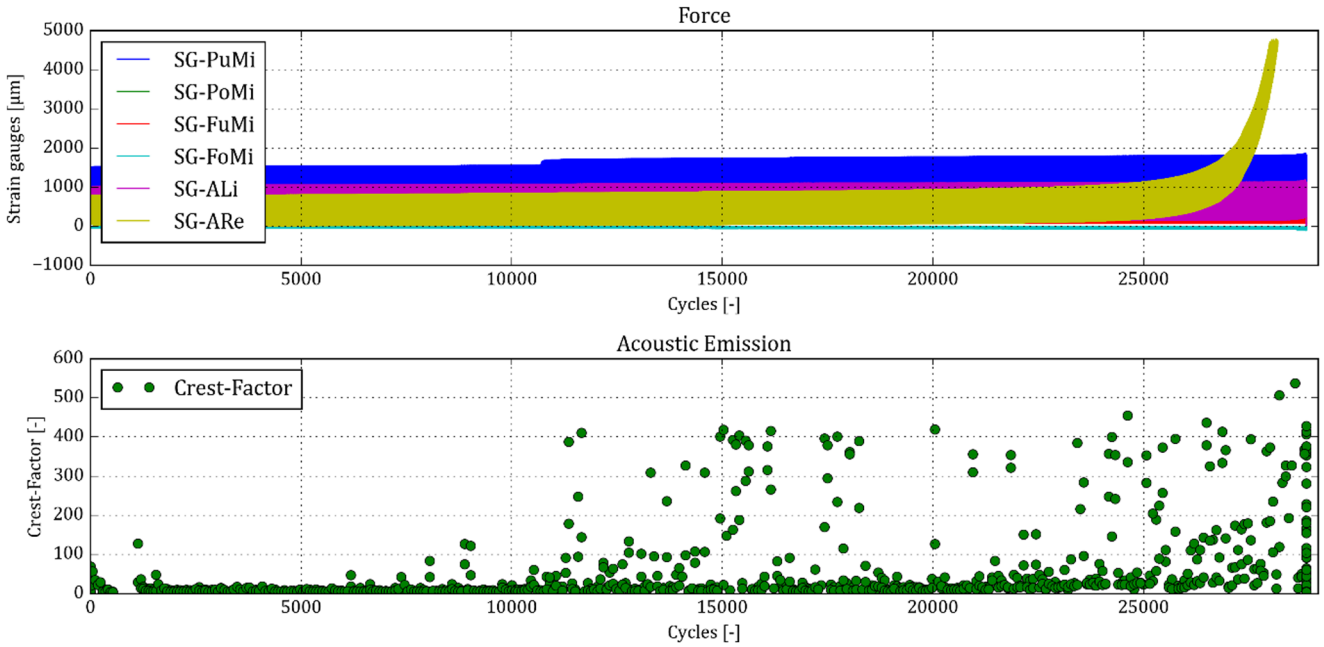


Fig. 5 Strain behaviour of the bonded specimen and corresponding AE signals during the test

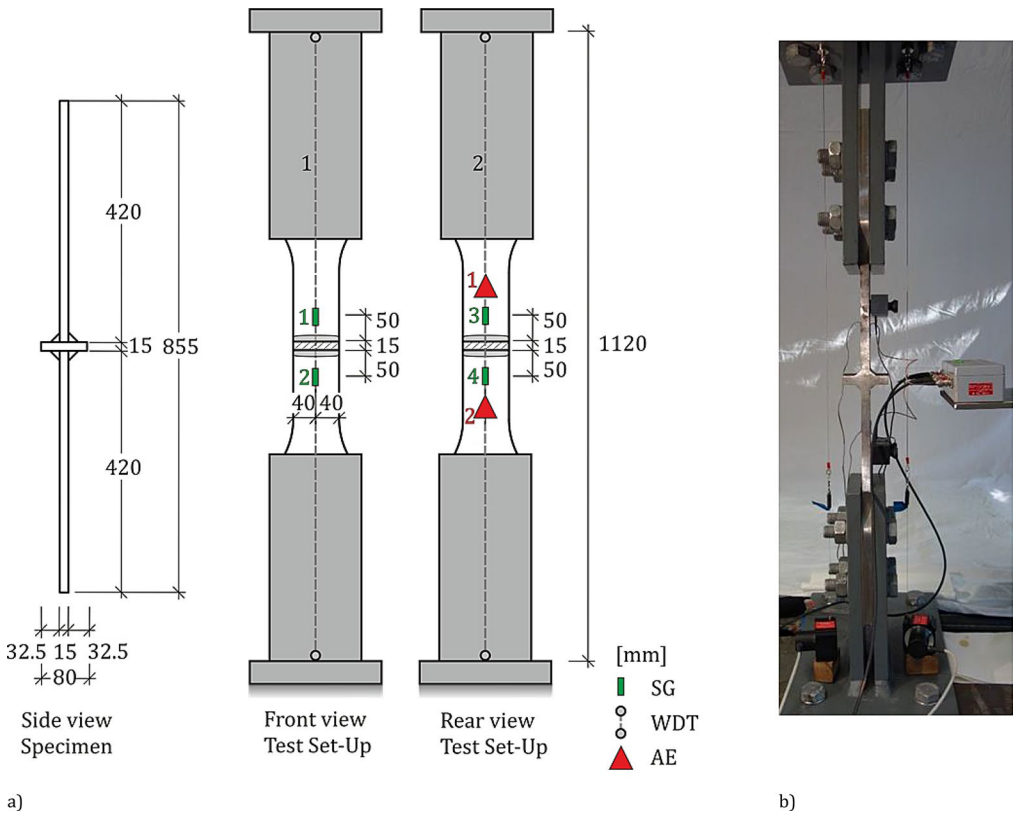


Fig. 6 Measurement technique of cruciform joint fatigue tests: **a**) Technical drawing and **b**) Photo

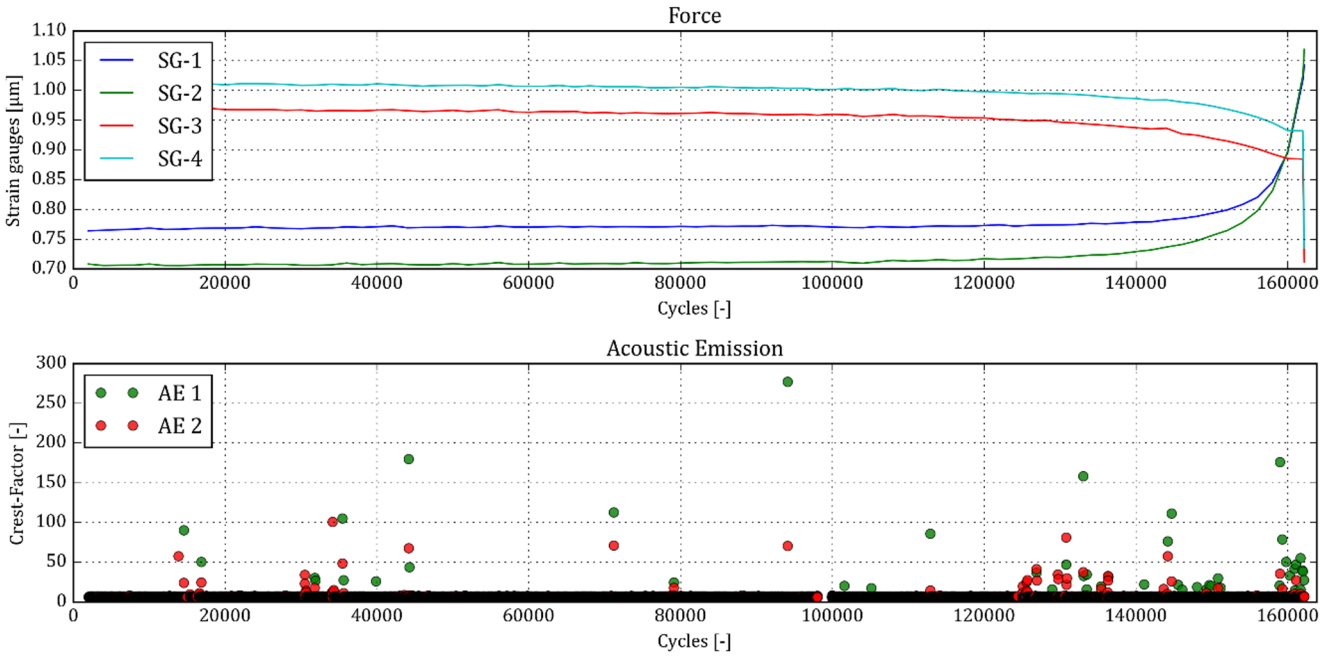


Fig. 7 Comparison of measurement signals by strain gauge and AE during a cruciform joint fatigue test

that absolute CF values depend on sensor coupling, noise environment, and waveform characteristics. Therefore, relative changes in CF over time are emphasized in our interpretation rather than absolute thresholds.

3 Discussion

This study indicates that acoustic emission (AE) may be more sensitive than traditional non-destructive testing methods, such as strain gauges, for detecting crack nucleation and growth. Preliminary findings suggest AE allows for earlier detection and improved monitoring of micro-cracks in steel structures, with promising correlations observed between AE features—particularly the crest factor—and various phases of crack initiation and propagation. However, comprehensive statistical validation is essential to confirm these results, as well as to determine the optimal analysis methodology for correlating AE signals with crack behaviour.

The investigations presented in this paper should be regarded as preliminary tests within the framework of the current running project. The main objective was to explore initial correlations between AE signals and crack initiation processes under fatigue loading. A comprehensive statistical validation involving a larger number of specimens is currently in preparation and will be carried out in the next phases of the project. These efforts will ensure a more robust evaluation of the proposed methodology and support its further development toward practical application.

The CF reflects the ratio between the peak amplitude and the root-mean-square (RMS) value of the AE signal. In fatigue-damaged steel, this value increases in response to impulsive, high-energy events such as dislocation avalanches or crack front jumps. These events are marked by short-duration, high-amplitude waveforms, which naturally elevate the CF. This makes CF particularly suited for early crack detection, as micro-crack initiation and coalescence often emit such transient signals.

Recent AE literature (for example [37, 38]) supports this, identifying CF as a sensitive indicator of damage evolution. While this study identifies qualitative trends, further work is ongoing to quantify a mathematical relationship between CF and material state parameters such as crack length or strain energy release rate. The analyses indicate a monotonic increase in CF with increasing micro-crack density and a correlation coefficient CF and optical crack length.

In the experiments presented here, the relevance of the AE signals was also evaluated using strain gauges only. Further basic experiments are currently being conducted on simple tensile tests and CT samples, in which crack strain gauges are also being used on a trial basis and a correlation of the AE signals is being carried out with the aid of high-resolution digital images and microscope images taken during the experiments. The results are currently being evaluated and will then be published.

A limitation in utilizing AE for crack detection is the challenge of interpreting the magnitude of AE signals. The distance between the source of the AE (namely, crack initiation or propagation) and the sensor significantly influences

the attenuation of signal intensity. This spatial relationship can lead to variability in recorded AE values, complicating accurate assessments of crack severity.

To address this limitation, future research should focus on developing a robust analysis methodology that accounts for these factors, ensuring reliable results regardless of sensor positioning, component geometry, or crack location. The presented observations demonstrate the feasibility of using AE for micro-crack prediction. However, the system is currently not designed for high Technology Readiness Level (TRL) deployment, therefore, some aspects like environmental or mechanical noise were not proved in this study. Further research is needed to validate the method under more diverse and practical conditions.

4 Conclusion and Outlook

This paper presents initial investigations into a new method for predicting micro-cracks during fatigue processes in steel structures using AE measurement techniques. The following important points were identified:

1. AE events commonly occur in steel structures and can be measured.
2. In static strength tests, some AE events occur during the transition from the elastic to the plastic phase, indicating the beginning of permanent deformation of the component or crack nucleation.
3. In fatigue strength tests, a higher number of AE events is detected from the beginning of the experiment, which indicates greater sensitivity and enables early detection of micro-cracks and monitoring of crack growth.

To facilitate crack detection, a crest factor was defined. Analysing the preliminary tests conducted, the following can be summarized:

1. Microstructural activity caused by elastic to plastic transformations and the formation of micro-cracks are associated with low CF values.
2. Increased microstructural activity such as growth and coalescence of micro-cracks correlates with a sharp rise in CF values.
3. Macro-crack-related CIF deflections have a higher mean value than those stemming from plastic deformation and micro-cracks.
4. Both stable and unstable macro-cracks growth is associated with a strong accumulation of CF deflections with significantly higher values.

In newly initiated research projects, a clear quantitative relationship between crack initiation and measured quantities of AE signals will be established to develop a prediction system for micro-cracks in fatigue-prone steel structures. Establishing a structural health monitoring system at the micro-crack level serves to detect damage at an extremely early stage before it impacts structural behaviour. This advancement in the steel construction, contributes to cost saving, resource efficiency and also sustainable environmental preservation.

The primary objectives of this research project are defined as follows:

1. Development and definition of requirements for a simple, economical, and durable monitoring system for detecting fine cracks.
2. Calibration of measurement methodology by defining an advanced crack initiation factor, calculated from measured AE signals that indicate initial crack formation.
3. Transferring the measurement methodology to component scale with varying levels of complexity to measure and assess even complicated cracking processes using AE.
4. Development of a holistic monitoring concept and its application for long-term external use to monitor fatigue-stressed structures.

The next steps in this research involve refining the AE measurement methodology, scaling it to more complex geometries, and developing a comprehensive monitoring concept for long-term external use. This work is expected to have broad implications for the steel construction industry, offering a simple, economical, and durable monitoring system that can prevent catastrophic failures and optimize resource use.

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Data Availability No datasets were generated or analysed during the current study.

Code Availability Not applicable.

Declarations

Ethics Approval Ethical standards were considered and respected.

Consent to Participate All authors declare their consent to participate.

Consent for Publication All authors declare their consent for publication.

Competing Interests The authors declare no competing interests.

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