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Detection and monitoring of the fatigue crack growth on welds – Application-oriented use of NDT methods

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Abstract

Early detection of fatigue cracks and accurate measurements of the crack growth play an important role in the maintenance and repair strategies of steel structures exposed to cyclic loads during their service life. Observation of welded connections is especially of high relevance due to their higher susceptibility to fatigue damage. The aim of this contribution was to monitor fatigue crack growth in thick welded specimens during fatigue tests as holistically as possible, by implementing multiple NDT methods simultaneously in order to record the crack initiation and propagation until the final fracture. In addition to well-known methods such as strain gauges, thermography, and ultrasound, the crack luminescence method developed at the Bundesanstalt für Materialforschung und -prüfung (BAM), which makes cracks on the surface particularly visible, was also used. For data acquisition, a first data fusion concept was developed and applied in order to synchronize the data of the different methods and to evaluate them to a large extent automatically. The resulting database can ultimately also be used to access, view, and analyze the experimental data for various NDT methods. During the conducted fatigue tests, the simultaneous measurements of the same cracking process enabled a comprehensive comparison of the methods, highlighting their individual strengths and limitations. More importantly, they showed how a synergetic combination of different NDT methods can be beneficial for implementation in large-scale fatigue testing but also in monitoring and inspection programs of in-service structures - such as the support structures of offshore wind turbines.

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1. Introduction

Monitoring of the fatigue process and early detection of fatigue cracks during the service life of dynamically loaded structures such as bridges, wind turbines, cranes, towers, etc. are important not only for the prevention of potential failure but also for the development of cost-effective, reliable, and even predictive maintenance strategies. Depending on the structural detail and operational conditions, different monitoring and inspection methods are suitable, as discussed for Nondestructive Testing (NDT) methods by Lampman et al. (2022). This study focuses on welded connections, generally known as the hot spots where stress concentrations occur and fatigue damage is anticipated, Chew et al. (2016). That makes them suitable for more local monitoring and inspection methods. Aside from general and close visual inspections, methods such as radiographic testing, dye penetrant testing, magnetic particle inspection, eddy current, ultrasound, and others can be used for inspections while strain measurements in the vicinity of welds are typically used for monitoring fatigue cracks and damage accumulation.

In this contribution, in frames of the research project SmartWeld (grant 03LB2022A), multiple NDT methods are used on two different welded details to detect the crack initiation and assess the fatigue crack growth on the surface and through the specimen thickness until the fracture. The methods include strain measurements, crack luminescence developed at BAM laboratories, ultrasound, and passive thermography. The beach marks are used to validate the results, Simunek et al. (2015). Generally, fatigue tests use the complete fracture as the failure criterion, while the crack initiation and growth are also of immense importance for practical applications. For example, realistic fatigue damage prediction requires models that can realistically represent the damage process, starting from the undamaged state through crack initiation until final fracture. One of the contributions of this study is the steps towards developing a more holistic database for fatigue tests that would provide more details on the test parameters like specimen geometry and the crack growth during S-N tests that can serve for the development and calibration of models for representing the fatigue degradation process. Additionally, the methods are applied simultaneously during testing, and this allows not only the comparison of the methods regarding their advantages and disadvantages but also the combining of the methods to assess the cracking process thoroughly and investigate the possibility of developing a measurement concept for large-scale testing, and inspection and monitoring of in-service structures. An initial comparison study between crack luminescence, strain gauges, and pressure measurement at closed tubular steel sections for crack detection on large-scale welded steel components was conducted by Thiele et al. (2019).

2. Measurement concept

2.1. Specimen geometry and testing configuration

The geometry of the tested specimens is shown in Fig.1. The first case is a dog bone with a welded hollow circular section that represents welded details such as the connection of a ladder to a wind turbine tower or similar. The second case is a standard double-sided butt weld. The same measurement concept was applied for the testing of both specimens to further investigate the benefits and limitations of the crack detection and propagation methods.

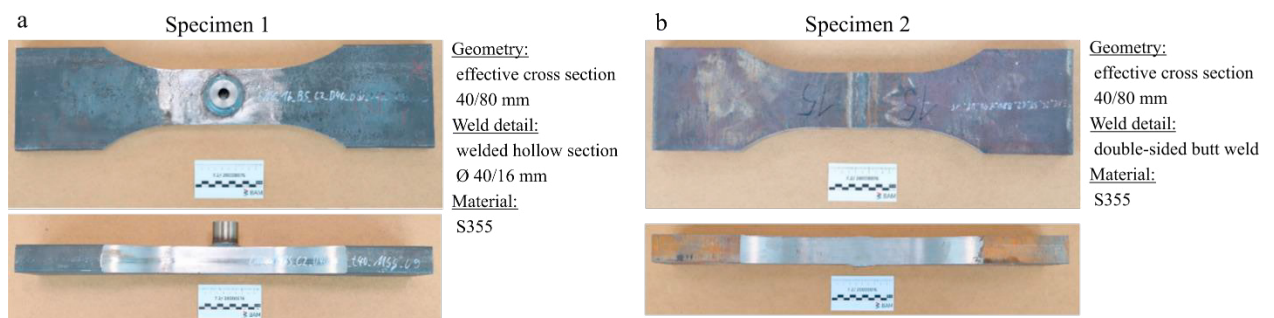


Fig. 1. (a) specimen 1 with a welded hollow section; (b) specimen 2 with a double-sided butt weld.



Fig. 2. Grinding of the weld toe transitions at specimen 2 and strain gauges positioning.

For specimen 1, the stress concentrations occur at two positions, above and below the welded section. For specimen 2, there are four broader areas where cracks could most likely occur, above and below the butt weld on both sides of the specimen. To limit the area of interest for specimen 2, and to provide a flat surface for ultrasound testing, the three weld toe transitions were grinded off (a well-known post-weld improvement technique, Hobbacher (2016)), leaving only one weld toe, where the cracks are expected (see Fig.2).

The testing configurations in the servo-hydraulic testing machine, with clamped specimens and the measurement equipment, are shown in Fig. 3. As mentioned before, the measurement methods included strain measurements, crack luminescence, ultrasonic testing, passive thermography, and the beach marks for the validation of the results. The specimens were loaded axially with a constant amplitude cyclic force (corresponding to a stress range of 210 MPa for specimen 1 and 230 MPa for specimen 2), with a load ratio of $R=0.3$, until a crack initiation was detected, after which the loading program with beach marks was applied, by halving the force amplitude (the mean force remained same) for 4 000 cycles and applying the full amplitude for next 20 000 cycles, repeated until the failure. The testing frequency was 10 Hz for the whole duration of the tests. Both specimens have an effective cross-section of c. 40x80 mm. More details are given for each measurement method in the following subsections.

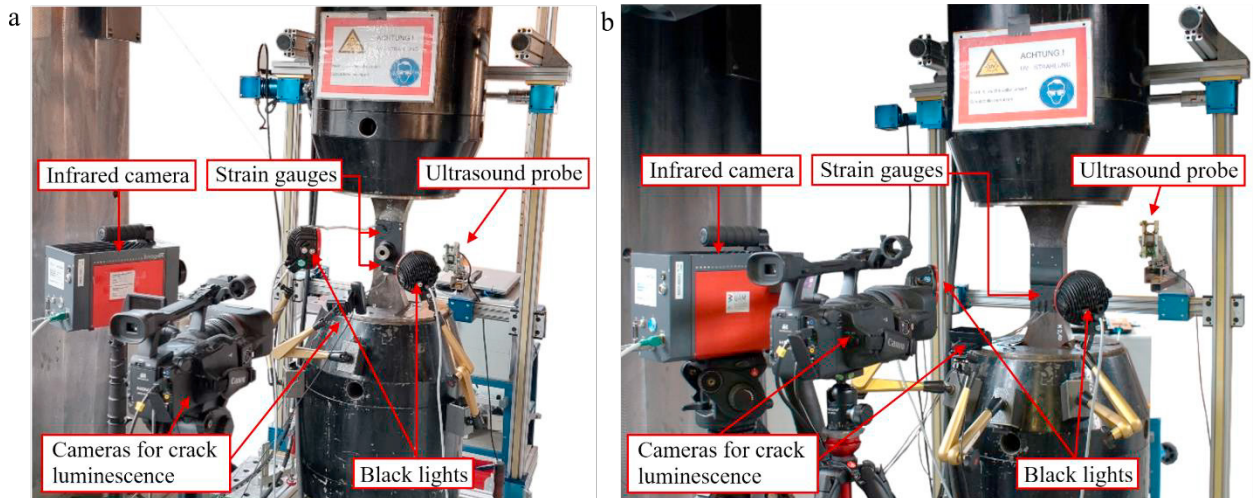


Fig. 3. Testing configurations with measurement setup and equipment. (a) Specimen 1; (b) Specimen 2.

2.2. Crack luminescence

Crack luminescence is a relatively new optical method for detecting and monitoring fatigue cracks on the surface of steel components, including the weld seams, as described by Hille et al. (2020). It was developed and patented at BAM laboratories by Mehdiانpour (2014). It is a two-layer coating system, where the first layer has fluorescent properties and is especially visible under black light, while the second layer is the covering black layer that prevents

light emission when there is no crack. When a crack occurs, the coatings also break, and it is possible to see the fluorescent layer framing the crack under black light. This makes the method especially suitable for crack detection, monitoring, and recording of its growth during the whole test with a camera. The automation of the crack detection and evaluation process, including the probability of detection studies for crack luminescence is currently being developed at BAM by Gerards-Wünsche et al. (2023).

2.3. Strain gauges

Strain measurement by strain gauges is a well-established local method also used for fatigue assessment based on strain/stress ranges, Keil (2017). It can be used to track the strain evolution in order to detect the occurring damage, or for measuring and counting the occurring local stress ranges during the exploitation or testing of a component. The strain gauges need to be positioned in the vicinity of the location where the crack is occurring, typically a notch or a stress concentration location. In this study, the strain gauges were positioned at the stress concentration locations at the $0,4t = 16$ mm distance from the weld toe according to IIW recommendations by Hobbacher (2016). For specimen 1, two strain gauges were used, above and below the welded section, and for specimen 2, three strain gauges were positioned along the ungrinded weld toe as seen in Fig. 2, in order to detect and localize the crack initiation. It is important to note here, that the left strain gauge (lower one in Fig. 2) did not function due to some technical problems, but the remaining two were working properly.

2.4. Ultrasonic testing

Ultrasonic testing can be used for flaw detection, sizing, and characterization in structural components, including crack depth. In this work, the COMPAS XL phased array device developed at BAM was used for the ultrasound examination, Schenk et al. (2006). The Synthetic Aperture Focusing Technique (SAFT) reconstruction was used as the evaluation method. The SAFT is a travel time-based analysis method. It combines a special measurement scheme with a subsequent imaging method. During the scanning process, the test volume region of interest is insonified by ultrasound waves. Echo signals from a wide angular range of the test specimen received at the probe position are a prerequisite for the reconstruction. Therewith the scanning provides an insonification of possible defects from various angles of incidence. More about SAFT can be read in Pitkänen (2006).

2.5. Thermography

Lock-in thermography can be used for the imaging of stress concentration in materials. Cyclic loading causes stress and temperature variations. The surface temperature change, which is directly proportional to the internal stress change, represents the sum of all internal stress changes reaching the surface. This thermoelastic effect can be evaluated using thermoelastic stress analysis (TSA), Dulieu-Barton and Stanley (1998). However, it is important to mention that the temperature variation investigated in TSA is in the order of mK, which is smaller than the noise level of the camera. Therefore, an advanced processing technique, the so-called lock-in analysis is applied, Breitenstein and Langenkamp (2003). The result of such an analysis is a phase and an amplitude image of the temperature variation. In this work, the thermal data is acquired with the Infratec ImageIR 8800, and the focus is on the amplitude images which show the amplitude of the temperature variation at the excitation frequency. Higher stress levels result in greater temperature variations, leading to higher values in the amplitude image. This amplitude information aids in detecting defects or structural weaknesses in the material.

2.6. Beach marks

Beach marks were created during both tests according to the above-described loading regime. The opened crack surfaces were investigated under the digital microscope VHX-7000N to document and analyze the beach marks. The visible beach marks served as a basis for the validation of the remaining measurement methods.

3. Results and discussion

All measurement techniques were applied during the whole test, continuously (crack luminescence and strain measurements) or in specific steps (ultrasound after a beach mark was performed and thermography every 5 minutes). In this way, it was possible to obtain comparable results between the methods for different phases of the fatigue process. Due to a large amount of obtained data, the work presented here focuses on two instances during both tests– detection, and evaluation of the crack initiation event and an example of crack propagation evaluation at a chosen time step corresponding to a specific beach mark.

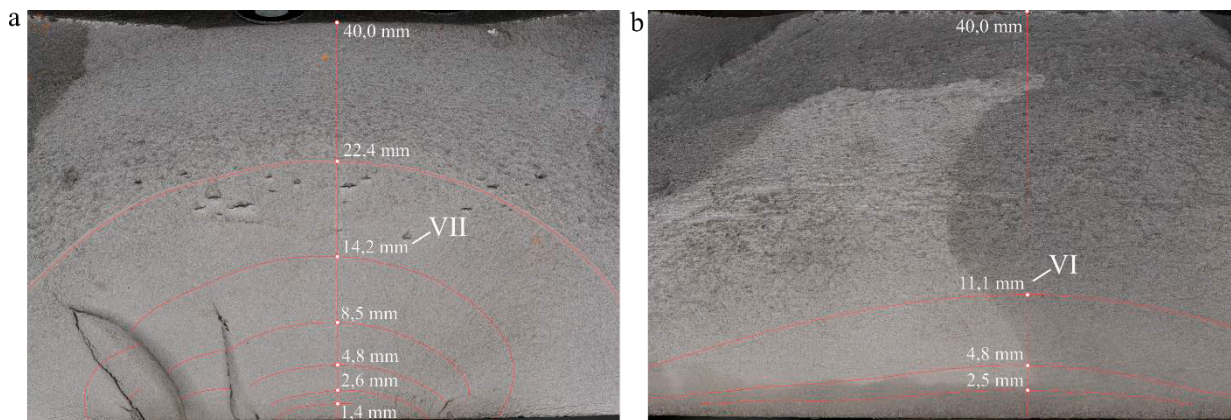


Fig. 4. Beach marks – distance from the bottom edge where the crack initiation takes place; (a) specimen 1; (b) specimen 2.

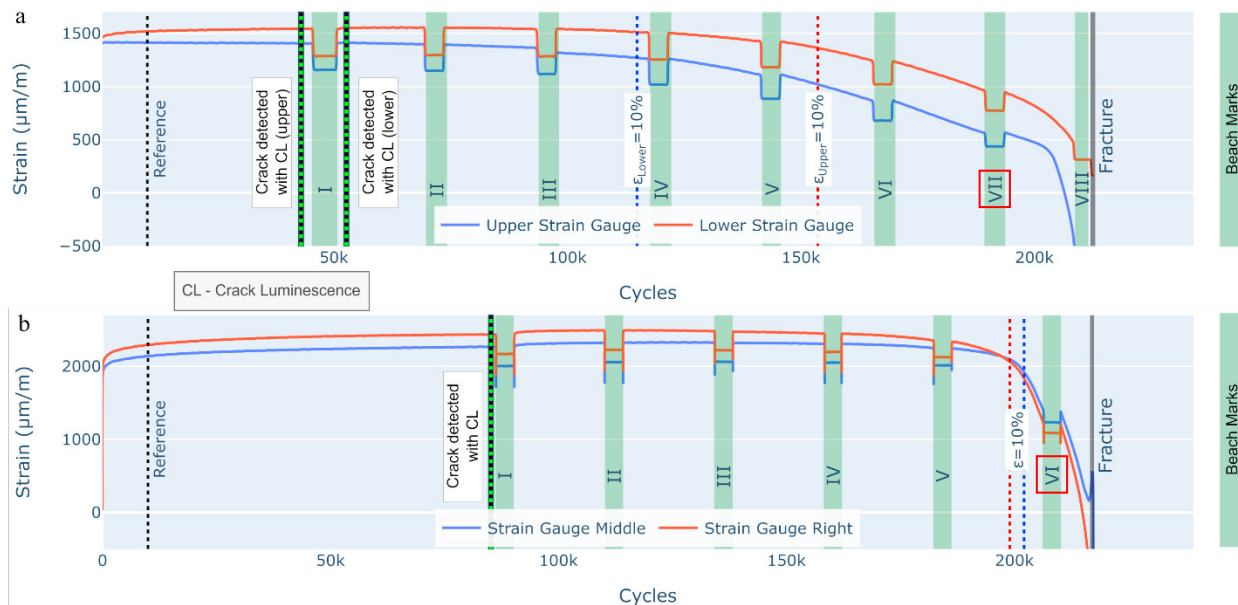


Fig. 5. Strain development with marked crack detection and beach marks; (a) specimen 1; (b) specimen 2.

The visible beach marks and their individual position starting from the edge where the cracks initiated are shown in Fig. 4. According to the number of cycles until fracture, for specimen 1, expected are seven beach marks on the fracture surface (the first crack initiated below the welded attachment, but the fracture happened above), and for specimen 2 six beach marks. This can also be seen in Fig. 5, where the strain measurements are shown over the number of cycles, and the beach marks are marked with Roman numbers. In the first case, more beach marks are

visible, presumably due to weld geometry and crack propagation pattern and speed. This can be confirmed by looking at the difference in strain development near the weld in Fig. 5. For specimen 1, the hot spot is smaller, and the crack gets deeper faster corresponding to higher strain change. For specimen 2, the hot spot is more spread over the specimen width and the crack grows relatively slower in depth corresponding to lower strain change and crack depth. This makes specimen 1 an easier task for fatigue crack evaluation.

However, given that the beach marks can be evaluated only after the fracture and the strain measurements typically do not provide information on crack size (for standardized specimens in fatigue testing there are techniques such as back-face strain compliance, Saeed et al. (2022)), the remaining three methods are utilized for the estimation of the surface crack length and crack depth. First, the crack initiation is discussed and later, the beach marks at 14,2 mm and 11,1 mm for specimens 1 and 2, respectively, are used for the crack size and depth estimation.

3.1. Crack initiation

The crack initiation on specimen 1 was first observed with crack luminescence below the welded section at around 43 000 cycles (Fig. 6 (a)). The estimated crack size was 7 mm. At that time, there was no crack observable with thermography, but the actual detection time should be investigated in the future. After the detection, the first beach mark was created. At around 53 000 cycles, a second crack initiation was observed above the welded section with crack luminescence. At c. 73 000 cycles, a clear indication of a crack was observed with thermography since the stress concentrations at the crack tips separated and a region with lower temperature change during loading became visible through darker colors. The crack size, i.e., the distance between crack tips was estimated to be 11 mm (Fig. 6 (b)). However, below the welded attachment there was still no indication of a crack with thermography. Therefore, for this specimen, crack luminescence showed an advantage for crack initiation detection, although the occurring crack above the welded section was also observed with thermography. A similar trend is observable in Fig. 5, where a larger strain variation is seen with the upper strain gauge, indicating a deeper crack.

For specimen 2, the crack was again detected with crack luminescence at c. 86 000 cycles. The crack was observable almost over the whole length of the weld toe, indicating a homogeneous stress distribution over the weld length. The length was estimated to be 69 mm. Thermography did not indicate a crack at that time and the detection time should be investigated in the future. After the crack detection, the loading program with beach marks was started. The summary for both specimens is shown in Table 1.

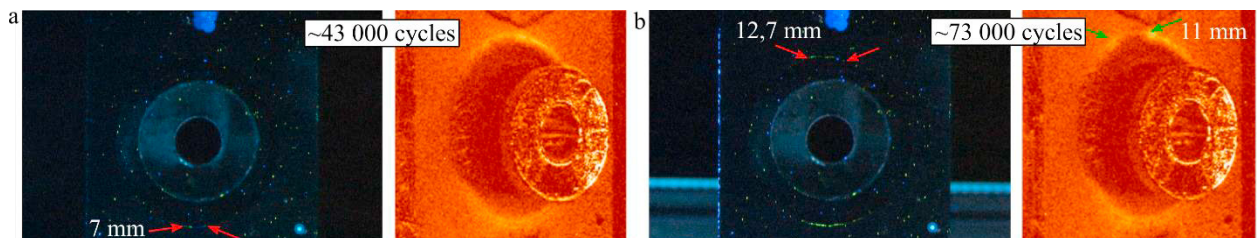


Fig. 6. Detection of crack initiation with crack luminescence (left image) and thermography (right image) at specimen 1; (a) crack initiation below the welded attachment at c. 53 000 cycles; (b) crack length estimation above the welded attachment at c. 73 000 cycles (beach mark II).

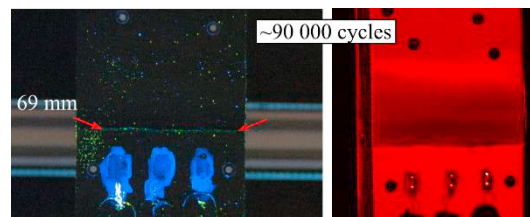


Fig. 7. Detection of the crack initiation with crack luminescence (left image) and thermography (right image) at specimen 2.

Table 1. Crack initiation detection.

		Specimen 1			Specimen 2	
		Nr. of cycles [n]	Indication		Nr. of cycles [n]	Indication
Crack luminescence	below	43 000	7 mm length	below	86 000	69 mm length
	above	53 000	indeterminate length			
Strain gauges	below	115 000	10% deviation	below middle	202 000	10% deviation
	above	153 700	10% deviation	below right	199 000	10% deviation
Thermography	below	N/A	N/A	below	N/A	N/A
	above	73 000	11 mm length			

3.2. Assessment of the crack length and depth

To evaluate the ability of the methods to estimate the crack length and depth, an example is presented here for the crack size corresponding to the beach marks at 14,2 mm (VII) and 11,1 mm (VI) for specimens 1 and 2, respectively. It is assumed that the beach marks represent the benchmark, i.e., the reference value to be estimated. The data obtained from crack luminescence and thermography is shown in Fig. 8, and for the ultrasound in Fig. 9.

For specimen 1, the crack propagation could be observed with both crack luminescence and thermography, where analogue stages of the crack growth were visible. This can be seen in Fig. 8 (a), at the cycle count corresponding to beach mark VII, where the crack tips started to separate and propagate more horizontally above the welded section. Before, the crack growth was following the weld form, as seen below the welded section in this example. The estimated crack length corresponding to the horizontal projection of the upper crack tips was 35 mm and 34 mm for crack luminescence and thermography, respectively. The corresponding length obtained by inspecting the beach mark was 35 mm. The ultrasonic testing, that was conducted directly after the beach mark VII was created, showed an indication of a defect at the 13 – 13,2 mm depth, as seen in Fig. 9 (a), which is in good correspondence with beach marks.

For specimen 2 (Fig. 8 (b)), the evaluation of the crack propagation was more challenging, given that the crack initiation occurred over a large portion of the specimen width. Especially with crack luminescence, which is a method for observing the surface cracks, is difficult to give a statement about the crack growth in such a scenario, unlike for specimen 1. However, with thermography, it was possible to identify the regions where the crack propagates faster, which was in good accordance with the beach mark shape. The estimated crack length was 77 mm and 74 mm, for crack luminescence and thermography, respectively. It was not possible to give an estimate of the surface crack length from the beach marks in this case, due to an unclear beach mark pattern at the left specimen side. The ultrasonic testing indicated a crack depth of 10 mm. The results for different methods are summarized and shown in Table 2.

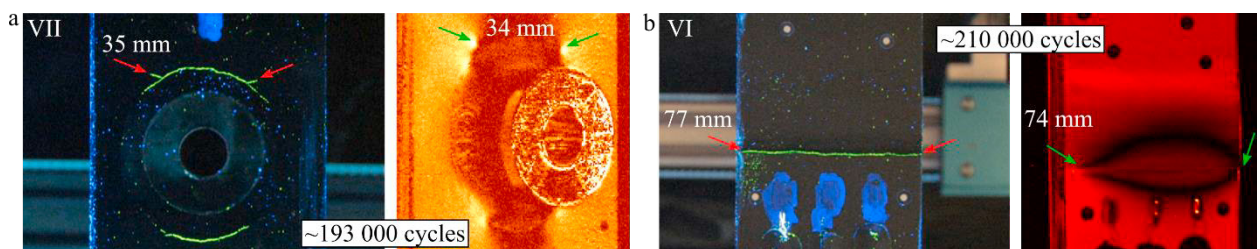


Fig. 8. Crack length determination with crack luminescence (left image) and thermography (right image); (a) specimen 1, beach mark VII; (b) specimen 2, beach mark VI.

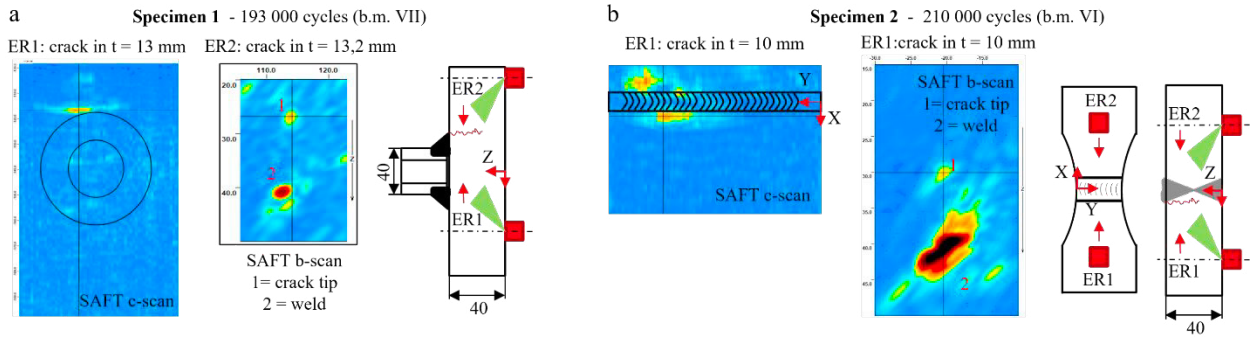


Fig. 9. Crack depth determination with ultrasonic testing; (a) specimen 1, beach mark VII; (b) specimen 2, beach mark VI.

Table 2. Crack propagation evaluation.

		Specimen 1	Specimen 2
		beach mark VII – 193 000 cycles	beach mark VI – 210 000 cycles
Crack length [mm]	Crack luminescence	35	77
	Thermography	34	74
	Beach marks	35	N/A
Crack depth [mm]	Ultrasound	13,2	10
	Beach marks	14,2	11,1

3.3. Database

In this work, the cycle number and the corresponding time represent the basis for the synchronization of different methods. The crack detection and beach marks define the course of the test and the evaluation of the results. To synchronize the data, the time series of each instrument were post-calibrated. This post-calibration was validated by changes within the time series that occurred regularly due to the phases of the beach marks and whose respective cycle numbers were therefore always obvious. The start and end points of the beach marks are visible through the strain gauges time series and from the testing machine log file. In the further course of this research, a direct synchronization of the data is planned instead of a post-calibration. For this purpose, a software/hardware combination is being developed that will not only perform the synchronization but also the data acquisition on as few devices as possible. The automatic issuing of triggers for starting/stopping different methods will be implemented. At the same time, scripts in Python programming language are being created for the data evaluation of the strain gauge time series and the image data from the crack luminescence and thermography cameras. This standardization will form the basis for a database that will not only allow for comparability of the methods but also for simplified further utilization in the future. A detailed description of the testing and specimen characteristics is being stored and will be used as metadata for publishing the reference data sets that would be available to the broader community for further utilization and studies.

4. Conclusions

In conclusion, this study has highlighted the effectiveness and usefulness of several methods in holistically monitoring crack initiation and propagation processes. These methods include crack luminescence, strain gauge measurements, ultrasonic testing, thermography, and beach mark analysis, all of which have been used to detect and/or evaluate fatigue cracks in steel components. The results indicate that crack luminescence is an effective technique for monitoring surface crack initiation and propagation. In parallel, thermography has proven to be effective in identifying areas of accelerated crack propagation and seems promising for crack initiation detection.

However, further evaluation of the measurements is needed for more insight into fatigue crack detection with thermography. Both methods also show potential for monitoring larger areas, which is important for large-scale testing and in-service monitoring. On the other hand, strain gauges, although of limited use in determining the exact crack size, were successful in signaling the area of crack initiation and growth and proved useful in calibrating the time series of other methods. They are very sensitive but provide only very local results. Ultrasonic testing provided a reasonable estimate of crack depth, and beach mark analysis served as a tool to validate various methods in terms of crack depth and length during laboratory testing. However, specimen geometry and load spectra significantly affect the formation of these beach marks, requiring an appropriate loading program in terms of the number of cycles between/during the beach marks and amplitude refinement to ensure the detectability of the beach mark patterns. Additionally, the potential of ultrasonic testing for large-scale tests, especially in an automated manner is still in question, which makes continuous measurement of the crack depth rather challenging. Additional methods, such as potential drop-based methods are being considered for further investigations.

It can be concluded that an effective recording of crack initiation and crack propagation is strongly dependent on individual specimen geometry, type of welding, and loading scenario. Therefore, suitable monitoring methods need to be chosen dependent on these facts and cannot be recommended in a general way. Ongoing development efforts are focused on meeting the challenge of improving the synchronization of all methods with novel software/hardware, streamlining data acquisition, and simplifying analysis, including a comprehensive database for methods comparison. Finally, this research marks the beginning of a series of studies aimed at testing the potential of different experimental setups for fatigue crack detection and evaluation on various specimen geometries aiming for developing the concepts for large-scale fatigue testing and in-service monitoring.

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References

- Breitenstein, O., Langenkamp, M. 2003. Lock-in thermography. Basics and Use for Functional Diagnostics of Electronics Components. Springer Berlin, Heidelberg.
- Chew, K.-H., Tai, K., Ng, E. Y. K., Muskulus, M., 2016. Analytical gradient-based optimization of offshore wind turbine substructures under fatigue and extreme loads. *Marine Structures* 47, 23-41.
- Dulieu-Barton, J. M., Stanley, P., 1998. Development and applications of thermoelastic stress analysis. *The Journal of Strain Analysis for Engineering Design* 33, 93-104.
- Gerards-Wünsche, P., Ratkovac, M., Schneider, R., Hille, F., Baeßler, M. 2023. A framework for assessing the reliability of crack luminescence – an automated fatigue crack detection system. *SPIE Smart Structures + Nondestructive Evaluation, Proceedings Volume NDE 4.0, Predictive Maintenance, Communication, and Energy Systems: The Digital Transformation of NDE*, Long Beach, California
- Hille, F., Sowietzki, D., Makris, R., 2020. Luminescence-based Early Detection of Fatigue Cracks. *Materials Today: Proceedings* 32, 78-82.
- Hobbacher, A. F. 2016. Recommendations for Fatigue Design of Welded Joints and Components. Springer.
- Keil, S. 2017. *Dehnungsmessstreifen*. Springer.
- Lampman, S., Mulherin, M., Shipley, R., 2022. Nondestructive Testing in Failure Analysis. *Journal of Failure Analysis and Prevention* 22, 66-97.
- Mehdianpour, M. (inventor) 2014. Crack Detection and Crack Monitoring by Means of Luminescence. European patent EP2693204 A1. Bundesanstalt für Materialforschung und -prüfung.
- Pitkänen, J. 2006. SAFT - Is it a tool for improved sizing in ultrasonic testing? 9th European Conference on NDT (ECNDT 2006), Berlin, Germany
- Saeed, H., Chaudhuri, S., De Waele, W., 2022. Calibration and validation of extended back-face strain compliance for a wide range of crack lengths in SENB-4P specimens. *Procedia Structural Integrity* 42, 967-976.
- Schenk, G., Völz, U., Dohse, E. 2006. COMPAS-XL - outstanding number of channels with a new phased array system. 9th European Conference on NDT (ECNDT 2006), Berlin, Germany
- Simunek, D., Leitner, M., Maierhofer, J., Ganser, H.-P., 2015. Fatigue crack growth under constant and variable amplitude loading at semi-elliptical and V-notched steel specimens. *Procedia Engineering* 133, 348-361.
- Thiele, M., Makris, R., Hille, F. 2019. Comparison of fatigue crack detection methods for high-cyclic loaded steel structures. 5th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures, Potsdam, Germany