DETECTION OF FATIGUE DAMAGE IN FASTENERS USING ULTRASOUND

ERFASSUNG VON ERMÜDUNGSSCHÄDEN IN BEFESTIGUNGSMITTELN MITTELS ULTRASCHALL

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SUMMARY

At present, there is a lack of efficient methods for detecting fatigue damage of fasteners in concrete components. The damage processes taking place in the anchoring system are usually characterized by means of global measurement variables such as the increase in deformation and the associated decrease in stiffness.

The ultrasound method is a promising alternative for a better understanding of the fatigue processes occurring in relation to steel fracture of the fastener. In this method, sound pulses are introduced into the component and reflected from defects. Based on the transit time and signal strength, conclusions can be drawn about the position and size of cracks that occur. In this paper, selected results of ultrasonic tests on two different fasteners are presented in order to verify the suitability of the measuring method.

ZUSAMMENFASSUNG

Bisher mangelt es an leistungsfähigen Verfahren, um Ermüdungsschädigungen an Befestigungsmitteln aus Stahl in Betonbauteilen zu erfassen. Die im Verankerungssystem ablaufenden Schädigungsprozesse werden in der Regel mit Hilfe globaler Messgrößen wie der Verformungszunahme und dem damit verbundenen Steifigkeitsabfall charakterisiert.

Dagegen stellt das Ultraschallverfahren eine Alternative dar, um die Ermüdungsvorgänge in Bezug auf Stahlbruch des Befestigungsmittels besser zu verstehen. Dabei werden Schallimpulse in das Bauteil eingeleitet und von Fehlstellen reflektiert. Daraus lassen sich Rückschlüsse über die Lage und Größe von Rissen ziehen. Im Beitrag werden die Ergebnisse von Ultraschalluntersuchungen an zwei Befestigungen vorgestellt, um die Eignung des Messverfahrens zu überprüfen.

1. FATIGUE BEHAVIOR OF FASTENINGS

The fatigue behavior of a fastener is influenced by the material characteristics of the components, which are part of the anchoring system to transfer the load into the concrete. Consequently, the fatigue resistance of fastenings is governed by different failure modes. In case of fatigue loading, basically comparable modes of failure can occur as under static loading, both in tension and shear direction. This includes e.g. steel, concrete cone, pull-out or bond failure. However, the fatigue resistance is a time dependent value and the decisive failure mode can change in relation to the number of load cycles.

Experimental work from Block and Dreier [1] and Karmazínová [2] indicates that steel failure is mostly becoming decisive at higher number of load cycles, when the anchors have sufficiently large edge and centre distance. Thereby, the fatigue failure typically starts by crack initiation at locations with high stress concentration such as welds, threads or geometry changes.

In the current practice, the fatigue performance of a fastener is commonly determined by experiments performed as constant amplitude tests. Previous studies mainly focused on the fatigue resistance characterized by an S-N diagram, the so-called *Wöhler* curve, which describes the fatigue strength as a function of the number of cycles to failure, see Block and Dreier [1], Karmazínová [2], Froehlich and Lotze [3], Lazzarin et al. [4]. Further tests showed that the degradation processes leading to failure are accompanied by the increase of deformation and decreasing of stiffness. As another indicator, the energy dissipated within the hysteresis loops has been investigated by Block, Dreier and Bigalke [5] and Ehrenstein and Drahtschmidt [6].

2. ULTRASOUND METHOD

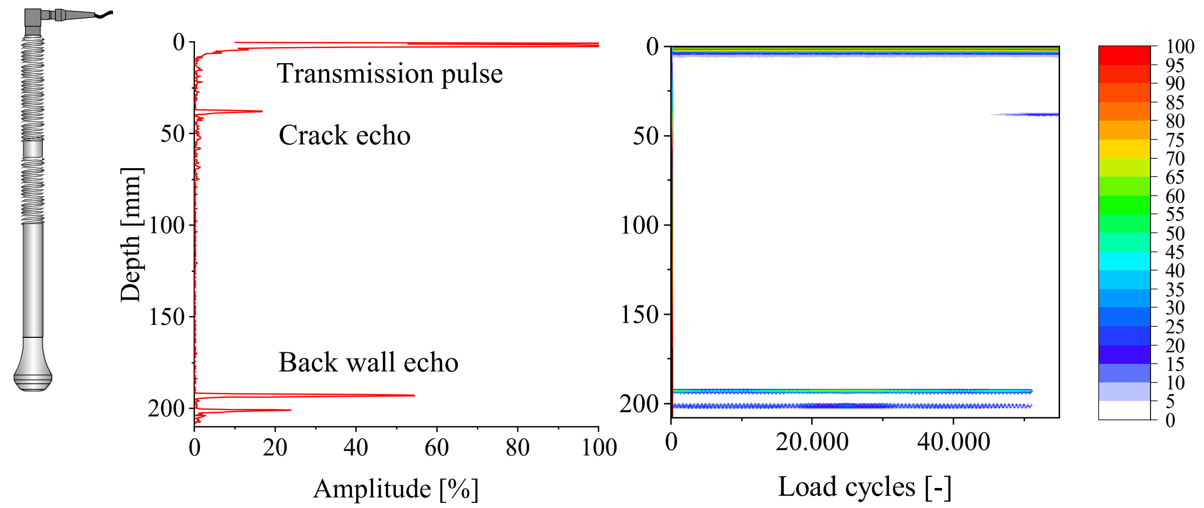
Existing test methods consider the global behavior of the entire anchoring system and provide only very limited information about the actual damage process in the fastener itself. Detailed knowledge of the damage location or the remaining fatigue life is missing or can only be given inaccurately.

Ultrasound measurements have been considered as an alternative method to directly control the fatigue damage process of the fastener in case of steel failure. The method is based on the measurement of the ultrasonic wave velocity, which has been used in the past, for example to determine the pretension force of bolts

[7] or for identification of different anchor types and their embedment length in concrete [8].

In general, there are two different methods available for ultrasonic measurements. In the ultrasonic method, pulses are introduced into a component by a transmitter. The signal is received by a receiver on the opposite side. In contrast, the pulse echo method uses only one probe, which can both transmit and receive. The sound reflected at the interfaces is registered by the probe and the elapsed time between its introduction and its return reflections is measured. With the aid of ultrasound, inhomogeneities and cracks in the material of sound-conducting materials can be detected.

In this work, the pulse echo method was used due to the fact that fastenings installed in the concrete are only accessible from one side. The basic procedure of the ultrasonic analyses applied during the fatigue tests can be described by the following figure. The signal is introduced into the fastener by the ultrasound probe mounted in the center of the anchor's head as shown in Fig. 1a. For evaluation and analysis of the signal available imaging methods were used. The A-scan forms the basic view, which shows the signal amplitude in relation to the anchor length as given in Fig. 1b. The B-scan consists of a series of (usually) colour-coded A-scans. This view is usually used to obtain the corresponding 2-D profile of a component by moving the head along an axis of the work piece. If, on the other hand, the ultrasound head is fixed, the signal amplitude can be measured over time depending on the number of load cycles as observed during the fatigue test (Fig. 1c).



(a) Anchor *(b) A-scan* *(c) B-scan*

Fig. 1: Procedure of ultrasound method for fastenings under fatigue load

3. EXPERIMENTAL INVESTIGATIONS

The suitability of the ultrasound method was investigated for two different types of fasteners, which are characterized by typical notch details that can cause failure by fatigue. The tests were performed with an undercut anchor of size M12 made of galvanised steel class 8.8 with an embedment depth of h_{ef} = 125 mm. This post-installed anchor was selected to detect fatigue cracks appearing in the thread of the bolt. The other sample was an embedded anchor plate with welded headed stud, where the fracture is usually expected in the area of the welded seam. Single headed studs with a diameter of 16 mm and 20 mm thick steel plates, both made of carbon steel S235, were used for the tests.

The main challenge was to ensure precise ultrasonic measurement under fatigue loading. In order to achieve reliable test results, preliminary investigations have been carried out before starting the actual series of tests. The focus of the pre-tests was to identify optimal equipment and parameters for the fatigue test in concrete. That included several conditions, such as the following:

- Selection of ultrasound probe
- Selection of couplant
- Coupling of probe
- Long-term behavior
- Influence of concrete.

The ultrasonic measurements were performed using an Olympus Omniscan MXU ultrasonic device. For the undercut anchors an ultrasound probe GE K10K-EN with a frequency of 10 MHz and a diameter of 5 mm was chosen. The headed studs were investigated by means of a magnetic ultrasound probe Olympus M1042 with 5 MHz frequency and 13 mm diameter. For all experiments glycerine was used as couplant between probe and fastener.

3.1 CRACK DETECTION

Crack detection tests have been performed on both fasteners to check at which depth cracks can be identified by the ultrasound image. The principle was verified on unloaded specimens provided either with a circumferential notch or with a one-sided notch. The notch was gradually inserted into the anchor to simulate crack propagation. After each step, an ultrasonic measurement was carried out.

The results provided in Fig. 2 and Fig. 3 indicate that the amplitude of the crack echo increases with deeper notch. Due to larger notch area, the amplitude of circumferential notches is higher than one-sided notches. Since in practice the crack formation usually starts at one side, crack detection from 0.5 mm depth applies for undercut anchors and 1.25 mm for headed studs. The signal strength for headed studs was obviously affected by the weld and different material layers.

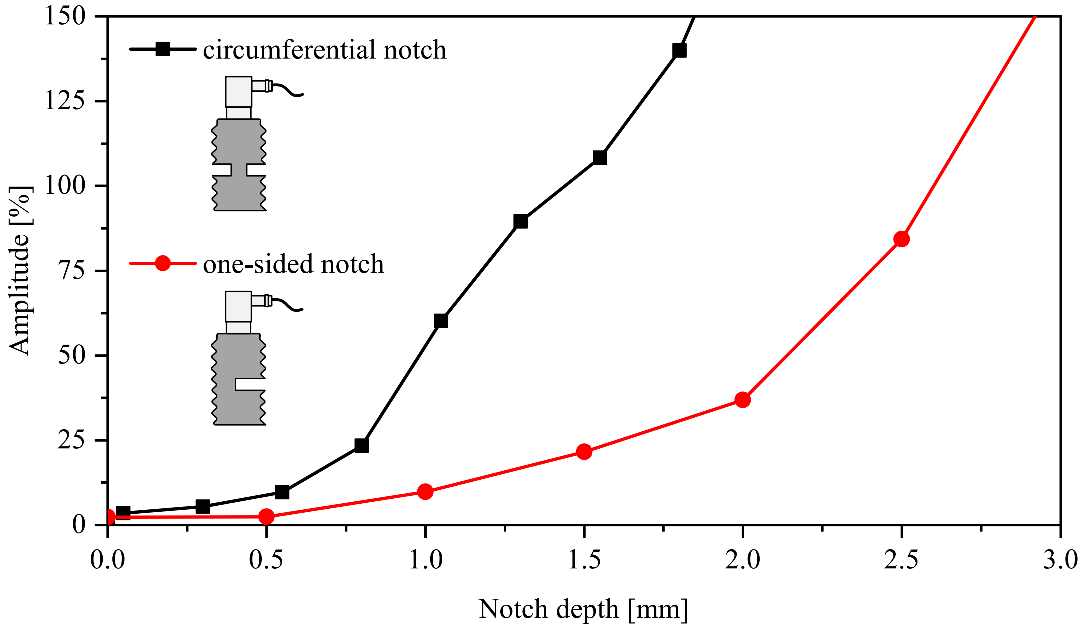


Fig. 2: Crack detection tests on undercut anchors

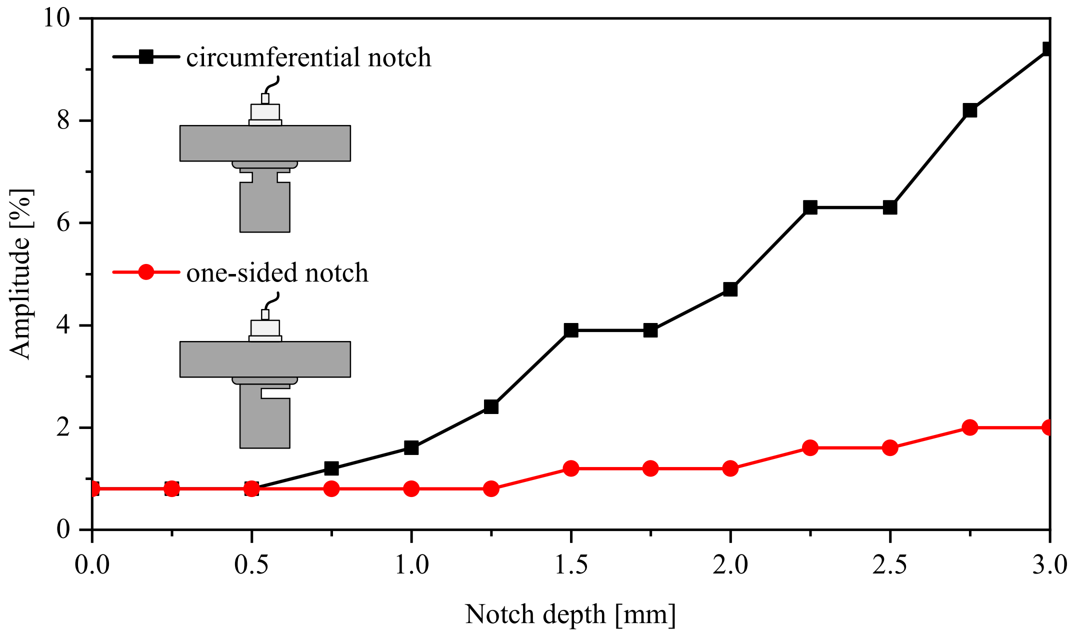


Fig. 3: Crack detection tests on headed studs

3.2 FATIGUE TESTS

The fasteners installed in uncracked concrete C20/25 were tested under centric tension loading and pulsating shear loading. Two different test setups were available for the experiments. The tension tests were performed using a servo-hydraulic cylinder with a load capacity of 100 kN. For the shear test, a 250 kN cylinder was used. All fatigue tests were carried out load-controlled with sinusoidal load regime of constant amplitude. The cycling frequency was chosen in the range between 2 Hz and 8 Hz depending on the load level set during the test.

In order to generate comparable and reproducible results, the position and contact pressure of the ultrasound probe must be kept constant throughout the entire duration of the fatigue tests. For this purpose special adapter components were designed as shown exemplarily for the fatigue tension tests in the figure below. For the undercut anchors, a mounting device was screwed onto the bolt (Fig. 4a). The contact pressure of the ultrasound probe was achieved via tightening a M20 screw at the top of the adapter. For all test series the torque moment was set to 4 Nm. The magnetic 5 MHz probe used for the headed studs could be fixed directly on the steel plate and was located in the centre of the anchor's shaft (Fig. 4b). In order to guarantee a proper sound transmission, the surface of each fastener was sanded and cleaned before coupling the probe.

With the designed mounting devices, ultrasonic measurements could be made during the test duration. In parallel, the number of cycles and the displacements of the fastener at upper and lower load were recorded continuously.

(a) Undercut anchor

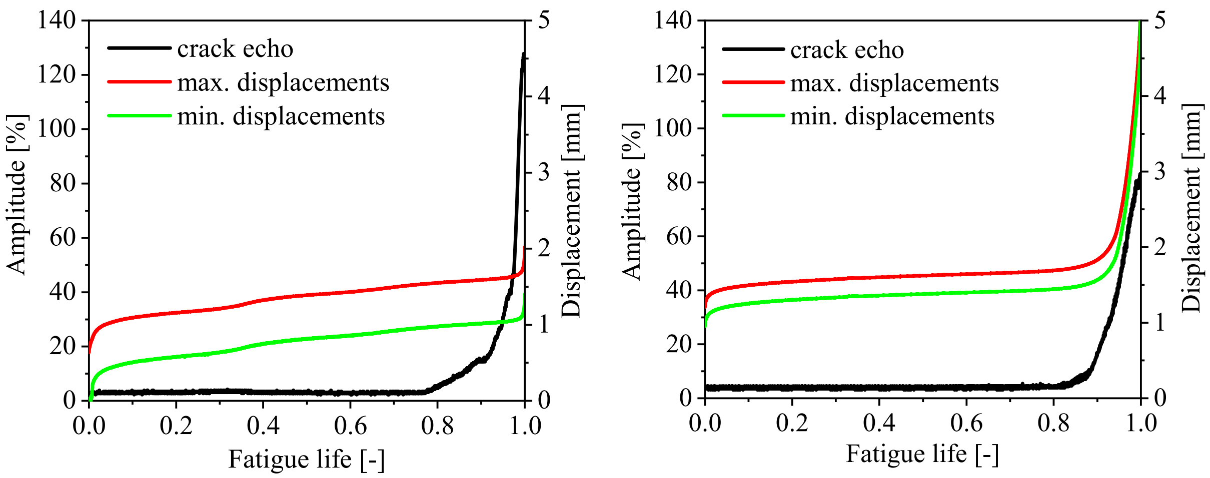
(b) Headed stud

Fig. 4: Coupling of ultrasound equipment during fatigue tension tests

4. TEST RESULTS

The fatigue behavior of fastenings under cyclic load is usually characterized by indicators such as deformation or stiffness. A nonlinear increase in the displacements or corresponding decrease in stiffness is considered as an indication of fatigue damage. Based on the performed fatigue tests, these measured values can be compared with the acquired data from the ultrasound recordings. During the tests, the amplitude of the defect or crack echo and its position were recorded.

Typical results obtained under tension and shear load are provided in Fig. 5. The measured displacements at upper and lower load and the amplitude of the crack echo are shown together as a function of the normalized fatigue life. It can be seen that all values increase significantly towards the end of the fatigue life. However, the amplitude of the ultrasonic signal in the crack area increases considerably before the displacement. This occurs in both tension and shear tests. Since the deformations during crack formation in steel are relatively small compared to the displacements of the fastener including the concrete, the damage can be detected more precisely by the use of ultrasound method.



(a) Tension load *(b) Shear load*

Fig. 5: Displacement vs. ultrasound signal during fatigue tests

With this direct method, not only the beginning of crack initiation in the steel can be made visible, but also the point of failure occurrence can be located along the embedment depth of the fastener. The failure locations that were observed for the tested anchors and headed studs are given in the following sections.

4.1 UNDERCUT ANCHORS

In the tension tests, the failure occurred in the first engaging thread of the bolt as shown in Fig. 6. Under shear load, two cracks could be detected at 50 mm in the area of the fixture and at 65 mm at the upper edge of the sleeve, see Fig. 7.

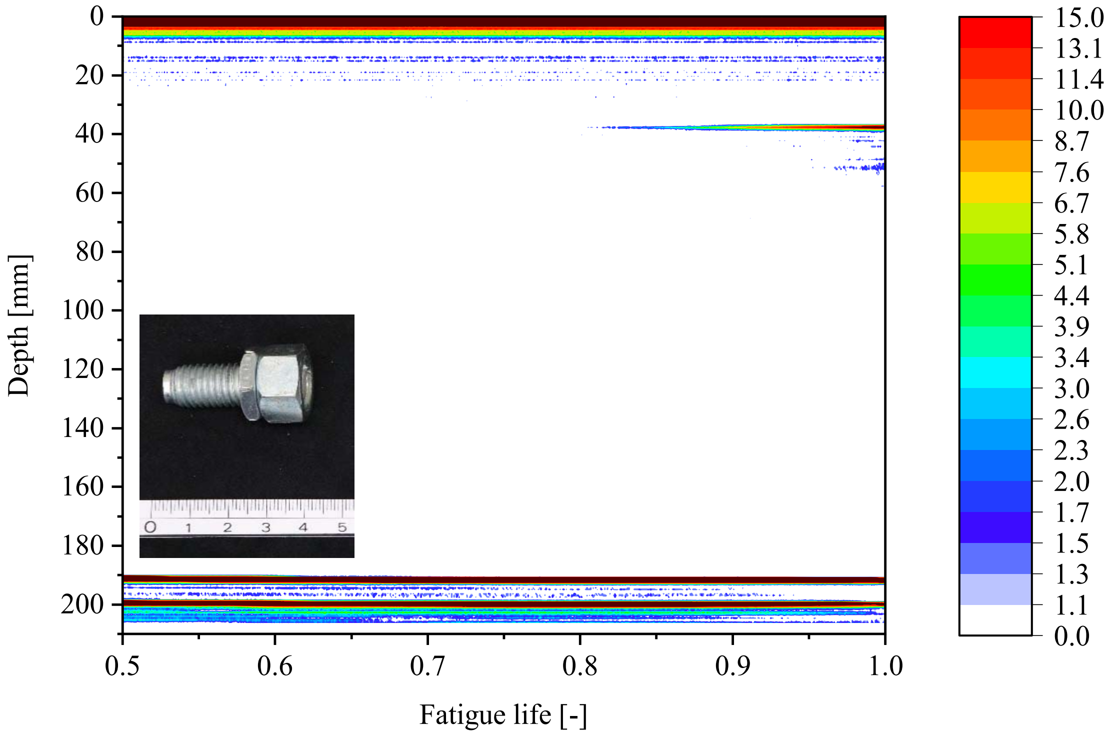


Fig. 6: B-scan of undercut anchor during fatigue tension test

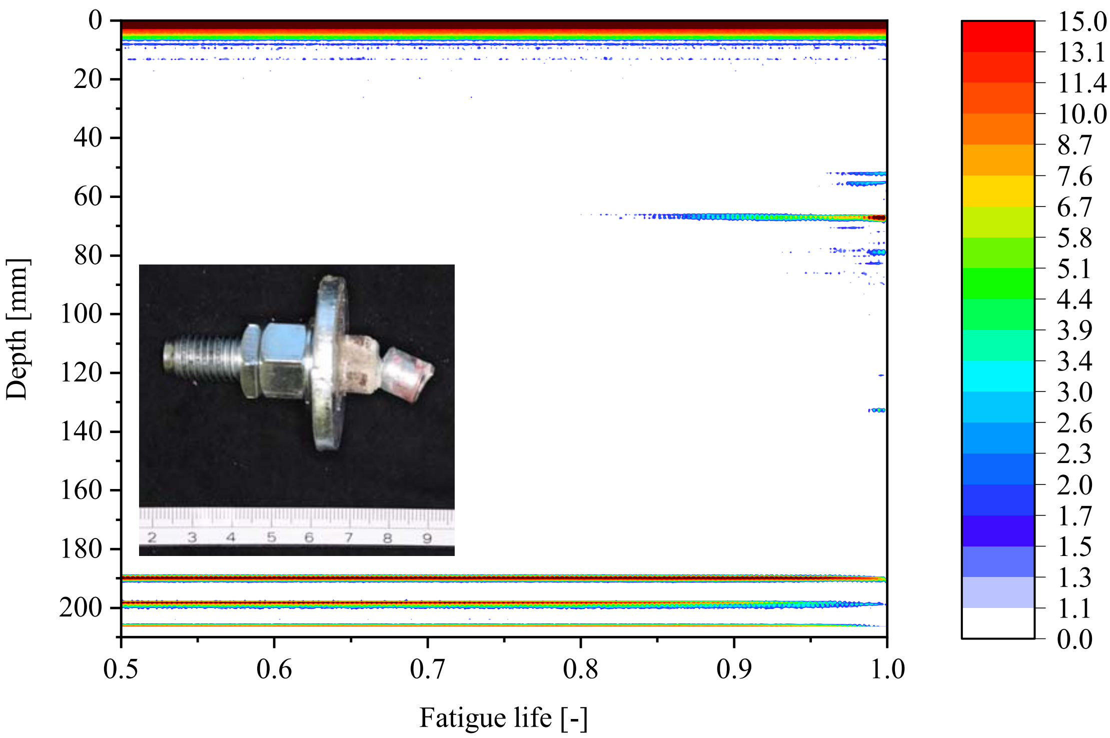


Fig. 7: B-scan of undercut anchor during fatigue shear test

4.2 HEADED STUDS

In all tests, failure of the welded seam occurred. The crack position was either in the steel plate (Fig. 8) or in the bolt (Fig. 9). These locations were observed under tension load as well as under shear load.

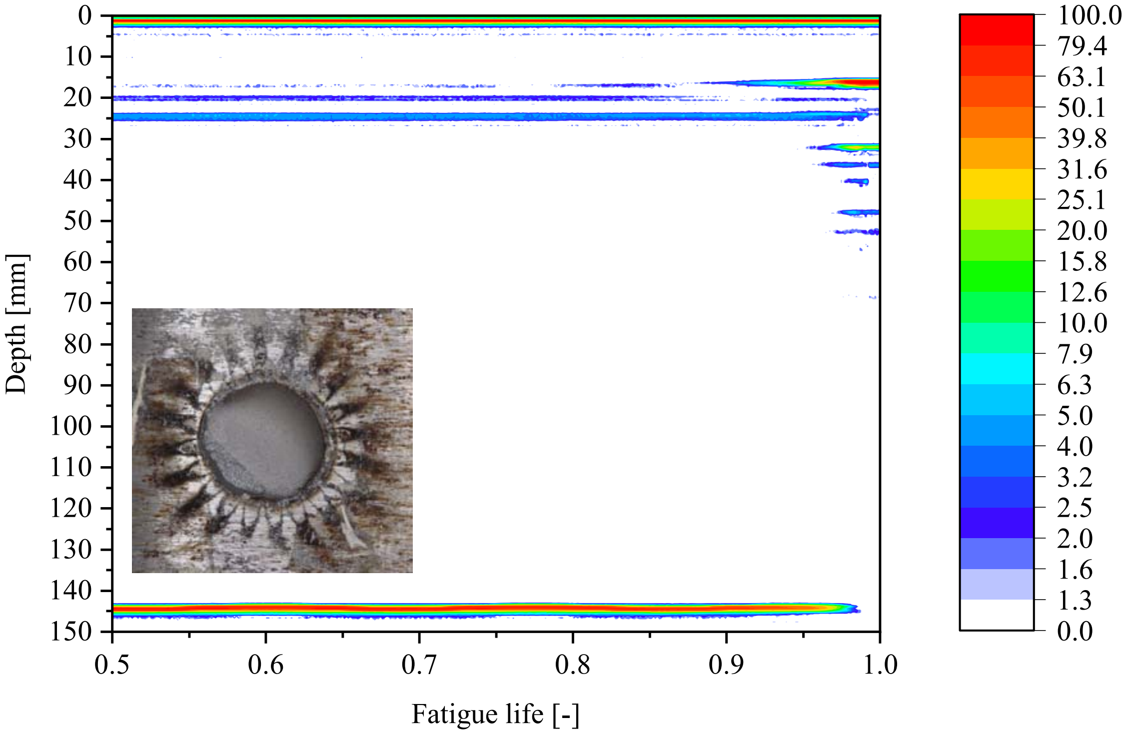


Fig. 8: B-scan of headed stud during fatigue tension test

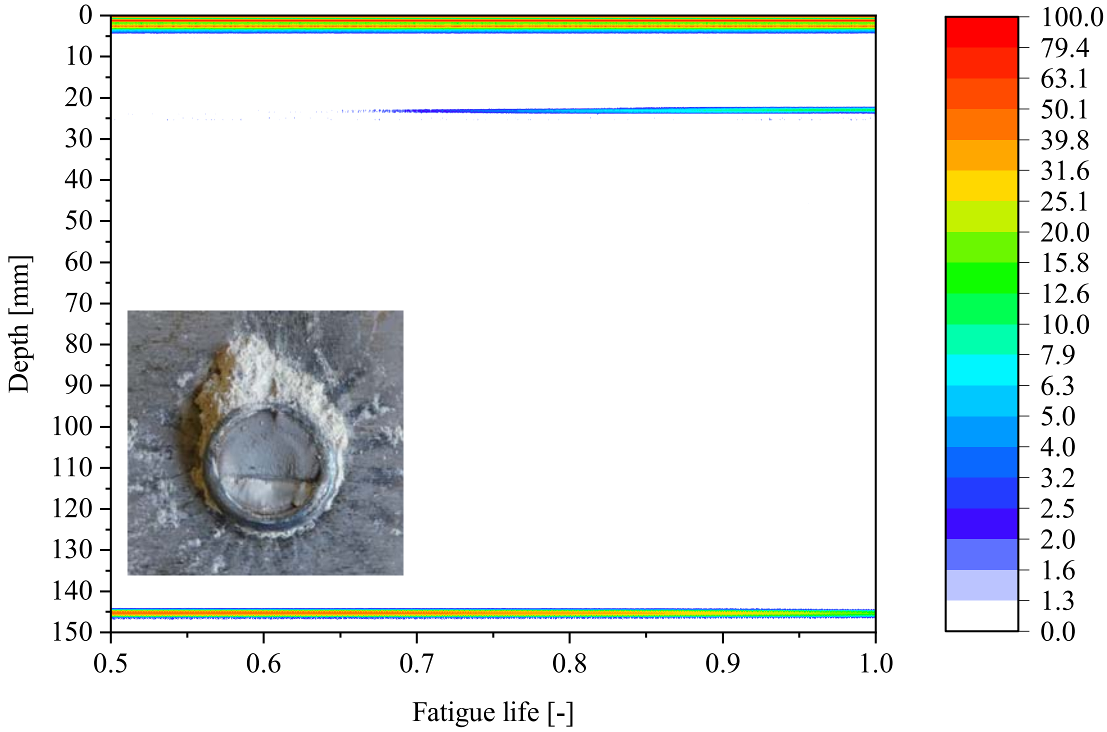


Fig. 9: B-scan of headed stud during fatigue shear test

Fig. 8 shows an example of a fatigue tension where the crack could be detected at a depth of 17 mm in the steel plate. However, the diagram provides also interfering areas, which obviously result from the boundary layers of the welded seam. Hence, the exact localization of the crack was somewhat more complicated than for the undercut anchors. In the shear tests, the crack formation usually appeared earlier than under tension load. The B-scan in Fig. 9 indicates that the crack in the bolt at 23 mm depth starts from 65% of the fatigue life, while the damage in case of tension was detected at around 90%.

5. SUMMARY

In this study, the ultrasonic pulse echo method was used to analyse the damage process of fastenings in concrete under fatigue loading. The method is particularly suitable for the detection of the crack development in case of steel failure.

The presented results are based on fatigue tests performed with two different types of fasteners. On the one hand undercut anchors were tested where steel fracture usually occurs in the area of the bolt thread and headed studs welded on anchor plates with expected failure of the welded seam on the other.

Using ultrasonic measurements, the exact position and time of crack formation could be determined. It was possible to make the fatigue damage process visible by means of local crack detection using the amplitude of the ultrasound signal. In comparison with the globally measured test values, such as the increase of displacements possible damage by cracks in the steel could be detected more clearly. Consequently, this non-destructive testing method has also great potential for predicting the remaining service life of fasteners installed in existing structures.

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