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Crack-Detection in old riveted steel bridge structures

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Abstract

In light of the scarcity of resources, the fundamental demand for economic and sustainable use of existing structures is becoming increasingly important. A large number of existing steel bridges fulfill their purpose in principle. But almost 30% of steel railway bridges in Germany are up to 100 years old. Considering deterioration as well as significantly increased loads, however, they must meet the current requirements of stability and fatigue resistance. Of fundamental importance is the realistic assessment of the state of fatigue of the steel bridge structures.

If no sufficient remaining fatigue life can be determined based on normative S-N-curve assessment, initiation of fatigue cracks has to be assumed. Steel bridges from the period 1880 to 1940 are usually riveted steel structures. Therefore, crack initiation occurs primarily at the edge of the rivet holes. In this early phase of crack growth, however, a crack at the rivet hole is still below the rivet head and therefore cannot be found in a visual inspection of the structure. For this reason, the remaining cyclic lifetime based on fracture mechanics is determined assuming a start length of the crack beyond the rivet head.

Currently, there is no practicable non-destructive testing method to detect hidden cracks in riveted joints. X-ray inspection requires complex precautions for occupational safety. Ultrasonic tests are also very expensive, since each rivet would have to be examined separately. This paper describes investigations using Lock-In-Thermography for crack detection in riveted joints.

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Keywords: Riveted Joints, Fatigue, Crack Detection, Look-In Thermography, Remaining Cyclic Lifetime

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1. Introduction

Although many riveted bridge structures made of old mild steel constructed in the period between 1880 and 1940 are still in use after decades of service, there is usually no need to replace them. When assessing these existing steel structures to decide on necessary rehabilitation or reinforcement measures engineers particularly requires information about the remaining cyclic lifetime of the material.

The assessment of the fatigue resistance of these structures is currently based on normative notch details, S-N-curves and a linear damage accumulation hypothesis. If sufficient remaining cyclic lifetime cannot be evaluated with this method, for railway bridges an operating time interval verification based on fracture mechanics is carried out. Thereby, a fatigue crack at the edge of the rivet hole is assumed which extends 5 mm beyond the edge of the rivet head and can thus be found visually during a bridge inspection. The potential of crack initiation and crack growth below the rivet head is not yet included in the assessment. Therefore, this part of fatigue life is the subject of a current research project. Initial studies have already shown that the growth of cracks at holes is significantly retarded by the prestressing force of the fasteners (rivets or bolts).

To include the early phase of crack propagation in the assessment of a steel bridge, it is necessary to detect reliable or exclude such a small crack in the structure. In this early phase of crack growth, however, the crack at the rivet hole is still covered by the rivet head. Recent investigations of the authors at parts of an aircraft wing (Bär et al 2010) indicates that fatigue cracks can be detected safely with a length less than 2 mm using Lock-In-Thermography. It was also possible to detect cracks under the surface. In this actual study the applicability of thermoelastic stimulated Lock-In-Thermography for detection of covered fatigue cracks at riveted steel structures is evaluated. Therefore, tests were performed on fatigue test specimens (figure 1) with fatigue cracks on the edge of the holes.

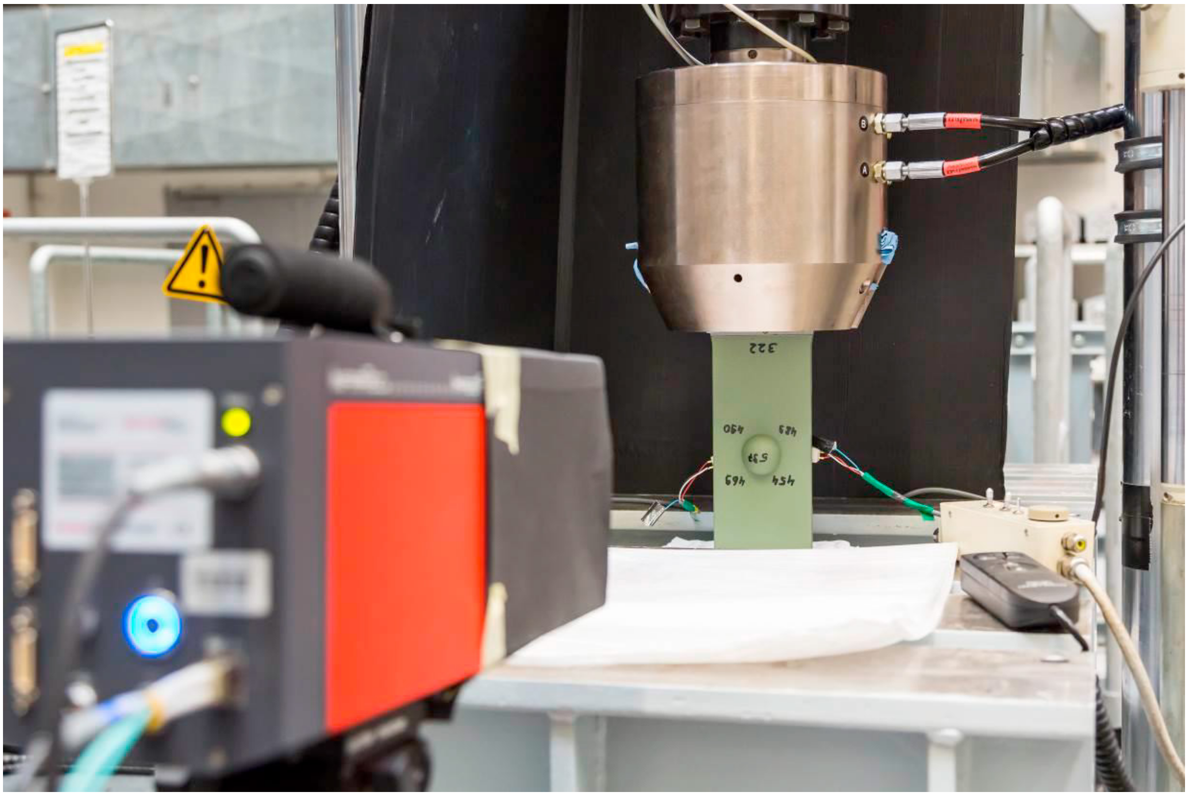

Fig. 1. Thermographic measurements during fatigue test at specimen 1.

2. Experimental Details

2.1. Specimen preparation and test procedure

Riveted components from old steel structures with fatigue cracks at the rivet holes are difficult to procure. The initiation of fatigue cracks in an originally riveted component is possible, but it is challenging to monitor the crack length at the edge of the holes. To analyze the applicability of thermoelastic stimulated Lock-In-Thermography for crack detection the location, shape and length of the crack(s) must be known. Therefore, tension specimens made of current steel grade S355 with one drilled rived hole (figure 2a) were produced. To affect crack initiation, the edges of the holes were notched by wire cutting. The notches had a width of 0.2 mm and a depth of 0.5 mm (figure 2b). Crack propagation gauges were installed at the notch roots on the backside of the specimens to detect the cracks and measure their length during cyclic loading. The crack length at the front was measured by a digital microscope.

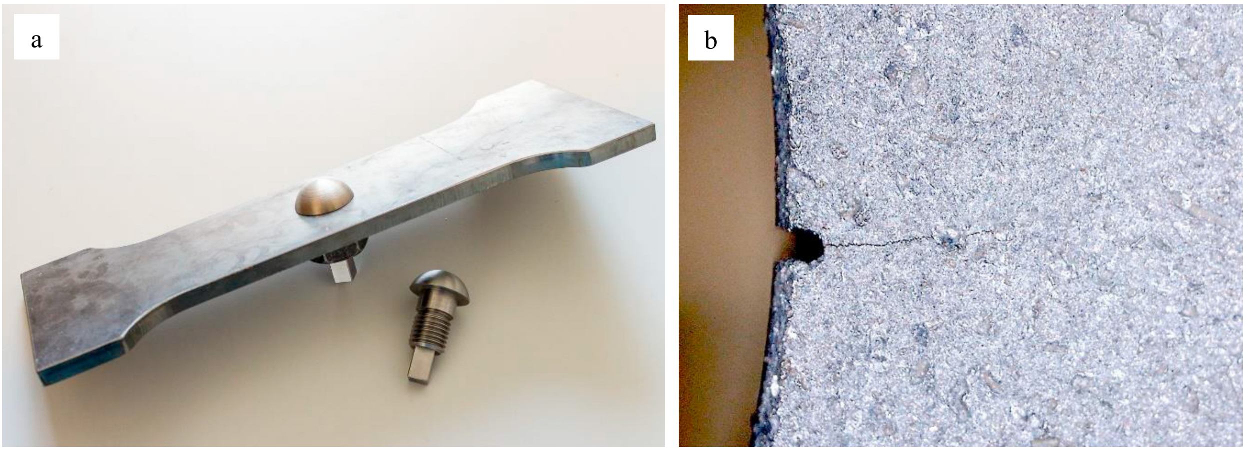

Fig. 2. (a) Tension specimen and rivet-like bolts, (b) Initial crack at the notched rivet hole at the front of a specimen.

To achieve crack initiation within a foreseeable time a cyclic tension loading with a stress range of $\Delta\sigma_{gross}$ = 110 MPa (stress ratio R = 0.1) was applied. During crack propagation the load level was gradually reduced to 40% of the initiation load. This load reduction should minimize the size of the plastic zone at the crack tip. The final crack geometry and locations are illustrated in figure 3. The final crack depth measured from the edge of the hole was between 2.5 and 3.5 mm. This length corresponds to approximately half of the excess width of a typical rivet head (7 mm at a rivet with a shaft diameter of 25 mm). After crack initiation the holes were closed by fitted rivet-like bolts (figure 2a). The front of the specimens was coated with a corrosion preventive coating which is currently used for maintenance of old steel structures (see figure 1). The mean coating thickness was about 500 µm around the rived head.

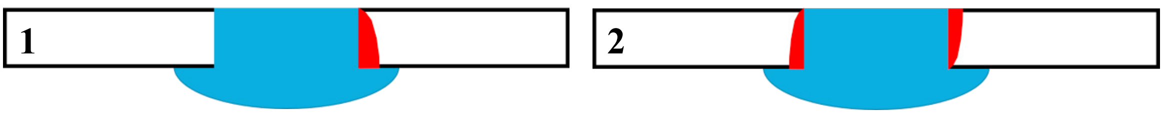

Fig. 3. Schematic drawing of the crack locations and geometry in specimen 1 and 2.

In order to use Lock-In-Thermography to detect cracks on riveted railway bridges, the measurement method must ideally operate under bridge operating conditions (typical traffic loads). Depending on the speed of the trains, the axle loads, the axle distances and the influence length of the components, the stress range, the number of cycles and the load frequency vary. Components of the main structure are subjected to higher stress ranges but must withstand fewer load cycles at lower loading frequencies than stringers and cross girders. Therefore, fatigue tests under pure tension loading (R = 0.1) were performed with gradually increasing stress range (44 MPa up to 80 MPa) and at different loading frequencies (0.25 up to 10 Hz).

2.2. Thermographic measurements

An alternating mechanical loading causes a cyclic change of the temperature according to the thermoelastic effect (Thomson 1853). With thermographic methods, especially the Lock-In-Thermography this can be used to gather information about the stress amplitude and dissipative effects due to plastic deformation. Several models have been suggested for the evaluation of the measured temperature signal, all are based on an incomplete Discrete Fourier Transformation (DFT). Beside the mean Temperature T_m and the thermo-elastic part T_E connected with the loading frequency f_L, the evaluation considers a dissipative part T_D (double loading frequency) and in the model of Bär and Urbanek (2018) additional higher harmonic frequencies. In this case the DFT can be written as:

$$T(t) = T_m + \underbrace{T_E \cdot e^{2\pi i(f_L \cdot t + \varphi_E)}}_{thermo-elastic} + \underbrace{T_D \cdot e^{2\pi i(2f_L \cdot t + \varphi_D)}}_{dissipativ\ 2f_L-part} + \underbrace{\sum_{k=1}^{N_{Nyquist}} T_{D_k} \cdot e^{2\pi i((k+2)f_L \cdot t + \varphi_k)}}_{higher\ harmonics} + \underbrace{\Phi(t)}_{Noise} \quad (1)$$

For a recorded sequence of images this evaluation must be performed for each pixel and results in an amplitude image and a corresponding phase image for each component in equation 1.

In case of a periodic stimulation the propagation of a thermal wave is coupled with the frequency (Marin 2010). The thermal diffusion length μ gives the distance at which the amplitude of the heat flux is reduced e-times from its origin. The thermal diffusion length can be calculated from the thermal conductivity k, the density ρ and the specific heat capacity c and the frequency of the stimulation, i.e. for a thermoelastic stimulation the loading frequency f_L using equation 2:

$$\mu = \sqrt{\frac{k}{\pi \cdot \rho \cdot c \cdot f_L}} \quad (2)$$

In figure 4 the resulting thermal diffusion length μ for the investigated steel is shown as a function of the loading frequency f_L. The thermal diffusion length shows an exponential decrease with increasing loading frequency. The highest probability of detection for cracks under a rivet head is therefore at low loading frequencies.

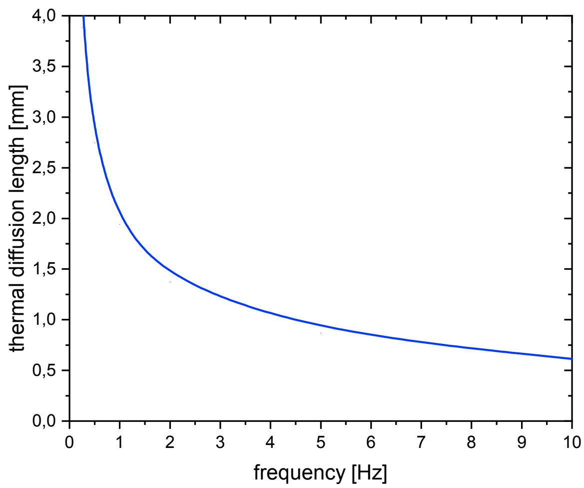

Fig. 4. Thermal diffusion length as a function of the loading frequency calculated with equation 2

The thermographic measurements were undertaken with an ImageIR 8300hp infrared camera. During the mechanical loading sequences with a duration of 10 and 20 s with a sample rate of 300Hz were recorded. The size of each recorded frame was 640 x 512 pixel and the spatial resolution was 0.255 mm/pixel. The evaluation according to equation 1 was performed with a self-developed Matlab program. Due to the small rigid body movement no motion compensation algorithm was applied.

3. Results

3.1. Thermographic measurements on specimen 1

The evaluation of the thermographic measurements with the DFT according to equation 1 revealed reasonable amplitude values for the thermoelastic E-Mode. The amplitude of the D-Mode, connected with plastic deformation, showed values in the magnitude of the noise, showing that a detection of cracks under the rivet based on the determination of the plastic zone in front of the crack tip is not possible.

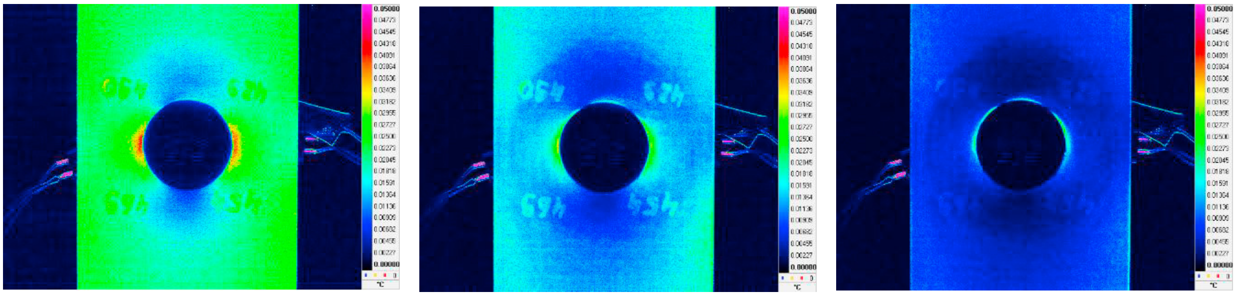

Fig. 5. E-Amplitude images of specimen 21 recorded at loading with 80 MPa and frequencies of 0.5, 1 and 2 Hz

Figure 5 shows E-Amplitude images of specimen 1 loaded with 80 MPa at loading frequencies of 0.5, 1 and 2 Hz. The rivet head shows no temperature signals, but on both sides of the rivet enhanced E-Amplitude values are visible. The influence of the loading frequency on the E-Amplitude values is also evident. The decreasing E-Amplitude values with increasing loading frequency can be attributed to the decreasing thermal diffusion length. This result clearly shows that a detection of cracks has to be undertaken with a low loading frequency to get a higher probability of detection. On the other hand, a lower loading frequency results to an attenuation of the temperature signal due to heat conduction within the specimen. Therefore, all following investigations were undertaken with a loading frequency of 0.5 Hz.

The influence of the loading amplitude on the thermal response is shown in figure 6. With increasing loading amplitude, the temperature increase on both sides of the rivet becomes more pronounced. In all images a slight anisotropy in the temperature field between the left and right side of the rivet is visible. Unfortunately, this anisotropy is not very pronounced, therefore it is not adequate for a safe detection of cracks under the rivet head.

To gain a better detectability, the temperature amplitudes along a line (see figure 6 d) with a width of 10 pixels across the specimen in the middle of the rivet were measured. Over the width of the line the mean value of the 10 E-Amplitude values were calculated. Figure 7 shows these values over the width of the specimen for a loading with 44 and 80 MPa at a frequency of 0.5 Hz. The x-coordinate represents the distance to the respective sample border. Additionally, the temperature signal was smoothed using the LOESS filtering method.

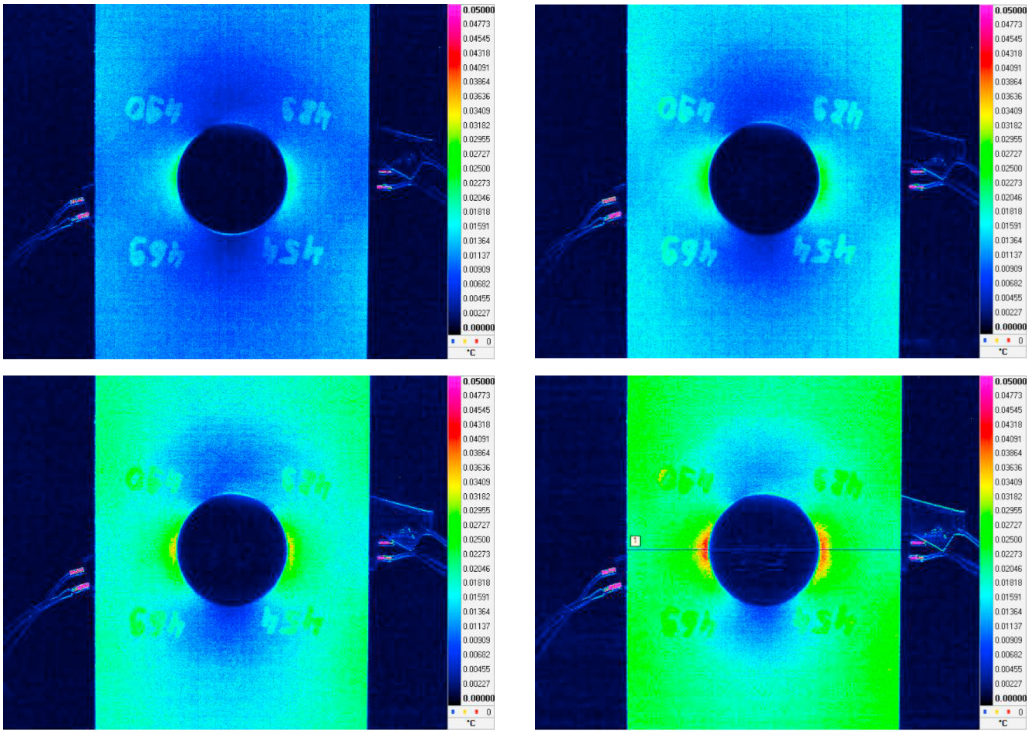

Fig. 6. E-Amplitude images of specimen 1 recorded at loading with 0.5 Hz and an amplitude of 44, 55, 66 and 80 MPa

In the run of the E-Amplitude values beside the very low values at the rivet, the asymmetry between both sides of the rivet is clearly visible. The differences are visible even at low loading levels but are more pronounced at higher loading levels. Obviously, this asymmetry is caused by the presence of a crack on the right side under the rivet head, whereby the higher amplitude values on the side without a crack are surprising.

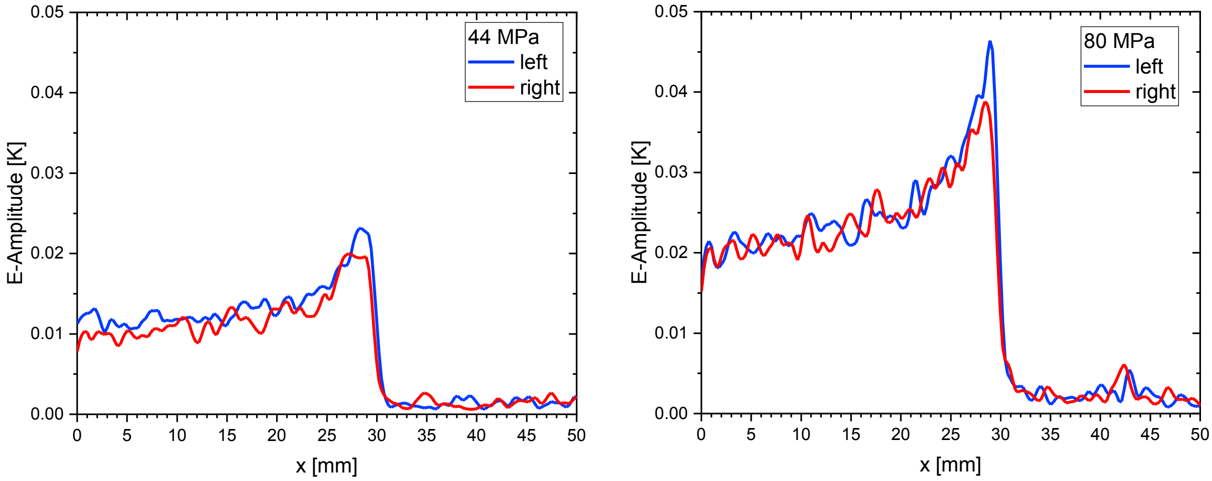

Fig. 7. E-Amplitude value determined over a line with a width of 10 Pixels over the rivet of specimen 1 recorded at loading with 0.5 Hz and an amplitude of 44 and 80 MPa.

3.2. Thermographic measurements on specimen 2

The thermographic investigation of specimen 2 revealed also only a slight asymmetry in the temperature field on both sides of the rivet head. The influence of the loading was found to be comparable with that in case of specimen 1. As in the case of specimen 1 along a line with a width of 10 pixel across the rivet head the E-amplitude values were determined. The direct comparison of this values determined on the left and right side of the rivet is shown in figure 8. Independent from the loading level a higher E-amplitude value is found on the right side of the rivet head. Due to the longer crack on the right side of the rivet this result is a bit astonishing. To rule out that this effect is caused by the experimental arrangement, the camera position was changed to get another perspective. These measurements delivered the same results, indicating that the measured anisotropy in the temperature fields is caused by the cracks under the rivet head.

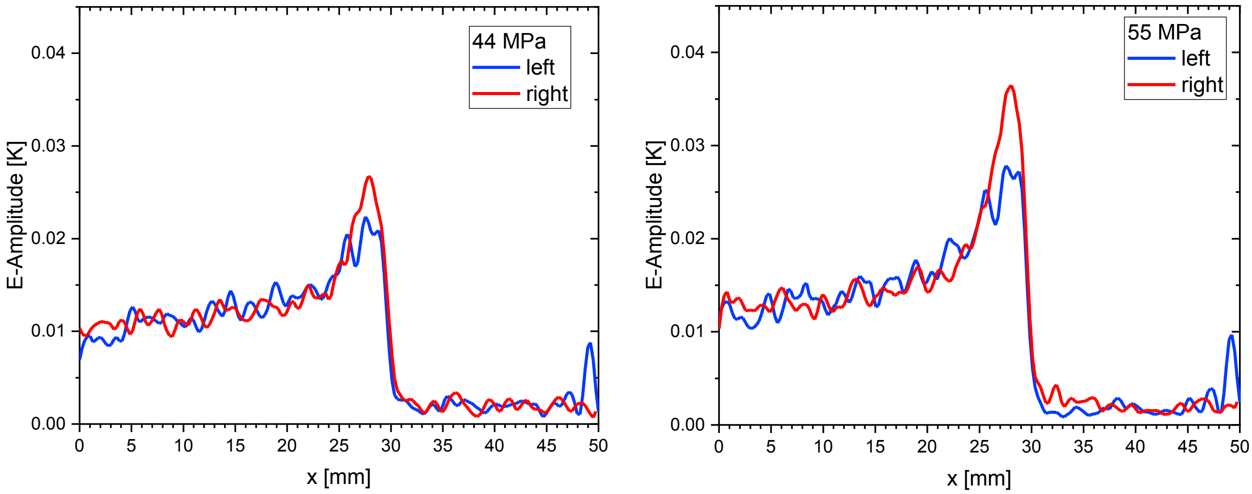

Fig. 8. E-Amplitude value determined over a line with a width of 10 Pixels over the rivet of specimen 2 recorded at loading with 0.5 Hz and an amplitude of 44 and 55 MPa.

4. Discussion

The investigation of pre-cracked specimen has shown that cracks under the rivet head can be detected with Lock-In thermography. Due to the low D-mode amplitude it is not possible to detect a crack based on the plastic deformation in front of the crack tip and the resulting temperature increase. To use this effect a significant higher loading would be necessary to achieve a higher temperature increase caused by dissipation of energy at the crack tip. For a practical use to detect cracks in riveted steel bridge structures this method is not practicable.

The E-amplitude revealed an asymmetry in the profiles measured on both sides of the rivet for both specimens. Obviously, this asymmetry is caused by the presence of a crack on one side (specimen 1) or the different crack shapes and length on both sides (specimen 2) under the rivet head. The E-amplitude profiles showed lower values on the side with a crack for specimen 1 and on the side with a longer crack for specimen 2. These results are a bit astonishing but can be explained by the evaluation method due to equation 1. The DFT evaluation bases on the assumption that the different effects can be attributed to fixed frequencies, the thermoelastic effect to the loading frequency (E-Mode) and the dissipative effects to the double loading frequency (D-Mode). New investigations on copper and an aluminum alloy by Bär et al (2019a) have shown, that this assumption is not met in several cases. They found that the temperature change due to dissipated energies in the investigated aluminum alloy were coupled with the loading frequency and, consequently, the E-amplitude values were affected leading to wrong values. Investigations on a high alloyed steel revealed the same behavior resulting in lower E-amplitude values than expected. To confirm this effect, appropriate tests will be carried out on the steel examined in this work.

When cracks are initiated on both sides of the rivet hole the detection of these cracks is more complicated. When the cracks on both sides have the same length and form a detection with a direct comparison is impossible. When the cracks are different in their shape as in case of specimen 2 the resulting differences in the stress profiles seem to be high enough to allow the detection of a crack under the rivet head even at lower loads. Another complication on real bridge structures arises from the loading condition. In the experiments a pure tension loading was applied, leading to the same stress state on both sides of the rivet. When additional forces lead to an uneven stress state, the comparison of the resulting stress profiles cannot be used for the detection of a crack under the rivet head. To improve this method and to extend it on real structures additional experiments on real structures must be performed. However, the presented method has the potential to detect cracks under the rivet head in real riveted bridge structures.

5. Conclusions

The experiments have shown that under uniaxial loading a detection of cracks under a rived head using thermoelastic stimulated Lock-In-Thermography is possible. Due to the thermal diffusion length, the probability of detection increases with decreasing loading frequency. For crack detection a direct comparison of the temperature profiles on both sides of the rivet must be undertaken. The small thermal effects allow detection when the crack length or geometry on both sides of the rivet hole is different. Another possibility would be to monitor a group of similarly stressed rivets to detect cracks. For the detection of cracks in real structures and under complicated loading conditions further investigations are necessary.

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