Detection of short cracks in riveted connections using Lock-In-Thermography

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1 Introduction

In view of limited resources, the fundamental demand for an economic and sustainable use of existing structures is becoming increasingly important. In principle, most existing steel bridges fulfil their purpose. Nevertheless, about 30% of the steel railway bridges in Germany are older than 100 years. In view of the deterioration and significantly increased loads, however, they must satisfy today’s requirements for stability and fatigue resistance. A realistic assessment of the fatigue condition of steel bridge structures is of fundamental importance.

Actually, the evaluation of the fatigue strength of these structures is based on normative notch details, S-N curves and a linear damage accumulation hypothesis. If a sufficient fatigue lifetime cannot be evaluated with this method, a service life interval check based on fracture mechanics is performed. A fatigue crack at the edge of the rivet hole is assumed which extends 5 mm beyond the edge of the rivet head to detect it visually in a bridge inspection. The cyclic lifetime during crack initiation and crack growth below the rivet head is not yet included in the evaluation. Therefore, this part of the fatigue life is the subject of a current research project [1] at the Dresden University of Applied Science. Initial investigations have already shown that the prestressing force of the rivets and the associated friction significantly retards crack growth at holes.

To include the early phase of crack propagation in the assessment, it is necessary to reliably detect such a small crack in the structure. Currently there is no practicable NDT method to detect hidden cracks in riveted joints. X-ray testing requires complex precautions for occupational safety. Ultrasonic testing is also very expensive, as each rivet must be examined individually. Recent investigations of the authors (see [2], [3]) indicates that fatigue cracks can be detected using thermoelastic stimulated Lock-In-Thermography. It was also possible to detect cracks under the rivet heads can be detected. This is possible despite the presence of a corrosion protection coating. The detectable crack length depends mainly on the level of stress and the loading frequency.

This paper reports investigations using thermoelastic stimulated Lock-In-Thermography as a NDT method for detection of hidden cracks in riveted joints. The results have shown that cracks below rivet heads can be detected. This is possible despite the presence of a corrosion protection coating. The detectable crack length depends mainly on the level of stress and the loading frequency.

Keywords

Fatigue crack, Crack propagation, Crack detection, Lock-In-Thermography, Riveted connection
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 find. 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 analyse the applicability of thermoelastic stimulated Lock-In-Thermography for crack detection the location, shape and length of the crack(s) should be known. Therefore, tension specimens made of current steel grade S355 with a drilled rivet hole (Figure 2) were produced. The specimen had a width of 100 mm, 12 mm thickness and a hole diameter of 25 mm.

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 3). Crack propagation gauges were installed near the notch root on the backside of the specimens (Figure 4) to detect the crack initiation and measure the crack length during cyclic loading. The crack length at front of the specimen was measured by a digital microscope.

After crack initiation, the hole was closed by a fitted rivet-like bolt (Figure 2). The frontside of the specimen was covered with a corrosion preventive coating that is typically used for maintenance of riveted steel structures (see Figure 1). The mean thickness near the rivet head was around 500 μm.

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 influence length of the components, the axle distances, the axle loads and the train speed, the load frequency, the number of cycles and the stress range vary. Components of the main structure are subjected to higher stress ranges but must withstand fewer load cycles at lower loading frequencies than cross girders or stringers. Therefore, fatigue tests under pure tension loading (R = 0.1) were performed with gradually increasing stress range (44 MPa up...
The resulting thermal diffusion length $\mu$ for the investigated steel is to 80 MPa) and at different loading frequencies (0.25 up to 10 Hz). These investigations were carried out on two tensile specimens with different crack geometry and relatively short cracks with a maximum length of 3 mm. The results of the related thermographic measurements are documented in [3].

Thermographic measurements with medium stress range, suitable loading frequency but different crack lengths should be carried out on the specimen described here. Therefore, fatigue tests under pure tension loading ($R = 0.1$) were performed with a stress amplitude of 66 MPa at a loading frequency of 0.5, 1 and 2 Hz. A new thermographic measurement was always carried out after approx. 40,000 load cycles. The crack geometry prior and at the end of the measurements is illustrated in Figure 5.

While the crack was approximately symmetrical at the beginning, crack propagation during the tests was very different at the frontside and backside of the specimen. This effect is due to the friction between rivet head and sample. While the crack on the backside (under the crack propagation gauge) could grow unimpeded, it was retarded under the rivet head. This phenomenon and its relevance for the remaining fatigue life of riveted steel bridge structures are discussed in detail in [1].

While the crack length on the backside could be measured with a gauge, the length on the front side had to be determined after the tests. For this purpose, the crack front was marked by a single static overload (double load magnitude). Afterwards the fatigue crack was further extended under cyclic loading. The remaining cross section of the tensile specimen was then brittlely fractured. After almost 300,000 load cycles during the measurements, the crack on the backside had a length of 11 mm while on the frontside it was still more than 1 mm below the rivet head. For the following evaluations, the crack length at the frontside was interpolated from the lengths measured on the fracture surface (Figure 5). The crack lengths for the individual thermographic measurements are given in Table 1.

| Measurement No. | Crack length backside (measured) [mm] | Crack length frontside (interpolated) [mm] |
|-----------------|--------------------------------------|----------------------------------------|
| 1               | 6.2                                  | 5.3                                    |
| 2               | 7                                    | 5.5                                    |
| 3               | 7.5                                  | 5.6                                    |
| 4               | 8                                    | 5.7                                    |
| 5               | 8.5                                  | 5.9                                    |
| 6               | 9.5                                  | 6.1                                    |
| 7               | 10.6                                 | 6.4                                    |
| 8               | 11                                   | 6.5                                    |

### 2.2 Thermographic measurements

An alternating mechanical loading causes a cyclic change of the temperature according to the thermoelastic effect [4]. For a specimen loaded with a stress amplitude $\sigma_a$ at a loading frequency $f$, the resulting temperature at a mean temperature $T_m$ is given by Equation (1):

$$T(t) = -T_m \cdot K_0 \cdot \sigma_a \cdot \sin(2\pi f_t \cdot t)$$

The parameter $K_0$ represents the thermoelastic constant and can be calculated from the coefficient of thermal expansion $\alpha$, the density $\rho$ and the specific heat capacity $c_p$ of the material. For unknown thermal emissivity of the surface or unknown material parameters the thermoelastic constant $K_0$ in equation (1) can be replaced by a constant $K_c$ by calibrating the system with defined stress amplitudes [5].

In a specimen loaded sinusoidal with a force the temperature change due to the thermoelastic effect results in a sine wave coupled with the loading frequency (E-Mode). According to Sakagami et al [6] and Brémont [7] dissipated energies are assigned to a sine wave with twice the loading frequency (D-Mode). 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 a incomplete Discrete Fourier Transformation (DFT). Beside the mean Temperature $T_m$ and the thermo-elastic part $T_t$ connected with the loading frequency $f$, the evaluation considers a dissipative part $T_D$ coupled with the double loading frequency and in the evaluation method suggested by Bár and Urbanek [5] additional higher harmonic frequencies. In this case, the DFT can be written as:

$$T(t) = T_m + T_D \cdot e^{2\pi i (f_t + k \cdot f)} + T_{th} \cdot e^{2\pi i (2f_t + k \cdot f)} + \sum_{k=1}^{N_{max}} T_{dk} \cdot e^{2\pi i (k+2f_t + k \cdot f)} + \Phi(t)$$

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 2.

In case of a periodic stimulation the propagation of a thermal wave is coupled with the frequency [9]. The thermal diffusion length $\mu$ gives the distance at which the amplitude of the temperature is reduced e-times from its origin. The thermal diffusion length can be calculated from the thermal conductivity $k$, the density $\rho$, the specific heat capacity $c$ and the frequency of the stimulation, i.e. for a thermoelastic stimulation the loading frequency $f_t$ using Equation 3:

$$\mu = \frac{k}{\pi \rho c f_t}$$

shown in Figure 6 as a function of the loading frequency $f$. 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.
The thermographic measurements were undertaken with an Infratec Image IR 8300hp infrared camera. During the mechanical loading sequences with a duration of 10 s with a sample rate of 293Hz were recorded. The size of each recorded frame was 640 x 512 pixel and the spatial resolution was about 0.25 mm/pixel. The evaluation according to Equation 2 was performed with a self-developed Matlab program. Due to the small rigid body movement, no motion compensation algorithm was applied.

3 Results of the thermographic measurements

3.1 Influence of loading frequency

Figure 7 shows E-Amplitude images at a crack length of 11 mm on the backside and 6.5 mm on the frontside loaded with 66 MPa at loading frequencies of 0.5, 1 and 2 Hz, respectively. The rivet head shows nearly no temperature effect but on both sides of the rivet enhanced E-Amplitude values are visible. The decreasing E-Amplitude values with increasing loading frequency can be attributed to the decreasing thermal diffusion length. In case of the measurement with 0.5 Hz a clear asymmetry of the measured temperatures on both sides of the rivet head is visible, indicating an asymmetric stress field caused by the crack on the right side of the rivet. At a loading frequency of 1 Hz the measured temperatures are significant lower and therefore the crack is hard to detect. At 2 Hz only a small region with increased temperatures at the rivet head is visible.

This result clearly shows the influence of the thermal diffusion length and thus the loading frequency. In order to get a higher probability for the detection of a crack under the rivet head, the measurements must be undertaken with a low loading frequency. Consequently, all following investigations were undertaken with a loading frequency of 0.5 Hz.

3.2 Crack Detection in E- and D-Mode

As mentioned above, the DFT evaluation results in amplitude and phase images in the different modes as described in Equation 2. The E-mode is caused by the thermoelastic effect and therefore coupled with the loading frequency. The D-mode is caused by dissipated energies due to plastic deformation and after Equation 2 it is coupled with twice the loading frequency. At a crack tip enhanced elastic stresses as well as plastic deformation are present. Therefore, a detection of cracks should be possible in amplitude images of the E-mode as well as the D-mode.

In Figure 8 the E-amplitude and the D-amplitude images of the measurement with 0.5 Hz at a crack length of 6.5 mm on the frontside are shown. In the E-Mode a clear asymmetry of the temperatures on both sides of the rivet head is visible. The higher temperature changes on the right side are caused by the elastic stresses in front of the fatigue crack, whereas on the left side the temperature amplitudes are due to the stress field of the rivet hole. In case of the D-mode image nearly no temperature effects around the rivet head are visible. Obviously, the temperature amplitudes caused by plastic deformation in front of the crack tip are too small to detect a crack under the rivet head, even at the highest investigated crack length.
3.3 Crack Detection in E-Amplitude images

In order to evaluate the possibilities of the detection of fatigue cracks under the rivet head with thermographic methods, measurements were undertaken at different crack lengths. The experiments started with a crack length of 5.0 mm at the frontside and ended with a length of 6.5 mm with which the crack tip was under the rivet head in all measurements. A series of thermographic measurements at different crack lengths is shown in Figure 9. In all cases the given crack lengths refer to the frontside.

At crack lengths below 5.5 mm no significant differences in the E-Amplitude images between the left and the right side of the rivet head are visible. Above a crack length of 5.5 mm the region with higher E-amplitude values on the right side of the rivet head become more and more pronounced, while the area on the left is independent of the crack length in terms of the measured temperature values and expansion. These results show that a visual comparison of the temperature fields on both side of the rivet head allows the detection of a crack growing on one side when its length exceeds 5.5 mm, which is still 2 mm below the extension of the rivet head.

3.4 Crack Detection in E-Amplitude profiles

To quantify the results of the visual impression of the thermographic measurements line profiles of the temperature amplitudes over the cross section of the specimen perpendicular to the loading direction as shown in Figure 10 were created.

To determine the profiles, a line with a width of 10 pixels across the specimen in the middle of the rivet was drawn. Over the width of the line the mean value of the 10 E-Amplitude values was calculated. Figure 11 shows these temperature profiles for a loading with 66 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.
All temperature profiles shown in Figure 11 show a comparable run. The E-Amplitude values are rising with increasing distance from the specimen border. The maximum values are found at the border of the rivet head and are followed by a significant drop of the amplitude values to nearly zero over the rivet head. In case of the measurement at a crack length of 5.3 mm nearly no difference between both sides near the rivet head is visible. With increasing crack length the maximum temperature values on the right side near the rivet head are increasing and the region with higher temperature values widens whereas the temperature profile on the left side of the rivet remains independent of the crack length. Due to the small amplitude values the differences are not very pronounced compared to the noise of the measurement. Therefore, an automation of the evaluation of the temperature profiles seems not to be very promising. However, the evaluation confirms the results of the visual comparison from chapter 3.3.

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. Obviously, this asymmetry is caused by the presence of a crack under the rivet head on the right side of the specimen. The higher temperature amplitudes are caused by the stress field in front of the crack tip. With increasing crack length, the maximum temperature in this field is increasing and the area is widened. This enhances the possibility to detect a crack under the rivet head. By visual comparison of the temperature field on both sides of the rivet head a crack with a length of more than 5.5 mm can be clearly detected. The visual impression is confirmed quantitatively by the line profiles. Unfortunately, the measured temperature amplitudes are very small. Therefore, an automated detection of cracks by the line profiles seems to be not very promising.

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 the detection with a direct comparison is impossible. When the cracks are different in shape or length the resulting differences in the stress profiles can be high enough to allow the detection of a crack under the rivet head even at lower loads (see [3]). 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 visual comparison of the stress profiles allows the detection of cracks under the rivet head even when the crack tip is still 2 mm away from the edge of the rivet head. Due to the fact that all measurements were performed with a corrosion preventive coating with a thickness of about 500 μm, the measurements were performed under realistic conditions. For the detection of cracks in real structures and under complicated loading conditions, further investigations are necessary. If a modern thermographic camera is used for the measurements, e.g. with an image size of 2,560 × 2,048 pixels, it is possible to examine a set of at least four rivets together at comparable resolution. If the related component is equally stressed in the area of several rivets, cracks on individual rivets can be detected more easily and reliably.

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