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Acoustic emission monitoring of fatigue cracks for railway steel bridge inspection

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ABSTRACT: Railway steel bridges are often affected by material fatigue, i.e. crack formation and crack growth at areas of high stress concentrations under millions of load cycles due to the traffic load. To support the continued safe operation of these structures a flexible and robust system solution for structural health monitoring is needed. It provides the responsible bridge inspector with useful information regarding the current condition and the future development of the monitored area. This offers the infrastructure operator an opportunity for optimised planning of inspection intervals and maintenance measures and helps to extend the service life of these structures. For this purpose, the RISE system was developed by TÜV AUSTRIA in close cooperation with the Austrian Federal Railways ÖBB. The RISE system monitors fatigue cracks and/or highly stressed areas using acoustic emission (AE). The system records the AE response from the monitored area while the material is stressed by the usual day-to-day railway operations. The analysis of the change of this material response over the monitoring period is used to predict the future development of the crack. In this paper the application of the RISE system for bridge inspection is presented for steel bridges in the railway network of ÖBB. The system solution is presented as a whole, from the installation on-site until the evaluation of the monitoring data and the obtained results supporting the responsible bridge inspectors.

KEY WORDS: SHMII-13; acoustic emission, fatigue cracks, steel bridges.

1 INTRODUCTION

Steel bridges are often affected by fatigue cracks due to cyclical loading caused by trains passing over them. Bridges at the end of their service life inevitably develop such cracks. The ÖBB team takes care of the maintenance of the bridges in its railway network and thus ensures the safety of the day-to-day train traffic. ÖBB employees inspect the bridges at regular intervals and assess their condition.

ÖBB was looking for a way to find a tool for these bridge inspectors to give them a way to monitor fatigue cracks and detect cracks at locations where cracks are suspected. In addition, this tool should be able to predict the future development of the condition of the monitored component when cracks already present, to help with a more precise planning for inspections intervals and repair measures. As part of the Rail4Future program co-financed by the Austrian Research Promotion Agency, the monitoring of cracks using acoustic emission (AE) was selected as the method. TÜV AUSTRIA and ÖBB have been cooperating for years in the implementation of acoustic emission as a monitoring tool for railway steel bridges. As part of this cooperation, a stand-alone solution, RISE (**R**emote **I**nspection **S**ystem **E**dge), has been developed. A monitoring solution for the detection and monitoring of fatigue cracks on railway steel bridges.

RISE offers monitoring as a service for railway infrastructure operators, from setting up the monitoring, recording the data to generating the report. In addition, a prediction on the future development of the crack is also provided.

This method is known as the failure forecast method (FFM). A method that is utilizing the near constant measurement data stream from the device to predict the time until the maximum utilization of the monitored component is reached.

The RISE device was developed with the focus point to be a reliable and easy to install acoustic emission monitoring system. RISE is specifically designed for monitoring due to its compact design, low power consumption and simple installation.

2 OVERVIEW OF MONITORING SYSTEM

2.1 Technical overview

RISE by TÜV AUSTRIA is an acoustic emission system designed for detection and continuous monitoring of fatigue cracks. RISE consists of a hardware component, the RISE-Core, which is installed on site and a server infrastructure for data evaluation and monitoring result presentation on an online dashboard. The data from the RISE-Core is sent to this data platform via a mobile network and an encrypted connection. The data stream is processed on the server. The results are displayed on a graphical online interface, the RISE dashboard, where they are accessible by the customer.

The RISE-Core is installed at the position where a crack is suspected, or an already existing crack needs to be monitored. The system has four acoustic emission channels. The connected piezoelectric sensors detect the mechanical waves generated by the growth of cracks inside the material. Acoustic emission occurs when the defects in the material are excited by a load. The propagation of the defect is accompanied by the release of energy in form of an elastic wave. Acoustic emission is therefore a passive non-destructive method. In the case of railway steel bridges, the load needed for activation of cracks is the passage of trains over the bridge from the usual daily

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traffic. Monitoring with the system therefore provides information about the acoustic emission material response to the currently operational load.

The preprocessing of the signals in the form of extraction of basic acoustic emission parameters takes place on site. The system is designed so that the power can be provided via a small off-grid solar system. A mobile network connection is required to outsource the needed computing power to a server. It is possible to use several RISE-Cores on one bridge. For every monitoring position one RISE system is required.

2.2 Theory of operation

Every time a train passes over the steel bridge, the material is stressed. This can cause fatigue crack growth to occur at locations with high stress concentrations due to periodic overloading of the material. The crack growth is accompanied by a stress reconfiguration and a sudden release of energy in form of elastic waves in the material. The mechanical waves propagate in the material and can be converted into an electrical signal utilizing the piezoelectric sensors. This signal is digitalized and the acoustic emission parameters that are relevant for further evaluation are extracted from it. The system therefore is recording the AE material response to the operational load.

As first processing of data on the server, located events are calculated. This method deals with combining the signal information from the whole sensor array and not an individual sensor only and providing the information about the point of origin of the mechanical wave. To indicate an acoustic emission event as a located event, several sensors must be excited by the mechanical wave and the strength of the electrical signal generated by the piezoelectrical element must exceed a specified threshold (in mV). In addition, the time difference on arrival at the different sensors must not exceed a certain specified value (1st-Hit Discrimination Time). This time value is related to the distance between the sensors and the time it takes for the mechanical wave to travel this distance at a defined speed of sound. The calculation of the wave's point of origin is calculated from the time differences of the individual signals, the speed of sound and the position of the sensors. The detection of the events relevant for further evaluation is carried out by 3 measuring sensors, which surround the crack or the monitored area in a triangular configuration.

So-called guard sensors are used to ensure that no noise from outside the monitored area interferes with the measurement. These are placed around the measuring array consisting of the three measuring sensors. Incoming waves that are first detected by one of the four guard sensors are not used to calculate the material response, as the system recognizes that the mechanical wave originated outside the monitored area of interest.

RISE provides a statement about the further development of the crack after a given measurement time. This method is known as the failure forecast method. The information helps the infrastructure operator to plan the inspection intervals and repair measures for ageing bridges. The method is based on rate-based structural health monitoring and requires near-continuous measuring data [1].

Many load-controlled processes, such as fatigue crack growth, show positive feedback. Crack growth accelerates as the degree of degradation progresses. The closer the system gets to the point where it has exhausted its capacity to withstand the load, the higher the rate at which the degradation progresses.

This point in time is therefore the time when the maximum utilization of the monitored component is reached. The advantage of this method is that it is not the crack growth per se that is monitored, e.g. the crack length, but the change in a measured value that is symptomatic for the degradation (see Figure 1).

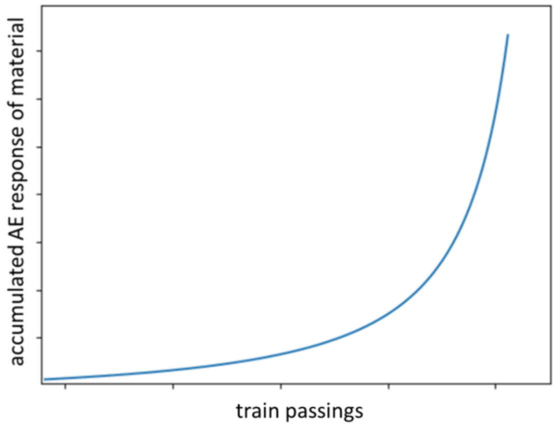

Figure 1 Illustration of the acoustic emission material response with the progression of a fatigue crack growth due to the cyclic loading of trains passing over the bridge.

In the case of acoustic emission monitoring, this value can be the energy of the acoustic emission signals, localized events, or hits detected from the monitored area.

Crack growth generates a mechanical wave that propagates through the material by releasing elastic energy stored in the crack tip. These mechanical waves can be converted into an electrical signal using piezoelectric sensors, which is then digitized and made available for further evaluation. The advantage of FFM over conventional methods for assessing degradation is that it does not require any detailed information about material properties and crack geometry. Only the material response to the operational conditions over time provides the data required to make a statement about future development.

Fukuzono [2] and Voight [3][4] were able to show in their works that there is a correlation for many degradation processes that can be expressed in Equation 1:

$$\frac{d^2\Omega}{dt^2} = A\left(\frac{d\Omega}{dt}\right)^{\alpha} \quad (1)$$

Ω is the measured variable associated with the degradation. In the case of monitoring fatigue cracks on steel bridges, the variable is the accumulated acoustic emission response of the material (see Figure 1). The two constants A and α are empirical parameters that are dependent on the process under consideration. The equation can be integrated in the range from t to time t_f (time of maximum utilization of the component) with $\alpha > 1$ (Equation 2):

$$\left(1/\frac{d\Omega}{dt}\right)^{\alpha-1} \approx (\alpha-1)A(t_f - t) \quad (2)$$

The equation can be further simplified for the case that $\alpha \approx 2$, which is the case for fatigue crack growth [1]. This can be

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verified from the measurement data by plotting the logarithm of the first and second time derivatives of Ω and finding α from the calculated slope.

So obtained equation shows a linear correlation (Equation 3).

$$\frac{1}{\dot{\Omega}} \approx A(t_f - t) \quad (3)$$

As the rate of change of the material response is very high at the point in time at which the maximum material utilization of the monitored component is reached, a statement can be made from the monitoring data about this point in time. For this purpose, the inverse rate of the material response is plotted against time. The calculated linear regression line intersects the time axis at the point where the inverse rate of change of the material response approaches zero (see Figure 2).

Based on the remaining time until the maximum utilisation of the component is reached, a traffic light rating system is set up and the operator is given a recommendation on how to proceed. If the time until maximum utilisation is reached is longer than the time window of a regular periodic inspection, further monitoring is only necessary within the designated time (green area). If the time interval is shorter than the time window of a periodic inspection, a permanent monitoring is recommended (yellow area). If the time to maximum utilisation of the component is very short, not only a further inspection is required, but also safety measures are appropriate (red area).

The failure forecast method is shown to be tolerant for random variable amplitude loading that is statistically stationary as it is the case for train passages that have a variety of train mass [7]. A significant change in the exploitation of the bridge would require a new monitoring of the material response due to drastically changed traffic loads.

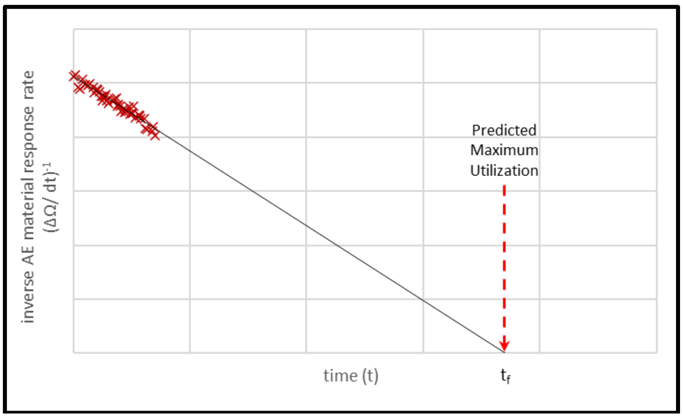

Figure 2 Illustration of application of the failure forecast method on continuous monitoring data. The linear regression line is intersecting the time axis at the time point of maximum utilization of useful life of the monitored component.

3 FIELD APPLICATIONS

3.1 Bridge with fatigue cracks in the area of the transverse stiffener to the main girder web plate

During the regular inspection of this bridge, cracks were discovered in the area of the main girder web plates. In the first on-site analysis, these cracks could be identified as fatigue cracks [5]. The cracks were limited to the connection detail of the transverse stiffeners welded to the main girder web plate.

Figure 3 Monitored position with the suspected crack at the welded connection of the transverse stiffener to the main girder web plate

A concept of measures was developed to carry out an objective assessment of the cracks on the main girder based on calculations and measurements and to make a statement about the future development. In the subsequent measurements, TÜV AUSTRIA was called in to help assess reinforcement measures by means of acoustic emission measurements at the crack positions [5]. Around 14% of the 140 identical elements were affected by the cracks. During this initial AE measurements, also at some reference points with no reinforcement installed, a new crack indication was detected. It was decided to do a further AE-monitoring using the RISE system at this position of interest (see Figure 3) and to assess the possible future development of the crack. The aim was to test the RISE as a tool for detecting cracks in the early stages and to use the measurement results of the monitoring to predict the future development of the cracks.

The measuring equipment required for the monitoring was installed while the bridge was in operation, so the train traffic was not affected. The piezoelectric sensors (VS150-RSC from Vallen, peak frequency at 150 kHz, integrated preamplifier with gain of 34 dB) were installed as shown in Figure 5. Three sensors were installed near the crack position. These sensors record the mechanical waves coming from the crack. To improve the coupling of the sensors to the surface, they were mounted with a coupling agent. In addition, the paint layer was removed off at the sensor positions. The sensors were attached to the surface using magnet holders. The connection to the sensors was made via BNC-cables (1.5 m). The RISE-Core measuring system was also attached near the measuring position using a magnetic holder. Four guard sensors were installed around the measurement position to shield the measurement setup from interfering noise from sources other than the crack position. These were positioned to suit the installation location in such a way that possible interference signals were first detected by the guard sensors and thus filtered in the signal processing. As a 230V connection was available near the bridge, the measuring system was connected to this. This was the only cable that had to be laid out to the measuring position.

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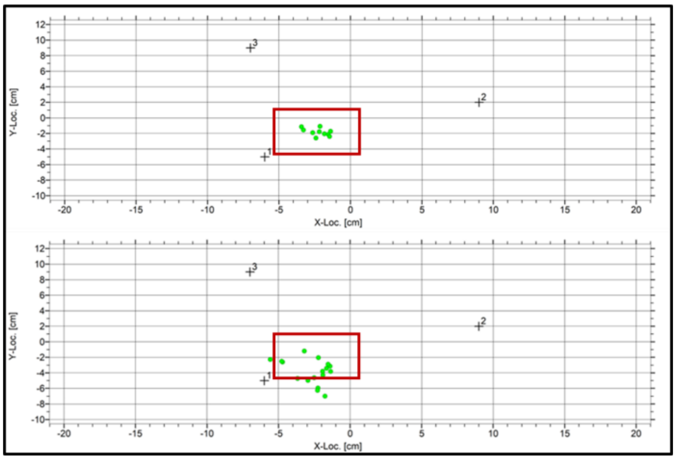

Figure 4 Top - Location map of events from pencil lead breaks at the position of the suspect crack. Bottom – Location map of events acquired after one train passage over the bridge in the position of the crack indication localized with pencil lead break test.

The functionality of the installation of the measuring device (RISE-Core) and the sensors for condition monitoring could be checked using user friendly installation software known as "Client Setup Mode". This software solution offers a supporting function for checking the functionality of the measuring chain, coupling verification of the sensors and localization in accordance with the EN 17391:2022-06 standard. Verification is carried out using a pencil lead break (0.5mm/ 2H, in accordance with ASTM E976). A simple and reproducible event with energy in the order of magnitude of crack growth events. To check the function and the correctness of the set parameters, pencil lead breaks were carried out in the area of the suspected crack (Figure 4).

Figure 5 AE sensor arrangement at the monitored position with suspected crack. Sensor 2, not in the picture, is positioned behind the connection detail in the distance of 12 cm from the suspected crack.

This area is also where the crack growth events are to be expected. The Figure 4 shows in the bottom map the localized events after a train passing over the bridge. The entire installation and inspection of the measurement setup can be carried out by a trained technician within one hour. The measurement period was 6 months.

During this time, the passings of the individual trains and the resulting AE material response were recorded.

3.2 Monitoring at five representative points on a riveted steel bridge

This case involves a riveted steel bridge built in 1936, which was found to be in good condition during a visual inspection by the ÖBB bridge inspectors. The bridge was to be given a new corrosion protection. As this is a cost-intensive maintenance measure for the infrastructure operator, the ÖBB wanted to help with additional useful information to support the final evaluation of the condition of the bridge through the responsible bridge inspectors.

With the help of the bridge inspectors, five neuralgic areas on the bridge were selected. These points were selected from the experience of the technicians responsible for the inspection as the components most affected by cracks and can thus be used to assess the general condition of the bridge. This field example deals with the measurement of the first selected area, a transverse stiffener in the area of the fixed bearing of the bridge. This case is an example for monitoring of a hot spot. A larger area is monitored than in the case of already known cracks. Here too, the 3 measuring sensors (see Figure 6) detect the incoming mechanical waves in a triangular arrangement, which are triggered in the material by the load of the trains crossing over the bridge.

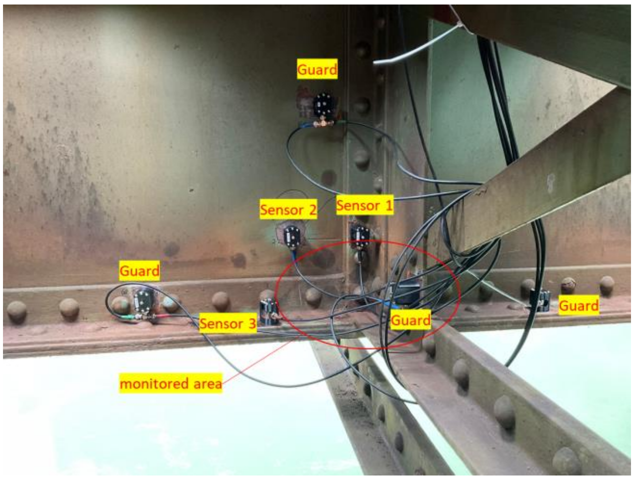

Figure 6 AE sensor arrangement at the monitored position for hot spot monitoring at the area of the riveted connection element of the transvers stiffener to the main girder.

The material response is evaluated for crack growth and provides information about the condition of the material in the monitored area. As commercially available magnetic sensor mounts are too large for the distance between the individual rivets, in-house developed sensor mounts are used for the riveted bridges. In addition, 4 guard sensors were applied around the triangular configuration of the measuring sensors in order to exclude spurious noise outside the measuring arrangement.

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Figure 7 Modular PV-solution for RISE.

As there was no power supply on site at this bridge, a modular PV system was installed (see Figure 7) to supply the RISE device with power.

RISE requires less than 10 W of power when all sensor channels are fully utilized. The entire equipment could be transported to the site by three men.

4 RESULTS

The material response was recorded by the RISE system during the monitoring process. The results of the cumulative plot of the AE material response can be seen in the Figure 8. At first glance, different trends in the material response can be recognised in the progression of the individual curves. The curve with the most pronounced progressive course is the Pinkabach bridge. A bridge that was completely dismantled in a single piece by ÖBB and equiped in the workshop with a shaker. It was subjected to a fatigue test [41]. As part of the Rail4Future project, TÜV AUSTRIA, in cooperation with ÖBB, carried out an acoustic emission measurement on the main girder bottom flange during the fatigue test, where an artificial crack was introduced and the AE material response during fatigue crack growth was observed.

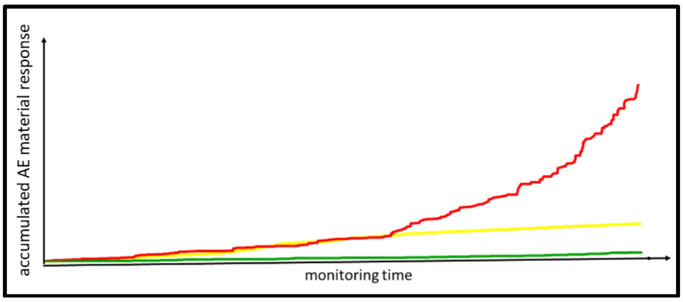

Figure 8 Comparison of AE material response of the different bridges. Monitoring time is normalized. Red: fatigue test on the Pinkabach bridge with artificial introduced crack. Yellow: monitoring of a bridge at crack position. Green: representative hot spot on a bridge with no known crack indications.

The crack had grown after its initiation at the notch near to the edge of the bottom flange in transversal direction almost till to the web plate at the centre of the girder.

The material response shows a progressive growth, which is a well-known trend in the acoustic emission for sever degradation. In comparison to the Pinkabach bridge, both the trends of the crack affected bridge and the riveted bridge show a linear progression. The slope of the cumulative AE response is significantly more pronounced on the crack affected bridge where crack monitoring was performed than on the riveted bridge.

The application of the FFM like in the Figure 9 delivered the prediction of time of maximum utilization of the monitored components for the two bridges. In the case of the crack monitoring, for example, it was possible to conclude that further monitoring should be carried out at the next scheduled inspection interval. The riveted bridge showed that the remaining time until maximum utilisation of the first monitored position is so far in the future that a new investment in a new corrosion protection will be resonable, when the other positions will show a similar result. Other positions on this bridge are still being monitored in order to make a general statement about the overall condition of the bridge. The results are made available to the customer on an online dashboard using a traffic light system. This allows the customer to track the status of their monitored bridges and components.

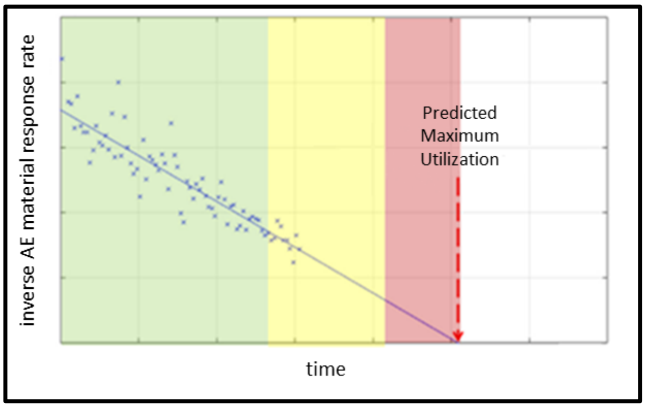

Figure 9 Failure forecast method applied on the monitoring data. Areas for the traffic light result grading system are marked.

5 SUMMERY

The system solution RISE by TÜV AUSTRIA was presented as an acoustic emission monitoring tool for railway steel bridges. The acoustic emission monitoring system is able to detect and monitor cracks. Based on the failure forecast method, a statement can be made about the condition of the monitored component and after several months of measurement a further prognose when the maximum utilization of the component is reached.

Two field examples were used to demonstrate how RISE could support the ÖBB bridge inspectors. A field case for identification of a suspected crack at the monitored component of interest was shown. After the detection of the crack a forecast for remaining time, until the maximum utilization time of the component, was done. In the second case a hot spot monitoring

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was shown. Where the component was monitored to make sure that it was in good condition and no crack activity was present.

The system helps the infrastructure operators and bridge inspectors to plan maintenance intervals, repairs and new reinvestments measures for ageing bridges. This saves the infrastructure operator costs and reduces the man-hours required for monitoring. The examples showed that the system can be installed easily and in a short time. The monitoring does not require any major interventions and the installation can often be carried out while the bridge is in operation. The results and recommendations for the customer can be made available via an online dashboard using an easy-to-understand traffic light system.

In addition to the numerous monitoring projects already carried out on railway steel bridges, further bridge monitoring projects are planned with the help of which RISE can be established as an indispensable tool in bridge inspection and a helpful addition to the classic periodic inspections.

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