Simplified Crack Appearance Monitoring at Welded Joints with Strain Gauges

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ABSTRACT

In the last decade a lot of methods, sensors and algorithms have been developed to promote structural health monitoring (SHM). As a consequence of the SHM axiom: Sensors do not measure damage, feature extraction is one of the main concerns to receive reliable sensor information. In this introduced SHM approach a minimum number of strain gauge sensors are applied to a steel structure to minimize signal processing and feature extraction. In this investigation a numerical model of the structure is required to identify local stress intensities according to a cyclic load. Once these hot spots are identified, strain gauges are applied in these zones on the real structure. At these zones fatigue becomes apparent and cracks will appear. The stress redistribution causes significant signal changes in the strain sensors and is highlighted if they are related to unaffected sensors. This master-slave concept was tested on noise barrier pillars which were mounted on the edge beam of a bridge. Cyclic loads caused by passing trains were simulated with a single mass exciter and cracks occurred at the welds between the pillar and a head plate. All tests were accomplished under environmental conditions and varying temperature. The cracks were identified by the introduced method and clear relations between different stress ranges, load cycles and crack occurrence are determined. The data from the numerical model are in a good agreement with the measurements.

INTRODUCTION

The monitoring of civil infrastructures and the transition to SHM applications is constantly extended because sensor systems outlast for extensive period of time on

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a structure. Originally, owners of infrastructure are interested in monitoring their structure if it is exposed to extraordinary loads or structural changes are applied. The benefit of the collected data for “condition assessment” comes to the point when sensors are installed during the manufacturing process of the structure [1]. Because the life-time of a civil structure is in the range of 100 years no complete data sets spanning an entire life time exist. For this reason experiments and parallel monitoring are executed to collect data and identify features within the signals and relate them to structural changes or faults. The task to find the right sensor and the according features is challenging because the research is widely spread [2].

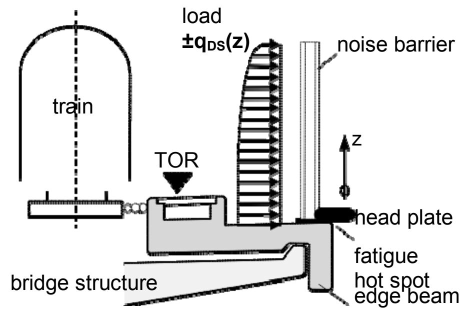

Figure 1. Cross-section of a bridge with noise barrier and the detail of the fatigue hot spot.

The presented approach is developed from the idea of using conventional strain gauge sensors which are very common to monitor infrastructure. They are cheap, easily applicable and data are quickly recorded with commercial soft and hardware. Strain according to load is the conventional application. The investigated feature is the stress redistribution in the vicinity of an occurring crack.

In the following paper the motivation and the method are described and experiments on a real structure under varying environmental conditions are presented.

Motivation

In Austria noise barriers at rail tracks in populated areas have become a standard action in the track design. With the demand of high speed tracks, the air pressure on the barriers increases with the velocity of the passing train. The cyclic loads caused by the passing trains lead to a distinct fatigue problem of the pillars, especially when the structure includes notches and welds. Investigations concerning the fatigue of the pillars are documented in [3] and a sketch of the hot spot of the structure and load is illustrated in Figure 1. The maintenance consideration of the Austrian Federal Railways results in experimental investigations on real structure components to develop a durability model of the noise barriers.

From these basic principals the sensor design was developed to monitor the hot spot to document the crack occurrence and the transition from the continuous material model to the fracture model.

IMPEMENTATION

Signals and feature extraction

In the experimental applications three different kinds of sensors are used. Strain gauge sensors to collect data $\varepsilon_i[t]$ in the vicinity of the hot spot, a displacement transducer $w[t]$ to control the experiment and the according load and a temperature sensor $T[t]$ to relate environmental temperature effects within the strain sensor signals. The resolution in the time domain is adapted to the expected events in the load history. In the executed experiments a harmonic forced vibration is applied to the noise barrier pillar by an electrodynamic vibration exciter (linear motor) to simulate the deformation caused by a passing train. This vibrations cause a constant stress range at the bearing of the cantilever beam. Hence, a reduction in the data recording is carried out by picking the maximum and minimum value of a time period τ. The reduced data $f[\tau_n]$ is given by

$$f_{\min}[\tau_n] = \min\{f[t](\mathrm{H}[t+\tau_n] - \mathrm{H}[t+\tau_{n+1}])\} \tag{1}$$

$$f_{\max}[\tau_n] = \max\{f[t](\mathrm{H}[t+\tau_n] - \mathrm{H}[t+\tau_{n+1}])\} \tag{2}$$

where $\tau_n = \tau n$, $n=0,1,2,3,\ldots$ and H is the Heaviside step function. The range $\Delta f[\tau_n]$ of the period follows from

$$\Delta f[\tau_n] = f_{\max}[\tau_n] - f_{\min}[\tau_n]. \tag{3}$$

The feature is extracted from the compressed signals $\Delta f[\tau_n]$ is a heuristic assumption of the marital model of the investigated structure. Let $\Delta\varepsilon_i[\tau_n]$ be the recorded and reduced strain range signals where i is the number of distributed sensors. $\Delta\varepsilon_0[\tau_n]$ is the master sensor defining the nominal strain and all other sensors are the slave sensors placed at the observed hot spot. Assuming a linear relation between the master and slave sensors according to a linear material model of the continuum then the feature $F_i[\tau_n]$ of the undamaged hot spot at the location i is given by

$$F_i[\tau_n] = \frac{\Delta\varepsilon_i[\tau_n]}{\Delta\varepsilon_0[\tau_n]} = \text{const}, \tag{4}$$

as long as strain in the structure is present and no cracks are available. Nonlinearities resulting from the geometrical behavior of the structure must be insignificant and strain occurring due to temperature has to be compensated. If a crack appears in the area of the hot spot, a stress redistribution will be recorded and Equation 4 is no longer fulfilled. The determination whether a crack is present or not is performed by an univariate outlier analysis for each slave sensor. The training data are taken from initially recorded features and the method is categorized as unsupervised learning [4].

Hot spot determination

To place the slave sensors on the right position on the monitored structure, the hot spots must be analyzed. The introduced method focuses on metallic structures where fatigue leads to cracks in the structure. A straight forward approach to characterize the hot spots is to seek for fatigue critical notches which are compared with a standard of assessed notches [5]. Such a standard contains numerous cases but practically they do not match exactly with the structure. Especially when the

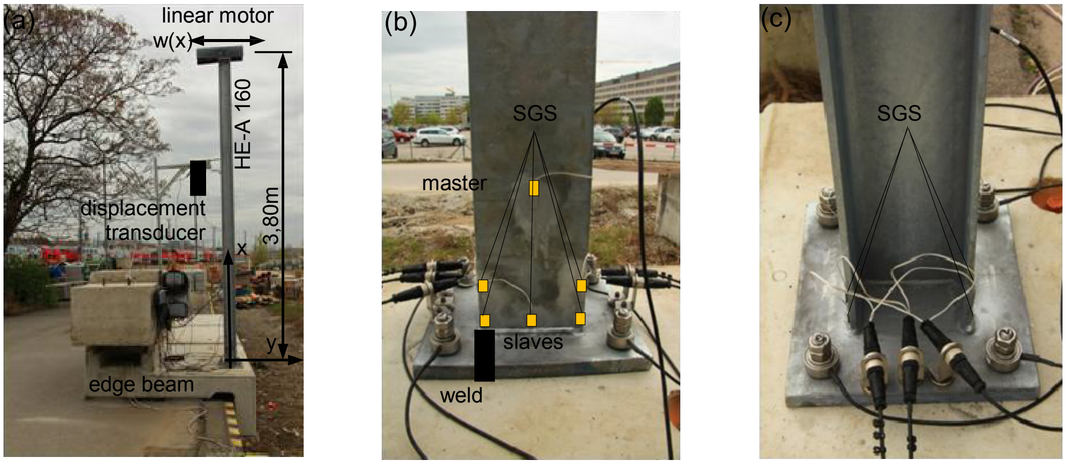

Figure 2. Experimental setup. (a) Noise barrier pillar on edge beam with electrodynamic vibration exciter on top, (b) strain gauge sensor (SGS) distribution and (c) coupling of tensioned and compressed sensor.

nominal stress of the detail cannot be estimated and the boundary conditions differ from the detail in the standard.

In the design process it is obligatory to use numerical models to optimize the structural design. These models with some adaption can be used to determine the stress intensive notches and their identification is essential for cyclic loaded structures. In this investigation finite element modeling is the preferred method to apply a stress analysis [6]. What comes with this analysis is that the strain distribution is identified and the strain gauges are placed according to the strain field. Additionally, the expected measuring values are evaluated.

EXPERIMENTAL APPLICATION

As mentioned above, the experiments focus on the investigation of the hot spots of noise barrier pillars (Figure 1). The air pressure on the noise barrier panels when a high speed train passes the wall causes a clear deformation. The design of the pillars on the edge beam of a bridge has to be investigated because the weld between the head plate and the I-beam cause a fatigue critical notch. Furthermore the positions of the bolts in the head plate lead to a stress distribution that provokes stress intensities in the weld. This will be explained in detail later. The preliminary conducted numerical studies resulted in a full scale test as illustrated in Figure 2. The experimental test setup is identical to the real design and to the application of a noise barrier in practice. Forced vibration tests were carried out under varying temperature conditions and the structural vibrations and deformations were realized by a single mass exciter on top of the pillar.

As demonstrated in Figure 2, 6 HE-A 160 I-beams with a 25mm head plate of structural steel S235 were tested on 3 concrete edge beams. The pillars were fixed on the concrete component with 4 M16 bolts. A cyclic load was applied by a linear motor on top of the pillar with a moving mass of 3.2kg. The vertical cantilevers were excited in their first eigenfrequency between 9.6 to 9.8 Hz, vibrating harmonically at the first eigenmode. The nominal stresses for the tests at the weld

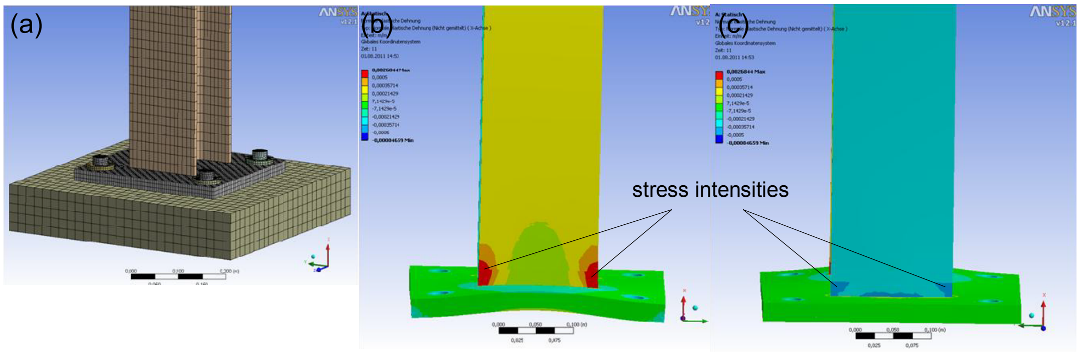

Figure 3. Finite element model to determine stress intensities. (a) discretization, strain in x-direction (deflection in y-direction) (b) tensioned flange and (c) compressed flange.

were determined at 2 different levels to evaluate a S-N curve of the investigated detail. Hence, 3 specimens were tested at a stress range $\Delta\sigma_1 = 120$ N/mm² and 3 at $\Delta\sigma_2 = 80$ N/mm².

The test were monitored by a deflection transducer (Figure 2a) at the height of x_D = 2.50m and 6 strain gauge sensors at the bottom of the pillar (Figure 2b). The top strain sensor is the master sensor to control the nominal stress and the other 5 sensors are the slaves to record the stress distribution in the vicinity of the weld. The strain sensors consisted of 2 quarter bridges, one is attached to the tensioned flange and the other to the compressed flange. Strain was recorded in the x-direction of the beam according to Figure 2. This configuration compensates strains caused by temperature and only the flexural strains are obtained. To assure uniform boundary conditions load cells at the bolts were used to control the pretension and the loss of tension during the running fatigue test. Thus, a stress redistributions caused by a loss of tension at the bolts was excluded. Finally a temperature sensor at the bottom of the I-beam recorded temperature variation over the test days.

Determining stress intensities with a finite element model

Before tests were carried out the structure has been discretized as 3D finite model with ANSYS. The concrete surface, the head plate, bolds and the I-beam

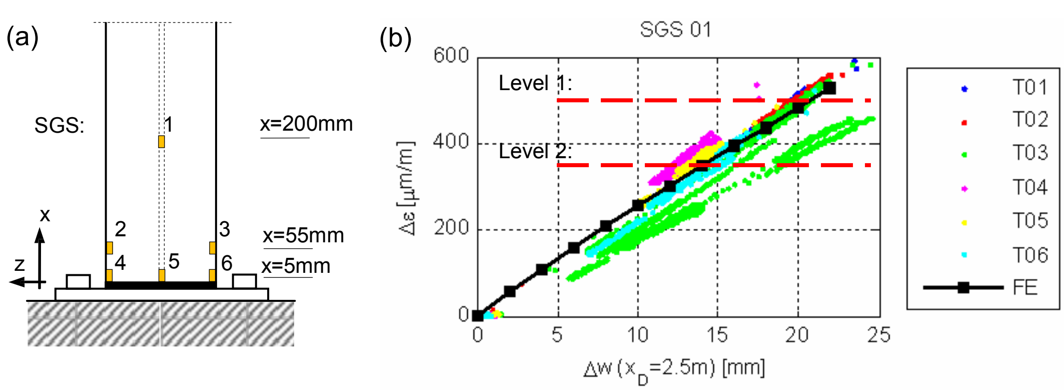

Figure 4. Comparison of FE results with the measurements. (a) Detail of the strain gauge sensor distribution and (b) strain in x-direction of SGS 01 according to the deflection of the beam.

were modeled with solid elements (Figure 3). Pre-stressed elements were used to simulate the stiffing of the structure caused by the pre-stressed bolts. Contact elements represent the connection between the components with rigid or flexible contact without fiction. The load steps in the solution process for the nonlinear problem were arranges as follows: First, the bolts were pre-stressed representing the tightening with a force of 35kN per bolt. Then the beam was deformed equal to the shape of the eigenmode with 1 mm steps in y-direction.

A plot of the strain distributions is presented in Figure 3b and c. The plots illustrate the tensioned and compressed flange when the beam is deflected. Due to the flexible head plate the compressed flange retains on the concrete support whereas the tensioned flange wraps the head plate. This results in stress intensities at the transition from the I-beam to the weld and the head plate. Cracks at the weld could be predicted and the hot spots are clearly identified. The notch stress was not determined because the notch or weld and the according radius was not modeled [6] within the simulation.

In Figure 4b a comparison of the numerical results and the measurements of the master sensor are presented. The results agree very well with the measurements whereby the specimens T01, T02 and T03 were tested on the stress range level 1 and the remaining ones on level 2. The decrease of the strain range of T03 (green) is addressed to a weak fastening which accrued during the test.

Crack detection with strain sensor features

In this section the described features are applied to the strain gauge sensor signals. The raw data of temperature, deflection and strain with a sampling frequency of 100 Hz are compressed as described by Equation 1 and 2. The time period τ is defined with 1 minute. A complete set of the data is exemplarily demonstrated in Figure 5a to c for the specimen T05. This beam was tested on the lower stress range level and was excited with a frequency of 9.6 Hz.

The test for the T05 beam lasted around 4 days and as it can be seen in Figure 5a the temperature profile has clear sequences over the days. This indicates a stable high-pressure weather with a temperature range between night and day of approximately 20°C. The deflection range at the displacement transducer (Figure 5b) seems to change stepwise from day to day. This plot is interpreted as response of the structure according to the constantly vibrating exciter. It is evident, that the response changes with the temperature. Is the temperature increasing, the structure heats slower than the air and the response is lowest at the afternoon when the steel reaches its maximum temperature. It is assumed, that the structure softens with increasing temperature. When the temperature decreases in the night the response increases but does not reach the level of the day before. If one has in mind the response function of a structure with low damping (0.5 to 1.0 %) the bandwidth of a response peak is very narrow in the frequency domain. Hence a slight change in frequency in case of response results in a significant change of the response amplitude. In Figure 5c the vibration of the beam is explicitly mapped to the strain gauge signals. In the region of 1.5 million load cycles sensor 4 differs from the others. To clarify its behavior the feature of Equation 4 is applied to the sensor signals and a univariate outlier analysis is performed. The discordancy is given by

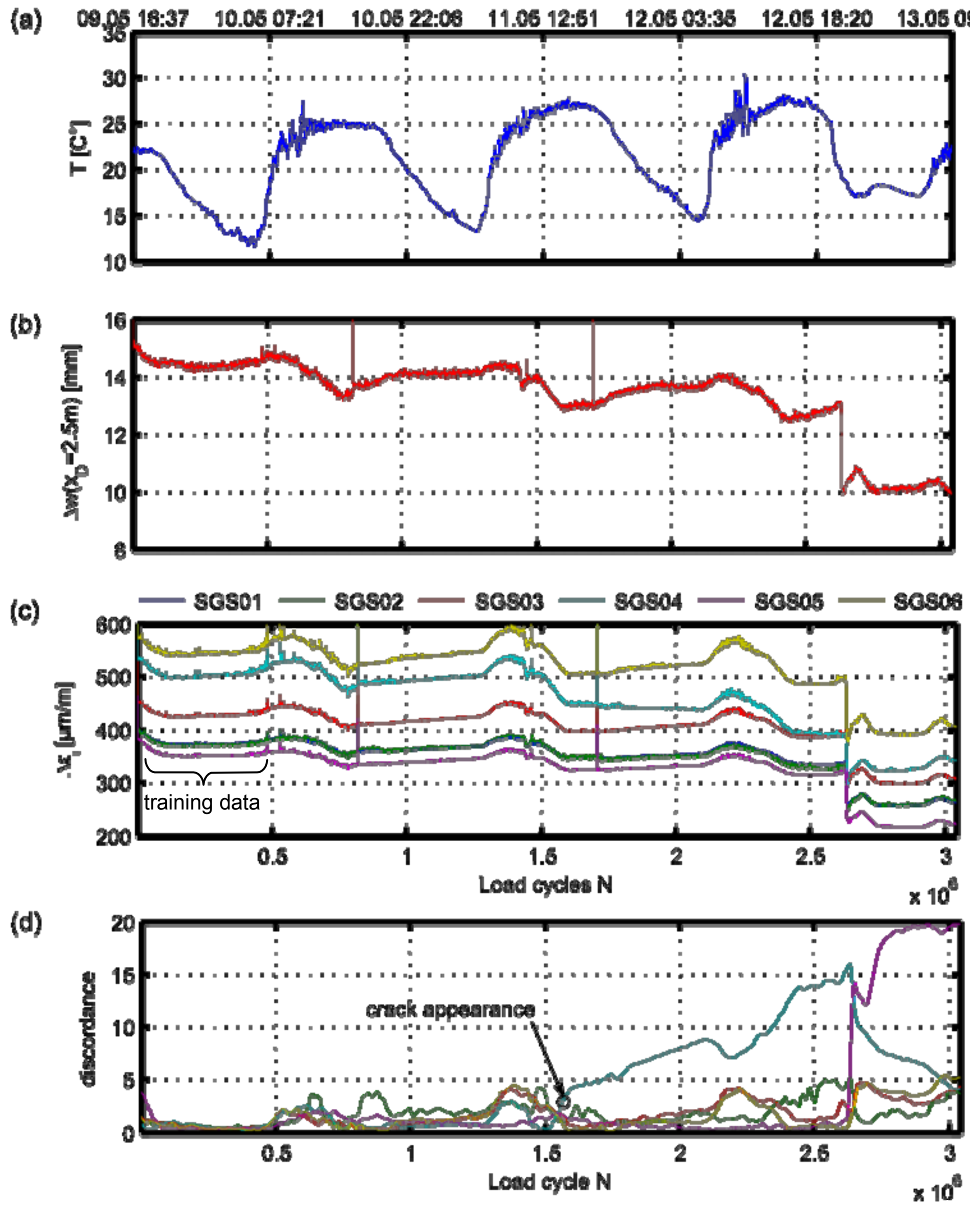

Figure 5. Compressed data of specimen T05. (a) temperature, (b) deflection range $\Delta f = f_{max} - f_{min}$ measured by the deflection transducer, (c) strain range of SGS01 to SGS 06 and (d) outlier of the extracted feature.

$$D_i[\tau] = \frac{|F_i[\tau] - \mu_i|}{\sigma_i}, \tag{6}$$

where μ_i is the mean and σ_i is the standard deviation of the senor *i*. The training data to determine the statistical parameters are taken from the fist 1000 sensor samples (baseline data).

The results are demonstrated in Figure 5d. In this plots the significant change of the sensor behavior is evident. A threshold for novelty detection was not assessed but with regard to the influence of temperature, 5 would be an exactable value. In the presented test a crack appears in the vicinity of sensor 4 after 1.563 million load cycles. The crack growth persists until 2.643 million load cycles when the response of the structure drops suddenly. At this point the crack has the critical size and the rigidity of the structure is lost. The structural change is now evident in the redistribution of all strain sensors. The detected crack is illustrated in Figure 6 and the visibility is only assured when the beam is vibrating and the opening and closing of the crack is observed.

CONCLUSIONS

The presented investigation clearly demonstrates that crack detection with strain gage sensors works perfect. If the hot spots of fatigue are evaluated by FEM the sensors are placed and cracks in the vicinity of the sensor are detected in an early stage. The introduced feature and the outlier algorithm respond clearly when a crack appears. Although the strain sensors are temperature compensated a deviation with change in temperature is observed. This is addressed to non-uniform temperature distribution of the beam.

From the presented analysis it is concluded that further feature and a clustering of novelties has to be achieved. The clustering would result in an accurate differentiation between environmental effects and the appearing of a fault. After some adoptions the SHM system will be applied on a noise barrier to get data from the passing train. The sensor net will be reduced to 1 master and 2 slave sensors and the long term stability will be tested in detail.

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