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Nondestructive methods for detection of hidden fatigue crack in the steel bridge element

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Abstract: In this paper we discuss applicability and usability of three non-destructive methods for investigation of fatigue crack propagation in railway bridge structural elements subjected to the repetitive loading. These methods are: an optical method based on the digital image correlation, the active thermography method and the classical x-ray radiographic method. In the section experiments we show that the results on the crack shape, its location and size obtained by these methods are in excellent agreement. At the same time the conditions at which the methods perform optimally differ making it a matter of a smart choice by experimenter to select the proper one.

Keywords: Fatigue crack, Detection, Non-destructive

1. Introduction

We study experimentally behaviour of orthotropic slabs, frequently used as railway and road bridges' construction elements, depicted on Fig. 1. These elements can support intense loads being at the same time light-weight, but the disadvantage is that they are prone to the fatigue damage due to the extensive use of welding in their production [1].

Series of experiments are planned to investigate the fatigue behaviour of these elements in harmonically changing repetitive loads. Our experience from the first experiments is that the fatigue cracks initially appear at the technological openings of the elements and then slowly grow up to predefined critical length at which the cyclic loading is stopped.

Our intention is not only to observe the crack growth, but also actively improve the elements' usability. To achieve this goal, we have decided to cement a carbon fibre textile patch on the most strained part of the element and study, how this stiffening influences the fatigue life of the element. At the end of the planned experimental work we will have three groups of specimens: the first resp., the second groups contain the elements in the original condition resp., with the reinforcing patch tested on the fatigue life, while each of the third group of elements is at the beginning subjected to the repetitive loading as the element without

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stiffening till its fatigue crack reaches a certain predetermined length. At this stage the reinforcing patch is applied and the element is tested for extension of its fatigue life. The last group simulates the typical situation when the fatigue crack is discovered during inspection on the real structure and the patch is applied as damage mitigation. If proved effective, it is clear that the service life extension of the engineering structures could bring a considerable savings and other potential benefits for the society.

2. Improved fatigue resistance of railway bridge elements

Fatigue is a phenomenon occurring in the metals parts of structures where a condition of small scale yielding is fulfilled due to local stress distributions caused by external repetitive loads and/or design geometry [2, 3]. Damage accumulation process initiates the fatigue crack first, then controls the speed of crack propagation, that determines the remaining service life of the structure. The service life of the structure can be improved by a careful choice of proper material and „fatigue-wise“ design. But, first of all, we have to take care of the bridges already in service, systematically search for methods, how to extend their service life or even loads they can safely support.

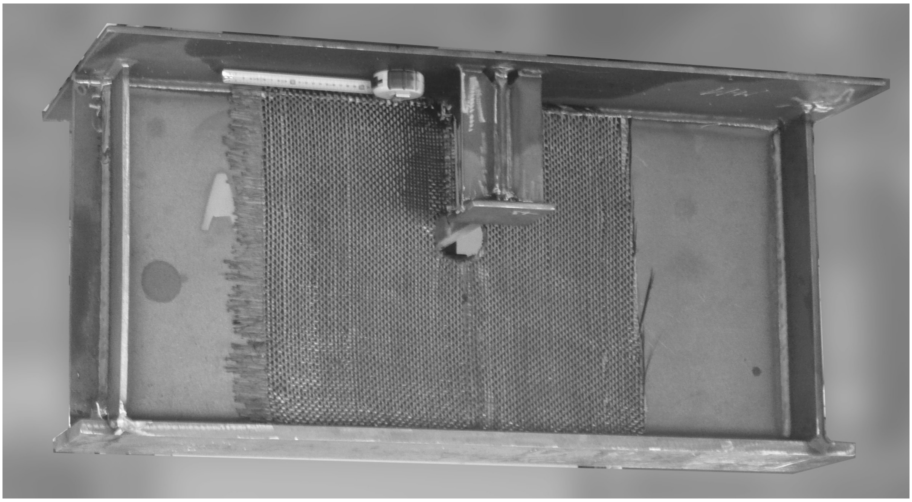

Fig. 1. Bridge element with applied carbon fibre patch on the slab with technological opening.

In our project we fulfil this far-reaching objective by observation of the effectiveness of adding the carbon fibre patches to the elements' service life. The idea behind this technique is to divide load between the original material and the patch, relieving some stresses from the metal part. The carbon fibres contribute with their stiffness and behave elastically up to their strength limit. When the fibres are bonded to the metal and then the whole part is subjected to the mechanical loading, the stresses in the both materials change elastically to accommodate the same strain. Once the yield point of the metal is reached, the proportion between stresses in the metal and the carbon fibres changes: the contribution of the fibres to the overall loads increases as a result of the fact, that the fibres are still in the elastic regime. However, this description applies only when the both materials are in the state of tension. As the sign of the load reverts during the cycle, the element is subjected to the compressive loading. In this state the fibres do not follow the plastic strain of the metal part. The reason for this is that fibres passed their elastic stability limit and start to prefer buckling to compression. The buckling of the fibres is accompanied with the breaking the bond between the metal and the patch and zeroing the patch contribution to the overall stiffness in compression.

The possibility that delaminated, but seemingly intact surface of the patch obscures the damage process evolution in the material underneath the patched element can lead to a potentially dangerous situation. It means that in these circumstances the crack can extend its length and the defect can reach a critical size preceding sudden collapse without recognizable signals. That is why a reliable monitoring of the crack length is necessary to truly take advantage of the fatigue life improvement of the bridge elements by the patch application. The following section compares three experimental techniques suitable for detection of sub-surface cracks.

Fig. 2. The radiograph of elements' opening (round white area on the right side of the image) with a fatigue crack depicted as a thin bright line propagating from the opening towards upper left corner of the image.

3. Experimental investigations by NDT crack detection methods

3.1. X-ray radiography

The method evaluates the dose of X-rays captured in imaging plate. To be more specific, the generator "Inspector XR200" as the X-ray source and the digital image plate system "DIMAP MK3" for scanning radiographs were used. The dose of radiation absorbed in imaging plate is related to the original intensity of X-ray radiation attenuated by the thickness and the density of the materials placed between X-ray source and the imaging plate. The important condition for proper radiography application is that the defect effectively reduces the thickness of the material. The presence of the crack in the plane normal to the radiation can, however, remain undetected.

In order to capture the defect, it is desirable to stop the loading cycle in the stage when the crack is the most open. Interestingly, in our settings it was in the unloaded state. Figure 2 presents the radiograph of the crack.

3.2. Digital image correlation

Digital image correlation (DIC) is used for computer-assisted acquisition of the displacement field on the surface of the studied body. The surface has to be covered with a random pattern of dots either of natural or artificial origin. Then the images of the body in the two different stages of loading are recorded. The image of the reference state is virtually divided into subsets and these subsets are searched for in the second image. The highest correlation between subsets in the two images indicate likely identical area.

The reason for DIC utilization and its huge popularity is its capability to automate determination of the displacement field. For more detailed description of DIC method see e.g. [4].

We have applied 2-color spray paint on the specimen surface and acquired two photographs at the opposite load extremes. The presence of the crack can be traced by step-like increase in the displacement field of the specimen surface (Fig.3).

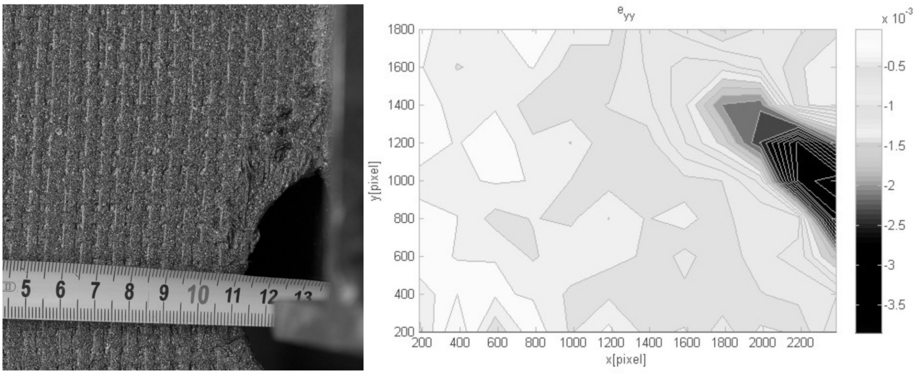

Fig. 3. The left part of the figure depicts two color paint sprayed on carbon fibre patch with attached measuring tape. The opening is shown as a black circular hole. On the right side of the figure strains determined by DIC method are presented in contour plots. The area of the highest strains corresponding to the darkest shadows of gray indicates the location and the extent of the crack.

3.3. Thermography

As the first attempt to use this method, the thermoelastic effect at the tip of the crack was searched for. The temperature range (fractions of degree of Celsius) and especially the shielding of the patch on the surface of the specimen were the main reasons for impossibility to detect and indicate change in the resolution of the thermocamera. Then the passive thermography method was replaced with the active one [5]. In this settings, the specimen was partially heated on the lower part of its back side and the transient temperature field evolution was then recorded. The presence of the crack has been revealed by an abrupt discontinuity in the temperature field as seen of Figure 4. The paint covering surface for use by DIC method was advantageous also for the thermography as it significantly reduced the reflectivity of the path and at the same time it increased the surface emissivity providing suitable conditions for the thermography.

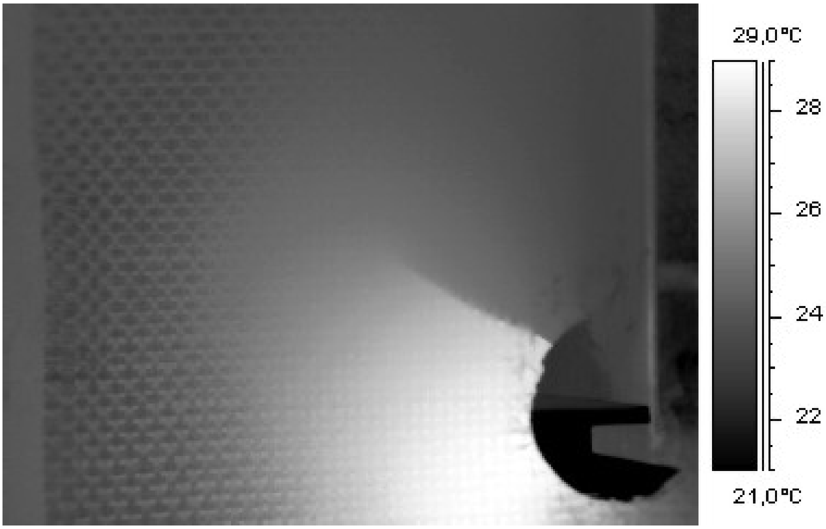

Fig. 4. Thermograph of the surface temperature around the opening. The crack acts as a barrier against the heat flow and therefore a notable discontinuity the temperature field develops.

4. Dicsussion

We have demonstrated that each of the presented methods successfully detected the crack and its length and location. It is also significant advantage that these methods are full-field, non-destructive and non-invasive techniques for detection of sub-surface damage. However, there are some differences and limitations of these methods that ought to be given careful attention. It means, due to underlying physical principles of these methods, it is not advisable to use them indiscriminately.

The thermography needs access to the back-side of the specimen for introduction suitable heat impulse to be studied in the transient heat field evolution, the impulse “propagates” through material slowly. On the other hand the slowness of the process contributes to the overall robustness of the method. Considerable advantage of the method is that can be used irrespectively to the state of the crack openness. On the other hand introduced heat shock is not possible to overlook as not influencing the whole system. In order to enhance the signal of the effect surface of the specimen has to be painted.

The DIC requires a specially treated surface by paint. As the main clue for crack detection is somehow discontinuous displacement field, the case when textile patch delaminates in substantial area, limits the possibility to “see” the crack, as two loading states are necessary for displacement field evaluation, the specimen has to be in loading device. On the other hand, access to the only one side of the specimen is necessary.

The X-ray radiography is capable of detection of the true dimensions of the crack. The highest contrast in the radiograph is attainable when the crack is captured in the open state. The principle of the method requires access to the both sides of the specimen. The method holds a health hazard as higher doses of X-ray radiation are required for dense metallic material penetration restricting its use in open-air conditions. The radiography method overcomes problems with delamination, which significantly limits applicability and resolution of DIC and thermography methods.

5. Conclusions

The methods presented in this paper do not represent a comprehensive list of all experimental methods available (for a complete review on NDT methods see [6]), they are not new and their application on the detection of the invisible crack is quite obvious. What makes it worth presentation is the simultaneous use of the methods offering a textbook clear comparison of their advantages and drawbacks at one glance.

At the same time we can state with some feeling of pride that the whole experiment was imagined and realized one afternoon in one hour time demonstrating the portability and the capacity of the rapid deployment of each of the discussed experimental method.

The last mentioned fact bring us back to the original motivation of the experimental work – finding means for extension of the service life of railway bridges. The true exploitation of the means for fatigue life extension is unthinkable without proper monitoring of the defect-prone parts of the bridges. The above mentioned methods set a standard that has to be met by any method selected for the monitoring.

Acknowledgements

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