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Comparison of fatigue crack detection methods for high-cyclic loaded steel structures

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ABSTRACT: At present, to produce renewable energy offshore wind farms play an important role. The available space combined with the more valuable wind conditions make offshore locations very attractive for wind powered energy production. In Europe a significant number of offshore wind farms already exist, especially in the North and Baltic Sea. In future this trend will continue, and further offshore wind farms will be built. The majority of offshore wind turbines are mounted on steel foundation structures. Due to the high-cyclic loading by wind and waves fatigue stress plays a substantial role regarding structural safety.

Besides the consideration of fatigue within the design process, to monitor existing steel structures for potential fatigue cracks during their life time is a major topic and a challenge.
For the structures of the offshore wind turbines are large and partially under water effective reliable methods for the detection of fatigue cracks are required.

This contribution presents investigations on different crack detection methods applied at high-cycle fatigue tests on small-scale welded steel samples as well as on large-scale welded steel components. The tests were conducted at the BAM laboratories. For crack detection mainly three different methods were used and compared. The first method regards to the measurement of strain by conventionally strain gauges. Secondly, the crack luminescence was used as a new and effective optical method for surface monitoring. And finally, crack detection by pressure differentials of the inner and outer section of tubular steel elements was investigated. A comparison study will emphasize the advantages and disadvantages of the different methods and show which of the described methods is potentially more suitable for an application on real offshore wind structures.

1 INTRODUCTION

The subject of material fatigue is of high relevance for several types of structures and structural components (Nussbaumer et al. 2018, IIW 2016). This applies in particular to structures of on- and offshore wind turbines, which are exposed to high cyclic loading. Cyclic loaded structural material as steel tend to show fatigue damage phenomena which finally might lead to fatigue failure (Pook 2007, Suresh 1994). Fatigue cracks as result of the fatigue process in structural steel lead to the weakening of highly stressed component details and are so of high relevance to the structural safety, also and especially for wind energy turbines.

Despite the safety margins in the design process of steel structures including the consideration of fatigue an accompanying monitoring during the structures service life is of significant importance (Farrar et al. 2006). Therefore, efficient and reliable methods for detecting and localizing fatigue cracks are of high interest for the operation of wind turbine structures. Those methods should fulfill different requirements. First, they need to be sensitive to fatigue cracks. They also should not work just locally, and last not least, they need to be long-term reliable. Possible methods could work as passive or active monitoring system and they could measure permanently or periodically. For a demanded crack detection system, especially the rough environmental conditions offshore are the essential challenge.

Within the framework of the here described experimental investigations several methods were applied and tested to study the fatigue detection behavior in the BAM laboratories. Investigations were executed on steel specimen (on material level) as well as on steel components with large wall thicknesses (on structural level). During these investigations, measurements have been carried out with strain gauges, with the method of crack luminescence and with the method of inner pressure. Aim was to determine the initiation of fatigue cracks as well as the break through event of a crack. The applied crack luminescence system was developed within a joint research project of BAM in cooperation with MR Chemie GmbH.

The contribution presents these investigations and the related results which will be compared and discussed. The results provide a basis for the suitability evaluation of the investigated methods regarding their application as detection method for fatigue cracks.

2 MEASUREMENT METHODS

In the presented study, three different measurement methods were investigated. For strain measurement strain gauges were used. For detection of crack initiation the crack luminescence and for the detection of the break through event the method of inner pressure were applied. The basic principles of these methods are shortly introduced.

2.1 Strain gauges

Strain gauges are widely used for the measurement of strain. They have a simple construction, are easy to use and have a high degree of accuracy and stability. The main principle is to measure the change in electrical resistance of wires embedded in the strain gauge caused by strain of the base material. Strain gauges are used for a relatively long time and a lot of experience is existent. The measured strain values are of high accuracy, although it is a local method which measures the strain exactly at the position of the applied strain gauge.

2.2 Crack luminescence

In addition to strain gauges the method of crack luminescence was applied. The method's principle is not to measure strain at the material but to detect cracks initially occurring at the material's surface (Makris et al. 2018, Mehdianpour 2015). In Figure 1 left, the basic principle of the method is illustrated. A crack luminescence system consists mainly out of two specific coatings. First, a special coating with fluorescent properties is applied on the steel component in the area of a potential fatigue crack (see Figure 1 right). In a second step the fluorescent coating is covered by a black coating. Since both coatings possess elasticity properties comparable to steel, in case of the appearance of a fatigue crack at the surface of the steel component both coatings will crack. Now on the crack edges the fluorescent coating layer lies open. With ultraviolet light (UV-lamp) the edges of the fluorescent layer and therefore the crack is clearly visible.

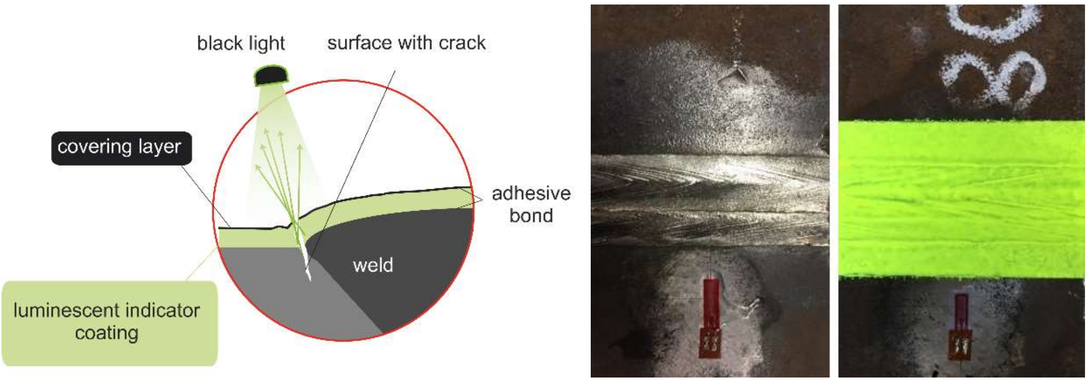

Figure 1: Schematic illustration of crack luminescence method (left) and example of an unprepared butt weld and the butt weld with luminescent coating (right)

This method enables the user to visually see the fatigue crack directly. Therefore, it is possible to determine the location of the crack as well as the length of the crack and also to observe the development of the fatigue crack.

2.3 Inner pressure

As a third method the monitoring of the inner air pressure of a closed component was investigated. This method requires components or structures with a closed and sealed volume like tubes or tanks. At the closed component a small over or under pressure will be applied. With an analog or digital manometer connected to the closed volume the state of inner pressure can be observed. An example of an inner pressure measurement setup is shown in Figure 2.

Figure 2: Measurement of inner pressure with analog and digital devices on tube

In case a fatigue crack grows through the components wall the inner pressure will start to adjust to the value of the atmospheric pressure. This pressure change can be measured and used as indicator for a break through event. The sensitivity relates strongly to the size of the observed volume and to the size of the fatigue crack as well as to the kind of cyclic loading. Furthermore, it indicates only the existence of a crack but provides no information about the location. This method is quite simple and a monitoring of the complete structure which forms the observed volume is possible.

3 INVESTIGATION RESULTS

The following experimental investigations were deployed on small-scale steel specimen as well as on steel components at the BAM laboratories. They were performed as fatigue tests on servo hydraulic test facilities at indoor climate. Within these tests fatigue crack initiation and crack break through events were generated on specimen with large wall thicknesses.

3.1 Crack initiation

The initiation of the fatigue crack was observed on material specimen as well as on steel components. The observation was done with strain gauges and crack luminescence. Some exemplary and characteristic results are presented in the following.

3.1.1 Material level

On thick steel specimen, high cyclic fatigue tests under tension load were performed. The specimens were butt welded steel plates with an effective cross section of 40 x 80 mm. An axial cyclic tension loading was applied with a frequency of 10Hz until the cross section was completely separated by the fatigue crack. Usually, the fatigue crack occurs near the butt weld. Therefore, strain gauges were applied in the middle of the specimen close to the weld (see Figure 1 right). One strain gauge on front side and one on back side of the specimen. Additionally, the region around the weld was prepared with crack luminescence on both sides to observe the complete area of the butt weld.

During the fatigue test the strains were measured continuously. Furthermore, the region of the weld was illuminated by ultraviolet light and permanent monitored by a video camera.

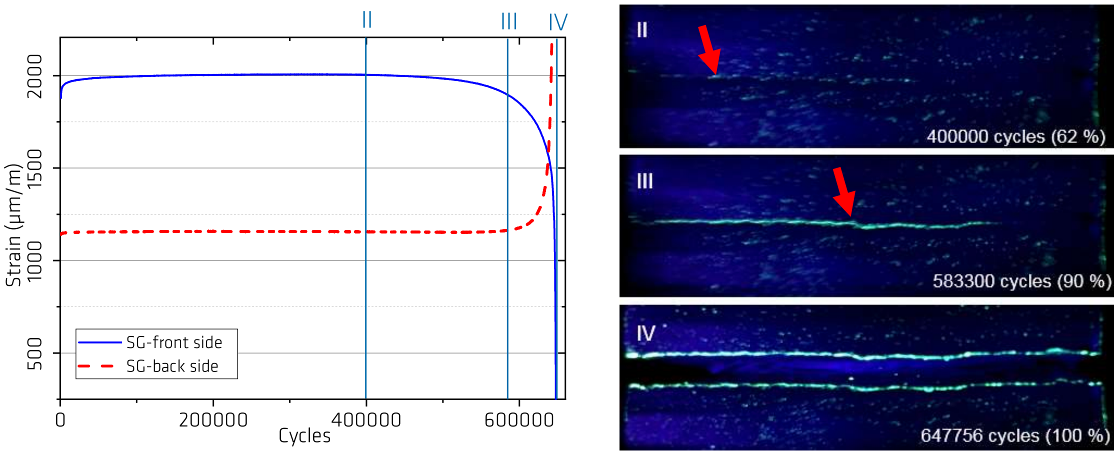

Figure 3: Development of strains on back and front side (left) and images of crack luminescence at different stages of fatigue process at the front side (right)

The development of the measured strains on both sides of the steel specimen are shown in Figure 3 left. Some images of the crack luminescence at different stages of life time are given in Figure 3 right. The three stages are also marked in the diagram of the strains (Figure 3 left).

The fatigue crack initiated at frontside of the specimen. The corresponding strain gauge signal shows a first slight decrease at about 62% of life time (mark II) as indication of a crack. Though, no change in strain was measured at the back side. At appr. 90% of life time a slight increase of strain at the backside was observed caused by stress redistribution while at front side at that point in time a decrease of 5% was reached. In the final stage both strain signals show an exponential progression up to failure of the specimen.

At stage II (62% life time) a clear blinking at the frontside of the specimen was observed in the crack luminescence video. However, this is not visible in the image of stage II in Figure 3 right. Later in stage III (90% life time) a significant long crack is visible (stage III) which finally leads to the failure of the specimen at about 647.756 load cycles (stage IV).

The measurements show a high sensitivity to crack initiation. But the strain gauges need to be placed close to the potential fatigue crack. On the other side, with the crack luminescence method a complete region can be observed and cracks are detected directly with their locations and their lengths.

3.1.2 Structural level

In addition to the tests on welded steel plates a fatigue test was done at component level on a butt-welded steel tube connection. The welded component was loaded under cyclic bending forces until a fatigue crack at the weld was initiated and has grown through the wall thickness. The measurement set up was similar to the above presented tests on steel plates. The strains were measured by strain gauges, applied outside on both sides of the weld, close to the weld and the expected crack location. In addition, the weld was monitored using the crack luminescence method.

Both methods were able to detect the crack initiation reliable and early between 24% and 26% of life time. In detail, the strain gauge was able to detect the crack slightly earlier than the crack luminescence. Otherwise, the crack luminescence method gives the exact location and the length of the crack. Using permanent video recording, it was also possible to observe the crack's development. At the time of crack detection by strain gauge and crack luminescence it was absolute impossible to visually see the crack by your eyes, even if the location was known.

As described, the usability of both methods for detection of crack initiation was confirmed. But it turned out that additional requirements were needed to achieved a sensitive measurement on the structural level. The optimal location of strain gauges could be hardly to be determined in advance. Also, the illumination and monitoring of larger regions for crack luminescence in a consistent quality is challenging.

3.2 Crack break through event

As a second case the crack break through event was investigated. For that experimental investigations at the structural level on butt-welded and closed tubes were executed.

The tubes were loaded under a cyclic bending load until a fatigue crack at the weld was initiated and has grown through the wall thickness. The crack initiation took place inside of the tube. The strains were measured with strain gauges applied outside at both sides of the weld close to the butt weld. They measured continuously. Inside the tube no strain gauges were applied. Therefore, the crack initiation could not be monitored directly.

For detecting of the break through event the crack luminescence was applied outside at the weld. It was illuminated by ultraviolet light and monitored permanently by a video camera. As for the strain gauges, no crack luminescence was applied inside of the tube for detecting crack initiation. The second method for detecting the break through event was the monitoring the inner air pressure of the tube. To do so, the tube was closed on both ends and a connection for air filling and pressure measurement was attached. A small overpressure of 0.5 bar was applied and permanently observed to detect the break through.

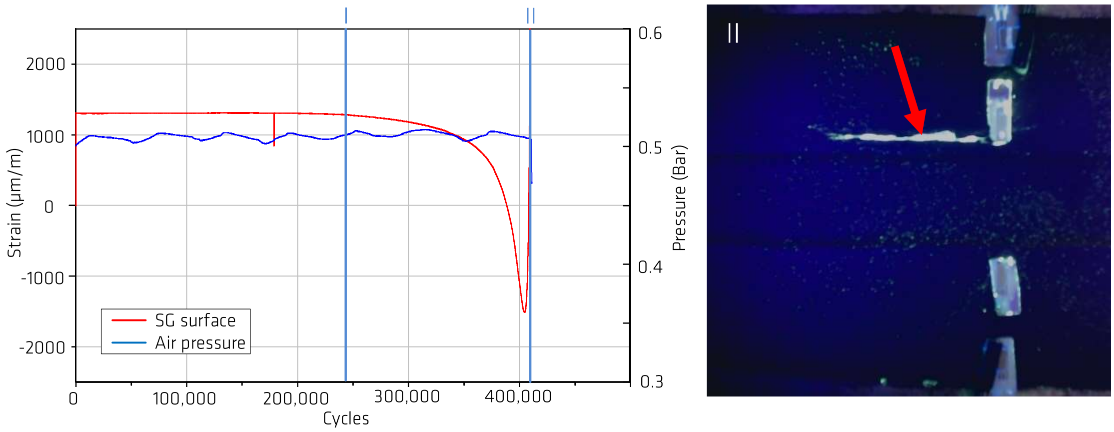

Figure 4: Strain development at surface together with inner air pressure (left) and image of crack luminescence shortly after the break through event (right)

Figure 4 left shows the development of strains measured by the strain gauge closest to the crack at the outside of the tube. Furthermore, the development of the measured air pressure is included in this diagram.

The crack initiation inside was at first measured by the strain gauge as a small decrease at stage I with about 58% of life time. In contrast to the strain measurement at the material specimen in 3.1, here a decrease of strain at the back side of the crack was measured. It was caused by stress redistribution effects within the tube structure. At the end significant compressive strains could be observed at this location before finally and again tension strains were measured.

As seen in Figure 4 left, the air pressure is stable for a long time only effected by daily influences. A significant and strong decrease as indication of the break through event was observed at 410,500 load cycles (stage II). The complete overpressure was lost during a relatively short time. With crack luminescence the break through was first detected at about 410,200 load cycles and therefore similarly to the air pressure. At stage II with 411,100 load cycles a crack was detected clearly (see Figure 4) which grew rapidly.

At the end the strain measurement at the opposite side of the crack initiation shows a sensitive behavior, related to the crack initiation. At the same time the strain measurement showed a different behavior in comparison to the measurements at the material specimen described in section 3.1. The break through event was detected very similar and reliable with the inner air pressure method and the crack luminescence method. The crack luminescence provides the location and the size of the crack while the air pressure loss is totally independent of the crack location and therefore gives no information about the location.

4 DISCUSSION AND CONCLUSION

In chapter 3 several experiences and results were presented for the detection of fatigue crack initiation and break through events of different fatigue tests. As detection methods strain measurements (strain gauges), crack luminescence and inner pressure were applied and compared. The fatigue tests were performed on steel specimens (material level) and on steel components (structural level) with large wall thicknesses. All three methods have individual limits of application as well as advantages and disadvantages. They will be evaluated based on experiences of the laboratory investigations, presented in this contribution.

4.1.1 Crack initiation

Strain gauge and crack luminescence show a very good and similar behavior of detection. The inner pressure method is not capable to detect crack initiation. Strain gauges need to be located very close to the potential crack position which must be known in advance. The measurement is very accurate and reliable. Though, information about the precise location of the crack and its length is hardly possible. The strain gauge is installed and measured permanently. Therefore, sufficient application at big structures with a number of potentially locations for fatigue cracks will be difficult and complex.

The crack luminescence method is able to observe a complete region. Therefore, the location of potential fatigue cracks has to be known only approximately. It is possible to detect the precise location as well as the length of the crack. Measurements must not be performed permanently, and measurement technique does not have to be installed permanently. Based on that, this technique is principally more suitable for large structures, compared to strain gauges. Although, it makes no differentiation between crack initiation and break through event.

4.1.2 Break through

Both methods, crack luminescence and inner pressure, show a suitable behavior and similar accuracy in detecting a break through event. Though, this statement strongly depends on the specific geometry of the considered structure. Strain gauges are hardly suitable for they need to be positioned exactly at the location of the break through crack.

Crack luminescence is not able to differ between crack initiation and break through event. It must be known in advance, on which side the cracking starts. On the other hand it is able to monitor a complete region of a potentially break through event. Furthermore, the precise location, the length and eventually the development of the crack can be determined. It is suitable for large structures and it is able to detect more than one crack with equal accuracy.

The measurement of inner pressure is only possible at closed and sealed structures like tubes. It only detects the break through events and is a simple method. The measurement system needs to be installed and operated permanently. The complete structure enclosing the measured volume is observed. The sensitivity is strongly dependent on the size of the volume, the size of the crack and the type of loading at the crack location. For the application of this method nearly no information about the potential location of the crack is needed. On the other hand, nearly no information will be received about the location, the size and the development of the crack. Further cracks on the same structure are also hard to be identified with the measurement.

4.1.3 Conclusion

For detecting crack initiation, the crack luminescence method as well as the measurement of strains by strain gauges showed a good suitability. However, strain gauges require an accurate knowledge about the potential crack location and crack luminescence is incapable to differ between crack initiation and break through. For the detection of a break through event, a good suitability was principally verified for the measurement of inner pressure as well as for the crack luminescence method. However, the inner pressure method can only be used on structures with closed volumes and its sensitivity depends strongly on the observed structure. In contrast, the crack luminescence method is very sensitive, though for the user it is hard to differ between crack initiation and break through, as mentioned before.

It must be considered, that the presented results only provide experiences with the three described methods, applied in the laboratory. But they give directions for possible applications on real structures. All methods have their advantages and disadvantages and it must be decided in each individual case about which methods will be more suitable. Further investigations related to methods for detecting fatigue cracks are planned at BAM.

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