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Citation for the original published paper (version of record):
al-Karawi, H., Franz von Bock und Polach, R., al-Emrani, M. (2021)
Crack detection via strain measurements in fatigue testing
Strain, In Press
http://dx.doi.org/10.1111/str.12384

(article starts on next page)

Received: 5 January 2021 | Revised: 11 February 2021 | Accepted: 1 March 2021

DOI: 10.1111/str.12384

FULL PAPER

strain WILEY

Crack detection via strain measurements in fatigue testing

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Funding information
Trafikverket; VINNOVA; Swedish Innovation Agency; Swedish Transport Administration

Abstract

Fatigue cracks have appeared as a significant issue for joints and connections in existing steel structures in the last decades. Therefore, those are a major inspection and maintenance matter for any steel structure's operator. This emphasises the importance of using a reliable detection method to determine the crack size and assessing the severity of such a crack on the structural integrity of a structure. In this article, the effectiveness of strain measurement in detecting fatigue cracks in transversal non-load carrying welded attachment subjected to out of plane axial loading is studied. Numerical analysis and experimental investigations allowed to correlate the decrease in strain measured by attached gauges to the crack depth at the weld toe. In addition, different strain evolution patterns were found during fatigue testing, and the fracture surfaces of the specimens were observed to interpret these patterns. Moreover, the crack position with respect to the weld toe surface was predicted via strain measurements.

KEYWORDS

crack detection, fatigue crack, fatigue testing, strain gauge, transversal attachment

1 | INTRODUCTION

Steel structures under cyclic loading are prone to fatigue damage, which is in welded structures triggered amongst other causes by notches, residual stresses and thermal impact. Fatigue is a localised progressive structural damage that occurs when the metal is subjected to repetitive loading that produces increased stresses at specific points such as connections. Fatigue damage accumulation eventually causes crack formation at highly stressed regions degrading the structural integrity significantly. If the structure is not continuously inspected or preventively maintained, fatigue cracks are expected to increase in size and lead to structural failure. Therefore, crack inspection has gained increasing interest amongst the operators lately, and regular maintenance programmes have been introduced in several manuals and recommendations.[1,2]

Structural health monitoring is an important step in evaluating the current conditions of the structure and updating the authorities with quantitative data on the structural condition, behaviour, load-carrying capacity or any form of deterioration. It is also essential for specifying the reasons behind material's deterioration, assessing the deterioration rate and estimating the residual life of the structure. Moreover, crack inspection is important for evaluating the necessity of maintenance or strengthening. It also serves in estimating the degree of damage and the potential costs to remove or control such damage.

There are several methods for inspecting cracks in welded details. These methods can be classified into several categories. In the first category, visual inspection and some aids such as dye penetrant or magnetic particles are used to specify the crack length and position. The second category comprises the methods which identify the crack position without determining the crack length or depth; infrared thermal imagining is an example of this category. In the third category, the crack depth is estimated via signal transfer such as ultrasonic testing. Fractomat/Krak Gages is another example of this category which works on the basis of the indirect potential drop method.[3] The last category comprises deformation or strain measurement, which also can be used to indicate the crack propagation's severity. The interested readers are referred to Al-Karawi et al.[4] for more detailed information on different crack detection methods in welded details.

Strain measurements have been extensively used for monitoring crack progression during fatigue testing.[4] Digital image correlation (DIC) is an optical method that can be used to acquire the overall two-dimensional or three-dimensional strain field in the area of interest. It was found that this method allows direct observation of microcracks and their propagations until the rapture.[5] The application of strain gauges and extensometers enables accessing the local stress distribution and changes. Special gauges manufactured by Hottinger Baldwin Messtechnik (HBM) commercial company can determine the crack propagation in different components. These gauges are available in different sizes and models to fit pieces of different geometries.[6]

In welded components, strain gauges are placed near the weld toe where the cracks are expected to initiate. For weld ends (e.g. longitudinal attachment), few strain gauges are enough to cover the potential crack area, whilst more strain gauges are required for transverse welds (e.g. butt welds and cruciform welded joints). Leitner et al.[7] found that a 20% decrease in the strain measured by an attached strain gauge at the end of longitudinal attachment corresponds to a 1.0 mm crack. Branco et al.[8] and Ramalho et al.[9] detected cracks of different depth from 1.3 to 6.1 mm by three strain gauges attached on both sides of transverse attachment. Al-Karawi et al. found a correlation between the strain drop and the fatigue crack size in transversal attachment.[10] Moreover, Otegui et al.[11] attached 10 strain gauges on T-joint welds to detect crack initiation and early crack growth.

Determining the existing crack size in any welded structures is very crucial in assessing the urgency of crack repair and selecting the right repairing method. The application of several post-weld treatment methods is limited by the existing crack size at the weld toe.[12] Besides, the residual fatigue life is also dependent on the existing crack size which implies that the inaccuracy in crack detection influences the remaining fatigue life.

The studies on crack detection in welded components via strain measurements are few in number. Moreover, the aforementioned studies[4,8,9,11,13] did not emphasise how the correlation between the crack size and the strain drop was obtained, calibrated and verified. Besides, the strain gauges were never—to the best of the author's knowledge—been used to identify the crack initiation position with respect to the surface. Therefore, this paper investigates cracks in transversal attachments using several strain gauges attached at the weld toe. The correlation between the strain drop and the crack length was verified and calibrated by numerical analysis and destructive and non-destructive testing. The effect of uncertainty in detection using strain gauges on residual fatigue life was studied numerically. Moreover, light was shed on the causes of obtaining different patterns of strain evolution during fatigue testing.

2 | METHODS

In order to understand and explain the dependency of the crack size on the strain field in the crack vicinity, three-dimensional numerical analysis was conducted using the commercial finite element analysis (FEA) software ABAQUS/CAE 2017. The numerical analysis was employed to find out the best configuration of the required strain gauges in order to detect short cracks. The study was limited to short cracks which post-weld treatment methods (e.g. grinding or ultrasonic impact treatment) can repair and cause a significant prolongation of fatigue life of the treated detail. Besides, in order to study the effect of uncertainty in crack detection on residual fatigue life, crack propagation analysis was conducted using the commercial two-dimensional finite element programme FRANC2D. The mesh was generated using the mesh generator CASCA.[14]

Fatigue tests were conducted on transverse non-load-carrying welded attachment under constant amplitude loading with a stress range $\Delta\sigma = 150$ MPa and a stress ratio $R = 0.29$ at room temperature. The specimens were made of S355 structural steel, and the weld filler material was made of metal core weld (C6LF). The material properties of both are given in Al-Karawi.[10] The testing rig and dimensions of the specimen are shown in Figure 1. Several auxiliary crack detection methods were employed to calibrate the strain drop against the crack size. A red dye penetrant was applied regularly during fatigue testing at the surface of the specimens. The dye penetrant flows into the crack, and the cyclic loading causes small bubble formations on the top of the crack indicating its position and size. Moreover, this would stain the crack surface and make it more distinct in later investigations (see Figure 2). The back wall of the specimens was scanned by ultrasonic testing. The scanning was repeated at several intervals in order to monitor any change.

Following ultrasonic testing, the measured crack size was verified by cutting the specimens in a position parallel to the weld line. Subsequently, some specimens were sliced in several pieces perpendicularly to the weld lines in order to make a metallographic inspection and visualise the crack shape, and polished sections were produced. Thereafter, the processed slices were investigated by an optical microscope in order to specify the crack initiation location.

3 | RESULTS

3.1 | FEA

Several three-dimensional finite element analyses were conducted on transverse non-load carrying welded attachments with different crack depths from 0.5 to 3 mm. In each analysis, a semi-elliptical crack shape was assumed with an aspect ratio $a/c = 1/10$. The aspect ratio was selected in accordance with the recommendations of the international institute of welding IIW.[1] The crack was modelled by assigning a two-dimensional partition in the geometry.

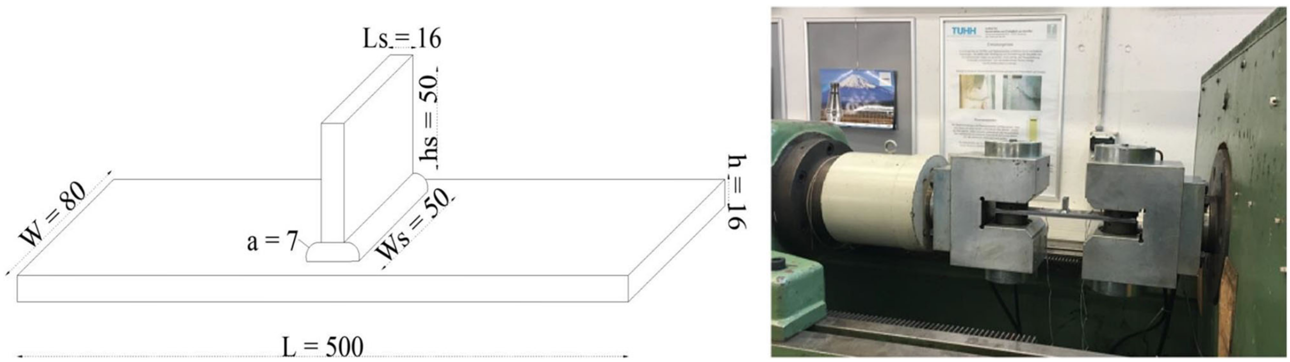

FIGURE 1 L: Dimensions of the specimen.R: Fatigue testing rig

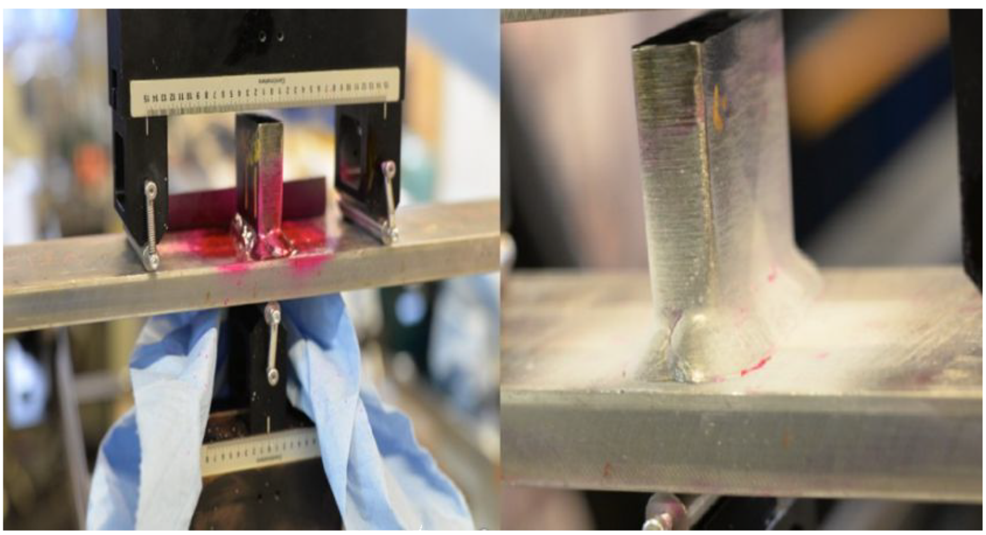

FIGURE 2 Red dye penetrant to expose the crack surface

Overlapping nodes were defined at the faces of the seam, which can separate during the analysis. The results of the analysis were acquired when the crack was fully opened. Elastic material proprieties were considered with Poisson's ratio $\nu = 0.3$ and Young's modulus $E = 210$ GPa.

Tensile axial stress with a stress range $\Delta\sigma = 150$ MPa was applied to open the crack surfaces. Double symmetry boundary conditions were considered to reduce the analysis effort. Ten-node quadratic tetrahedron solid elements (i.e. C3D10 in Abaqus notation) were used to create the mesh. About 1 mm element size was considered everywhere in the model except the area around the modelled crack where the mesh size was refined to 0.1 mm. The choice of the local mesh size was based on a convergence study in the local strain values. The model is described in Figure 3.

The effect of the crack depth on the surface strain at different positions from 1 to 5 mm off the weld toe was studied. These positions resembling the centre of the presumable attached strain gauge in the experiments (see

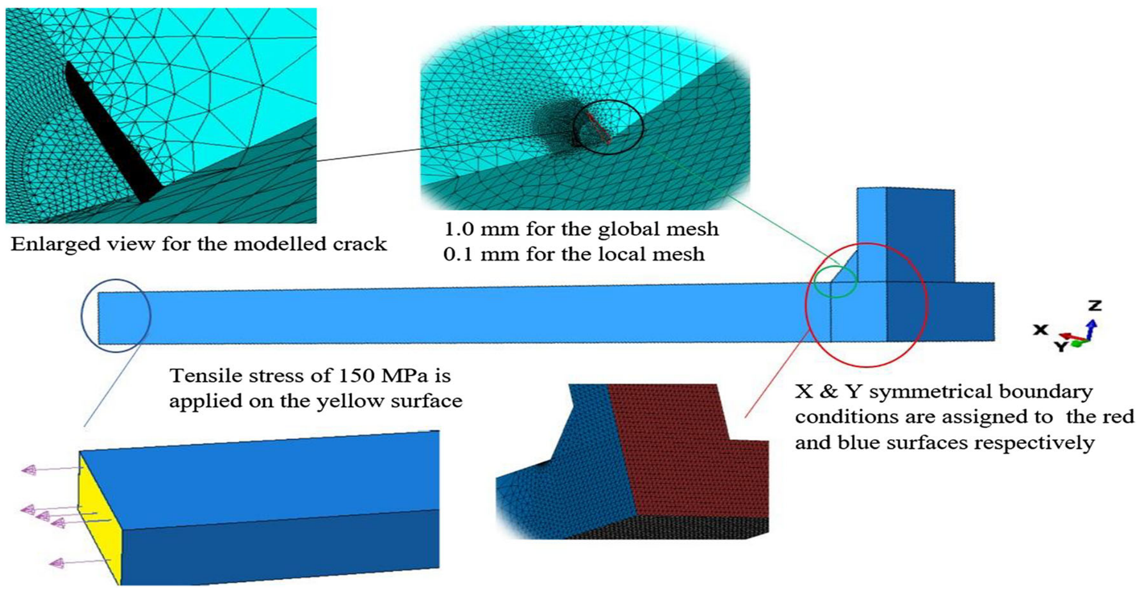

FIGURE 3 Finite element model description of cracked transverse attachment

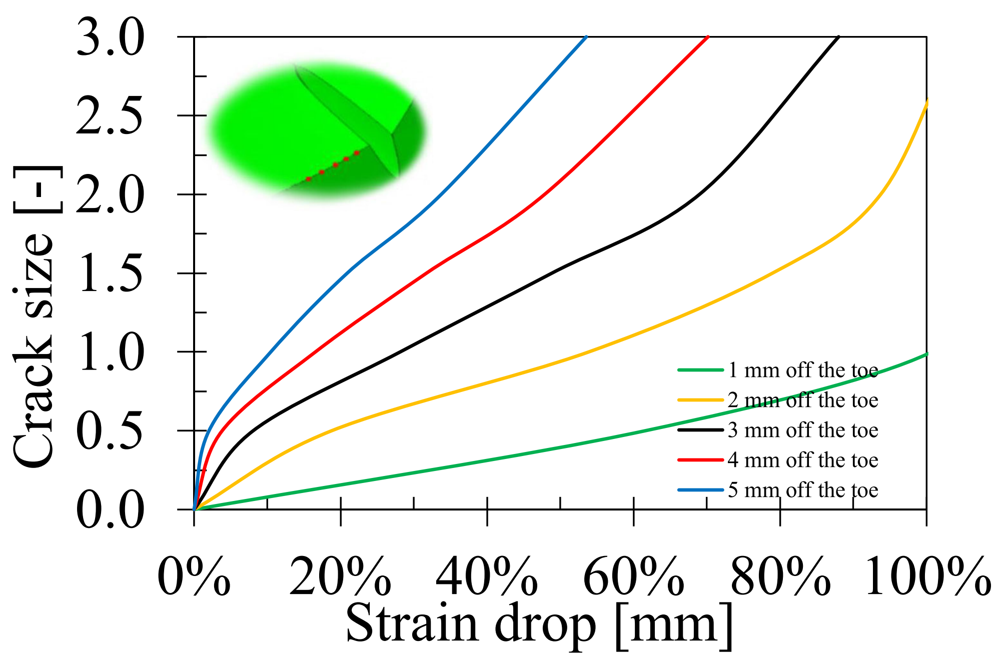

FIGURE 4 Crack depth effect on the surface strain values measured at different positions

Figure 4). More tangible strain drop can be obtained for deep cracks. In addition, the crack would be sensed earlier (i.e. at a smaller strain drop) if the strain gauge is placed closer to the weld toe. However, the strain gauges are sensitive and might become damaged during the dye penetrant application. Hence, their links should not be placed right at the weld toe.

The crack might initiate anywhere over the weld line, which implies that several strain gauges were needed to cover the whole attachment length. Hence, if the crack initiates between two adjacent strain gauges, it would be sensed later, and a smaller strain drop would be obtained. This is illustrated in Figure 5, which presents a sensitivity analysis of the lateral shift of the strain gauge with respect to the crack centre. The different coloured curves in the figure refer to different studied crack sizes (i.e. $a = 0.5, 1, 1.5, 2$ mm). Herein, there will be no tangible strain drop if 1 or 1.5 mm crack initiates 4 or 5 mm from the crack centre respectively.

In the light of the conducted analysis, each specimen was instrumented with a total of 10 strain gauges, 5 at each side. The centre of the gauge was placed 2 to 3 mm off the toe. This way, more than 30% strain drop would be obtained when a crack deeper than 1 mm existed at the weld toe. However, the crack might initiate in the mid distance of two adjacent strain gauges. Therefore, a lateral distance between gauges of 6 mm (i.e. 3 mm is the maximum possible distance of the crack centre) was selected so that the strain drop can be still tangible. The configuration of the attached strain gauges is shown in Figure 6. The used strain gauges (which has a designation number of 1-LY1x-0.3/120) were ordered from HBM manufacturer.[6]

3.2 | Experimental results

The instrumented specimens were fatigue tested under a stress range $\Delta\sigma = 150$ MPa and a stress ratio $R = 0.29$. The strain drop was observed, and the destructive and the non-destructive testing mentioned in Section 2 revealed the existing crack sizes. An inverse correlation was found between the obtained crack depth and the strain drop measured by any of the attached gauges as shown in Figure 7. It is mention-worthy that this correlation can be solely used for similar transverse attachment with similar strain gauge configuration.

If different geometry is to be studied, FEM analysis is needed to correlate the strain drop to the size of the crack. Based on the measured crack surfaces, a relationship was established between the crack length and crack depth (see Figure 8). Despite having a good coefficient of correlation, the crack length cannot be used to reflect the crack depth, especially for shallow cracks. For instance, a crack depth of 1.6 mm corresponds to a crack length of either 6 or 11 mm. Nonetheless; surface crack detection can still be beneficial in assessing the severity of the crack.

The change in strain values measured by the attached strain gauges during fatigue testing was recorded, and different progression patterns were plotted in Figure 9. The tests were aborted when a 25% drop in any of the attached

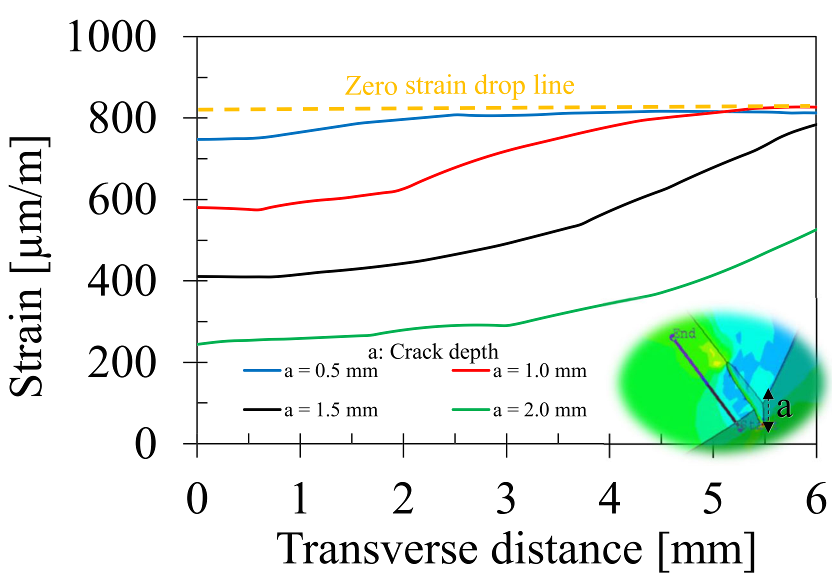

FIGURE 5 Crack depth effect on the surface strain values measured at different positions

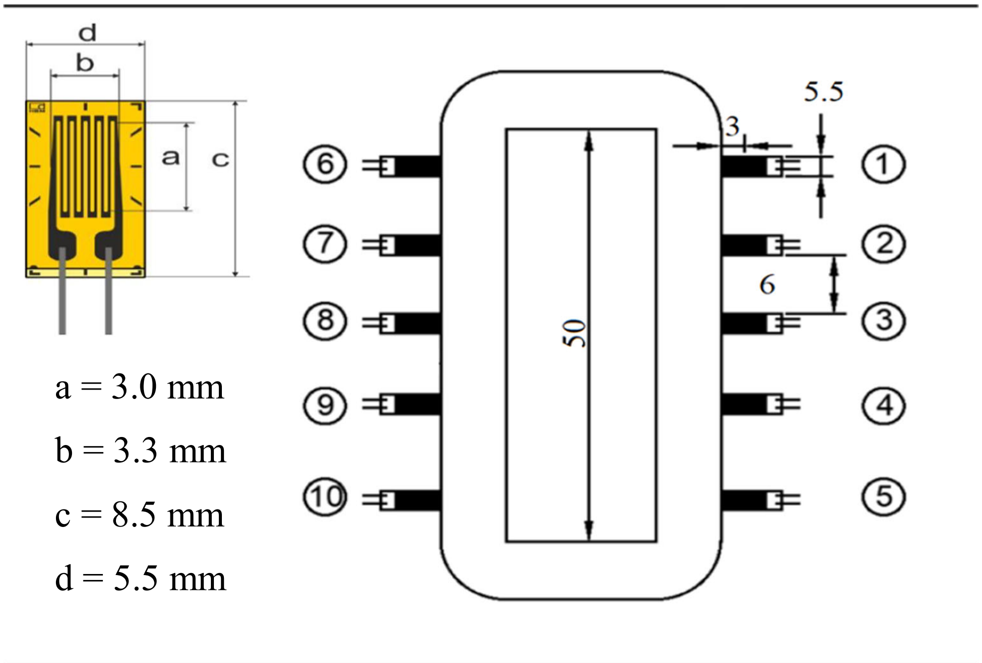

FIGURE 6 Strain gauge configuration and the selected gauge parameters

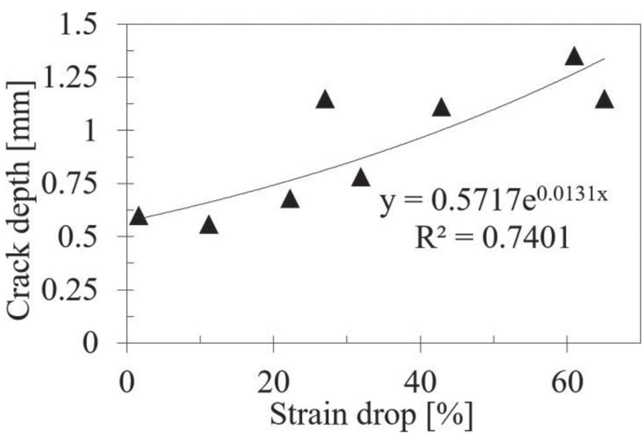

FIGURE 7 Crack depth versus strain drop correlation

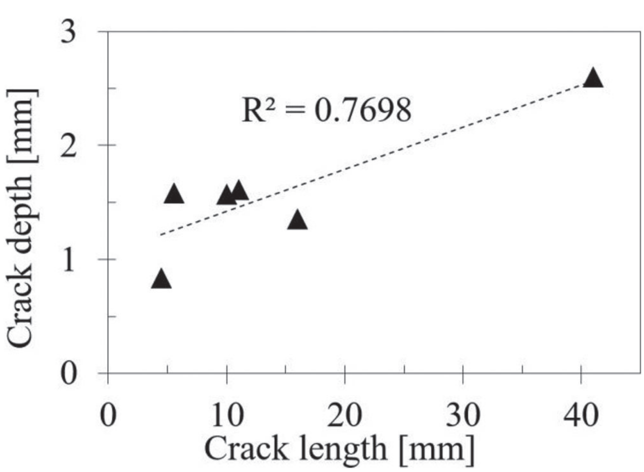

FIGURE 8 Crack depth versus crack length

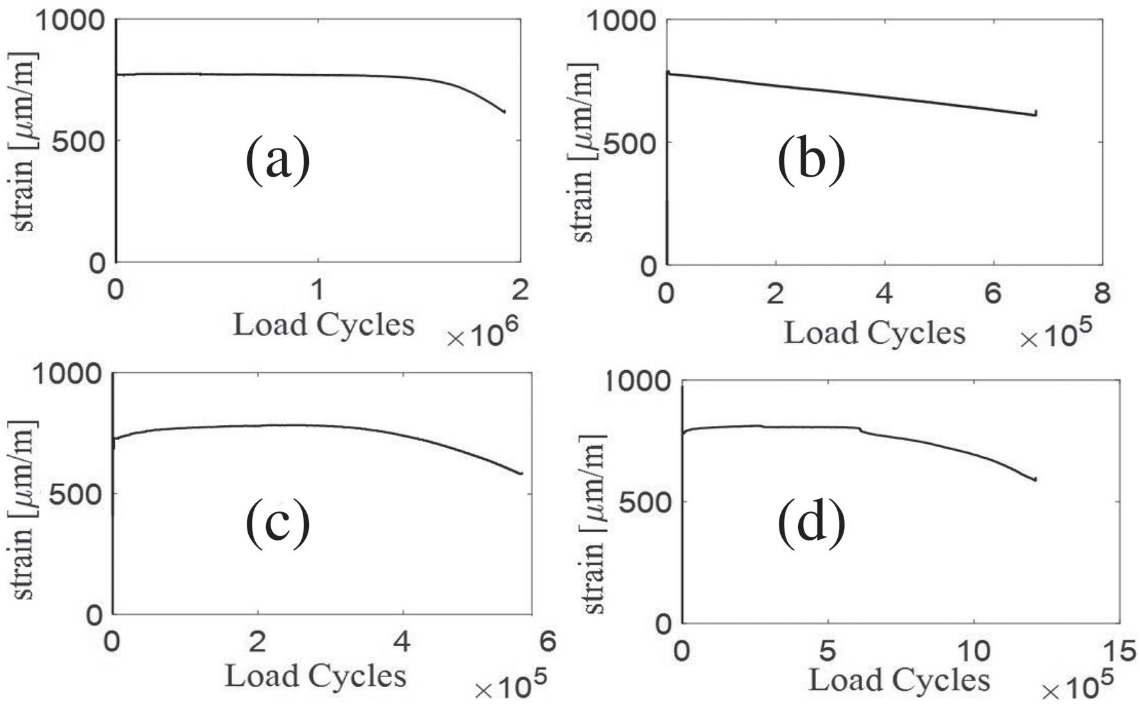

FIGURE 9 Different mean strain drop patterns observed during fatigue testing

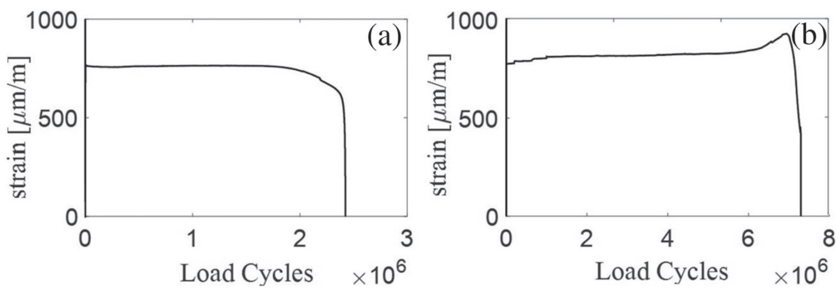

FIGURE 10 (a, b) Difference between the strain drop pattern for surface and subsurface cracks, respectively

gauges was reached. In some cases, the strain value decreased from the beginning (i.e. case B) which might be explained by the presence of an undercut close to the strain gauge location. This implies that crack initiation life is short. In case C, strain increase followed by a decrease was observed (i.e. curve concaved down); this might be explained by the local strain hardening in the steel grains at the weld toe. On the contrary, the steel grains might be weaker in cases A and D, which explains why the strain did not show a significant increase.

Two additional different strain drop patterns are given in Figure 10. Herein, fatigue tests were aborted at failure. The first pattern in the figure (case A) is similar to the patterns shown in Figure 9. However, the second one (i.e. case B) was different as the strain suddenly increased after six million cycles. Therefore, these two specimens were prepared for metallographic inspection and investigated using an optical microscope, as described in Section 2. The surfaces of the prepared slices are shown in Figure 11. On the left figure, the crack was nucleated from the surface and propagated downward. On the contrary, the crack nucleated below the surface in the right figure and then propagated upward until it reached the surface. When the crack nucleated below the surface, then the stresses were redistributed around the crack to bear the load. This led to a stress increase at the surface in the crack initiation phase, which is seen in Figure 10b. The figure also shows the unremoved spatter from the first welding run, which caused the subsurface crack nucleation.

In Figures 9 and 10, only one curve was plotted per specimen. This was motivated by the formation of a single crack in each specimen which resulted in a remarkable decrease in strain in the closest gauge. The rest of the gauges exhibited little or no strain drop. Nevertheless, the formation of multiple cracks in transverse welds subjected to fatigue loading is possible[15] and was also observed in the here presented experiments. In two of the studied specimens, strain drop was obtained in two adjacent strain gauges (see Figure 11). The rate of strain drop was faster in the red curve at the beginning of fatigue testing. Then, the drop in the black curve became larger (Figure 12).

The fracture surfaces of these two specimens were prepared and presented in Figure 13. In the first one (case A), two adjacent cracks were observed ahead of the position of the strain gauges. The small crack might have initiated first, then the big crack formation caused both a strain drop in the corresponding gauge (i.e. black curve) and an increase in the strain in the adjacent one (i.e. red curve) due to stress redistribution. On the other hand, 35 mm long crack was found at the positions of several strain gauges (including the two ones shown in Figure 12) in the second specimen (case B). This long crack might have consisted of several cracks which thereby merged under fatigue loading.

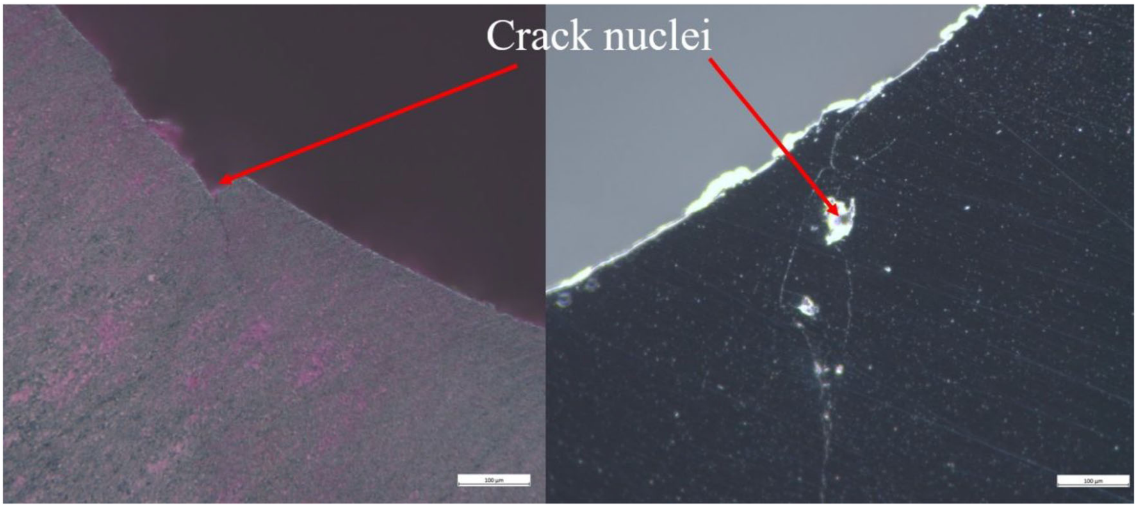

FIGURE 11 Surface and subsurface crack nucleation, respectively

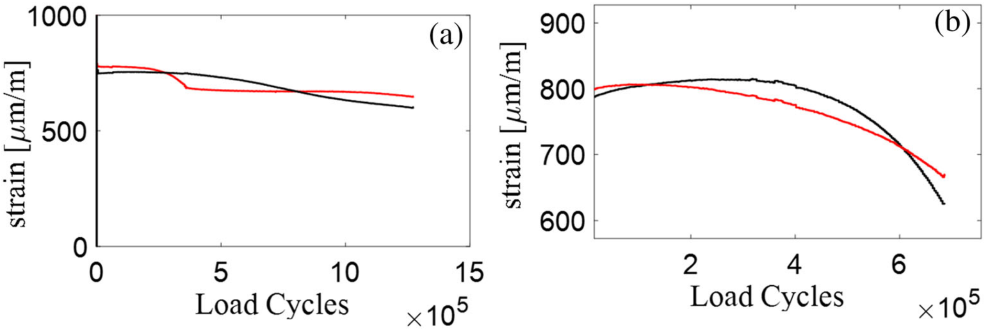

FIGURE 12 (a, b) Examples on strain drop in two adjacent strain gauges

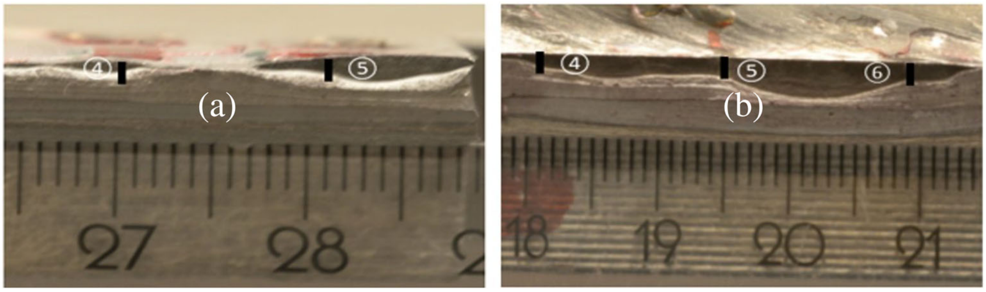

FIGURE 13 (a, b) Fracture surface of specimens corresponding to Figure 12

4 | DISCUSSION

4.1 | Crack size versus strain drop

The results from the FEA were compared to those obtained from destructive testing in Figure 14. The strain values were acquired at 3 mm off the weld toe. The figure shows that the crack size corresponding to specific strain drop obtained from FEA was smaller than those obtained from destructive testing. This is because the crack initiation position might be transversely shifted from the strain gauge, as shown in Figure 5. However, the error was relatively small, and the use of FEA in controlling the number and the location of the required strain gauges for crack detection was validated.

4.2 | Crack initiation position versus strain evolution

The crack initiation positions varied between the specimens. This can be explained by the local differences between them. These differences can be related to either the local geometry (i.e. undercut height) or residual stress. An undercut is a weld flaw that causes a local reduction in the cross-sectional thickness of the base metal near the weld toe due to the excessive heat associated with welding. Three-dimensional geometry scanning was employed to investigate the undercut height distribution in different specimens, see Figure 15. The figure shows how the position of the largest undercut in each specimen (i.e. marked with coloured circles) varies for each specimen.

In addition to the undercut height, the difference in crack initiation positions can be traced back to the residual stress distribution in different positions over the base plate. The hole drilling method was employed to investigate the in-depth distributions of residual stress in different locations over the weld toe; see Figure 16. The sign of the surface residual stress in both measurement points was compressive which is favourable for fatigue strength. However, this favourable effect is dependent on the amount of residual stress which differs largely in both measurement points.

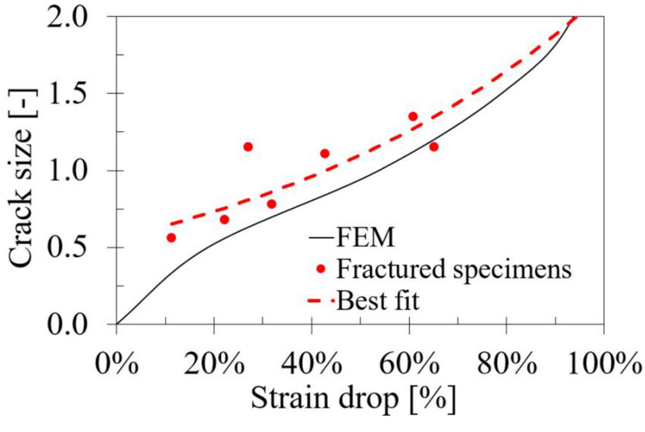

FIGURE 14 Strain drop versus crack depth

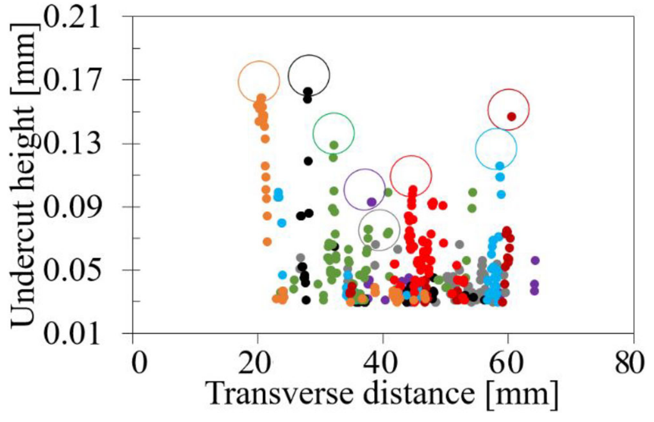

FIGURE 15 Undercut height over the base plate width (the maximum in each specimen are circled)

In order to confirm that the difference in crack nucleation positions caused the differences in strain patterns shown in Figures 10 and 3d, linear elastic FEA was conducted. The same loading and boundary conditions described in Section 3.1 were used. Eight-node linear brick elements with size 1 mm were used in the model. The crack propagation was simulated by deactivation of the element at which the crack reaches. The elements were removed sequentially in each step. In total, five steps were run, and five elements were removed. Two cases were considered: the removal of the elements started from the top (surface crack) and propagated downwards in the first case. Subsurface crack was simulated in the second case by removing the bottom element first and top element at the end.

Figure 17 shows the analysis results for surface and subsurface cracks. Noticeably, the curve corresponding to subsurface crack is similar to the one shown in Figure 10 (case B). The strain increased as the effective area underneath decreased because of the crack formation. This reasoning can again be used to explain the strain increase in other gauge neighbouring the closest gauge to the crack (see Figure 18). On the other hand, the curve that corresponds to the surface crack does not look identical to case A in Figure 10. This is because the first step of the analysis started with cracking the top element, whilst more than 2×10^5 cycles were required to cause a crack formation and a drop in strain value in reality as shown in Figure 10.

4.3 | Detection's uncertainty versus residual fatigue life

The use of strain measurement entails some uncertainties in crack detection as mentioned earlier. For instance, a strain drop of 25% can correspond to crack size from approximately 0.6 mm to approximately 1.2 mm, as shown in Figure 7. In order to study the effect of this uncertainty on residual life, two crack propagation analyses were conducted using

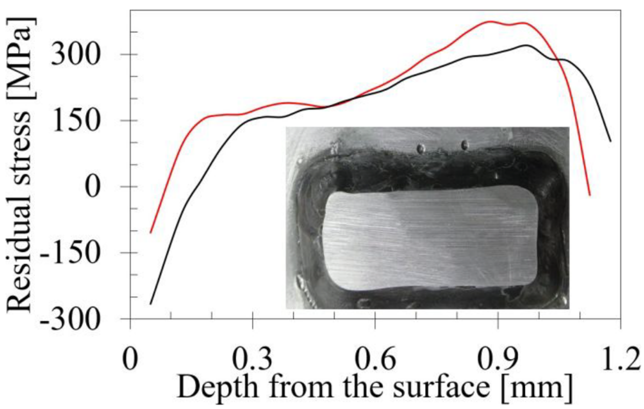

FIGURE 16 In-depth welding residual stress distribution for two different positions in the same specimens

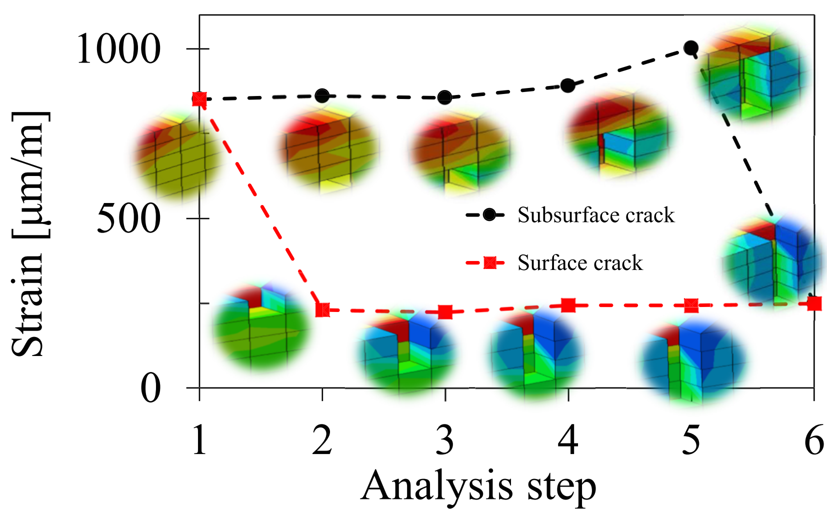

FIGURE 17 The effect of crack initiation position with respect to the surface on the strain drop pattern

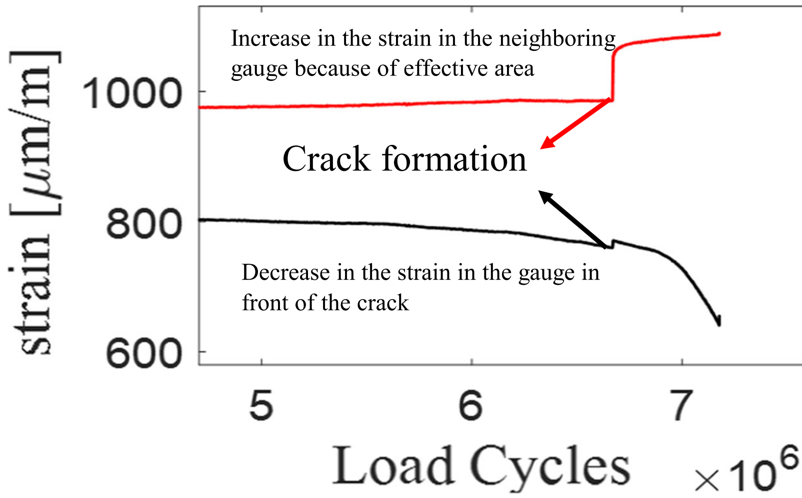

FIGURE 18 The effect of crack formation on the neighbouring strain gauge

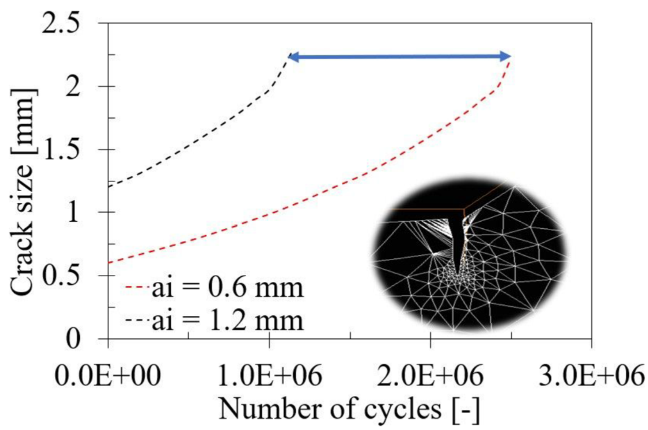

FIGURE 19 Crack propagation curves for different initial crack sizes

the commercial software FRANC 2D with two initial crack sizes (0.6 and 1.2 mm). Paris law parameters C and m were selected in accordance with the recommendations,[1] and the elastic material proprieties E and ν were selected to be 210 GPa and 0.3, respectively. The analysis was terminated when the crack reached 2 mm. The crack closure approach was implemented, and the crack propagation direction was automatically determined by the software. Remarkably, the residual life corresponding to crack size of 0.6 mm is more than double the life corresponding to crack size of 1.2 mm, as shown in Figure 19. This emphasises the importance of early crack detection.

5 | CONCLUSIONS AND SUMMARY

In this article, strain measurements were used to determine the existing crack size at the weld toe of transversal welded attachments. The studied specimens were instrumented with several gauges to measure the strain. The study involved experimental and numerical investigations. Besides, different patterns of strain evolution during fatigue testing were observed. The following conclusions could be made

- A correlation was found between the existing crack size and the local strain decrease in the crack vicinity. This correlation was obtained numerically and confirmed by destructive and nondestructive testing.
- The lateral distance between the crack origin and the position of the closest strain gauge affects the measurement. A lower strain drop would be obtained if the crack origin is closer to the gauge position and vice versa. Besides, this

lateral distance was the reason behind the alteration found between the numerically obtained correlation and the results of the destructive testing.

- The local differences between the specimens such as undercut height and residual stress could be the reasons behind the difference in crack position with respect to the attachment.
- Different strain evolution patterns were found during fatigue testing. In most of them, strain decrease started after a specific number of cycles. However, strain decrease commenced from the beginning in some cases. In other cases, a gradual strain increase followed by a decrease was observed.
- Studying the strain drop patterns, numerical analysis and observing the fracture surfaces enabled detecting the position of crack origin with respect to the surface. A sudden increase in strain followed by a quick drop afterwards indicates the presence of a subsurface crack.
- Multiple cracks can appear in transverse attachments. Upon fatigue testing, these cracks might coalesce and form larger cracks.
- Fracture mechanics analysis revealed that the uncertainty in crack detection affects the residual fatigue life of the structure significantly.

ACKNOWLEDGEMENTS

The work presented in this paper has been conducted within the research project "*LifeExt*" with funding from the Swedish Transport Administration (*Trafikverket*) and the Swedish Innovation Agency (Vinnova). Thanks and gratitude are awarded to Joakim Hedegard and Martin Edgren for their contributions.

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How to cite this article: Al-Karawi H, RUF von Bock und Polach, Al-Emrani M. Crack detection via strain measurements in fatigue testing. *Strain*. 2021;e12384. https://doi.org/10.1111/str.12384