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ON THE DAMAGE DIAGNOSIS BASED ON STRUCTURAL ANALYSIS DATA

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ABSTRACT

One of the major challenges of Structural Health Monitoring (SHM) is to handle the enormous amount of data during the monitoring action. This is due to the fact that common SHM approaches monitor the entire structure on all kind of damages in order to obtain all eventualities of damage. The idea of this contribution is to use the information of the parts sizing in order to identify so called hot spots, i.e. possible damage locations and the corresponding kind of damage like cracks or delaminations. With this information a SmartSHM system is set up, which monitors only the hot spots on the most likely failure. To cover uncertainties and accidental damages an additional monitoring of a global parameter has to be set up. This approach is shown based on an example of a four point bending test with a rectangular cross-section.

KEYWORDS : *Structural Health Monitoring, Structural Damage Indicators, Four Point Bending Test, Cracked Structure*

1. THE SMARTSHM APPROACH

The main target of SHM is to monitor the damage state of a structure in service online and during the whole lifetime. The monitoring has to be reliable and informative. Not only the information whether the structure is damaged or not is important. Also the location of damage and the corresponding mode and size has to be evaluated for a full Level 4 Diagnosis [1]. This information is necessary in order to predict the remaining lifetime of the damaged part and to schedule maintenance. Therefore most of the current SHM systems are designed to monitor the entire structure with multiple sensors. The target is to have a full understanding of the current state of the structure and to detect every potential failure mode on all possible positions. This approach results into an enormous amount of data which has to be recorded and analysed.

This contribution focuses on an alternative SHM approach. If potential positions and types of damages are known apriori, the required SHM system can be less complex. In this case monitoring can focus on critical areas of the structure, the so called hot spots [2]. With this knowledge it is possible to arrange sensors in a set-up which is most suitable for the expected damage. The knowledge of potential damages is generated in the sizing process. In general uncertainties are already taken into account during sizing. Design loads and design values are used in a conservative manner alongside with safety factors in order to provide reliable structure strength despite all potential uncertainties. Within sizing critical areas and their potential failure modes are already analysed. Therefore there is no need to analyse every single part of the structure in high detail. The knowledge obtained by sizing can be used in order to set up a so called SmartSHM system, which monitors only hot spots on the most likely failure [2]. The amount of data gathered by a SmartSHM system is far less than achieved

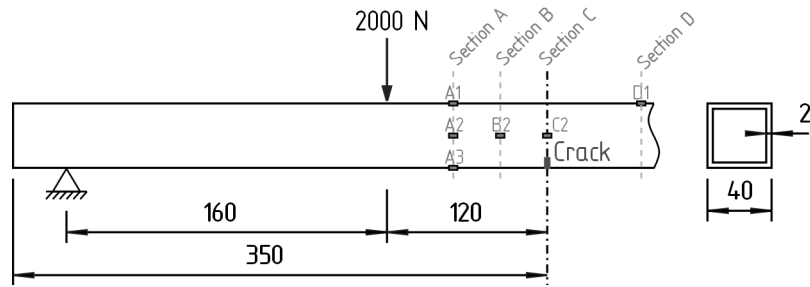


Figure 1 : Test set-up for four point bending specimens

by a typical SHM system. Accidental uncertainties like impacts can be covered by using an additional global monitoring system.

The SmartSHM approach performs indirect damage monitoring by analysing the change in the structural behaviour due to damage, i.e. deformations. These are the structural damage indicators. Damages like cracks or delaminations have an influence on the stress state under load. This is reflected by the deformation and by the strain state and can be used for the set-up of a SmartSHM system.

2. FOUR POINT BENDING TEST WITH A DAMAGED SPECIMEN

2.1 Test set-up

The typical test set-up of a four point bending test is shown in Fig. 1. Within this example the critical area is found between the two load application points. This segment of the beam is exposed to pure bending which results into a linear stress distribution over the cross section. Apparently cracks typically occur on the bottom side of the beam due to high tensile stresses. In general the neutral axis is stress-free. If a crack occurs the behaviour on this position will change. The neutral axis shifts away from the crack and the former neutral axis is exposed to stress. The corresponding stress state for a non-damaged and a damaged cross-section is shown in Fig. 2.

The specimen consist of aluminium profile with rectangular cross-section. Within the test the crack is located in the symmetry plane. The crack is introduced by a saw cut.

In total six strain gauges were used to monitor the specimen. The locations are shown in Fig. 1. The distance between sections A, B and C is equal to edge length (40 mm). Section D is symmetric to section A. Section C refers to the damaged section. Strain gauges A1 and D1 are located in the centre of the upper flange (compression loaded). Strain gauge A3 is located in the centre of the lower flange (tension loaded). Strain gauges A2, B2 and C2 are at the neutral axis.

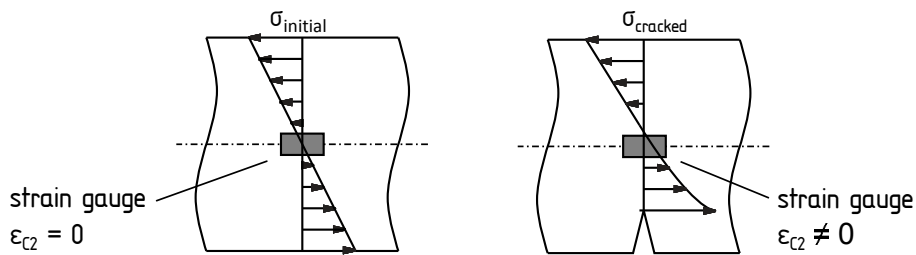


Figure 2 : Stress state for a non-damaged (left) and a damaged (right) cross section

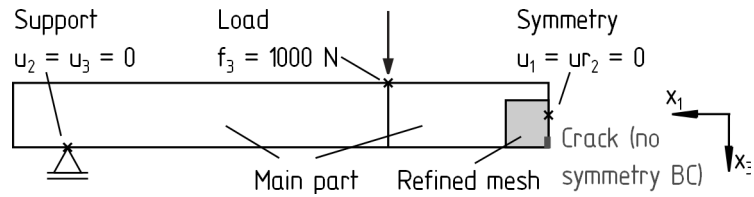


Figure 3 : Boundary conditions and meshing approaches of the FEM model

3. FINITE ELEMENT MODEL

The test is also modelled with Finite Element Method (FEM). The model consists of two areas with different meshing approaches. The major part of the specimen is modelled with shell elements. In close proximity to the crack a refined mesh with solid elements using incompatible bending modes is used in order to reproduce stress peaks at the crack tip. In addition the x_2 - x_3 symmetry plane is used. The crack is within the symmetry plane. A sketch of the model is shown in Fig. 3.

The two different element types are connected with a tie constraint. The thickness of the shell elements and their rotational degrees are considered. Boundary conditions and loads are applied to the reference nodes. The referring cross-sections are connected with a kinematic coupling constraint to the reference nodes. This constraint is not applied for nodes of the cracked surface in the symmetry section. Therefore those nodes are removed from the boundary conditions of symmetry. The referring elements behave as the elements in a full model where the crack is modelled by means of node separation. The material model is assumed to be full linear elastic. However the test results indicates nonlinear behaviour at piston loads over $2 \cdot 1$ kN due to plasticity for cracked specimens (see subsection 4.1). Therefore the applied force is limited to $2 \cdot 1$ kN.

4. RESULTS AND EVALUATION

4.1 Test results and evaluation

Fig. 4 shows strain gauge data for a crack length $a = 2.5$ mm. Strain gauge C2 indicates plasticity for piston loads higher than 2 kN in the damaged cross section. Strain gauges A1, A3 and D1 are

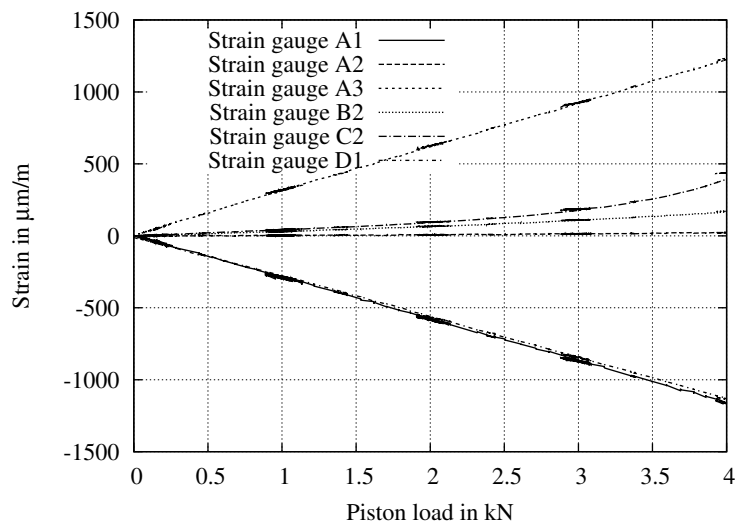


Figure 4 : Strain gauge data for crack length $a = 2.5$ mm

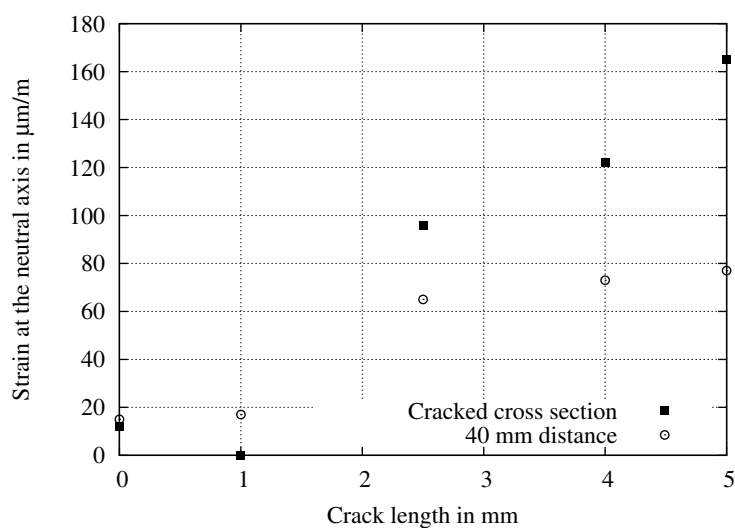


Figure 5 : Strain at the neutral axis (strain gauge C2 and B2)

unaffected by the crack. However they are slightly disturbed by the load application. For further investigation a piston load of 2kn is considered. The strain at the neutral axis (strain gauge C2 and B2) is shown in Fig. 5 for different crack lengths.

There are multiple effects influencing strain at the neutral axis in the cracked section. Considering the effective cross-section, the second moment of area is reduced due to the crack. Furthermore the effective centre of gravity is moving in the opposite direction of the crack. This results into tensile strain at the former neutral axis. However this effect is disturbed by the stress concentration at the crack tip. High tensile stresses with high leverage have to be compensated by the stress distribution. Therefore there is a shift of the strain towards compression. Both effects act simultaneously. For smaller crack lengths the effect of stress concentrations in the flange is predominant. If the crack separates the flange, the changed cross-section properties are dominating.

4.2 FEM results and evaluation

In order to validate FEM results longitudinal strain is evaluated at strain gauge positions. Strains are compared to the corresponding strain gauge data from the test in Fig. 6. The plotted curves show good agreement between test and FEM. Further investigations are performed on the results obtained by FEM.

The strain at the neutral axis for strain gauge positions C2 and B2 are compared to FEM results in Fig. 7. The two contrary effects for the shift of the neutral axis (see subsection 4.1) are clearly visible in the results achieved by FEM. If the crack occurs only in the flange, strain at the former neutral axis will be negative in the damaged section due to stress concentration. However the distance of B2 to the crack tip is rather high. Therefore the influence of the stress concentration is less and the measured strain is positive. If the flange is completely separated, the changed properties of the effective cross-section are dominant. Strain is positive at both positions. For higher crack lengths the strain at the neutral axis is underestimated within FEM. This is due to linear material model. For higher crack lengths the influence of plasticity at the crack tip increases.

Fig. 7 indicates that strain at the former neutral axis is influenced by the crack in a distance of at least 40mm. Therefore strain at the neutral axis is evaluated in FEM and plotted over distance in Fig. 8 for multiple crack lengths. Within the chosen set-up the curves are symmetric. The curves show a local minimum at the damaged section. The maximum at 15...20mm indicates that the effect of

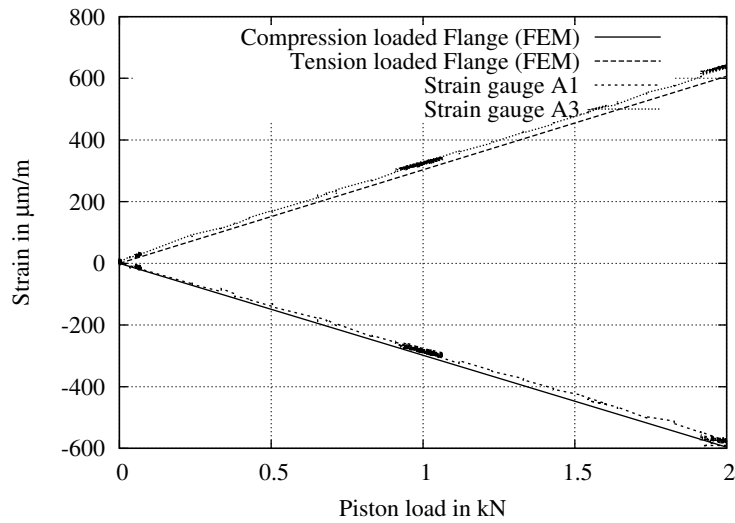


Figure 6 : Flange strain compared to strain gauge data

stress concentration decays. When the crack occurs only in the flange, there is a zero-crossing. At this position the two opposing effects neutralise each other.

5. APPLICATION OF SMARTSHM

According to Fig. 7 there is a range in which strains at the neutral axis are sensitive to damage. However only one monitoring position is insufficient to determine a distinct crack length and position. The same strain can be achieved at a location which is close to a small crack and a location which measures huge crack in an high distance. However a distinct result can be achieved by monitoring two locations with a known distance to each other.

Obviously strain is dependent from the size of the crack and the corresponding distance. In this contribution an approximation is made in order to describe the dependencies. Therefore a second order

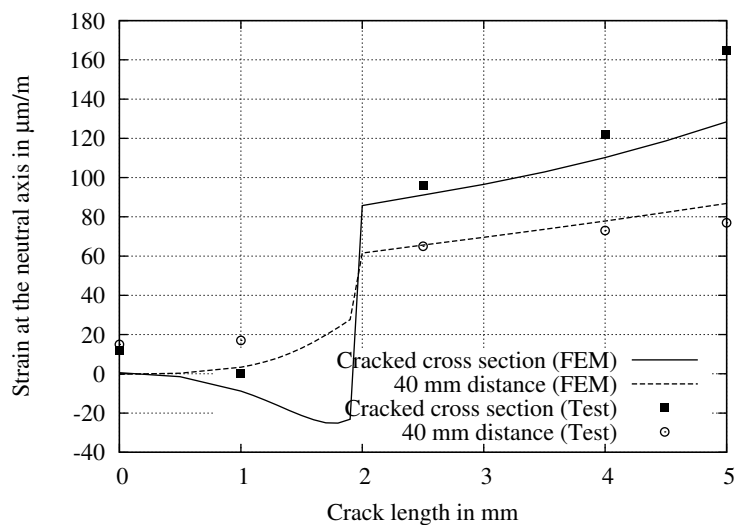


Figure 7 : Strain at the neutral axis (strain gauge positions C2 and B2)

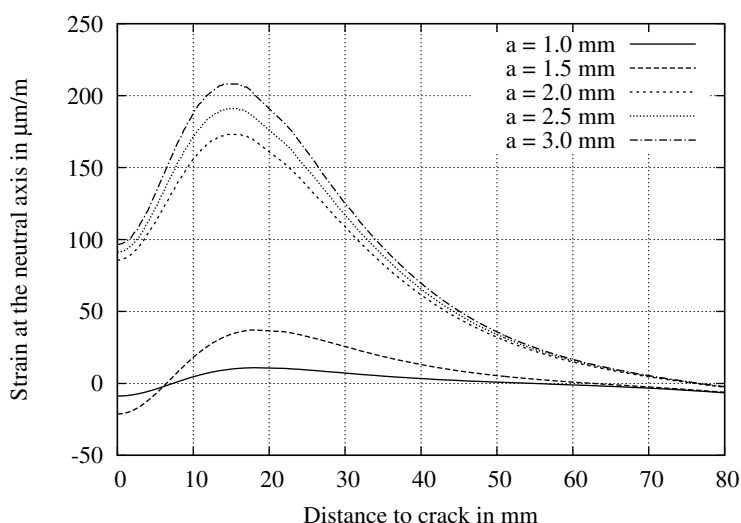


Figure 8 : Influence of the distance to the crack on the strain of the neutral axis

polynomial is superimposed with a logistic function. Within this function \bar{x} describes the absolute value of the distance to the cracked section.

$$\varepsilon_0(x) = [a_2 \bar{x}^2 + a_1 \bar{x} + a_0] \left[1 - \frac{1}{1 + (s - 1) e^{-k\bar{x}}} \right] \tag{1}$$

This approach needs five independent sampling points in order to determine its coefficients. The derivatives and values of both extrema are used. An additional point in between is chosen as fifth sampling point. This approximation shows good agreement between both extrema and is acceptable up to $\bar{x} = 40$ mm. However for higher distances the strain tends to zero. Therefore those positions are not applicable for damage evaluation.

Based on FEM data a set of curves is created. Each curve belongs to one specific crack length. They are shown in Fig. 10. As previously mentioned, two monitoring positions with a known distance

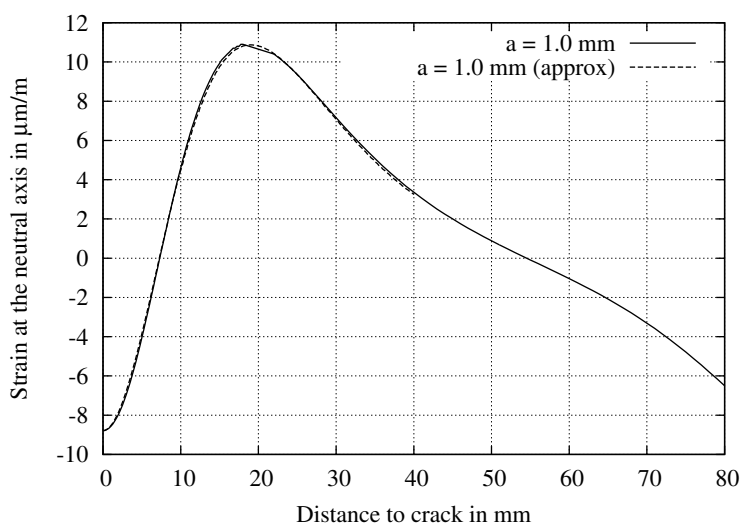


Figure 9 : Approximation in comparison to FEM Results for $a = 1.0$ mm

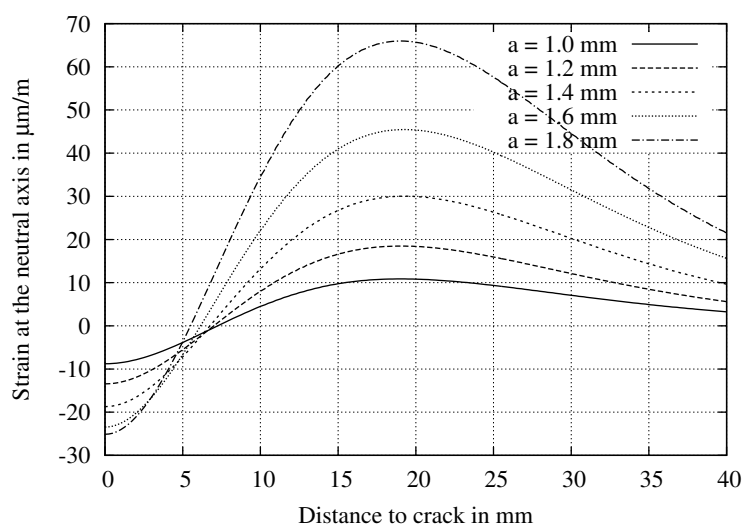


Figure 10 : Set of curves for damage evaluation

to each other provide enough data to determine crack length and its location. Based on the set of curves a small script can be created which evaluates each curve with the data of monitoring. In the first loop it determines the minimum of the least square method and the referring distance between the monitoring positions and the crack. In the second loop the total minimum of the whole set of curves is determined and the crack length identified. This algorithm is very simple and therefore easy to implement within a SHM system.

Using an equal monitoring position pattern with a uniform spacing of 40mm within the hot spot area, the crack is always within the sensitivity range of two positions. In this rather simple example only seven positions are needed in order to cover the whole hot spot area and to make a full Level 4 Diagnosis based on sizing knowledge. If the specimen is undamaged, all positions will measure a zero signal. Therefore sending and recording of data is not necessary.

CONCLUSION

In this contribution a SmartSHM approach was presented based structural analysis data. Due to the chosen set-up the potential damage type and a so called hot spot area were identified apriori. This contribution showed the results of a test and FEM analysis in order to verify sensitivity of indirect damage measurement. Change of strain at the neutral axis was used as structural damage indicator. It had an high sensitivity with a distance of 40mm to the damaged section. Damage size and location were determined by the use of an approximation. Based on FEM analysis a set of curves was introduced as approximation for strain over distance to the damaged section. Each curve was related to a specific damage size. With this approach the data of only two monitoring positions are needed for a full Level 4 Diagnosis. When the structure is undamaged, all positions will measure a zero signal. Therefore sending and recording of data is not necessary.

In this contribution a constant and known bending moment was applied on the specimen. However there is a linear relationship between stresses and the bending moment and therefore between strains and the bending moment. This linear relationship alongside a sufficient loads monitoring can be used for more complex cases. Uncertainties are in general already covered by sizing. However the approach presented within this paper may be augmented with a global monitoring system in order to detect accidental damages. In this case a full Level 4 Diagnosis is not needed. When the structure is damaged by an accident an inspection is always necessary.

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