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Crack diagnosis of metallic profiles based on structural damage indicators

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Abstract. Structural Health Monitoring (SHM) faces several challenges before large-scale industrial application. First of all damage diagnosis has to be reliable. Therefore, common SHM approaches use highly advanced sensor techniques to monitor the whole structure on all possible failures. This results in an enormous amount of data gathered during service. The general effort can be drastically reduced, if the knowledge achieved during the sizing process is used. During sizing, potential failure modes and critical locations, so called hot spots, are already evaluated. A very sensitive SHM system can be developed, when the monitoring effort shifts from the damage to its impact on the structural behaviour and the so called damage indicators. These are the two main components of the SmartSHM approach, which reduces the monitoring effort significantly. Not only the amount of data is minimized, but also reliability and robustness are ensured by the SmartSHM approach.

This contribution demonstrates the SmartSHM approach by a cracked four point bending beam. To show general applicability a parametric study considering different profiles (bar, box, I, C, T, L, Z), crack positions and lengths has been performed. Questions of sensitivity and minimum size of the sensor network are discussed based on the results of the parametric study.

1. SmartSHM
In order to ensure structural integrity, Structural Health Monitoring (SHM) must be capable of monitoring the damage state of a structure in service during the whole lifetime. Potential damages have to be detected before they become critical to the structural integrity. In addition to the information whether the structure is damaged or not, informations about the location of damage and the corresponding mode and size has to be evaluated. This leads to a full Level 4 Diagnosis [1]. But a Level 4 Diagnosis does not enable to assess a damage. For damage assessment the loading state also has to be known. With that set of information the remaining lifetime of the damaged part can be predicted in order to define and schedule repair actions.

A common SHM approach is to design a system that is able to monitor the entire structure. The target of such a system is to have a full understanding of the current state of the structure in order to detect every potential failure on all possible positions. In most cases, this approach leads to a rather complex sensor network and an enormous amount of data which has to be recorded and analysed. However, most structures which are in use nowadays are analysed in detail during sizing process. Due to the structural analysis, stress and strain state of the structure under given load cases are already known. Critical areas of the structure, so called hot spots, and the
corresponding predominant failure modes are investigated while sizing. This knowledge can be used in order to set up a so called SmartSHM system [2]. Within this approach, the monitoring focuses on the detection of the expected damages at certain hot spots of the structures.

The second important element of SmartSHM, besides focussing on hot spot areas with their corresponding failure modes, is the application of structural damage indicators. From sizing process, stress and strain state of the theoretically intact structure are known. In general, a damage results into a characteristic change of the structural behaviour, e.g. a crack causes a redistribution in stress at tensile loading while a delamination causes a stiffness reduction. Relating the current structural behaviour to a reference state, a damage can be detected by evaluating the change. That change of the structure’s response can be described with the structural damage indicator

\[ \eta_d = \frac{X(x,t) - X_0(x)}{X_0(x)}, \]

where \( X(x,t) \) describes the structural parameter at the current structural state and \( X_0(x) \) at the reference state, which is in general the intact structure at service launch. That structural damage indicator is the monitored object. So SmartSHM does not focus on the direct measurement of damage itself, but on its implication on the structure’s response.

The third element, which makes the SmartSHM approach smart, is the way the reference state is chosen. Equation (1) indicates that the damage indicator \( \eta_d \) is very sensitive to a structural parameter with zero signal at reference state. In that case even a weak signal, i.e. a small change in the structural parameter \( X(x,t) \) due to a damage, leads to a high damage indicator \( \eta_d \). Therefore it is more efficient to monitor the location with the most severe effect on the damage indicator rather than near to the damage. A further advantage of the presented approach is that all sensors will measure a zero signal, if the structure is undamaged. Therefore, sending and processing of data is not necessary and the amount of monitoring data is reduced significantly. With some further investigation of the characteristics of the damage indicator, a damage can be localized, qualified and quantified [3].

SmartSHM is not designed to detect uncertainties like misuses or impacts. However, during the sizing process uncertainties are already taken into account by the implementation of design load and design values along with safety factors. Still those damages can be detected by an additional global monitoring. Since the probability of those accidental events is rather small and as they represent extreme events, a level 1 diagnosis (i.e. the information whether the structure is damaged or not) is feasible. In this case, a damage signal within the global monitoring would lead to an immediate inspection.

2. Application of the SmartSHM approach on a four point bending beam
The cracked four point bending beam is used as striking example for SmartSHM. The general test setup is shown in Figure 1. The maximum bending moment is reached between both load application points. This area is identified as hot spot and therefore, SmartSHM focuses on monitoring the middle span. Considering linear-elastic material response, the stress distribution is linear over cross-section as shown in Figure 2 (left). The upper flange is compression loaded. Therefore, the corresponding failure mode is buckling. The lower flange is tension loaded. Its corresponding failure mode is cracking. This contribution focuses on a potential crack in the lower flange.

At this point the hot spot and the corresponding failure mode of the structure are known. Hence, the crack in the lower flange of the mid span is the most likely damage which can occur at standard conditions of service. The next step following the SmartSHM approach is to evaluate the change of the structure’s response due to that damage and to derive the most suitable damage indicator. For that reason a crack is introduced in the lower flange of the mid span.
and the resulting stress redistribution is analysed. Figure 2 (right) shows the expected stress distribution.

A possible damage indicator is the decrease of strain in the lower flange directly adjacent to the crack. Applying a strain gauge at this position, comparable high change in the absolute value will occur. However, the reference value is also maximal. Being aware of the conclusions drawn from Equation (1), it is recommended to look for a structural parameter which is (almost) zero in the undamaged (reference) state. By definition, the neutral axis is free of stress and strain under pure bending. If a crack occurs, the neutral axis shifts away from the crack and the former neutral axis is exposed to stress and hence to strain. Therefore, longitudinal strain at the original neutral axis is chosen to be the damage indicator within this example. The general suitability of this damage indicator was demonstrated numerically and experimentally in [3]. However, this approach raises a lot of additional questions. First of all, does the approach also work for other cross-section types than shown in [3]? Second, within which distance is the damage indicator influenced by the crack? And are the characteristics of the damage indicator constant with varying distance to the crack? These questions are answered in this contribution on the base of extensive numerical investigations, considering different profiles (bar, box, I, C, T, L, Z) and crack positions.

3. FEM model of the parametric study

The above mentioned four point bending beam with crack is computed with the Finite Element Method. The beam is meshed with second order solid elements. The mesh is highly refined in close proximity to the crack in order to reproduce stress peaks at the crack tip. The crack itself is modelled by node separation. The model includes plasticity. However, crack growth is not considered. The material data is summarized in Tab. 1. A static load $F$, smaller than failure load, is applied in the shear centre of the cross-section by distributing coupling constraints. Weighting factors are chosen to be linear. The supports are modelled with kinematic coupling constraints, ensuring a uniform support load distribution.

Within the parametric study, the applied moment is assumed to be constant. The cross-section properties are derived under the condition, that in every case the longitudinal stress of the undamaged cross-section is equal to +100 MPa at the potential crack position. Therefore, the section modulus is constant. In addition, the length-to-height-ratio $l/h$ of the beam is assumed

Figure 2. Stress state for a non-damaged (left) and a damaged (right) cross-section [3]
to be constant. This leads to a beam length $l$ which is dependent on the height $h$. Since the moment is assumed to be constant, the force $F$ is dependent on the height $h$ as well. The selected profiles and the corresponding geometries are shown in Figure 3. The derived values are summarized in Tab. 2.

In the first step of the parametric study, the crack is placed in the middle section. Afterwards, two additional crack positions are introduced. The second crack is shifted towards one load application point. The last crack is applied outside of the critical area where bending moment is decreasing linearly. A distance of $h$ to the load application is chosen in order to reduce the influence of the disturbance. The considered crack positions are shown in Figure 3.

![Cracked four point bending beam](image)

**Figure 3.** Geometry of the four point bending beam and considered crack positions

| Profile | $h$ - Height | $w$ - Width | $t$ - Thickness | $l$ - Total length | $F$ - Force |
|---------|--------------|--------------|-----------------|-------------------|-------------|
| Bar     | 35 mm        | 17.5 mm      | -               | 420 mm            | 2620 N      |
| Box1    | 40 mm        | 40 mm        | 2 mm            | 480 mm            | 2293 N      |
| Box2    | 50 mm        | 25 mm        | 2 mm            | 600 mm            | 1834 N      |
| C       | 42 mm        | 42 mm        | 2 mm            | 504 mm            | 2183 N      |
| I       | 42 mm        | 42 mm        | 2 mm            | 504 mm            | 2183 N      |
| T       | 68 mm        | 68 mm        | 3 mm            | 816 mm            | 1349 N      |
| Z       | 60 mm        | 30 mm        | 3 mm            | 720 mm            | 1528 N      |
| L       | 84 mm        | 28 mm        | 4 mm            | 1008 mm           | 1092 N      |

**Table 2.** Variation of parameters used in the study
4. Results and evaluation

The presentation and evaluation of the results are divided into three parts. Since the I-profile is the most suitable cross-section type for bending problems, it is analysed in detail in the first part. In the second part, the selected cross-sections are compared to each other. Afterwards the influence of the crack position is discussed.

4.1. I-profile

Figure 4 shows the strain at the former neutral axis within a distance of $\pm h$ to the crack in the middle section. As explained earlier, a crack leads to a stress redistribution which affects the former neutral axis over a certain distance. A change of the damage indicator can be observed within a distance of $\pm h$ to the cracked cross-section. However it becomes smaller for higher distances. This trend complies Saint-Venant’s Principle. In addition the extend of redistribution shows a direct correlation to the damage size.

Multiple effects are responsible for the extend of redistribution. A crack in general leads to a separation and therefore to a reduced effective cross-section. This influences the effective centroid and the section modulus. However this approach is only valid for an undisturbed cross-section. In case of a sudden change of cross-section due to crack, stress concentration at the crack tip occurs. These two effects are counteracting and have to be superimposed. For larger cracks the effect of the shifting centroid is predominant. This can be easily seen for crack lengths in range of 2 mm and 4 mm. There is a major jump in the level of stress redistribution at a crack length of 2 mm. This curve represents a complete cut-through of the flange. Therefore, the crack introduces a severe change of effective cross-section and hence a severe change of centroid position. In addition, plasticity occurs at the crack tip. However, for smaller crack lengths the influence of plasticity on the strain at the former neutral axis is low. For large crack lengths plasticity shows a significant impact on the results. Stress concentration at the crack tip is limited and a large area with high stresses and strains occurs, resulting in high strain at the former neutral axis within the cracked cross section. This effect can be easily seen for a crack length of 5 mm.

![Figure 4. Strain at the former neutral axis for different crack lengths (I-profile)](image)

4.2. Comparison of cross-section types

The change of strains of all considered cross-sections is compared in Figure 5, where the change of strain relative to each maximum value is plotted for a crack length of 4 mm. The maximum absolute values of strain are shown in Tab. 3. The curves are derived at the z-coordinate of
Figure 5. Strain relative to each maximum value for a crack length of 4 mm

| Profile | Max. change of strain | Profile | Max. change of strain |
|---------|------------------------|---------|------------------------|
| I       | 185.4 μm/m             | C       | 336.4 μm/m             |
| Bar     | 5.0 μm/m               | T       | 0.5 μm/m               |
| Box1    | 51.9 μm/m              | L       | 6.7 μm/m               |
| Box2    | 18.2 μm/m              | Z       | 8.1 μm/m               |

Table 3. Maximum absolute value of strain at the monitored positions

centroid. In most cases this point coincides with the neutral axis. However, for L and Z-profile oblique bending is present due to the rotation of principal axis of inertia. Therefore the measuring points are not strain-free in the undamaged case. Still deviations in proximity of crack are easily visible. This attests feasible and robust application of the general approach, even if a strain free reference state is not present (e.g. due to sensor misplacement or interfering loads).

Most curves shown in Figure 5 have comparable behaviour. The maximum deviation is reached within certain distance to the cracked cross-section. Within the cracked cross-section high stress concentrations occurs at the crack tip. Therefore, the amount of measured strain is reduced. However, for I and C-profile stress concentration leads to significant plasticity. Those two curves reach their maximum deviation within the cracked cross-section. In case of flange cut-through a large amount of stress is redistributed. For I and C-profile this stress is transferred to the web, leading to high stress concentration and plasticity. Those two profiles show very high sensitivity to crack (see Tab. 3). Sensitivity for T-profile is rather poor. Therefore some numerical scatter is visible within the curve. However the influence of a crack within a T-profile is very low. In this case a crack just cuts through a very small area and is less critical. The change of centroid and section modulus is small.

4.3. Influence of the crack position
The influence of the crack position is investigated for three different positions: \( x_{\text{Crack}} = 3h, 5h \) and \( 6h \) (reference crack). Strain at the former neutral axis for those three models is plotted in Figure 6. The cracks at \( 5h \) and \( 6h \) are within the hot spot area. Therefore stress and strain redistribution is similar. The curve for \( 5h \) indicates larger deviations at the left end due to boundary conditions. At this point the load \( F \) is applied to the cross-section with distributing coupling. A comparable behaviour is present for a crack position of \( 3h \). However the level of the absolute change of strains is lower due to a reduced acting bending moment by a factor of
Figure 6. Strain at the former neutral axis for a crack length of 2 mm for chosen crack positions

\[
\frac{4}{3}
\]
Therefore, the curve is scaled with a factor of \(\frac{4}{3}\) in order to compensate the difference of bending moment. The remaining deviations indicate the effect of plasticity. Due to non-linear material, the relationship between load and strain is non-linear and larger strains occur.

5. Level 4 damage diagnosis and sensor layout

As shown in the previous section, a crack introduces a characteristic disturbance of strain on the former neutral axis. There is certain distance from cracked cross-section, where this damage indicator is sensitive to the crack. The value of the damage indicator is directly correlating to the crack length, the distance to the cracked cross-section and the acting bending moment. Therefore, only one monitoring spot is insufficient to determine a distinct crack length and position. The same level of change in strain under given load might be achieved at a location which is close to a small crack and at a location which has a high distance to a huge crack. If two monitoring locations with a known distance to each other are used within the sensitivity range of the damage, a distinct result of crack length and position can be obtained [3]. In addition, a Loads Monitoring is needed. For the example presented within this contribution, a feasible Loads Monitoring can be achieved via two strain gauges within one cross-section. The gradient between both measurements is in direct relationship to the applied bending moment.

In earlier studies, strain at the former neutral axis was approximated by a second order polynomial, which was superimposed with a logistic function. The coefficients of the approximation were derived by numerical studies, which were verified by test results. With that approach multiple functions with similar shape for certain crack lengths were derived [3]. They can be modified by the effect of plasticity.

To perform a Level 4 Diagnosis, data of at least two sensors with given distance between both sensors is required alongside Loads Monitoring. A rather simple script can be created which perform a loop over the whole set of approximation curves and determine the best fitting curve. This curve refers to a certain crack length and is used in a second step to evaluate the distance of the crack to both sensor positions. This algorithm allows a very efficient evaluation of the sensor signal. Since critical crack length is known from sizing, it contains an intrinsic damage assessment. The algorithm is illustrated in Figure 7.
6. Conclusion
In this contribution, the SmartSHM approach is presented on the basis of a cracked four point bending beam. SmartSHM uses the knowledge obtained during sizing process and within structural analyses. The monitoring effort is focussed on critical areas and the corresponding predominant failure modes. Afterwards, the investigation of the impact of the damage on the structural behaviour leads to the most suitable and sensitive damage indicator, which can be used to design an efficient and robust sensor network. In order to cover accidental damages, the presented SmartSHM can be augmented with a simple global monitoring.

Applicability and sensitivity of the SmartSHM approach is discussed on basis of a parametric study considering varying metallic profiles. For most cases, high sensitivity is achieved by the use of strain at the former neutral axis as damage indicator under pure bending. Due to a zero reference signal, even small deviations are easy to determine. The results of the parametric study show a direct correlation of the chosen damage indicator to the length and distance of the cracked cross-section. In addition, the applied bending moment needs to be derived with Loads Monitoring. For severe stress redistribution, the effect of plasticity has to be considered.

In the presented example, two sensor positions within the influenced range are needed alongside loads monitoring. The data can be processed by a set of curves. A rather simple script is able to identify the curve matching sensor signals and conclude length and position of the crack. Since critical damage size is known from sizing, this approach enables an intrinsic damage assessment.

Within future investigations, SmartSHM will be applied on more complex structures. Still, hot spots, the corresponding failure modes and the most suitable structural damage indicator can be derived by the use of structural analyses.

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