Laboratory experiment for damage assessment using the DAD-method

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ABSTRACT: In the following, a new analytical method, the Deformation Area Difference (DAD) method for damage assessment of bridge structures is applied using experimental test results of a statically loaded beam. An essential prerequisite for the application of this method is a high precise measurement of the deflection line. In this paper, the results from a laboratory experiment using modern measurement techniques such as photogrammetry and displacement sensors are discussed. A reinforced concrete beam is stepwise loaded until reaching the ultimate limit state. The DAD-method is applied to the resulting data from the measurements and the outcome is discussed for further optimisation of the method. In principle, the measured deflection line of the beam contains already essential information on discontinuities which occur due to cracking. These entries are processed and visualised using the DAD-method. This study shows that a high accuracy of the measurement techniques in combination with the DAD-method can become an effective tool for damage detection.

1 INTRODUCTION

Modern assessment methods show clear progress in the field of measurement technology and provide tools for new opportunities in inspection and condition assessment of real structures. Reliable early detection of damages of bridges would allow timely preventative maintenance and the costs could be maintained within reasonable limits. Several research projects already proved that damages due to dynamic excitations or static stresses cause changes in the structural responses of structures (Obrien, et al., (2017)) (Zhang, et al., (2017)) (Wickramasinghe, et al., (2016)). However, the challenge is to develop a method, which allows reducing the substantial effort of bridge inspection and the mass of data in order to avoid erroneous condition assessment. Thus, combining modern measurement techniques and condition assessment of structures could provide a contribution to the state-of-the-art.

Stiffness reducing damages on bridge structures always correlate to the load-deflection behaviour. Particularly, local damage causes a discontinuity in the course of the deflection line of structures. However, the effect of the discontinuity is generally not directly visible in the deflection course and the dimension of the discontinuity depends on the degree of damage. For the evaluation of structures, non-destructive loading tests are required which remain within the serviceability limit state. This implies that only small deflections can be produced and that precise measurements of the deflection line are required.

Riveiro, et al., (2013) investigates in his research work possibilities to measure the under clearance and the geometry of bridge by inspection with laser scanning and photogrammetry. The laser scanner data showed good accuracy ranging from 0 to 1 cm. For the photogrammetry, he compared four different calibrated cameras such as Canon 5D, Canon 10D, Canon 450D and

Canon 1000D. The reached accuracy of the photogrammetry ranges from 0,50 cm to 2,0 cm. The precision of laser scanner technology is commonly between ±2 and ±50 mm (Tsakiri, et al., (2006)). A similar approach has been chosen by Stöhr, et al., (2006) in his work about damage detection by static loading tests. He measured the inclination angle at support and loaded an experimental beam with a moving load along the longitudinal axis. The measured influence line showed at the position of the generated damage a discontinuity. However, the accuracy of the inclination measurement was not high as noises in the course appeared and therefore reliable detection of the damage remained difficult.

In this paper, a new method for damage detection and localisation based on load-deflection experiments is presented. The precise measurement of the deflection line is achieved by using latest measurement techniques such as photogrammetry. First analyses of the DAD-method have already been published in Erdenebat, et al., (2016). Beside the description of the theoretical basis of the method, the results of a new experimental laboratory test will be presented.

2 THE DAD-METHOD

The basis for the application of the DAD-method is a load-deflection experiment on a real structure and a theoretical modelling of the structure with the finite element method. In the following, the data from a laboratory experiment will be used to illustrate the DAD-method (Figure 1). The method is based on the deflection line of a structure measured as accurately as possible. The stiffness of the structure is directly related to the bending moment and the curvature. While the bending moment is defined by the static load, the curvature (Figure 1b) can be calculated from the second derivation of the deflection line (Figure 1a). The inclination angle corresponds to the first derivation of the deflection line. Figure 1 illustrates courses from the linear and non-linear calculation of the experimental beam. The linear calculation serves as reference system in undamaged condition for the application of the DAD-method. In undamaged condition, the experimental beam has no cracks. Therefore, the courses are steady whereas the non-linear calculation comprises discontinuities provoked by cracking.

However, results from the real deflection measurements include noises depending on the standard deviation of the applied measurement techniques. As a consequence, the second derivation of the deflection line will lead to an increase of these noises which makes a clear distinction between damage and measurement inaccuracy quite challenging. Therefore, the DAD-method investigates not directly the development of curvature, but the area between the curvatures (equation (3)), which are calculated on one hand using the measured deflection line ($\kappa_d(x)$ in Figure 1b) and on the other hand from the theoretical model of the structure ($\kappa_t(x)$ in Figure 1b). In order to calculate the area between the curvatures, the integral of the curvature is needed as it corresponds to the inclination angle, which is the first derivation of the deflection line. The same applies for the area (equation (2)) between the damaged inclination angle $\varphi_d(x)$, and the theoretical inclination angle $\varphi_t(x)$ (Figure 1c) as the integration of the inclination angle corresponds again to the deflection line. As a consequence, the area between both inclination courses can be directly calculated with the deflection values and the measured raw data (equation (2)). Equation (1) shows the calculation of the area between the measured deflection line $w_d(x)$ and theoretical deflection line $w_t(x)$. The upper half of Figure 1d indicates the stiffness $EI_t(x)$ of the beam calculated from the linear curvature line $\kappa_t(x)$ (Figure 1b). The beam remains uncracked and no stiffness reduction can be observed. In contrast, the lower half of Figure 1d shows the stiffness $EI_d(x)$ from the non-linear calculation including the development of cracking. The remaining stiffness of the beam in the cracked area is about 40 %. The area of the stiffness reduction of the non-linear calculation corresponds to the area of the changes on the curvature due to non-linear behaviour.

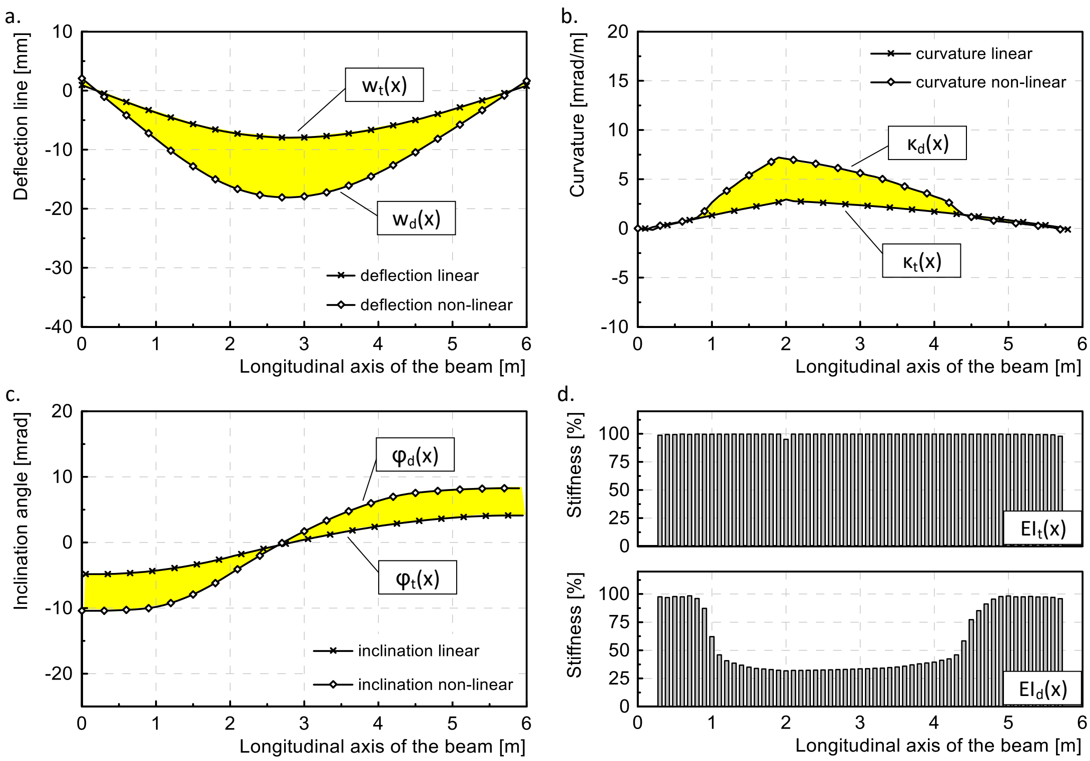

Figure 1. Main principles of the DAD-Method

$$\sum_{i=1}^{n} \Delta A_{w,i}^{2} = \sum_{i=1}^{n} \left[\int_{i-1}^{i} w_{d,i}(x)dx - \int_{i-1}^{i} w_{t,i}(x)dx \right]^{2} \tag{1}$$

$$\sum_{i=1}^{n} \Delta A_{\varphi,i}^{2} = \sum_{i=1}^{n} \left[\int_{i-1}^{i} \varphi_{d,i}(x)dx - \int_{i-1}^{i} \varphi_{t}(x)dx \right]^{2} \tag{2}$$

$$\sum_{i=1}^{n} \Delta A_{k,i}^{2} = \sum_{i=1}^{n} \left[\int_{i-1}^{i} k_{d,i}(x)dx - \int_{i-1}^{i} k_{t}(x)dx \right]^{2} \tag{3}$$

The special feature of the DAD-method is that the area between the damaged and theoretical courses is considered in finite distances section by section. The size of the section is defined according to the density of the measuring grid respectively according to the mesh size of the finite element model of the structure. Therefore, the precision of the damage localisation by the DAD-method depends on the section size and the measurement accuracy. The DAD-values will be calculated for each section from i-1 to i according to equation (4) for the deflection, according to equation (5) for the inclination angle and according to equation (6) for the curvature. The DAD-values will be calculated as normalized values from the squared area value of each section divided by the sum of the square of the total area of all sections. The equations (4) to (6) include already the integrated area values of equations (1), (2) and (3). For the determination of the DAD-values from curvature, the inclination angle values will be used (equation (6)), whereas as for the determination of the DAD-values from inclination angle, the deflection line values will be used (equation (5)). For the DAD-values from deflection line, no integral calculation is needed and the DAD-values can directly be calculated from the deflection values (equation (4)).

$$DAD_{w,i}(x) = \frac{\Delta A_{w,i}^2}{\sum_{i=1}^{n} \Delta A_{w,i}^2} = \frac{[w_d(x_i) - w_t(x_i) - w_t(x_{i-1}) + w_d(x_{i-1})]^2}{\sum_{i=1}^{n}[w_d(x_i) - w_t(x_i) - w_t(x_{i-1}) + w_d(x_{i-1})]^2} \quad (4)$$

$$DAD_{\varphi,i}(x) = \frac{\Delta A_{\varphi,i}^2}{\sum_{i=1}^{n} \Delta A_{\varphi,i}^2} = \frac{[w_d(x_i) - w_d(x_{i-1}) - w_t(x_i) + w_t(x_{i-1})]^2}{\sum_{i=1}^{n}[w_d(x_i) - w_d(x_{i-1}) - w_t(x_i) + w_t(x_{i-1})]^2} \quad (5)$$

$$DAD_{k,i}(x) = \frac{\Delta A_{k,i}^2}{\sum_{i=1}^{n} \Delta A_{k,i}^2} = \frac{[\varphi_d(x_i) - \varphi_d(x_{i-1}) - \varphi_t(x_i) + \varphi_t(x_{i-1})]^2}{\sum_{i=1}^{n}[\varphi_d(x_i) - \varphi_d(x_{i-1}) - \varphi_t(x_i) + \varphi_t(x_{i-1})]^2} \quad (6)$$

3 LABORATORY EXPERIMENT

3.1 *Experimental setup*

The experimental beam is a reinforced concrete beam with a total length of 6,00 m of concrete class C40/50. It is a statically determined system with a span length of 5,60 m. The beam was loaded at 1,80 m from the left support using a hydraulic press with path control mode (Figure 2). The measurement of the deflection is realised by photogrammetry and displacement sensors. The measurement with photogrammetry requires special targets with numbered barcodes. The targets from number 2 to 60 are positioned on the beam (Figure 2) and those from number 61 to 77 are fixed on the floor and on the walls of the test hall and serve as reference points.

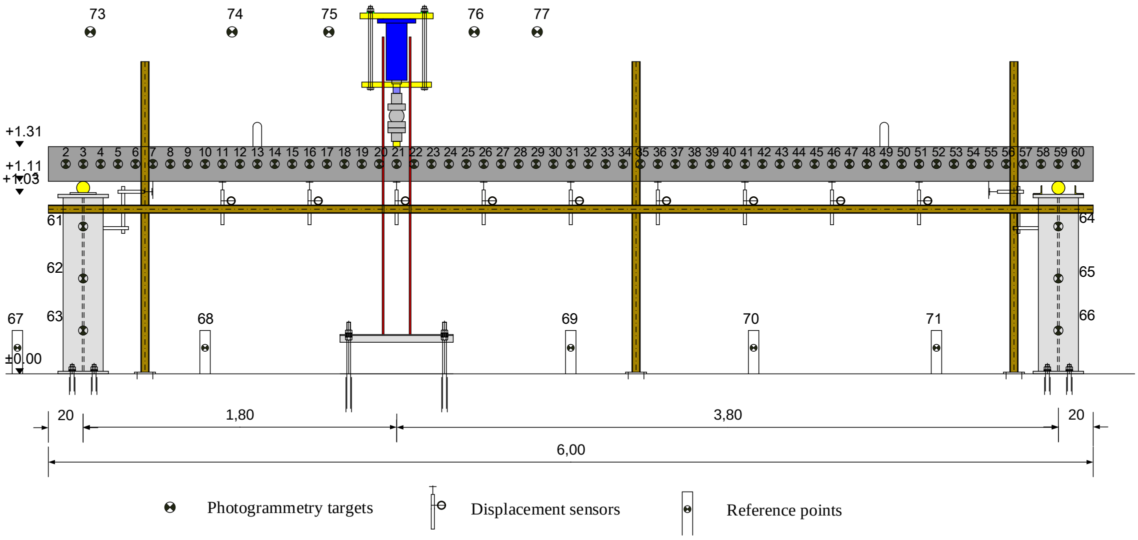

Figure 2. Experimental setup and numbering of the targets for photogrammetry

3.2 *Experimental procedure*

The beam with a span length of 5,60 m (Figure 2) has been gradually loaded with 5,0 kN, 10,0 kN, 15,0 kN, 20,0 kN, 30,0 kN and 40,0 kN. Subsequently, the measurement of the deflection and the crack detection are carried out. The cracking of the concrete in the tensile zone leads to a stiffness reduction. Theoretical calculation shows that the beam will be already cracked at the first load step of 5,0 kN. From load step 10,0 kN to 30,0 kN, the cracked area will increase. Due to the crack detection during the experimental procedure, the cracked area could be measured. The cracks for load step 5,0 kN were dispersed over a length of about 3,0 m, for 10,0 kN about 3,6 m, for load step 15,0 kN resp. 20.0 kN about 4,2 m and for load step 30,0 kN about 4,6 m. The failure of the concrete in the compression zone occurred at 40,0 kN at 2,1 m from the left side of the beam (Figure 2).

3.3 *Measurement techniques*

The applied measurement techniques are essentially close-range photogrammetry (Jiang, et al., (2008)) and inductive displacement sensors. The inductive displacement sensors are known as a high precise measurement technique. However, the DAD-method requires a continuous measurement of the deflection line over the whole length of the analysed structure. Therefore, the application of the displacement sensors on long bridge structures is not reasonably feasible. In total, nine displacement sensors are applied for the deflection measurements. These are sensors from HBM (Höttinger Baldwin Messtechnik) with a measuring length of 50 mm and 100 mm. In contrast, the close-range photogrammetry has high potential to show a good alternative provided that the accuracy satisfies the requirement. Due to the technological advances, the photogrammetry has already been used for bridge inspection as well as for the documentation of historical old bridges, the development of finite element models (Arias, et al., (2007)), for crack monitoring (Nishiyama, et al., (2015)), or detection of large-scale concrete columns for automated bridge inspection (Zhu, et al., (2010)). In this study, a calibrated full-frame digital SLR camera Nikon D800 in combination with the photogrammetry software Elcovision 10 is used.

Before starting the load deflection test, an additional test to compare the accuracy of the two measurement techniques has been carried out. Thereby, the experimental beam is simply lifted at one side and released to its original position. Figure 3 shows the measurements of the displacement by comparing the results of the sensors and of the photogrammetry after the release to the original position. The results showed good correlation between the two measurement techniques in the range of ± 0,10 mm.

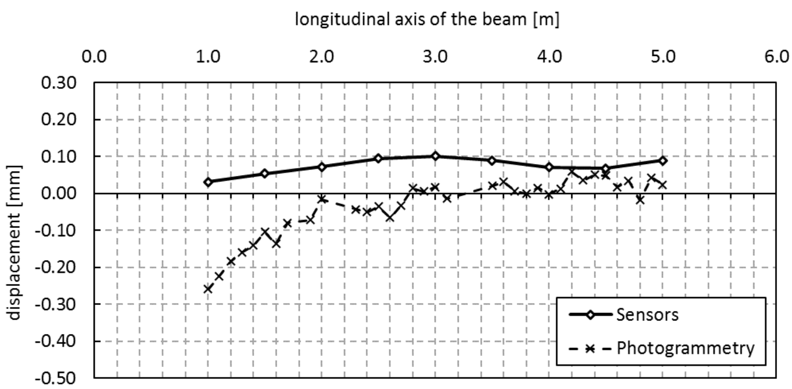

Figure 3. Comparison of the accuracy of displacements sensors and photogrammetry

4 ANALYSIS OF THE MEASURED DATA

Figure 4a shows the different deflection lines from linear calculation, non-linear calculation and from the measurements for load step 20,0 kN. In the deflection line, the noises due to measurement accuracy are not visible. The first derivation of the deflection line, the inclination angle (Figure 4b) shows already first impacts of noises, whereas the impact becomes clearly visible in the second derivation of the deflection line, the curvature (Figure 4c).

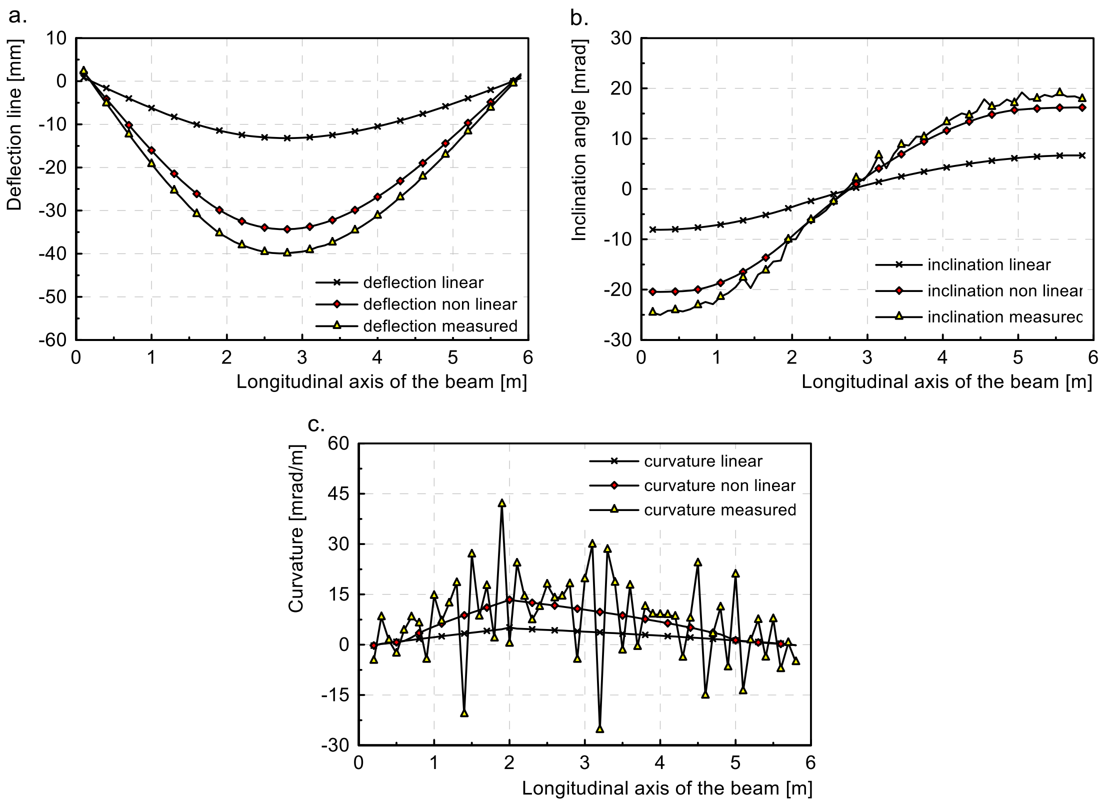

Figure 4. Comparison of the deflection line, the inclination angle and the curvature for load step 20 kN from linear, non-linear calculation and from measurement

4.1 DAD-values and damage detection

In the following, Figure 5 to Figure 7 show the main results from the laboratory experiment. The left part of these figures shows the detected crack area represented over the length of the beam and the right part illustrates the course of the DAD-values calculated from the curvature (equation (6)). The dashed lines in the figures limit the cracked area and the dot-dashed lines represent the position of both supports of the beam. The results of load step 20,0 kN (50 % of the ultimate load), load step 30,0 kN (75 % of the ultimate load) and load step 40,0 kN (ultimate load) are presented. At load step 20,0 kN (Figure 5), many cracks have been detected at mid-span. The DAD-values are calculated from the curvature and show discontinuities in the area with reduced stiffness due to cracking. At load step 30,0 kN (Figure 6), the cracked area is increased. The peaks in the course of the DAD-values show discontinuities at same location. The failure of the beam occurs by reaching the compression strength of concrete at 40,0 kN in the compression zone of the beam. The total cross section of the beam is cracked at a distance of 2,0 m from the left support, which could reliably be identified and localised using the DAD-values (Figure 7).

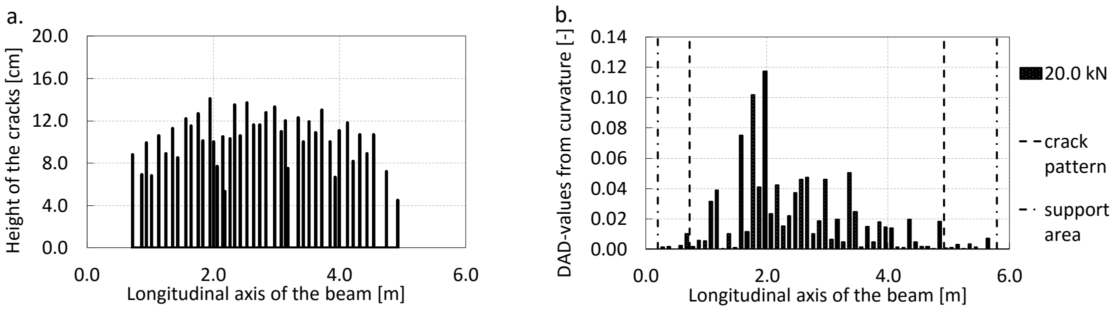

Figure 5. Load step 20,0 kN: a. Detected cracks, b. DAD-values from curvature

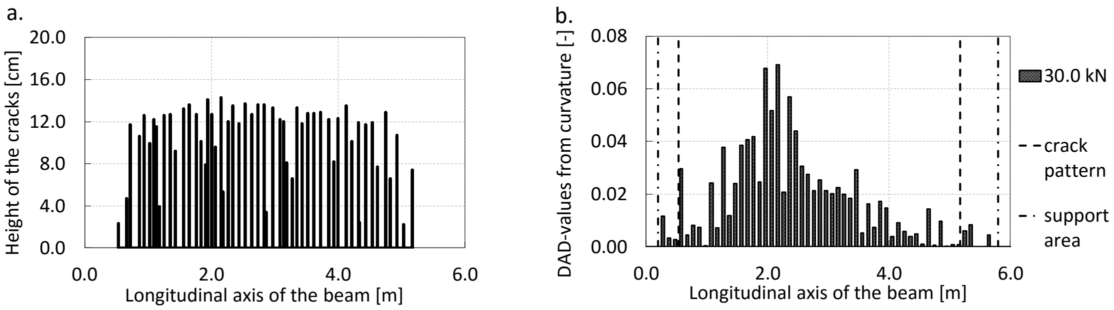

Figure 6. Load step 30,0 kN: a. Detected cracks, b. DAD-values from curvature

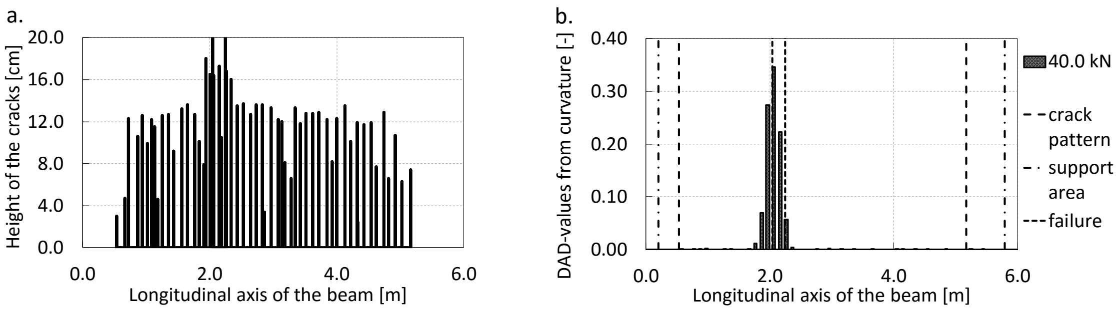

Figure 7. Load step 40 kN (ultimate load): a. Detected cracks, b. DAD-values from curvature

5 SUMMARY AND CONCLUSION

In this paper, the so-called Deformation Area Difference method (DAD-method) was introduced and explained. The main objective of the method is to identify and localise damage on structural constructions such as bridges. The application of this method requires precise data of a load deflection test on a real structure. These deflection measurements must be realised with high precision providing a deflection line along the longitudinal axis of the structure. The high precision measurement can be guaranteed by modern measurement techniques such as photogrammetry.

Besides the theoretical description of the method, the results from a laboratory test with a reinforced concrete beam are presented. The gradually loaded beam cracks at different locations leading to a stiffness reduction. This change is also identified in the course of the deflection line. This correlation can be identified using the DAD-values and allows to the identification and localisation of the damaged area. The results from the laboratory experiment showed that the method is not only working in theory, but could also be applied on measurements from real structures. Therefore, the DAD-method will constitute a useful method for condition assessment of real structures in terms of damage localisation.

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