Condition assessment and damage localisation for bridges by use of the Deformation Area Difference Method (DAD-Method)

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ABSTRACT

Already today, a huge number of bridges are in an ailing condition due to their increasing age and due to an increased traffic volume, especially of heavy transport vehicles. To assess their load bearing capacity and subsequently predict their remaining life span, every bridge needs to be analysed by condition assessment. The consequences of unreliable condition assessment should not be underestimated, as most bridge constructions constitute cost intensive and indispensable infrastructures. Thus, modern condition assessment methods, easy and obvious in their application, are needed in order to reduce future investigations.

To offer an easy handling alternative to evaluate the condition of bridges, the Deformation Area Difference Method has been developed. Hereby, the accruing deformation of bridges under a static load will be analysed with the help of modern measurement equipment. Therefore, the resulting deformation curves like the deflection, the inclination angle and the curvature curves, will be analysed in one diagram together with the results out of initial measurements or theoretically calculated deformation curves. The DAD-Method is then applied on the surface difference area between those two curves for the deflection, the inclination and the curvature. It will be demonstrated that a localisation of damage is possible, independent from the degree of damage.

In this study, the applicability of the DAD-Method including the comparison of innovative measurement techniques using a laboratory specimen is investigated. For further explanation of the background of the DAD-Method, the results from a FE-calculation are presented.

Keywords: bridge, condition assessment, damage localisation, DAD-Method.

1. Introduction

More than 39.000 bridges currently exist in the road network of the Federal Republic of Germany. Their average age is between 30 and 50 years. According to BASt (Bundesanstalt für Straßenwesen) 5 % of these bridge structures have the highest priority for inspection. Due to a high ratio of large bridges, however, they represent about 25 % of the total bridge area (Bundesministerium für Verkehr und digitale Infrastruktur 2015). By comparison, the number of bridges in the USA reaches an amount of 600.000 (Scheer 2010), of which more than 11 % (resp. 66.000) are categorised as deficient structures and require significant maintenance or replacement. The average age of all bridges in the USA is 43 years and the deficient ones are about 65 years old. In the next 10 years, every fourth bridge in the USA (170.000) will be older than 65 years (Lee und Goldberg 2013). Unfortunately, this number is located far above the number of presently deficient bridges. In addition, each bridge requires regular structure inspection, which should be economical and reliable.

The classical inspection methods are tapping of concrete surface for assessment of cavities, measurement of cracks, chemical investigation on concrete parts to assess the risk of corrosion, examination of concrete strength with a "Schmidt Hammer" (Szilágyi 2013) or drilling core extraction and measurement of support displacement, etc. Other inspection methods, namely non-destructive methods, are increasingly gaining importance: electrochemical potential measurement to determine the chloride-induced reinforcement (Markeset und Myrdal 2007), Ultrasound Echo Principle and impact echo method (Chaudhary 2013), infrared thermography (Cotič, et al. 2015) to localise moisture damage (Srinivasan, et al. 2009), laser measurements for large scale preliminary investigation (Bundesministerium für Verkehr, Bau und Stadtentwicklung 2013), etc. The long term monitoring method is used for the supervision of the whole structure (Helmi, et al. 2015), by which the structural change due to variable loads over a longer period is controlled. However, the monitoring requires intense and extensive engineering work. A remaining risk of incorrect assessment of bridge exists because the result is influenced by many factors (for example: temperature, load situation and weather).

This paper presents a Method that has simple application and evaluation. The Deformation Area Difference Method (DAD-Method) can be applied to a non-destructive load deflection test of a bridge. The principle of the method is the bending line from which the inclination angle and the curvature can be determined to identify the discontinuity of the static system or local damage of a structure. The special features of the DAD-Method are the insensitivity to the degree of damage and to global influence, as well as only requiring a theoretical reference system. Moreover, the DAD-Method requires numerical modelling of the bridge and precise deflection measurement which constitutes the main challenge. In order to identify a suitable measurement technique, a laboratory test setup of a reinforced concrete beam is prepared (**Fig. 1**). The beam is loaded in several load steps and the deflection is measured with modern instruments. The application of the DAD-Method is presented in the following by means of theoretical calculation of the test beam.

Fig. 1. Laboratory test setup of a reinforced concrete beam

2. Background of the DAD-Method

The special feature of the DAD-Method is the independence both from a real reference system and from the degree of damage. The background of the method is finding and localising the discontinuity (damage) of a static system due to further processing of deflection data. Damage entails a local stiffness reduction of the static system, which in turn increases the deflection. The deflection can be generally determined according to equation (1).

$$w(x) = \int_0^l \frac{M(x)}{EI(x)} \overline{M}(x) dx = \int_0^l \kappa(x) \overline{M}(x) dx = \int_0^l \frac{1}{r}(x) \overline{M}(x) dx \qquad (1)$$

$$k(x) = -w''(x) = \frac{1}{r} = \frac{-\varepsilon_{c2}}{x} = \frac{\varepsilon_{s1} - \varepsilon_{c2}}{d} = \frac{\varepsilon_{s1}}{d-x} = \frac{M(x)}{EI(x)} \qquad (2)$$

The bending stiffness EI(x) is not constant along the longitudinal axis of the beam. This means that between the moment and the curvature of a cross section, there exists a nonlinear relation. The curvature can be determined by the strain state of the cross section (**Fig. 2**), which is a result of the inner force balance (Baumgard 2012). The curvature corresponds to the second derivation of the bending line and depends on the strain conditions and on static depth (equation (2)). The bending stiffness EI(x) of every section dx (**Fig. 2**) can be calculated from the moment M(x) divided by the curvature k(x). Indeed, the local stiffness reduction of a structure can be determined from the second derivation of the measured bending line on the basis of precise deflection measurement.

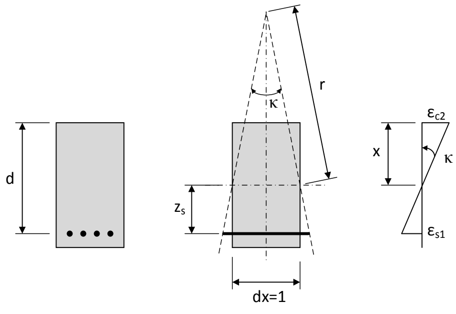

Fig. 2. Relation between curvature and strain (Zilch und Zehetmaier 2010)

As already mentioned, the prerequisite of DAD-Method is a load deflection test of a bridge structure with precise measurement of the bending line. The theoretical bending moment for the load deflection test is known. The curvature can be determined as second derivation of the bending line. Accordingly, it is possible to recognise a local stiffness reduction from the course of the bending line.
A non-destructive condition assessment of bridges requires a load deflection test in serviceability limit state. Therefore, only small deflections need to be produced. In general the load can be generated by a single truck or by several trucks depending on the static system of the bridge. Using such curvature values increases the risk of incorrect assessment for the localisation of discontinuities in the static system. However, the DAD-Method enables a precise localisation of discontinuity also for small deflections. The procedure of the method is, firstly to develop a FE-model of the bridge, then to compare the calculated deflection with the measured deflection. Subsequently, the DAD-values are used to detect an invisible discontinuity of the deformation behaviour of the static system.

2.1 Theoretical basis of the DAD-Method

The theoretical basis and individual steps for the application of DAD-Method are explained in the following using an example. The bridge has for the example a span of 30 m (**Fig. 3**). The FE-mesh for this example is chosen with 2,00 m, thereby the bridge is divided into 15 elements along the longitudinal direction. This means, deflection values are available every 2,00 m. A deflection measurement every 2,00 m is also achievable in situ. Local damage is generated by reducing the stiffness at the position between x=6 m and x=8 m. By calculation, respectively, by the deflection measurement, the basic information of the bending line along the longitudinal axis of the beam, of undamaged respectively damaged systems, becomes available (**Fig. 3**).

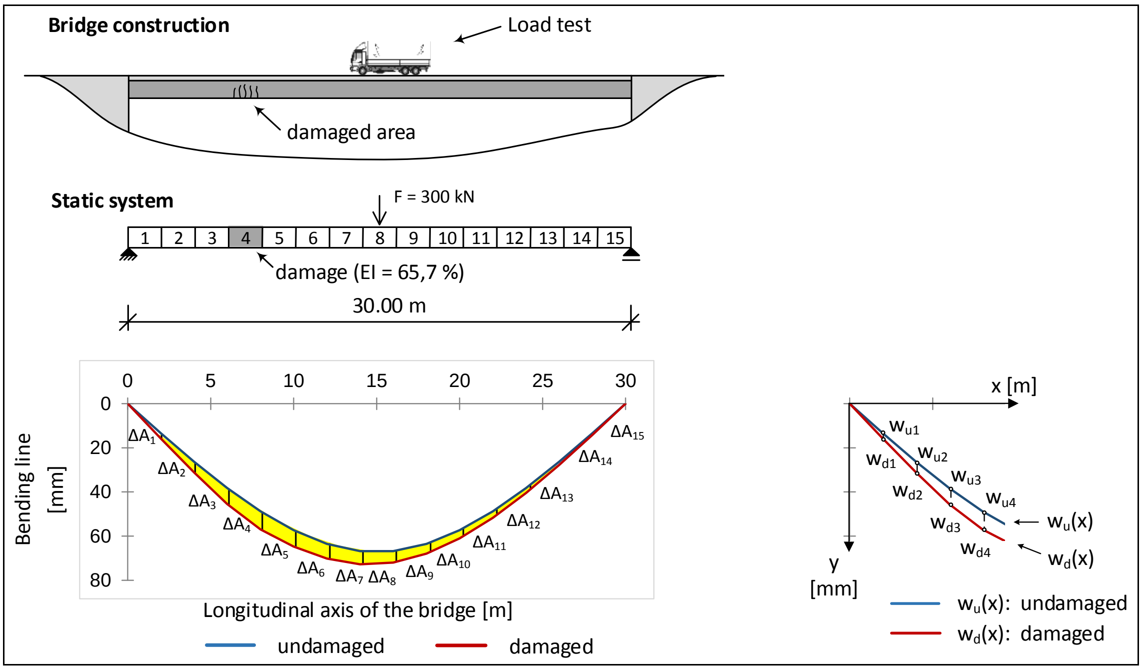

Fig. 3. The example of a bridge with local damage (above), the static system with 15 elements (in the middle), the course of the bending line with and without damage (bottom left), the measured and calculated values of the bending line (bottom right)

Now the first derivation of the bending line is calculated and respectively the inclination angle is determined with the equations (3), (4) and according to **(Fig. 3)**. The resulting inclination angle is shown in **Fig. 4**. The second derivation of the bending line is determined using equations (5), (6) and according to **Fig. 4** in order to determine the curvature. In **Fig. 5**, the course of curvature is shown.

$$w_u'(x) = \varphi_u(x) = \frac{y_{u,i+1} - y_{u,i}}{x_{u,i+1} - x_{u,i}} \tag{3}$$

$$w_d'(x) = \varphi_d(x) = \frac{y_{d,i+1} - y_{d,i}}{x_{d,i+1} - x_{d,i}} \tag{4}$$

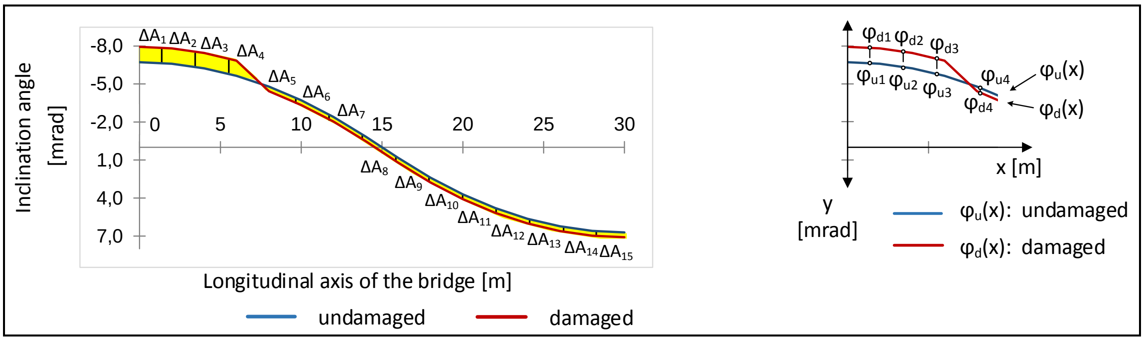

Fig. 4. The course of inclination angle of the bridge with and without damage (left), the measured and calculated values of the inclination angle (right)

$$w_u''(x) = \varphi_u'(x) = \kappa_u(x) = \frac{y_{\varphi u,i+1} - y_{\varphi u,i}}{x_{\varphi u,i+1} - x_{\varphi u,i}} \quad (5)$$

$$w_d''(x) = \varphi_d'(x) = \kappa_d(x) = \frac{y_{\varphi d,i+1} - y_{\varphi d,i}}{x_{\varphi d,i+1} - x_{\varphi d,i}} \quad (6)$$

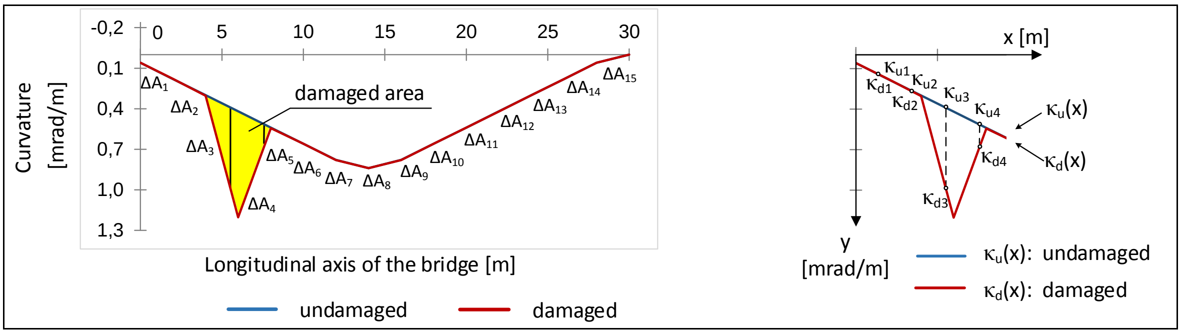

Fig. 5. The course of curvature of the bridge with and without damage (left), the measured and calculated values of the curvature (right)

As shown in **Fig. 3**, **Fig. 4** and **Fig. 5**, the basis of the DAD-Method is to differentiate the area between the undamaged and damaged courses. The localisation of the damage for this example becomes obvious when looking at the course of curvature, because the degree of damage (65,7 %) was chosen relatively large in order to provide clear illustration. The discontinuity or damage is clearly locatable. The individual steps are explained in the following using the formulas (from (7) to (12)). First, the areas between the undamaged and damaged courses (bending line, inclination, curvature) are divided in regular distances (equations (7), (8) and (9)), thus demarcating the 15 individual areas. Then, the individual areas are squared and normalised by the squared total area (equations (10), (11) and (12)). The graphical illustration of DAD-values are presented in **Fig. 6**. The discontinuity of the static system can be easily seen in the courses of the bending line and inclination (**Fig. 6**), however a clear localisation of the damage is possible by consideration of the DAD-values from curvature (**Fig. 6**). The precision of localisation depends on the density of the FE-mesh and the density of measuring points. The determination of the existing stiffness of the static system becomes possible by using the measured or calculated curvature values (equation (2)).

$$\Delta A_{i,w} = (x_{wu,i+1} - x_{wu,i})\frac{(y_{wd,i+1} - y_{wu,i+1} - y_{wu,i} + y_{wd,i})}{2} \quad (7)$$

$$\Delta A_{i,\varphi} = (x_{\varphi u,i+1} - x_{\varphi u,i})\frac{(y_{\varphi d,i+1} - y_{\varphi u,i+1} - y_{\varphi u,i} + y_{\varphi d,i})}{2} \quad (8)$$

$$\Delta A_{i,\kappa} = (x_{\kappa u,i+1} - x_{\kappa u,i})\frac{(y_{\kappa d,i+1} - y_{\kappa u,i+1} - y_{\kappa u,i} + y_{\kappa d,i})}{2} \quad (9)$$

$$DAD_{i,w} = \frac{\Delta A_{i,w}^2}{\sum_1^n \Delta A_{i,w}^2} \quad (10)$$

$$DAD_{i,\varphi} = \frac{\Delta A_{i,\varphi}^2}{\sum_1^n \Delta A_{i,\varphi}^2} \quad (11)$$

$$DAD_{i,\kappa} = \frac{\Delta A_{i,\kappa}^2}{\sum_1^n \Delta A_{i,\kappa}^2} \quad (12)$$

with:

DAD	= Deformation Area Difference
$DAD_{i,w}$	= Deformation area difference value from section i resulting from the bending line
$\Delta A_{i,w}^2$	= Deformation area difference of the segment i between the observed bending lines
$\sum_1^n \Delta A_{i,w}^2$	= Total area difference enclosed by the observed bending lines
$DAD_{i,\varphi}$	= Deformation area difference value from section i resulting from inclination angle
$\Delta A_{i,\varphi}^2$	= Deformation area difference of the segment i between the observed inclinations
$\sum_1^n \Delta A_{i,\varphi}^2$	= Total area difference enclosed by the observed inclinations
$DAD_{i,\kappa}$	= Deformation area difference value from section i resulting from curvature
$\Delta A_{i,\kappa}^2$	= Deformation area difference of the segment i between the observed curvatures
$\sum_1^n \Delta A_{i,\kappa}^2$	= Total area difference enclosed by the observed curvatures

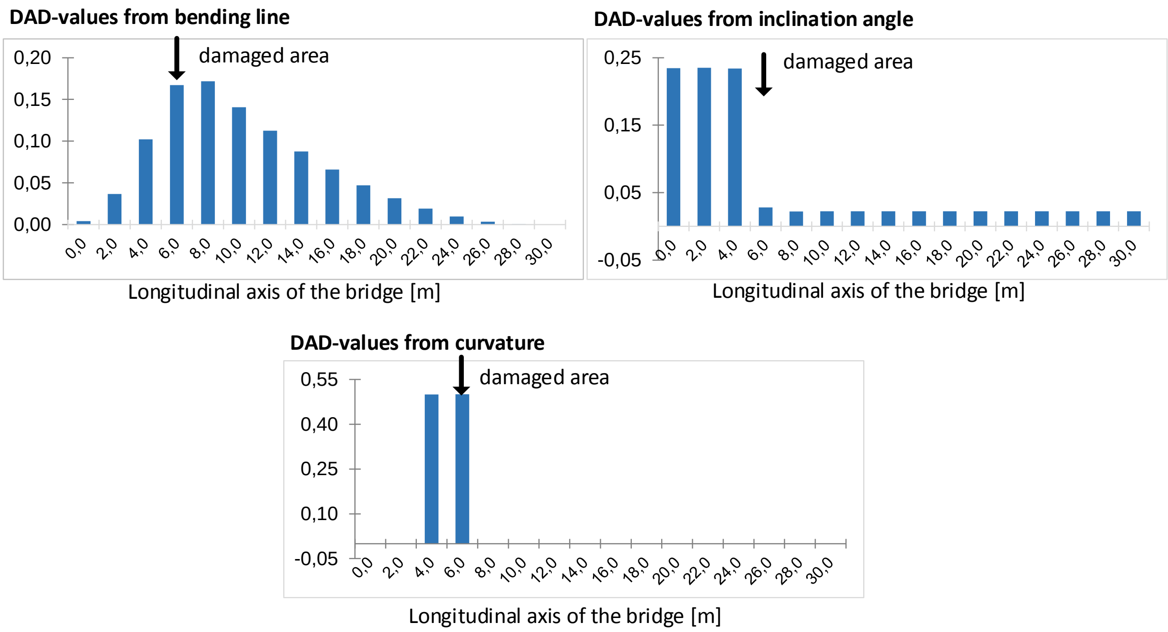

Fig. 6. DAD-values from bending line, inclination and curvature

3. Application of DAD-Method

A laboratory test with a reinforced concrete beam is prepared in order to compare appropriate measurement techniques. The prepared concrete beam is single spanned (**Fig. 7**). The beam is loaded stepwise until yielding of reinforcement. The main materials are concrete C40/50 and reinforcement steel B500B. The load stages are shown in **Table 1**.

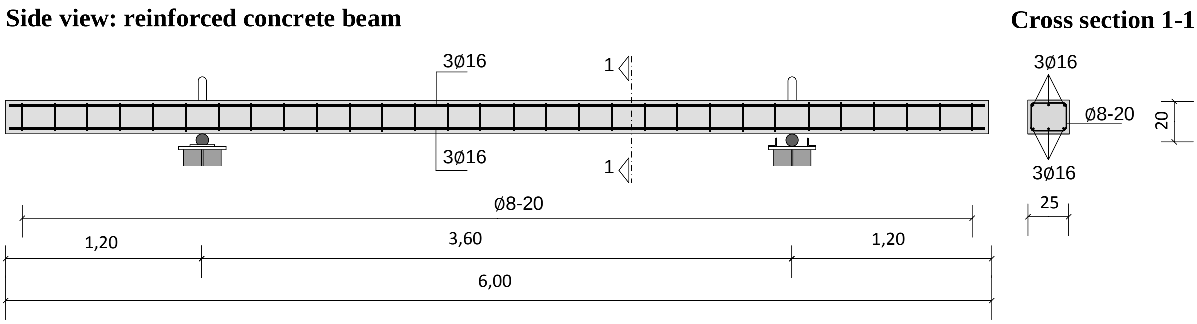

Fig. 7. Test specimen – Reinforced concrete beam

Table 1. Load steps [kN]

Nr.	#	1	2	3	4	5	6	7	8	9
Load	[kN]	0,00	3,00	5,23	10,00	15,00	20,00	30,00	40,00	50,00

3.1 *The stiffness reduction of the reinforced concrete beam due to loading*

The example in Section 2 has been presented based on a theoretical example using linear calculation. However, the stiffness of a reinforced concrete beam decreases by increasing load due to cracking, yielding of the reinforcement or failure of the concrete in the compression zone. In **Fig. 8**, the linear and non-linear behaviours of the test specimen are illustrated. The non-linear behaviour is shown here on results from the FE-program Sofistik, whereas a comparison of several non-linear calculations will be presented in Section 3.2. The beam shows a linear behaviour until the cracking load F_{cr} is reached. At this point, the first stiffness reduction arises. The second stiffness reduction of the reinforced concrete beam occurs upon reaching the yielding strength of the reinforcement at 50 kN. The concrete compression reaches the limit of 3,50 ‰ under the load of 54 kN, which determines the failure of the element.

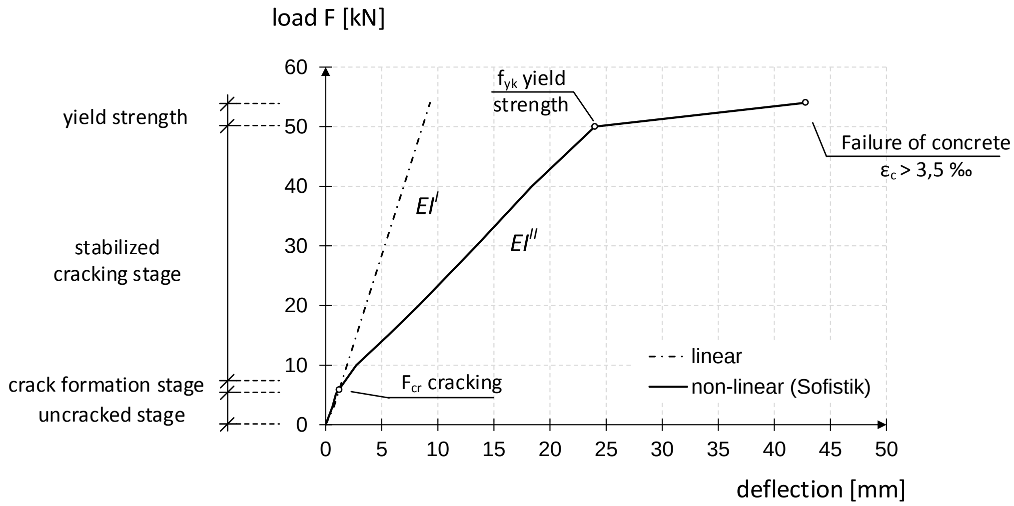

Fig. 8. Non-linearity of the reinforced beam

3.2 *Load deflection behaviour of the laboratory beam*

For preliminary design of the girder, various approaches have been used to compare them. These involve a linear calculation, a non-linear analysis with Sofistik and RSTAB, a simplified manual calculation and an iterative calculation using Excel. The procedure of simplified manual calculation will be described hereafter. As described in equation (2), the reduced stiffness is determined from the bending moment and the curvature. However, the compression zone of concrete is simplified as a rectangular zone (**Fig. 9**). This has the consequence that the accuracy is lower at smaller load levels. First, the compression zone height x is determined from the bending moment, then the lever arm of internal forces z. Using the known compression area, the internal forces Z_{s1d} and D_{cd} can be determined, from which the tensile strain of steel is calculated. Now using the steel tensile strain ε_{s1}, the static height d and the compression zone height x, the curvature κ and the stiffness EI of the beam are calculated (equation (2)). The simplification lies on the safe side (smaller inner lever arm), whereby the yield point of the tensile reinforcement is reached at 40 kN which is demonstrated in **Fig. 11** by the bend in the course of the "simplified" deflection at 40 kN. The basic procedure of the iterative calculation with excel is similar to the simplified manual calculation. Here the compression area is not simplified, but the coefficient k_a (to consider the lever arm height) and the coefficient α_R (to consider the stress curve in the compression zone of concrete) are taken into account. The non-linear respectively iterative calculation starts with the cracking of concrete in the tensile zone. In the range of the second stiffness reduction (Section 3.1), the strain of the reinforcement (ε_{s1}=2,50 ‰) is defined as limit, while the compression of concrete ε_{c2} constitutes the iterative input value (**Fig. 9**). At the next stiffness reduction, the constraint is the maximum concrete compression (ε_{c2}=3,50 ‰), whereby the strain of reinforcement is iterated between ε_{s1}=2,174 ‰ and ε_{s1}=25,0 ‰ until the internal forces are in equilibrium. Subsequently, the curvature can be calculated according to equation (2) by using the strain values. Now the determination of the stiffness reduction and the deflection becomes possible due to the curvature values and the virtual forces. The calculated stiffness reduction and the deflection are shown in **Fig. 11** in graphical form.

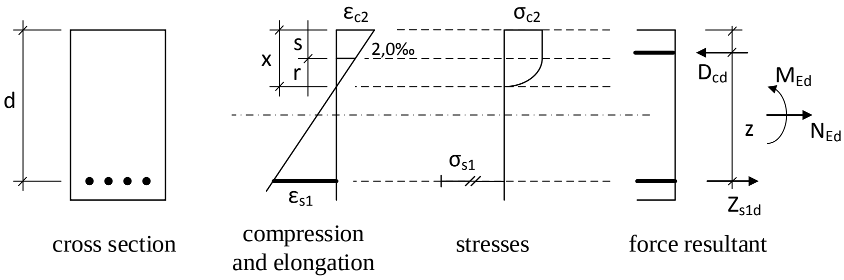

Fig. 9. Basis of the simplified and iterative calculation

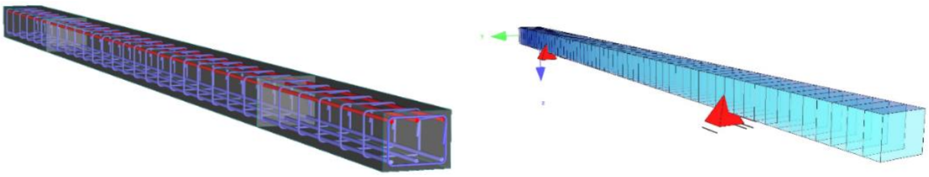

Fig. 10. Modelling of the beam with RSTAB (left), with Sofisitk (right)

Table 2. Calculated bending for the different load steps

Load level	iterative Excel	simplified	RSTAB	Sofistik	linear
[kN]	[mm]	[mm]	[mm]	[mm]	[mm]
0,00	0,00	0,00	0,00	0,00	0,00
3,00	0,73	0,90	0,70	0,61	0,73
5,23	1,11	1,60	1,10	0,92	1,10
10,00	2,95	3,10	2,40	2,72	1,90
15,00	5,28	4,70	4,40	5,56	2,74
20,00	7,71	6,50	6,80	8,29	3,58
30,00	12,64	10,30	12,10	13,43	5,27
40,00	17,59	14,70	17,60	18,39	6,95
50,00	26,33	24,43	24,90	24,01	8,63

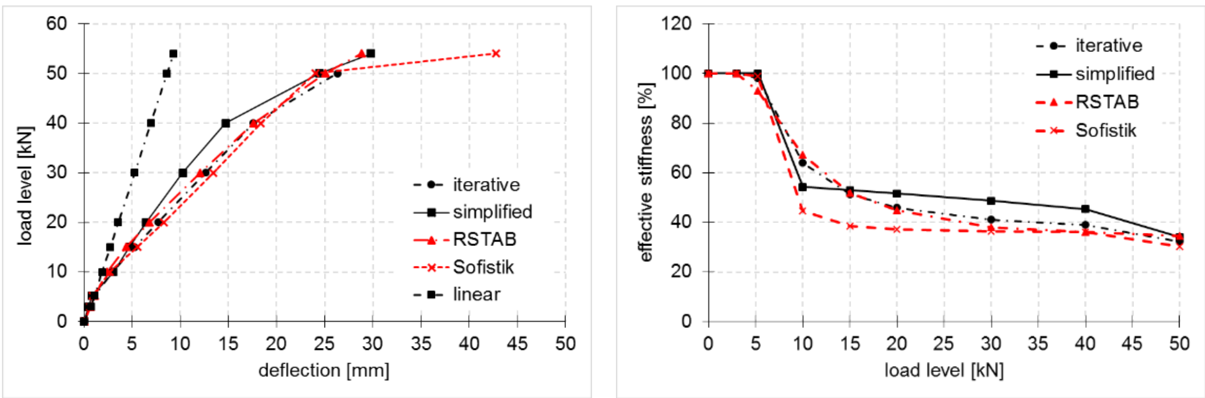

Fig. 11. Load-deflection curve (left), stiffness reduction (right)

The cracking of the reinforced concrete beam is often underestimated, whereas the stiffness can be reduced on an average by 50% (**Fig. 11**) (Fastabend 2002).

3.3 DAD- Method on the laboratory beam

As already mentioned, the DAD-Method does not necessarily require a real reference system, but only a theoretical modelling of the structural system in the undamaged state. In this case, a linear calculation of the deflection is provided as a reference system. The inclination angle and the curvature can be determined mathematically from the first and second derivatives of the bending line. The results of the linear analysis are shown in the following diagrams as dashed blue lines. A realistic calculation of the test body is carried out by a non-linear calculation with finite elements and is shown in the following diagrams as solid red lines.

To illustrate the DAD-values, in the following, the load steps are selected at 10 kN, 30 kN, 50 kN and 54 kN. At load step 10 kN, the first stiffness reduction already occurred due to cracking. At 30 kN, the stiffness reduction does not increase significantly, but the cracked area becomes larger. The second stiffness reduction occurs under the concentrated load of 50 kN and the yield strength of the steel is then reached. The load is further increased until the concrete fails in the compression zone.
In **Fig. 12** a large deflection difference between the linear and non-linear calculation induced by the reduced stiffness can be noticed. For this case, as shown in **Fig. 13**, a discontinuity of inclination angle can be considered. However, the detection of the discontinuity is only possible by considering the curvature (Section 2). The detection of the discontinuity is now determined and localised using the DAD-values (**Fig. 14**). The stiffness of the reinforced concrete beam is calculated for the different load steps with the values from curvature and bending moment, which can be observed in **Fig. 14** to **Fig. 17**.

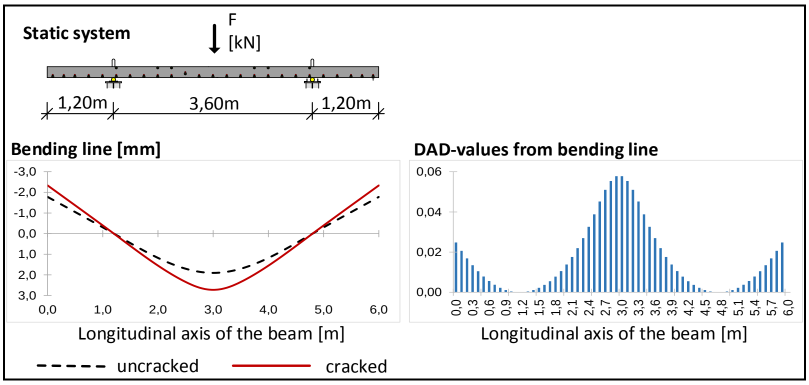

Fig. 12. Load step 10kN, left: Bending line with full and reduced stiffness, right: DAD-values from bending line

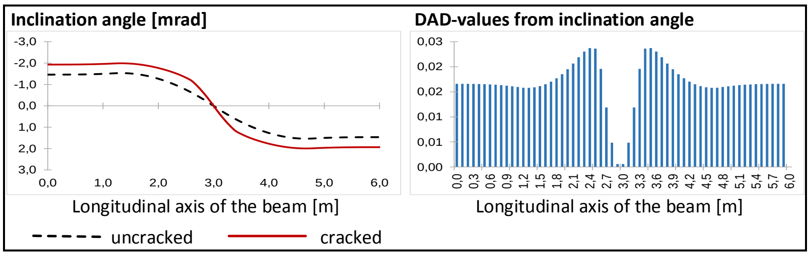

Fig. 13. Load step 10 kN, left: inclination with full and reduced stiffness, right: DAD-values from inclination

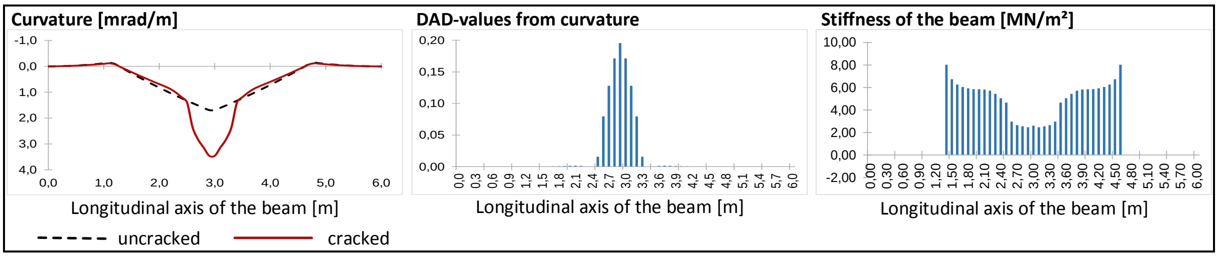

Fig. 14. Load step 10 kN, left: curvature with full and reduced stiffness, middle: DAD-values from curvature, right: stiffness at midspan

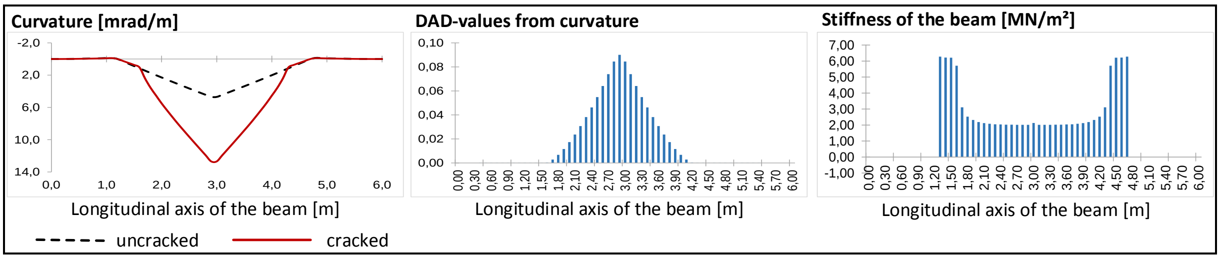

Fig. 15. Load step 30 kN, left: curvature with full and reduced stiffness
middle: DAD-values from curvature; right: stiffness between the supports

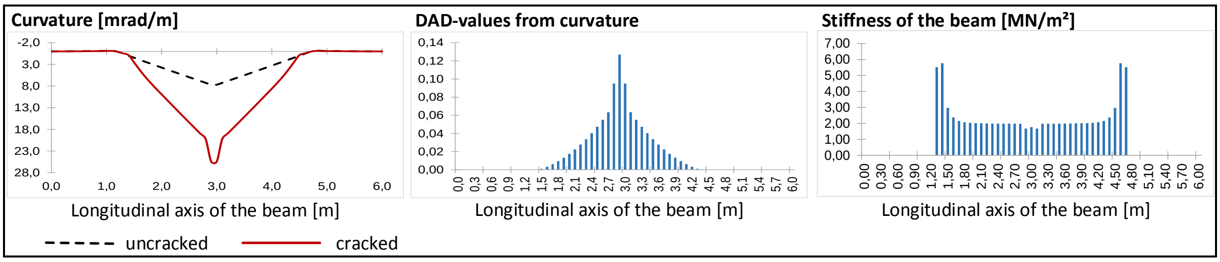

Fig. 16. Load step 50 kN, left: curvature with full and reduced stiffness
middle: DAD values from curvature, right: stiffness between the supports

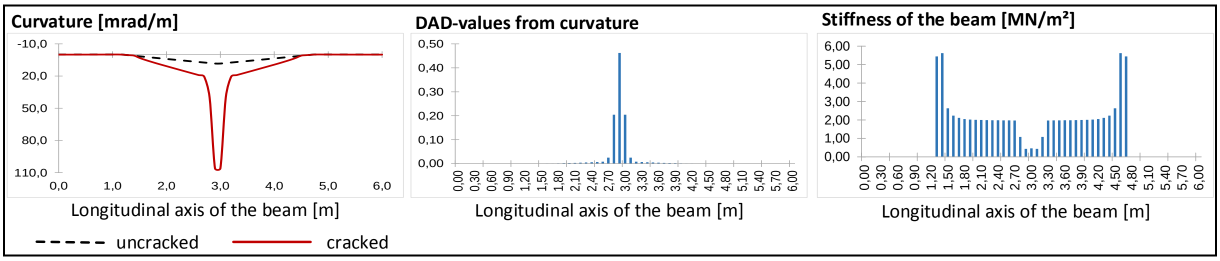

Fig. 17. Load step 54 kN, left: curvature with full and reduced stiffness
middle: DAD values from curvature, right: stiffness between the supports

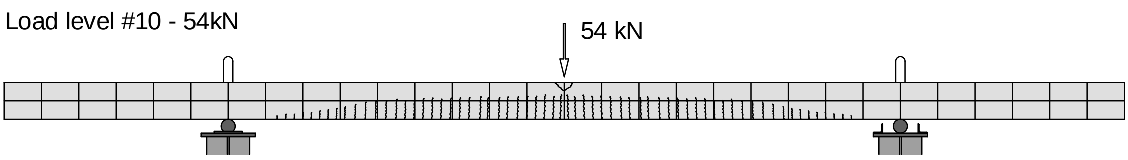

Fig. 18. Load step 54 kN, failure of concrete in the compression zone at midspan,
yield point of tensile reinforcement is already achieved

4. Summary and outlook

The presented DAD-Method is simple to use and is based on familiar knowledge for engineers. Using the DAD-Method, the global influences such as weather and asphalt rigidity can be neglected. The smallest discontinuity of the structural system becomes apparent due to the DAD-values. With reference to the theoretical calculation, it has been shown that the detection of the damage becomes possible by means of a precise deflection measurement. The localisation of local stiffness reduction can be detected using the DAD-Method and the degree of damage using the curvature values from the measurement results. In the next step of the investigation, a load deflection test takes place, in which different measurement techniques are compared. The considered measurement techniques are the digital levelling, laser scanner, total station, photogrammetry, displacement sensors and strain gauges.
By using a suitable measuring instrument and finite element models, the DAD-Method allows to localise the damage of a bridge construction and determine its degree, thus leading to an economical and time-saving solution for condition assessment of bridges.

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