Potential of the Deformation Area Difference (DAD)-Method for Condition Assessment of Bridge Structures

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ABSTRACT: The construction industry ranks in the back rows in terms of digitalization. The numerous existing bridge structures require considerable effort for inspection and reliable assessment of their condition. However, the state-of-the-art for inspecting these structures still relies on the visual inspection realized by bridge inspectors. The current paper summarizes several research projects in the field of condition assessment of bridge structures at the University of Luxembourg by analysing the structural response due to dynamic excitation and static loading tests.

The latest development aims at using the most modern measurement techniques by combining them to a new method, the Deformation Area Difference (DAD)-Method in order to simplify and automatize at most the inspection process. The proposed DAD-Method is based on conventional static load deflection tests. It allows the localization of stiffness-reducing damage by using a very precise measurement of the deflection line and by combining this outcome to the deflection line generated by a simplified finite element model of the bridge. In order to investigate the condition of a bridge by the DAD-Method modern measurement techniques such as photogrammetry and laser scanning are used. In the framework of the conducted research, these techniques are also compared to traditional measurement systems such as total station and inductive displacement sensors as well as to digital levelling sensors. By theoretical examples and experimental tests, it can be shown that the DAD-Method is able to detect and localize damage when the damage level is dominant on the measurement noise.

This paper investigates also the application of the method on a real bridge structure in Luxembourg. All of the above-mentioned measurement techniques were used, whereby the photogrammetry is applied using both, stable tripods and an autonomous flying drone. This allows examining the accuracy of the different measurement systems when applied on a real-size structure.

1 INTRODUCTION

The condition of the existing bridges, the increase of their average age and their preservation is nowadays a great challenge. Indeed, bridge structures are not only confronted to an increasing traffic level, but also the proportion of heavy trucks has significantly increased in the recent years. Heavy-duty trucks are primarily affecting the roads and the bridge structure condition. For instance, the influence of a truck with an axle load of 10 tons corresponds to the impact of 160.000 car axles with 0,50 tons and for an truck axle load of 11,5 tons the corresponding number of the car axles amounts to 280.000 [1]. The country specific standards require regular visual bridge inspection, which commonly varies between two and six years [2]. In case of uncertainties and conspicuities during a visual inspection, further methods such as acoustic or ultrasonic methods

[3], radiography, magnetic or thermal field methods [4] could be applied. However, a drawback of the visual inspection is that for larger bridge structures the inspection is time and cost consuming. Furthermore, damage, which is inside the load bearing structure, will remain undetected [5]. Results from research projects using condition assessment methods based on dynamic or static parameters show that structural responses such as eigenfrequencies [6] [7] [8] and deflection curves [9] [10] contain information which can be used to detect stiffness reducing damage.

The current paper summarizes several research projects in the field of condition assessment of bridge structures at the University of Luxembourg. The main contributions are in line with the doctoral theses and publications of Bungard [11], Scherbaum [12] and Erdenebat [13]. [14]. The focus of these studies ranges from linear and non-linear dynamic analysis to static load deflection investigations. The results of various finite element models, laboratory tests and real bridge experiments collected over the years are presented. All of the presented bridge tests are carried out in Luxembourg. The results from dynamic analysis confirm that damage changes the structural response parameters such as eigenfrequencies, eigenmodes and damping. However, the sensitivity of the structural response due to dynamic excitation is low. Further influence factors, such as e.g. the stiffness change of the asphalt layer in function of temperature variation, has also been analysed and some experimental results will be presented. Compared to the condition assessment based on dynamic parameters, the condition assessment based on static loading tests allow not only the identification of damage but also its localization. However, a continuous measurement of the deflection line with high precision is indispensable. The presented so called “Deformation Area Difference (DAD) Method” bases on static load deflection experiment to detect local stiffness reducing damage.

2 CONDITION ASSESSMENT BASED ON DYNAMIC EXCITATION

Eigenfrequencies and mode shapes as a global structural response depending on the stiffness of a structure characterize the structural response to dynamic excitation. Thus, in principle, stiffness reducing damage will affect these parameters. However, damage identification and in particular their localization will remain difficult as the dynamic response of a structure is always a global response of this structure. Thus, identifying an exact position of a local damage out of a global response is challenging. However, damage identification and in particular there localization will remain difficult as the changes of the eigenfrequencies and mode shapes are not directly correlated to the stiffness of the system. This is only possible by means of a dense measurement grid and by using mode shape information respectively information of its derivate like the mode shape curvatures. However, the measurement accuracy as well as the data evaluation and interpretation remain challenging.

Within a first research project [11], condition assessment using dynamic excitation was performed on reinforced and prestressed beams in various finite element model-based calculations and subsequent laboratory tests. The aim of the study was to analyse how damage affect the modal properties and how to use the findings for condition assessment of structures. The investigated reinforced concrete beam was subjected to a stepwise loading leading to gradual cracking and to yielding of the reinforcement. Within the test, static parameters such as deflection and strain along the cross section’s height were measured and in addition, dynamic parameters such as eigenfrequencies and damping values have been recorded. In summary, all measured parameters presented changes as a result of stiffness reduction. However, the changes of the dynamic parameters remain small in comparison to the static parameters.

Based on these results, a first method has been developed which is based on the calculation of the area differences of mode shapes measured for different damage stages. In order to allow damage localisation, the beams were first subdivided in finite sections over the length of the structure. Furthermore, a normalization by dividing by the sum of all area differences is needed. The squaring allows to increase the sensitivity of the results. In order to respect also the impact of higher eigenfrequencies, the sum of the all eigenfrequencies measurements for each section is created. The method is presented in equation (1) as Mode shape Areas Differences MSAD [11].

$$MSAD\ in\ part\ i = \left[\frac{\Delta Ai_1^2}{\Delta A_1^2} + \frac{\Delta Ai_2^2}{\Delta A_2^2} + \cdots + \frac{\Delta Ai_1^2}{\Delta A_1^2}\right] = \sum_{m=mode\ 1}^{mode\ n} \left[\frac{\Delta Ai_m^2}{\Delta A_m^2}\right] \qquad (1)$$

3 THE DEFORMATION AREA DIFFERENCE (DAD) METHOD

As the deformation of a structure depends on the stiffness, the deflection curve behaves continuous if no stiffness change appears in the load bearing structure. The curvature $\kappa(x)$ of a structure is given by the relation of the moment M(x) and the bending stiffness EI(x), which can be approximated by the double derivation of the deflection (equation (2)).

$$\kappa(x) = \frac{M(x)}{EI(x)} \cong w"(x) \qquad (2)$$

In order to enable the identification of damage and even to provide its location, a continuous measurement of the deflection along the longitudinal axis of the structure is necessary. Thus, the technical challenge lies not only in a very fine measurement grid, but also in a very precise data acquisition owed to the double derivation calculation. However, stiffness changes may also occur due to e.g. a variable cross-section of a bridge structure along its longitudinal axis. All these considerations complicate the condition assessment of structures based on a load deflection tests.

The so-called “Deformation Area Difference (DAD) Method”, which has been developed by the Laboratory of Solid Structures at the University of Luxembourg, tries to balance the above-mentioned drawbacks. It enables the localization of stiffness reducing damage based on load deflection experiments. In principle, there are two requirements for the successful application of the method. On the one hand, the measurement of the deflection line along the structure have to be acquired as precise as possible and on the other hand, a theoretical deflection curve of the structure needs to be used as reference curve.

The theoretical model respectively a finite element calculation is needed in case no initial reference measurement on the bridge structure is available. Furthermore, the finite element calculation is used to consider structural elements, which is leading to stiffness changes and differs from any damage. It is known that a theoretical model usually cannot exactly represent measured values. However, this is not a problem as the exact modelling of the structure is not a prerequisite for the application of the DAD method. Thus, the continuous deflection curve of the finite element analysis is not used in a direct comparison with the measured data but only as a complementary item by the DAD method to ensure only the damage induced stiffness reductions. The DAD method detects exclusively discontinuities of the load-bearing structure, so not the extent of the damage. The DAD method enables the detection of every smallest stiffness change in the structure compared to the continuous curve from the reference system.

The DAD-method investigates the area between the curvature curve from the reference system and the curvature curve from the deflection measurement. The following theoretical example of a 54 m long bridge illustrates the method. A load deflection experiment is carried out on a bridge structure with a local damage, which is equivalent to a stiffness reduction of 60% at a given point. The black line in Figure 1 illustrates the curves from the undamaged reference system. In the three diagrams, the deflection $w_t(x)$, the inclination angle $\varphi_t(x)$ and the curvature $\kappa_t(x)$ are represented. The red line shows the deflection $w_d(x)$, the inclination angle $\varphi_d(x)$ (first derivation of the deflection line) and the curvature $\kappa_d(x)$ for the damaged structure.

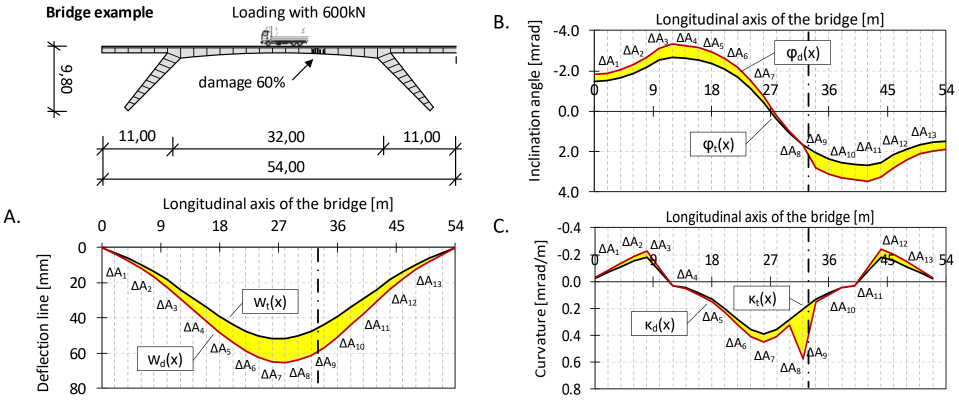

Figure 1 Principle of the DAD-method, investigation of the area differences.

The DAD-method particularly considers the area difference between the reference and the damaged curves (yellow area in Figure 1). The area is divided into small regular sections. Each area is squared and normalized by the sum of the individual squared areas (equation (3)).

$$DAD_{\kappa,i}(x) = \frac{\Delta A^2_{\kappa,i}}{\sum_{i=1}^{n} \Delta A^2_{\kappa,i}} = \frac{[\varphi_d(x_i) - \varphi_d(x_{i-1}) - \varphi_t(x_i) + \varphi_t(x_{i-1})]^2}{\sum_{i=1}^{n}[\varphi_d(x_i) - \varphi_d(x_{i-1}) - \varphi_t(x_i) + \varphi_t(x_{i-1})]^2} \quad (3)$$

The section length should be chosen in accordance with the measurement grid. The squaring of the individual section parts leads to an increase of the sensitivity of the method. Figure 2 shows the detected damage applying the DAD-method on the example shown in Figure 1 where the damage could be clearly identified and localized. Further investigations are currently concentrating on [14] the minimization and smoothing of noise effects.

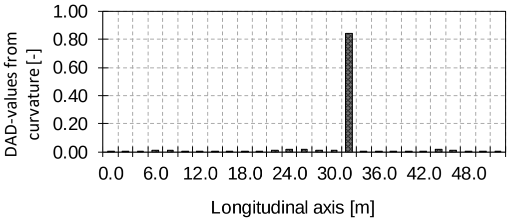

Figure 2 Detected local damage by application of the DAD-method

4 INFLUENCE OF THE ASPHALT LAYER ON THE CONDITION ASSESSMENT OF BRIDGE STRUCTURES

In case of in situ experiments on bridge structures, the condition assessment depends on all stiffness-influencing factors. Especially, the asphalt deck plays here an important role as its stiffness is highly depending on the environmental temperature conditions. While the asphalt layer is only considered as loading at design stage and its stiffness is neglected, this assumption is not anymore valid when an in-situ condition assessment of a bridge structure is being performed. The relation of the stiffness of the asphalt layer and its bond behaviour depending on temperature variations were investigated in the laboratory and real bridge structures.

4.1 Laboratory tests

Figure 3 shows the experimental setup of a laboratory test where a hollow prestressed slab element with a length of 1,8 m is analysed for two different variations, one with and one without an asphalt layer. The specimens are loaded at mid span within a climatic chamber. The considered temperature variations ranged from -10°C, 0°C, 10°C, 20°C, 30°C to 40°C. The structural responses are measured by strain gauges and by inductive displacement sensors.

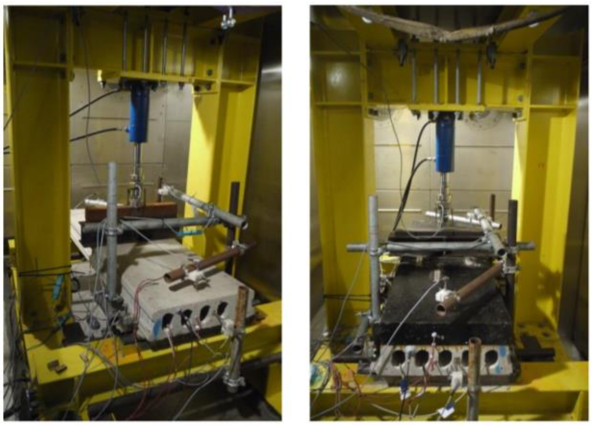

Figure 3 Setup of the static test without asphalt layer (left) and with asphalt layer (right) [12]

Figure 4 shows the measured deflections for the test slabs without (left side) and with (right side) asphalt layer. The denomination K-1 to K-8 indicate the order of the temperature variation for the experimental procedure. In the left diagram, it can be clearly seen that the measured deflection behaviour in the repeated loading processes is nearly independent from the temperature variations. However, the right diagram shows a strong influence of the asphalt layer depending on the temperature variations. As the asphalt behaves very stiff at low temperatures, the stiffness of the specimen increases accordingly. Comparing with the deformation measured at 20°C, the influence of the asphalt at 40°C amounts to about 13%, while this effect is responsible for a reduction of about 53% for a temperature of -10°C. So, a clear influence of the asphalt layer on the stiffness could be demonstrated.

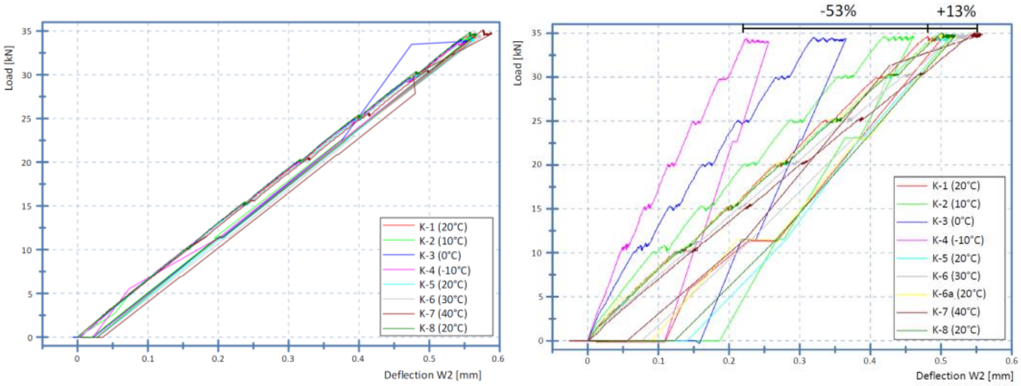

Figure 4 Force deformation diagram - slab without asphalt (left) and slab with asphalt layer (right) [12]

4.2 Bridge experiments

To investigate the impact of temperature variation on the stiffness of the asphalt layer and thus, on the condition assessment of bridge structures, in situ loading tests analysing the load-deformation behaviour were performed on different bridges (Figure 5).

The bridge in Moestroff is a prestressed concrete slab bridge with a total length of 71 m and three spans. The height of the construction amounts to 1,27 m and the width to 12,37 m. The bridge structure was loaded at mid span by four trucks with an individual weight of about 44 tons per truck. The bridge in Useldange consists of two spans with a total length of 37 m. It is a composite structure of steel S355 and concrete C45/55. Two trucks with the weight of about 44 tons loaded the bridge. The main aim of this study was to find out to what extend the asphalt layer affects the stiffness of the whole structure. The load deflection tests were carried out at different seasons and at different temperatures. The average temperatures of the asphalt layer of the Moestroff bridge during the different tests which were spread over a year amounted to 5°C for January, 10°C for March and 45°C for July, whereas the temperatures of the Useldange bridge were about 10°C for February and about 23,5°C for August. The deflection of the bridge in Moestroff increased about 21 % for a temperature difference of 35°C, whereas the deflection behaviour of the bridge in Useldange increased by about 11% for a temperature difference of 14°C. These results clearly show that for the condition assessment of bridges the stiffness of the asphalt layer has to be taken into consideration.

Figure 5 Climatic influence on the deflection behaviour of the bridges in Moestroff (left) and in Useldange (right) [12]

5 REAL BRIDGE TEST A WITH STEPWISE DAMAGING PROCESS

Within the framework of a reorganization of the urban planning, several intact bridge were demolished on the Plateau Kirchberg of Luxembourg City. The Laboratory of Solid Structures of the University of Luxembourg could take this opportunity for performing several experimental investigations by introducing controlled damage to three bridges. Two of these bridges are shown in Figure 6. On the left side of Figure 6 the “Deutsche Bank bridge”, a prestressed concrete slab bridge built in 1974 with a total length of 51 m and a construction height of 70 cm, is presented. The right side of Figure 6 shows the “Champangshiehl bridge”, a 103 m long 2 span prestressed box girder bridge built in 1966. Both bridges were gradually damaged by cutting in several steps selected tendons and the response of the structure to static loading and dynamic excitation was studied for each damage level.

For the “Deutsche Bank” bridge, different damage scenarios have been investigated, whereby a first step consisted in removing the asphalt layer. For this bridge, the contribution of the asphalt layer on the total stiffness of the bridge structure was found to be low. This could be explained by the fact that the temperature range for which the defection line was measured before and after removal of the asphalt layer was only between 10° and 30°C. In summary, the influence of the local cutting of the bonded tendons leaded only to a very small impact on both the static and the dynamic parameters. Although, 31% of the prestressing force were finally cut, no cracking occurred and thus, no measurable stiffness reduction could be detected. A re-anchoring of the tendons leaded to a limitation of the impact to the area close to the cutting zone. An analysis showed that if the measured parameters would be judge according to the minimum requirements

of the DAfStb-RIL loading test [15] or to the visual inspection according to DIN 1076 [16] this bridge would have still passed the quality check.
The “Champangshiehl bridge” is prestressed by 32 internal tendons with a parabolic course, whereby in the year 1987 further additional 8 external strands were added inside the box girder. The aim of the study was to study which damage level would lead to measurable deformation and to a stiffness reducing impact. Three different damage scenarios were planned: for scenario 1, 20 tendons were cut at the bottom side of the cross-section in the mid of the bigger span length, for scenario 2, 8 tendons were cut on the top of the cross-section in the area of the middle support structure and for scenario 3, all 8 external tendons were cut inside the box girder.

Figure 6 “Deutsche Bank bridge” (left) [11] and the “Champangshiehl bridge” (right) [12]

The loading of 245 ton was achieved by 38 beam blanks of the steel production. The first damaging scenario generated an increase of the deflection of 48 % (12,09 mm) in the large field at the position of maximum bending moment whereas the second scenario did not lead to an increase, but even to a decrease of the deflection of about 1,92 mm. Here, a rearrangement of forces took place. Scenario 3 leaded to a deflection increase of about 20,47 m.

In general, the tests on the two bridges showed that damaging affected their deformation behaviour. However, for damage scenario 2 of the “Champangshiehl bridge” nearly no impact on the defection and cracking could be observed.

6 HIGH-PRECISE DEFLECTION MEASUREMENTS

6.1 Laboratory tests

In the previous experiments, the deflection line was always only measured at defined positions by levelling and inductive transducers. Not only that the deflection line is only represented by a polyline with some discrete measurement points, a main drawback of the inductive transducers is that they have to be fixed independently from the load bearing structure on a separate scaffold and thus, that they are also affected by strain variations due to temperature changes.

As the application of the presented DAD-method needs high precision, new measurement techniques were tested in laboratory experiments to enable the measurement of a continuous deflection line over the whole structure length with high precision. Figure 7 presents two different experimental series realized on reinforced concrete beams. Due to the stepwise loading of the beams, the load-deformation curve were established by monitoring successively the uncracked phase, the first crack, the successive crack development and the yielding of the reinforcement until reaching the failure in the compression zone. The aim of the study is to increase the measurement accuracy of the deflection line to a precision, which allows the application of the DAD-method for damage detection and localization. In order to compare the measurement accuracy of different measurement techniques several instruments like laser scanner, close-range photogrammetry, total station, levelling and displacement sensors were used. Under laboratory conditions the achieved accuracies were for the different measurement techniques the following: laser scanner about 3,0 mm, photogrammetry about 0,08 mm, total station about 0,25 mm, levelling about 0,06 mm and displacement sensors about 0,04 mm.

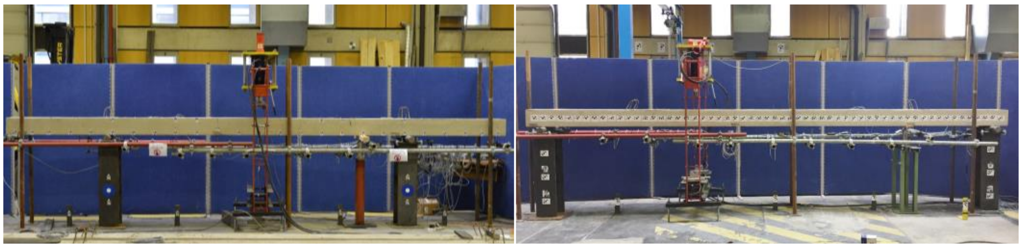

Figure 7 Laboratory experiment setups, beam with cantilever (left) [13] and single span beam (right) [14]

From the experimental tests, it can be concluded that under laboratory conditions the photogrammetry proved its applicability with a highly precise measurement of the deflection line. According to the state of the study, the photogrammetry has prevailed because of its convenient handling, reliable and high precise results. Figure 8 presents some results of the beam test for the application of the DAD-method using photogrammetry measurement data (left beam in Figure 7) [13]. On the left side, the detection of the cracked area at 35% of the failure load and on the right side the localization of the concrete failure in the compression zone at failure load can be identified.

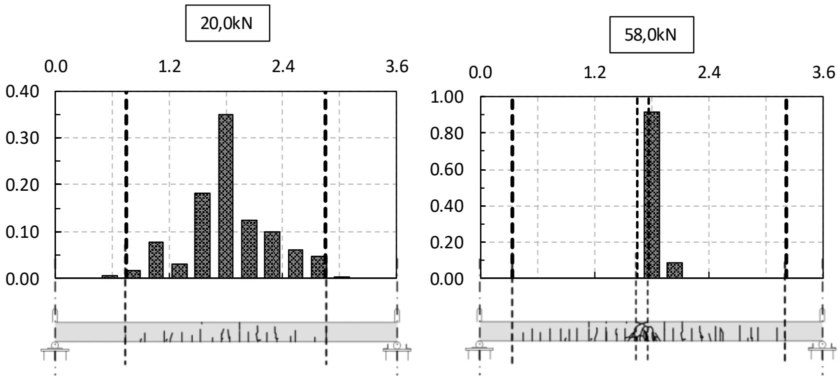

Figure 8 Detection of the cracked area (left) and localization of the concrete failure in the compression zone (right), both applying the DAD-method [13]

6.2 *Real bridge test*

Both, the theoretical examples and the laboratory tests proved the ability of the DAD-method to identify and to localize stiffness reducing damage. In order to investigate the applicability of the method on a real scale bridge a further bridge experiment have been carried out in Altrier in September 2018 in Luxembourg (Figure 9) [17]. The bridge construction consists of a 30 m single span prestressed slab structure. The bridge is loaded by 6 heavy trucks with a weight of about 33 tons. The deformation measurements were realised by a close-range photogrammetry and by using a large-size drone. The stability of the autonomous drone flight as well as the achievable accuracy were investigated.

Figure 9 Real bridge load deflection experiment [17].

7 CONCLUSION

Both the dynamic excitation and static loading of bridge structures showed measurable structural responses when damage leaded to a reduction of the stiffness of the structures. However, the assessment of the condition of structures remains difficult when measurements are not compared to a reference. As a reference, initial measurements or results generated with a non-linear finite element model could serve. In particular, it could be shown that the asphalt layer, which is only considered as an additional weight on bridge structures at the design phase, significantly influences the load deflection behaviour and that its actual stiffness has to be taken into account for performing a reliable condition assessment. This influence, which depends mainly on the structure's temperature, was demonstrated in loading tests realized within a climatic chamber and on a real scale bridge at different seasons. The laboratory test showed an 13 % influence of asphalt layer on deformation behaviour for a temperature decrease from 40°C to 20°C and 53 % for a temperature decrease of from 20°C to -10°C. In comparison, the both real bridge experiments in winter and in summer showed an asphalt layer influence of about 11 % for $\Delta T=35°C$ and 21 % for $\Delta T=14°C$.

The paper presents also a new so-called "Deformation Area Difference (DAD)" method. The requirement of the method is a static load deflection experiment providing the deflection line with high precision. As reference system, a simplified theoretical finite element model or measurements of the initial state of the bridge could serve. A theoretical example describes the background of the method. Further laboratory experiments for successful localization of cracked area as damage are also discussed. The stiffness reduction resulting from cracking amounted about 60 % and the maximum deflection of the beam did not exceeded the serviceability limit state. The requirement of high precise deflection measurements is investigated applying the most modern measurement techniques such as laser scanner, close-range photogrammetry, total station, levelling and displacement sensors. The achieved accuracies was for laser scanner 3,0 mm, for total station 0,25 mm, for photogrammetry 0,08 mm, for levelling 0,06 mm and for displacement sensors about 0,04 mm. Further developments with regard to the measurement technique led to the use of an autonomous flying drone to improve the handling of bridge surveying as many bridge structures are going over traffic roads, rivers, railways or slopes, wherefore the application of a drone would be very useful.

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