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The Deformation Area Difference (DAD) method for condition assessment of reinforced structures

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ABSTRACT

The investigation and condition assessment of bridges have a very high priority in the construction industry today. Particularly, due to the fact that many bridge structures are getting old and partly reach the end of their useful life, the control and condition assessment of bridge structures have become very important and essential. The present research work introduces an efficient new method for condition assessment called the Deformation Area Difference (DAD) Method. This new method represents an attractive alternative to visual inspection and long-term monitoring. In this paper, the new method with its theoretical background is presented and explained by means of a laboratory experiment and some additional theoretical calculation examples. The experimental investigations have been realised on a reinforced concrete beam, which has been gradually loaded until failure. For each load step, the stiffness reduction and the apparent cracking have been monitored. High-precision measurements such as close-range photogrammetry, digital levelling and displacement sensors have been used for the determination of the deflection curve. The DAD method has been applied to identify the area of the crack pattern of the laboratory experiment. Furthermore, the method is discussed with regard to the load level and the precision of the deformation measurements. On the basis of the laboratory experiment, the applicability of the DAD method for damage detection could be proven. Furthermore, the sensitivity of the method with regard to the damage degree, the static system, the damage position and the impact of temperature variation were analysed.

1. Introduction

Owners of civil engineering structures have to ensure the load bearing capacity, safety and durability of structures under consideration of the economic efficiency. This requires regular and competent inspections of these structures, such as bridges, which are key elements of a long-term economic conservation strategy. In future years, the biggest challenge years will be to develop procedures, which allow an easy and cost-effective condition assessment of bridge structures. Many of the existing bridge structures worldwide were built using reinforced and prestressed concrete design concepts. The origins of most of the damages of reinforced or prestressed concrete structures, which lead to a stiffness reduction, occur inside of the structures. Currently the control and the condition assessment tasks are carried out by visual inspection [1,2], leading to a detailed damage analysis if required. Today bridge structures are subjected to increasing traffic volumes while vehicles are also becoming heavier. Furthermore, with increasing age the bridges are also exposed to chemical attacks caused by, e.g., water or oil penetration [3]. Techniques such as radar detection [4], infrared thermography [5], ultra-sonic measurement [6], half-cell method [7], impact-echo method [8], chain dragging and hammer sounding [9] are suited for large-scale non-destructive investigations. The functionality of these methods is commonly similar, whereby each inspection technique is specialised for detection of certain damage types and has its own characteristics and limitations. Most of them are used for condition assessment of bridge decks, but the applicability is limited, e.g., to a certain range of temperature, to a certain depth where damage can still be localised, to a certain moisture content or due to challenging data interpretation, etc. [10]. In contrast, methods like the calcium-carbide method, endoscopy [11], rebounding hammer (Schmidt hammer) [12] or laboratory investigations are deployed to further locate and characterise an identified damage after a visual inspection of the bridge structure. Using the given inspection methods stiffness reducing damages cannot reliably be detected.

A global or local stiffness reduction such as, e.g., concrete cracking, failure of tendon or reinforcement and a deficit of tendon coupler can influence the load bearing capacity of a structure, which can be analysed by a load-deflection experiment. Several research projects are

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focused on the identification of stiffness reducing damages by means of dynamic and static analysis of bridge structures [13–15]. It has been proven [16] that the dynamic and static experimental data include decisive information about the stiffness reduction and the respective damages. Boumechra [17] presented in his work a new approach for damage identification for bridge structures using numerical calculations. Particularly, he took into consideration the static load deflection behaviour of two models with generated damage. The analysing factor was the deflection value at one position, but with variable position for an applied static force. Using his algorithm, he ascertained an approximate correspondence of damage detection. However, his method for damage detection requires the analysis of the initially undamaged beam, which poses a problem for existing bridge structures. A definitive and exact conclusion of the condition of a structure cannot be provided using the results of one single load deflection analysis when no reference measurements for a known reference condition are given. Stöhr et al. [18] investigated in their work the influence line of a laboratory beam and a real bridge with local damages. Thereby, an inclinometer was installed at the support, measuring the change of the inclination angle with load increase. A discontinuity in the curve of the influence line could be identified due to damage of the structure. However, by considering only the measured influence line the localisation of damage turned out to be difficult because of its unsteady curve and some noise in the measurement. The measured influence line could be used for the identification of structural damage, but the measurements were affected by noise. In their further research, it is planned to use measured static influence lines for finite element model updates in order to allow a reference-free condition assessment. Li [19] investigates the issue of damage identification of structures using optical measurements. In the extended literature review, the dynamic damage identification methods and static response data-based damage identification methods are compared. In comparison to dynamic-based identification methods, the literature of static methods is limited. Static load deflection methods often require continuous displacement measurements along the beam, which is unrealistic depending on the size of structure, on the local conditions or on the measurement techniques. Therefore, some research develop methods such as spline interpolation or moving load analysis to generate a complete set of displacement data [20,21].

He et al. [22] present a damage detection method for beam structures which are loaded by a quasi-static moving load. This deflection method is based on displacement measurements where the relationship between damage parameters and displacement influence lines is investigated. The theoretical background of the method which is based on Euler-Bernoulli [23], is presented numerically and experimentally. First the localisation of the damage is achieved by using the displacement influence line (DIL). Then the damage index is quantified. The changes in the DIL point to damages whereas the damage localisation index is calculated. The damage quantification requires a certain number of displacement sensors, which should measure close to damage. The results from the calculation and from the experiment show peaks in the area of damages. However, the author mentions difficulties for damage detection due to measurement noise effects. Further corresponding damage detection methods using moving loads are presented in [24–26]. Sun et al. [27] develop a method based on curvature to detect damages in structures such as bridges. The damage respectively the discontinuity of the curvature curve is identified by using static load deflection measurement with variable load positions. The measurement takes place using a displacement sensor at mid-span of the beam. Furthermore, they investigate the influence of measurement noise and trie to reduce noise effects. The localisation of discontinuities was possible depending on the ratio of noise and damage.

Another approach for condition assessment of bridges is given by dynamic excitation of the structures and analysis of their response. These methods need reference measurements and thus, require long-term structural health monitoring over a longer time period [28]. Therefore, a large volume of observation data has to be processed and reliably evaluated. The installation of a bridge monitoring system is often linked to the issue of establishing and guaranteeing a fixed reference point for the measurement techniques. Moreover, the dynamic data analysis requires broad experience and practice to differentiate all external influences such as environmental impacts, various traffic loads, the stiffness influencing asphalt layer [29] and temperature effects [30]. By using dynamic analysis the global excitation of a structure is provoked, which includes all global effects of structure such as the influence of the support conditions, the stiffness change due to temperature variation of asphalt etc. In order to identify all influencing factors, several in-situ bridge tests have been carried out. Sung et al. [31] tried to determine the initial static and dynamic behaviours using a series of experiments on a newly constructed bridge to determine its initial condition. Using the finite element model updating the evaluation of bridge safety thresholds could be defined. Tracking and monitoring of the bridge will continue into the future to make appropriate decisions in case of threshold exceedance. The further optimisation of dynamic analysis could show potentials for condition assessment of bridges, but the related efforts and time consumption should be taken into account.

Lee [32] used the ambient vibration data for the damage diagnostic of steel girder bridges. The potentially damaged member of the bridge is screened with the mode shape curvature, which is calculated from the second derivatives of the identified mode shapes. The localisation of damage was realised, but there were some false damage alarms at several locations in the screening process. With an increasing number of influencing factors on the data set, the probability of errors and ambiguous results increases.

So, it has been proven by several studies that the dynamic and static experimental data included decisive information about the stiffness reduction and respective damages. However, the fundamental problem of the condition assessment of bridges and damage detection remains the unknown initial condition of existing bridge structures as well as their sensitivity to global effects such as changes of temperature/humidity and changes of support conditions. The existing inspection techniques are specialised for certain damage types and have limited usability as well as reliability. Furthermore, the noise in the measurements of static or dynamic tests complicates a meaningful and clear condition assessment of existing bridges.

In order to solve these problems, a method, which does not depend on global effects, was developed within this research work to analyse and evaluate the remaining load-bearing capacity and reliability of existing structures. The proposed Deformation Area Difference (DAD) method requires data from a reference system this could be as well measurements from the initial condition of the structure as a numerical non-linear finite element model of the structure. The method is able to indicate all kind of stiffness reduction due to local damage of a bridge structure, independent of the degree of damage. The method is based on a simple load-deflection experiment using a specific data processing. The DAD-method is the first method which is able to detect all kind of damage by comparing a reference state to a modified damage state, being able to identify large damaged areas as well as small local damage. Furthermore, this is the first time that the deflection line over the whole length of a structure is measured and investigated as the current methods are too sensitive to noise effects. This is different for the DAD-method when combined to innovative measurement technologies where point clouds with minimum standard deviation are generated. Using the data of the load-deflection experiment, the inclination angle and the curvature were determined, whereby the discontinuity of the structure along the longitudinal axis can be detected and localised in case of local damage-induced discontinuities. However, the inclination angle and the curvature are calculated from the first, respectively second derivation of the deflection line, which behave unsteady without a precise measurement. Therefore, to validate the method on real structural elements, laboratory experiments on a gradually loaded reinforced concrete beam have been realised and several measurement