VISION DATA EMPLOYED FOR CRACK DETECTION AND LOCALIZATION

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Summary

Nowadays, non-contact measurement systems have found application in the Structural Health Monitoring of civil engineering structures for the detection, localization and assessment of damage. In the field of static deflection measurement, the vision based techniques have become more popular. The deflection curve obtained by image processing and analysis methods can be analyzed in order to detect and localize the change of the curvature, which implies the appearance of a crack. In this paper, the vision based deflection measurement system is discussed. The deflection of beam-like structures is computed by means of digital image correlation. The damage detection and localization is based on the irregularity detection by means of analyzing the deflection curve. A new approach and some selected methods for damage detection and localization will be highlighted and their results obtained in the laboratory setup will be presented and discussed.

Keywords: digital image correlation, image processing, damage detection and localization, wavelet transform, strain energy, deflection curvature analysis.

1. INTRODUCTION

Structural Health Monitoring (SHM) [1, 2] involves the integration of sensors, data transmission, processing and analysis for the detection, localization and assessment of damage within a structure leading to its failure. Damage in SHM is defined as a change in the material properties or the geometry of a structure, which can adversely affect its rigidity and which alters the dynamic and static properties. Generally, SHM methods are divided into two major groups: local and global methods. The latter are applied if a global change in the geometry of a structure can be observed. In practice, the most frequently used methods of damage detection are based on the analysis of variations in dynamic properties caused by the damage [3, 4]. The vibration-based damage identification methods are classified as model-based and non-model-based. The model-based methods identify damage by comparing a theoretical model, usually based on the finite elements, with test data obtained in experimental measurements of the structure [5]. Comparing the updated model with the original one provides information on the damage location and its severity. Non-model-based methods apply signal processing algorithms for the analysis of structures' response signals in time and frequency, as well as time-frequency, domains. Model-based damage detection methods make use of changes in modal parameters between the intact and damaged states of the structure to provide the damage indicators for the localization and assessment of damage. There are many different damage indicators: changes in the natural frequencies [6], changes in the Modal Assurance Criteria (MAC) across substructures [7], changes in the Coordinate Modal Assurance Criterion (COMAC) [8], changes in modal strain energy [9, 10] and changes in mode shape curvature [11]. However, obtaining dense dynamic data requires high cost devices, such as a laser vibrometer. Moreover, the excitation of large structures can be costly and difficult. The acquisition of static profiles requires much less effort, which makes the damage detection methods based on changes in deflection shapes more attractive for practical use. A lot of damage detection methods based on the analysis of changes in the deflection curve have been developed. The author of [11] described the use of curvature of the deflection in damage detection and localization. The second derivative was obtained by numerical differentiation. A different method of damage detection based on the strain energy of a beam was presented in [12]. This involved a comparison between the strain energy of the reference and damaged states of the structure. In order to avoid the problems associated with noise gain in numerical computation, Hensman [13] proposed the application of Gaussian process in damage detection. The localization of a crack was one of the hyper-parameters of the covariance function. The covariance parameters are optimized based on the measurement data and the damage localization corresponds to the covariance function for which the marginal likelihood of the model is largest. Jang [14] presented a strain damage locating vector (DLV) method combining DLV and static strain measurements. Guo Hui-yong et al. [15] applied a strain energy and evidence theory for damage detection. The evidence theory method was proposed to identify structural damage locations. Then, structural modal strain energy was utilized to quantify structural damage extents. Chen Xiao-Zhen et al. [16] developed a method of damage identification based on the grey system theory. In his work, the grey relation coefficient of deflection curvature was defined and used to locate damage in the structure. Hui Li [17] et al. proposed a new damage identification method based on fractal dimension (FD). The location of damage in the beam was determined by the fluctuation of the contour of the estimated FD and the extent of the damage was estimated by an FD-based damage index. The author [18] presented the application of roughness measurement as a damage detection tool. The signal is decomposed into two parts: smooth and rough and the damage is localized by analysis of the irregularities of the rough part.

In most of these methods, a densely sampled deflection curve is necessary for the correct damage detection and localization. As the structure becomes more complex, more sensors are needed, which increases the cost of the system installation. Sometimes, it is extremely challenging to attach sensors to a structure because of the environmental conditions or the geometrical constraints. Non-contact vision systems can be a good alternative to contact type transducers. They are easy to use, accurate, low cost and universal tools which can be applied in deformation measurements. Jing [18] et al. presented a use of the computer vision technology to capture the static deformation profile of a structure, and then employ profile analysis methods to detect damages. Staszewski and Patsias [19] presented an application of the wavelet transform for damage detection based on optical measurements. The continuous wavelet transform (CWT) coefficients of both the damaged mode and the approximation function were computed, and thus a reliable damage index could be obtained by taking their difference.

In this paper, the developed vision based method dedicated for in-plane measurement of civil engineering structures' displacement fields is presented. Moreover, the paper introduces a novel damage detection and localization method based on fitting line segments to the displacement field of the beam. The sensitivity of the damage detection algorithm has been tested in a series of lab experiments. The developed method has been compared with a curvature based irregularity detection algorithm.

1.1. Vision based in-plane deflection measurement method

The proposed vision based method [1, 2] of the in-plane deflection measurement consists of the following steps: calibration of the system, image acquisition, and deflection measurement by means of the digital image correlation coefficient. The scale coefficient, which gives information about the length corresponding to one pixel on the image, is obtained by calibration using an object with known geometric dimensions. In the next step, the reference image and one or more images of the construction under the load are acquired. The photographs can be taken from distinct points in space. The homography mapping H transforms the images in order to remove projective distortions from the image of one, particular, plane of the structure. In the third step, the reference image is divided into intensity patterns. Each of the patterns is matched with the corresponding pattern on the image of the structure under the load by means of the normalized cross correlation coefficient (NCC). The deflection curve is computed as the difference between positions of the equivalent image patches on two images. The last step is scaling the deflection curve using the scale coefficient. The method is schematically shown in Figure 1.

1.2. Image rectification

The homography [18, 19] is a mapping between two sets of points on the plane. If coplanar points' positions are given in homogeneous coordinates, the homography can be represented by a 3-by-3 matrix denoted as H. In the developed measurement system, the homography mapping was introduced for reduction of perspective distortions of an image of one given plane of the construction. The homography matrix H is computed from a set of corresponding points by the DLT algorithm [18]. At least four pairs of coplanar corresponding points are necessary and sufficient to compute the matrix H if no three of them are collinear. In the presence of a noise in real image data, a larger set of corresponding points must be used. The plane of the construction is rectified when all image points are transformed by the homography mapping [1,2].

1.3. Deflection measurement by digital image correlation

The Digital Image Correlation (DIC) method consists of the following three steps: the object's surface preparation; acquisition of the object's image before and after loading, and computation of the displacement field. The construction's surface should have a random gray intensities distribution, which can be a natural texture or artificially made random pattern attached to the structure or painted on it. The basic principle of digital image correlation is matching of the same image path between the two images acquired before and after deformation [19].

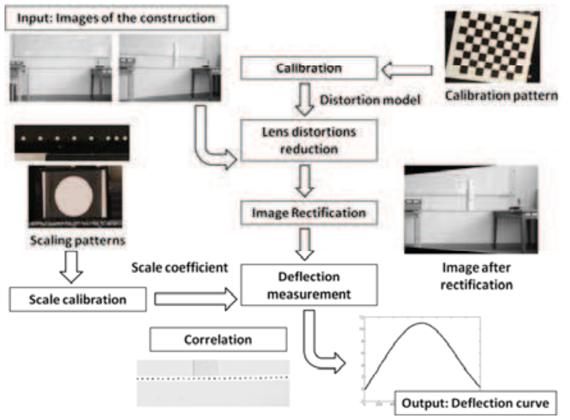


Fig.1. The proposed vision based measurement system of the in-plane deflection of the constructions

In order to compute the displacement of a construction's point, a square or rectangular reference patch of pixels centered at a measurement point is chosen from the reference image and used to match its corresponding location in the deformed image. To evaluate the similarity degree between the reference image path and the search region on the deformed image, the normalized cross-correlation (NCC) is applied. The matching is performed by searching the peak of the correlation function over the search window. The difference in the position of the reference subset center and the deformed image subset center gives the displacement of a point. The NCC coefficient is given by Equation 2 [19].

$$NCC(u,v)\frac{\sum_{x,y}\left(f_n(x,y)-\bar{f}_n\right)\left(f_d(x-u,y-v)-\bar{f}_d\right)}{\sqrt{\sum_{x,y}\left(f_n(x,y)-\bar{f}_n\right)^2\sum_{x,y}\left(f_d(x-u,y-v)-\bar{f}_d\right)^2}} \quad (1)$$

Where:
fn(x,y) – an intensity value for a pixel with coordinates (x, y) on the reference image;
$\bar{f}_n$ - mean value of intensities of the pattern on image before deformation;
fd(x-u,y-v) – intensity value for a pixel with coordinates (x, y) on the image after deformation;
$\bar{f}_d$ - mean value of intensities of the pattern after deformation;
x,y – position of the pattern on reference image;
u,v – displacement of the pattern between two images;

In the process of deflection measurement, the reference image of the unloaded construction is divided into a set of intensity patterns. Each of the patches is matched with a corresponding pixel subset on the image of the loaded structure. The displacement vector is computed as the difference between positions of the pattern on two images. The method performed on each of the points of interest gives a complete course of deflection of the analyzed object. The correlation coefficient computes the position of the pixel as an integer value on the pixel grid. When the sub-pixel methods are introduced [1, 2], the measurement's accuracy increases up to 0.01-0.1 parts of pixel. An overview of the deflection measurement is presented in Figure 2.

2. CONDITIONS OF THE EXPERIMENT

In order to test the efficiency of the developed diagnostic methods, a series of experiments were performed. Cantilever beams were loaded at a free end with a 0.41 kg mass and damaged by cutting.

Beams with dimensions 40 mm x 60 mm x 4 mm had a random speckle pattern placed on the face side, for vision-based deflection detection by the Digital Image Correlation (DIC) method. In the experiment, the developed software tool "Wiz2D Deflection" was used as software to calculate the deflection curve. At the beginning of each experiment, a number of images were taken which were used for the configuration of the software and which served later as a reference for diagnostic algorithms. Then, a perpendicular cut, 16 mm deep, was introduced to the beam. After each 2 mm deepening 10 images were taken. Deflection curves calculated from the images were averaged and transferred to the diagnostic algorithms. In Figure 2. the restrained beam with optical noise is shown. For the whole experiment 5 beams were used (two cuts in each beam)

In Figure 3, there is a reference image from Wiz2D Deflection with points marked, where deflection was calculated by the DIC method (Correlation windows). The frame of reference is connected to the first correlation window from the left. The images were taken with a Canon EOS 5D MK2 camera with a Canon 24-7-F/2.8L lens (Fig. 3)

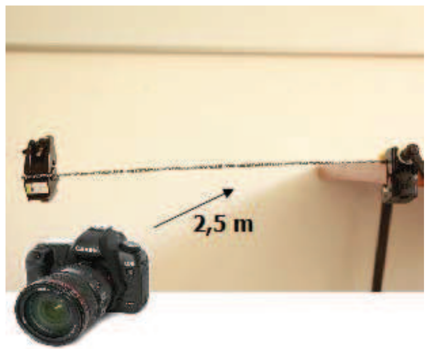


Fig. 2 – Experimental setup

Fig. 3 – Beam with correlation windows

3. DAMAGE DETECTION ALGORITHMS

Wiz2D Deflection calculates the position changes of corresponding points on the reference and measurement (after the introduction of damage) images. Due to the fact that both images were taken under the same load conditions, differences in the calculated deflection curves were caused by the damage introduced.

Two deflection curves were transferred to Matlab software and, after subtraction, the deflection difference curve was used by two independent algorithms, developed by the authors, for damage detection and localization.

3.1. „2nd derivative" - Algorithm based on deflection difference 2nd derivative calculation

At the first stage of the algorithm, filtering of the deflection difference curve is performed, so the sharp changes caused by the measurement noise and resulting large values of the first derivative are eliminated. The smoothing is performed by a 5-element kernel. After filtration, the first derivative of the curve is calculated, the same filtration process is applied, then, calculation of the 2nd derivative and the last smoothing is performed. The maximum value of the obtained curve is treated as the damage indicator and the index of the maximum value is used for damage localization.

In Fig. 4 all stages of the calculations are presented. Efficiency of the presented algorithm is independent of damage localization. However, large measurement noise can lead to errors and false indications of damage. An example of a malfunction of an algorithm is shown in Fig. 5: Noise caused false damage detection. Such errors can be eliminated by adequate setting of the threshold level and control of environment conditions which allows the noise level obtained from the correlation algorithm to be lowered. (Proper lighting, vibration reduction, proper settings of camera).

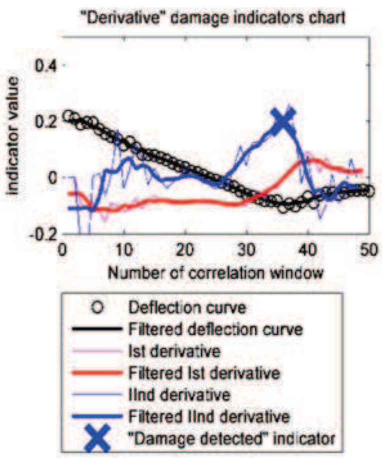


Fig. 4. Stages of 2nd derivative calculation from deflection difference curve

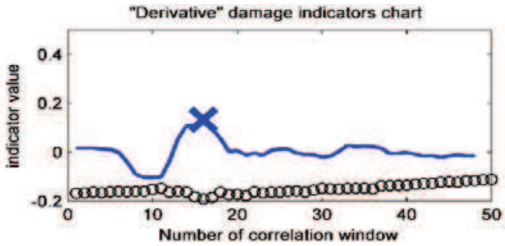


Fig. 5. An example of error caused by high level of noise

3.2. „Line segments" - Method based on geometrical characteristics of the deflection difference curve

Due to the fact that beam load is constant, the only result of damage presence is a break on the deflection curve at the point of damage. The algorithm fits two line segments into the deflection difference curve in such a way that the aggregate matching error is minimal. The index of points between the segments that give the best matching result is the damage localization index. The angle between two segments is the degree of damage indicator. In Fig. 6a, the deflection difference curve is presented with line segments fitted and damage localization marked. The algorithm is resistant to measurement noise, as the fitting of the line segments is performed on a large set of data and scattered breaks in the deflection difference curve do not affect the overall result. However, its drawback is the necessity of limiting the range of damage search in comparison to the "Derivative" method. The algorithm cannot search for damage on the ends of the measurement range, because if the minimal possible length of the line segment is too small, the noise sensitivity sharply increases, as well as the possibility of false damage detection caused by the level of noise at the ends of the measurement range. (See Fig. 6b)

4. RESULTS DISCUSSION

Measurements were taken according to the order described in Section 2. Deflection curves were calculated and used by the diagnostics algorithm. Information concerning the difference of deflection on the end of the measured beam for the maximum depth of cut is essential for the results evaluation. This difference ranges from 0.3 to 0.6 mm (dependent on the position of the cut) which, for the used scale of 0.1360 mm/px results in a position difference in an image between 2.2 to 4.4 pixels.

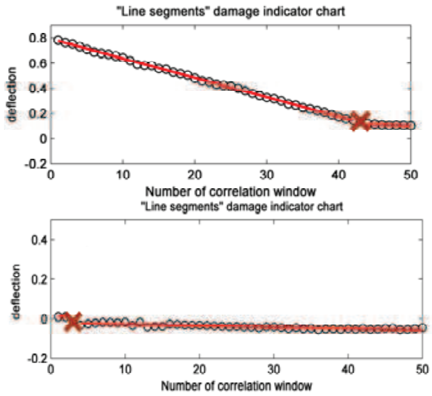
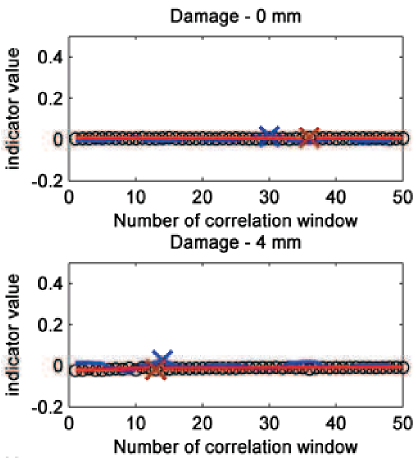


Fig. 6. a) – Deflection difference curve with line segments fitted and detected damage point marked b) – False damage detection caused by poorly chosen the minimal line segment length and large noise

Diagnostic algorithms were used for damage detection and localization. The threshold levels were adjusted so the noise would not trigger the detection and to obtain high sensitivity while maintaining a low number of errors. Based upon the location of damage and each correlation window, an index where damage should be detected was computed for each cut. Successful localization was defined as a resulting index at most 3 correlation windows from the expected one. This range was dictated by the observations of algorithm performance: An algorithm which detects the same damage results in indexes from a range of 4 correlation windows.

In Figure 7, the deflection difference curve is shown, as well as the results of the diagnostic algorithms for one cut of different depths. The cut was located at a distance of 430 mm from the left end of the beam, so the correct damage index should appear in 37th correlation window. The damage was detected between 35th and 40th correlation window.



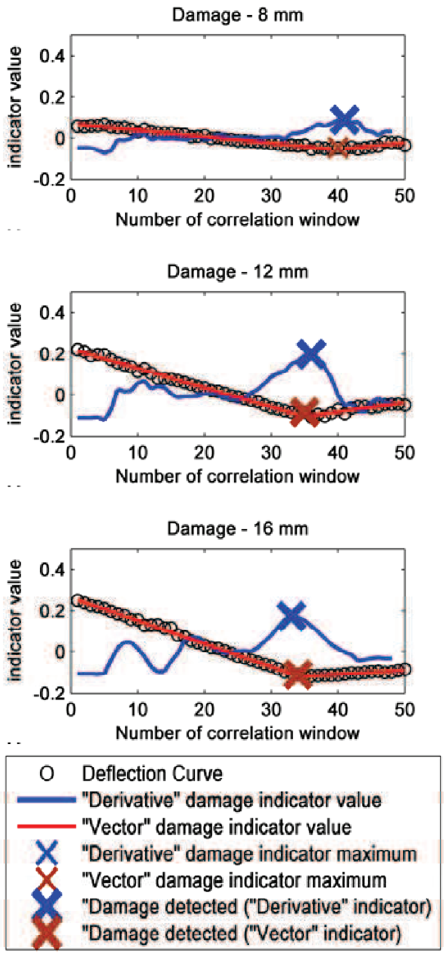


Fig 7. Differences in deflection difference curve caused by the increase of damage; performance of detection algorithms

In Table 1, efficiency of the damage detection and localization as a function of its depth is shown. With the increase in depth, the probability of detection grows. For the maximum depth of the cut (16 mm) the "Line segments" method achieved 100% success. For the given threshold values, no method was able to detect cuts smaller than 6 mm.

In Table 2, efficiency of the damage detection and localization as a function of its location is shown. A significant growth in sensitivity of the method as the location of damage nears the right side of the measurement range is visible. This is caused by the fact that, if the load is constant, the difference in deflection is proportional to the lever arm used and the sensitivity is proportional to the deflection.

Table 1 – Efficiency of damage detection and localization in a function of its depth

Cut depth	Percentage of correct classification		Percentage of errors	
2mm	0,0	0,0	0,0	0,0
4mm	0,0	0,0	0,0	10,0
6mm	20,0	0,0	10,0	20,0
8mm	10,0	10,0	10,0	0,0
10mm	30,0	10,0	10,0	0,0
12mm	50,0	30,0	10,0	10,0
14mm	70,0	90,0	0,0	0,0

Table 2 – Efficiency of damage detection and localization in a function of its location

Cut position	Quantity of correct classifications		Quantity of errors	
270 mm	3	1	0	0
300 mm	1	2	1	0
330 mm	0	2	2	0
350 mm	2	2	2	0
380 mm	1	2	0	0
400 mm	3	2	0	3
430 mm	4	2	0	0
460 mm	5	5	0	1
480 mm	5	3	0	0

5. CONCLUSIONS

As a result of the conducted experiments, a high sensitivity of damage detection in the developed method was attained. The 16-mm-deep cut was successfully detected in all of the beams used, despite the fact that, for the cuts close to the right side of the measurement range, the deflection difference of the end of the beam was only 0.3 mm. In the field of damage detection as a function of cut depth, the results were satisfactory. For the cuts close to the restrain (on the right side of the measurement range) the number of correct matches reaches 5 out of 8 possible, which means that in some cases cuts of less than 8 mm deep were detected. The efficiency of detection is dependent on the deflection difference between the non-damaged and damaged structure, so it could be increased by applying greater load to the beam. It is also worth noting that both algorithms work independently and have fixed threshold levels. By connecting the two algorithms and lowering the thresholds, if both algorithms suggest damage in the same place the sensitivity may be improved significantly.

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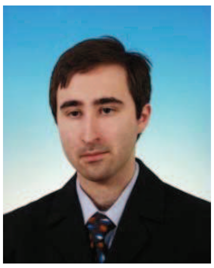

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