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Non-destructive Structural Condition Assessment Method Using Multi-sensor Fusion

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ABSTRACT

Civil infrastructure deterioration and its impact on lifetime structural performance is one the foremost concerns of civil engineers. Various structural damage weakens civil infrastructures, and consequently the degrading infrastructures are getting more susceptible to extreme events. Extensive research efforts have been devoted to developing effective and non-destructive damage assessment methods utilizing the neutral axis (NA) as the NA change has been known to be a sensitive damage indicator. However, existing methods for assessing structural health condition are not practically effective as they are affected by many factors including the temperature change. Therefore, this research proposes a new structural condition assessment method using an equivalent neutral axis (ENA) that can be estimated based on acceleration and strain measurements with the help of the sensor fusion technique. Numerical simulation study is conducted on reinforced concrete beam models to investigate the performance of the proposed ENA damage indicator with respect to the sensor configuration and damage level. Also, experimental tests will be conducted to further validate the proposed method and prove the sensitivity of the ENA to structural damage. The results show a good agreement between the analytical data and the estimated displacement values.

Introduction

The displacement is considered as a direct indicator for structural integrity as it can be used as a limit to satisfy

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the serviceability of any structure [1,2]. It can also be used to implement the structural health monitoring of any existing structures. Displacement can be determined using direct or indirect approaches. The method of using linear variable differential transformers, GPS and laser is considered as examples for direct approaches. Otherwise, the indirect approaches include using strain gauges and accelerometers. Using the direct approaches faces difficulties in installation or feasibility of this installation especially for huge structures. Therefore, the indirect approach of accelerometers and strain gauges will be used to measure displacement in this study. Previous studies reconstructed displacement through classical Fourier transform method [3],[4] and variational statement of an inverse problem [5] but without minimizing the error results because of the uncertainty of initial conditions used during the integration of acceleration to calculate the corresponding displacement. Moreover, Shin et al. [6] generated an algorithm which uses vibration strains measured by Fiber Bragg Grating sensors to estimate bridge vibration displacement. However, these measures have their own features that restrict the indirect estimation's use. A low-frequency drift in the estimated displacement is caused by the double integration of acceleration, therefore high-pass filters are frequently utilized to decrease the drift. Park et al. [7] proposed a multimeric data-based indirect displacement estimate approach. The Sorok Bridge, a cable-stayed bridge in Korea, was used to verify this dynamic response data. The aim of this paper is to reconstruct the displacement by using acceleration and strain gauge measurements without the initial conditions and without utilizing a reference frame to decrease the amount of error with a computationally and cost-efficient method based on the combination between the acceleration-based techniques which estimate the zero-mean displacement, while the strain-based techniques can measure the low-frequency components.

Methodology

This study uses the previous proposed approach which combines acceleration and strain gauge measurements to derive displacement values [6] by implementing a MATLAB code then compares it to an analytical model using SAP2000 and experimental test. As proposed by Hong et al. and Lee et al. [5],[8], the final displacement equation can be simplified to Eq. 1.

$$u = (L^T L + \lambda^2 I)^{-1} L^T L_a \underline{a} (\Delta t)^2 \tag{1}$$

Where L_a matrix is an identity matrix except for the first and last values are replaced by $1/\sqrt{2}$, I is the identity matrix of order (the number of the time intervals + 3), Δt is a step length for the time marching algorithm, which is often referred to as a time increment, L is linear algebraic operator and is equal to $L_a L_c$, The L_c matrix is defined below as shown in Eq. 2, λ is the optimal regularization parameter and $\underline{a}$ the vector of measured acceleration [6].

$$L = [1\ \ -2\ \ 1\, 0\ \ 0\, 1\ \ -2\, 1\ \ \cdots\ 0\ \vdots \ddots \vdots\ 0\ \cdots\ 1\ -2\, 1\, 0\ \ 0\, 1\ -2\, 1\ \ ] \tag{2}$$

The proposed method assumes linear relationship between displacement and strain as shown in the following Eq. 3:

$$\{u\}_{m\times 1} = D_{m\times n}\{\varepsilon\}_{n\times 1} \tag{3}$$

Where $D_{m\times n}$ is a transformation matrix and $\{\varepsilon\}_{n\times 1}$ is the strain vector, therefore using the linear relationship of strain [9] and by minimizing the error between the measured and estimated displacement, the following expression can be used:

$$u = (L^T L + \lambda^2 I)^{-1}(L^T L_a \underline{a} (\Delta t)^2 + \lambda^2 D \, \{\underline{\varepsilon}\}) \tag{4}$$

Using strain value at the second term of Eq. 4 enhances the ability of capturing the low frequency component of u.

Experimental and Analytical Study

Numerical Simulation

In this study, a simply supported beam was modeled using SAP 2000 and by applying a sine wave as shown in Fig. 1 at the mid span of the beam on, the acceleration, displacement and bending moment for any section of the beam can be determined. MATLAB code was generated to reconstruct the displacement from the acceleration and strain data.

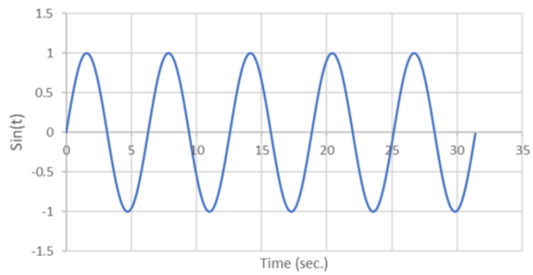

Figure 1. 1 Hz Sine wave loading

Beam Setup

Two reinforced concrete beams with a 90 inches span, 10 inches width and 18 inches depth were prepared for this experiment. Both beams constructed using 4000 pounds per square inch compressive strength concrete and 60 kips per square inch reinforcing steel yield strength. The reinforcement configuration of the experimental beam consisted of #4 stirrups at 6.5 inch on center and two #8 top and bottom longitudinal reinforcing bars. A steel frame will be mounted on top of the simply supported beam for the LVDTs as shown in Fig. 2. The measuring instruments for displacement, the linear variable differential transformers (LVDTs), accelerometers and strain gauges will be placed in the locations marked in Fig. 3. The most important location for data retrieval will be at the center of the beam where the equipment will be placed on the side instead of the top of the beam. This is due to the loading plate location being directly at the mid span of the beam. The beam will be subjected to a sine wave loading to measure the corresponding acceleration, strain, and displacement. This test was performed before for another two beams starting by a random vibration for a minute then loading increments of 15 kips up to 60 kips and increments of 10 kips after that till 90 kips and finally increments of 15 kips again till failure.

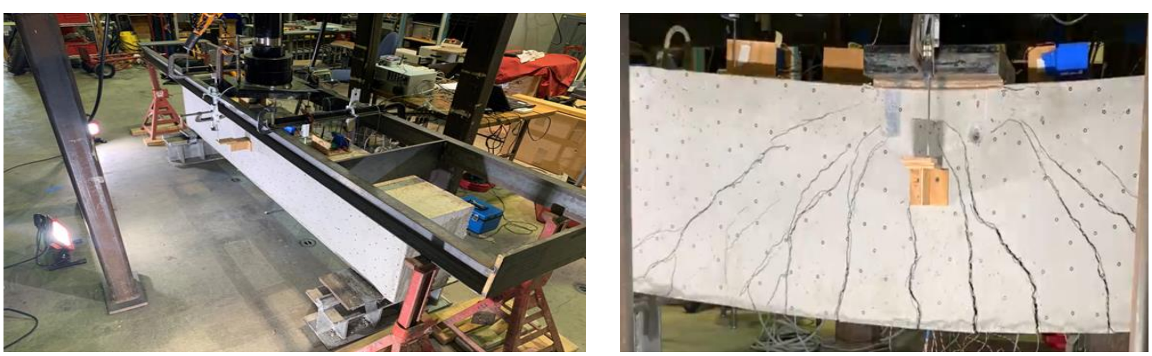

Figure 2. RC beam test setup (left) and the RC beam at the end of the test.

Measuring Instruments

Wireless accelerometers mounted onto the beam with screws and attached to a wooden container were used to measure the acceleration applied to the beam. Strain gauges used to measure small deformations in length, measured in micro strain. Electrical resistance strain gauges will be selected in this research for their economic value and efficiency of setup. LVDT is used to measure one dimensional physical displacement, in this research LVDTs will be placed at quarter and mid span to measure the actual displacement.

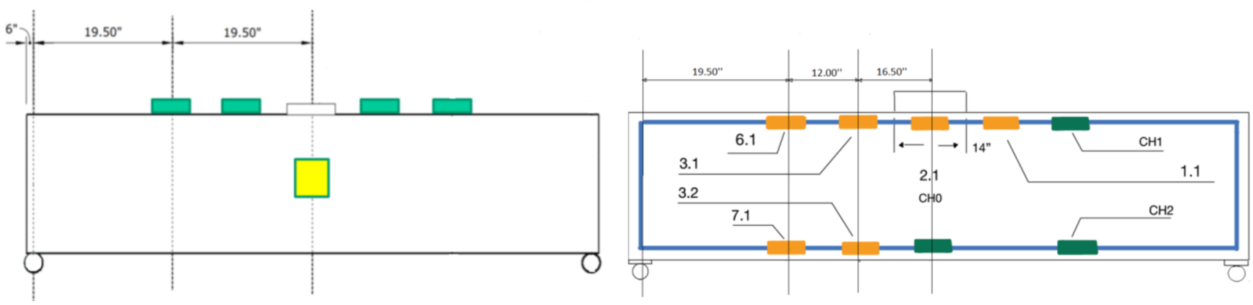

Figure 3. Location of accelerometers (left) and strain gauges (right) on RC beams

Results and Discussion

The displacement results generated by SAP2000 were compared with the reconstructed displacement as shown in Fig. 4.

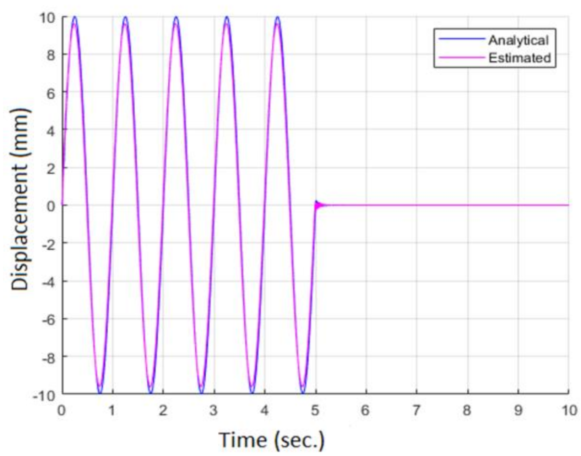

Figure 4. One Hertz Sine Wave SAP2000 Displacement vs. Reconstructed Displacement Method

The reconstructed displacement, the red line, matches the exact displacement, the blue line. The previous experiment was hard to validate using SAP2000 model and the reconstructed displacement method due to the random vibration at the start of the test, therefore another experiment will be held with a well-defined sine wave loading pattern to be easily validate using SAP2000 and reconstructed displacement method.

Conclusion

The indirect displacement estimation approach using the fusion of multimeric data of strain and acceleration was presented. The proposed approach using the multimeric data fusion was found to accurately estimate the displacement response with the lowest error level and without calibration testing with reference data.

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