Abstract

The article discusses the damage localization of concrete columns by means of vibration analysis techniques. The method for detecting and locating damage is based on the analysis of the dynamic characteristics of a structure, such as eigenfrequencies, mode shapes and modal damping. The article discusses the comparison of the diagnostic results of a full-scale experiment performed on the construction site with the finite element model of column. This article considers the damage localization technique of the reinforced concrete column based on the determination of the structure damage index. The article contains the review of the damage localization results with the different positions of the mono-axial accelerometer sensors along the column. During the research a software was developed to perform an automated diagnosis of reinforced concrete structures with the optimized arrangement of the accelerometer sensors using ANSYS Multiphysics to perform the finite element analysis of the structure and to determine their eigenfrequencies and mode shapes. The finite element analyses demonstrated that increasing the number of sensor locations allows determination of the location of the damage is more accurate, while the use of additional modes for structure shaping provides little advantage and can sometimes lead to a deterioration in the performance of the vibration-based damage detection techniques.

Keywords: damage detection; structural vibration; structural engineering; structural health monitoring; mode shapes; concrete column;
1. a large number of similar structures;
2. algorithmization actions performed in the process of diagnosis;
3. the aging structures and need repair or replacement;
4. the economic problems associated with the suspension of operation of structures.

Most of the damage identification methods are based on data obtained by Fourier-transform spectra of the dynamic design of responses to different external influences. Damage to structures are usually local, which makes the possibility of their identification by analyzing mode shapes [1-3].

Determination of eigenfrequencies and mode shapes of vibrations of mechanical systems - one of the most important tasks, which allows to receive integrated information about the state of the structure [4-6]. The aim of this paper is to analyze the results of the vibration method of determining the degree of damage of reinforced concrete columns, and the development of a software module for the damage localization of structures.

2. Full-scale and numerical experimental research

The main purpose of this research is the evaluation possibilities of damage detection methods in the absence of a forced exposure to construction. The research structure is finite-element model of reinforced concrete columns of rectangular cross section which is modeled by a small defect in the form of a prismatic form of emptiness. In this case the column has the cross-sectional dimensions 0.50 × 0.50 m, height of 4.00 m. The dimensions of damage 0.15 × 0.15 m, the height is 0.05 m. The defect is displaced by 1.50 meters relative to the lower end of column. The concrete class - B30 (modulus Eb = 32,5 × 103 [MPa]), \( \rho = 2500 \) [kg / m³], \( v = 0.16 \).

![Fig. 1. Information and damage model of concrete reinforced column](image)

In the course of the research has been used program of finite element modeling - ANSYS Multiphysics and developed in the course of operation, the system software for damage localization [7]. The ANSYS modal analysis was carried out design - identified eigenfrequencies and mode shapes of the structure shown in Fig. 2.
Once the model has been constructed, the columns were modeled damage 0.15m in length, width 0.15 m and height 0.05 m, 1.5 m from the lower end of the column. Three variants of arrangement accelerometer sensors were carried out in the course of the experiment: the first in which the measurements were carried out 6 monitoring points, the second - 9 points of measurement, and a case in which 12 measurement points were used. Displacements in the supports were considered to be zero.

It is also considered the case where the damage is located at a distance of 0.50 m from the support, calculated using 12, 9, and 6 monitoring points in the three-dimensional model was built using the first mode shape.

However, in order to obtain more accurate of modal shape structure in the calculation of intermediate values between each pair of adjacent accelerometer sensor locations was estimated using a natural cubic spline interpolation scheme, which enforced continuity of the second derivative at measurement points and a zero second derivative at the simple supports.

The best damage localization was achieved using 12 monitoring points, the accuracy of the location of the defect was 0.1 M. When monitoring a 6-point error localization defect was 0.4 M. It should be noted that the precision with which can be determined by the location of defects by means of vibration diagnostics methods implemented decreased, when damage structures located near the bearing.
3. Numerical study

The damage index method is based on local changes in modal strain energy [8]. In discrete form, the index takes the following form. The j-th point monitoring for the i-th mode shape of structure numerical value of the index of damage is calculated as follows:

$$
\beta_{ij} = \frac{\left(\int_0^L \left(\varphi_i^0(x)\right)^2 \, dx + \int_0^L \left(\varphi_i^*(x)\right)^2 \, dx\right) \times \int_0^L \left(\varphi_i^0(x)\right)^2 \, dx}{\left(\int_0^L \left(\varphi_i^0(x)\right)^2 \, dx + \int_0^L \left(\varphi_i^*(x)\right)^2 \, dx\right) \times \int_0^L \left(\varphi_i^0(x)\right)^2 \, dx} = \frac{\text{NUM}_{ij}}{\text{DEN}_{ij}}
$$

(1)

where $\varphi_i^0(x)$ and $\varphi_i^*(x)$ are continuous mode shape curvature functions for the i-th mode in terms of distance, x, along the column, corresponding to the undamaged and damaged structures, respectively, based on the second derivatives of continuous displacement mode shape function, $\varphi_i(x)$ and $\varphi_i^*(x)$. In addition, L is the length of the column, and a and b are the limits of a segment of the beam over which the damage is being evaluated. In discrete form, assuming that the spacing between points in the mode shape vectors is uniform, calculation of the damage index is carried out by:

$$
\beta_{ij} = \frac{\left(\sum_{k=1}^n \left(\varphi_k^0\right)^2 \right) + \left(\sum_{k=1}^n \left(\varphi_k^*\right)^2 \right)}{\left(\sum_{k=1}^n \left(\varphi_k^0\right)^2 \right) + \left(\sum_{k=1}^n \left(\varphi_k^*\right)^2 \right)}
$$

(2)

in which all the variables have been defined previously. If more than one mode is used, a single index for each location, j, is formed by:

$$
\beta_j = \frac{\sum_{i=1}^n \text{NUM}_{ji}}{\sum_{i=1}^n \text{DEN}_{ji}}
$$

(3)
Assuming that the set of damage indices for the structure represents a sample population of a normally distributed random variable, a normalized damage indicator $Z_j$ for a given location may be calculated as follows:

$$Z_j = \frac{\beta_j - \mu_\beta}{\sigma_\beta}$$  \hspace{1cm} (4)

where $\mu_\beta$ and $\sigma_\beta$ are the mean and standard deviation of damage indices, respectively. Damage indices falling two or more standard deviations from the mean (i.e., $Z_j \geq 2$) are defined as being indicative of a possible damage location [9].

4. Conclusions and recommendations

VBDD techniques are capable of assessing the condition of an entire structural component simultaneously and are not limited to the interrogation of accessible regions [10]. As a result of the study were obtained reliable values of the localization of the damaged area, it shows that by using the method for determining the index of damage with a sufficient degree of accuracy to predict the location of structural damage, provided precise definition of the first mode shape of the structure.

The numerical results presented in this paper have shown the effectiveness of the considered damage localization methods. Its application in practice will reduce the time construction inspection by the preliminary determination of places for accelerometer sensors.

The accuracy of damage localization was directly proportional to the spacing between measurement points. Increasing the number of measurement points will therefore lead to a proportional increase in localization accuracy. Methods of determine damage index of structure investigated were found to be extremely effective at pinpointing the location of damage when mode shapes were very well-defined with a large number of measurement points. Notwithstanding the challenges associated with achieving this level of mode shape definition in practice, this result confirms the soundness of VBDD theory and its usefulness for damage localization [11, 12].

References