Using local stiffness indicator to examine the effect of honeycombs on the flexural stiffness of reinforced concrete beams

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ABSTRACT

Experimental modal analysis was performed on RC beams with honeycombs. The mode shapes were extracted, and the eigenvectors were used in determining the mode shape equations using nonlinear regression. The equation used in the regression was the generalized solution of transverse vibration of a Bernoulli–Euler prismatic beam. By utilizing the regressed phase variable, the global flexural stiffness was evaluated. It was observed that the global stiffness dropped with increasing volumes of the honeycombs in the beam. The results were compared with values computed using the secant modulus from the load–deflection plot obtained upon loading at each load stage and the trend was similar. The local stiffness indicator was used successfully to locate the region of the honeycombs.

1. Introduction

Periodic structural condition monitoring of reinforced concrete structures is necessary to ensure that they provide a continued safe service condition. Conventional assessment procedures usually rely on visual inspection and location-dependent methods. This study proposes the application of experimental modal analysis to determine the location of damage in the form of honeycombs in reinforced concrete (RC) beams. There have been several significant investigative studies carried out to determine the existence and the severity of defects in structures using one or more of their modal properties by researchers like Dong et al. [1], Javor [2], Kam and Lee [3], Lim [4], Liu [5], Maeck et al. [6], Narkis [7], Penny et al. [8] and Rizos et al. [9]. Several researchers have used various vibration-based approaches to study structural damage and condition monitoring and fault diagnosis of structural systems like beams [10–20], frame structures [21,22], bridges [23] and rotors [24–29]. In most of the dynamic tests conducted on actual structures the fundamental natural frequencies have been utilized and found to be the most convenient parameter to be studied as shown by Cawley and Adams [30] and Konig and Giegerich [31]. It was found that the most easily observable change is the reduction in natural frequencies, and most investigators use this feature in one way or another. Casas [32] proposed a method of surveillance of concrete structures through monitoring the characteristics of the natural frequencies and mode shapes. Varying success has been reported where the change in modal damping has been utilized, while some work has been reported on the use of change of mode shape to detect damage.

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Ratcliffe [33] presented a technique for locating damage in a beam that uses a finite difference approximation of a Laplacian operator on mode shape data. In the case of a damage, which is not so severe, further processing of the Laplacian output is necessary before damage location could be determined. The procedure is found to be best suited for the mode shape obtained from fundamental natural frequency. The mode shapes obtained from higher natural frequencies may be used to verify the damage location, but they are not as sensitive as the lower modes. Yoon et al. [34] expanded the 'gapped smoothing method' for identifying the location of structural damage in a beam by introducing a 'globally optimized smooth shape' with an analytic mode shape function and the procedure used only the mode shapes from the damaged structure. The method could detect local stiffness losses associated with local thickness reduction of less than 1% in the case of narrow and wide damage, 13 mm and 126 mm, respectively, with finite element analysis. Embedded fiber-optic Bragg grating (FBG) sensors have also been used to measure the dynamic characteristics of systems which could be useful for application in construction inspection procedures [35–39].

Instead of using mode shapes in obtaining spatial information about sources of vibration changes, an alternative method is by using the mode shape derivatives, such as curvature. It is noted that for beams, plates, and shells there is a direct relationship between curvature and bending strain. Pandey et al. [40] demonstrated that absolute changes in mode shape curvature could be a good indicator of damage for the cantilever and simply supported analytical beam structures, which they considered. The changes in the curvature increased with increase in damage. The curvature values were computed from the displacement mode shape using the central difference approximation. Stubbs et al. [41] conducted studies on offshore structures. Topole and Stubbs [42] further showed that it was feasible to use a limited set of modal parameters to detect structural damage. Stubbs and Kim [43] also showed that localizing damage using this technique without baseline modal parameters was possible. This approach was confirmed by Chance et al. [44] who found that numerically calculating curvature from mode shapes resulted in unacceptable errors. As a consequence measured strains were instead used to measure curvature directly, and this improved results significantly.

Maeck et al. [6] used a technique to predict the location and intensity of damage directly from measured modal displacement derivatives. The technique, direct stiffness derivation, uses the basic relation that the dynamic bending stiffness, *EI*, in each section is equal to the bending moment, *M*, in that section divided by the corresponding curvature; and the dynamic torsion stiffness, *GJ*, in each section is equal to the torsional moment, *T*, in that section divided by the corresponding torsion rate or torsion angle per unit length. Direct calculation of the first and second derivatives from measured mode shapes results in oscillating and inaccurate values. A smoothing procedure, which is weighted residual penalty-based technique, is applied to the measured mode shapes. The technique is further validated on a reinforced concrete beam, which was gradually damaged and using instruments such as accelerometers, displacement transducers, and strain gauges

Some work was done by Omar and Clarke [45] on the effect of honeycombs on the shear capacity of beams. Khezel et al. [46] performed a feasibility study on using modal testing as an inspection and surveillance tool to determine honeycombs. Mode shape data was analyzed using various modal assurance techniques, thus improving the possibility of locating the defect regions. Geometric mean operator was proposed. The square is chosen instead of the square root for more efficient calculation of this operator since it deals with the deviation value y_m from the geometric mean of the neighboring values. This operator ensures that the deviation of y_m from the neighboring values is always positive and that it will be magnified whenever there is a deviation.

This paper describes the determination of the location of damage in reinforced concrete beams due to honeycombs through modal testing. Modal tests on the beams were conducted to determine the modal parameters, namely frequencies and mode shapes. Modal parameters are functions of the physical properties of the structure, and changes in the physical properties will cause detectable changes in these modal properties. The main objective of the study is to establish indicators for the purpose of correlating this behavior.

Several studies have been carried out to identify damage in structures using the modal properties. Mostly changes in the natural frequencies have been utilized and found to be most convenient. Monitoring the natural frequencies together with the mode shapes was also proposed. Changes in modal damping and mode shapes have been utilized to detect damage. The mode shape derivatives, such as curvature have also been used. Very limited work has been done on honeycombed RC beams. This study proposes the application of experimental modal analysis and applies the local stiffness indicator to determine the locations the honeycombs in the RC beams.

2. Material and methods

It is assumed that conditions allow for the following equation to hold:

$$\frac{d^4V}{dx^2} - \lambda^4 V = 0 \tag{1}$$

where

$$\lambda^4 = \frac{(\rho A \omega^2)}{EI} \tag{2}$$

Changes in *EI* as a result of damage will result in changes in $|\lambda^4|$ which may be referred to as the local stiffness indicator (LSI). The RC beams were also load tested by applying a point load at point 0.5*L*. In the load test, the applied load and deflection were measured during loading. The graph of load versus deflection was plotted. The gradient of the linear portion in the graph gave the bending characteristic of the test beams. Subsequently, the flexural stiffness of the beam was calculated from the load–deflection graph.

In this study, three RC beams were cast. The dimensions of the reinforced concrete beams were 150 mm wide and 250 mm deep. The beams were simply supported across an effective span of 2200 mm on steel rollers placed on concrete blocks. The use of steel rollers on concrete blocks as supports may cause problems in examining the response signals due to restraining forces acting on the beams and resulting in a non-perfect boundary conditions of a simply supported system. The method would have limited applicability at the vicinity of the supports for only certain modes. The beams were a control beam, a defect beam L5 and another defect beam L5 × 2 with various volumes of honeycombs. The dimensions of the mortar blocks are given in Table 1.

The method used for creating the honeycombs in this investigation was by precasting mortar blocks with a known amount of polystyrene beads and placing them at the mid-span of the beam prior to casting the beams. Modal testing was also carried out on these beams.

Modal test was performed using transfer function technique on the RC beams, which were simply supported on steel rollers placed on concrete blocks. An accelerometer was used to pick up the response of the test beam under forced excitation. The excitation resulting from the input force was measured using a force transducer. In order to minimize spurious signals the RC beams were randomly excited using white noise signal input to a shaker, which was permanently placed at the quarter span for all test beams. To further enhance the quality of the input signals a filter could have been used but this was not done. A method based on combination of mode shapes and mode shape curvatures from the undamaged and damaged states could also make the method more robust and less vulnerable to noise.

The accelerometer was moved from one coordinate point to another to pick up a total of fifty-six response signals along the length of the beam. The transfer functions were acquired through a signal analyser. Initially, the transfer function spectrum within a 5 kHz frequency span was obtained in order to locate roughly the resonant frequency peaks of all the flexural modes within the band. Subsequently, zooming within a 100 Hz span of the resonant frequency peak of a particular mode was carried out. The measurements were made using a block size of 400 lines thus giving a resolution of 0.25 Hz per spectral line. A dual-channel analyzer was used to acquire the signals and to obtain the frequency response functions (FRF) from the response and the excitation force. By using modal analysis software, the curve fitting process was performed on the transfer function spectra obtained to extract the modal parameters i.e. natural frequency, mode shape. A total of ten normal bending modes were acquired in this manner. Fig. 1 depicts the set-up of the modal testing.

Table 1
Labels and dimensions of the mortar blocks.

Label	Dimensions of mortar blocks ($L \times W \times H$ mm)
L5	440 × 90 × 90
L5 × 2	440 × 90 × 180

Three concrete beams, one control and two others with honeycombs, of dimension 2400 mm overall length, 150 mm wide and 250 mm deep were prepared. They were reinforced with three 10 mm diameter high-yield bars with stirrups and minimal concrete cover of 25 mm was provided. The beams were simply supported on steel rollers placed on concrete blocks across an effective span of 2200 mm. Three parallel lines were drawn on top of all the beams. Fifty-six (56) coordinate reference points 40 mm apart were marked along all the lines. The top surfaces of the beams were marked with 168 grid points along three lines across the span of the beams, which served as the measurement points for the modal test. All the parameter measurements were taken at these points. The concrete for the test beams were designed in accordance to DOE method for grade 40 with 150 mm slump to give the desired workability. The method used for creating the honeycombs is by precasting mortar blocks with a known amount of polystyrene beads and placed at the mid-span of the beam, at various depths about the centroid of the cross section, prior to casting the beams. The dimensions of the mortar block L5 are 440 mm × 90 mm × 90mm and block L5 × 2 are 440mm × 180mm × 90mm. The density of these two blocks were 1600 kg/m^3 instead of 2440 kg/m^3.

Modal test was performed using transfer function technique on the RC beams, which were simply supported on steel rollers placed on concrete blocks. This test was used to determine the flexural strength and stiffness of the test beams by applying load of 0.75 kN/min until failure for all test beams.

3. Results and discussion

In order to simplify the system and avoid lengthy and complex non-linear analyses, the following assumptions were made for this technique namely:

(a) The beam is a Bernoulli–Euler type with limitations on thickness and depth-to-length ratio so torsion effects can be neglected.
(b) The honeycombs or other damage are not too severe so the system remains continuous and homogeneous and the Bernoulli–Euler equation can be applied as a fair approximation.

For an Euler beam the equation $\lambda^4 = \frac{y^{(iv)}}{y} = \frac{\rho A \omega^2}{EI}$ applies. The values of $|\lambda^4|$, which may be referred to as the local stiffness indicator (LSI) drawn as bar charts for an undamaged beam, remain constant along the length of the beam. Any changes to the natural frequencies or flexural stiffness due to occurrences of damage in the beam will show changes in the value of $|\lambda^4|$. For the beams with defects, it is approximated that the generalized equation applies.

To determine the location of damage, the indicator $|\lambda^4|$ is used to determine the general region of the honeycombs. In addition, curve-fitting technique employing the Chebyshev series rationals was performed on the experimental mode shape to prepare the data before applying the fourth order centered finite-divided difference formula. This was

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