Determination of damage location in RC beams using mode shape derivatives

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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 locationdependent methods. This study proposes the application of experimental modal analysis to determine the location of damage in the form of load-induced cracks and 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 [1–9]. 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 [10, 11]. 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 [12] 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.

Ratcliffe [13] 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 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 the 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. [14] expands 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 uses only the mode shapes from the damaged structure. The method can 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.

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. [15] demonstrated that absolute changes in mode shape curvature can be a good indicator of damage for the cantilever and simply supported analytical beam structures, which they considered. The changes in the curvature increase with increase in damage. The curvature values were computed from the displacement mode shape using the central difference approximation. Stubbs et al. presented a method based on the decrease in the curvature of the measured mode shapes or the modal strain energy between two structural degrees of freedom [16]. Topole and Stubbs further showed that it was feasible to use a limited set of modal parameters to detect structural damage [17,18]. Stubbs and Kim also showed that localizing damage using this technique without baseline modal parameters was possible [19]. This approach was confirmed by Chance et al. [20] 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. [21] 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, E I , 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 a weighted residual penalty-based technique, is applied to the measured mode shapes. The technique is further validated by Maeck and De Roeck [22] on a reinforced concrete beam, which was gradually damaged, and using instruments such as accelerometers, displacement transducers, and strain gauges.

Khezel [23] 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 (GMO) 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 load-induced cracks and 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, which are mass, damping, and stiffness; and changes in the physical properties will cause detectable changes in these modal properties. The main objective of the research study is to establish indicators for the purpose of correlating this behavior.

Experimental programme

In this investigation, five 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 concrete blocks as in

Fig. 1.

The first was a beam with a crack at 0.5L (Table 1) and the second was a beam with a crack at 0.7L (Table 2). A 20 mm deep saw-cut was introduced across the first beam at the soffit points at 0.5L and across the second beam at the soffit points at 0.7L. A concentrated point load was then applied at the position where the saw-cut was located. A load cycle comprised of the load applied incrementally in the following manner: zero to maximum loading at increments of approximately 0.75 kN each time and unload from maximum loading to 0 kN with decrements of approximately 0.75 kN each time. Fig. 3 depicts the set-up for the static loading test. The first beam was then subjected to maximum loading of 25 and 43 kN and modal testing carried out at each cycle while the second beam was subjected to maximum loading of 25, 41, 43, and 46 kN and again modal testing was carried out at each cycle. Crack widths, crack depths, and modal parameters were recorded for both beams at all cycles. Measurements for crack width of both beams were recorded from both sides of the beams at the level 230 mm from the top surface of the beams by using two crack gauges. Tables 4 and 5 list the average crack width for both beams, respectively.

The final three 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 3. 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 as shown in Fig. 4. Modal testing was also carried out on these beams.

Modal test

The modal test was performed using a transfer function technique on the RC beams, which were simply supported 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. 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. 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 and damping. A total of ten normal bending modes were acquired in this manner. Fig. 1 shows the actual modal test set-up and Fig. 2 depicts the setup of the modal testing.