EXPERIMENTAL INVESTIGATION INTO VIBRATION CHARACTERISTICS OF A CRACKED RC T-BEAM

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ABSTRACT:

The presence of damage causes changes in the physical properties of a structure which in turn alter its dynamic response characteristics. The monitoring of the changes in the response parameters of a structure has been widely used for the assessment of structural integrity, performance and safety. However, it has proven to be challenging to identify and estimate damage severity when this damage is induced by cracks. Irregular variations in the measured vibration response characteristics have been observed depending upon whether the crack is *closed*, *open* or *breathing* during vibration, the degree of severity and modal type. These variables consequently affect the effectiveness of structural integrity assessment. The main focus of this paper is to investigate the dynamic characteristic behaviour of a RC T-beam element subjected to four different crack conditions and attempt to identify optimal parameters common to all crack states which can be used for assessment of structural condition.

1. INTRODUCTION

The analysis of the dynamic response characteristics of a structure subjected to excitation and the subsequent monitoring of the changes in the response parameters is an effective tool for the assessment of structural integrity. These response parameters characterise the 'global' properties of the structure and have been widely used for in-service monitoring and evaluation of structural integrity after extreme events such as earthquakes. However, problems have been identified when these parameters are used for damage identification studies in RC T-beam subjected to flexural cracking. The irregular variations observed in the response parameters during the damage identification studies affected the capability to correctly identify damage. Three primary sources were anticipated for these variations: local stiffness discontinuity due to '*breathing*' of cracks; a geometric influence caused by lack of proper constraints at the end supports and amplitude nonlinearity due to impulsive events at the crack interface.

In the past, various researchers conducted investigations into the vibration characteristics of defective structures (Dimarogonas, 1996; Brandon et al., 1999). The spectral contents, phase history and other similar properties have been used for the identification of nonlinear response behaviour in a defective cantilever beam (Brandon, 1998; Brandon and Sudraud, 1998; Léonard et al., 2001). Considerable effort has also been placed on analytical modelling for the prediction of the vibration properties in structural elements subjected to '*breathing'* cracks (Chu and Shen, 1992). However, many of these studies are based on controlled experiments conducted on simple structural elements, specific material type and crack conditions. Therefore, it is difficult to extend these techniques to structural integrity assessment of complex situations such as RC structures subjected to arbitrary and multiple cracks. The objective of this paper is, therefore, to conduct an investigation into the response characteristic behaviour of a simply supported RC T-beam element subjected to multiple and arbitrary crack states. The response parameters obtained from the following crack conditions were used in conjunction with a simple analytical bilinear model for conducting this study:

LC0: initial 'pristine' condition where the beam is subject to minor cracks due to self weight; represents the *closed crack state;*
LC1: intermediate flexural cracking condition where the beam is subjected to an added mass equivalent of 1.0 kPa; represents the progressively growing *open crack state;*
LC2: increased flexural cracking condition induced by an added mass equivalent of 2.25kPa; represents the progressively growing *fully open crack state;*
LC3*: breathing crack state* due to opening and closing of cracks during vibrations, after removal of ***LC2*** loading condition.

2. SIMPLE ANALYTICAL MODEL FOR DIFFERENT CRACK CONDITIONS

The simulation of a *breathing* crack state in a Single Degree of Freedom (SDOF) system was presented using a piecewise linear time record based on a bilinear stiffness model concept. The spectral contents for the simulated free vibration response of the undamped SDOF system were determined using 2048 data points obtained from 20 cycle time records for each crack condition (Fig. 1a). The overlaid plots of the response spectra for different crack states indicate that the spectral pattern for the *breathing* crack is very different from others. Higher frequency harmonics were observed at integer multiples of the fundamental frequency of the bilinear model (Fig. 1c). The phase plane also indicates the existence of two foci and some abrupt changes in velocity of the bilinear model which are indicative of impulsive events at the crack faces. These observations will be used in the following sections for investigation of similar behaviour in the experimental results.

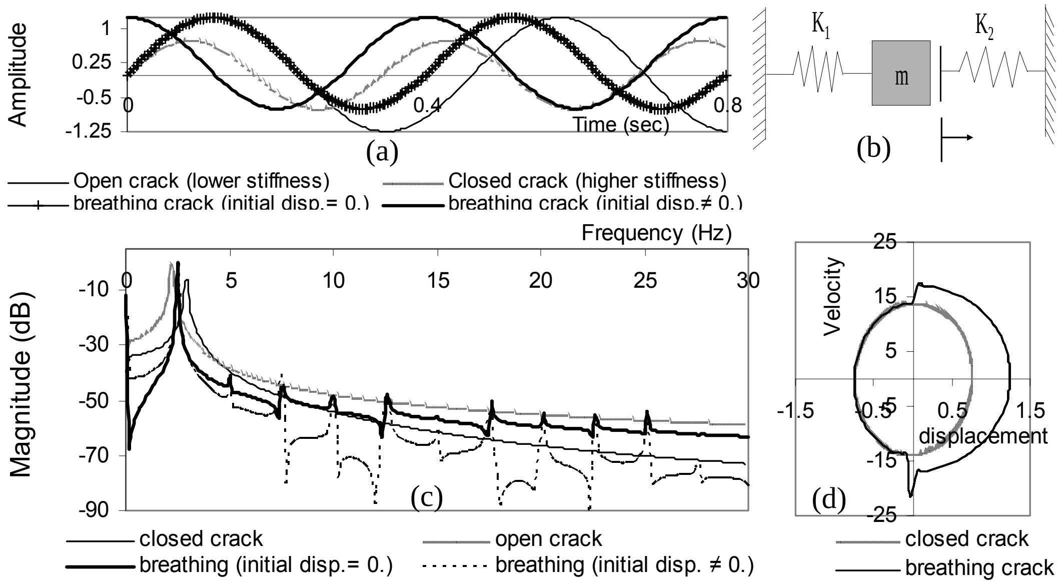

Figure 1 Free vibration response analysis for undamped SDOF system: (a) piece-wise linear time record; (b) bilinear stiffness model; (c) response spectra; (d) phase plane

3. EXPERIMENTAL STUDIES

The 9.4m long simply supported RC T-beam was constructed at the University of Melbourne using normal strength concrete for the flat slab section $(1.7m \times 0.12m)$ and high strength concrete for the web section $(0.25m \times 0.25m)$, (Haritos, 2003). A series of dynamic tests were conducted involving the measurement of vibration responses for different crack conditions using accelerometers while an impact hammer was used for the source of excitation. Consequently, FFT and modal analysis were performed on the response data to obtain Frequency Response Functions (FRFs) and modal parameters in the frequency domain. The relevant analysis results are presented, (see Figs. 2-5).

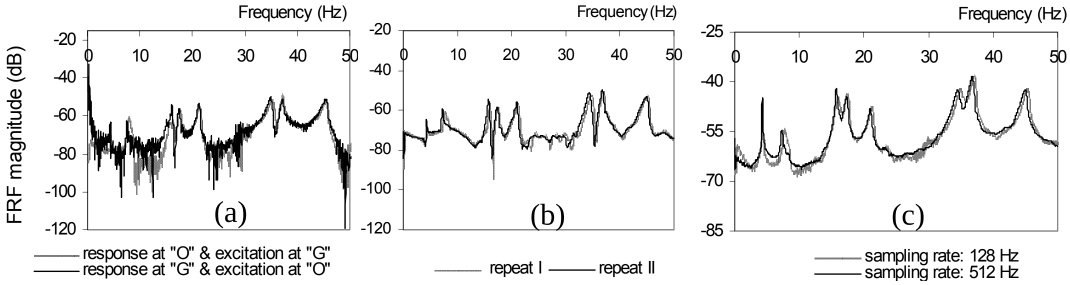

Figure 2 FRF data quality assessment: (a) reciprocity check; (b) amplitude linearity check; (c) measurement repeatability check (for *breathing* crack condition: ***LC3***)

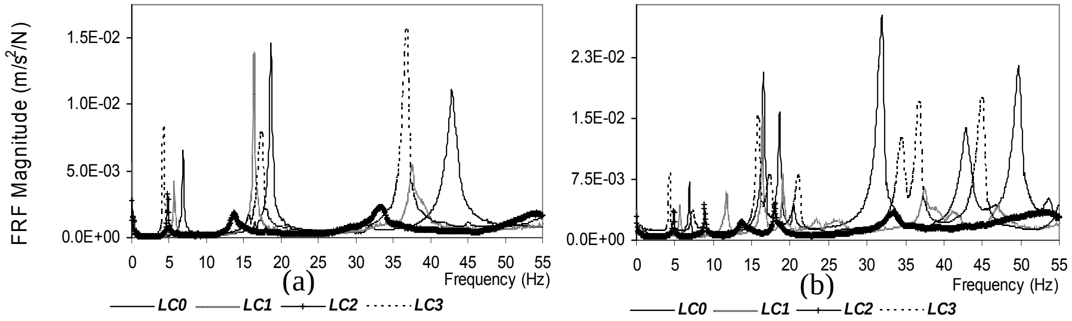

Figure 3 Comparison of ensemble average FRFs for all crack conditions (a) bending dominated modes; (b) all modes

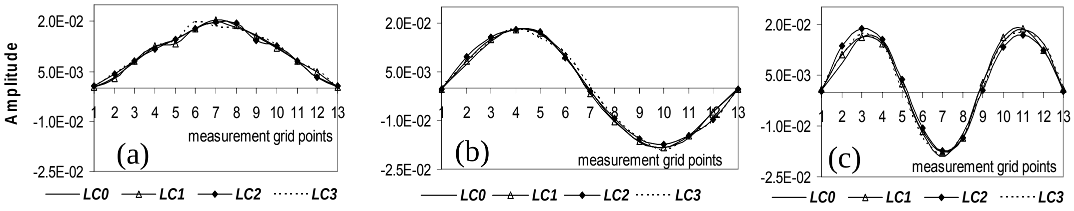

Figure 4 Comparison of mass-corrected mode shapes for flexural modes and for different crack conditions: (a) first mode; (b) second mode; (c) third mode

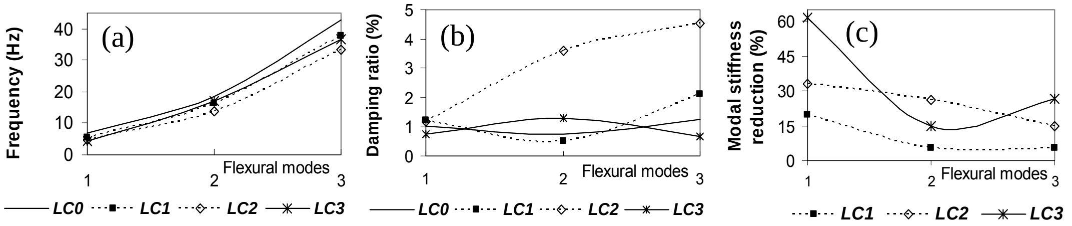

Figure 5 Comparison of modal parameters and modal stiffness properties for flexural modes: (a) natural frequencies; (b) modal damping ratios; (c) modal stiffness reduction

4. DISCUSSION ON VARIATIONS IN THE RESPONSE PARAMETERS

(i) Natural frequency: The general consensus in the literature is that the natural frequencies for the closed crack state should be higher than those from other crack states and the frequencies for the breathing crack state should lie between those for the closed and open crack states. However, the current analysis results indicate substantial inconsistent variation across the modes, especially for non-flexural modes (Fig. 3 and 5a). For the first mode, the frequency for the breathing crack condition is lower than those from all other crack conditions. For other modes, the frequencies from the ***LC2*** exhibited the lowest value while the breathing crack frequencies tend to straddle between those from ***LCO*** and ***LC1***. However, the changes in the frequencies for the ***LC1*** and ***LC2*** cases are influenced by the combined effects of the changes in the stiffness *and* mass properties. This fact can be observed clearly from the relationships between undamaged and damaged parameters obtained from the Eigen equation in terms of its key parameters such as mode shapes for the closed crack condition (ϕ); changes in the frequencies $(\Delta\omega)$; changes in mode shapes $(\Delta\phi)$; changes in stiffness and mass matrices (ΔK), (ΔM), respectively, and given by:

$$\Delta\omega^2 = \frac{\{\phi\}^T[\Delta K]\{\phi\} - \omega^2\big(\{\phi\}^T[\Delta M]\{\phi\} + \{\phi\}^T[\Delta M]\{\Delta\phi\}\big)}{\{\phi\}^T[\Delta M]\{\phi\} + \{1\}} \tag{1}$$

(ii) Modal stiffness: The change in modal stiffness for flexural modes, as determined using equation (1), indicates regular variation across the modes except for the second mode (Fig. 5c). The maximum percentage reduction relative to the undamaged state (***LC0)*** was observed for the *breathing* crack condition (***LC3)*** and for the first mode.

(iii) FRF amplitudes: Damage reduces local stiffness and increases flexibility of a structural element. Therefore, the peak FRF amplitudes for ***LC0*** are expected to be lower while those from ***LC3*** are higher than those from other states. However, the present experimental results reveal the difficulties associated with conducting any practical comparison for peak FRF amplitudes for different crack conditions, especially for non-flexural modes (Fig. 3b). For flexural modes, more regular behaviour was observed for ***LC0*** and ***LC3***. On the other hand, the FRF amplitudes from the fully open crack state were found to be the lowest for all modes and crack conditions. One of the possible explanations for this irregular variation is the influence of the added mass on the FRF amplitudes. The following equation derived from the Eigen equation indicates the influence of combined changes in stiffness and mass properties on the amplitude of inertance FRFs:

$$\overline{H}(\omega) = \frac{-\omega^2}{[\overline{K}] - \omega^2[\overline{M}]} = \frac{-\omega^2 H(\omega)}{H(\omega)\big(([\Delta K] - \omega^2[\Delta M]\big) - \omega^2} \tag{2}$$

where $\overline{H}(\omega)$ is the inertance FRF for the damaged states, $H(\omega)$ is the inertance FRF for the undamaged state, $[\overline{K}] = [K] + [\Delta K]$ and $[\overline{M}] = [M] + [\Delta M]$.

Another possible explanation for the irregular variation is that the changing nature of the crack condition during experimental tests due to the influence of the added mass causes time-dependent variation in the response data resulting in a so-called non-stationary response. It is also reported in the literature that in the case of an open crack state, the capability of the crack zone to transmit vibration tends to degrade since the vibration sensor could be measuring the responses from that part of the uncracked beam which is stiffer than the entire beam.

(iv) Mode shapes: Similar to other modal parameters, the changes in mode shape increase with an increase in damage severity. In the current results, the variations observed in mode shapes were induced by the combined effects of the changes in stiffness and mass properties. The overlaid plots for mass-corrected mode shapes for different crack states are presented for flexural modes (Fig. 5). Though these changes are consistent across the modes and across crack states, they were not sensitive enough to clearly identify stiffness changes in the T-beam due to arbitrary and multiple cracks.

(v) Modal damping: Modal damping increases with an increase in crack severity, amplitude of vibration and loading intensity. Though the current results exhibit this tendency for some crack conditions in the flexural modes, damping values are inconsistent particularly for the breathing crack state. Moreover, the damping values reached their maximum for the partially opening crack condition (***LC2***), (Fig. 5b).

5. CONCLUSIONS

This investigation has provided useful information regarding response parameters obtained from progressively induced crack conditions in a RC T-beam element. However, our goal for identification of consistent response parameters which can be used reliably for structural integrity assessment was hampered by encountering substantial irregularities in the response parameters across the modes and across crack condition states. The following conclusions can be drawn from this study:

- The dynamic testing of a structure with high level mass loading may not be reliable since it may cause non-stationary behaviour in the response signals.
- The nature of the harmonic characteristics and the absence of higher mode participation observed in the fully open crack case is a strong indication of the existence of geometric nonlinearity. Furthermore, the observation of high correlation in the non-flexural modes in all crack states indicate that the end supports of the test beam provided improper (non-linear) torsional restraint.
- There is no evidence for the occurrence of *breathing crack* condition and impulsive events of cracks since there is no similarity between spectral patterns observed from analytical and experimental results. Moreover, reciprocity and linearity checks conducted on the FRF data indicate no evidence of amplitude nonlinearity.

Finally, the modal stiffness reduction appears to be more sensitive to crack states, as expected, but for the test T-beam investigated here the reduction did not appear consistent between modes. Consequently, use of response parameters in combination would be more reliable than using them individually for structural integrity assessment, as each such response parameter is not without some form of deficiency.

REFERENCES

Brandon, J. A. (1998) Some insights into the dynamics of defective structures, Proceedings of the Institution of Mechanical Engineers Part C- Journal of Mechanical Engineering Science, 212**,** 441-454.

Brandon, J. A., Stephens, A. E., Lopes, E. M. O. and Kwan, A. S. K. (1999) Spectral indicators in structural damage identification: a case study, *Proceedings of the Institution of Mechanical Engineers Part C- Journal of Mechanical Engineering Science,* Vol 213, pp 411-415.

Brandon, J. A. and Sudraud, C. (1998) An experimental investigation into the topological stability of a cracked cantilever beaM, *Journal of Sound and Vibration,* Vol 211, pp 555-569.

Chu, Y. C. and Shen, M.-H. H. (1992) Analysis of forced bilinear oscillators and the application to cracked beam dynamics, *AIAA Journal*, 30**,** pp 2512-2519.

Dimarogonas, A. D. (1996) Vibration of cracked structures: A state of the art review, *Engineering Fracture Mechanics,* Vol 55, pp 831-857.

Haritos, N. (2003) Static and dynamic testing of two floor beams, Melbourne University Private Ltd Report, MUP 2002-151 (2).

Leonard, F., Lanteigne, J., Lalonde, S. and Turcotte, Y. (2001) Free-vibration behaviour of a cracked cantilever beam and crack detection, *Mechanical Systems and Signal Processing*, Vol 15, pp 529-548.