CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

Boundary condition is a major factor affecting the dynamic properties of structures. In general, laboratory test beams have only been utilized on free-free and cantilever support conditions, where the data obtained are more robust and better suited to cope with the damage identification techniques. Therefore, it seems appropriate to extend the scope of this investigation to different support conditions such as spring and fixed roller supports, which closely resemble the support conditions in actual structures. Besides that, the obtained modal data is more practical for damage identification of the structures. Hence, the interest on the effects of boundary conditions on damage identification was the motivating factor behind this research work and the conclusions drawn are listed in the following sections.

6.2 CONCLUSIONS

The obtained modal data from the test beams on different boundary conditions, namely, free-free, spring and fixed roller support, were used to derive the effects of boundary condition. It was observed that the change in boundary conditions significantly affected only the first two flexural modes.

In contrast with general perception, the comparison of natural frequencies for the first two flexural modes indicated that the stiffer the support condition, the lower the natural frequencies. The measured natural frequencies were reduced from the free-free to spring to fixed roller support conditions. For the higher modes, the change in boundary conditions did not significantly affect the natural frequencies which exhibited a slight increase in the values.

By comparing the amplitude of mode shapes, variations were observed in the first two flexural modes. The amplitude of the vibration was reduced when the support condition was changed from the free-free to spring and from the spring to roller. However, the amplitude of the higher mode shapes showed only slight changes or remained unchanged as compared with the free-free support case.

For modal damping, a consistent trend of increase in damping ratio was observed in the flexural modes when the stiffer support condition was encountered. In comparison, the change in damping ratios for the torsional mode was less sensitive than that of the flexural mode when there is a change in boundary conditions. For higher modes, the change in boundary conditions had a less significant effect on the damping ratios.

Natural frequency had been successfully used as a damage indicator. It not only verified the occurrence of damage but also identified the damage location for the free-free, spring and fixed roller support conditions. The percentage drop in natural frequencies indicated the occurrence of damage and its magnitude possibly enabling one to evaluate the severity in the structure. Beside that, the change in natural frequencies for a particular mode is a function of the crack location which can be used to identify the crack location in the structure.

The percentage drop in natural frequency consistently increased with the reduction in the stiffness of the boundary conditions. By comparison, the percentage drop in natural frequencies for flexural modes were more sensitive than the torsional modes. The change in boundary condition also significantly affected the sensitivity of damage detection, where the percentage drop in natural frequencies reduced as the support stiffness increased, especially for the lower modes. The formation of a plastic hinge at the crack location caused a higher decrease in the flexural frequencies.

The damage location in the beam was identified using the percentage drop in natural frequencies which is shown to be a function of the crack location. The underlying concept is that the percentage drop in natural frequency is proportional to the curvature mode shape at the crack location. In other words, a high percentage drop in natural frequencies indicates that the crack is located at a high curvature zone for that particular mode. By utilizing the first six flexural modes enabled the identification of the crack location. The natural frequency is a sensitive damage indicator which was able to detect the damage location when the cut was 0.17h for the free-free condition, and 0.28h for the spring and fixed roller support conditions.

Changes in mode shapes and curvature mode shapes are not sensitive damage indicator as compared to the frequency based damage indicator. The displacements in mode shape and changes in relative amplitude were significant noticeable when the cut was greater than 0.61h but they did not give any clear indication of the damage location. No trend was noticeable for the first two flexural modes when the stiffer boundary conditions were encountered.

From the changes in curvature mode shapes, the Laplacian equation successfully identified the damage location for the free-free condition when the damage was fairly severe. However, it was not able to detect the damage location for the beams with stiffer support conditions. The advantage of this technique is that it does not require prior knowledge of the datum or undamaged state.

Using a combined algorithm, the problems of insensitivity of detecting damage at higher modes and stiffer boundary conditions using the Laplacian was overcome. The combined algorithm utilized the values of the Laplacian which was then substituted into the geometric mean operator (GMO) in order to increase the deviation at the damage location, especially that of the higher modes. The distinct anomaly at the damage location was clearly noticeable for all the boundary conditions. Besides that, it was more sensitive to detect the damage as compared to the Laplacian operator.

The modal assurance criterion (MAC) and co-ordinate modal assurance criterion (COMAC) factors were not sufficiently sensitive for damage detection purpose. Both techniques were only capable to identify the occurrence of fairly severe damage in the beams when the crack depth ratio exceeded 0.61. The changes in MAC values were inconsistent as the damage severity increased, possibly due to its sensitivity to measurement errors [38]. The changes in COMAC values not only occurred at the damage location but were also noticeable at other locations. This could be due to the formation of a plastic hinge, which significantly affected the mode shape globally.

The direct use of changes in natural frequencies did not identify the number of cracks in the beam for the dual crack case. However the minimum percentage drop in natural frequency provided significant information which indicated that the cracks were located at the low curvature zone for a particular mode. The number of cracks and their locations in the beam were successfully identified using a combination of results from two modes. This was possible because the anomalies appeared separately for each of the two modes and the location depended on the change in curvature mode shape.

In model updating, the finite element (FE) models of the free-free and fixed roller support beams correlated well with the experimental results. Correlation was achieved by reducing the difference in natural frequencies between the FE and the experimental results and also by matching the MAC values. The FE natural frequencies was different by less than 4 percent except for the first two flexural modes of the fixed roller support beam. The MAC values for all the mode pairs exceeded 0.9 which indicated that the comparison of mode shapes was sufficiently correlated for the mode pairs (CMPs).

Subsequently using the updated FE model, a simple frequency based damage identification technique was developed for predicting the location and severity of the damage. This technique was based on the assumption that the reduction of the flexural stiffness *EI* values at the crack location is the same for all the flexural modes. Consequently, by plotting the normalized *EI* along the beam against the normalized natural frequencies, the crack location and severity of damage can be identified by the intersection point on the curves.

For identifying the crack in the fixed roller support beam, modification of this technique was necessary due to the inaccuracy of the measured natural frequencies. A bar graph of the difference in normalized *EI* along the beam was plotted and the minimum value indicated the crack location. However, this technique provided two possible crack locations for symmetrical mode shapes.

6.3 SUMMARY OF CONTRIBUTIONS

1. It was apparent that the measured natural frequencies and mode shapes of the first two flexural modes were not capable in evaluating and identifying the crack in the beam due to the effects of boundary condition. Therefore, the modal data of higher modes were necessary for damage identification because they were less affected by the changes in boundary conditions.
2. The changes in natural frequencies not only verified the occurrence of damage but also identified the damage location. However, weaknesses were discovered in this technique. Firstly, prior knowledge of datum state is required. Secondary, there are two possible crack locations for symmetrical mode shape. Finally, change in natural frequencies does not directly indicate the number of cracks present in the beam.

3. The mode shape based method does not suffer the prior knowledge of datum state and the symmetrical mode shape problems as the frequency based method. The Laplacian indicated that the change in mode shape curvature was local in nature due to the localized damage. However it was insufficient for detecting local change in structural stiffness when stiffer boundary conditions were encountered, and thus becomes necessary to use other forms of algorithm. Therefore, the combined method was proposed which increased the deviation at the damage location and eliminated the fluctuation value of positive to negative as presented in Laplacian. The results of combined method indicated that the distinct anomaly was present at the damage location for all the boundary conditions, especially for the higher modes. The number of cracks can also be determined using the combined results of two modes.
4. Combination of frequency based and mode shape based methods provided a way to evaluate the damaged state and to detect the damage location. The change in natural frequencies was a sensitive damage indicator in order to verify the damage and to identify the possible crack location, and the combined method provided the exact crack location and number of cracks. By combining the information of changes in natural frequencies, the distortion caused by factors other than damage can be eliminated and provided accurate results for the crack location and number of cracks.
5. The updated FE model enabled the prediction of the behavior of modal properties due to the damage induced and provided useful modal data for the damage identification purpose. By combining the results of FE modeling and experimental, the FE normalized flexural stiffness EI against the measured normalized natural frequencies can be plotted along the beam, and the intersection point on the curves indicates the crack location and severity of

damage. If there are no intersection points on the curves, the modified technique can be applied whereby the minimum value of the difference in normalized *EI* indicates the crack location. The applicability of this technique is dependent on the degree of correlation of the FE model with the experimental model. If the correlation is unsatisfactory, the technique is not valid for damage identification purposes.

6. In this study, it was established that modal data provided sufficient information in order to determine the presence, location and severity of the damage by using the various techniques for damage identification. The change in natural frequencies directly identified the occurrence and location of damage. Besides that, it also indicated the severity using the combined results of both experimental modal and FE analyses. Furthermore the combined method enabled the identification of the exact crack location and number of cracks in the beam. The damage identification techniques utilized were applicable not only for the free-free but also the spring and fixed roller boundary conditions.

6.4 RECOMMENDATIONS

Further work and refinement is essential in order for this study on damage identification techniques with different boundary conditions to be meaningful and practicable. Thus, some recommendations are made for the purpose of extending and diversifying the current study:

1. The stiffer support condition significantly affects the modal data for damage identification purpose, especially the lower modes. Further development of modal testing methods is essential in order to reduce the noise effect and obtain more accurate modal data.

2. Laplacian operator is the method to estimate the curvature mode shape using the amplitude mode shape, and the estimation may not represent the exact curvature mode shape. Therefore, the measurement of the strain mode shape may give more accurate indication because the curvature mode shape is directly related with the strain mode shape. The MAC and COMAC using strain mode shape data may also provide good indication since the change in curvature mode shape is more sensitive than the change in amplitude mode shape due to localized damage. It is therefore possible to provide more sensitivity of damage identification procedure.
3. The application of damage identification techniques to civil engineering structures is of practical interest. Therefore, it is still a challenge to demonstrate whether damage localization and quantification for a real-life structure can be obtained using the present techniques. A large scale reinforced concrete beam of experimental model should be carried out and tested on different boundary conditions. The present frequency based and mode shape based methods should be implemented, and the FE model of reinforced concrete beam on different boundary conditions should also be modeled and implemented in the proposed technique. Thus, the study could be extended to actual structures in order to determine whether the present techniques are practical or not.