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A benchmark study of dynamic damage identification of plates

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Vibration-based methods for damage detection of structures are researched extensively among the academic community. Yet only limited success in practice has been reported. A major hurdle is understood to be the discrepancy between the assumed availability of pertinent modal data and the measurability of such data from actual experiments. However, dedicated critical studies into the practicality and limitation of modal testing for structural damage detection are scarce. This paper presents a laboratory investigation, along with finite-element (FE) analysis, into the extent to which modal frequencies and mode shapes may be measured in a plate-like structure and their general sensitivities to different levels of damage. The order of measurable modes and the measurement accuracy are assessed on the basis of the actual measurement in conjunction with FE predictions. Changes in the measured modal properties are examined in light of the pattern and severity of damage. Results indicate that with a typical modal testing it is possible to obtain the first 5–6 modes for a plate structure with sufficient accuracy in the frequencies but with a gross error of around 10% in the mode shapes. Using solely a few measurable natural frequencies will be insufficient to identify the occurrence and the degree of crack-induced damage. Mode shapes can be more indicative of local damage in a plate, especially when it involves an edge crack.

1. Introduction

In the realm of structural health monitoring and damage detection, vibration-based techniques offer a means of assessing the global health of a structure. Vibration-based damage detection methods use observed changes in the modal properties of a structure to infer damage. In many applications it may be reasonable to assume that damping and mass do not change; consequently, changes in vibration behaviour can be attributed to changes in the stiffness of a structure.

Numerous vibration-based methods have been developed in the past three decades with the aim of application in the damage detection in structures, as evidenced in several comprehensive reviews of the relevant literature, for example Doebling *et al.* (1996), Sohn *et al.* (2001) and Montalvão *et al.* (2006). However, very little has been reported on the successful implementation of such methods in real-life applications. This lack of success in real applications is a testament that there is a considerable gap between the research exercise and the reality in the structural identification and damage detection field.

The feasibility of a vibration-based method in the damage detection of real structures depends on many factors, chiefly the underlying sensitivity of the measurements to the damage of interest, accuracy of the required measurements, and the versatility of the inference/inverse problem solving algorithms. While the sensitivity and the soundness of an algorithm may be reasonably understood through theoretical and numerical analysis, the quality of the required measurement data can only be assessed by way of dedicated experimental studies. However, despite the seemingly obvious need, the practicality aspect is not always rigorously checked in the development of a theoretical methodology.

The aim of the present study is to provide a critical benchmark assessment on the limitation of the classical modal test and the usefulness of the acquired modal data in the identification of damage in a typical modal experiment environment. More specifically, it aims to provide insight into the following questions.

(*a*) How many modal frequencies and mode shapes may be reliably measured and what would be the margin of errors associated with these measurements, especially in a plate-like structure?

(*b*) With such a (limited) set of measurable modal data, what should be a realistic expectation in terms of their use for structural damage detection?

The study is carried out using laboratory experiment in conjunction with finite-element (FE) exploration. As a matter of fact, laboratory experiment represents a crucial step towards the real-life implementation. Laboratory models are simplified versions of real structures, in this respect they usually lack the complexity and uncertainty a real structure would exhibit. However, instrumentation, data acquisition and processing are real, and the measurement errors set a somewhat lower bound in a real-life application. Moreover, with a laboratory model one can generate a variety of damage scenarios, allowing for an observation on the sensitivity of the measured response with the change of damage state, and thus the detectability of such damage. This kind of flexibility of making structural alterations is not possible in an actual structure.

Existing laboratory model tests have mostly been concerned with one-dimensional (1D) beam-like structures. Comprehensive experimental evaluation on two-dimensional (2D) plate structures is generally lacking. The present study focuses on the experimental modal analysis for a plate-like structure. A laboratory test model plate was made such that the natural frequencies of the model resemble those of slabs seen in buildings and bridge decks. Various damage scenarios were created on the test model plate. Complete experimental modal testing was conducted to extract the natural frequencies and mode shapes for the plate in its pristine and damaged states. To assist in the experimental observations and interpretation of the results, FE models were also developed and used in the explorations. The correlation between this FE model and the observed behaviour of the plate under differing damage states is examined with the view of providing insight into the damage sensitivity and the measurement errors in plate-like structural components.

2. Brief review of modal property-based methods and related laboratory experimental studies

2.1 Modal property-based methods

A range of non-destructive techniques have already been developed and are widely used in industry. However, these tools are only effective in detecting damage on a local scale, which implies that a prior knowledge of the damage location is required. Even if the location is known, the application of these techniques requires that the damage location be freely accessible, which obviously will not always be the case. For these reasons, structural health monitoring (SHM) research over the past 30 years has largely been focused on assessing the global structure.

There are a wide number of damage detection methods based on changes in dynamic properties but they can essentially be condensed into a few categories

(*a*) changes in frequency and mode shape
(*b*) changes in mode shape curvature
(*c*) changes in dynamically measured flexibility
(*d*) linear/non-linear problems.

Only the methods based on changes in natural frequency and mode shapes are commented on in what follows.

Changes in modal frequencies infer a change in stiffness in the structure resulting from damage. Doebling *et al.* (1998) argued that changes in frequency correlate with damage in a structure with more certainty than methods relying upon changes in mode shape curvature. However, a number of studies have found that frequency shifts are not actually a very robust indicator of damage. Farrar *et al.* (1994) conducted an experiment on a highway bridge in which no change in natural frequency was recorded despite a 21% stiffness reduction at a cross-section level in the structure. This lack of sensitivity in the measured frequency to localised stiffness change highlights a fundamental characteristic of such a global method, that the damage severity must be a combined measure of both the local severity (e.g. stiffness reduction at a section level) and the spreading area.

Local damage will often only reveal itself in terms of shifts in high-frequency modes. As noted in Farrar *et al.* (2001), Salawu (1997) and Doebling *et al.* (1998), it is often hard to identify these high-frequency modes owing to a greater spectral density and higher noise-to-modal frequency ratio. In addition, high-frequency modes are more difficult to excite owing to the increased energy requirements.

Methods based on tracking frequency changes are also potentially capable of locating damage within a structure, in addition to identifying whether a structure is actually damaged. Salawu (1997) explains how changes in frequency will be different for each mode and hence how damage can be located. However, a number of other studies have highlighted the limitations of this technique. Doebling *et al.* (1998) point out that, although it is possible to gather spatial information based on changes in a number of modes, there may not be a sufficient number of modes exhibiting a significant change in frequency. Salawu (1997) continues to indicate that much greater diagnostic accuracy is gained when damage occurs in areas of high stress. Additional complications are introduced when considering that a small crack in one region may result in the same loss of stiffness as a very large crack in another region.

Identifying changes in mode shapes provides another potential basis for identifying damage within a structure. Previous researchers have employed a number of different methods to identify damage from mode shape data. The most commonly used analyses involve the use of the modal assurance criterion

(MAC), or some variation thereof. In tests on a beam damaged by a saw-cut, Fox (1992) found single number measures of mode shape changes (e.g. MAC) are relatively insensitive indicators of damage. The 'node line MAC' was found to be more sensitive to changes in mode shape resulting from damage. This analysis utilises a MAC based in measurement points close to a node for a particular mode of vibration. Stubbs *et al.* (1992) and Kim *et al.* (2003) used further variations on the MAC to isolate the region of damage within a structure. The study used the co-ordinate MAC (COMAC) in conjunction with the PMAC (partial MAC).

2.2 Brief review of experimental considerations and previous tests on plate-like structures

The process of laboratory testing is obviously highly dependent upon the type of structure being investigated, type of damage introduced and desired results. The following section looks at a number of laboratory/in situ tests and takes note of details required by all experimental set-ups; such as accelerometers, data acquisition and data processing techniques.

Salawu (1997) found that a 5% change in modal frequency was needed in order to detect damage confidently. Equally, he noted that a 5% change was possible owing to changing ambient conditions such as temperature and humidity. Although tests conducted in a controlled lab environment will show much less variation, changes in ambient conditions should always be borne in mind when comparing data. Kenley and Dodds (1980) also found that a 5% change in overall stiffness was necessary in order to detect damage confidently in an offshore platform. They reported that global mode frequencies were detectable to within 1% whereas the ill-defined power spectrum at higher frequencies increases the error in detected local modal frequencies to 3%.

Pavic and Reynolds (2003) report that if only the response frequency is measured (as in a heel drop or impact hammer test), there is insufficient information for closely spaced modes to be separated in the power spectrum. This is of particular importance in real floors and structures where symmetry or repetitive geometry makes the probability of closely spaced modal frequencies very high.

The importance of positioning and attachment of sensors to the test surface has been highlighted by a number of authors. Farrar *et al.* (2001) noted that during their test of a 3·5 m concrete column, a number of sensors had to be removed from the data set because they were too insensitive. Salawu (1997) suggested that a basic numerical model of the structure should be produced and sensors placed where the sum of the modal deflection magnitudes is greatest. Sensors placed at boundaries yielded erroneous results. Hanagan *et al.* (2003) found the mounting of the sensors is critical in gaining useful data.

The source of excitation for the test structure warrants careful consideration and should be dependent upon the specific test objectives; as indicated by Hanagan *et al.* (2003). A shaker was found to yield superior quality data when compared to impact hammer excitation. However, impact hammer excitation is presumed to be adequate unless repeatability of excitation signal or particularly high-quality data are desirable. Raebel *et al.* (2001) noted that the coherence of data dropped above 30 Hz when using a heel drop on a 26 × 10 ft concrete floor.

Raebel *et al.* (2001) reported that good coherence was displayed in data gained from any level of excitation, assuming that the level exceeded ambient noise levels. Hanagan *et al.* (2003) suggested that a signal-to-noise amplitude ratio (S/N) of above 100 usually ensures high-quality data. However, if the excitation level is too great, rattling and other non-linear behaviour may be induced and hence the quality of the data will be reduced. Hanagan *et al.* (2003) and Raebel *et al.* (2001) both report that the location of excitation has little bearing on data quality so long as nodal lines and supports are avoided.

The most appropriate record length depends upon the excitation source, level of damping and spacing of modes within the frequency spectrum (Hanagan *et al.*, 2003). Leakage occurs between power spectra peaks if the signal has not sufficiently dissipated before the end of the record. Conversely, if the signal dissipates too quickly most of the measured response will consist of noise. Raebel *et al.* (2001) report that for a heel drop on a large concrete floor, using an 8 s record length, the signal had not sufficiently subsided and hence significant leakage was observed.

Averaging a number of modal data sets obtained from subsequent runs of the same test is an important step in gaining useful results. Farrar *et al.* (2001), Hanagan *et al.* (2003) and Raebel *et al.* (2001) all report that three averages is usually sufficient to remove the effect of noise in a lab environment. The increased background noise associated with in situ testing in a real plate-like structure would require increased levels of averaging.

The majority of research documented in the literature relates to bridges, line-like elements such as beams and columns, and offshore platforms. While the basic theory and procedure described within these papers is useful to the present study, much of the detail is not especially relevant. However, a number of specific studies into vibration-based damage detection in plate-like elements have been identified and are outlined below.

Richardson and Mannan (1992) tested a 500 × 190 × 8 mm aluminium plate. Mode shapes and modal frequencies in the pristine state were measured using an impact excitation method. Damage in the form of a 25 mm saw cut was introduced to the edge of the plate. Modal frequencies were measured after the introduction of damage and the location of damage was identified using a pseudo-inverse search technique to locate the greatest reduction in stiffness. Saitoh and Takei (1996) applied the above techniques to a plate containing a crack. They reported a small decrease in modal frequency when damage was introduced.

However, MAC values showed no change in mode shape between the damaged and undamaged structure.

Swamidas and Chen (1995) found that the best data for locating a crack in a cantilevered FE plate were the strain mode shape. Chen and Swamidas (1996) reported that a plate with a half thickness crack showed less than a 4% change in resonant frequency.

A cantilevered steel plate 0·5 m long was investigated by Friswell *et al.* (1994). The plate was damaged by saw cuts and an algorithm was applied with reasonable success. The algorithm correctly identified damage but gave a number of false positive results in the undamaged structure.

3. Experimental programme

The experimental testing was designed to investigate the measurement of changes in frequency and mode shape in a plate-like structure, with the application of progressive damage.

3.1 Test structure and different damage scenarios

Selection of the plate material was not essential for the present investigation. However, it was desirable to keep the natural frequencies of the test plate in a similar range to those observed in typical structural slabs, for example a bridge deck. Thus, an aluminium plate of dimensions 1200 × 500 × 3 mm was selected, and the plate was clamped at the two ends, resulting in a clear span length of 1·0 m. Preliminary analysis indicated the test plate would have the first bending and first torsional frequencies about 16 and 26 Hz, respectively. Figure 1(a) shows the undamaged test plate with clamped supports. The grids and dots were marked for the purpose of zoning and placement of accelerometers.

Besides the undamaged state, different damage scenarios were introduced by cutting slots (mimicking cracks) in the test plate in a progressive manner. Six damage scenarios, shown in Figure 1(b), were simulated. Damage 1–4 (D1–D4) were within the plate boundaries whereas damage 5 and 6 (D5–D6) introduced a discontinuity along the edge of the plate. D1 took the form of a fully penetrating slot, 100 mm long and 5 mm wide. D2 was a further 100 mm extension of D1. Similarly, damage D4 was a continuation of D3; D6 of D5.

3.2 Test method and modal analysis procedure

The modal test was conducted with impact excitation using an instrumented hammer. The response of the plate to the impact excitation was measured by an array of accelerometers, whose size and weight were small enough (5 g) such that their possible interference to the stiffness and mass of the test plate was negligible.

As can be seen from Figure 1, in total there were 50 measurement points to represent a reasonable resolution of the extracted mode shapes. Instead of using 50 accelerometers in one go, the test for each damage scenario was completed in ten sub-tests, with five accelerometers placed at one row of measurement points at a time. The impact location during the tests remained unchanged, while a reference accelerometer was maintained at a fixed location so that the results from different subsets of tests can be combined or 'glued' using a modal analysis procedure (Brownjohn *et al.*, 2003) to form the complete measurement set with all 50 measurement points. A multi-channel dynamic data acquisition system (Wavebook® series) was used for conditioning and recording the impact input and the acceleration response signals. A sampling rate of 1000 Hz over 20 s was found to be suitable. Figure 2 shows a typical frequency spectrum.

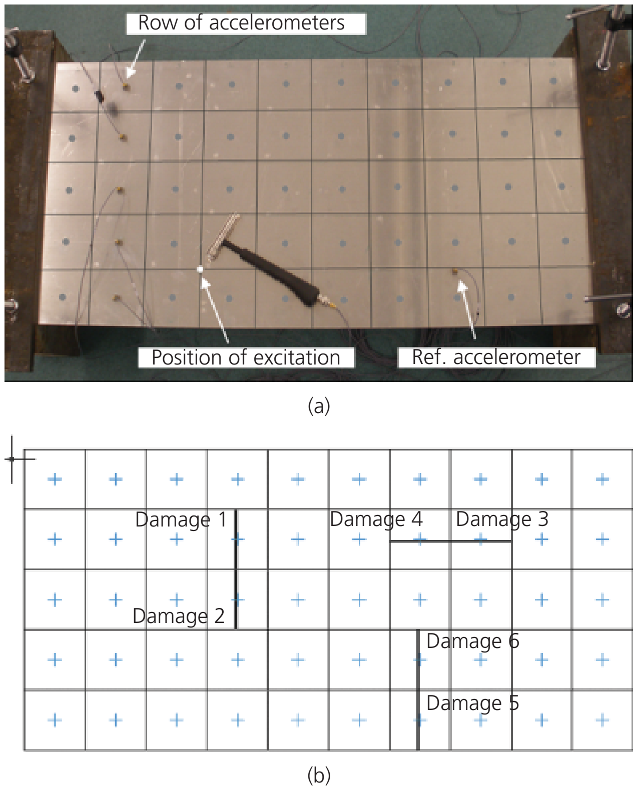


Figure 1. Test set-up and progressive damage scenarios: (a) test plate and test set-up; (b) progressive damage scenarios

4. Test results and general comparison

Natural frequencies and mode shapes of the undamaged test plate were extracted as described in the previous section. Changes in these modal parameters were monitored as cumulative damage was applied to the plate, in the manner previously explained. Changes in modal parameters were used to infer damage in the test plate, with varying success.

4.1 Natural frequencies and their variation with progressive damage

Table 1 shows a summary of the natural frequencies and their cumulative reductions obtained for each stage of the test plate. The accuracy of the measured frequencies was assessed by repeated tests on the same state of the structure, and the results

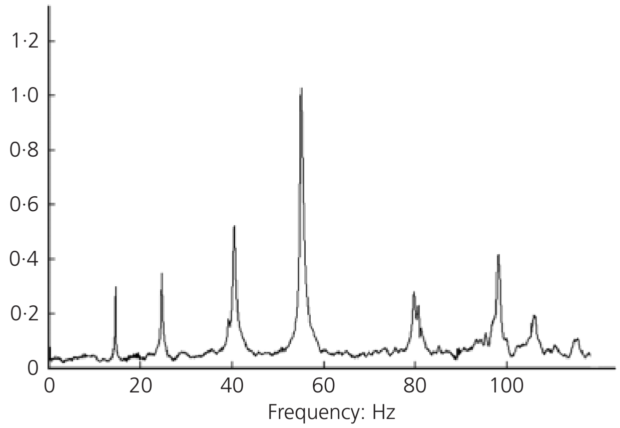


Figure 2. Typical measured frequency response spectrum

indicated that the margin of deviation was of an order of 0·1%, which was negligible.

Figure 3 plots the variation and incremental percent change (with respect to the preceding state) of individual modal frequencies at each progressive stage of damage. The details of these modes, as can be identified from the measured mode shapes (see Figure 4), are also indicated in Table 1.

From Table 1 and Figure 3 the following may be observed.

(*a*) The first and third bending modes (total mode 1 and 5) appear to be insensitive to the increased severity of damage

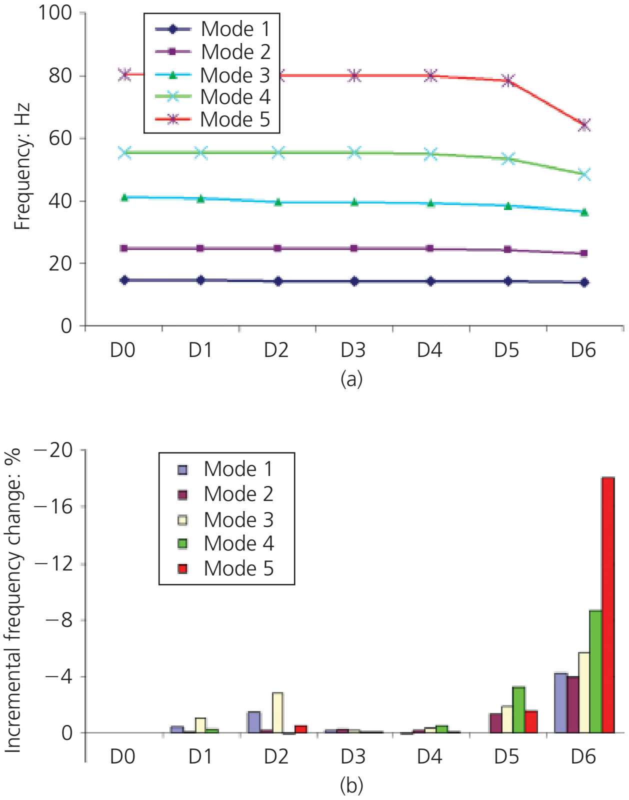


Figure 3. Variation of measured natural frequencies with progression of damage: (a) variation of measured natural frequencies; (b) incremental change of frequencies

Measured	Mode 1 (bending)	Mode 2 (torsion)	Mode 3 (bending)	Mode 4 (torsion)	Mode 5 (bending)
Undamaged	14·51 (0·0%)	24·68 (0·0%)	40·90 (0·0%)	55·49 (0·0%)	79·93 (0·0%)
Damage 1	14·55 (+0·3%)	24·71 (+0·1%)	40·66 (−0·6%)	55·40 (−0·2%)	80·47 (+0·7%)
Damage 2	14·34 (−1·2%)	24·66 (−0·1%)	39·53 (−3·3%)	55·44 (−0·1%)	80·03 (+0·1%)
Damage 3	14·31 (−1·4%)	24·59 (−0·4%)	39·46 (−3·5%)	55·36 (−0·2%)	79·92 (−0·0%)
Damage 4	14·32 (−1·3%)	24·54 (−0·6%)	39·30 (−3·9%)	55·05 (−0·8%)	79·81 (−0·2%)
Damage 5	14·32 (−1·3%)	24·20 (−1·9%)	38·57 (−5·7%)	53·29 (−4·0%)	78·54 (−1·7%)
Damage 6	13·71 (−5·5%)	23·26 (−5·8%)	36·37 (−11·1%)	48·65 (−12·3%)	64·34 (−19·5%)
FE analysis					
Undamaged	14·62 (0·0%)	25·12 (0·0%)	40·34 (0·0%)	55·44 (0·0%)	78·82 (0·0%)
Damage 1	14·55 (−0·48%)	25·10 (−0·08%)	39·94 (−0·99%)	55·29 (−0·27%)	78·77 (−0·06%)
Damage 2	14·35 (−1·85%)	25·08 (−0·16%)	38·87 (−3·64%)	55·23 (−0·38%)	78·15 (−0·85%)
Damage 3	14·35 (−1·85%)	25·07 (−0·20%)	38·85 (−3·69%)	55·19 (−0·45%)	78·00 (−1·04%)
Damage 4	14·36 (−1·78%)	25·04 (-0·32−)	38·80 (−3·82%)	54·94 (−0·90%)	78·41 (−0·52%)
Damage 5	14·20 (−2·87%)	24·64 (−1·91%)	37·97 (−5·88%)	53·57 (−3·37%)	77·14 (−2·13%)
Damage 6	13·70 (−6·29%)	23·56 (−6·21%)	35·54 (−11·9%)	49·29 (−11·1%)	63·05 (−20%)

Table 1. Summary of measured and FE calculated natural frequencies (percent figures in parentheses are cumulative changes with respect to the undamaged frequencies)

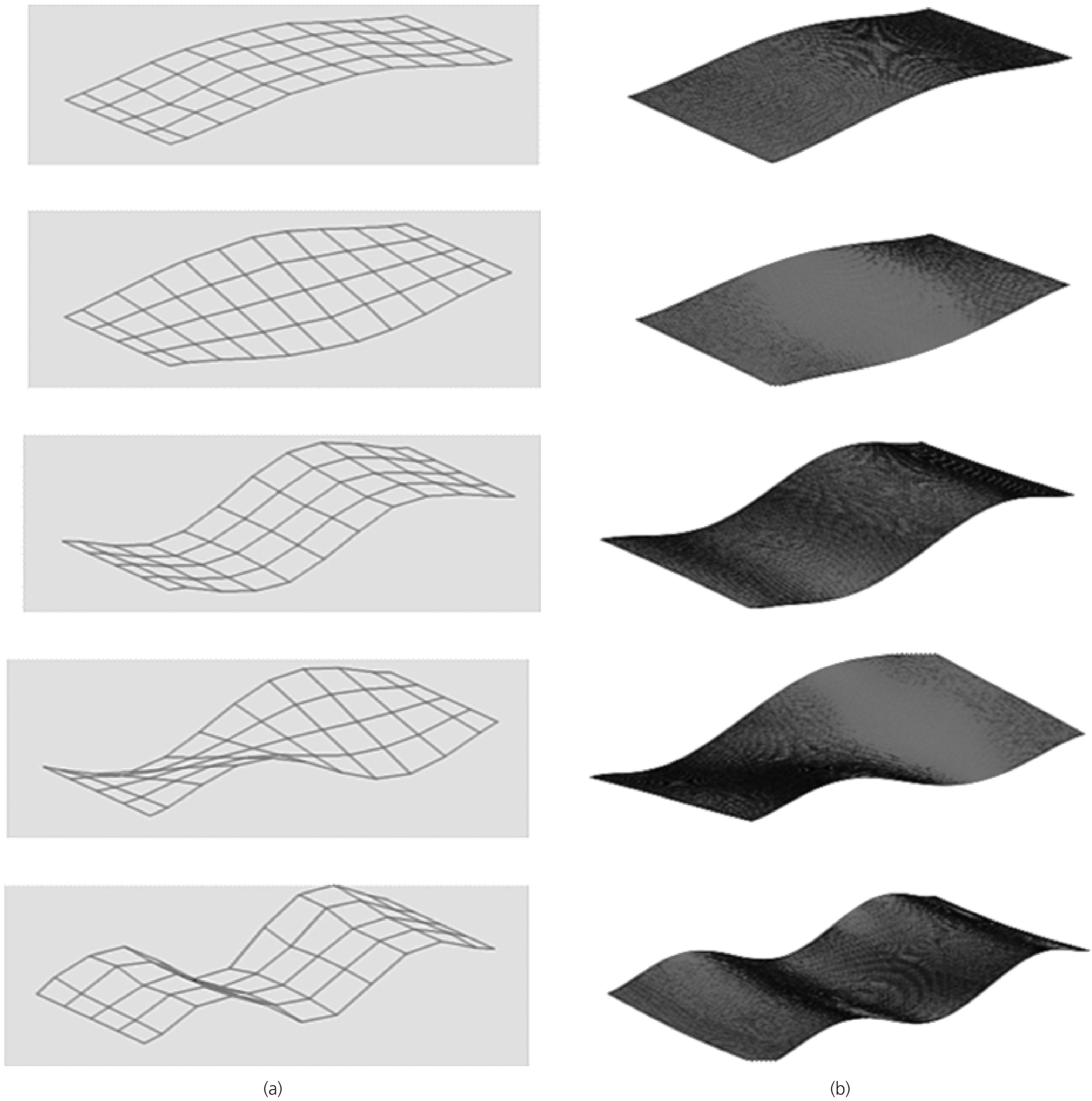


Figure 4. A general comparison of measured and simulated mode shapes for the undamaged plate: (a) measured; (b) FE simulated

until damage level 5. This is expected because the locations of the transverse cracks (D1–2) are close to the counter-flexure points of these mode shapes for the fixed-end plate, while the longitudinal cracks (D3–4) have little effect on the stiffness about the transversal axis.

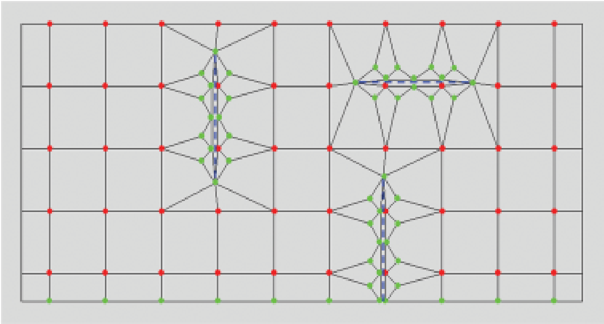
(*b*) For the converse reason, the second bending mode (mode 3) is much more sensitive to the transverse cracks; it exhibits a reduction of the frequency by 3·3% when D2 is introduced, and a further reduction of about 2·5% and then 8% when D5 and D6 occurred, respectively. Similar to the other bending modes, the second bending frequency exhibits little change (increment) when the longitudinal crack is introduced at D3–4.

(*c*) The torsional modes (total mode 2 and 4) are not sensitive to the cracks within the plate, but they (especially the second torsion mode) appear to be significantly more sensitive to cracks cutting through the edge of the plate.

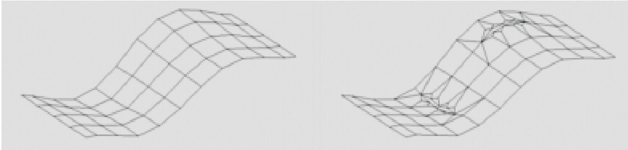
(*d*) The abrupt change in the case of D6 may be interpreted as a result of a significant modification to the mode shapes due to such a severe edge crack, as can be observed from the measured mode shape shown later (Figure 6).

4.2 Measured mode shapes

Figure 4 shows the extracted mode shapes of the undamaged test plate. These plots were constructed using only the regular grid points as indicated in Figure 1. Shown in the figure are also modes calculated using the FE model, which will be described in detail later together with an assessment of the error margin in the measured mode shapes. The shapes of these modes of vibration in the undamaged plate help to explain the differences in relative sensitivities of different modal frequencies observed above. Namely, natural frequencies are most greatly affected by damage when it occurs in an area of high curvature in the corresponding mode shape. For example, mode shape 3 (M3) is observed to have greater curvature in the region where D2 occurred than mode shape 1. Therefore, M3 is more sensitive to damage in this area. The measured mode 5 is found to be the third bending mode and as such would have been expected to show higher sensitivity to damage applied in a transverse direction: D1 and 2. However, upon further inspection this damage is found to be in an area of low curvature in M5; hence the insensitivity. The lack of response of modes 2 and 4 to damage D1–4 is attributable to their torsional shapes. However, these torsional modes were sensitive to D5 and 6, owing to their significant effect on the torsional stiffness in the surrounding area.



(a)



(b)

Figure 5. Measurement grid for cracked plate and improvement in measured mode shapes: (a) arrangement of additional measurement points; (b) measured mode shapes for D4. Left = regular grid; right = enhanced grid

In addition to plots for the undamaged test plate, mode shapes were extracted at every stage of the progressive damage application. While the 50 grid accelerometers were suitable to measure regular mode shapes, it was clearly difficult to capture the detail at local regions using this sparse grid. To examine how effectively a denser sensing grid could help map up changes around the location of crack damage, a number of additional measurement points were added. Herein points were only added around the known crack locations, but in practice this could represent an overall denser array of measurement points when the location of damage is not known. The sensing grid for damage scenario D6 is shown in Figure 5. Red (dark) dots represent the regular grid accelerometers; green (light) dots represent additional accelerometers and the blue dashed lines show locations of damage. The row of accelerometers along the bottom edge of the plate was added with the introduction of damage D5.

For a general comparison, Figure 5(b) shows the difference between the second bending mode shape plotted using the regular and additional measurement points as compared to that plotted using only the regular grid, for damage D4. It can be seen that the more refined sensing mesh does exhibit certain irregularity around the damage location. Here, one side of the crack is seen to rise while the other side falls (not clearly visible from the 3D plot owing to relatively small deflections). In conjunction with the earlier observation of generally small change in modal frequencies up to this level of damage, the above observation indicates that for the detection and diagnosis of crack damages in a plate component, a sufficiently dense measurement grid would be necessary.

Figure 6 illustrates the measured mode shapes for D2, D4 and D6, respectively. A general inspection tends to suggest that cracks within the inside area of the plate (D1–4) do not significantly change the mode shapes, although certain modification in the local area around the crack does appear. On the other hand, a crack cutting through the edge of the plate appears to introduce an abrupt change in the continuity of the mode shape over an extended area around the crack location. It is noted that after the introduction of the damage D4, the measured mode 5 tends to exhibit a combined longitudinal and transverse bending profile.

4.3 Graphical description of mode shape changes owing to damage

The plots of mode shapes were essential in ascertaining which mode each natural frequency belongs to, especially with the staging-up of damage as the mode order could switch between two different damage scenarios. Because of the relatively low precision in the measured mode shapes (to be discussed further in Section 5), as well as the low spatial resolution, which is intended to represent a practical measurement situation, in the present study no attempt is made to evaluate the mode shape derivatives, such as mode shape curvature, in relation to the damage. Instead, a direct mode shape contour plot is examined to see whether such plots could assist in a quick assessment of the mode shape data.

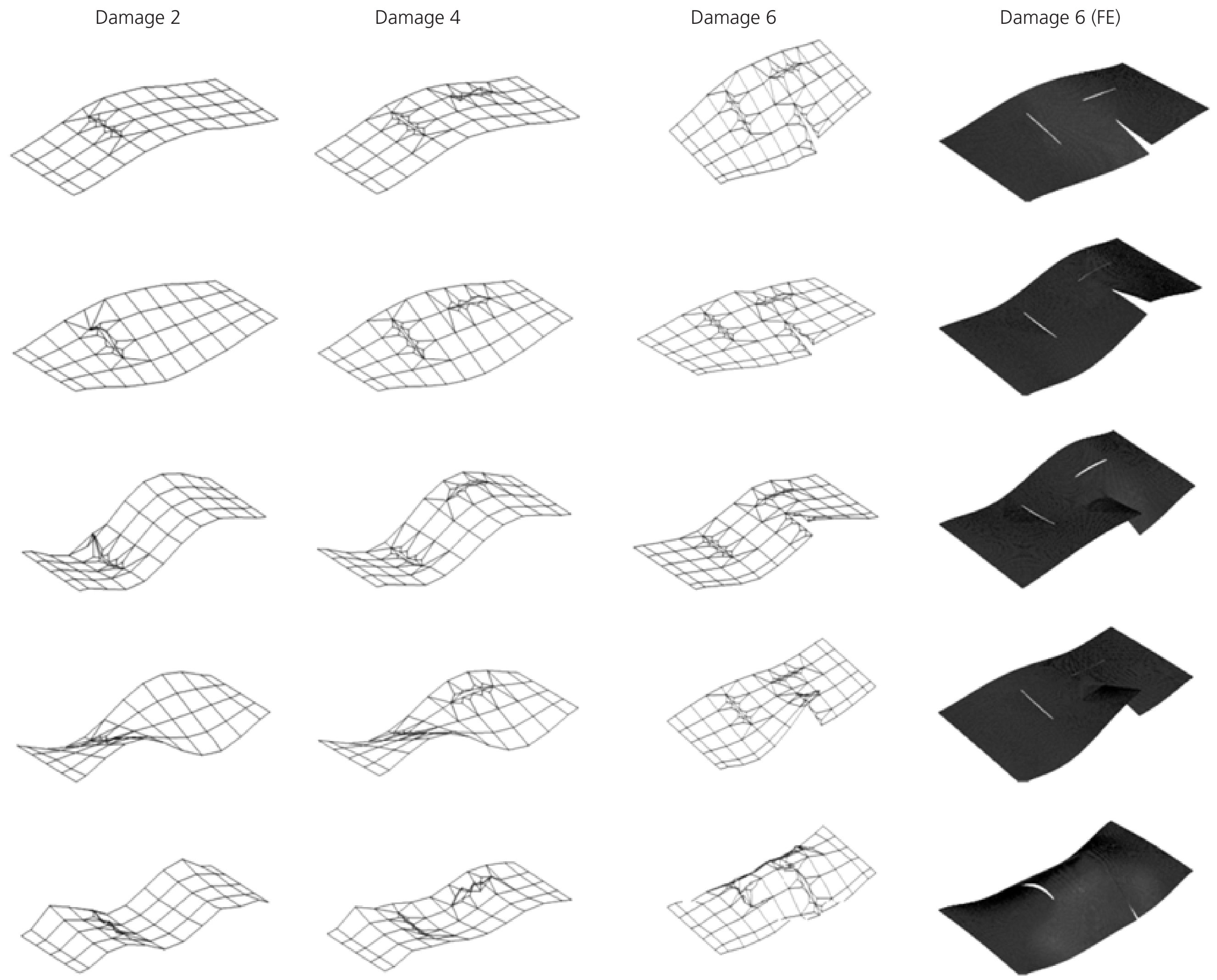


Figure 6. Measured mode shapes for D2, D4 and D6 (top to bottom: modes 1 to 5)

Only data collected from the grid accelerometers were used for plotting the contours, and the magnitudes of deflection are plotted here: that is, no account is taken of the phase of the mode. Dark purple indicates small deflections, while blue signifies small deflections. All mode shapes were normalised so that the quadratic mean (root-mean-square, or RMS) of the modal deflections equals 1·0.

The plots in Figure 7(a) show the contours of the experimentally acquired mode shapes of the undamaged test plate. Modes 1, 3 and 5 are seen to be longitudinal bending modes, while modes 2 and 4 have torsional shapes. It is possible to identify the shape of modes from these plots, but there are obvious errors in the plotted shapes: undamaged mode shapes for a symmetrically stiff slab should, in turn, also be symmetrical.

The contours for the damage D4 and D6 scenarios are shown in Figures 7(b) and 7(c) respectively. For damage D4, distortion in the mode shapes is visible only in model 5, and this is consistent with the observation of a change of the measured mode 5 towards a combined longitudinal and transverse bending profile from Figure 6. For D6, apparent distortion occurs in both modes 4 and 5. The generally slight alteration of the mode shape contours in other modes, even with a degree of damage such as D4 and D6 in the present case, tends to suggest that the mode shape information at this level of resolution will not be of much further use regardless of how sophisticated an inverse identification procedure is used.

5. Finite-element analysis and correlation with test results

A FE model can serve various purposes in a model-based structural identification/damage detection investigation. In a

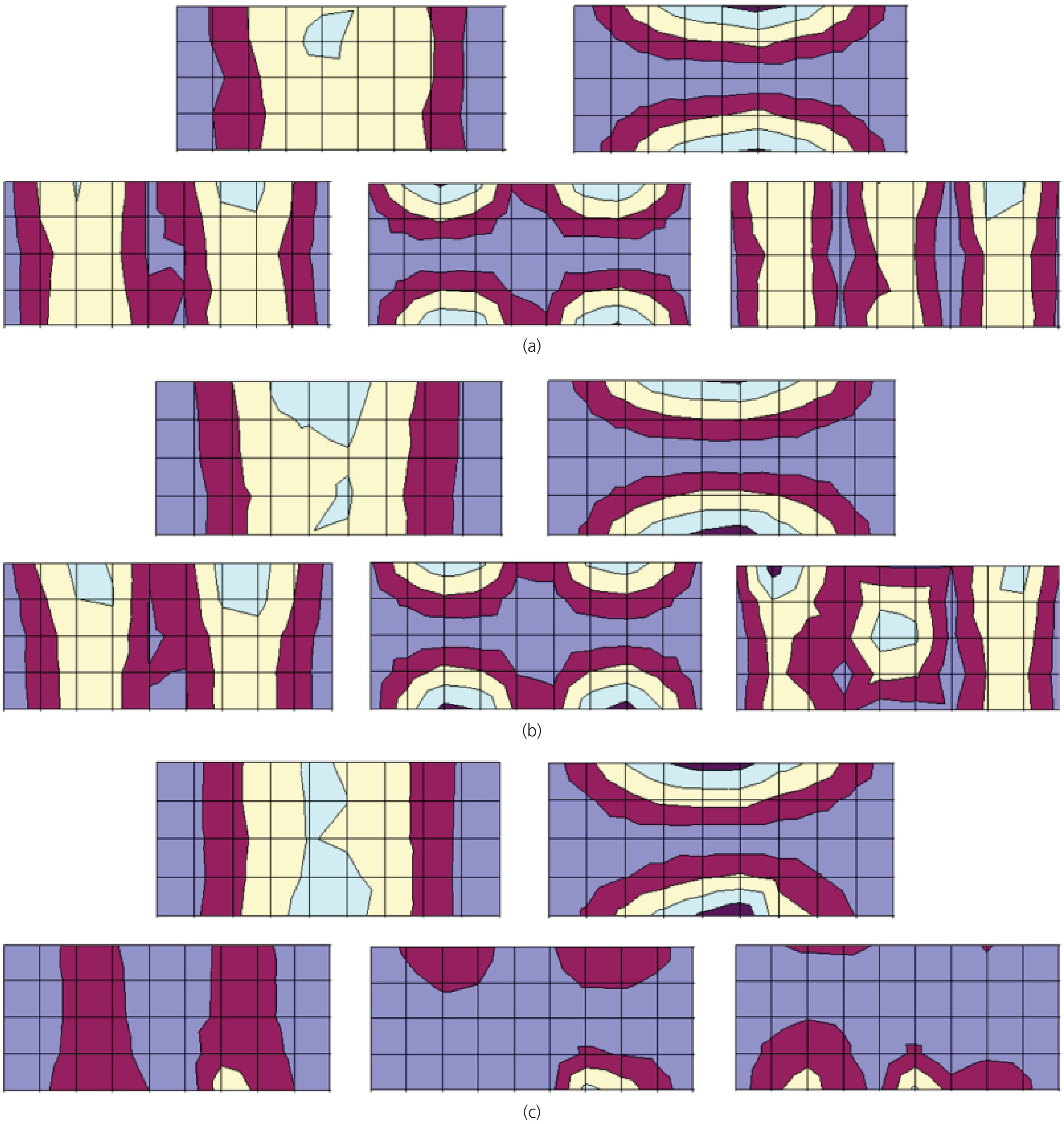


Figure 7. Experimental deflection contour plots (M1 and M2 first row, M3 → M5 second row): (a) undamaged plate; (b) after introduction of D4; (c) after introduction of D6

broader classification, the use of an FE model may be divided into two categories

(*a*) forward application, in which the FE model can be used to evaluate the possible variation of the modal parameters owing to various structural changes in the structural system
(*b*) inverse application, in which the FE model is used to represent the real physical system by way of an inverse parameter adjustment, or FE model updating, so that the FE-predicted response matches the measured counterparts.

In the present study the FE model is applied mainly for the category (a) purpose, although a limited updating of the FE model will be incorporated to facilitate comparison with the experimental results.

5.1 Modelling considerations

Two different types of FE models were considered, one using solid brick elements, and the other using shell elements. In both model explorations, a mesh convergence study was carried out to ensure the adopted FE models themselves are sufficiently accurate. As the thickness of the plate was small and only cut-through cracks needed to be simulated, use of conventional shells was deemed to be sufficient. Finally the 1000 × 500 × 3 mm test plate was modelled using a mesh grid of 5 mm-squares of S8R (ABAQUS) shell elements. The thickness of each element was set to 3 mm and material properties followed those of aluminium. The material properties of aluminium used in the FE model of the plate were: Young's modulus = 69 GPa, Poisson ratio = 0·33 and density = 2600 kg/m^3. Figure 8 shows the first six mode shapes of the final undamaged mesh. The corresponding modal frequencies are 16·51, 26·63, 45·52, 61·20, 81·90 and 89·50 Hz respectively.

5.2 Examination of general effect of crack damage on the modal properties of plate

In the FE model, crack damage can be simulated by removing a row of elements so that a 'slot' appeared through full thickness of the FE model. The first series of scenarios was focused on the effect of the location of a transverse crack on the slab modal properties. A transverse crack of length about 200 mm, that is 40% of the plate width, was centred on the plate and shifted along the length of the plate. Results (not shown) confirm that the location of damage has a marked effect on reductions in modal frequencies; the magnitude of the reduction in frequency is closely related to the mode shape curvature at the location of damage for a particular mode.

In order to assess the sensitivity of the modal frequencies of the plate to the degree of damage, a series of FE analyses was run with differing crack lengths. Figure 9(a) illustrates the variation of the frequencies for the first six modes with increase of the crack length at the mid-span of the slab. It can be observed that (a) up to a crack length of 50% the entire section width, the reduction in all the natural frequencies is not more than 6%, and (b) beyond this level of crack length, most modes show a much steeper reduction in the frequencies.

A close examination of the mode shape reveals a significant change in the mode shape as the crack propagates; as shown in Figure 9(b), the initial third bending mode (mode 6) increasingly involves bi-axial bending in the present one-way slab configuration. This signifies that, if mode shapes were not tracked as damage was incrementally applied, it would have been very difficult to match the damaged mode shapes to their undamaged counterparts in a plate-like structure.

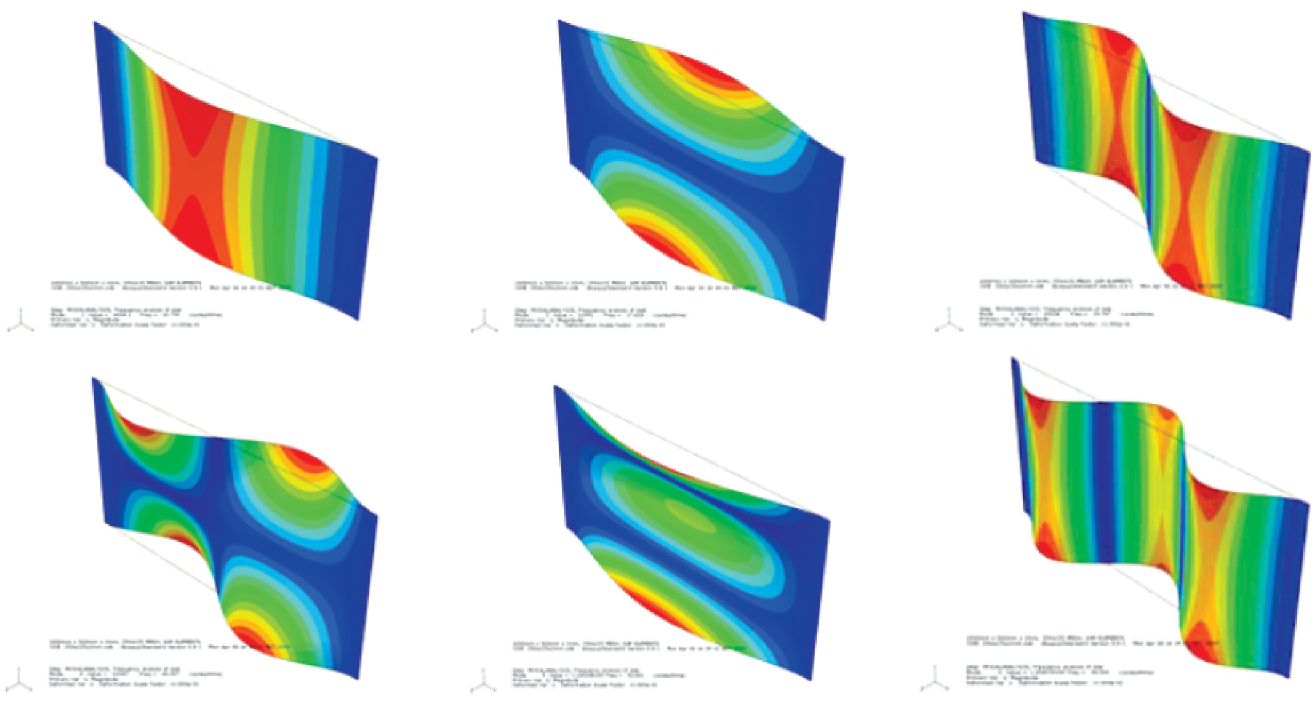


Figure 8. Computed mode shapes. Top left = M1, bottom right = M6

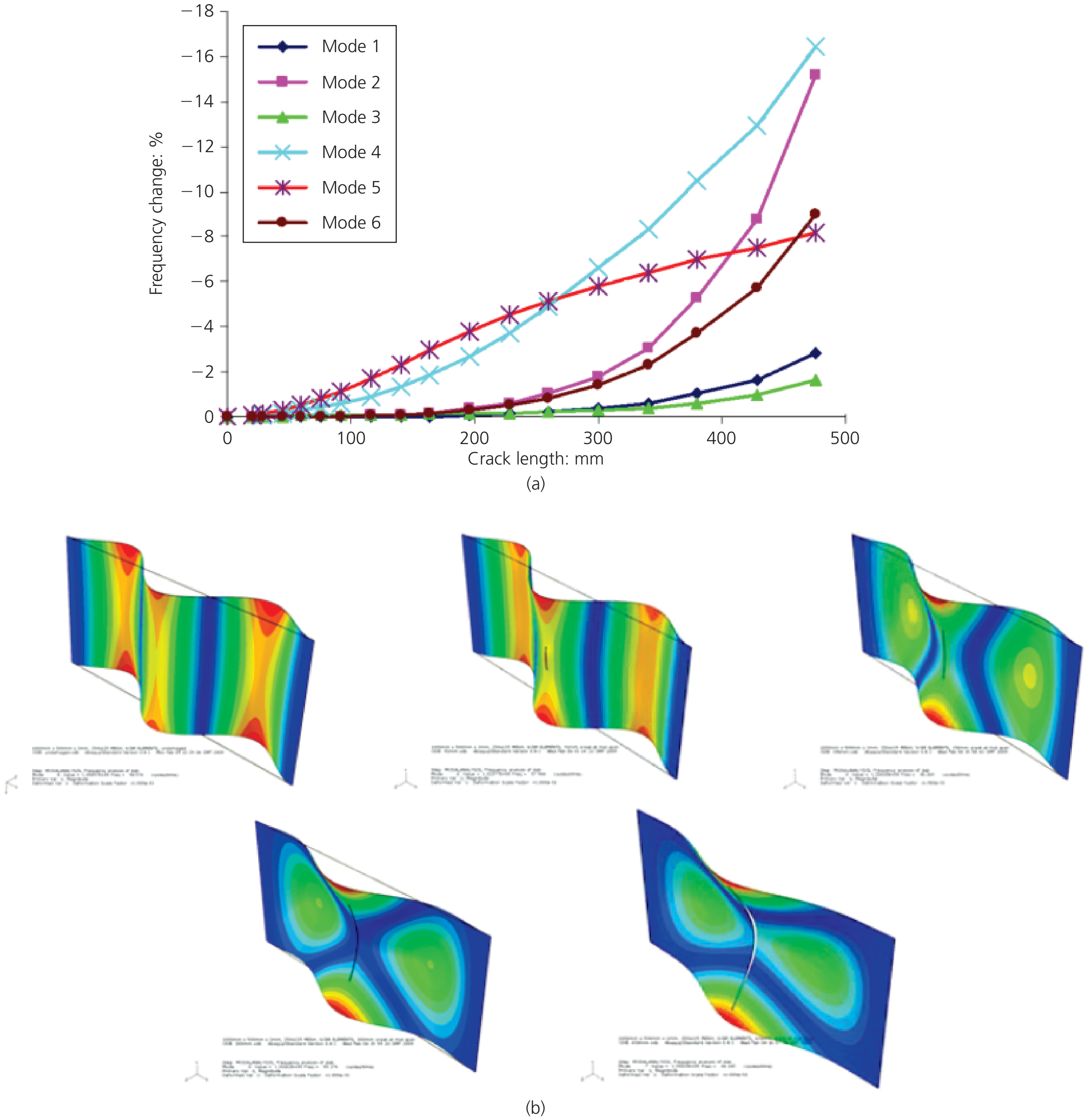


Figure 9. Variation of modal frequencies and mode shape (mode 6) with increase of crack width at mid-span: (a) frequency reduction from undamaged; (b) variation of mode-6 shape with increase of mid-span damage

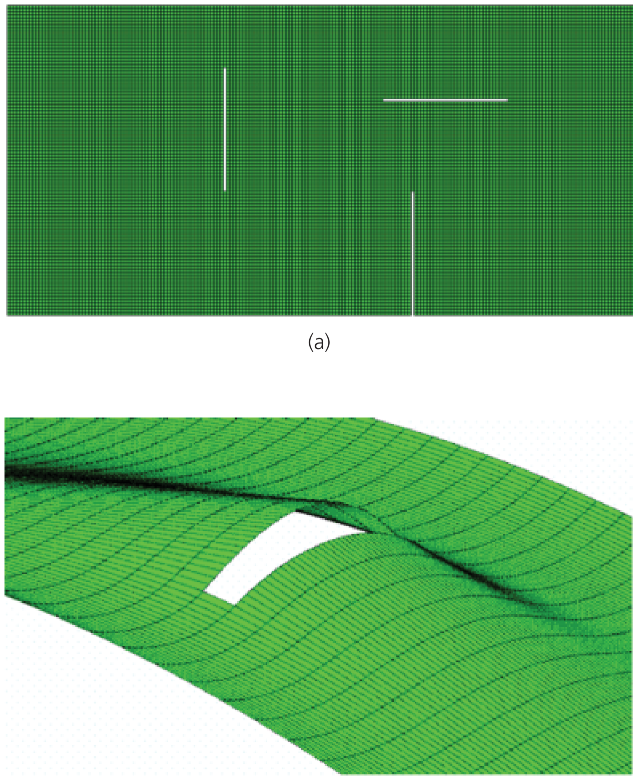
5.3 Simulation of the test plate and progressive damage

The basic FE model described in the previous section is employed to simulate the laboratory test plate and the effects of the various damage scenarios on the measured modal parameters. Although a detailed inverse procedure for the FE model updating (parametric identification) is not attempted in the present study, the FE analysis provides a vital means for examining the sensitivity of the modal properties to damage and assessing the margin of errors in the measured modal data (mode shapes in particular) from the laboratory tests.

Before the FE model was used to simulate the various damage scenarios, a gross FE model updating (calibration) was performed so as to ensure that the basic FE model closely represented the test plate in its pristine state. This was achieved by matching the FE-predicted natural frequencies to the measured counterparts. Table 2 shows the measured modal frequencies in comparison with the predicted frequencies using the FE model. As can be seen, the predicted frequencies using the initial FE model with perfectly fixed ends are markedly higher than the experimental frequencies, indicating a grossly stiffer structure than in the real test structure. Inspection of the test plate and test set-up revealed that little uncertainty existed with the physical properties and the geometry of the undamaged plate; however, owing to an imperfect clamping arrangement, the supports provided by two channel beams at the two ends of the plate appeared to have some degree of flexibility.

To represent the effect of such non-rigid support conditions in the FE model, a strip of virtually rigid zone was added at both ends of the plate, and a set of rotational springs were introduced to connect the plate end to the fixed support. For totally fixed ends, the spring stiffness would approach infinity. Two variable spring constants are considered (same for both ends); one represents the bending stiffness of the support and another represents the torsional stiffness. The spring constants are tuned, starting from very large values, until a satisfactory match of the FE-predicted and experimental natural frequencies is achieved. As shown in Table 2, the accuracy of the predicted frequencies using the updated FE model as compared with the test results is within 2%.

The progressive damage scenarios tested on the lab model, described in Section 3.1, were replicated in the FE model in a step by step manner according to the same schedule described for the lab test plate. Figure 10 shows how damage was modelled within the FE mesh for the final damage scenario. The computed mode shapes using the FE model for the undamaged and damaged states of the plate are included in Figure 4. The results exhibit a good general match to their experimental equivalents.



(a)

(b)

Figure 10. Simulated cracks in FE model and calculated local mode shape: (a) simulated 'crack' in FE model (final damage pattern); (b) calculated mode shape for damage 1 and 2

The modal frequencies resulting from the damage are summarised in Table 1, and they are also shown in Figure 11. The variations plotted in Figure 11(a) are very similar to those obtained from the lab test. The plot of incremental changes in frequency in Figure 11(b) also shows similar patterns to those described for the test plate. The incremental changes give a greater insight into the sensitivities of different natural frequencies to the applied damage. As with the test plate results, the modes 1, 3 and to a lesser extent mode 5, were all seen to be

Mode	Experimental f_t: Hz	FE (initial) f_{a0}: Hz	$(f_{a0} - f_t)/f_t$: %	FE (updated) f_a: Hz	$(f_a - f_t)/f_t$: %
1 (bending 1)	14·51	16·51	13·8	14·62	0·76
2 (torsion 1)	24·68	26·63	7·90	25·12	1·78
3 (bending 2)	40·90	45·52	11·3	40·34	−1·37
4 (torsion 2)	55·49	61·20	10·3	55·44	−0·09
5 (bending 3)	79·93	81·90	2·46	78·82	−1·39

Table 2. Differences between FE and experimental modal frequencies

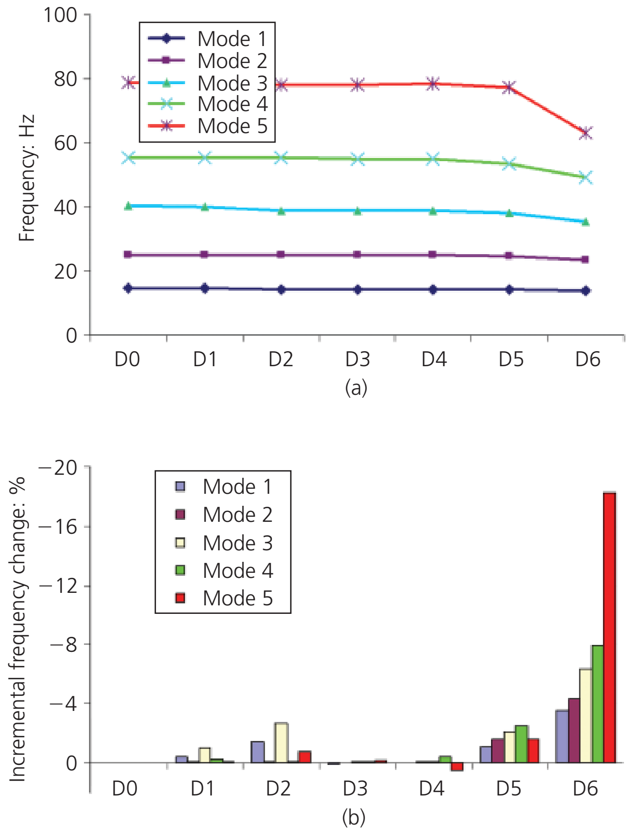


Figure 11. Variation of FE-predicted natural frequencies with progression of damage: (a) variation of FE-predicted natural frequencies; (b) incremental change of FE frequencies

relatively more sensitive to damage D1 and 2. However, for D1 the maximum frequency reduction is still not more than 1·0% (mode 3), and for D2 the maximum cumulative frequency reduction is just about 3·6% (incremental reduction 2·5%). Damage D3 and 4 are observed to have little effect on any modes owing to a lack of cross-damage curvature. Similar to the experimental results, all modal frequencies are greatly reduced by D5 and 6, with sensitivity increasing with modal order.

5.4 Assessment of margin of errors in the measured mode shapes

The FE model after the correction of the boundary conditions can be regarded as a good representation of the test plate, especially in terms of the mode shapes. Thus, using the FE computed mode shapes as reference 'exact' results, an assessment of the margin of error in the measured mode shapes can be made.

For this purpose, the mode shapes are normalised with respect to the quadratic mean (root-mean-square, RMS), as has been mentioned in Section 4.3, so that the RMS of the normalised mode shape equals unity. Such a normalisation avoids the normalised mode shape deflections being susceptible to errors at a single point, such as in the case where a normalisation is done with respect to the maximum modal deflection. By checking the deviation of the normalised measured mode shapes against their FE-predicted 'exact' counterparts, an array of errors at individual mode shape grid points, or error vector, can be obtained. The RMS of the error vector is then used as an indicator of the overall error for the particular mode shape. Considering that the normalised mode shape has the RMS equal to unity, the above RMS of the error vector can also be interpreted in terms of an overall percentage error on a basis of 1·0.

As an example, Figure 12 plots the measured and FE-predicted mode shapes (mode 1 and 3) and their difference for the plate at damage D3. It can be observed that, although the measured mode shapes exhibit a good resemblance to their 'exact' counterparts, the errors in the individual mode shape deflections lie in a range of $-0{\cdot}2\sim0{\cdot}2$. The overall magnitude of the errors, as represented by the RMS of the error vector, is found to be 0·08 (or 8%) and 0·10 (or 10%) for mode 1 and mode 3, respectively.

Similarly, the measured mode shapes for the undamaged and other damaged scenarios are checked against their respective FE counterparts, and the overall margin of error is calculated for each mode under each damage scenario. The results may be summarised as follows.

(*a*) The measured mode 1 (first bending mode) and mode 2 (first torsion mode) exhibit a similar level of error, in the range 5~9% in all damage scenarios.
(*b*) The measured mode 3 (second bending mode) and mode 4 (second torsion mode) also exhibit a similar level of error, in the range 8~14%.
(*c*) The measured mode shapes for mode 5 exhibit a much larger error margin, mostly in a range of 20~40% in different damage scenarios. Besides the expected increase in errors in such a higher order mode, the influence of bi-axial bending on mode 5 (and 6) introduced additional complication.
(*d*) The levels of damage in the plate do not appear to affect directly the accuracy in the measured mode shapes.

6. Conclusions

Testing on the laboratory model plate showed that the natural frequencies in a plate-like structure could be identified with a high degree of accuracy. In general, it was possible to identify natural frequencies in the plate for the first 5–6 modes with an error well below 1%. In spite of this accuracy, the natural frequencies in such a plate component are generally insensitive to the crack-induced structural changes. Slightly higher sensitivity at certain mode frequencies could occur depending upon the location and orientation of the crack; longitudinal bending frequencies are more sensitive to transverse cracks near the larger curvature positions, but are insensitive to cracks along the longitudinal axis.

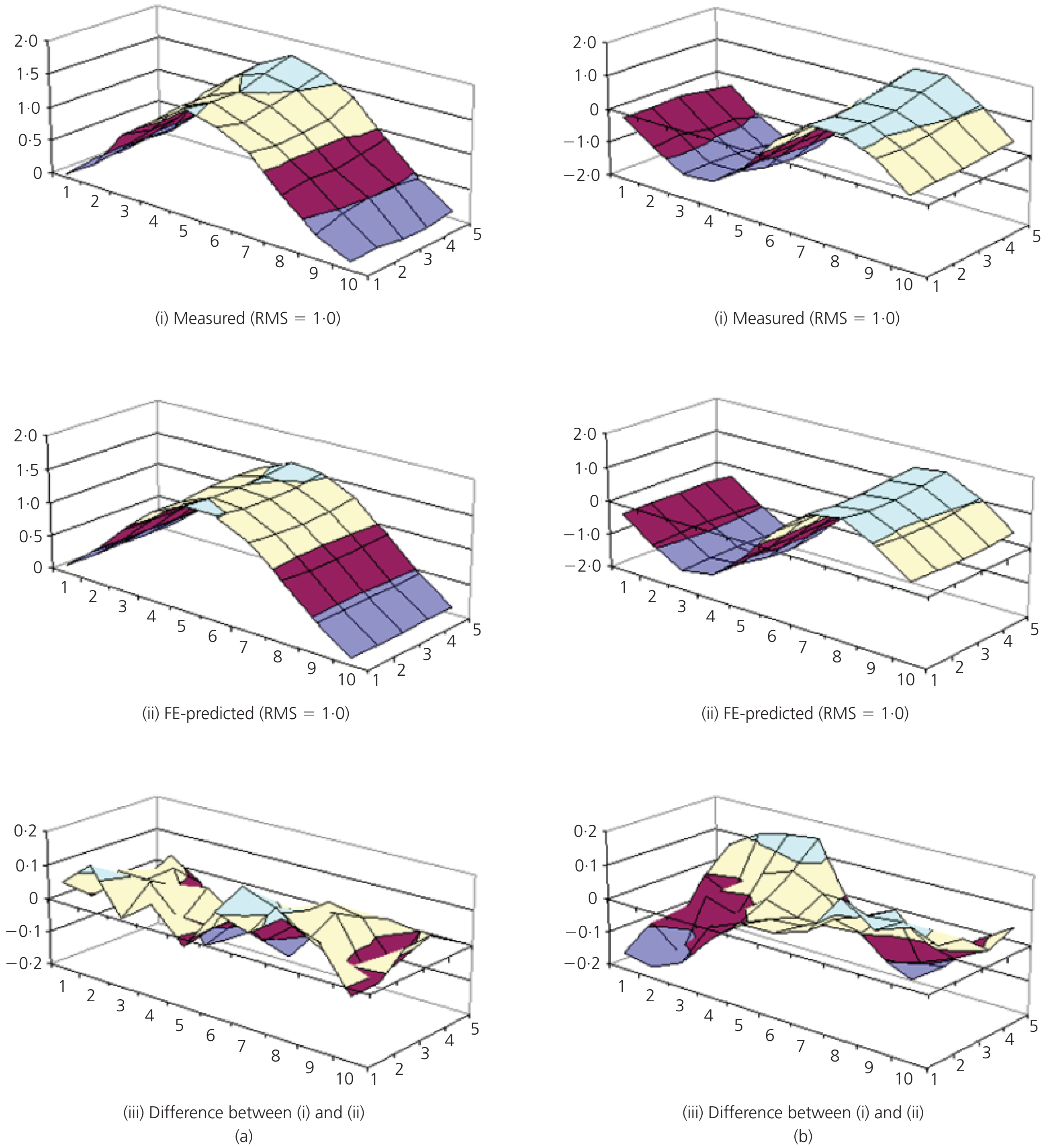


Figure 12. Typical comparison between measured and FE-predicted mode shapes (mode 1 and 3, damage D3) for estimation of margin of measurement error: (a) mode 1; (b) mode 3

From the testing, it was possible to extract clear mode shapes for the first 5–6 modes using a measurement grid of 10 × 5 nodes. However, it appeared to be difficult to track crack-induced variation from the mode shapes with this level of resolution, even when an internal crack (not through the edge) extended to 40% of the plate width. With an enhanced density of measurement points around the crack location to about three times the above resolution, the discontinuity (abrupt changes) owing to a major crack appeared to become detectable from the mode shapes.

The above observations are confirmed by the corresponding FE analysis. The FE parametric results further indicate that even with error-free data, the first few natural frequencies would be insensitive to major cracks extending up to an order of 40% of the plate width, unless a crack cuts through the plate edge.

By comparing the RMS-normalised measured mode shapes and their FE-predicted counterparts, an assessment of the margin of error in the measured mode shapes is made. It is found that for mode 1 and 2 (first bending and first torsion mode) the margin of error was in a range of 5∼9%, and for mode 3 and 4 it was in a range of 8∼14%, while for mode 5 (and higher) the error was markedly larger.

The study reported in this paper did not attempt to involve any specific inverse procedure actually to identify the damage from the measurement data. However, the results provide a clear benchmark for a quick assessment on the feasibility of monitoring and detecting crack damage in a plate-like structure under a certain measurement scheme before any specific inverse procedure may be engaged. From a more general perspective, this study tends to suggest that modal analysis in a classical framework could face difficulty when applied in the damage assessment for real-life structures, owing fundamentally to the limited availability of modal data and the large measurement errors contained in the mode shapes. Innovative solutions need be sought to enable the measurement of higher order, diversified modal information.

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