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An experimental investigation on the effectiveness of damping changes for damage detection in a Fibre Reinforced Plastic Plate

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Abstract

Fibre reinforced plastics (FRP) are extensively used because of their high specific strength and stiffness. However, throughout their service life, such materials are susceptible to damages, which when accumulated may result in catastrophic failure. Studies on effects of stiffness loss due to damage has been exercised by quite a large number of researchers but very less investigators have involved the variations in dissipative behaviour in combination with such stiffness loss. However, damage in these structures not only causes local reduction of stiffness but is also observed with increased dissipation behaviour. One of the most convenient ways to carry out health monitoring exercise to detect damages is to conduct systematic vibration testing. The present study investigates the likely changes in natural frequencies and mode shapes of a rectangular FRP composite plate along with damping factors due to the induced damage. The FRP plate considered has been modal tested and dynamic responses i.e., natural frequencies, mode shapes and modal damping factors are derived through curve-fitting technique from the frequency response function measurements. In this study, changes in dynamic responses due to a locally induced damage in the FRP plate is studied. For this, in order to maximize the effects of local reduction in the stiffness on the modal parameters, a partial-cut is provided in a localised region of the plate in the first damage case. In the second damage scenario, the partially-cut area has been filled with epoxy resin matrix to create a region with localised change in material properties and with limited stiffness loss. Damping changes has been observed to be significant and more sensitive than variations in natural frequencies and mode shapes. The study suggests that damping parameters along with stiffness changes together can be put into practice to develop an effective vibration-based health monitoring scheme

Keywords: FRP, modal analysis, damping, damage detection.

1. Introduction

Fibre Reinforced Plastics (FRP) are widely used in weight sensitive applications, such as in the field of aerospace, marine, automotive etc. because of its high specific strength and specific stiffness. These infrastructure facilities made of FRP are supposed to operate over long period of time under exposed environmental conditions and may deteriorate considerably. Throughout their service life, such laminates are susceptible to damages, resulting from mechanisms like matrix cracks, fibre-matrix debonding, fibre breakage etc. Accumulation of these initial damages can propagate to cause a catastrophic failure at global structural level. Therefore, regular and systematic inspection is necessary.

Practicing engineers as well as researchers has been taking interest in the field of structural damage detection for decades to develop a robust damage identification process. Any novel technique thus developed must be reasonably sensitive to small level of damages. One such popular global damage detection method is vibration-based damage detection method [1-3]. It puts into practice the traditional vibration testing equipment to extract modal dynamic responses of the structure from measured input force and resulting accelerations. The basic philosophy behind such vibration based structural damage detection method is that modal parameters i.e., natural frequencies, mode shapes, modal damping factors, frequency response functions are sensitive to changes to the physical properties of the structure.

Results obtained using such techniques differ in appearance for different structures having differing stiffness and dissipation behaviour, thus requiring individual investigation.

FRP structures can be tailored to varying stiffness differences in orthogonal directions, for example, plates having unidirectional fibres have a completely separate look of the response characteristics as compared to a FRP plates with woven roving type of quasi-static fibres.

In most of the established methodologies of damage identification in structures, natural frequencies, mode shape and mode shape curvatures were primarily used [4-8]. Some studies have also observed alterations in the dissipative properties due to induced damage. Williams and Salawu advocated that damping parameters can be an indicator for damage in conditions where frequency and mode shapes deemed unresponsive to damage [9]. Modena *et al.* measured vibration responses before and after the introduction of cracks in a reinforced concrete structure and

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found that the difference in the modal damping ratio was more significant than the frequency changes [10]. Daneshjoo and Gharighoran studied variation in damping ratio of cracked reinforced beams introduced by static point load [11]. The damping ratio was found to increase with increasing load. Studies have also been carried out on damped response of fibre reinforced composites subjected to damage. Kyriazoglou *et al.* correlated the variations in specific damping capacity with damage severity in composite beams [12]. In a study done by Kıral *et al.* , it has been observed that although the variations in natural frequencies due to damage were inconsistent, the damping ratios always increased with damage severity [13]. Montalvão *et al.* formulated a damage indicator for damage localisation based on damping changes and was implemented for detection of delamination in carbon fibre-reinforced plastic plate [14]. Kostka *et al.* proposed an in-situ diagnostic procedure for damage identification by monitoring changes in modal damping ratios caused by local changes in damping [15].

In the present investigation, a rectangular FRP plate having woven roving fibres used within polyester resin matrix has been considered. Experimental modal analysis has been performed on the FRP plate to extract the modal properties, i.e. frequencies, mode shapes and modal damping factors before and after inducing damage. The changes in the dynamic responses due to the induced damage are then correlated to find their effectiveness for damage detection.

2. Experimental Investigation

In the present study, a rectangular woven roving fibre-reinforced plastic (FRP) plate with average thickness of 10 mm and size 400mm x 300mm has been experimentally investigated. The FRP plate is suspended by means of elastic chords from a rigid frame to replicate free- free boundary condition. Modal test has been performed on the plate by imparting impact excitation force through an instrumented hammer (type 8206-002 of B&K) and simultaneously measuring the acceleration responses through an accelerometer (Delta Tron 4507 of B&K).

The measured force and response time signals have been converted to frequency domain using Fast Fourier Transforms (FFT) through spectrum analyzer (3560-C-L4 of B&K). The frequency response functions (FRF) are processed utilizing PULSE Labshop software by dividing the Fourier transforms of the responses with the Fourier transforms of the force signals [16]. The measured FRFs were then curve-fitted to obtain the natural frequencies, mode shapes and modal damping factors using the software MEScope [17]. The schematic diagram of the modal test is described in Fig. 1.

Both the undamaged plate and the damaged plates are modal tested and results are compared to observe the changes in the responses. It may be noted that due to the almost equal elastic moduli of the woven roving fibres in orthogonal directions, the peaks in FRFs occur in much more condensed manner as compared to any unidirectional laminate, thus the frequency range could be reduced for improved accuracy. By keeping the frequency range within 0-600 Hz, five modes have been considered for the study. The plate is discretized into a grid of 6x6 elements to obtain the measurement points. There are 49 measurement points to cover the entire spatial domain. Single point measurement system with roving impact hammer has been used for the modal test by keeping the accelerometer fixed at measurement point number 34. The position of the induced damage on the FRP plate considered for the study is shown below in Fig. 2. The actual experimental plates are shown in Fig. 3.

In this study, two damage cases have been considered. For the first damage case, a partial cut is provided to a local region involving four elements (element no. 8,9,14,15) as shown in Fig. 3(b). A one-sided cut was made to a depth less than the thickness of the plate from the top. For the second case, an attempt has been made to create a region with different material (thus damping) properties and minimum stiffness loss by filling up the partially cut area with epoxy resin as shown in Fig. 3(c). Epoxy resin is selected so that the freshly introduced material can be easily integrated with the old component matrix. Modal test has been performed on the undamaged, as well on the same structure when damaged so that results are not affected from different samples of structures.

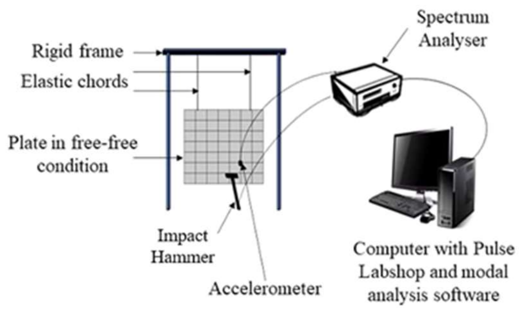


Fig. 1. Schematic diagram of the experimental modal testing set-up.

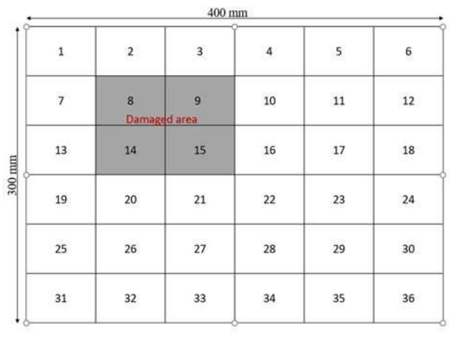
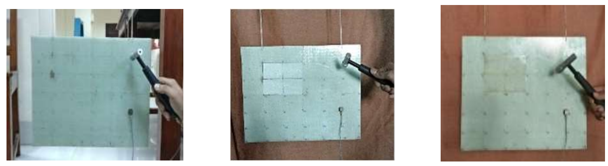


Fig. 2. Schematic diagram of the rectangular FRP plate with induced damage location.



(a) (b) (c)

Fig. 3. Experimental setup for modal test: (a) undamaged plate, (b) damage case-1, (c) damage case-2

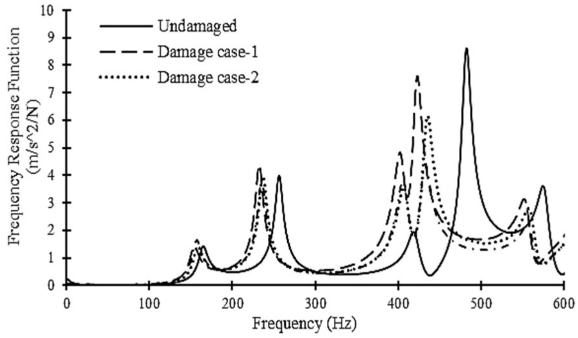


Fig. 4. Comparison of FRF curves of the undamaged and the damaged cases

3. Results and Discussion

The comparison of cross-point FRFs for the undamaged plate and the damaged plate is provided in Fig. 4. The cross-point FRFs are for an excitation given at point 17 with respect to the accelerometer position fixed at point 34. The resonant position of the FRFs represents the modal frequencies and the shifts in resonating positions in FRFs in damaged plates compared to the undamaged plate signifies the changes in modal frequencies due to the induced damage. They are found to be very small, although can be distinguished easily in figures, both in term of shifts as well as in FRF magnitudes.

From the measured FRFs, mode shapes have been obtained by curve-fitting process using MEScope software as shown in Fig. 5. Modal damping factors have been obtained using the standard half-power point method [18] using the same software. Percentage change in values of modal frequencies and the modal damping factors obtained from experimental modal analysis for the undamaged plate and the damage cases are compared in Table-1. It may be easily noted that for this FRF plate with woven roving, there is consistent decrease in stiffness and in turn, subsequent increase in damping.

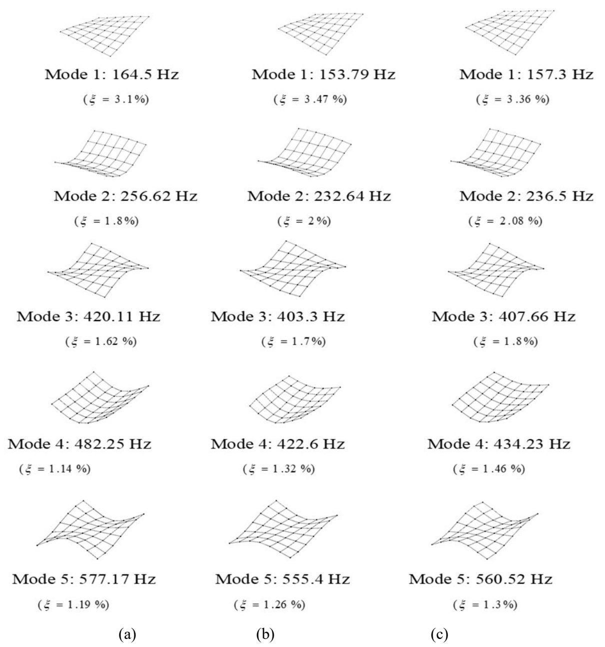


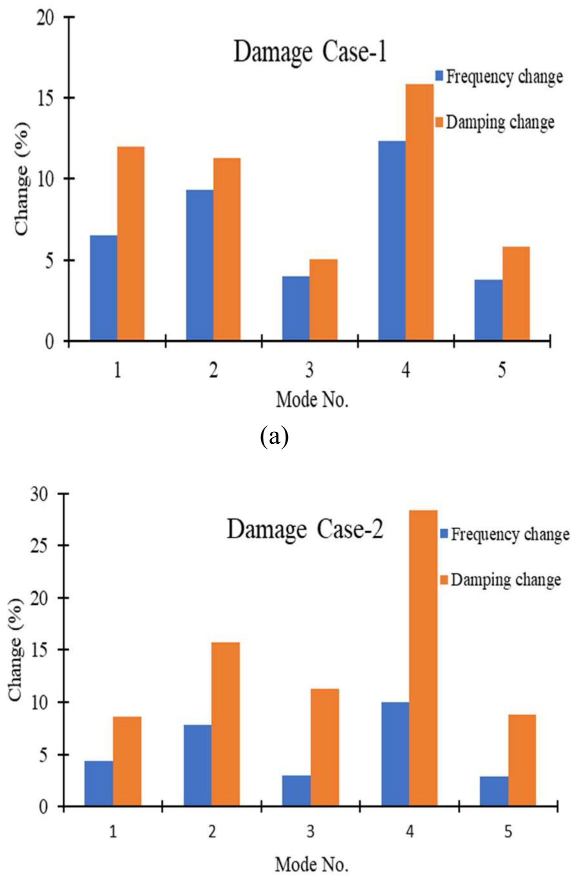
Fig. 5. Experimentally obtained mode shapes: (a) undamaged plate, (b) damage case-1, (c) damage case-2

Table-1. Experimentally obtained modal frequencies and modal damping factors.

	Undamaged		Damage case-1				Damage case-2			
Mode	Freq. (Hz)	Modal Damp. (%)	Freq. (Hz)	Diff. (%)	Modal Damp. (%)	Diff. (%)	Freq. (Hz)	Diff. (%)	Modal Damp. (%)	Diff. (%)
1	164.5	3.1	153.79	-6.51	3.47	12.01	157.3	-4.38	3.37	8.65
2	256.62	1.8	232.64	-9.34	2.0	11.33	236.5	-7.84	2.08	15.74
3	420.11	1.62	403.3	-4.0	1.7	5.03	407.66	-2.96	1.8	11.32
4	482.25	1.14	422.6	-12.37	1.32	15.82	434.23	-9.96	1.46	28.41
5	577.17	1.19	555.4	-3.77	1.26	5.83	560.52	-2.88	1.23	8.79

In damage case-1, a maximum decrease of 12.37% in modal frequency has been observed in mode no. 4 due to the local reduction in stiffness from the partial cut in the plate. Along with decrease in modal frequencies, an increase in modal damping factors has also been observed, with a maximum increase of 15.82% in the same 4^{th} mode. The variations in frequencies and damping factors for each mode are shown in Fig. 6(a). Thus, it can be seen that the variation in damping is at least similar in order with the changes in stiffness, hence the natural frequencies.

The damage case-2 scenario has been attempted to create a local change in material properties in the plate with minimum stiffness loss. In many earlier investigations, people just removed material thus changing the mass substantially, so the changes in frequencies which depends upon the relative stiffness change with respect to the mass changes was heavily affected. This is not the case in practice



(b)

Fig. 6. Percentage change in frequencies and modal damping factors for each damage case.

where actually damages occur due to formation of crack with almost no change in mass. In this case, the slight gain in stiffness has been reflected through the increase in modal frequencies from damage case-1. However, there has been a significant increase in modal damping factors compared to the changes natural frequencies. A maximum change of 28.41% in damping factor for the fourth mode has been observed whereas a variation of 9.96% in fourth modal frequency has been observed. The variations in modal frequency and modal damping factors for damage case-2 are compared in Fig. 6(b), which shows that damping changes have been more significant than natural frequencies. In both the damage cases, the fourth mode showed maximum variations in both frequency and damping, hence selected for this demonstration. The effect of size and location of damage can be established by conduction of a detailed further parametric study.

4. Conclusion

In this investigation, the viability of damping changes in comparison to changes in natural frequencies for rectangular woven-roving FRP composite plates for damage identification has been studied. The study observed damping parameters to be somewhat more significant than the expected variation in natural frequencies in most damage cases. However, unlike unidirectional composite plates, FRP plates with woven-roving plates has almost identical stiffness and perhaps, identical dissipation characteristics in orthogonal directions. The investigation assessed that a local damping mechanism in conjunction with a much more stable globally defined modal properties make the changes in both the stiffness and damping parameters enough sensitive to a local damage. Most model-based damage identification approaches incorporate elastic parameters such as mode shapes and natural frequency for quantifying stiffness loss as an indication of damage. The present study is novel in that sense that it suggests inclusion of damping measures into the possible damage sensitive parameter sets along with the usual frequency-based parameters for an overall effective damage identification strategy for FRP composite plates.

Disclosures

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