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Small delamination detection in carbon fibre reinforced polymer composite beam by NDT and vibration analysis

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Fibre reinforced polymer (FRP) composites have been prone to damages such as delamination, debonding, matrix cracking and fibre breakage. In this paper, detailed study has been carried out on determining the presence of small delamination in sub layers of carbon fibre composite beam using various non-destructive tests (NDT) and vibration signal analysis. We have concluded that ultrasonic and X-Ray Diffraction (XRD) tests have found to be more effective in detecting small delamination than X-Ray radiography and thermography tests. In the vibration test, we have observed that the natural frequency decreases and the rate of damping increases in delaminated carbon fibre composite beam as compared to composite beam without delamination. Besides, the fast fourier transform (FFT) results of vibration signal of delaminated beam have clearly shown higher harmonics and side bands. Finally, we have concluded that online vibration test can also be used effectively to detect presence of small delamination in FRP composites.

Keywords: Carbon fibre, Delamination, Non-destructive testing (NDT), Vibration test

1 Introduction

Carbon fibre reinforced polymers are extensively used in aerospace sector Katunin[1]. It is also being widely used now in automotive, defence, sporting goods, electronics and electrical, marine, biomedical industries Seo[2].This is due to their light weight, low cost, high strength to weight ratio and fatigue life as compared to other metals Park[3]. Besides having diverse application, damages such as delamination, debonding, barely visible impact damage Polimeno[4]. Beside, matrix cracking, fibre breakage, voids, porosity are inevitable during their manufacturing and service life. These damages degrade the strength and durability of the composites thereby making it prone to failure. Hence it is very much essential to understand the different damage prediction as well as detection techniques of composite with the advancement of different technologies. Several non destructive tests (NDT) have been carried out for the diagnostic monitoring of composites like X-ray Radiography, Ultrasonic Testing, X-ray Diffraction, IR Thermography *etc*. Unnporsson[5] have observed NDT methods can successfully use to fatigue damage evaluation and remaining useful life prediction based on acoustic emission and the electrical properties of composites. Andrews[6] have studied about activated carbon fibre composites for its specific use in environmental applications such as clean-up of flue gas and decontamination of ground water. They have performed three-point bend tests to determine characteristic properties like flexural modulus and yield strength. Riddick[7] have given details about type I failure of a carbon fibre reinforced composite in which the introduction of carbon nanotubes has improved the fracture toughness. Delamination detection in multi-layered composite materials was investigated by Bajaba[8]. Who however observed, there was a small effect on the frequency of multilayer component. Marques[9] have performed the analysis of delamination on carbon fibre based laminates. Results have shown a proper choice of selecting cutting speed, drill geometry or feed rate on the reduction of delamination. Sane[10] have done an investigation on the behaviour of a carbon fibres epoxy composite plate by making use of static pull loads involving analytical and experimental methods. Callioglu[11] have successfully investigated both numerically and analytically the subsequent effect of different delamination lengths and orientation angles on the natural frequencies of symmetric beams. The analytical method has been created utilizing Timoshenko's beam theory. The outcomes have compared with each other. When delamination length in the beam increased, the natural frequency showed a

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decreasing trend but the trend changes with the fibre orientation angle. Several contributions have already been made by different authors Lee[12], Borovkov[13] and Lingen[14] from time to time for experimental and numerical investigations into the behaviour of damaged multilayer composite structures. Sowjanya[15] have studied structural and vibration investigation of delaminated composite beams where analysis was done by varying the delamination length. The delamination effect on the modal parameters of different laminates is being presented by Della[16] Comparison of different NDT methods on detection of delamination with varied diameters and depths in composites is studied by Cheng[17]. Some researchers have also investigated the application of high-frequency waves in damage detection in laminated aero-structures which can be found in Pasquali[18,19], Muc[20] and Ochôa[21]. The use of vibration characteristics in structural damage detection has been studied by several researchers Rucka[22], Fan[23], Gallego[24] and Yang[25]. However most of the papers are based on the stress and strain analysis part to optimized mathematical model to deal with fracture study of composite structures is still a matter of great challenge for the research community. In this paper various Non-destructive Testing methods are carried out in order to find out the presence of delamination zone within the delaminated composite beam. Subsequently, the dynamic analysis of beam with delamination and beam without delamination in carbon fibre composite beam has been studied. The natural frequencies and damping rate in the delaminated and without damaged composite beams have been found experimentally.

2 Experimental Procedure

The six carbon fibre composite beams made from AS4 fabric are taken for experiments and Teflon strips are used between the layers to give small delamination. For the detection of delamination, experiments were carried out to find out the exact zone and depth of delamination. These experimental processes involve non-destructive Testing to keep the internal structure undisturbed and not to manipulate with the size of delamination. The specimens are carbon fibre composite beams which have a mass of 336 gram each and a density of 1.696 x 10^{-6} kg/mm³. The specimens have dimension of 300mm x 30 mm x 2.2 mm. The mechanical properties of carbon fibre composite taken are Young's modulus in three axis E_1 = 140GPa, E_2 = 8.963GPa, E_3 = 4.8GPa, modulus of rigidity G_{12} = 7.1GPa, G_{13} = 2.55GPa, G_{23} = 4.8GPa, and Poisson's ratio γ_{12} = 0.3, γ_{13} = 0.41, γ_{23} = 0.3 respectively. The following NDT tests are carried out on the specimens to detect small delamination.

2.1 X-Ray Radiography

X-Ray is used to detect internal defects or fractures in materials that allow X-Ray penetration, without having to manipulate the material. In this way, the material remains in the same physical condition before and after the test. Therefore, it is one of the NDT processes. In this research work, digital X-Ray Radiography was carried out to determine the delamination present in the carbon fibre composite beam. In this work, GE X-Ray machine is used.

2.2 Ultrasonic Inspection

Ultrasonic testing (UT) is used as NDT method in determining damages and defects of composite structures. Generally, there is conversion of ultrasonic signal into an electrical signal which is amplified and subsequent displaying on an oscilloscope Cantwell[26].Three forms of scans are available: A, B, C. C scan was performed as it was found to be suitable for delamination detection. In this paper, ULTRASONIX testing machine is used.

2.3 X-Ray Diffraction

X-ray diffraction takes place when any wave strikes an array of scatterers. When the spacing is equal between the scatterers and the impinging wave, diffraction is produced. In this experiment, the angle of incidence of X-Ray was varied from 10° to 80°. The scanning rate was kept at 5°/min. The specimen was tested using Ultrasonic testing and approximate delamination region was found out for XRD test in Shimadzu, Japan XRD Machine.

2.4 Thermography

This technique depends solely on the absorption and heat dissipation in a composite structure which is damaged. Generally active and passive thermography is used in which the former method involves an uninterrupted heat flow whereas the later involves a sudden rise in temperature on the surface of the component. Defects are detected by IR sensitive cameras. In this work the passive thermography is done using FLUKE (TI 32).

2.5 Vibration Test

This setup involves use of a carbon fibre composite beam as a cantilever, an accelerometer, connecting cables, FFT analyzer (OROS-34) and a laptop loaded with NV GATE noise and vibration analysis software. For free vibration test, the beam is clamped at one end, keeping a length of 275mm free and an accelerometer is mounted at the other end of the beam. The FFT analyzer collects the vibration data and shows it in the FFT plots in laptop display. In this test, the cantilever beam is given an initial displacement of 20mm vertically and released such that it vibrated freely and allowed to damped on its own. The corresponding vibration data is recorded in the laptop. Three sets of readings are taken, each using beam with delamination and beam without delamination. Further harmonic excitation test was conducted with the help of electro dynamic exciter to compare vibration spectrum of beam with delamination and beam without delamination as shown in Fig. 1.

3 Results and Discussion

First X-Ray radiography is carried out on the beam specimens the image is shown in Fig. 2.

The problem with X-Ray radiography is sometimes unable to detect very minute defects. Hence, other non-destructive processes have to be carried out to inspect the small delamination.

Then the specimen was tested with ultrasonic test for delamination detection. As shown in the Fig. 3, the test specimen with white marks shows the delaminated area detected by ultrasonic test device.

In the X-Ray diffraction analysis, it is found that the carbon fibre composite beam has lesser crystalline intensity in the areas where delamination is present. The following graphs as shown in figure-4 (a), (b), (c) and (d) represent the extent of crystal packing intensity within the structure. It can be inferred from XRD result of the areas -2 of beam in Fig. 4(b) where delamination is present; shows lesser presence of crystals which may be due to the presence of voids.

In the thermographic tests, the delaminated composite beam has been heated up to temperatures 50, 90, 150, 240 and 300 °C using a heater and

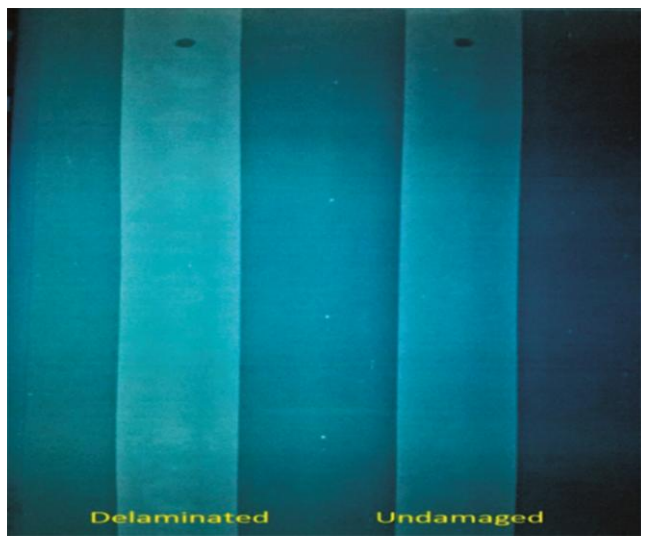

Fig. 2 — X-Ray radiography image carbon fibre beams.

Fig. 1 — Setup for vibration test for carbon fibre beams.

Fig 3 — White spot are small delamination area detected by ultrasonic test and numbers are marked for XRD analysis.

with the help of an infrared camera, thermographic image has been taken as shown in Fig. 5. The result has been somewhat inconclusive as it failed to show any presence of delamination. One of the reasons for it might be that there may be an opening on the outside of the composite that may be leading to the delamination area. Hence, the void areas are getting cooled in the same manner as the other areas. Therefore, all the areas are showing the same heat gradient.

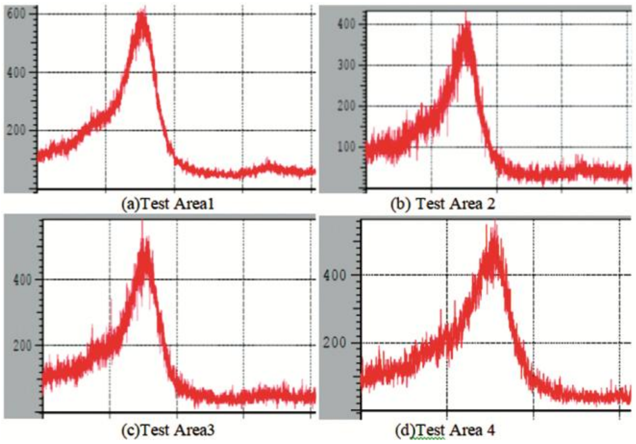

Fig. 4 — X-Ray diffraction crystalline intensity graph.

The experimental result from the free vibration test with an OROS four channel FFT analyzer is performed and the test results are shows in Fig. 6. It can be clearly seen the rate of damping are varies on presence delamination Fig. 6(b).

Table 1 results clearly indicate that the natural frequency is lower in case of delaminated composite beam as compared to beam without delamination.

Finally, the FFT plots of online vibration test in Fig. 7 and Fig. 8, of beam without delamination and with delamination respectively, these plots shows super harmonics and side bands.

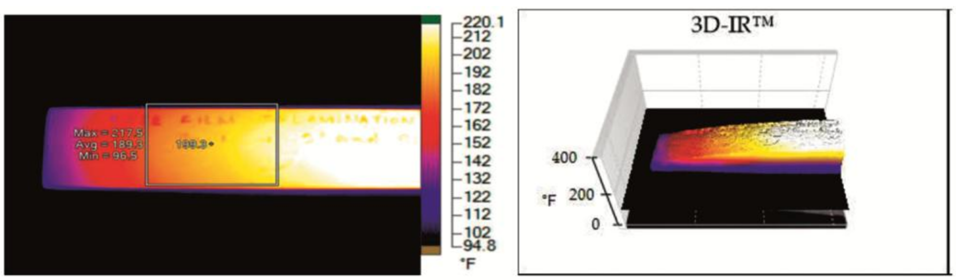

Fig. 5 — Thermographic images of the carbon fibre delaminated composite beam.

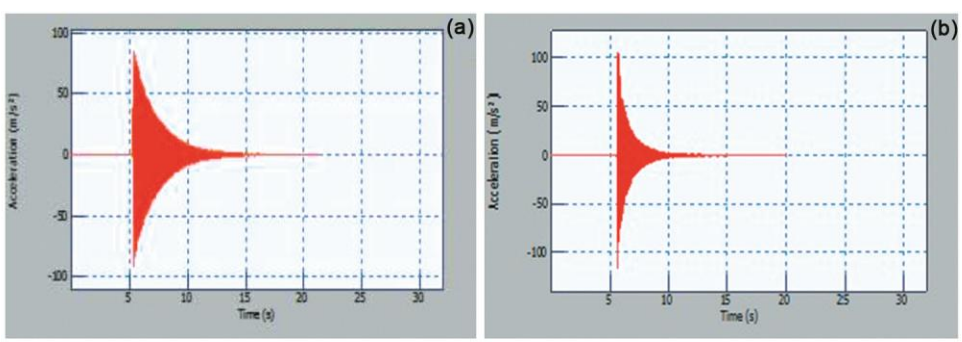

Fig. 6 — Time versus acceleration graph for carbon fibre composite without delamination (a) and with delamination (b).

Table 1 — Comparison of natural frequencies of beam without delamination and beam with delamination.

Mode	Natural frequencies(in Hertz) Beam Without delamination	Beam with delamination
1^{st} mode	20.9238	19.9245
2^{nd} mode	120.7035	118.7534
3^{rd} mode	263.6757	258.9843

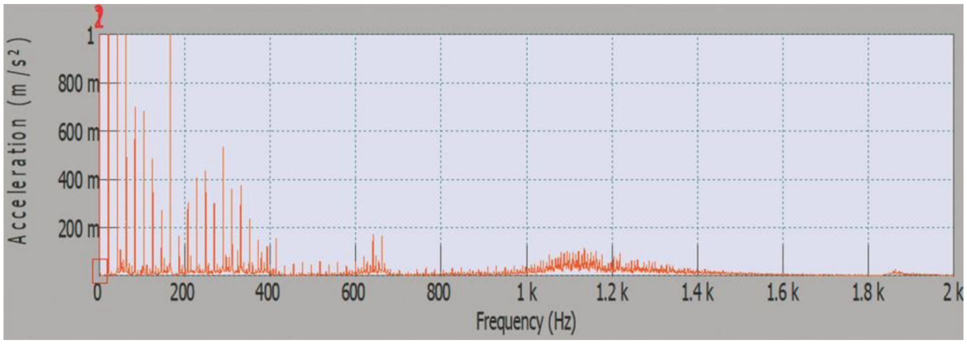

Fig. 7 — FFT plot of composite beam without delamination.

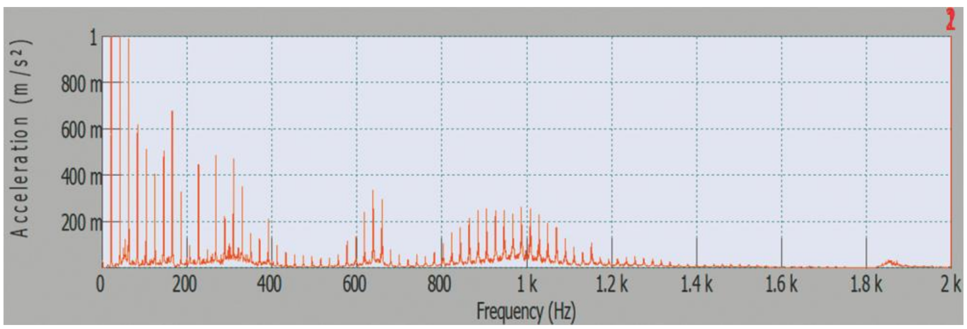

Fig. 8 — FFT of composite beam with delamination.

4 Conclusions

Non-destructive tests are performed to locate the small delamination length and area within the carbon fibre composite beams. Vibration test gives the natural frequency and damping rate of the carbon fibre composite structure from which we can infer which composite has delamination. It is concluded that the most accurate results are provide by vibration test, ultrasonic test and XRD test. Ultrasonic test is a very reliable process because it provides the exact location and the depth at which the delamination is present, It is also observed that due to presence of delamination, the natural frequency decreases and the rate of damping increases in delaminated carbon fibre composite beam besides FFT results of the online vibration signal of delaminated carbon fibre composite beam clearly shows higher harmonics and sidebands. These observations can be used in any FRP composite structures to effectively detect and locate small delamination.

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