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Fault Diagnosis of Cracked Cantilever Composite Beam by Vibration Measurement and RBFNN

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Abstract In the current investigation numerical and radial basis function neural network (RBFNN) are adopted for diagnosis of fault in a cantilever composite beam structure present in form of transverse cracks. The presence of cracks a severe threat to the performance of structures and it affects the vibration signatures (Natural frequencies and mode shapes). The material used in this analysis is graphite fiber reinforced polyimide composite. The Numerical analysis is carried out by using commercially available software package ANSYS to find the relation between the change in natural frequencies and mode shapes for the cracked and un-cracked composite beam. Which subsequently used to the design of smart system based on RBFNN for forecast of crack depths and locations following inverse technique. The RBFNN controller is developed with relative natural frequencies and relative mode shapes difference as input parameters to calculate the deviation in the vibration parameters for the cracked dynamic structure. The output from the RBFNN controller is relative crack depth and relative crack location. Results from numerical analysis are comparing with experimental results having good agreement to the results predicted by the RBFNN controller.

Keywords: *crack, natural frequencies, Mode shapes, RBFNN, Ansys*

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1. Introduction

The use of composite materials in various construction elements has increased substantially over the past few decades. These materials are particularly widely used, where a large strength-to-weight ratio is required. Likewise to isotropic materials, composite structures are subjected to various types of damage, mostly cracks and delamination. Cracks or other defects in a structural element affect its dynamical behavior and change its stiffness and vibration signatures. Subsequently, the natural frequencies and mode shapes of the structure contain information about the location and dimensions of the damage.

Finite element and component mode synthesis methods are adopted by Kisa, M [1]. The influence of the location and depth of the cracks, and the volume fraction and orientation of the fibre on the natural frequencies and mode shapes of the multiple cracked cantilever beam with transverse cracks, are explored. Krawczuk M, et al. [2] proposed two models witch gives valuable information about the location and size of defects in the beams. This method makes it possible to construct beam finite elements with various types of cracks. If the stress intensity factors for a given type of crack are known. Discrete Wavelet Transform based method is presented for the identification of multiple cracks in polymeric laminate composite beam by Andrzej K [3]. Two Damage identification algorithms are established for assessment of damage using modal test data which are similar in concept to the subspace rotation algorithm or best feasible modal analysis method by Hu et al. [4]. Suresh et al. [5] have presented a method considering the flexural vibration in a cantilever beam having transverse Crack. They have computed modal frequency parameters analytically for various crack locations and depths and these parameters are used to train the neural network to identify the damage location and size. Tian, J. et al. [6] proposed method of crack detection in beam like structures by wavelet analysis. First introduce a rotational spring in the cracked-beam model, and calculate the transient flexural wave propagation by the Reverberation Matrix Method. Then at any point in this beam, thearrival time of waves with different group velocities can be identified by means of analysis of wavelet transform Wave. Loutridis S. et al. [7] develoed a new method for crack detection in beams based on instantaneous frequency and empirical mode decomposition. The dynamic behaviour of a cantilever beam with an open crack under harmonic excitation is explored both theoretically and experimentally. A simple single-degree-of-freedom system with varying stiffness is employed to simulate the dynamic behavior of the beam. The time-varying stiffness is exhibited using a simple periodic function. Both simulated and experimental response data are analyzedby applying empirical mode decomposition. The Hilbert transform and the instantaneous frequency of each oscillatory mode is obtained. Mehrjoo et al. [8] have presented a fault detection inverse algorithm to evaluate the damage concentrations of joints in truss bridge structure using back propagation neural network method. Agosto et al. [9] have applied neural network method with a combination of vibration and thermal damage detection signatures to develop a damage defection tool. They have applied the developed technique on sandwich composite for the determination of crack severity. Saravanan et al. [10] have dealt with the robustness of an artificial neural network, wavelet and proximal support vector machine based on fault diagnostic approach for a gear box. They have used the proposed methodology for fault diagnosis in bevel gear box.

In the present study, an inverse technique has been adopted for predict of cracks. Numerical and RBFNN analysis performed to study the dynamic response of a multiple cracked cantilever composite beam. A smart RBFNN technique is designed and is used to the damage intensity and severity. The experimental results are compared with numerical and RBFNN results. A close agreement between the results observed.

2. Numerical Analysis

The numerical analysis is brought out for the cracked cantilever composite beam shown in Figure 1, to locate the mode shape of transverse vibration at different crack depth and crack location. The cracked beams of the current research have the following dimensions.

- Length of the Beam (L) = 800 mm; Width of the beam (W) = 50 mm; Thickness of the Beam (H) = 6 mm;
- Relative crack depth ($\psi_1 = a_1/H$) = from 0.0833 to 0.5;
- Relative crack depth ($\psi_2 = a_2/H$) = from 0.0.833 to 0.5;
- Relative crack location ($\beta_1 = L_1/L$) = from 0.625 to 0.875;
- Relative crack location ($\beta_2 = L_2/L$) = from 0.125 to 0.9375;
- Properties of Graphite fiber reinforced polyimide composite material in analysis:
- Young's modulus of fiber = E_f = 275.6 GPa;
- Young's modulus of matrix = E_m = 2.756 GPa;
- Modulus of rigidity of fiber = G_f= 114.8 GPa;
- Modulus of rigidity of matrix = G_m = 1.036 GPa;
- Poisson's ratio = ν_f = 0.2; Poisson's ratio = ν_m= 0.33;
- Density of fiber = ρ_f = 1.9 gr/cm^3; Density of matrix = ρ_m = 1.6 gr/cm^3;

The numerical analysis is accepted by using the finite element software ANSYS in the frequency domain and obtain natural frequencies, and mode shapes.

A higher order 3-D, 8 node element having three degrees of freedom at each node: translations in the nodal x, y, and z directions (Specified as SOLSH 190 in ANSYS) was selected and used throughout the analysis. Each node has three degrees of freedom, making a total twenty four degrees of freedom per element. The layers stacking in ANSYS shown in Figure 2. The results of the numerical analysis for the first three mode shapes for un-cracked and cracked beam (ψ_1 = 0.166, ψ_2 = 0.333 and β_1 = 0.25, β_2 = 0.5) are shown in the Figure 3.

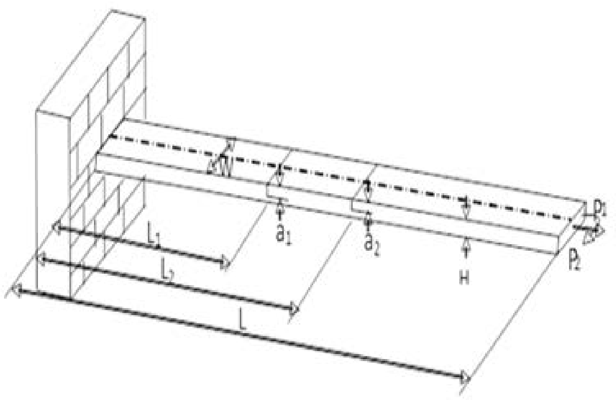

Figure 1. Geometry Cantilever beam with multiple cracks

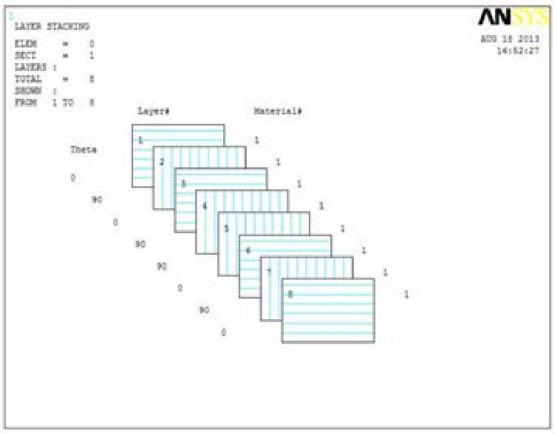

Figure 2. Layers Stacking in ANSYS

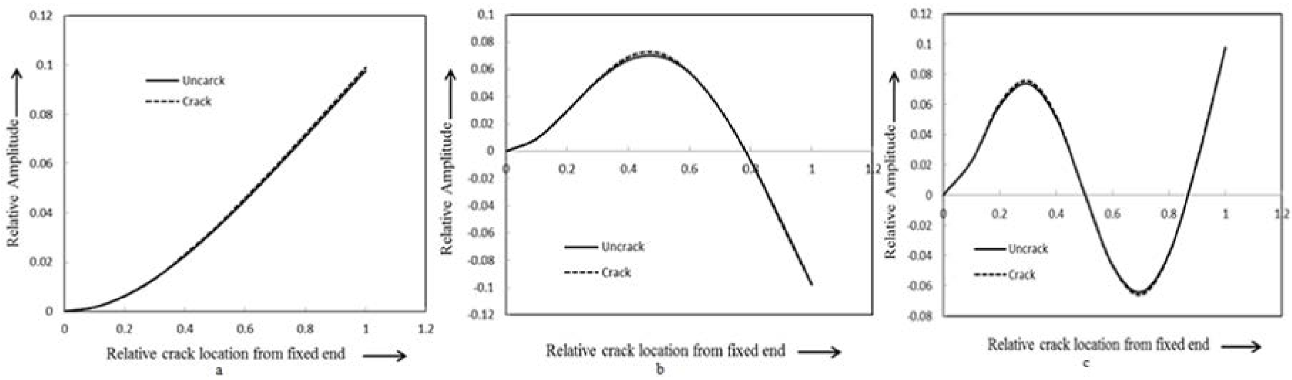

Figure 3 a. Relative Amplitude vs. Relative crack location from fixed end (1st mode of vibration). **b.** Relative Amplitude vs. Relative crack location from fixed end (2nd mode of vibration). **c.** Relative Amplitude vs. Relative crack location from fixed end (3rd mode of vibration)

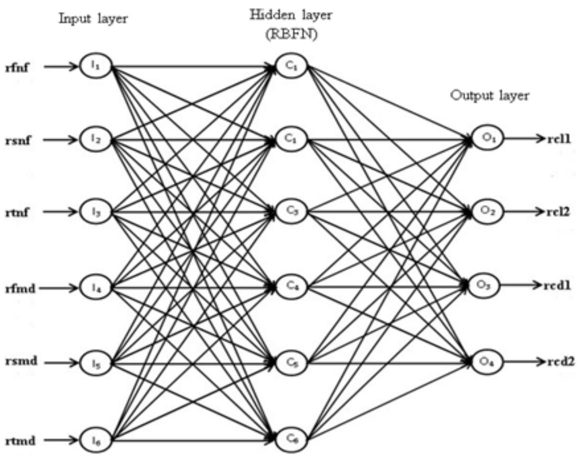

Figure 4. RBFNN Model

3. Radial Basis Function Neural Network (RBFNN) Analysis

The radial basis function neural network, as a type of feed-forward neural network has recently attracted extensive research interest because of its simple architecture, high approximation and regularization capability, and good local specialization and global generalization ability. The parameter of RBFNN involves the numbers of neurons in input layer, hidden layer and output layer, RBF centers and width of neuron in hidden layer and linear weight connected to the hidden layer and output layer. Each neuron in hidden layer of RBFNN produces a radically symmetric response around a node parameter victor called a center. As well known the performance of RBFNN critically relies on the selection of RBF centers. RBF center located through clustering techniques by which RBF centers are selected randomly from input data and adjusted constantly by clustering algorithm until they no longer change. The RBFNN controller has been developed for detection of the relative crack locations and relative crack depth having six input parameters and two output parameters as shown in Figure 4. The linguistic term used for the inputs are as follows; Relative first natural frequency = "rfnf"; Relative second natural frequency = "rsnf"; Relative third natural frequency = "rtnf"; Relative first mode shape difference = "rfmd"; Relative second mode shape difference = "rsmd"; Relative third mode shape difference = "rtmd. The linguistic term used for the outputs are as follows; Relative first crack location = "rcl1" Relative second crack location = "rcl2" Relative first crack depth = "rcd1" Relative second crack depth = "rcd2". The input layer has six neurons, three for first three relative natural frequencies and other three for first three average relative mode shape difference. The output layer has four neurons, which represents relative crack locations and relative crack depths.

The relative natural frequency and relative mode shape difference used in the above analysis can be defined as follows.

$$\text{Relative natural frequency} = \frac{(\text{Natural frequency of cracked beam})}{(\text{Natural frequency of un-cracked beam})}$$

$$\text{Relative mode shape difference} = \frac{\begin{pmatrix}\text{Amplitude of un-cracked beam} \\ -\text{Amplitude of cracked beam}\end{pmatrix}}{(\text{Amplitude of un-cracked beam})}$$

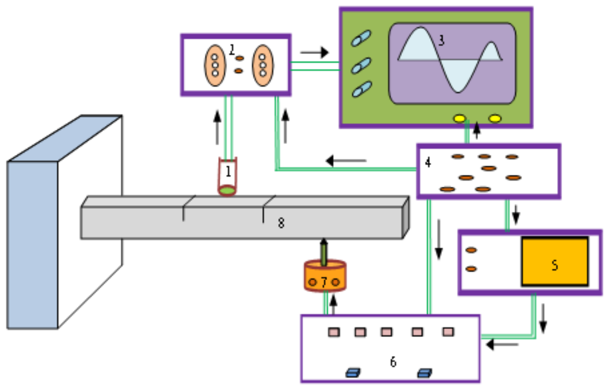

Figure 5. Schematic block diagram of experimental set-up

1. Data acquisition (Accelerometer); 2. Vibration analyser; 3. Vibration indicator embedded with software (Pulse Labshop); 4. Power Distribution; 5. Function generator; 6. Power amplifier; 7. Vibration exciter; 8. Cracked Cantilever

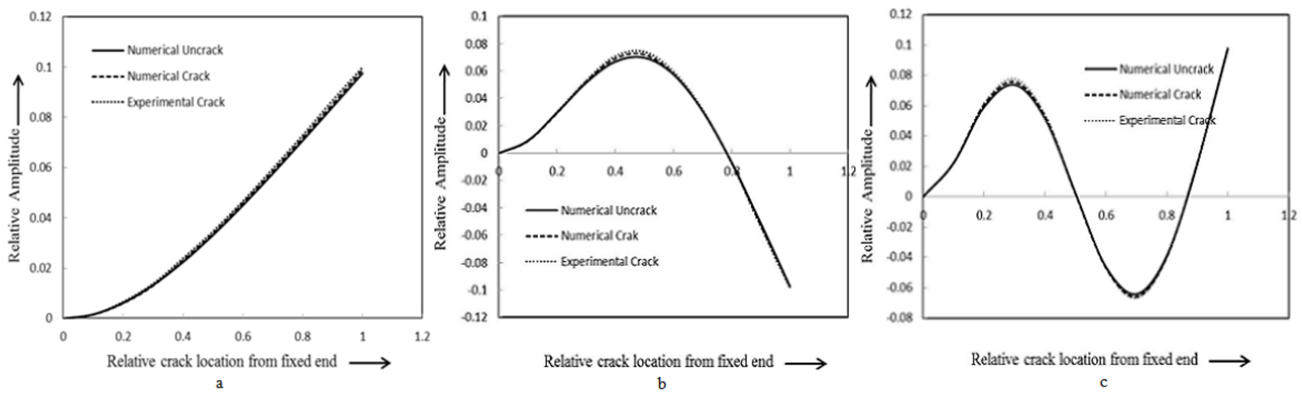

Figure 6 a. Relative Amplitude vs. Relative crack location from fixed end (1st mode of vibration). **b.** Relative Amplitude vs. Relative crack location from fixed end (2nd mode of vibration). **c.** Relative Amplitude vs. Relative crack location from fixed end (3rd mode of vibration)

4. Experimental Investigation

To validate the numerical analysis result, an experiment on composite beam has been performed shown in Figure 5.

A composite beam was clamped at a vibrating table. During the experiment the cracked and undamaged beams have been vibrated at their 1st, 2nd and 3rd mode of vibration by using an exciter and a function generator. The vibrations characteristics such as natural frequencies and mode shape of the beams correspond to 1st, 2nd and 3rd mode of vibration have been recorded by placing the accelerometer along the length of the beams and displayed on the vibration indicator. The surface specimens were cut with EDM wire cut machine to ensure high accuracy of cracked model. The experimental results are in close justification with neural analysis results. These results for first three modes are plotted in Figure 6. Corresponding numerical results for the cracked and un-cracked beam are also presented in the same graph for comparison. The comparison of results between RBFNN controller, numerical analysis and experimental analysis shown in Table 1.

Table 1. Comparison of results between RBFNN model, Numerical analysis and Experiment analysis

Relative first natural frequency "rfnf"	Relative second natural frequency "rsnf"	Relative third natural frequency "rtnf"	Average Relative first mode shape difference "rfmd"	Average Relative second mode shape difference "rsmd"	Average Relative third mode shape difference "rtmd"	RBFNN Model relative 1st crack depth "rcd1" 1st crack location "rcl1" 2nd crack depth "rcd2", 2nd crack location "rcl2"				Numerical relative 1st crack depth "rcd1" 1st crack location "rcl1" 2nd crack depth "rcd2", 2nd crack location "rcl2"				Experimental relative 1st crack depth "rcd1" 1st crack location "rcl1" 2nd crack depth "rcd2", 2nd crack location "rcl2"			
						rcd1	rcl1	rcd2	rcl2	rcd1	rcl1	rcd2	rcl2	rcd1	rcl1	rcd2	rcl2
0.9978	0.9983	0.9878	0.0036	0.0329	0.0141	0.159	0.17	0.16	0.42	0.164	0.24	0.23	0.49	0.161	0.19	0.18	0.44
0.9987	0.9972	0.9981	0.2936	0.3428	0.2623	0.18	0.19	0.407	0.66	0.24	0.24	0.414	0.73	0.19	0.20	0.409	0.68
0.9936	0.9976	0.9987	0.0138	0.014	0.0832	0.164	0.373	0.23	0.622	0.159	0.368	0.18	0.618	0.157	0.367	0.16	0.616
0.9976	0.9991	0.9988	0.0014	0.0041	0.0812	0.332	0.123	0.414	0.49	0.327	0.119	0.410	0.45	0.325	0.117	0.409	0.43
0.9849	0.9982	0.9869	0.0134	0.0211	0.0119	0.414	0.372	0.22	0.622	0.410	0.367	0.19	0.618	0.408	0.365	0.18	0.616
0.9989	0.9973	0.9974	0.0017	0.0025	0.0079	0.46	0.21	0.20	0.71	0.44	0.18	0.18	0.68	0.42	0.17	0.16	0.66
0.9979	0.9985	0.9993	0.0087	0.0036	0.0042	0.43	0.119	0.18	0.42	0.48	0.123	0.22	0.46	0.41	0.117	0.16	0.40
0.9962	0.9989	0.9991	0.0036	0.9729	0.2263	0.409	0.118	0.326	0.868	0.414	0.123	0.330	0.873	0.407	0.117	0.324	0.866

5. Conclusion

The conclusions derived from the various analyses as mentioned above are depicted below.

1. The numerical analysis results are well agreed with RBFNN controller results.
2. The study of vibration signatures of the cracked composite beam shows a variation of mode shapes and natural frequencies for the cracked and un-cracked beam.
3. The results from numerical analysis, RBFNN analysis are compared with the experimental results. They show good judgment.
4. This method can be employed as a health monitoring tool for vibrating damaged dynamic structures.

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