International Journal of Civil and Structural Engineering– IJCSE
Volume 2 : Issue 1 *[ISSN : 2372-3971]*
Publication Date: 30 April, 2015

Structural Crack Detection in Composite Materials using Neural Networks

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Abstract— **Online structural health monitoring becomes as a promising tool to ensure of the safety of the structure with low cost, short time and high effectiveness. Existing of crack in the structure makes the structure weaker and unsafe and it may propagate to complete fracture and catastrophic failure. Different methods are developed to predict the location and depth of a crack. In this paper, Artificial Neural Network (ANN) theory is used to predict the generated data for different crack locations and crack depth based on changes in natural frequencies and mode shapes of a healthy structure. The ANSYS software based on finite element (FE) principles is used to generate data for solid or fibre reinforced composite cantilever (and simply supported) beams. Natural frequencies for different important vibration modes are obtained based on linear vibration analysis. The effects of ply orientation, crack location, crack depth and end supports on the natural frequencies and corresponding mode shapes are investigated. Results of ANSYS software was first compared with some well-known theoretical cases for verification purpose and then results of artificial neural network (ANN) are compared with ANSYS software generated data. The results indicate high accuracy of ANN on predicting size and location of cracks in the studied structures.**

Keywords— Structure, Health monitoring, Crack, Artificial Neural Network, Finite Element, ANSYS.

I. Introduction

Structural Health Monitoring (SHM) is a good technique to ensure of the safety of the structure and improves its life. Measuring the structure natural frequencies considered as a good indicator of structure safety. The natural frequencies of structure include a crack will decrease due to changing of its properties compared with the healthy structure. Depends on the crack depth and location (crack ratios), the reduction in natural frequencies will vary.

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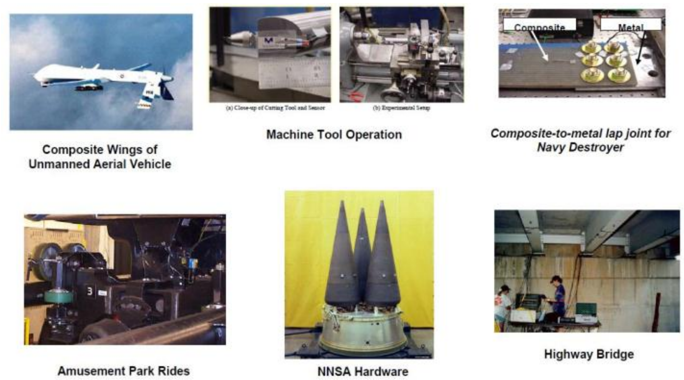

Figure 1 Some areas of applying SHM [2]

The multi-degree-of-freedom system has a number of natural frequencies and mode shapes which is equal to the number of system DOF.

Beams have many types of mode shapes; bending on axis (translation mode), torsion (rotational mode), and the both mode can be coupled (coupling mode). If the structure exposed to an external force and the frequency of that force coincidence with the first bending natural frequency of the structure the resonance will occur in the first bending mode shape and so on for other modes.

The potential direct benefits of a SHM system are numerous, including real-time monitoring and reporting, reducing down time, and improving safety and reliability, while reducing maintenance costs.

The reduction of down time and improvement in reliability enhances the productivity of the structure. Obtaining information on the behaviour of the structure from inside, SHM can improve the design of future structures. The next benefit of SHM is its inherent characteristic as a non-destructive testing (NDT) method [1]. SHM is an inspiration topic for many civil, aerospace, marine, and mechanical engineers. Figure 1 shows some areas that may benefit from application of SHM.

Adopting the materials used in different engineering applications depend on several factors such as the application of the structure, the desired performance for the structure, the cost of the material, the mechanical, thermal and chemical properties of the material, the safety required for the structure, and types of loads act on the structure.

In general, composite is a combination of materials, and it has different properties from its components. Fibre reinforced composite is the type of composite materials that have good properties to use in different fields especially when light and strong structures are required [3].

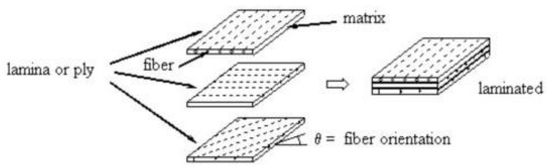

Figure 2 Fibre reinforced composite lamina

Fibre reinforced composite material is produced from fibre and matrix. Figure 2 shows the construction of the fibre reinforced composite lamina.

Fibre is one component of fibre reinforced composite which has filament shape. The main functions of fibres are to carry the load and provide stiffness, strength, thermal stability and other structural properties [4]. The graphite fibre is widely used and contains at least 99 wt % carbons while carbon fibre is defined as the fibre containing at least 92 wt % carbons [5]. Matrix is another component of fibre reinforced composite, it covers the fibres. The epoxy matrix is commonly used because of better mechanical properties.

Some advantages of using fibre reinforced composite structures are high specific strength ratio (low density with high tensile strength), high corrosion resistance, high toughness, high creep resistance, the response to temperature change is small, and it has high damping to reduce the input loads. Some disadvantages of using fibre reinforced composite structure are given as material costs are relatively high, difficulties in manufacturing, delimitation problem, and delimitation is separating between two lamina.

II. Crack in Structures

Crack in structure is an undesirable condition that makes the structure weak and unsafe; therefore, the crack detection is important topic in SHM to ensure of the safety of structure. The existence of crack in structure may cause the effects as after crack appears, it will propagate, the stiffness of the structure will decrease, crack decreases the natural frequencies of the structure and increases the opportunity to occur the resonance, stress concentration will appear on the crack tip, and structure became less safety.

Cracks can be classified with respect to structure axis into transverse cracks, these cracks perpendicular to the beam axis as shown in Figure 3; longitudinal cracks, these cracks parallel to the structure axis; and slant cracks, these cracks are in angle with structure axis.

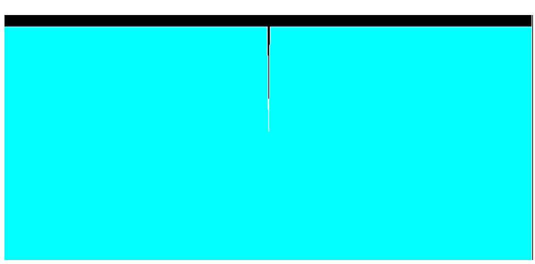

Figure 3 Structure contain transverse crack

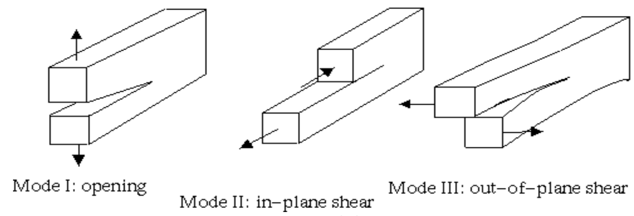

Figure 4 Basic modes of fracture in structures

Cracks can be classified into internal crack which is not open to surface of structure, and the surface crack which is open to the surface of structure. There are many factors for appearing crack in structure such as: temperature variation of the structure, humidity variation of the structure, elastic deformation, manufacture defects, welding defects, and chemical reaction.

There are three basic modes of fractures in a crack structure as follows [6]:

Mode 1: opening mode which is the most dangerous mode. It will appear when the crack plane is normal to the direction of the tensile loading.

Mode 2: in-plane shear mode, in this mode the crack each of crack face try to slides with respect to another face, it is called as in plane crack because the fracture not causing the structure move out of its original plane.

Mode 3: out-of-plane shear, in this mode each of crack faces slide with respect to another face causing their movement out of its original plane.

A. *Crack Detection*

Traditional non-destructive tests (NDT) are appropriate methods to crack detection when the tested area is small. Some of traditional non-destructive tests include visual inspection, this test can find the large surface cracks, but in most cases the cracks are very small and it cannot found visually; dye-penetrations test, this test can find only the surface defects based on capillary action; magnetic particle test, which used to inspect the surface cracks and internal cracks which is very close to surface, this method cannot inspect the crack in non-ferrous materials; radiography test, the most disadvantage for this method its danger because of using radioactive elements; ultrasonic test, it inspects the cracks through the difference behaviour of sound when it passes through crack. The smart method to detect the crack is through studying the effect of crack on natural frequencies of structure and to find relations between crack ratios and natural frequencies of structure. This is considered as a (NDT) method to deal with different crack types.

III. Finite-Element Method (FEM) Analysis of Cracks

Through the continuous development in engineering structures, the complex structures have appeared in different fields so the engineering analysis of these structures have seemed more complicated. FEM comes as a strong numerical method to analysis the structures and to provide very useful insight into the complex structures. In this study, ANSYS is

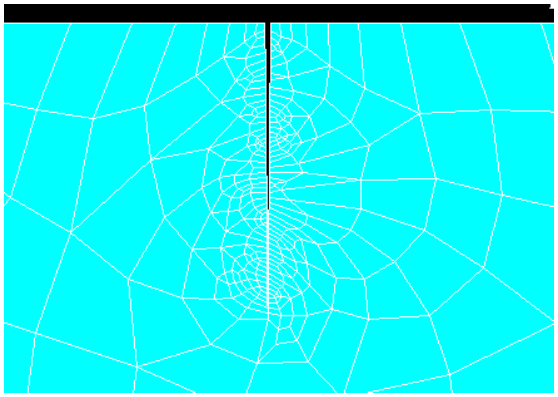

Figure 5 Crack shape and ANSYS mesh

the software tool is used as the FEM solver to investigate cracks.

A. *Crack Modelling using ANSYS*

To model a crack in a structure, the crack must satisfy some sensitive conditions found in real crack situations such as stress concentration on the crack tip and the size of the crack. Triangle shape is a useful shape for modelling the crack, easy to use, and provides robust results in vibration analysis. Figure 5 shows the triangle shape model of crack in a beam with the corresponding FE mesh using ANSYS.

Like solid elements, there are many elements to model the composite beam in ANSYS. Wang [7] have used shell element which proved its ability to solve composite structures. SHELL181 is the element was selected to get natural frequencies and mode shapes for cracked composite beam [8]. SHELL181 is well-suited for linear, large rotation, and/or large strain nonlinear applications.

IV. Artificial Neural Network (ANN)

With progress in artificial intelligence (AI) fields, it is feasible to make the computer learn and solve problems based on a training data supplied from environment or from previous experiences. The trained program then stores this knowledge and makes it available to use. This process of learning is known as artificial neural network.

Artificial Neural Network (ANN) is a very similar to the human nervous system (human neural network) which works through receiving data, processing it, understanding it and making a rational decision with respect to the received information; then it stores the knowledge acquired from this experience to use it in the future. ANN provides a strong tool for many engineering problems. ANN can do classification and curve fitting input data and provides output prediction. The superiority of ANN is that it makes an approximate relation between inputs and outputs when there is no explicit relation, due to complexity of problem, so as no mathematical formulation can be found to relate outputs to inputs in concrete

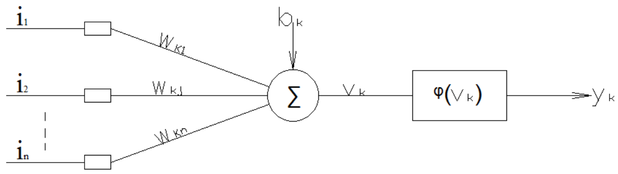

Figure 6 Neuron architecture

manner. ANN is trained in this paper to relate crack depth and crack location in a structure to its natural frequencies.

A. *Neuron Architecture*

Artificial Neural Network (ANN) is made of many processes considered as neurons. Neuron is a processing unit in the network that has the architecture as shown in Figure 6. The neuron process contains:

- Set of synaptic links each one characterized by weight (w_{kj}).
- Biasb_k.
- An adder (∑) for summing the input signal multiplies by respective weight plus the bias.
- Activation function applied on the output of adder to limit the output of neuron between [-1, 1], [0, 1] or between another two limits.

From Figure 6, the mathematical description of the neuron k can be summarized through equations 1, 2, and 3.

$$u_k = \sum_{j=1}^{n} w_{kj}\, i_j \tag{1}$$

where u_k is the output of adder before adds the bias, i_j is the input j, and w_{kj} is the synaptic weight between neuron k and input j. The output of adder after adds the bias, V_k, is given by:

$$V_k = u_k + b_k \tag{2}$$

where b_k is the bias value and the output of neuron after applying the activation function, y_k, is given by

$$y_k = \varphi V_k \tag{3}$$

where φ is the activation function.

In this paper, the software tool STATISTICA is used to create a neural network. STATISTICA uses Multilayer perception using back propagation learning algorithm with one hidden layer.

V. Results and Discussions

A. *Verifying Numerical Results*

In this paper, to verify numerical results on modelling cracks for a solid beam and a laminate composite beam, the ANSYS solutions for natural frequencies of the beams are compared with some reported results in literature. There are four test cases examined as follow:

Case 1: Solid cantilever beam with single crack.

The beam geometries are given as: L=0.8 m and B=H=0.02 m. The used properties of material are given by: $E=2.1\times10^{11}$ and $\rho=7800$ kg/m^3. The crack depth is 2 mm, located at 0.12 m from the beam root. The ANSYS numerical solutions are compared for the first three modes with reference [9] in Table 1.

Table 1 Solid cantilever beam results with single crack (Case 1)

Mode no	Reference [9]	Present	Error %
1	26.1015	26.109	0.03
2	163.5959	163.582	0.01
3	456.3634	456.029	0.07

Case 2: Solid cantilever beam with double crack.

The same solid beam as in the case of 1 is used except that two cracks with depths of 2 mm and 3 mm are located at 0.12 m and 0.4 m from the beam root; respectively. The results are summarized for the first three modes in Table 2.

Table 2 Solid cantilever beam with double crack (Case 2)

Mode no.	Reference [9]	Present	Error (%)
1	26.0694	26.137	0.26
2	162.7112	163.19	0.29
3	456.3611	457.083	0.16

Case 3: Fibre reinforced composite healthy beam.

Here, the beam geometries are used as: L=0.11179 m, B=12.7 $\times$ 10^{-3} m and H=3.38 $\times$ 10^{-3} m. The properties of material of the composite beam are taken as: E_1 =37.41Gpa, E_2 =13.67Gpa, G_{12} =5.478Gpa, G_{13} =6.03Gpa, G_{23} =6.666Gpa, ν_{12} =.3 ,and ρ=1968.9 kg/m^3. The ANSYS results are compared for the first three modes with reference [10] in table 3.

Table 3 Fibre reinforced composite cantilever healthy beam comparing case 3

Mode no.	Reference [10]	Present	Error (%)
1	120.5	122.699	1.82
2	752.5	767.871	2.1
3	2093.8	2152	2.8

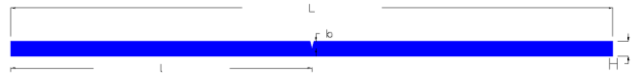

Figure 7 Solid cracked beam geometrical definitions

Case 4: Fibre reinforced composite healthy beam

Next beam geometries used here is as: L=0.5 m, B=0.1 m and H=0.005 m. The beam properties of material are used as: E_m = 2.76 GPa, E_f = 275.6 GPa, G_m = 1.036 GPa, G_f = 114.8 GPa, ν_f =0.2, $\nu_m = .33$, ρ_f = 1900 kg/m3 , ρ_m = 1600 kg/m^3.volume fraction =90, and volume fraction =90. The results are shown in Table 4.

Table 4 Fibre reinforced composite cantilever healthy beam (Case 4)

Mode no.	Reference [7]	Present	Error (%)
1	28.807	28.803	0.01
2	180.561	179.38	0.65

B. *Solid Cantilever Beam Natural Frequencies*

In this section, the first three natural frequencies of cantilever beam are found using ANSYS software to train MLP network of ANN. The results are then compared between ANN and ANSYS. The solid beam which used in this exercise has the following geometries and properties:

L=0.8 m and B=H=0.02 m.

ρ = 7800 kg/m^3, E = 2.1 $\times$10^{11} N/m and ν = 0.35

Figure 7 shows the beam shape and its crack shape, position, and depth.

From Figure 7, there is two crack ratios, crack depth ratio and crack location ratio, both ratios are defined as *a=b/H* where *a* is the crack depth ratio, *b* is the crack depth, and *H* is the height of the beam. The second ratio, *s*, is called crack location ratio defined as *s=1/L* where *l* is the distance between the crack tip and root of beam and *L* is the beam length.

Figures 8 to 10 compares ANSYS results with ANN predictions for the first three natural frequencies for the solid cantilever beam at different crack ratios. From Figure 8, it is evident that the ANN curve followed the ANSYS curve perfectly; this mean the neural network was trained extremely well to find the first natural frequency precisely. It can be observed from Figure 9 that there is very little deviation between ANN and ANSYS second natural frequency results in peak points of the curve. From Figure 10, the two curves have identically fit each other exhibiting high accuracy 0f the ANN results for the third natural mode.

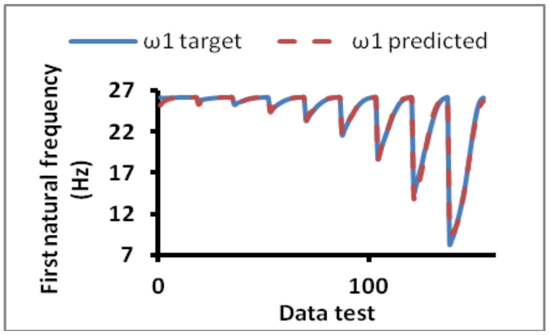

Figure 8 First natural frequencies for cracked solid cantilever beam

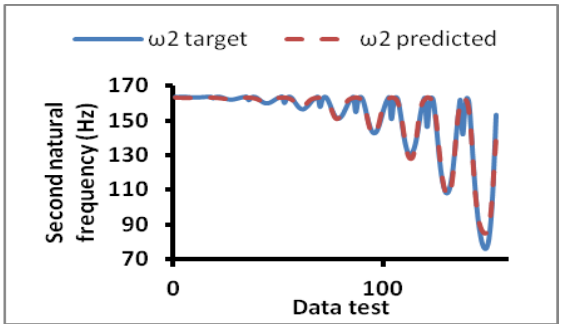

Figure 9 Second natural frequencies for cracked solid cantilever beam

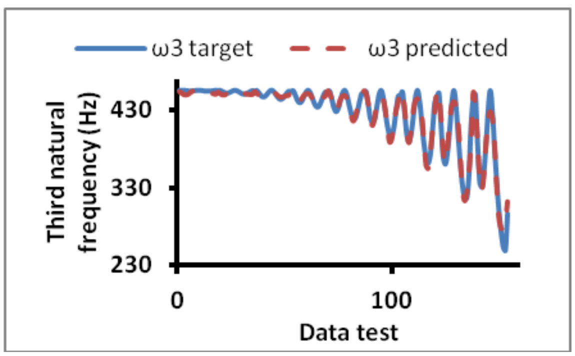

Figure 10 Third natural frequency for cracked solid cantilever beam (ANSYS=solid line, ANN=dash line)

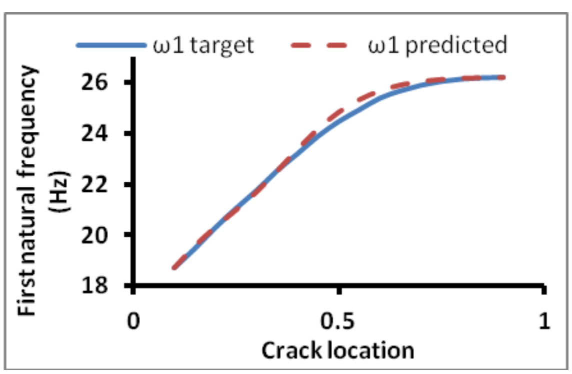

Figure 11 First natural frequencies versus the non-dimensional crack locations

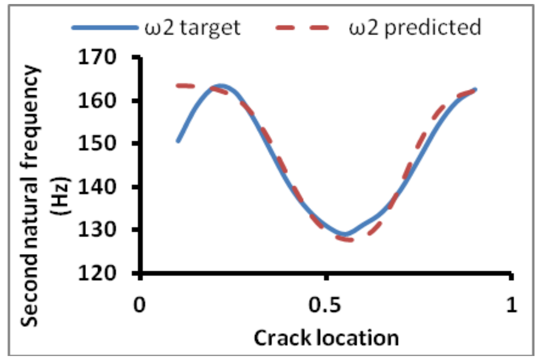

Figure 12 Second natural frequencies versus the non-dimensional crack locations

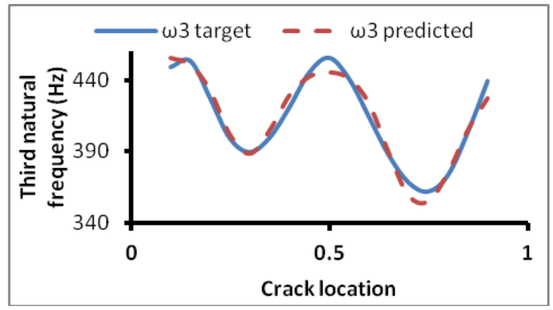

Figure 13 Third natural frequencies versus the non-dimensional crack locations

(Crack depth ratio=0.7, ANSYS=solid line, ANN=dash line)

Figures 11 to 13 show comparison between ANSYS results and ANN prediction to find the relationship between the first three natural frequencies and non-dimensional crack locations at crack depth ratio of 0.7, for the cantilever solid beam. From Figure 11, it is observed that the ANN prediction curve does match perfectly well with the ANSYS numerical results for the first natural frequency. The ANN has slightly over predicted for crack locations from 0.5 to 0.8. In Figure 12, two curves have the same behaviour for the second natural frequency except at near to root of crack locations. In Figure 13 for the third natural frequencies, there is slightly deviation between two curves at the peak of curves; i.e. crack location 0.5 and 0.8.

C. *Fibre Reinforced Composite Cantilever Beam Natural Frequencies*

In this section, the first three natural frequencies of cantilever beam are obtained using ANSYS software. Then, these frequencies are used to train MLP network for the ANN prediction. Next, the results between ANN and ANSYS are compared.

The fibre reinforced composite which is used in this work has a fibre volume fraction equal to 0.5 and a fibre orientation of 90 degrees, with the following geometries and properties as shown in Tables 5 and 6.

Table 5 Fibre reinforced composite beam geometries

L (m)	B (m)	H (m)
0.5	0.1	0.005

Table 6 Fibre and matrix properties for the fibre reinforced composite beam

	E (GPa)	G (GPa)	ρ (kg/m3)	ν
Fibre	275.6	114.8	1900	0.2
Matrix	2.756	1.03	1600	0.35

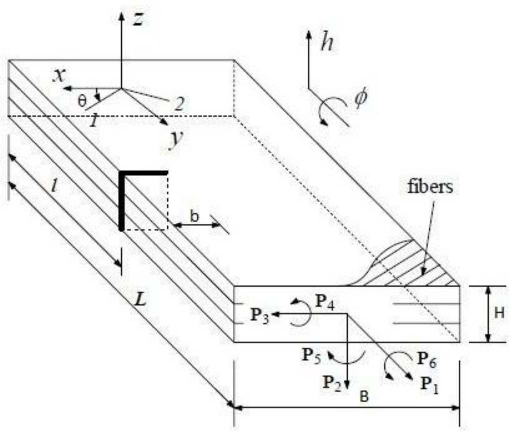

Figure 14 Fibre reinforced composite beam geometry [7]

Figure 14 shows the fibre reinforced composite beam geometry, and its crack ratios; crack location ratio and the crack depth ratio.

Figures 15 to 20 compare the numerical results of ANSYS with the prediction by the ANN for the first three natural frequencies of fibre reinforced composite cantilever beam for different crack ratios.

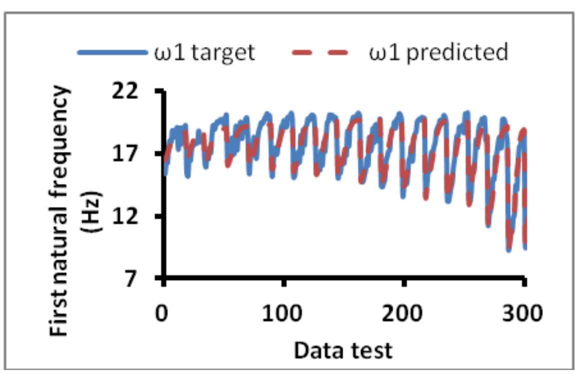

Figure 15 First natural frequency for cracked fibre reinforced composite cantilever beam

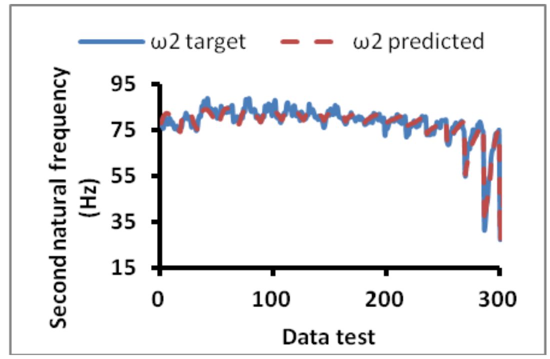

Figure 16 Second natural frequency for cracked fibre reinforced composite cantilever beam

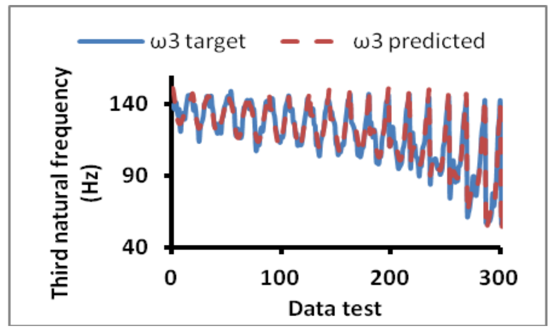

Figure 17 Third natural frequency for cracked fibre reinforced composite cantilever beam (ANSYS=solid line, ANN=dash line)

In comparison with Figures 8 to 13 for solid beams, it is evident that the ANN have perfectly predicted the ANSYS results as shown in Figure 15 to 20 for the cracked fibre reinforced composite cantilever beam except it has smoothen numerical wiggles due to multi-layer structure of the composite beam. The template is designed so that author affiliations are not repeated each time for multiple authors of the same affiliation. Please keep your affiliations as succinct as possible (for example, do not differentiate among departments of the same organization). This template was designed for two affiliations.

VI. Concluding Remarks

Online structural health monitoring can be achieved using Artificial Neural Network (ANN) in particularly composite materials to ensure safety of structure with low cost, short time and high effectiveness. Vibration characteristics are used hear as a good non-destructive indicator on structural health monitoring. The simple rule is that the natural frequency mode of a cracked structure is lower than natural frequency of the healthy beam. This will be used through training ANN by experimental or numerical data to predict the crack depth and location. Here, ANSYS software tool was used to generate vibration modes of several structures including solid and fibre reinforced composite beam to train the ANN software tool. Vibration analysis of fibre reinforced composite beam is particularly more complicated than solid beam.

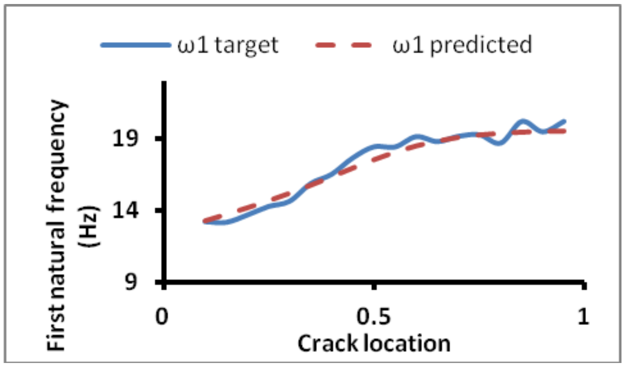

Figure 18 First natural frequency versus the non-dimensional crack locations for cantilever fibre reinforced composite beam

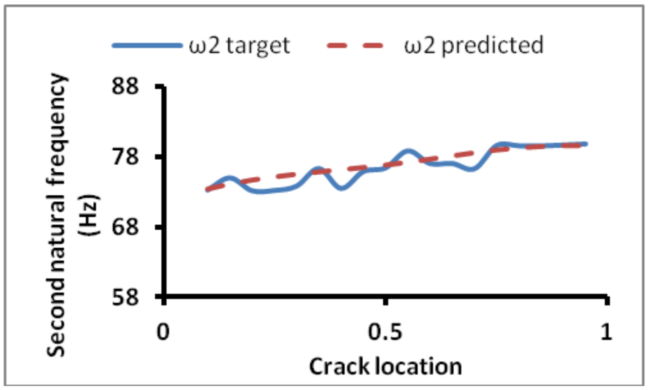

Figure 19 Second natural frequency versus the non-dimensional crack locations for cantilever fibre reinforced composite beam

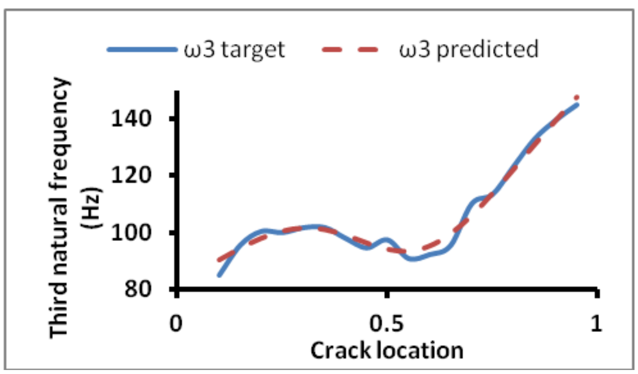

Figure 20 Second natural frequency versus the non-dimensional crack locations for cantilever fibre reinforced composite beam

(Crack depth ratio=0.7, ANSYS=solid line, ANN=dash line)

However, the good characteristics of fibre reinforced composite material like high strength-to-weight ratios stiffness-to-weight ratios has made this material the focus of attention for new applications in engineering. ANSYS software shows high accuracy in vibration analysis of the aforementioned structures. Hence, ANSYS results for a solid beam is first verified by some approved theoretical solutions. Then, artificial neural network has been trained using the ANSYS data. Next, the results of ANSYS and the trained ANN are compared for several solid and fibre reinforced beams for the first three important natural frequencies. The high accuracy of results suggests applicability of the discussed methodology to be implemented in practical health monitoring schemes. This is the subject of current research.

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