VIBRATIONAL ANALYSIS AND CRACK DETECTION OF A TAPERED CANTILEVER COMPOSITE BEAM WITH OPEN TRANSVERSE CRACK

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Abstract - *Damage detection methods have been considerably increased over the past few decades. A crack in a structural member introduces local flexibility that would affect vibration response of the structure. This property may be used to detect existence of a crack together with its location and depth in the structural member. The presence of damage leads to changes in some of the lower natural frequencies and mode shapes. Tapering beams are used in diversities for their economic, aesthetic and other considerations in architecture, aeronautics, robotics and other innovative engineering applications. More recently they have been the subject of numerous studies. Present study deals with the vibration and buckling behavior of linearly singly tapered wind turbine blades which is a composite beam with single open transverse crack. First three natural frequencies are found out using ANSYS software for many cracked locations and depths. Using the obtained data fuzzy logic controller was designed and the results obtained predict crack position with maximum error of 10.67% and crack depth with maximum error of 14.67%.*

Key Words: **Fuzzy logic, composite beam, tapered cantilever beam, membership functions, defuzzification, crack, vibrational analysis, matlab, ansys, FIS editor**

1. INTRODUCTION

Inspection of wind-turbine blade is quite difficult since they are multi-layered, has variable thickness and is made up of anisotropic materials such as composite materials which have high strength to weight ratio. So, they are inspected by non- destructive methods. This chapter describes the crack in beams, composite materials and the use of non-destructive methods such as artificial intelligence methods such as artificial neural network and fuzzy logic for the identification of cracks using the dynamic characteristics of beam.

2. THEORETICAL BACKGROUND

2.1 Crack Theory

The most common structural defect is the existence of a crack. Cracks are present in structures due to various reasons. The presence of a crack not only cause a local variation in the stiffness but it could affect the mechanical behavior of the entire structure to a considerable extent. They may also occur due to mechanical defects. Generally, they are small in sizes. Such small cracks are known to propagate due to fluctuating stress conditions. If these propagating cracks remain undetected and reach their critical size, then a sudden structural failure may occur.

1.3 Composite Structures

Composite materials are the macroscopic combination of two or more distinct materials with enhanced properties. The aim of using the composite materials is for high strength to weight ratio and to meet the applications with specific properties. The current study uses E-glass fibers glued together with epoxy glue. E-glass or electrical grade glass was originally developed for standoff insulators for electrical wiring. It was later found to have excellent fiber forming capabilities and is now used almost exclusively as the reinforcing phase in the material commonly known as fiber glass. Glass fibers and epoxy resins are glued together by means of hand lay-up process to attain the desired orientation and stacking sequences.

Fig -1: Preparation of specimen using hand lay up

2.3 Fuzzy Logic Technique

Fuzzy logic is a problem-solving control system methodology that lends itself for implementation in systems ranging from simple, small, embedded microcontrollers to large, networked, workstation-based data acquisition and control systems. The theory of fuzzy logic systems is inspired by the remarkable human capability to operate on and reason with perception-based information. The rule-based fuzzy logic provides a scientific formalism for reasoning and decision making with uncertain and imprecise information.

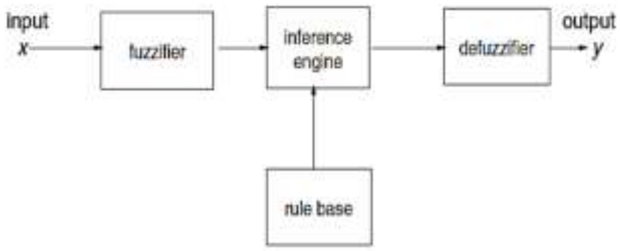

Fig- 2: Diagram of Fuzzy logic interference system

3 MODELLING AND ANALYSIS

3.1 Determination of Elastic Properties of Composite Beam

Fiber-reinforced polymer (FRP) is composed of two material phases: fiber and polymer matrix. Fibers are impregnated into the polymer matrix to form a macroscopically orthotropic layer of material with distinctly higher mechanical properties along the fiber direction compared to the transverse directions.

Table -1: Mechanical properties of glass fibre and polymer matrix

Material	Properties	values
Glass fiber	Elastic Modulus (GPa)	74
	Shear Modulus (GPa)	29.6
	Density (Kg/m³)	25000
	Poisons ratio	0.25
Epoxy resins	Elastic Modulus (GPa)	4
	Shear Modulus (GPa)	1.43
	Density (Kg/m³)	1100
	Poisons ratio	0.4

Following Equations are used for the determination of elastic properties.

$E_1=E_f.V_f+E_mV_m$

$E_2 = (E_fE_m)/ (V_mE_f + V_fE_m)$

Or $(1/E_2) = (V_m/ E_m) + (V_f/ B_f)$

$\mu_{12}= \mu_f.V_f + \mu_mV_m$

$G_{12} = (G_fG_m) / (V_mG_f + V_fG_m)$

Or $(1/G_{12}) = (V_m/G_m) + (V_f/G_f)$

Where,

E_1 = young's modulus in x direction

E_2 = young's modulus in y & z direction

G_{12}= Shear modulus

μ_{12}= poisons ratio in xy and yz directions

$\mu_{21=}$ poisons ratio in xz direction

Vf = fiber volume fraction

Vm= epoxy matrix volume fraction

Ef = young's modulus of fiber

Em= young's modulus of the epoxy matrix

V_m=1-vf

3.2 Vibrational Analysis Using Ansys 16.2 software

ANSYS is commercial finite element software with capability to analyze a wide range of different problems. Like any finite element software, ANSYS solves governing differential equations by breaking the problem into small elements.

SHELL 181 element is used for the analysis. SHELL181 is suitable for analyzing thin to moderately-thick shell structures. It is a four-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z axes. (If the membrane option is used, the element has translational degrees of freedom only). The degenerate triangular option should only be used as filler elements in mesh generation

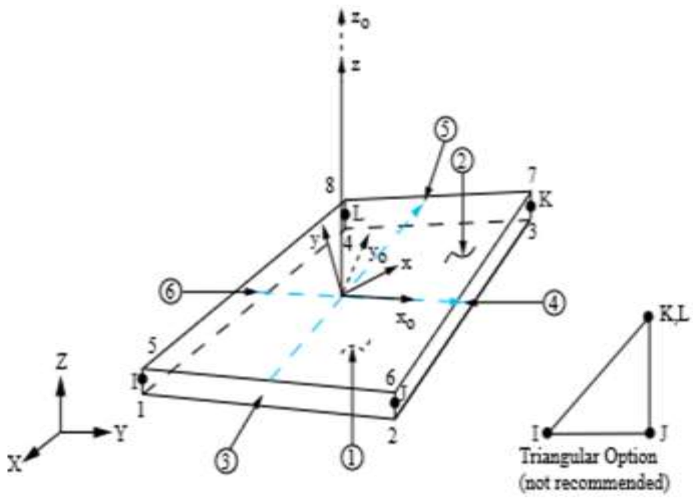

Fig -3: Shell 181 element

3.3 Modelling of Cracked and Un-Cracked Beams

Modal analysis is conducted for the free vibration responses of the beam. Design Modeler in ANSYS is used to create the geometry of both cracked and un-cracked beam which is then modeled in ANSYS Multiphysics.

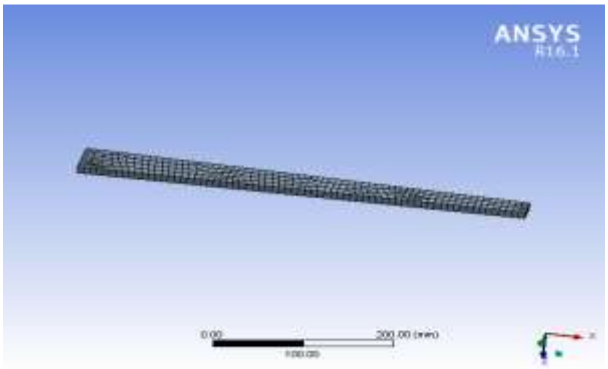

Fig -4: Meshing of healthy beam of ANSYS 16.1

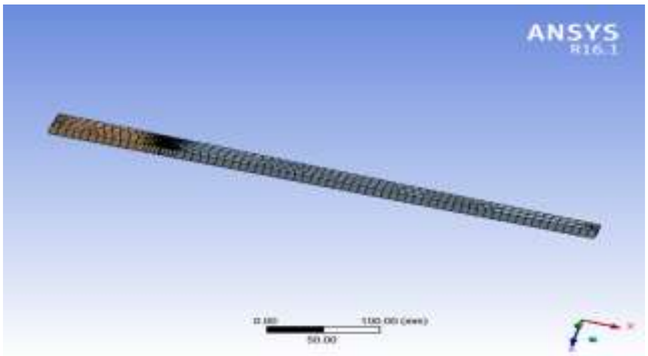

Fig -5 : Meshing of cracked beam at 100mm from fixed end 5mm depth

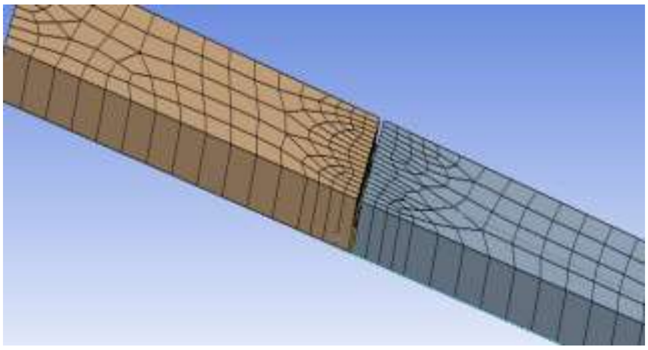

Fig -6: Meshing of the cracked portion

Layer	Material	Thickness (mm)	Angle (°)
(+Z)			
10	gfrp	1	90
9	gfrp	1	0
8	gfrp	1	90
7	gfrp	1	0
6	gfrp	1	90
5	gfrp	1	0
4	gfrp	1	90
3	gfrp	1	0
2	gfrp	1	90
1	gfrp	1	0
(-Z)			

Fig -7: fibre orientation and layer stacking in ANSYS 16.2

Each fabric layer corresponds to 2 different fiber orientations (fibers at 0°and 90°), two different layers were used to simulate each ply. Figure 7 shows the stacking sequences of laminates in ANSYS 16.2. The finite element analysis using ANSYS software was used in modal analysis to obtain the natural frequencies. The cracked zone mesh has been properly refined and the convergent test was carried out for all the results and it is shown in fig 7.

3.4 Fuzzy Logic Technique For Crack Detection

Fuzzy logic is a tool for Embedding Human structured knowledge (Experience, Expertise and Heuristic). P.L. Zadeh says: "Fuzzy Logic may be viewed as a bridge over the excessively wide gap between the precision of classical crisp logic and the imprecision of both the real world and its human interpretation". Fozzy logic attempts to model the way of reasoning that goes in the human brain. Almost all of human experience is stored in the form of the If-Then rules. Human reasoning is pervasively approximate, non-quantitative, linguistic and dispositional.

3.4.1 Fuzzy set

A fuzzy set, as the name implies, is a set without a crisp boundary. That is the transition from "belongs to a set" to not belong to a set is gradual and this smooth transition is characterized by membership functions that give fuzzy sets flexibility in modeling commonly used linguistic expressions. A membership function assigns to each element in the set under consideration a membership grade, which is a value in the interval [0, 1].

3.4.2 Membership functions

The basic structure of a fuzzy interface system consists of three components: a rule base, which contains a selection of fuzzy rules, a database which defines thememembership functions used in the fuzzy rules and a reasoning mechanism, which performs the interface procedure. The membership function μA(x) describes the membership of the elements x of the base set X in fuzzy set A, where by μA(x) a large class of function can be taken. Reasonable functions are often piecewise linear function, such as triangular or trapezoidal functions. The value for the membership function can be taken in the interval [0, 1]. When the functions are nonlinear the Gaussian membership function will be taken for the smooth operation.

3.4.3 Fuzzy Logic

In Crisp logic, the truth values acquired by proposition or predicates are 2-valued, namely True, False which may be treated numerically equivalent to (0, 1). However in fuzzy logic, truth values are multivalued such as absolutely false, partly true, absolutely false, and very true and so on and are numerically equivalent to 0-1.

3.4.4 Fuzzy if then rule

A fuzzy if-then rule (also known as fuzzy rule, fuzzy implication or fuzzy conditional statement) assumes the form "if x is A then y is B". Where A and B are linguistic values defined by fuzzy sets on universes of discourse x and y respectively. Often "x is A" is called the antecedent or premise, while "y is B" is called the consequence or conclusion.

3.4.5 Fuzzy Mechanism used for Crack Detection

The fuzzy controller has been developed where there are 3 inputs and 2 outputs parameter. The natural linguistic representations for the input are as follows

Relative first natural frequency = "F"

Relative second natural frequency = "S"

Relative third natural frequency = "T"

The natural linguistic term used for the outputs are

Relative crack depth = "D"

Relative crack length= "L"

The crisp values of relative crack location and relative crack depth are computed using the center of gravity method

4 RESULTS AND DISCUSSIONS

4.1 Modal analysis data for the design of fuzzy controller

For the design of fuzzy logic technique was obtained from the modal analysis. Cracks were modelled at 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 320, 340, 360, 380, 400, 420, 440, 460 and 480mm from the fixed end at depths 1, 2, 3, 4, 5, 6mm from the top of the beam.

In order to design the fuzzy interference system, the data obtained from Ansys 16.2 is normalized by dividing it with the natural frequencies of the healthy beam.

The results obtained from the modal analysis shows variations in the first three natural frequencies. These variations are shown in the following graphs. The graph is plotted for various crack locations. It also shows that when the crack location is nearer to the fixed end, it states a steep slope and when the crack location moves to the free end the graph becomes straighter.

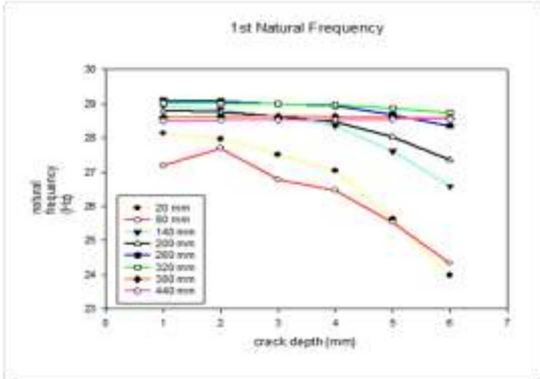

Fig -8: Variation of first natural frequency for various crack locations

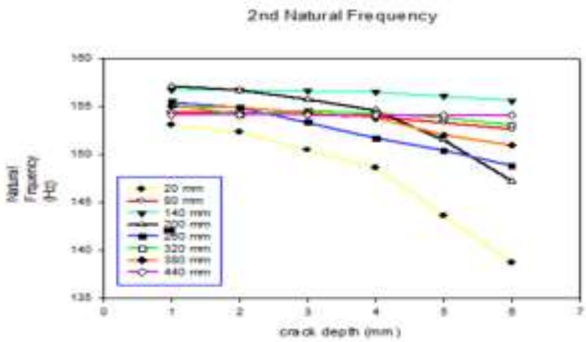

Fig -9: Variation of second natural frequency for various crack locations

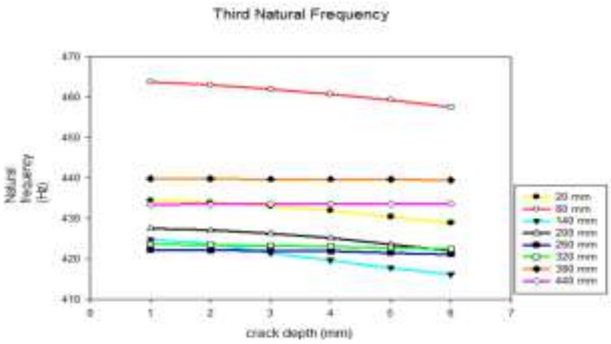

Fig -10: Variation of third natural frequency for various crack locations

4.2 CRACK IDENTIFICATION USING FUZZY LOGIC TECHNIQUE

A fuzzy interface system in MATLAB is used for the design of fuzzy controller for the crack identification.

Triangular membership functions have been used to define the input and output membership functions. Thirteen membership functions are defined for the first relative natural frequency ranging from F1 to F13. Fourteen membership functions have been defined for the second relative natural frequency ranging from S1 to S14. Twelve membership functions have been defined for the third relative natural frequency ranging from T1 to T12. Twenty-three membership functions have been defined for the third relative crack location ranging from L1 to L23. Six membership functions have been defined for the third relative crack depth ranging from D1 to D6.

Relative natural frequencies of cracked beam is the ratio of natural frequencies of the cracked beam to the natural frequencies of the un-cracked beam. Relative crack depth is the ratio of the depth of the crack from the top of the beam to the depth of the beam i.e. 10 mm. Relative crack position is the ratio of the position of crack from the fixed end to the total length of the beam i.e. 500mm.

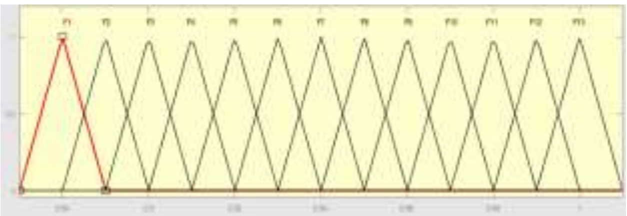

Fig -11: triangular membership functions for the first relative natural frequency

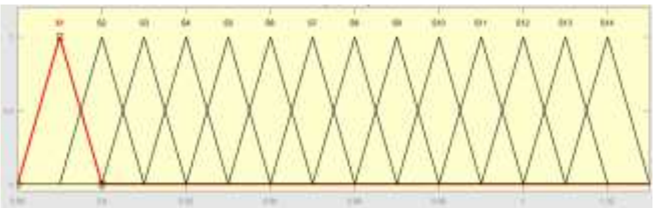

Fig -12: triangular membership functions for the second relative natural frequency

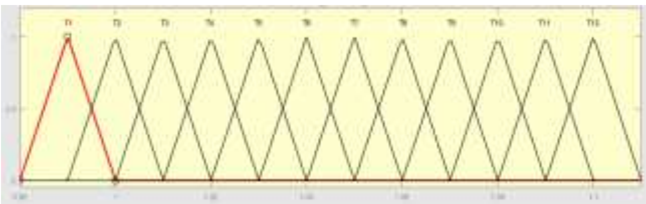

Fig -13: triangular membership functions for the third relative natural frequency

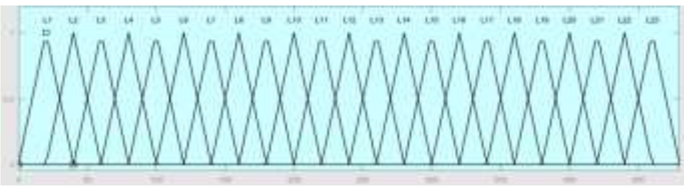

Fig -14: triangular membership functions for the relative crack location

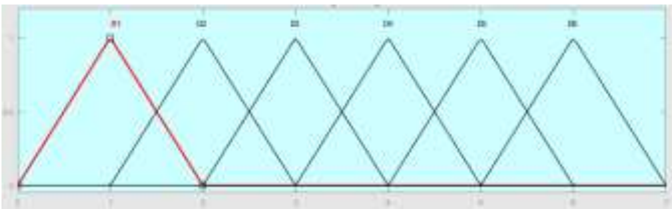

Fig -15: Triangular membership functions for the relative crack depth

In order to design the fuzzy controller about 108 fuzzy rules have been defined, referring almost various crack cases.

Table -2: Few set of rules defined in the Fuzzy System

Sl. No.	Rules	weight
1	If(F is F1) and (S is S1) and (T is T1) then(L is L1) (D is D1)	0.75
2	If(F is F10) and (S is S10) and (T is T5) then(L is L1) (D is D2)	0.5
3	If(F is F8) and (S is S8) and (T is T4) then(L is L1) (D is D3)	0.25
4	If(F is F7) and (S is S7) and (T is T4) then(L is L1) (D is D4)	0.25
5	If(F is F2) and (S is S4) and (T is T4) then(L is L1) (D is D5)	0.75
6	If(S is S5) and (T is T4) then(L is L1) (D is D6)	0.75
7	If(F is F10) and (S is S11) and (T is T5) then(L is L2) (D is D1)	0.5
8	If(F is F10) and (S is S10) and (T is T5) then(L is L2) (D is D2)	0.25
9	If(F is F7) and (S is S10) and (T is T5) then(L is L2) (D is D3)	0.5
10	If(F is F7) and (S is S9) and (T is T5) then(L is L2) (D is D4)	0.5
11	If(F is F2) and (S is S7) and (T is T5) then(L is L2) (D is D5)	0.75
12	If (S is S5) and (T is T4) then(L is L2) (D is D6)	1
13	If(F is F8) and (S is S11) and (T is T9) then(L is L3) (D is D1)	0.5
14	If(F is F7) and (S is S11) and (T is T9) then(L is L3) (D is D2)	0.75
15	If(F is F6) and (S is S10) and (T is T9) then(L is L3) (D is D3)	0.75

For the testing of the fuzzy controller a cracked beam with various crack location and crack depth is taken in the rule viewer in FIS EDITOR, MATLAB. It has been seen that the desired output is obtained without much difference with the ANSYS results. The crisp output values are obtained by defuzzification using the centroid of area method.

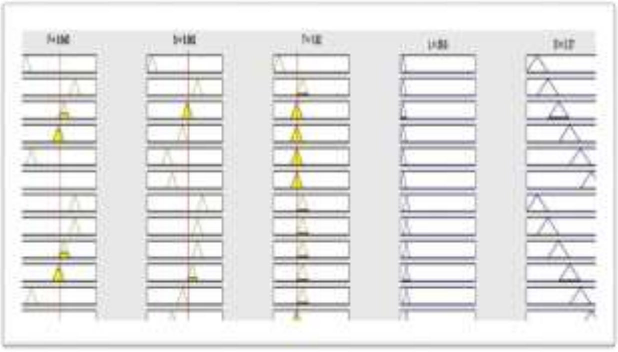

Fig -16: Fuzzy System Result on Crack location 30 mm and crack depth 3 mm and rule No. 3 and 10 is activated.

Fig -17: Fuzzy System Result on Crack location 50 mm and crack depth 2 mm and rule No. 2, 7, 8 and 13 is activated

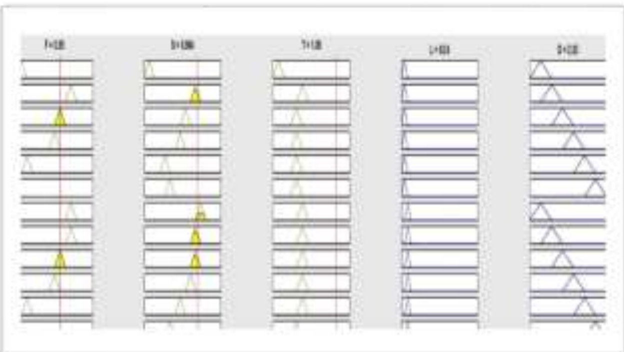

Fig -18: Fuzzy System Result on Crack location 70 mm and crack depth 3 mm and rule No. 14 and 24 is activated

Fig -19: Defuzzification by centroids of area rule when the input [0.964;0.9845;1.024] is given for crack location 30 mm and crack depth 3 mm

5 CONCLUSION

From the discussions, it has been concluding that the natural frequencies of the structure are varied when there occurs a change in the geometry or mass. Here the model has changed due to the presence of crack, since the presence of crack leads to the change in the local flexibility of the structure. By using this theory, a controller has been designed to program the changes in natural frequency and its effect on the crack variations. Since the programming using the data will not achieve the crisp output as in the case of normal programming, an artificial intelligence technique has been introduced, where an amount of human reasoning has to be applied for the results. So, a fuzzy controller has been designed and the results obtained are with a maximum of 8.8% error in crack location identification and 24.68 % error in crack depth identification.

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