"ONLINE FUNCTION MONITORING OF FAULTY BEAM (CRACKED) USING FUZZY LOGIC TECHNIQUE"

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By

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CERTIFICATE

This is to certify that the project entitled, “ONLINE FUNCTION MONITORING OF FAULTY BEAM (CRACKED) USING FUZZY LOGIC TECHNIQUE” submitted by ‘Mr. Shivam Gupta’ in partial fulfillments for the requirements for the award of Bachelor of Technology Degree in Mechanical Engineering at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the report has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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ABSTRACT

Early detection of damage is of special concern for engineering structures. The traditional methods of damage detection include visual inspection or instrumental evaluation. A comparatively recent development for the diagnosis of structural crack location and size by using the finite element method and Fuzzy logics techniques. A method based on measurement of natural frequencies is presented for detection of the location and size of a crack in a cantilever beam. Numerical and programming in MATLAB is done for solving the eular equation for un-crack beam to obtain first three natural frequencies of different modes of vibration considering various boundary conditions for the beam. Here ALGOR software package is used for finite element analysis of both crack and un-crack cantilever beam taking input file as a CAD design developed in AUTOCAD 2006. Experiments is done for total 21 models of crack beam having different crack location and crack depth and it generates natural frequency for 5 modes of vibration. Fuzzy controller here used comprises of three input variables (fnf, snf, tnf) with Gaussian MF and two output variables (rcl, rcd) are generated with Triangular MF. Fuzzy analysis is done based on some set of fuzzy rules obtained from the information supplemented by finite element analysis and numerical analysis. The proposed approach has been verified by comparing results obtained from fuzzy logic technique and finite element analysis.

The results show the successful detection of the undamaged and damaged states of structural part with very good accuracy and repeatability.

CHAPTER 1

GENERAL INTRODUCTION

1.1 Introduction:

All things vibrate. Think of musical instruments, think of riding in a car, think of the tires being out of balance, think of the rattles in an airplane when the pilot is revving up the engines or the vibration under your feet when a train goes by. Usually, however, vibration is bad and frequently unavoidable. It may cause gradual weakening of structures and the deterioration of metals (fatigue) in cars and airplanes.

Vibration is about frequencies. By its very nature, vibration involves repetitive motion. Each occurrence of a complete motion sequence is called a cycle. Frequency is defined as so many cycles in a given time period. One cycle per second is equivalent to one Hertz.

Cracks present in machine parts affect their vibrational behaviour like the fundamental frequency and resonance. The amplitude of vibration increases and the occurrence of resonance shifted as crack length increases. Structural failure refers to loss of the load carrying capacity of a component or member within a structure or of the structure itself. Structural failure is initiated when the material is stressed to its strength limit, thus causing fracture or excessive deformations. When this limit is reached, damage to the material has been done, and its load-bearing capacity is reduced permanently, significantly and quickly. In a well-designed system, a localized failure should not cause immediate or even progressive collapse of the entire structure. Ultimate failure strength is one of the limit states that must be accounted for in structural engineering and structural design. Therefore intensive research has been going on amongst the scientists and engineers to find an effective methodology to predict the location and intensity of damage beforehand.

So in this report I am presenting two different approaches. First approach refers to:

1) Fuzzy Logic
2) FEA

1.2 Fuzzy Logic:

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multi-valued logic . But in a wider sense, which is in predominant use today, fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree. Fuzzy logic is a convenient way to map an input space to an output space. Fuzzy logic is all about the relative importance of precision: How important is it to be exactly right when a rough answer will do? In contrast with binary sets having binary logic, also known as crisp logic, the fuzzy logic variables may have a membership value of only 0 or 1. Just as in fuzzy set theory with fuzzy logic the set membership values can range (inclusively) between 0 and 1, in fuzzy logic the degree of truth of a statement can range between 0 and 1 and is not constrained to the two truth values {true (1), false (0)} as in classic predicate logic. And when linguistic variables are used, these degrees may be managed by specific functions, as discussed below. Fuzzy logic has been applied to diverse fields, from control theory to artificial intelligence, yet still remains controversial among most statisticians, who prefer Bayesian logic, and some control engineers, who prefer traditional two-valued logic.

1.3 Importance of Fuzzy Logic:

Here is a list of general observations about fuzzy logic:

- **Fuzzy logic is conceptually easy to understand:** The mathematical concepts behind fuzzy reasoning are very simple. What makes fuzzy nice is the "naturalness" of its approach and not its far-reaching complexity.
- **Fuzzy logic is flexible:** With any given system, it's easy to massage it or layer more functionality on top of it without starting again from scratch.
- **Fuzzy logic is tolerant of imprecise data:.** Everything is imprecise if you look closely enough, but more than that, most things are imprecise even on careful inspection. Fuzzy reasoning builds this understanding into the process rather than tacking it onto the end.

- **<u>Fuzzy logic can model nonlinear functions of arbitrary complexity</u>:** You can create a fuzzy system to match any set of input-output data. This process is made particularly easy by adaptive techniques like Adaptive Neuro-Fuzzy Inference Systems (ANFIS), which are available in the Fuzzy Logic Toolbox.
- **<u>Fuzzy logic can be built on top of the experience of experts</u>:** In direct contrast to neural networks, which take training data and generate opaque, impenetrable models, fuzzy logic lets you rely on the experience of people who already understand your system.
- **<u>Fuzzy logic can be blended with conventional control techniques</u>:** Fuzzy systems don't necessarily replace conventional control methods. In many cases fuzzy systems augment them and simplify their implementation.
- **<u>Fuzzy logic is based on natural language</u>:** The basis for fuzzy logic is the basis for human communication. This observation underpins many of the other statements about fuzzy logic.

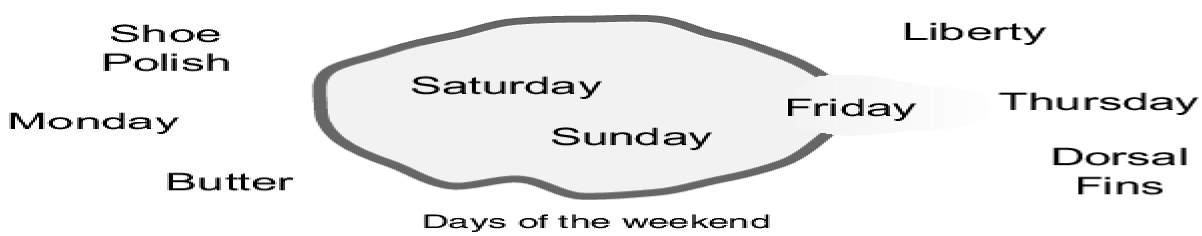
1.4 Foundation Of Fuzzy Logic:

1) Fuzzy Set
2) Membership Function
3) Logical Operations
4) If-Then Rules

Fuzzy Set:

Fuzzy logic starts with the concept of a fuzzy set. A fuzzy set is a set without a crisp, clearly defined boundary. It can contain elements with only a partial degree of membership.

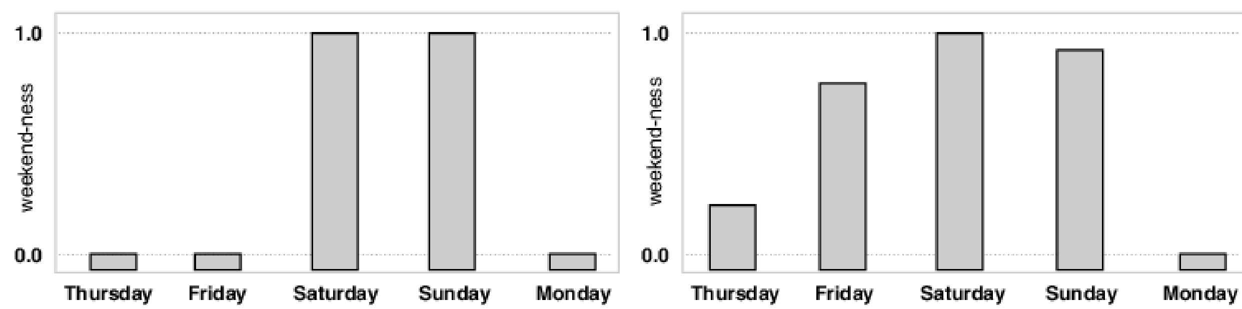
To understand what a fuzzy set is, first consider what is meant by what we might call a classical set. A classical set is a container that wholly includes or wholly excludes any given element. For example, consider the set of days comprising a weekend. The diagram below is one attempt at classifying the weekend days.



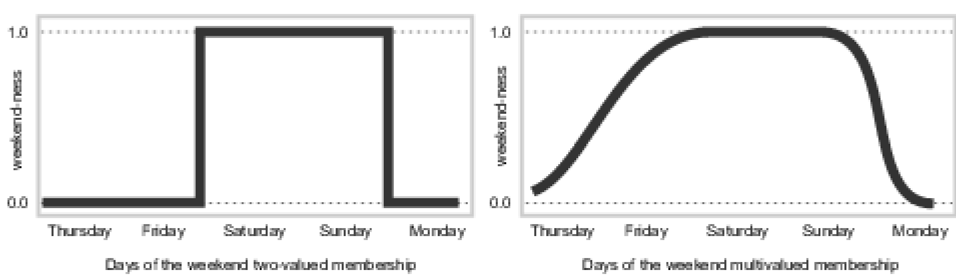
Most would agree that Saturday and Sunday belong, but what about Friday? It feels like a part of the weekend, but somehow it seems like it should be technically excluded. So in the diagram above Friday tries its best to sit on the fence. Classical or normal sets wouldn't tolerate this kind of thing. Either you're in or you're out. Human experience suggests something different, though: fence sitting is a part of life.

“In fuzzy logic, the truth of any statement becomes a matter of degree.”

Below on the left is a plot that shows the truth values for weekend-ness if we are forced to respond with an absolute yes or no response. On the right is a plot that shows the truth value for weekend-ness if we are allowed to respond with fuzzy in-between values.



now consider a continuous scale time plot of weekend-ness shown below.



Membership Function:

A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. The input space is sometimes referred to as the universe of discourse, a fancy name for a simple concept.

A classical set might be expressed as

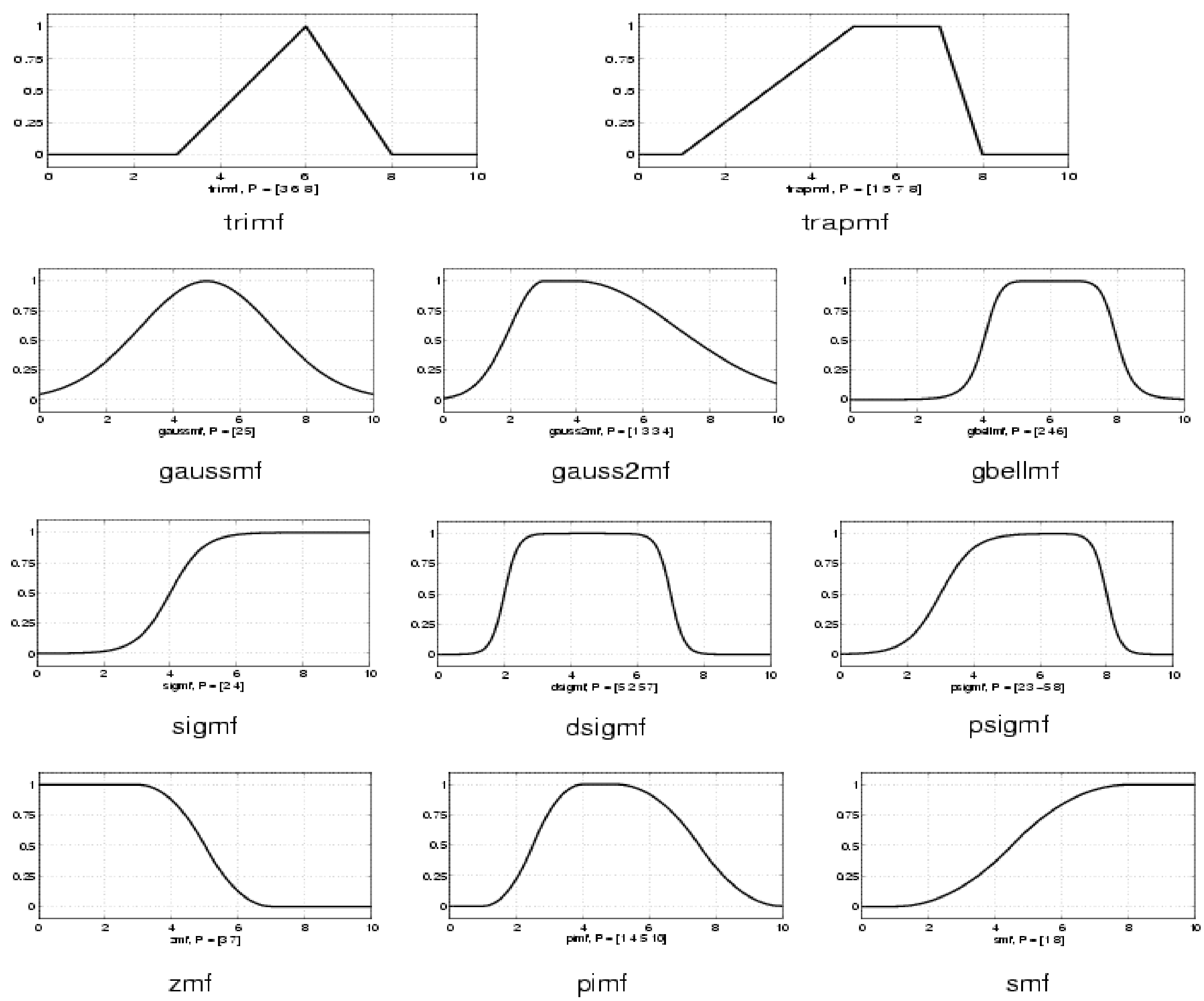
$A = \{x \mid x > 6\}$

A fuzzy set is an extension of a classical set. If X is the universe of discourse and its elements are denoted by x, then a fuzzy set A in X is defined as a set of ordered pairs.

$A = \{x, \mu A(x) \mid x \in X\}$

$\mu A(x)$ is called the membership function (or MF) of x in A. The membership function maps each element of X to a membership value between 0 and 1.

The Fuzzy Logic Toolbox includes 11 built-in membership function types. These 11 functions are, in turn, built from several basic functions: piecewise linear functions, the Gaussian distribution function, the sigmoid curve, and quadratic and cubic polynomial curves. For detailed information on any of the membership functions mentioned below, turn to Functions — Alphabetical List. By convention, all membership functions have the letters mf at the end of their names.



Logical Operations:

The most important thing to realize about fuzzy logical reasoning is the fact that it is a superset of standard Boolean logic. In other words, if we keep the fuzzy values at their extremes of 1 (completely true), and 0 (completely false), standard logical operations will hold. As an example, consider the standard truth tables below:

A	B	min(A,B)
0	0	0
0	1	0
1	0	0
1	1	1

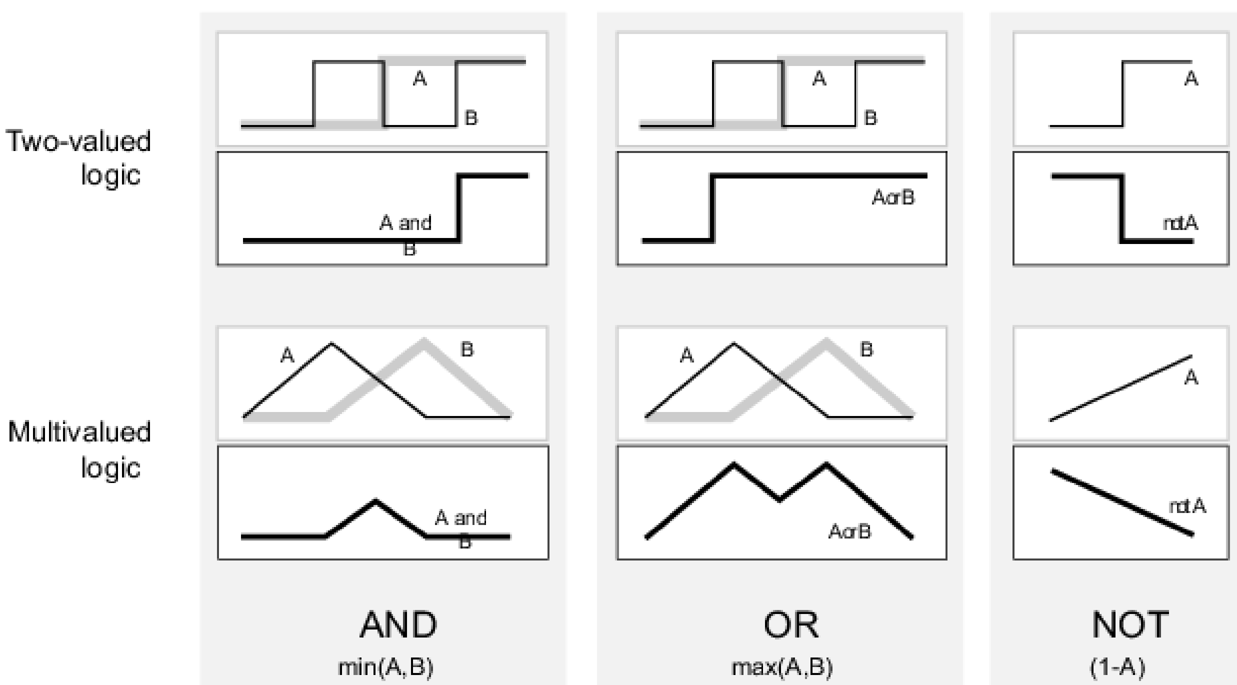
Fuzzy Intersection (AND)

A	B	max(A,B)
0	0	0
0	1	1
1	0	1
1	1	1

Fuzzy Union (OR)

A	1 - A
0	1
1	0

Fuzzy Complement (NOT)



If-Then Rules:

Fuzzy sets and fuzzy operators are the subjects and verbs of fuzzy logic. These if-then rule statements are used to formulate the conditional statements that comprise fuzzy logic. A single fuzzy if-then rule assumes the form if x is A then y is B where A and B are linguistic values defined by fuzzy sets on the ranges (universes of discourse) X and Y, respectively. The if-part of the rule "x is A" is called the antecedent or premise, while the then-part of the rule "y is B" is called the consequent or conclusion.

Interpreting if-then rules is a three-part process. This process is explained in detail in the next section:

1) **Fuzzy inputs:** Resolve all fuzzy statements in the antecedent to a degree of membership between 0 and 1. If there is only one part to the antecedent, this is the degree of support for the rule.

2) **Apply fuzzy operator to multiple part antecedents:** If there are multiple parts to the antecedent, apply fuzzy logic operators and resolve the antecedent to a single number between 0 and 1. This is the degree of support for the rule.

3) **Apply implication method:** Use the degree of support for the entire rule to shape the output fuzzy set. The consequent of a fuzzy rule assigns an entire fuzzy set to the output. This fuzzy set is represented by a membership function that is chosen to indicate the qualities of the consequent.

1.5 Fuzzy Inference System:

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. The process of fuzzy inference involves all of the pieces that are described in the previous sections: membership functions, fuzzy logic operators, and if-then rules. There are two types of fuzzy inference systems that can be implemented in the Fuzzy Logic Toolbox: Mamdani-type and Sugeno-type.

Fuzzy inference systems have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems, and computer vision. Because of its multidisciplinary nature, fuzzy inference systems are associated with a number of names, such as fuzzy-rule-based systems, fuzzy expert systems, fuzzy modeling, fuzzy associative memory, fuzzy logic controllers, and simply (and ambiguously) fuzzy systems.

In the Fuzzy Logic Toolbox, there are five parts of the fuzzy inference process: fuzzification of the input variables, application of the fuzzy operator (AND or OR) in the antecedent, implication from the antecedent to the consequent, aggregation of the consequents across the rules, and defuzzification.

Step 1. Fuzzify Inputs: The first step is to take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. In the Fuzzy Logic Toolbox, the input is always a crisp numerical value limited to the universe of discourse of the input variable (in this case the interval between 0 and 10) and the output is a fuzzy degree of membership in the qualifying linguistic set (always the interval between 0 and 1). Fuzzification of the input amounts to either a table lookup or a function evaluation.

Step 2. Apply Fuzzy Operator: Once the inputs have been fuzzified, we know the degree to which each part of the antecedent has been satisfied for each rule. If the antecedent of a given rule has more than one part, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. This number will then be applied to the output function.

n the Fuzzy Logic Toolbox, two built-in AND methods are supported: min (minimum) and prod (product). Two built-in OR methods are also supported: max (maximum), and the probabilistic OR method probor.

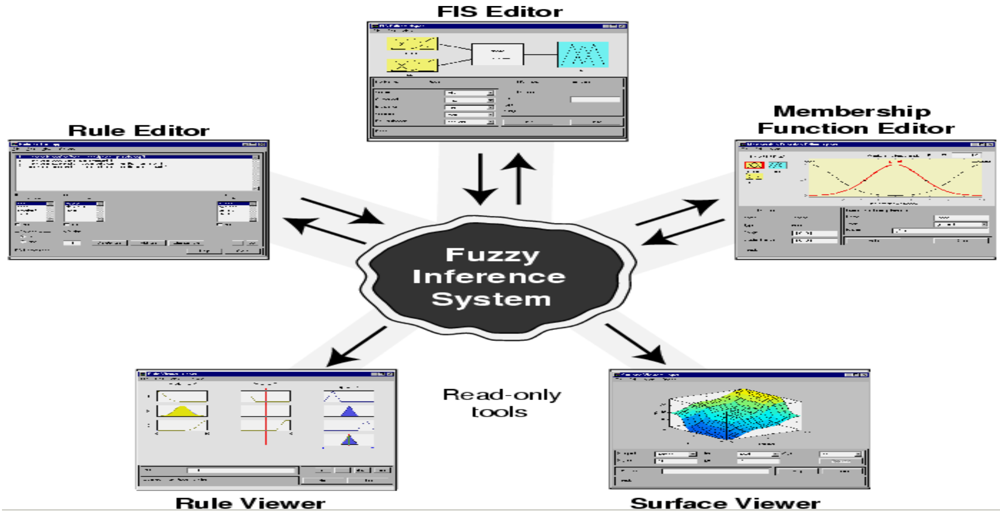
Step 3. Apply Implication Method: Before applying the implication method, we must take care of the rule's weight. Every rule has a weight (a number between 0 and 1), Once proper weighting has been assigned to each rule, the implication method is implemented. The input for the implication process is a single number given by the antecedent, and the output is a fuzzy set. Implication is implemented for each rule.

Step 4. Aggregate All Outputs: Since decisions are based on the testing of all of the rules in an FIS, the rules must be combined in some manner in order to make a decision. Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set. The output of the aggregation process is one fuzzy set for each output variable.

Step 5. Defuzzify: The input for the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output is a single number. As much as fuzziness helps the rule evaluation during the intermediate steps, the final desired output for each variable is generally a single number. Perhaps the most popular defuzzification method is the centroid calculation, which returns the center of area under the curve.

1.6 Building System with the Fuzzy Logic Toolbox:

For building a system we will use the graphical user interface (GUI) tools provided by the Fuzzy Logic Toolbox. Although it is possible to use the Fuzzy Logic Toolbox by working strictly from the command line, in general it is much easier to build a system graphically. There are five primary GUI tools for building, editing, and observing fuzzy inference systems in the Fuzzy Logic Toolbox:



1) **The Fuzzy Inference System or FIS Editor:** The FIS Editor handles the high-level issues for the system: How many input and output variables? What are their names? The Fuzzy Logic Toolbox doesn't limit the number of inputs.
2) **The Membership Function Editor:** The Membership Function Editor is used to define the shapes of all the membership functions associated with each variable.
3) **The Rule Editor:** The Rule Editor is for editing the list of rules that defines the behavior of the system.

4) **<u>The Rule Viewer</u>:** They are strictly read-only tools. The Rule Viewer is a MATLAB based display of the fuzzy inference diagram shown at the end of the last section. Used as a diagnostic, it can show (for example) which rules are active, or how individual membership function shapes are influencing the results.

5) **<u>The Surface Viewer</u>:** The Surface Viewer is used to display the dependency of one of the outputs on any one or two of the inputs — that is, it generates and plots an output surface map for the system.

1.7 What Is Finite Element Analysis?

The finite element method works by breaking a real object down into a large number (1,000s to 100,000s) of elements, such as little cubes. The behavior of each little element, which is regular in shape, is readily predicted by set mathematical equations. The computer then adds up all of the individual behaviors to predict the behavior of the actual object.

The finite in finite element analysis comes from the idea that there are a finite number of elements in a finite element model. Previously, engineers employed integral and differential calculus, which breaks objects down into an infinite number of elements.

The finite element method is employed to predict the behavior of things with respect to virtually all physical phenomena:

- Mechanical stress (stress analysis)
- Mechanical vibration
- Heat transfer (conduction, convection and radiation)
- Fluid flow (Both liquids and gaseous fluids)
- Various electrical and magnetic phenomena
- Acoustics

➢ What Is Node?

A node is a coordinate location in space where the degrees of freedom (DOFs) are defined. The DOFs for this point represent the possible movement of this point due to the loading of the structure. The DOFs also represent which forces and moments are transferred from one element to the next. The results of a finite element analysis, (deflections and stresses), are usually given at the nodes.

- What Is An Element?

An element is the basic building block of finite element analysis. An element is a mathematical relation that defines how the degrees of freedom of a node relate to the next. These elements can be lines (trusses or beams), areas (2-D or 3-D plates and membranes) or solids (bricks or tetrahedrals).

1.8 Applications OF FEA:

FEA has become a solution to the task of predicting failure due to unknown stresses by showing problem areas in a material and allowing designers to see all of the theoretical stresses within. This method of product design and testing is far superior to the manufacturing costs which would accrue if each sample was actually built and tested. Here cracked beam has been analyzed through finite element method using software known as ALGOR. This software package has several applications in mechanical event simulation and computational fluid dynamics. Here it is used for finite element analysis of natural frequency modal of cracked beam where the input is been given from CATIA designing software. The mesh is generated in the input modal and then after specifying boundary conditions it is analyzed in FEA editor which finally gives output in three modes natural frequencies.

1.9 Typical Steps in FEA Using ALGOR:

In a typical stress analysis, there is a basic set of steps that the analysis usually follows:

1. Create a mesh (a grid of nodes and elements) that represents the model
2. Define a unit system
3. Define the model's analysis parameters
4. Define the element type and parameters
5. Apply the loads and the constraints
6. Assemble the element stiffness matrices
7. Solve the system of linear algebraic equations
8. Calculate the results
9. Review the results
10. Generate a report of the analysis results

These steps are usually broken up into three stages:

- Setting up the model: Steps 1-5
- Analyzing the model: Steps 6-8 (These steps are automatically performed by ALGOR)
- Results evaluation: Steps 9 and 10

CHAPTER 2

LITERATURE SURVEY

Different researchers have discussed damage detection of vibrating structures in various ways. They are summarized below.

Free and forced vibration analysis of a cracked beam were performed by S Orhan et al. [1] in order to identify the crack in a cantilever beam. Single- and two-edge cracks were evaluated. The study results suggest that free vibration analysis provides suitable information for the detection of single and two cracks, whereas forced vibration can detect only the single crack condition. However, dynamic response of the forced vibration better describes changes in crack depth and location than the free vibration in which the difference between natural frequencies corresponding to a change in crack depth and location only is a minor effect. The Euler–Bernoulli beam model was assumed. The crack is assumed to be an open crack and the damping has not been considered in this study. A fault diagnosis method based on genetic algorithms (GAs) and a model of damaged (cracked) structure is proposed by M Taghi V Baghmisheh, M Peimani, M. H. Sadeghi and M M Ettefagh et al. [2]. For modeling the cracked-beam structure an analytical model of a cracked cantilever beam is utilized and natural frequencies are obtained through numerical methods,. The identification of the crack location and depth in the cantilever beam is formulated as an optimization problem, and binary and continuous genetic algorithms (BGA, CGA) are used to find the optimal location and depth by minimizing the cost function.

F Léonard, J Lanteigne, S Lalonde and Y Turcotte et al. [3] proposed a study based on cracks that occurred in metal beams obtained under controlled fatigue-crack propagation. Spectrograms of the free-decay responses showed a time drift of the frequency and damping: the usual hypothesis of constant modal parameters is no longer appropriate, since the latter are revealed to be a function of the amplitude. An experimental investigation has been carried out by M. Karthikeyan and R. Tiwari et al. [4] to establish an identification procedure for the detection, localization, and sizing of a flaw in a beam based on forced response measurements. The experimental setup consisted of a circular beam, which was supported by rolling bearings at both ends. The actual force applied to the beam was measured by a piezoelectric force transducer Resonant frequencies, amplitude, and phase information of responses were utilized in the identification algorithm for subsequent estimation of flaw parameters. The method of detection of location of crack in beams based on frequency measurements is proposed by S. P. Lele and S. K. Maiti et al. [5] is extended here to short beams, taking into account the effects of shear deformation and rotational inertia through the Timoshenko beam theory and representing the crack by a rotational spring. Methods for solving both forward (determination of frequencies of beams knowing the crack parameters) and inverse (determination of crack location knowing the natural frequencies) problems are included.

Sensibility analysis of the inverse problem of the crack parameters (location and depth) determined by M B Rosales, C P Filipich and F S Buezas et al. [6]. An efficient numerical technique is necessary to obtain significant results. Two approaches are herein presented: The solution of the inverse problem with a power series technique (PST) and the use of artificial neural networks (ANNs). An alternative technique for crack detection in a Timoshenko beam is proposed by W Dansheng, Z Hongping, C Chuanyao and X Yong et al. [7] based on the first anti-resonant frequency. Unlike the natural frequency, the anti-resonant frequency is a local parameter rather than a global parameter of structures. An impedance analysis of a cracked beam stimulated by a harmonic force based on the Timoshenko beam formulation is investigated the proposed method is verified by a numerical example of a simply-supported beam with a crack. Identification of crack location and depth in a cantilever beam using a modular neural network approach is proposed by S Suresh, S N Omkar, R Ganguli and V Mani et al. [8]. The flexural vibration in a cantilever beam having a transverse surface crack is considered and the modal frequency parameters are analytically computed for various crack locations and depths using a fracture mechanics based crack model. These computed modal frequencies are used to train a neural network to identify both the crack location and depth.

A model-based approach is developed by Zhigang Yu and Fulei Chu et al. [9] to determine the location and size of an open edge crack in an FGM beam. The *p*-version of finite element method is employed to estimate the transverse vibration characteristics of a cracked FGM beam. A rational approximation function of the stress intensity factor (SIF) with crack depth and material gradient as independent variables is presented in order to overcome the cumbersomeness and inaccurateness caused by the complicated expression of the analytical SIF solution in crack modeling. An analytical, as well as experimental approach by H. Nahvi and M.

Jabbari et al. [10] to the crack detection in cantilever beams by vibration analysis is established. An experimental setup is designed in which a cracked cantilever beam is excited by a hammer and the response is obtained using an accelerometer attached to the beam. The proposed method is based on measured frequencies and mode shapes of the beam. An analytical approach for crack identification procedure in uniform beams with an open edge crack, based on bending vibration measurements, is developed by N. Khaji, M. Shafiei and M. Jalalpour et al. [11]. The method is based on the assumption that the equivalent spring stiffness does not depend on the frequency of vibration, and may be obtained from fracture mechanics. The results provide simple expressions for the characteristic equations, which are functions of circular natural frequencies, crack location, and crack depth. a new method for crack detection in beams based on instantaneous frequency and empirical mode decomposition is proposed by S. Loutridis, E. Douka and L.J. Hadjileontiadis et al.[12]. The dynamic behaviour of a cantilever beam with a breathing crack under harmonic excitation is investigated both theoretically and experimentally The time-varying stiffness is modelled using a simple periodic functionIt follows that the harmonic distortion increases with crack depth following definite trends and can be also used as an effective indicator for crack size.

The research work by W Zhang, Z Wang and H Ma et al. [13] illustrates the crack identification method combining wavelet analysis with transform matrix. Firstly, the fundamental vibration mode was applied to wavelet analysis. Secondly, based on the identified crack locations, a simple transform matrix method requiring only the first two tested natural frequencies was used to further identify the crack depth. Nonlinear vibration of beams made of functionally graded materials (FGMs) containing an open edge crack is studied by S. Kitipornchai, L.L. Ke, J. Yang and Y. Xiang et al. [14] based on Timoshenko beam theory and von Kármán geometric nonlinearity. The Ritz method is employed to derive the governing eigenvalue equation which is then solved by a direct iterative method to obtain the nonlinear vibration frequencies of cracked FGM beams with different end supports. An analysis of cracked beam structure using impact echo method proposed by E Çam, S Orhan and M Lüy et al. [15]. Here the vibrations as a result of impact shocks were analyzed. The signals obtained in defect-free and cracked beams were compared in the frequency domain Experimental results and simulations obtained by the software ANSYS.

A theoretical and experimental dynamic behavior of different multi-beams systems containing a transverse crack is presented by P. N. Saavedra and L. A. Cuitiño et al. [16]. The additional flexibility that the crack generates in its vicinity is evaluated using the strain energy density function given by the linear fracture mechanic theory. Based on this flexibility, a new cracked finite element stiffness matrix is deduced, which can be used subsequently in the FEM analysis of crack systems. Experimental characterization of multiple cracks in a cantilever beam utilizing transient vibration data following a probabilistic approach by H.F. Lam, C.T. Ng and M. Veidt at al. [17] puts forward a practical method for detecting multiple cracks on beams by utilizing transient vibration data. the Bayesian statistical framework is followed in the proposed crack detection method, which consists of two stages. In the first stage the number of cracks is identified by a computationally efficient algorithm that utilizes the Bayesian model class selection method. In the second stage, the posterior probability density function (PDF) of crack characteristics (i.e., the crack locations and crack depths) are determined by the Bayesian model updating method.

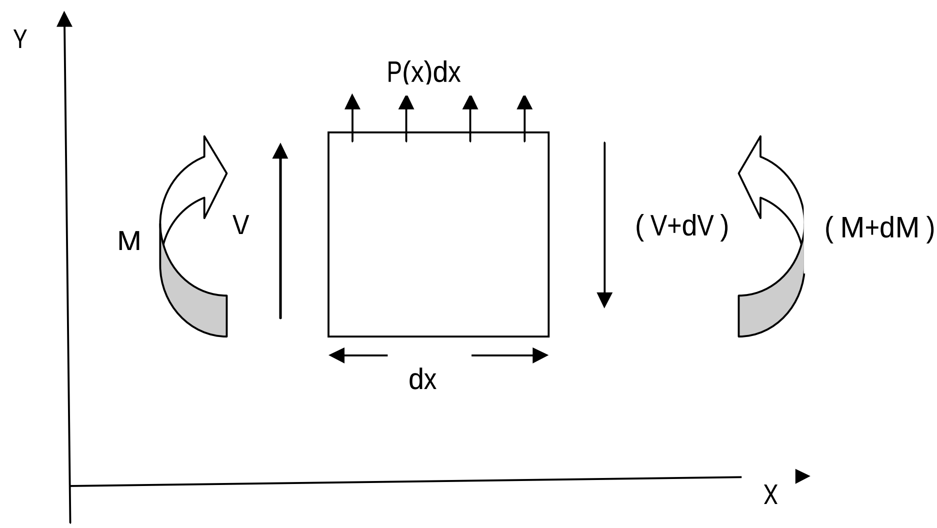
Y M Kim, C K Kim and G H Hong et al. [18] presents Fuzzy set based crack diagnosis system in which the system adapts fuzzy set theory to reflect fuzzy conditions, both for crack symptoms and characteristics which are difficult to treat using crisp sets. The inputs to the system are mostly linguistic variables concerning the crack symptoms and some numeric data about concrete and environmental conditions Using these input data and based on built-in rules, the proposed system executes fuzzy inference to evaluate the crack causes under consideration. The built-in rules were constructed by extracting expert knowledge, primarily from technical books about concrete and concrete cracks. A practical approach for analyzing the response of structures with fuzzy parameters is developed by U. O. Akpan, T S Koko, I R Orisamolu and B K Gallant et al. [19]. The methodology involves integrated finite element modelling, response surface analysis and fuzzy analysis.The merit of the proposed methodology is computational efficiency without compromise on accuracy and this is demonstrated through some example problems. The mobile robot navigation control system has been designed by S K Pradhan, D R Parhi and A K Panda et al. [20] using fuzzy logic. Fuzzy rules embedded in the controller of a mobile robot enable it to avoid obstacles in a cluttered environment that includes other mobile robots.

CHAPTER 3

THEORITICAL ANALYSIS

3.1 Vibrational Analysis of Eular Equation For Beam

To determine the differential equation for the lateral vibration of beams, consider the forces and moments acting an element of the beam showing in fig.



V and M are shear and bending moments, respectively and p(x) represents the loading per unit length of the beam.

By summing forces in the Y-direction –

$dV - p(x)dx = 0$ …………..(i)

By summing moments about any points on the right face of the element,

$dM - Vdx - \frac{1}{2} p(x)\,(dx)^2 = 0$ ………………(ii)

In the limiting process these equations results in the following important relationship –

$\frac{dV}{dx} = p(x)$ ………(iii)a and $\frac{dM}{dx} = V$ …………(iii)b

The first part of eqn(iii) states that the rate of change of shear along the length of the beam is equal to the loading per unit length and the second states that the change of the moment along the beam is equal to the shear.

From eqn(iii) we obtain the following –

$$\frac{d2_M}{dx^2} = \frac{dV}{dx} = p(x) \quad \ldots\ldots\ldots\ldots\ldots\text{(iv)}$$

The bending moment is related with the curvature by the flexure equation which for the coordinates indicates in fig is,

$$M = EI\frac{d2_y}{dx^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\text{(v)}$$

Substituting this relation into Eqn (iv), we obtain –

$$\frac{d2}{dx^2}\left(EI\frac{d2_y}{dx^2}\right) = p(x) \quad \ldots\ldots\ldots\ldots\ldots\text{(vi)}$$

For a beam vibrating about its static equilibrium position under its own weight the load per unit length is equal to the inertia load due to its mass and acceleration. Since the inertia force in the same direction as p(x) as shown in fig. we have by assuming harmonic motion.

$$p(x) = \rho w^2 y \quad \ldots\ldots\ldots\ldots\text{(vii)}$$

Where ρ is the mass per unit length of the beam. Using this relation the equation for the lateral vibration of the beam reduced to –

$$\frac{d2}{dx^2}\left(EI\frac{d2_y}{dx^2}\right) - \rho w^2 y = 0 \quad \ldots\ldots\ldots\ldots\ldots\text{(viii)}$$

In the special case where tha flexure rigidity EI is a constant, the above equation may be written as –

$$EI\frac{d4_y}{dx^4} - \rho w^2 y = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\text{(ix)}$$

On substituting,

$$\beta^4 = \frac{\rho w^2}{EI} \quad \ldots\ldots\ldots\ldots\ldots\text{(x)}$$

We obtain the fourth-order differential equation –

$$\frac{d4_y}{dx^4} - \beta^4 y = 0 \quad \ldots\ldots\ldots\ldots\text{(xi)}$$

For the vibration of a uniform beam, the general solution of eqn (xi) can be shown to be:

$$y = A\cosh\beta x + B\sinh\beta x + C\cos\beta x + D\sin\beta x \quad \text{…………..(xii)}$$

To arrive at this result we assume a solution of the form –

$$y = e^{ax} \quad \text{…………….(xiii)}$$

Which will satisfy the differential eqn when –

a = ± β and a = ± i β

Since, $e^{\pm\beta} = \cosh\beta x \pm \sinh\beta x$

$$e^{\pm i\beta} = \cos\beta x \pm i\sin\beta x$$

Hence solution will be in the form of eqn (xii) is readily established.

The Natural Frequency of vibration are found from eqn (x) to be –

$$w_n = \beta_n^2\sqrt{\frac{EI}{\rho}} = (\beta_n l)^2\sqrt{\frac{EI}{\rho l^4}}$$

Where the no. β_n depends on the boundary conditions of all problem. The following table lists numerical values of $(\beta_n l)^2$ for typical end conditions.

Beam Configuration	$(\boldsymbol{\beta_1 l})^2$ **Fundamental**	$(\boldsymbol{\beta_2 l})^2$ **Second Mode**	$(\boldsymbol{\beta_3 l})^2$ **Third Mode**
Simply supported	9.87	39.5	88.9
Cantilever	3.52	22.0	61.7
Free-Free	22.4	61.7	121.0
Clamped-Clamped	22.4	61.7	121.0
Clamped-Hinged	15.4	50.0	104.0
Hinged-Free	0	15.4	50.0

3.2 Local Flexibility Of a Cracked Beam Under Bending And Axial Loading

(Parhi et al. [21])

The presence of a transverse surface crack of depth ‘a1’ on beam of width ‘B’ and height ‘W’ introduces a local flexibility, which can be defined in matrix form, the dimension of which depends on the degrees of freedom. Here a 2x2 matrix is considered. A cantilever beam is subjected to axial force (P1) and bending moment (P2), shown in figure 1a, which gives coupling with the longitudinal and transverse motion.

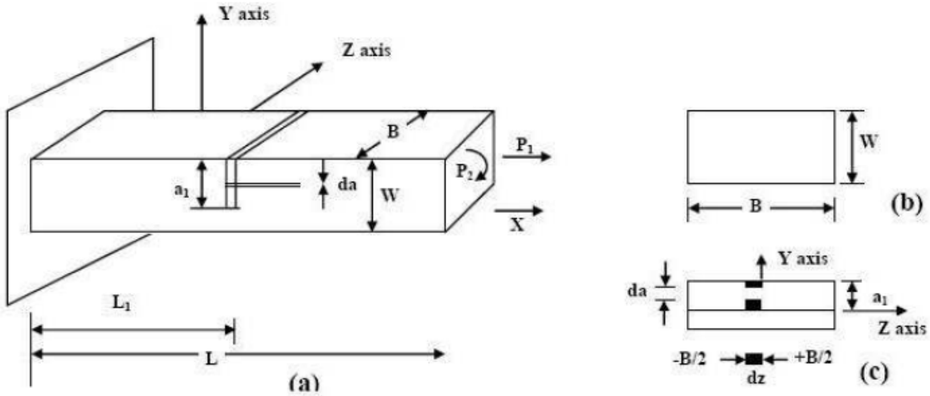


Figure 1: Geometry of beam, (a) Cantilever beam, (b) Cross-sectional view of the beam. (c) Segments taken during integration at the crack section

Fig 1. Parhi et al.[21]

The strain energy release rate at the fractured section can be written as (Tada et al.1973);

J = (KI1 + KI2)2/ E’ , where 1/ E’ = (1- v2)/E , for plain strain condition

= 1/E , for plane stress condition

KI1 and KI2 are the stress intensity factors of mode I (opening of the crack) for load P1 and P2 respectively the value of stress intensity factors from previous studies (Tada et al.1973) are;

$$K_{I1} = \frac{P_1}{BW}\sqrt{\pi a}\left(F_1\left(\frac{a}{W}\right)\right)$$

$$K_{I2} = \frac{P_2}{BW^2}\sqrt{\pi a}\left(F_2\left(\frac{a}{W}\right)\right)$$

Where expressions for F1 and F2 are as follows

$$F_1\left(\frac{a}{W}\right) = \left(\frac{2W}{\pi a}tan\left(\frac{\pi a}{2W}\right)\right)^{0.5}\left\{\frac{0.752 + 2.02\left({}^{a}/_{W}\right) + 0.37\left(1 - sin\left({}^{\pi a}/_{2W}\right)\right)^3}{cos\left(\frac{\pi a}{2W}\right)}\right\}$$

$$F_2\left(\frac{a}{W}\right) = \left(\frac{2W}{\pi a} tan\left(\frac{\pi a}{2W}\right)\right)^{0.5} \left\{\frac{0.923 + 0.199\left(1 - sin\left({\pi a}/{2W}\right)\right)^4}{cos\left(\frac{\pi a}{2W}\right)}\right\}$$

Let Ut be the strain energy due to crack, then from Castigliano's theorem, the additional displacement along the force Pi is:

ui = ∂Ut/∂Pi (1)

The strain energy will have the form

$$U_t = \int_0^{a_1} \frac{\partial U_t}{\partial a} da = \int_0^{a_1} J da \qquad (2)$$

Where J=$\frac{\partial U_t}{\partial a}$ the strain enery density function.

From equation (1) and (2), thus we have,

$$ui = \frac{\partial}{\partial a}\left[\int_0^{a_1} J da\right] \qquad (3)$$

The flexibility influence coefficients Cij will be, by definition,

$$C_{ij} = \frac{\partial u_i}{\partial P_j} = \frac{\partial^2}{\partial P_i \partial P_j} \int_0^{a_1} J(a) da \qquad (4)$$

To find out the final flexibility matrix we have to integrate over the breadth B,

$$C_{ij} = \frac{\partial u_i}{\partial P_j} = \frac{\partial^2}{\partial P_i \partial P_j} \int_{-B/2}^{+B/2} \int_0^{a_1} J(a) da\, dz \qquad (5)$$

Put the value of strain energy rate from above, equation (5) modifies as,

$$C_{ij} = \frac{B}{E'} \frac{\partial^2}{\partial P_i \partial P_j} \int_0^{a_1} (K_{11} + K_{12})^2 da \qquad (6)$$

Putting,

ξ= (a/W) and dξ = (da/W)

We get,

da= W dξ and when a=0; ξ=0; a= a1, ξ = a/W = ξ1

From the above condition equation (6) converts to

$$C_{ij} = \frac{BW}{E'} \frac{\partial^2}{\partial P_i \partial P_j} \int_0^{\xi_1} (K_{11} + K_{12})^2 d\xi \qquad (7)$$

From the equation (7) calculating C11, C12 (=C21) and C22 we get,

$$C_{11} = \frac{BW}{E'} \int_0^{\xi_1} \frac{\pi a}{B^2W^2} 2\big(F_1(\xi)\big)^2 d\xi = \frac{2\pi}{BE'} \int_0^{\xi_1} \xi \big(F_1(\xi)\big)^2 d\xi \qquad (8)$$

$$C_{12} = C_{21} = \frac{12\pi}{E'BW} \int_0^{\xi_1} \xi F_1(\xi) F_2(\xi) d\xi \qquad (9)$$

$$C_{22} = \frac{72\pi}{E'BW^2} \int_0^{\xi_1} \xi F_1(\xi) F_2(\xi) d\xi \qquad (10)$$

Converting the influence co-efficient into dimensionless form

$$\overline{C_{11}} = C_{11} \frac{BE'}{2\pi} \; ; \; \overline{C_{12}} = C_{12} \frac{WBE'}{12\pi} = \overline{C_{21}} \quad ; \quad \overline{C_{22}} = C_{22} \frac{BE'W^2}{72\pi}$$

The local stiffness matrix can be obtained by taking the conversion of compliance matrix i.e.

$$K = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}^{-1}$$

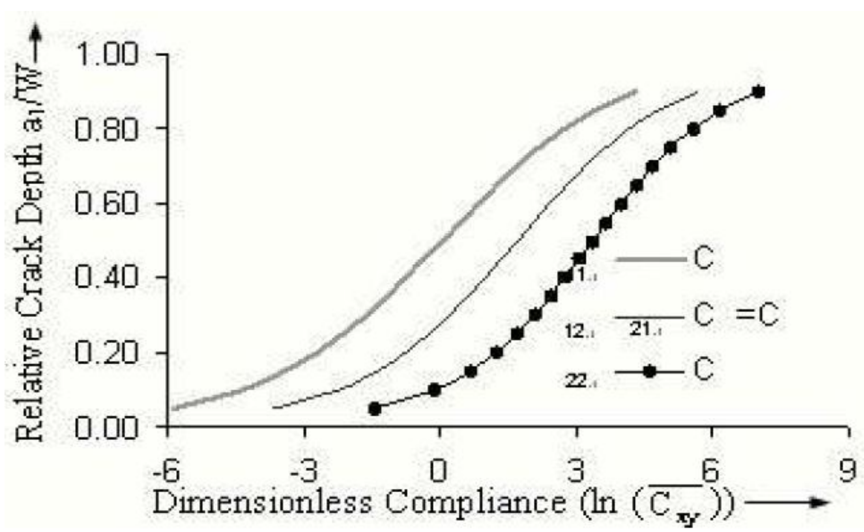


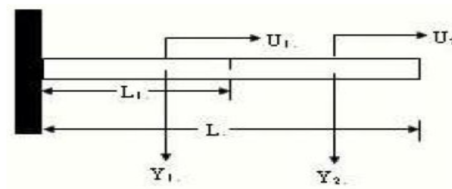
Figure 2. Variation of dimensionless compliances to that of relative crack depth. Parhi et al.[21]

3.3 Analysis of vibration characteristics of the cracked beam

(Parhi et al. [21])

3.2.1 Free Vibration:

A cantilever beam of length 'L' width 'B' and depth 'W', with a crack of depth 'a1' at adistance 'L' from the fixed end is considered shown in figure 1. Taking u1(x, t) and u2(x, t) as the amplitudes of longitudinal vibration for the sections before and after the crack andy1(x, t), y2(x, t) are the amplitudes of bending vibration for the same sections shown in figure 3.



The normal function for the system can be defined as,

$$\overline{u_1}(\bar{x}) = A_1 cos(\overline{K_u}\,\bar{x}) + A_2 sin(\overline{K_u}\,\bar{x}) \quad (11a)$$

$$\overline{u_2}(\bar{x}) = A_3 cos(\overline{K_u}\,\bar{x}) + A_4 sin(\overline{K_u}\,\bar{x}) \quad (11b)$$

$$\overline{y_1}(\bar{x}) = A_5 cosh(\overline{K_y}\,\bar{x}) + A_6 sinh(\overline{K_y}\,\bar{x}) + A_7 cos(\overline{K_y}\,\bar{x}) + A_8 sin(\overline{K_y}\,\bar{x}) \quad (11c)$$

$$\overline{y_2}(\bar{x}) = A_9 cosh(\overline{K_y}\,\bar{x}) + A_{10} sinh(\overline{K_y}\,\bar{x}) + A_{11} cos(\overline{K_y}\,\bar{x}) + A_{12} sin(\overline{K_y}\,\bar{x}) \quad (11d)$$

Where,

$$\bar{x} = \frac{x}{L}, \bar{u} = \frac{u}{L}, \bar{y} = \frac{y}{L}, \beta = \frac{L_1}{L}$$

$$\overline{K_u} = \frac{\omega L}{C_u}, C_u = \left(\frac{E}{\rho}\right)^{1/2}, \overline{K_y} = \left(\frac{\omega L^2}{C_y}\right)^{1/2}, C_y = \left(\frac{EI}{\mu}\right)^{1/2}, \qquad \mu = A\rho$$

Ai ,(i= 1,12) constants are to be determined, constants are to be determined from boundary conditions. The boundary conditions of the cantilever beam in consideration are:

$$\overline{u_1}(0) = 0\,;\ \overline{y_1}(0) = 0\,;\ \bar{y}_1'(0) = 0\,;\ \bar{u}_2'(1) = 0\,;\ y_2''(1) = 0\,;\ y_2'''(1) = 0$$

At the cracked section,

$$\overline{u_1}(\beta) = \overline{u_2}(\beta)\,;\ \overline{y_1}(\beta) = \overline{y_2}(\beta)\,;\ \overline{y_1}''(\beta) = \overline{y_2}''(\beta)\,;\ \overline{y_1}'''(\beta) = \overline{y_2}'''(\beta)$$

Also at the cracked section, we have:

$$AE = \frac{du_1(L_1)}{dx} = K_{11}\big(u_2(L_1) - u_1(L_1)\big) + K_{12}\left(\frac{dy_2(L_1)}{dx} - \frac{dy_1(L_1)}{dx}\right)$$

Multiplying both sides of the above equation by $AE/LK_{l1}K_{l2}$, we get,

$$M_1M_2\bar{u}'(\beta) = M_2(\bar{u}_2(\beta) - \bar{u}_1(\beta)) + M_1(\bar{y}_2{}'(\beta) - \bar{y}_1{}'(\beta))$$

Similarly,

$$EI\frac{d^2y_1(L_1)}{dx^2} = K_{21}(u_2(L_1) - u_1(L_1)) + K_{22}\left(\frac{dy_2(L_1)}{dx} - \frac{dy_1(L_1)}{dx}\right)$$

Multiplying both sides of the above equation by $EI/L^2K_{21}K_{22}$, we get

$$M_3M_4\overline{y_1}''(\beta) = M_3(\bar{u}_2(\beta) - \bar{u}_1(\beta)) + M_4(\bar{y}_2{}'(\beta) - \bar{y}_1{}'(\beta))$$

Where,

$$M_1 = \frac{AE}{LK_{11}}, M_2 = \frac{AE}{K_{12}}, M_3 = \frac{EI}{LK_{22}}, M_4 = \frac{EI}{L^2K_{21}}$$

The normal functions equation 11, along with the boundary conditions as mentioned above yield the characteristic equation of the system as

$$|Q| = 0,$$

This determinant is a function of natural circular frequency (ω), the relative location of crack (β) and local stiffness matrix (K) which in turn is a function of relative crack depth(a1/W).

3.2.2 Forced Vibration:

If the cantilever beam with transverse crack is excited at its free end by a harmonic excitation (Y=Y0 sin (ω t)), the non-dimensional amplitude at the free end may be expressed as $\bar{y}_2(1)=y_0./L=\overline{y_0}$. Therefore the boundary conditions for the beam remain same as before as except the boundary condition which is modified as $\bar{y}_2(1)=\overline{y_0}$

The constants Ai, i=1, to 12 are then computed from the algebraic condition

Q_1 D=B_1 (13)

Q_1 is the (12 x 12) matrix obtained from boundary conditions as mentioned above,

D is a column matrix obtained from the constants,

B_1 is a column matrix, transpose of which is given by,

B_1^T = [0 0 0 y 0 0 0 0 0 0 0 0]

CHAPTER 4

STUDY OF VIBRATIONAL BEHAVIOUR OF UNCRACKED BEAM

4.1 MATLAB Program For Solving Eular Equation For Beam:

```
E=input('enter the young's modulus of the beam material');
d=input('enter the mass per unit length of the beam');
I=input('enter the moment of inertia of the cross section');
L=input('enter the length of the beam');
C=zeros(4,4);
n1=input('For 1st node:Enter 1 for free;Enter 2 for hinged;Enter 3 for fixed');
n2=input('For 2nd node:Enter 1for free;Enter 2 for hinged;Enter 3 for fixed');
if(n1==1)
   C(1,:)=[1 0 -1 0];
   C(2,:)=[0 1 0 -1];
end
if(n1==2)
   C(1,:)=[1 0 1 0];
   C(2,:)=[1 0 -1 0];
end
if(n1==3)
   C(1,:)=[1 0 1 0];
   C(2,:)=[0 1 0 1];
end
i=0;
c=1;
while (c<4)
```

```
if(n2==1)
    C(3,:)=[cosh(i+0.01) sinh(i+0.01) -cos(i+0.01) -sin(i+0.01)];
    C(4,:)=[sinh(i+0.01) cosh(i+0.01) sin(i+0.01) -cos(i+0.01)];
end
if(n2==2)
    C(3,:)=[cosh(i+0.01) sinh(i+0.01) cos(i+0.01) sin(i+0.01)];
    C(4,:)=[cosh(i+0.01) sinh(i+0.01) -cos(i+0.01) -sin(i+0.01)];
end
if(n2==3)
    C(3,:)=[cosh(i+0.01) sinh(i+0.01) cos(i+0.01) sin(i+0.01)];
    C(4,:)=[sinh(i+0.01) cosh(i+0.01) -sin(i+0.01) cos(i+0.01)];
end
s1=det(C);
if(n2==1)
    C(3,:)=[cosh(i-0.01) sinh(i-0.01) -cos(i-0.01) -sin(i-0.01)];
    C(4,:)=[sinh(i-0.01) cosh(i-0.01) sin(i-0.01) -cos(i-0.01)];
end
if(n2==2)
    C(3,:)=[cosh(i-0.01) sinh(i-0.01) cos(i-0.01) sin(i-0.01)];
    C(4,:)=[cosh(i-0.01) sinh(i-0.01) -cos(i-0.01) -sin(i-0.01)];
end
if(n2==3)
    C(3,:)=[cosh(i-0.01) sinh(i-0.01) cos(i-0.01) sin(i-0.01)];
    C(4,:)=[sinh(i-0.01) cosh(i-0.01) -sin(i-0.01) cos(i-0.01)];
end
s2=det(C);
if(s1>0)&&(s2<0)
```

```
    beta=i/L
    w=(i^2)*sqrt(E*I/(d*L^4))
    c=c+1;
    i=i+0.02;
  else
    i=i+0.01;
  end
  if(s1<0)&&(s2>0)
    beta=i/L
    w=(i^2)*sqrt(E*I/(d*L^4))
    c=c+1;
    i=i+0.02;
  else
    i=i+0.01;
  end
end
```

Output:

```
enter the young's modulus of the beam material : 69000000000
enter the mass per unit length of the beam : 126
enter the moment of inertia of the cross section : 0.00000001
enter the length of the beam : 1
For 1st node: Enter 1 for free; Enter 2 for hinged; Enter 3 for fixed : 3
For 2nd node: Enter 1 for free; Enter 2 for hinged; Enter 3 for fixed : 3

beta  =  4.7500        beta  =  7.8500        beta  = 11.0100

w  =  52.7991          w  =  144.2044         w  =  283.6703
```

4.2 FEA analysis using ALGOR

ALGOR is a general-purpose multiphysics finite element analysis software package developed by ALGOR Incorporated for use on the Microsoft Windows and Linux computer operating systems. It is distributed in a number of different core packages to cater to specifics applications, such as mechanical event simulation and computational fluid dynamics. ALGOR's complete product line includes InCAD technology for direct CAD/CAE data exchange and full associativity with each design change in Solid Edge for use with any analysis type within FEMPRO, ALGOR's easy-to-use, single user interface. ALGOR's wide range of simulation capabilities includes static stress and Mechanical Event Simulation (MES) with linear and nonlinear material models, linear dynamics, fatigue, steady-state and transient heat transfer, steady and unsteady fluid flow, electrostatics, full multiphysics and piping. So for analysis in ALGOR we need to first generate CAD model and then this model is analyzed in the software by generating mesh and giving boundary conditions.

Natural frequency has been found out for different modes of Fixed-Fixed un-cracked beam by using MATLAB programming and FEA analysis in ALGOR which are tabulated as shown:

MODE TYPE	NATURAL FREQUENCY (/sec)	
	Using MATLAB	Using FEA Analysis
1st	52.7991	52.7955
2nd	144.2044	145.392
3rd	283.6703	267.866

Now further need to do both Fuzzy and FEA Analysis in ALGOR for cracked beam by giving some crack on the span of beam of a certain depth.

CHAPTER 5

CRACK DETECTION USING FEA

5.2 STEPs For FEA of Cracked Beam Modal Using ALGOR:

STEP 1: Generation of model in a designing software:

The cracked beam model having single crack are generated in CAD software (AUTOCAD 2006) having different crack depths and crack location. For single crack 21 models are generated, crack depth varying from 1 mm to 3 mm and crack location from 100mm to 700mm.

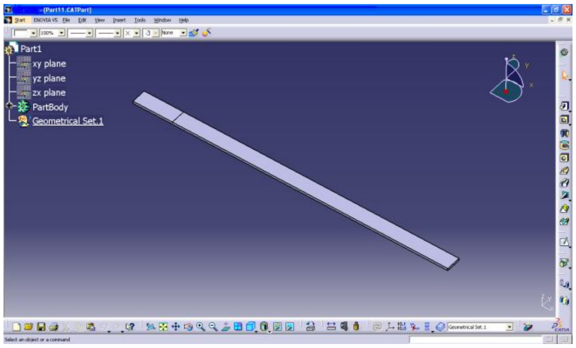
The uncracked beam model having following specification-

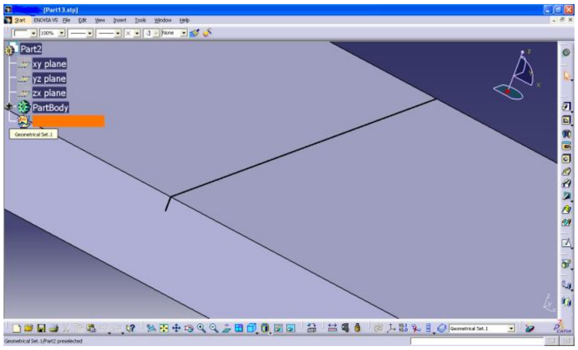
- Length (L) = 800mm
- Width (B) = 38mm
- Height (W) = 6mm

Crack Depth (a_1) = 1mm, 2mm, 3mm

Crack Location (l) = 100, 200, 300, 400, 500, 600, 700mm from the fix end of the cantilever

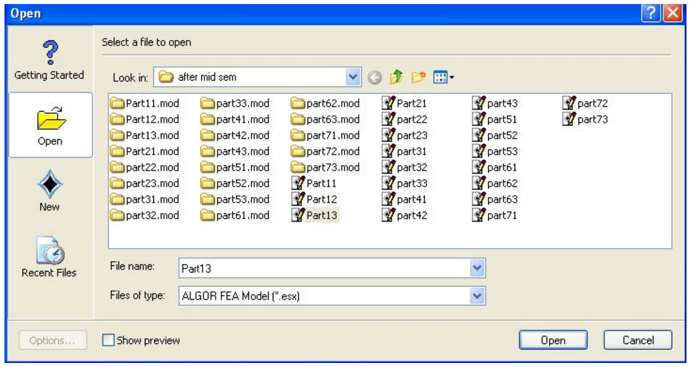
Figure shows a model generated in CAD with , l=100mm, a_1=1mm





Zoomed view of crack :

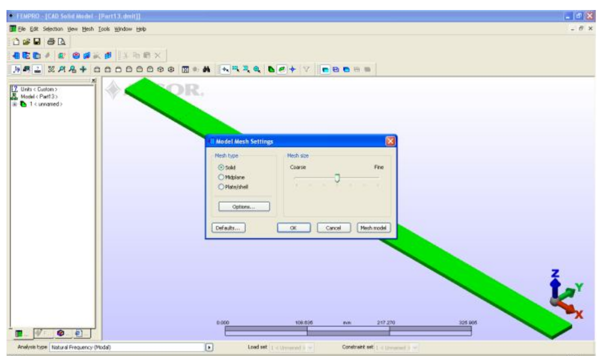
STEP 2: The file is saved in .stp format and opened in FEMPRO as an Input File which is a part of ALGOR for finite element analysis as shown :



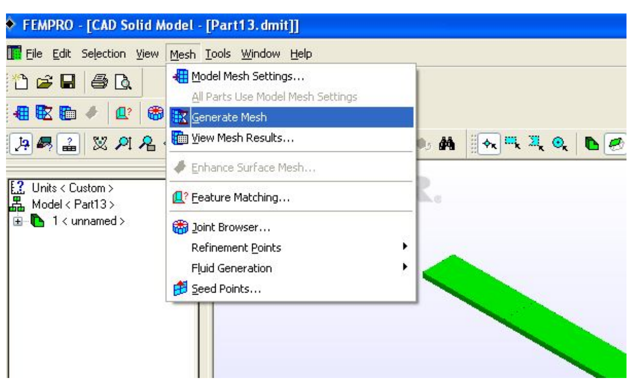
STEP 3: Natural frequency modal is chosen for design scenario and mesh settings are shown In subsequent figure:

Single Analysis : Linear/Natural Frequency(modal)

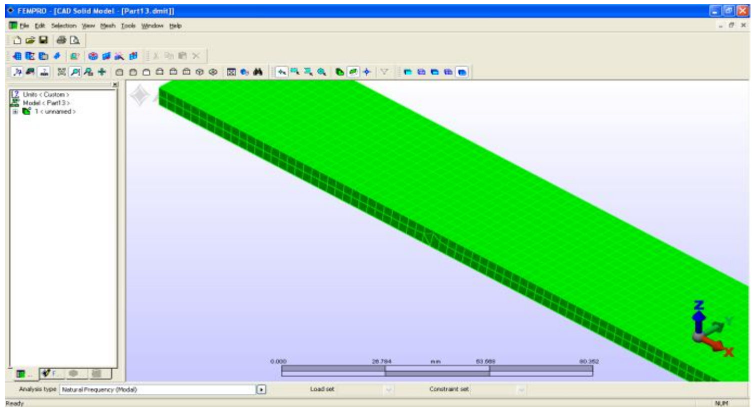
Modal Mess Setting : Mesh type/Solid



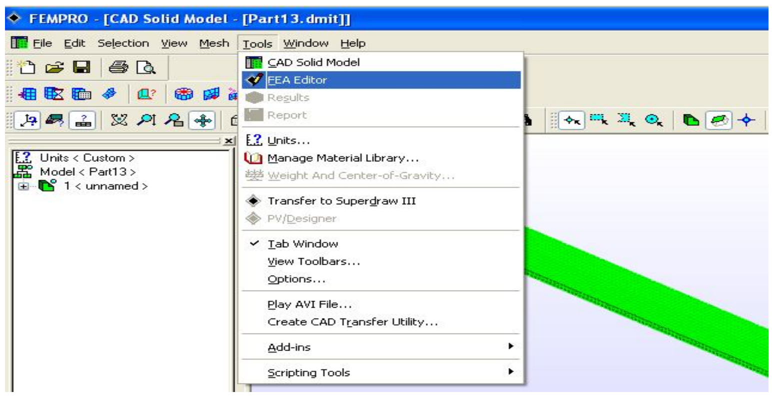
STEP 4: Now mesh is generated as shown:



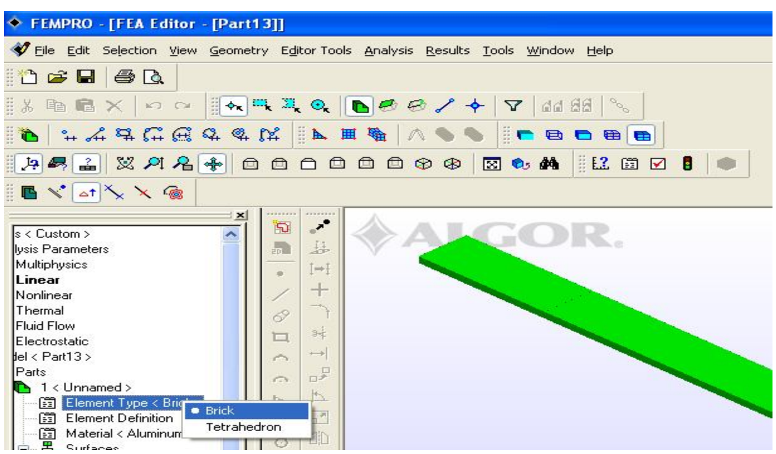
STEP 5: Now the model will be look like this :



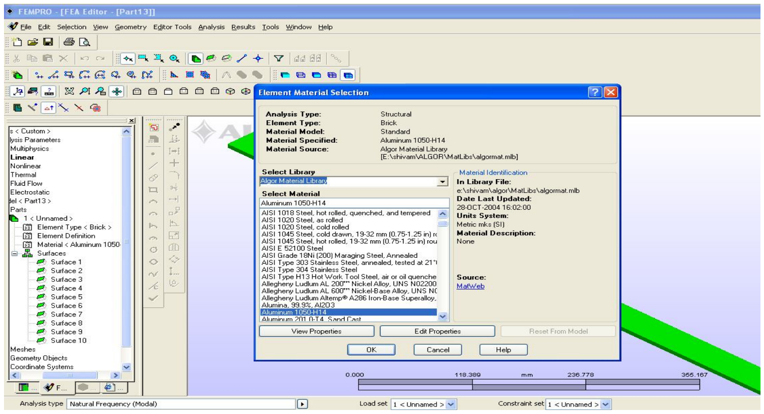
STEP 6: After meshing is done FEA editor is opened:



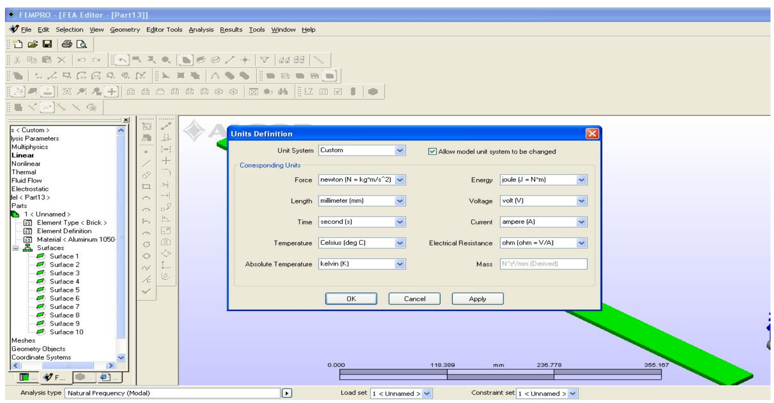
STEP 7: Element type is set as brick type:



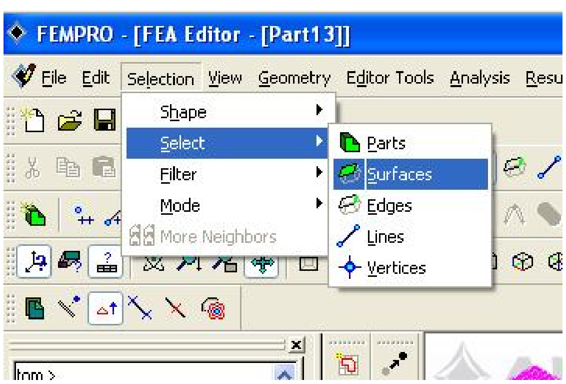
STEP 8: Material is chosen as per requirement. Here Aluminium 1050-H14 is selected :

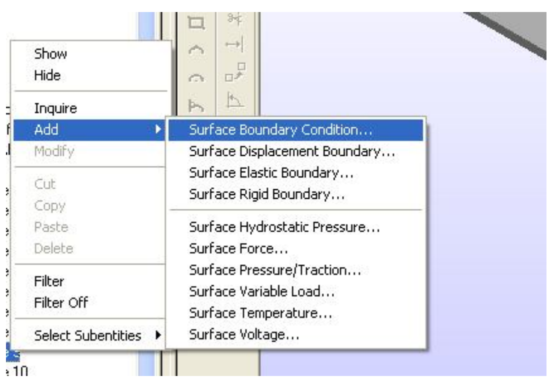


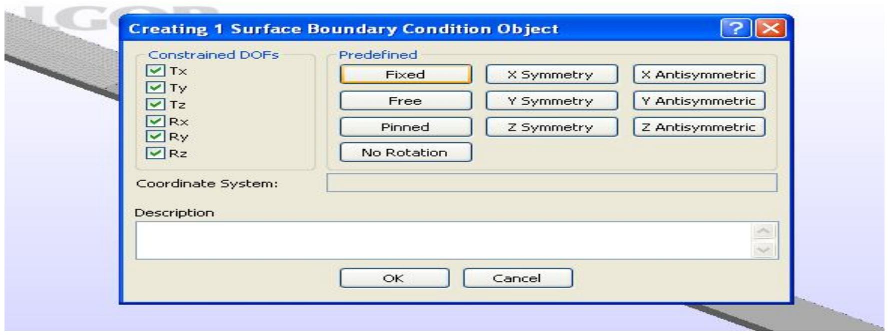
STEP 9: Units are defined as:



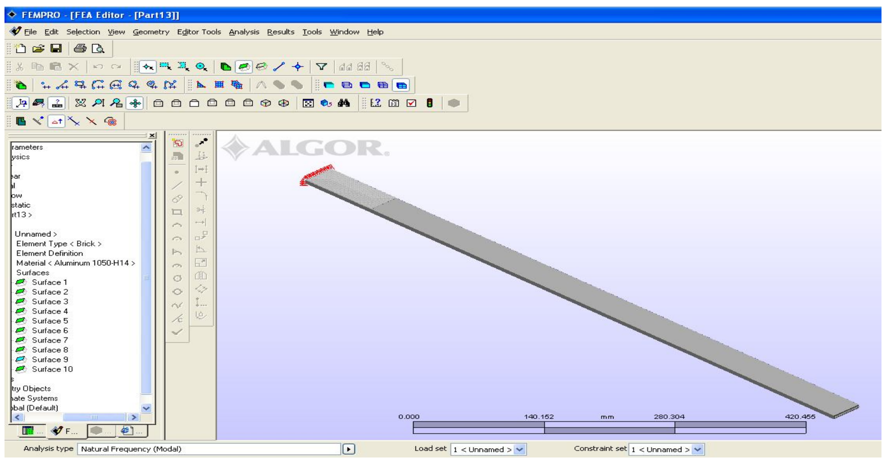
STEP 10: Surfaces of modal is selected and surface boundary conditions are set:



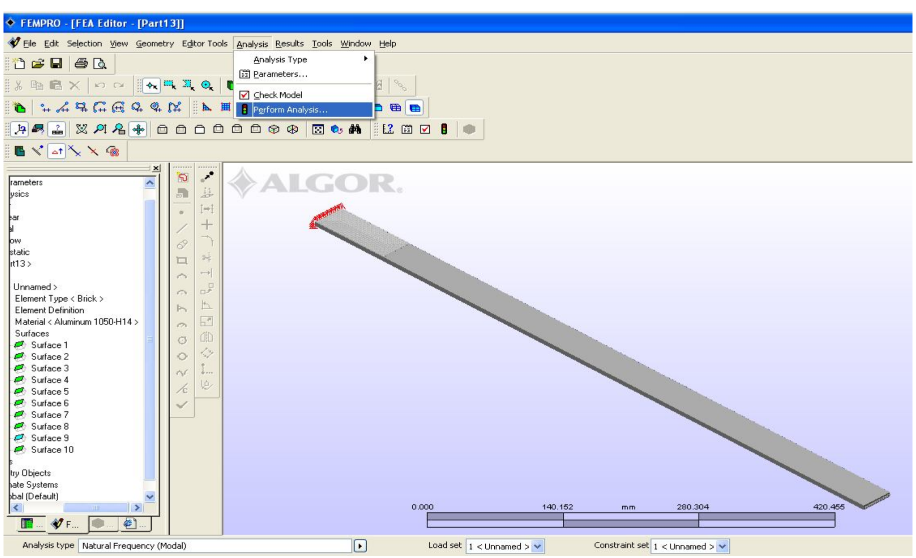




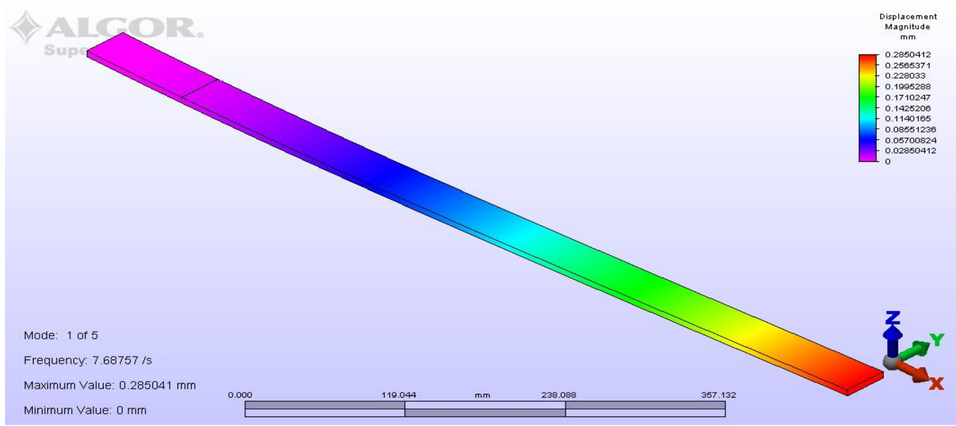
The modal would become like:



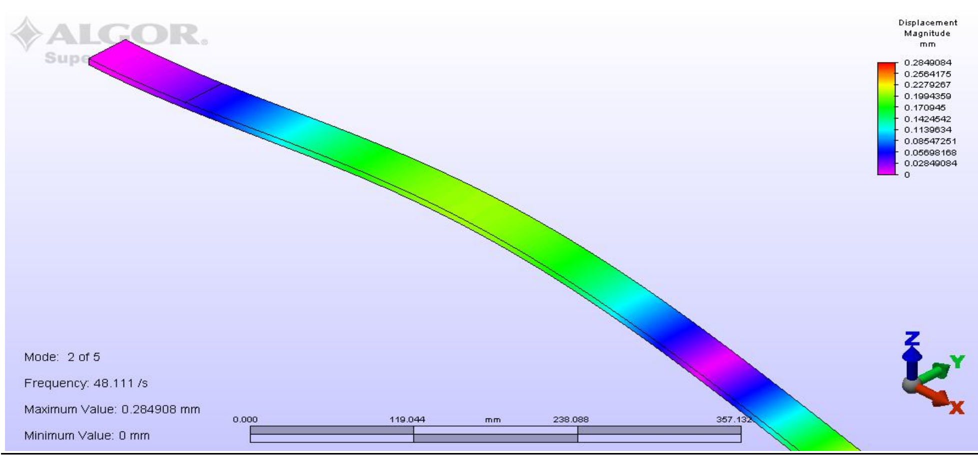
STEP 11: Now we'll click perform analysis button in the toolbar and the modes would be shown as below:



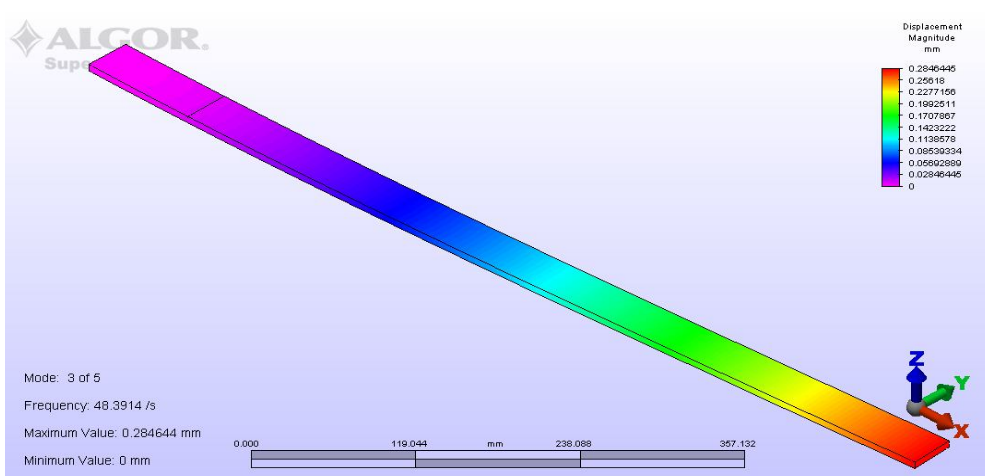
First mode of vibration:



Second mode of vibration:



Third mode of vibration:



5.3 Computation table for Natural Frequency using ALGOR:

Sl No.	Relative Crack Depth(rcd)	Relative Crack Location(rcl)	Fnf (/s)	Snf (/s)	Tnf (/s)
1	0.5	0.125	7.69345	48.0475	48.287
2	0.333	0.125	7.66641	48.0782	48.2795
3	0.167	0.125	7.68657	48.111	48.3914
4	0.5	0.25	7.72106	48.1593	48.3777
5	0.333	0.25	7.66319	48.0908	48.3221
6	0.167	0.25	7.6831	48.0954	48.4007
7	0.5	0.375	7.64557	47.8803	48.2719
8	0.333	0.375	7.66627	48.0194	48.3637
9	0.167	0.375	7.67963	48.1156	48.4076
10	0.5	0.5	7.66479	47.7739	48.346
11	0.333	0.5	7.67646	48.0897	48.3975
12	0.167	0.5	7.68094	48.2138	48.4126
13	0.5	0.625	7.67362	47.8839	48.3938
14	0.333	0.625	7.67487	47.9791	48.4078
15	0.167	0.625	7.67725	48.1324	48.4153
16	0.5	0.75	7.67854	48.0744	48.4123
17	0.333	0.75	7.67645	48.0599	48.4154
18	0.167	0.75	7.67681	48.1095	48.4166
19	0.5	0.875	7.68616	48.419	48.5865
20	0.333	0.875	7.67679	48.0916	48.4177
21	0.167	0.875	7.67673	48.0957	48.4173

CHAPTER 6

CRACK DETECTION USING FIS

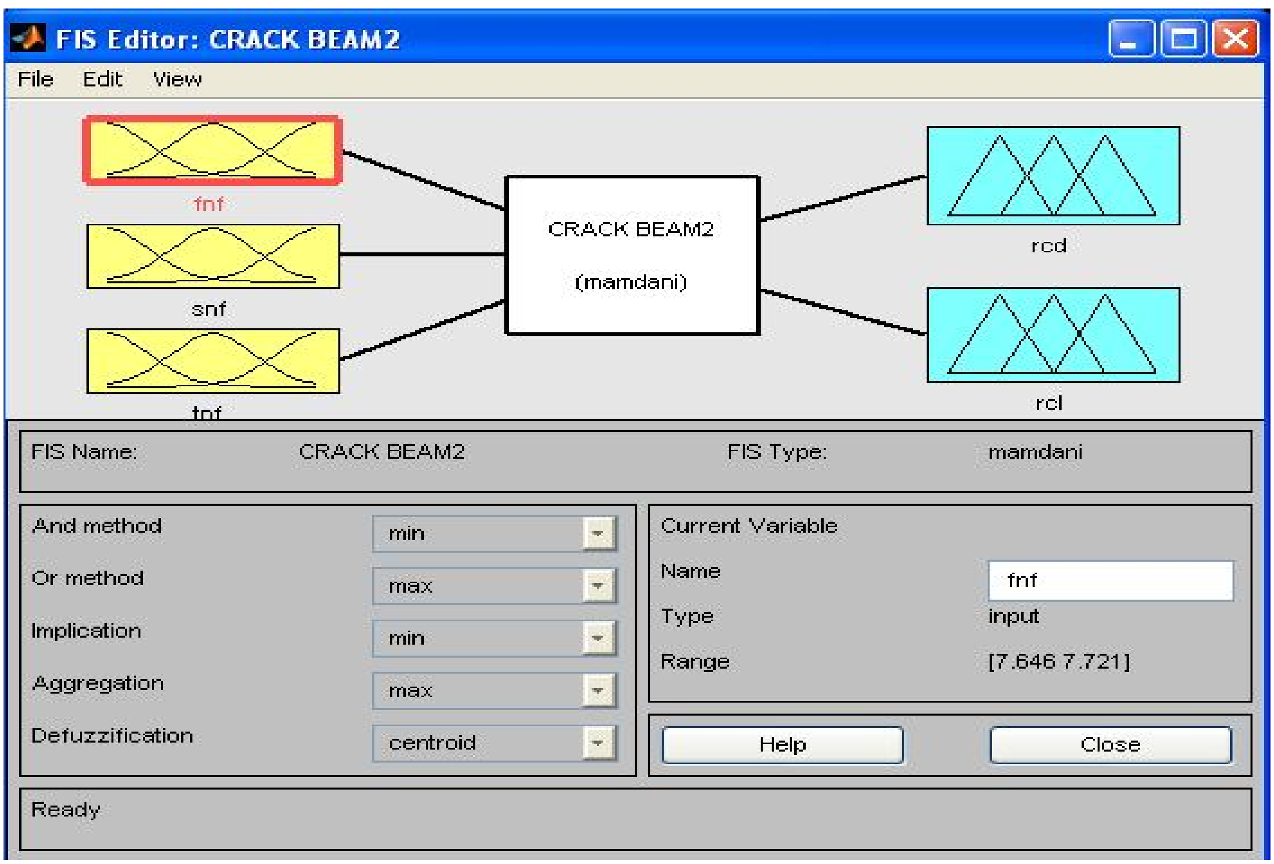
6.1 Analysis of the Fuzzy Controller (FIS Editor) :

The fuzzy controller developed has got three input parameters and two output parameters. The linguistic term used for the inputs are as follows;

- First natural frequency = "fnf";
- Second natural frequency = "snf";
- Third natural frequency = "tnf";

The linguistic term used for the outputs are as follows;

- Relative crack location = "rcl"
- Relative crack depth = "rcd"



6.2 Description of fuzzy Linguistic term :

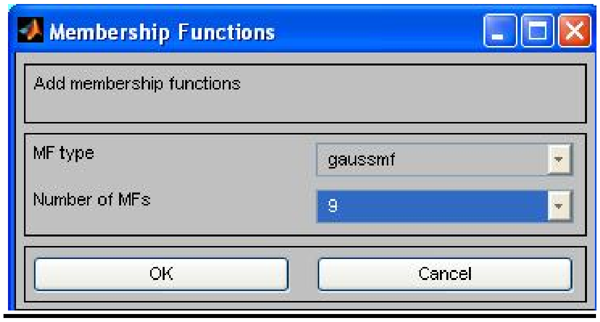
Membership function name	Description and range of MF
L1F1,L1F2,L1F3,L1F4	Low ranges of natural frequency for 1st mode of vibration in descending order respectively
M1F1	Medium ranges of natural frequency for 1st mode of vibration
H1F1,H1F2,H1F3,H1F4	Higher ranges of natural frequency for 1st mode of vibration in ascending order respectively
L2F1,L2F2,L2F3,L2F4	Low ranges of natural frequency for 2nd mode of vibration in descending order respectively
M2F1	Medium ranges of natural frequency for 2nd mode of vibration
H2F1,H2F2,H2F3,H2F4	Higher ranges of natural frequency for 2nd mode of vibration in ascending order respectively
L3F1,L3F2,L3F3,L3F4	Low ranges of natural frequency for 3rd mode of vibration in descending order respectively
M3F1	Medium ranges of natural frequency for 3rd mode of vibration
H3F1,H3F2,H3F3,H3F4	Higher ranges of natural frequency for 3rd mode of vibration in ascending order respectively
SD1,SD2,………..SD9	Small ranges of relative crack depth in descending order Respectively
MD	Medium range of relative crack depth
HD1,HD2,………HD9	High ranges of relative crack depth in ascending order respectively
SL1,SL2,………..SL18	Small ranges of relative crack location in descending order respectively
ML1,ML2,ML3	Medium range of relative crack location in ascending order
BL1,BL2,……….BL18	High ranges of relative crack location in ascending order respectively

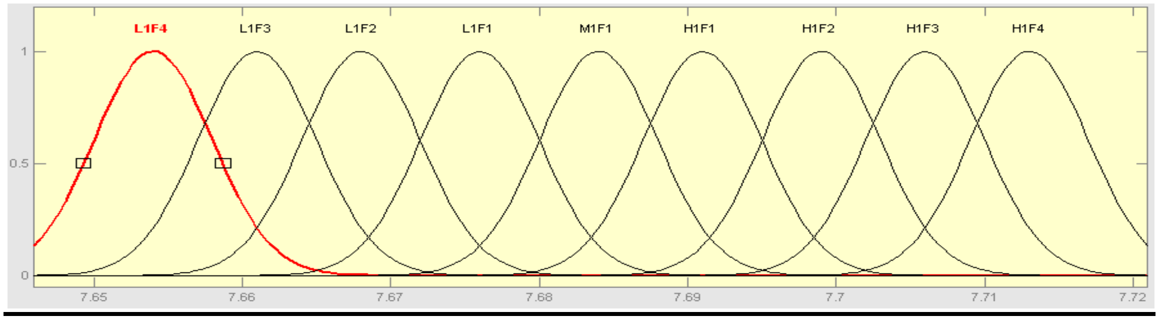
6.3 Membership Function Editor :

Here in fuzzy controller GAUSSIAN MF is used for inputs(fnf, snf, tnf) and TRIANGULAR MF is used for outputs(rcd, rcl).

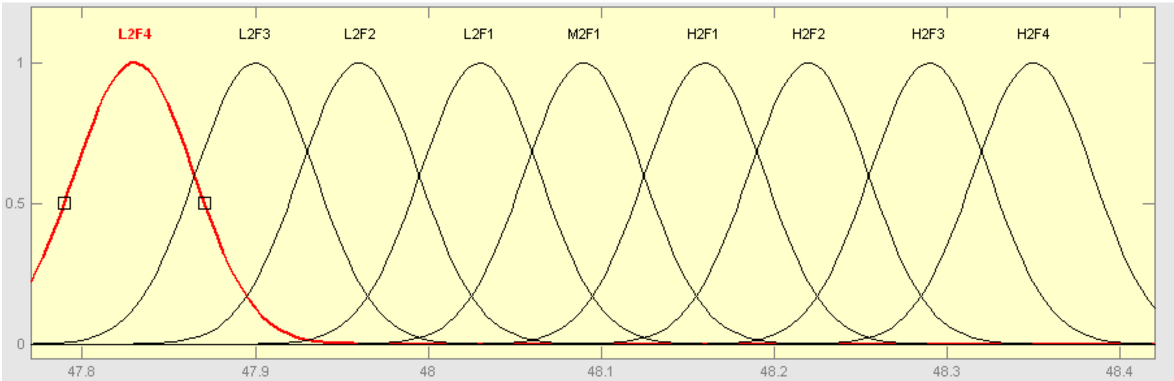
The process of specifying the membership functions is as follows,

1. Select the variable (input/output) by double-clicking on it. Set both the Range and the Display.
2. Select Add MFs... from the Edit menu. The window below opens

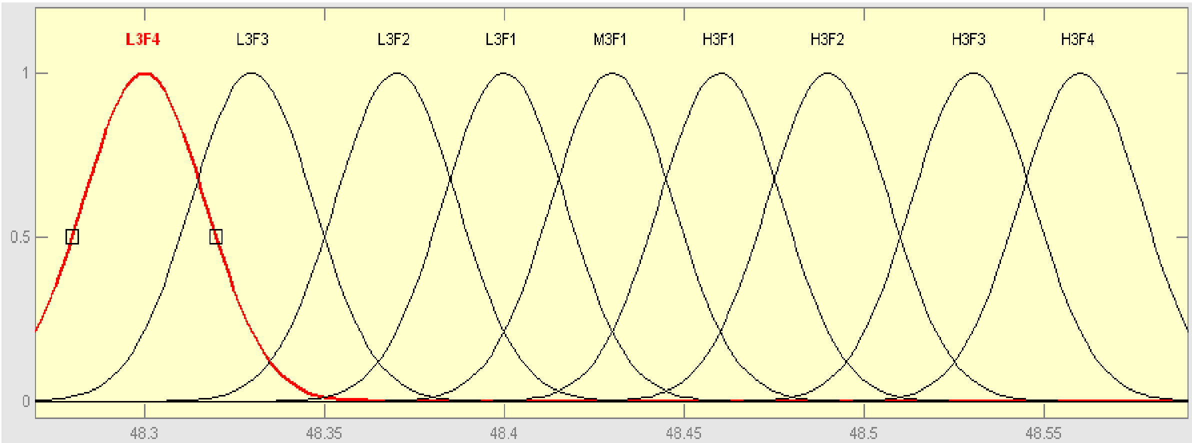




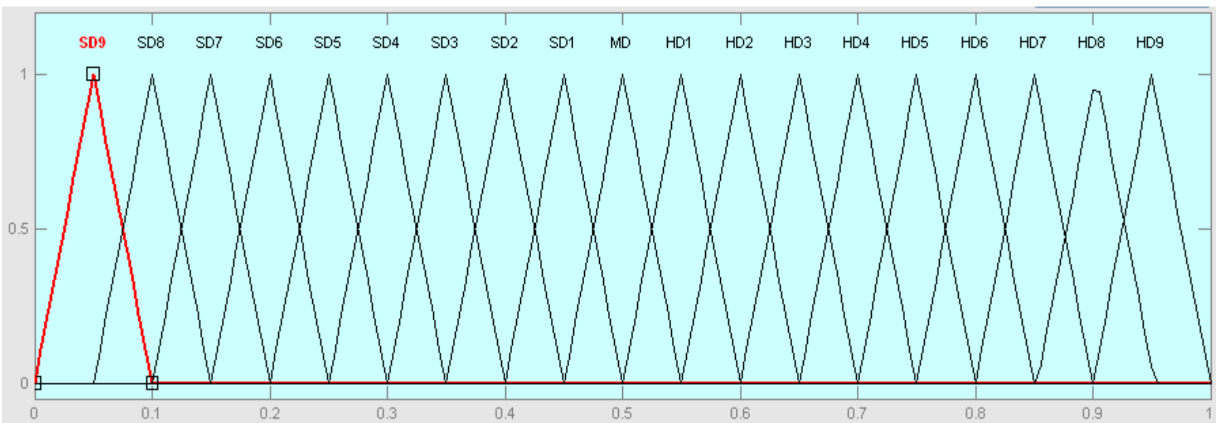
MF for natural frequency for 1st mode of vibration(fnf)



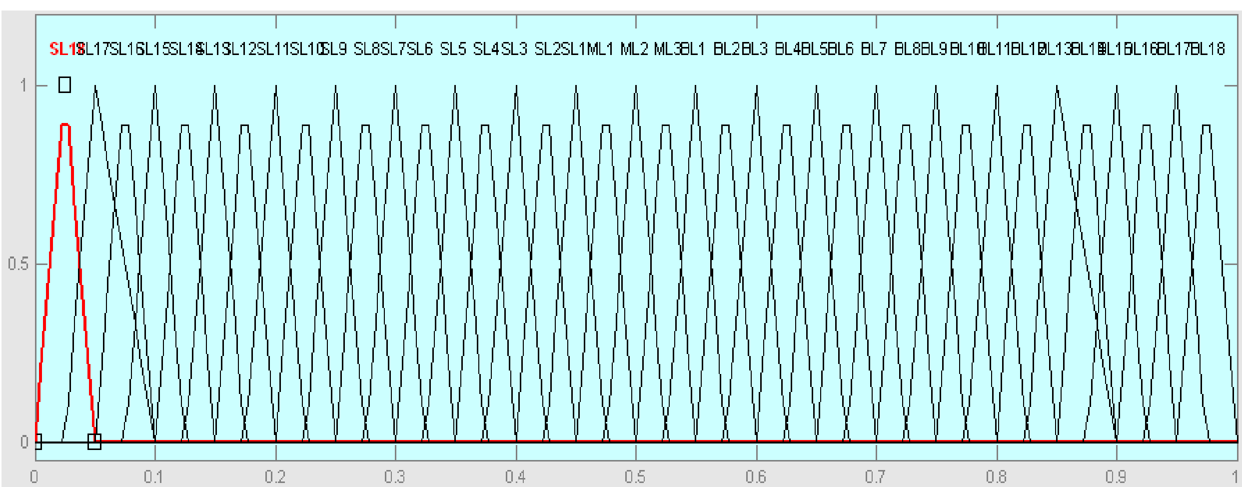
MF for natural frequency for 2nd mode of vibration(snf)



MF for natural frequency for 3rd mode of vibration(tnf)



MF for relative crack depth (rcd)



MF for relative crack location (rcl)

6.4 Rules Editor :

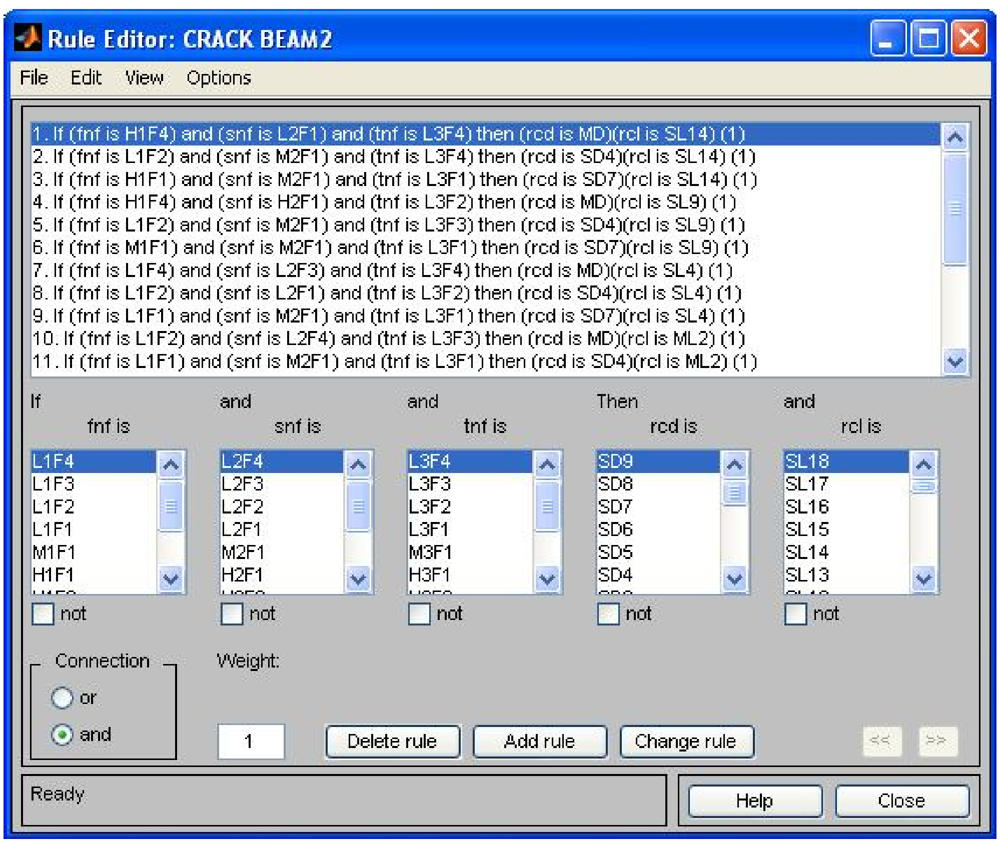
To insert the first rule in the Rule Editor, select the following:

- H1F4 under the variable fnf
- L2F1 under the variable snf
- L3F4 under the variable tnf
- The AND radio button, in the Connection block
- MD under the output variable, rcd
- SL14.under the output variable rcl

The resulting rule is:

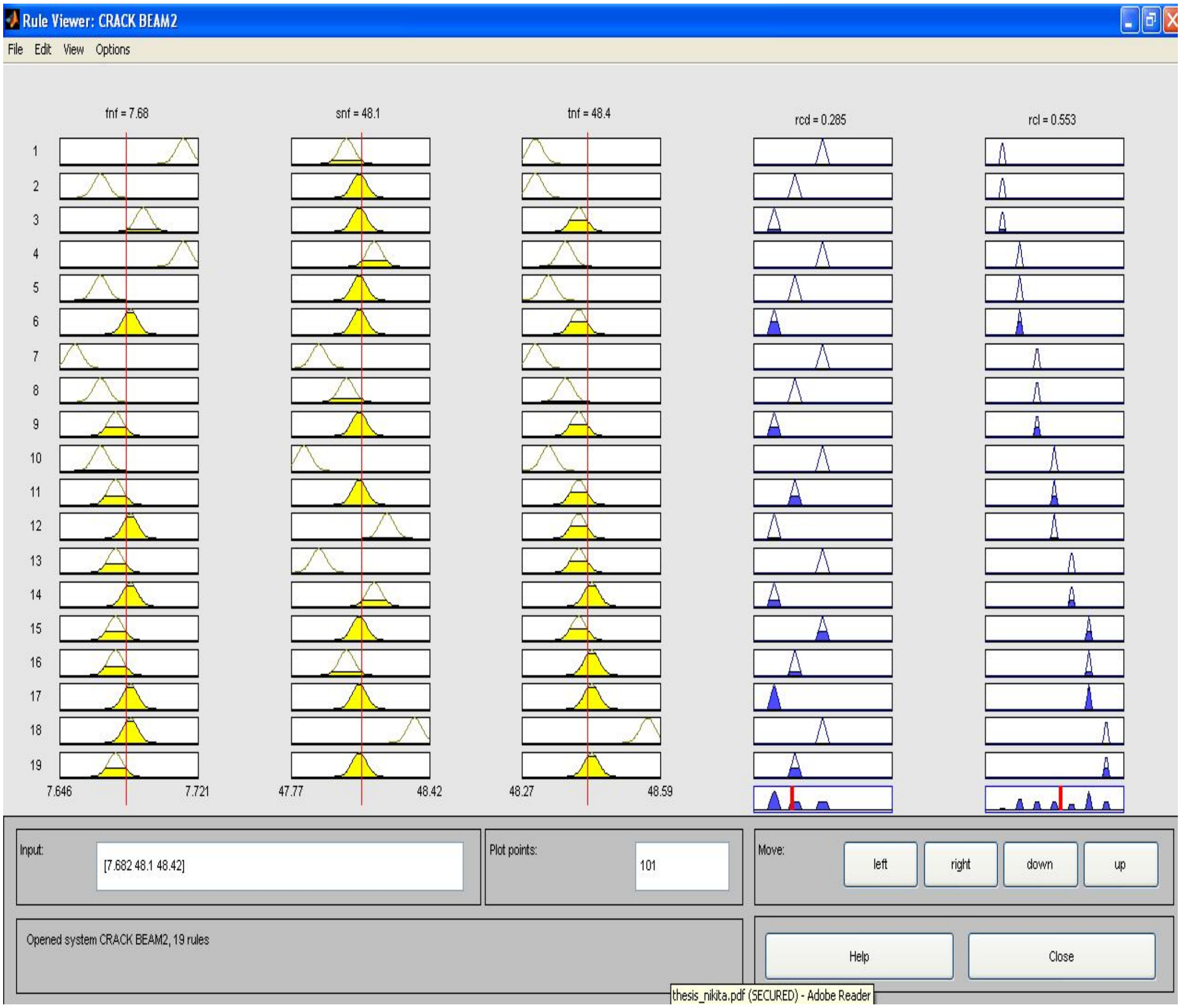
if (fnf is H1F4) and (snf is L2F1) and (tnf is L3F4) then (rcd is MD)(rcl is SL14)

The numbers in the parentheses represent weights. Follow a similar procedure to insert the rest of the rules. To change a rule, first click on the rule to be changed. Next make the desired changes to that rule, and then click Change rule.



6.5 Rules Viewer :

The Rule Viewer allows you to interpret the entire fuzzy inference process at once. The Rule Viewer also shows how the shape of certain membership functions influences the overall result. The defuzzified output value is shown by the thick line passing through the aggregate fuzzy set. Since it plots every part of every rule, it can become unwieldy for particularly large systems, but, for a relatively small number of inputs and outputs, it performs well (depending on how much screen space you devote to it) with up to 30 rules and as many as 6 or 7 variables.



6.6 Comparison between FEA and FL :

Sl No.	Fnf (/s)	Snf (/s)	Tnf (/s)	FEA analysis		Fuzzy Controller	
				(rcd)	(rcl)	(rcd)	(rcl)
1	7.69345	48.0475	48.287	0.5	0.125	0.5	0.195
2	7.66641	48.0782	48.2795	0.333	0.125	0.3	0.129
3	7.68657	48.111	48.3914	0.167	0.125	0.164	0.218
4	7.72106	48.1593	48.3777	0.5	0.25	0.5	0.25
5	7.66319	48.0908	48.3221	0.333	0.25	0.3	0.195
6	7.6831	48.0954	48.4007	0.167	0.25	0.256	0.459
7	7.64557	47.8803	48.2719	0.5	0.375	0.5	0.375
8	7.66627	48.0194	48.3637	0.333	0.375	0.304	0.39
9	7.67963	48.1156	48.4076	0.167	0.375	0.307	0.549
10	7.66479	47.7739	48.346	0.5	0.5	0.5	0.5
11	7.67646	48.0897	48.3975	0.333	0.5	0.317	0.546
12	7.68094	48.2138	48.4126	0.167	0.5	0.152	0.541
13	7.67362	47.8839	48.3938	0.5	0.625	0.5	0.625
14	7.67487	47.9791	48.4078	0.333	0.625	0.335	0.664
15	7.67725	48.1324	48.4153	0.167	0.625	0.303	0.584
16	7.67854	48.0744	48.4123	0.5	0.75	0.317	0.56
17	7.67645	48.0599	48.4154	0.333	0.75	0.316	0.594
18	7.67681	48.1095	48.4166	0.167	0.75	0.312	0.598
19	7.68616	48.419	48.5865	0.5	0.875	0.5	0.875
20	7.67679	48.0916	48.4177	0.333	0.875	0.308	0.602
21	7.67673	48.0957	48.4173	0.167	0.875	0.31	0.601

CHAPTER 6

DISCUSSION AND CONCLUSION

Discussion:

Discussion based on the output generated by Fuzzy Controller used and the information supplemented by FEA analysis in ALGOR is as follows:

It is already known that the natural frequency decreases as the crack depth increases in a structural part. Firstly determination of natural frequency of different modes of vibration is done for un-cracked beam numerically (solving Eular Equation For Beam in vibration analysis), using MATLAB programming analysis and then FEA analysis in ALGOR. Afterwards FEA analysis is considered for Cracked Beam in ALGOR. Here total 21 models have been used taking different combinations of relative crack location and relative crack depth. Several steps have been shown to develop a natural frequency modal based on FEA which is explained through an example and all the frequencies values are tabulated in article 5.3. It is clear from analysis that the natural frequency of different modes of vibration can be precisely obtained from this method.

Now considering the second approach in which fuzzy inference system is used. The present fuzzy controller used Gaussian MF for input variables and Triangular MF for output variables shown in article 6.3. Linguistic terms used in this fuzzy controller for variables are given in article 6.2. Some of examples of the rules for present controller is tabulated in article 6.4 Now this controller is used to obtained the defuzzified values of output variables (rcl, rcd) based on the natural frequencies developed in FEA analysis in ALGOR.

A comparison is made between these two approaches in article 6.6 which shows the relative crack depth and relative crack location as output. But in actual FEA obtains natural frequency for different modes of vibration from the input as crack location and crack depth, whereas fuzzy takes 1st three frequencies as input and obtained relative crack depth and relative crack location as output.

CONCLUSION :

The present investigation based on the Fuzzy Controller, Numerical Analysis and the FEA Analysis draws the following conclusions.

- Inputs for FEA are crack location and crack depth and outputs are natural frequency for different modes of vibration whereas inputs for fuzzy controller are natural frequency and outputs are crack depth and crack location.
- The fuzzy controller is developed with Gaussian membership function for inputs and Triangular membership function for output and results shows that Gaussian MF predicts more accurate results than Triangular.
- Crack depth and crack location of a beam can be predicted by fuzzy controller is within nanoseconds. Hence it saves considerable amount of computation time.
- Significant changes in natural frequency observed at the vicinity of crack location.
- When the crack location is constant but the crack depth increases, the natural frequency of the beam decreases.
- When the crack depth is constant and crack location from the cantilever end varied, Natural frequencies of first, second and third modes are also increased.
- By Comparing the Fuzzy results with the FEA results it is observed that the developed Fuzzy Controller can predict the relative crack depth and relative crack location in a very accurate manner.
- Results based on fuzzy techniques are not much accurate as it depends on some training pattern of fuzzy controller, whereas in ALGOR, it is much accurate as it is based on finite elements. But it is not practically suitable as natural frequency can be obtained practically but crack location and crack depth are not possible as they are very small values.

Here a new approach can be suggested which is based on the combination of both ALGOR and Fuzzy, in which natural frequency obtained in algor can be used as input for fuzzy controller for determination of accurate value of crack depth and crack location.

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