

Numerical Simulation of Cantilever Beam with Multiple Cracks Using Neural Networks and Multiple Regression Analysis Tool

Chappa. Santosh Kumar¹, M.Y.Prasada Rao², L.V.V.Gopala Rao³, Dilleswararao.Chintala⁴

P.G Student, Department of Mechanical Engineering, MVGR College of Engineering, Vizianagaram, India¹

Assistant Professor, Department of Mechanical Engineering, MVGR College of Engineering, Vizianagaram, India²

Associate Professor, Department of Mechanical Engineering, MVGR College of Engineering, Vizianagaram, India³

Lecturer, Department of Mechanical Engineering, MRAGR Government Polytechnic, Vizianagaram, India⁴

ABSTRACT: In recent years, intense research on the detection of crack using the vibration based techniques has been done and various approaches have been developed by researchers. The work reported in this paper is part of an ongoing research on the experimental investigations of the effects of cracks and damages on the integrity of structures, with a view to detect, quantify, and determine their extents and locations. In the present study, vibration analysis is carried out on a cantilever beam with two open transverse cracks, to study the response characteristics. Suitable boundary conditions are used to find out natural frequency and mode shapes. The simulations have been done with the help of ANSYS14.0 software. A neural network for the cracked structure is trained to approximate the response of the structure by the data set prepared for various crack sizes and locations. Feed-forward multi-layer neural networks trained by back-propagation are used to learn the input (the location and depth of a crack)-output (the structural natural frequencies) relation of the structural system. With this trained neural network minimizing the difference from the measured frequencies and also carried out Multiple Regression Analysis to learn input-output relation in similar fashion. A comparative study is performed to check the crack depth and location effects on natural frequencies for beams of rectangular and I cross section. It is verified from the present analysis that the presence of crack decreases the natural frequency of vibration. The mode shapes also change considerably due to the presence of crack. The frequency of the cracked cantilever beam decreases with increase in the crack depth for all modes of vibrations.

KEYWORDS: Crack Detection, Natural frequency, Neural Networks, Multiple Regression Analysis.

I. INTRODUCTION

It is required that the structures must safely work during its service life. However, presence of crack damages may lead to breakdown of structures. Crack is one of the most common faults that if develops, may cause catastrophic damages in structures. Therefore, it must be detected in the early stage when it is small. Crack-like defects in mechanical and civil engineering structures are a problem that received considerable attention by researchers. Since beam type structures are very common used in bridge girders, railway tracks, steel construction and machinery industries, for the last few decades engineers and scientists are working on various techniques for detection of crack in the beamlike structure. It has been observed that for damage/crack detection non-destructive testing is preferable over destructive testing. Many researchers have carried out different non-destructive methodologies for crack detection but it has been observed that the vibration based method is fast and inexpensive for crack/damage identification. Depending on the assumptions, the type of analysis, the overall beam characteristics and the kind of loading or excitation, a number of research papers containing a variety of different approaches have been reported in the relevant literature. Damage can be analysed through visual inspection or by the method of measuring frequency, mode shape and structural damping. Damage detection by visual inspection is a time consuming method and measuring of mode shape as well as structural deflection is difficult rather than measuring frequency. The presence of crack induces local flexibility, which affects

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the dynamic behaviour of the whole structure as a result the reduction occurs in natural frequency and mode shape. By considering the changes in those parameters crack can be identified in terms of crack depth and crack location.

II. RELATED WORK

Crack damage leads to reduction in stiffness also with an inherent reduction in natural frequency. Kaushar H. Barad et. al. [1] presented a method for detection of crack in cantilever beam which is based on frequency measurement. Experimental method and finite element method is used to analyse modal parameters of the cracked cantilever beam by D.K.Agarwal and D.R.Parhi [3].Irshad A Khan and Dayal R Parhi [4] studied the vibration characteristics of cantilever beam with two cracks. Two types of beams are considered for study i.e. cantilevers beam and fixed-fixed beam. Dong Wei et. al. [5] proposed analytical method for solving the free vibration of cracked functionally graded material (FGM) beams with axial loading, rotary inertia and shear deformation. Yoona Han-Ik et al.[6] have investigated the influence of two open cracks on the dynamic behaviour of a double cracked simply supported beam both analytically and experimentally. In all previous studies, the effects of both the crack and the load on the natural frequency of rectangular beams were studied, in the present study, vibration analysis is carried out on beam of I cross section and made comparison with rectangle beam. It has been reported that ANN approach can be applied to damage detection [7], because neural networks can be trained to recognise given patterns and to classify other untrained patterns [9]. ANN technique based on vibration characteristics have been used for damage identification in different structures, such as beam structure [8].

III. METHODOLOGY

In the present work, vibration analysis is carried out on a cantilever Aluminium beam with two open transverse cracks. The study is aimed at detecting the size and location of crack in cantilever beam. Free vibration finite element analysis of crack free beam and a series of cracked beams are performed. Suitable boundary conditions are used to find out natural frequencies and mode shapes. The simulations have done with the help of ANSYS 14.0 software. Comparison studies are performed on natural frequencies and mode shapes of cracked and cracked free beam. Identification of crack depth and its location is determined by two different methods, namely, ANN analysis and Multiple Regression analysis.

IV. FINITE ELEMENT ANALYSIS

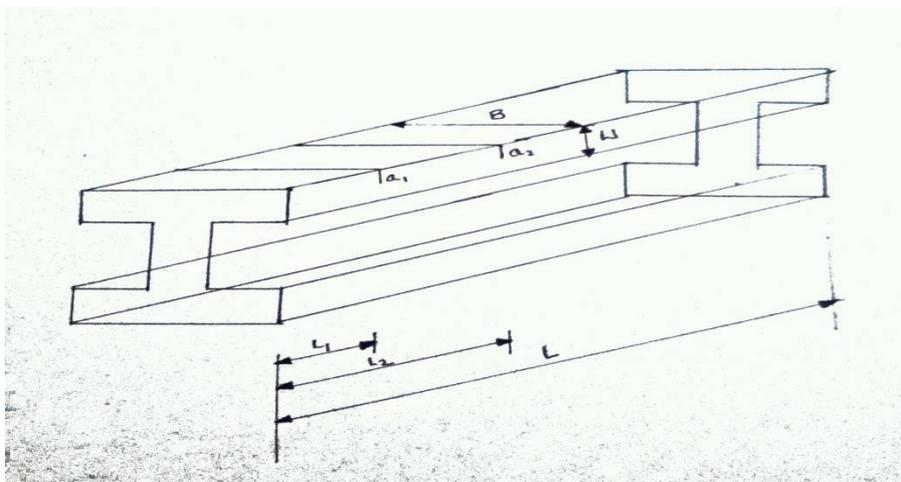


Fig.1 Cantilever beam with two transverse cracks

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Finite element model of a cantilevers beam with two open transverse cracks are developed in ANSYS environment. The dimensions of the beam are shown in Fig.1 Material properties of the beam are shown in Table. In order to perform modal and structural analysis of the beam is performed following the steps outlines below.

V. MODAL ANALYSIS

Following steps show the guidelines for carrying out Modal analysis

Define Materials:

- 1.Set preferences. (Structural)
- 2.Define constant material properties.

Model the Geometry:

3. Create the geometry

Generate Mesh:

- 4.Define element type. Mesh the area.

Apply Boundary Conditions:

- 5.Apply constraints to the model.

Obtain Solution:

- 6.Specify analysis types and options.
7. Solve.

Table Beam Characteristics

BEAM	Density (Kg/m3)	Poisson Ratio	Elastic Modulus (N/m2)	Length (m)	Depth (m)	Thickness (m)	inner face height (m)	Width (m)	Flange thickness (m)	Web thickness (m)
RECTANGULUR	2713	0.334	0.724x10 ¹¹	0.8	0.05	0.006	—	—	—	—
I-SECTION	2713	0.334	0.724x10 ¹¹	0.8	—	—	0.02	0.02	0.005	0.005

Finite element software, ANSYS version 14 is used for free vibration analysis of the crack free and cracked beams. Beam length, thickness and depth are along X axis, Y axis and Z axis respectively in ANSYS coordinate system. A 20-node three dimension structural solid element under SOLID 186 was selected to model the beam because it is suitable for all structural analysis and it is mid node element which gives the more accurate result. Fig shows finite element model of a cracked beam. The modal analysis of cracked and crack free beams are performed. The Block Lanczons mode extraction method is used to calculate the natural frequencies of the beam. The corresponding mode shapes for both cracked and cracked free beam are also captured. The displacement values are used as a numerical data of ANN and Multiple Regression Analysis tool for subsequent identification of crack length and location of the beam.

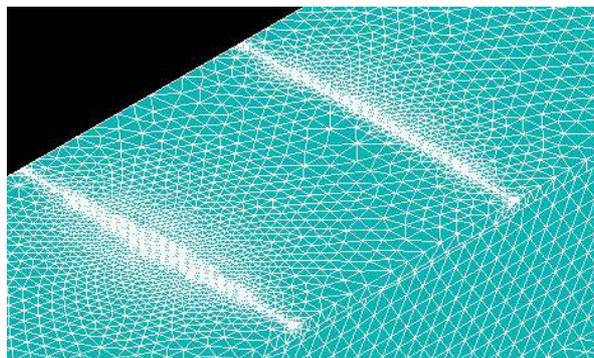


Fig.2: Details of Crack Zone

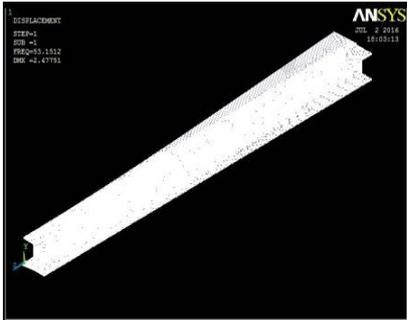


Fig.3

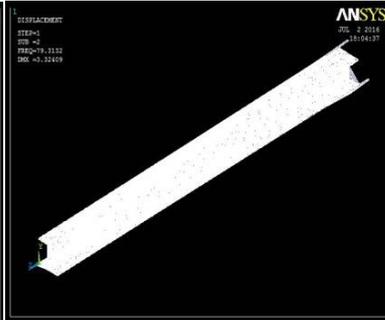


Fig.4

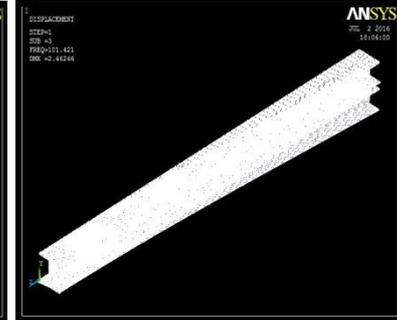


Fig.5

Fig.3 First mode of vibration, $a_1/w=0.5$, $a_2/w=0.5$, $L_1/L=0.35$, $L_2/L=0.4$

Fig.4 Second mode of vibration, $a_1/w=0.5$, $a_2/w=0.5$, $L_1/L=0.35$, $L_2/L=0.4$

Fig.5 Third mode of vibration, $a_1/w=0.5$, $a_2/w=0.5$, $L_1/L=0.35$, $L_2/L=0.4$

Table. Variation of frequencies at different Relative crack depths when Relative Crack location at $L_1/L=0.28$, $L_2/L=0.32$.

Crack depth (a1=a2) m	f1	f2	f3
0.0003	53.1512	79.3132	101.421
0.0006	53.1363	79.2974	101.397
0.0009	53.0974	79.2721	101.34
0.0012	53.0075	79.2286	101.212
0.0015	52.7938	79.1468	100.944
0.0018	52.383	78.9178	100.48
0.0021	36.2265	74.1278	95.5043
0.0024	36.2057	74.0942	95.4433
0.0027	36.1896	74.0702	95.392
0.003	36.1626	74.0287	95.3368

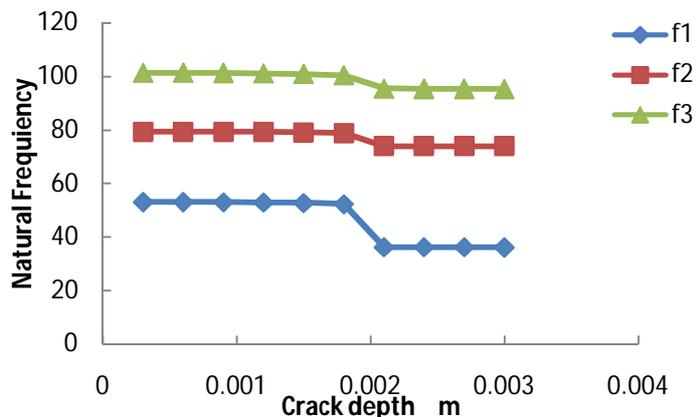


Fig.6 Variation of frequencies at different Relative crack depths

VI. ARTIFICIAL NEURAL NETWORKS APPROACH

The Artificial Neural Network (ANN) technique is a different approach. It is inspired in the brain information processing through a much interconnected parallel structure. It does not involve governing equations but it needs a training set of data. The knowledge of the ANN is then acquired through a learning process in which both input and output (desired) data is supplied to the network. The so-called Multi-layer Perceptron architecture consists of a first layer with the input vector, a final layer with the output vector and intermediate layers (known as hidden layers) that link to the other layers through weighted connections. A simple representation of an ANN with a single hidden layer is depicted in Fig.7 In this work, a single hidden layer and the back-propagation training algorithm are used. The results of the frequency values for all the studied cases, as described in previous Section. As is usual, a portion of the data is chosen randomly to train the ANN (training set to fit the weights), and the other portion (15%) to validate the data.

The clamped-free beam of Figure 1 has a length of $L=0.8$ m, Inner face height of the beam $=0.02$ m, Flange width of the beam $=0.02$ m, Flange thickness of the beam $=0.005$ m, Web thickness of the beam $=0.005$ m the material properties are $E = 0.724 \times 10^{11}$ N/m², Poisson's ratio $= 0.334$, $\rho = 2713$ kg/m³. For the preparation of the learning data, 10 sets of a crack depths $a_1=a_2=0.0003$ to 0.003 m (step size $=0.0003$ m) are introduced at the 17 different crack locations

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L1=0.04 to 0.68m (step size=0.04m) and L2=0.08 to 0.72m (step size=0.04m). Totally 170 cases or patterns (10 different crack depths and 17 different crack locations) are solved for the first three frequencies. The patterns which consist of 170 sets of data are used to train the neural network of Figure .Because of the nature of the sigmoid activation function, i.e., saturation function, the output variables should be scaled by the user, to be within the most active range of the sigmoid function. Scaling rule that minimum and maximum values are set to 0.1 and 0.9 is usually suggested. Through some trials, a network with neuron arrangement (input-hidden-output) of 4-13-3 trained with 8 iterations for the 170 patterns are concluded to be the best for our application. Mean-square error (MSE) is employed as a measurement of modelling performance. The mathematical expression can be described as follows:

$$MSE = \frac{\sum_{i=1}^N (e_i)^2}{N}$$

Where e_i denotes an error at pattern i and N is the total number of patterns.

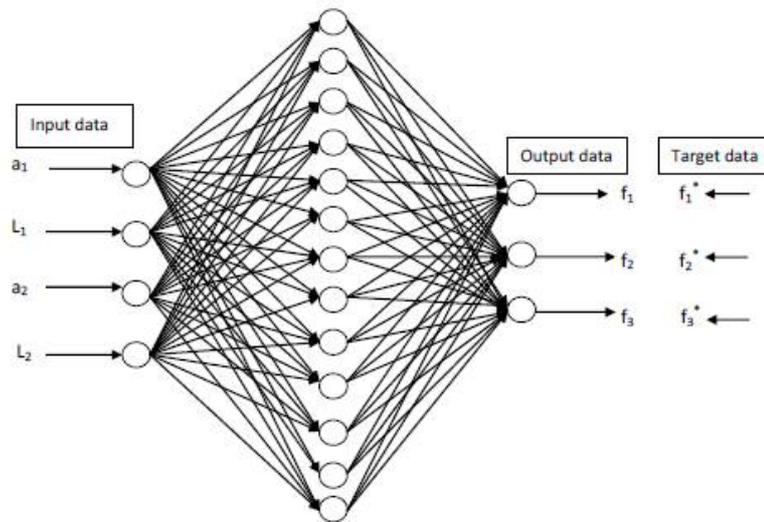


Fig.7 Three-layer neural network with neuron arrangement of 4-13-3.

VII. MULTIPLE REGRESSION

A statistical tool that allows you to examine how multiple independent variables are related to a dependent variable. Once you have identified how these multiple variables relate to your dependent variable, you can take information about all of the independent variables and use it to make much more powerful and accurate predictions about why things are the way they are. This latter process is called “Multiple Regression”.

The Formula for Multiple Regression:

$$Y = a + b_1X_1 + b_2X_2$$

Y = A predicted value of Y (which is dependent variable)

a =The”Y intercept”

b_1 =The change in Y for each 1 increment change in X_1

b_2 =The change in Y for each 1 increment change in X_2

X_1 = Independent Variable 1

X_2 = Independent Variable 2

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VIII. RESULTS AND DISCUSSIONS

Table: Variation in Natural frequency in cantilever beam of I-cross section Without crack and crack at depth $a_1=a_2=0.0021$, Location at $L_1=0.04, L_2=0.08$.

Natural Frequency	Without crack	With crack
f1	53.143	27.4876
f2	79.304	70.1851
f3	101.41	85.3439

The first, second and third natural frequencies corresponding to various crack locations and depths are obtained from the modal analysis of the beam in ANSYS environment, the frequency of the cracked cantilever beam decreases when compared with cantilever beam without crack.

Table. Variation of frequencies at different Relative crack lengths when Relative Crack depth at $a_1=a_2=0.0012$

S.NO	CRACK DEPTH	L1	L2	ANSYS			ANN			MRA		
				F1	F2	F3	F1	F2	F3	F1	F2	F3
1	0.0012	0.04	0.08	52.6796	78.895	100.74	53.667	79.3176	101.428	44.88111	76.6115	96.6506
2	0.0012	0.08	0.12	52.7478	78.895	100.83	53.717	79.3193	101.439	45.6098	76.8389	97.105
3	0.0012	0.12	0.16	52.8165	79.065	100.93	53.752	79.3203	101.454	46.3385	77.0664	97.5593
4	0.0012	0.16	0.2	52.8639	79.117	101	52.941	78.888	100.182	47.06719	77.2938	98.0136
5	0.0012	0.2	0.24	52.9225	79.165	101.08	52.985	79.1369	100.747	47.79588	77.5213	98.4679
6	0.0012	0.24	0.28	52.9675	79.203	101.15	53.073	79.1584	100.895	48.52458	77.7487	98.9222
7	0.0012	0.28	0.32	53.0075	79.229	101.21	53.178	79.1189	100.959	49.25327	77.9761	99.3765
8	0.0012	0.32	0.36	53.0438	79.255	101.27	53.285	79.0914	101.013	49.98196	78.2036	99.8308
9	0.0012	0.36	0.4	53.0741	79.266	101.3	53.382	79.1087	101.074	50.71065	78.431	100.285
10	0.0012	0.4	0.44	53.1022	79.28	101.35	53.463	79.1561	101.136	51.43935	78.6585	100.739
11	0.0012	0.44	0.48	53.1209	79.286	101.38	53.514	79.2088	101.193	52.16804	78.8859	101.194
12	0.0012	0.48	0.52	53.1382	79.295	101.41	53.575	79.2528	101.244	52.89673	79.1133	101.648
13	0.0012	0.52	0.56	53.1505	79.3	101.43	53.621	79.2829	101.288	53.62543	79.3408	102.102
14	0.0012	0.56	0.6	53.1608	79.304	101.44	53.616	79.3007	101.325	54.35412	79.5682	102.557
15	0.0012	0.6	0.64	53.1681	79.311	101.45	53.655	79.3107	101.353	55.08281	79.7957	103.011
16	0.0012	0.64	0.68	53.1743	79.326	101.47	53.704	79.3167	101.377	55.81151	80.0231	103.465
17	0.0012	0.68	0.72	53.1794	79.333	101.48	53.743	79.3211	101.402	56.5402	80.2506	103.92

Totally 170 cases or patterns (10 different crack depths and 17 different crack locations) are solved for the first three frequencies. The patterns which consist of 170 sets of data are used to train the neural network and for Multiple regression analysis.

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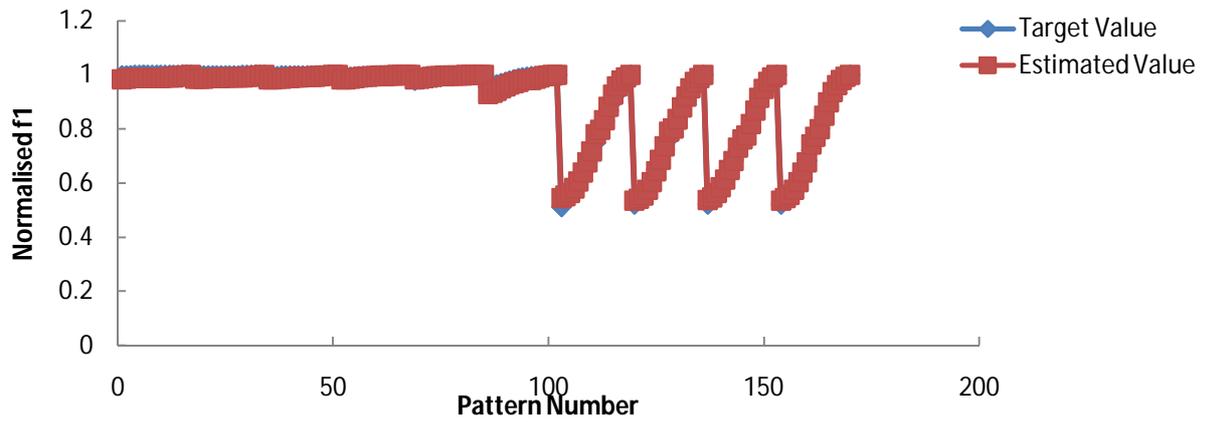


Fig.8: Comparison of the first estimated natural frequencies from the neural network to target values

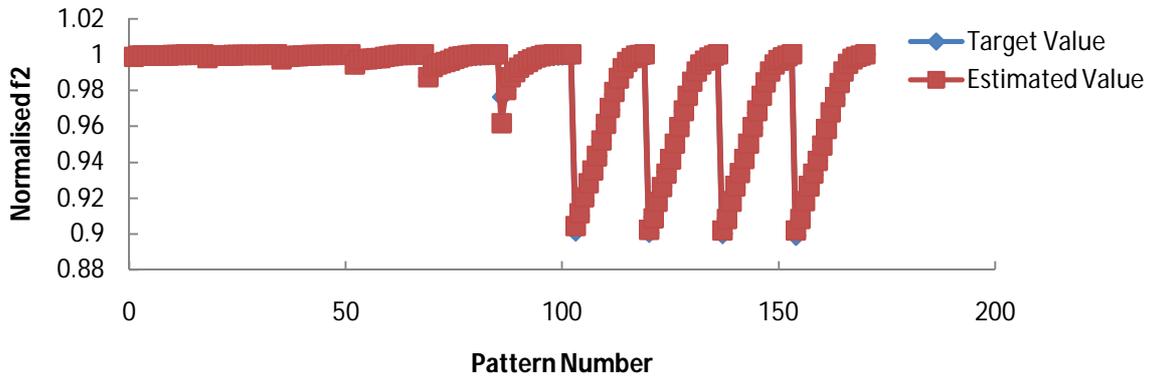


Fig.9: Comparison of the Second estimated natural frequencies from the neural network to target values

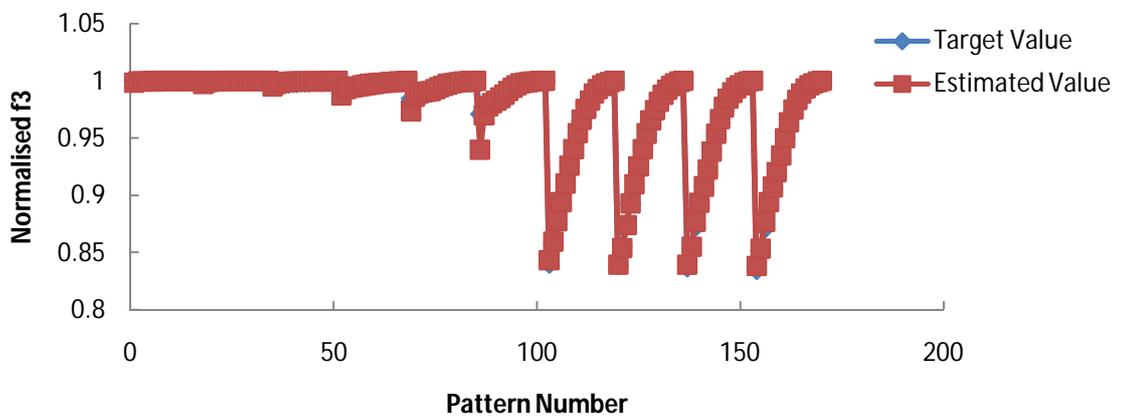


Fig.10: Comparison of the Third estimated natural frequencies from the neural network to target value

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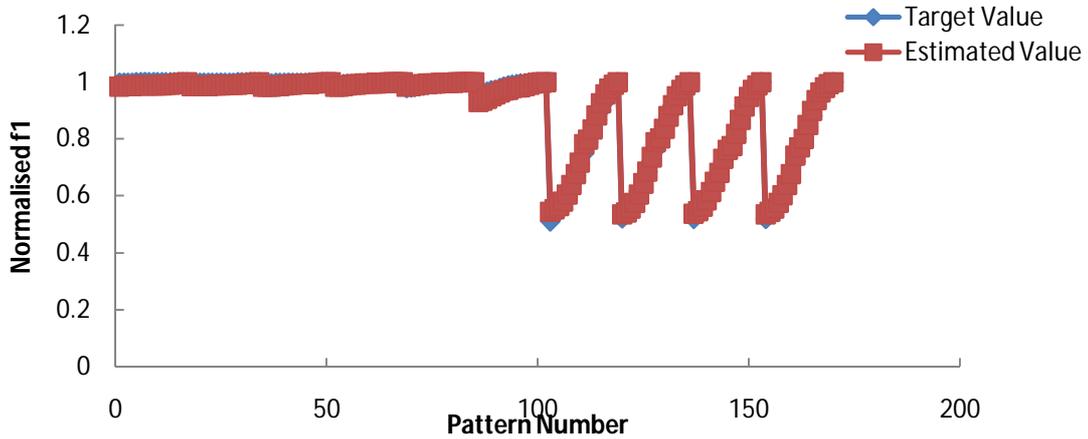


Fig.11: Comparison of the First estimated natural frequencies from the MRA to target values

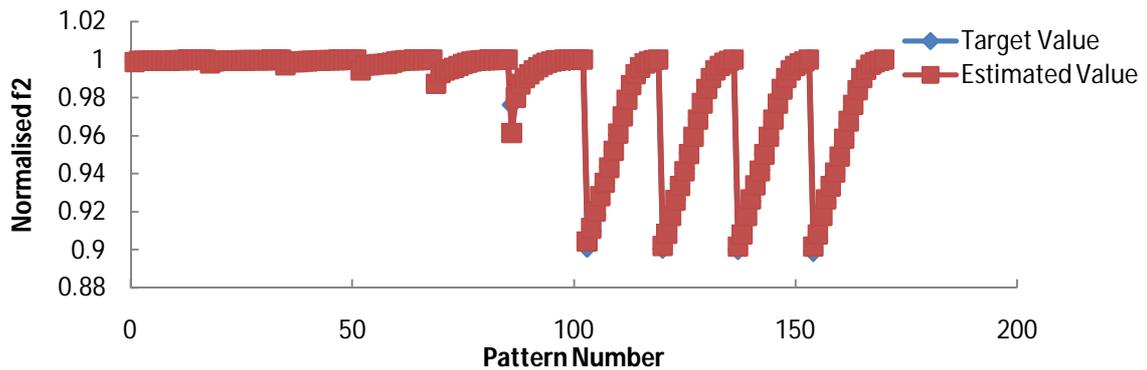


Fig.12: Comparison of the Second estimated natural frequencies from the MRA to target values

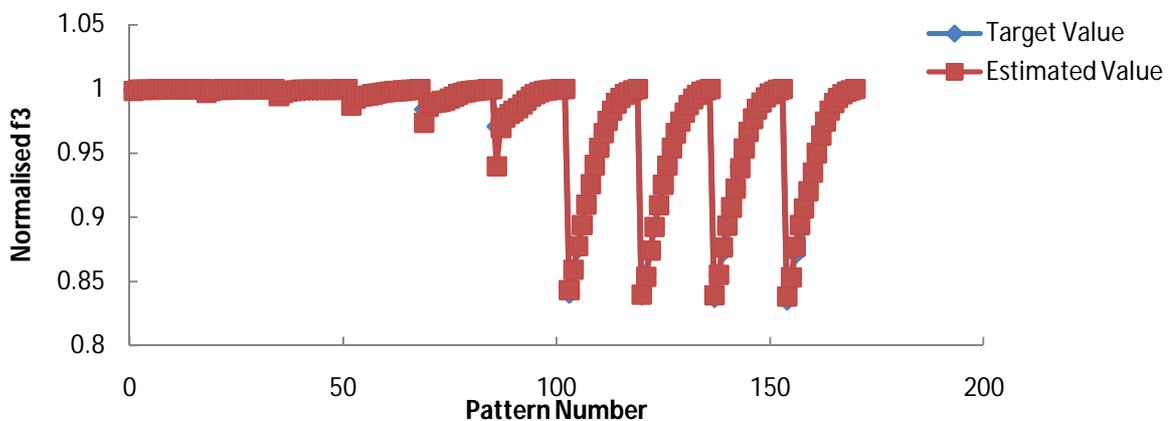


Fig.13: Comparison of the Third estimated natural frequencies from the MRA to target values

The estimated natural frequencies from the network are compared to the target values as shown in Fig.8-10. The estimated natural frequencies from the multiple regression analysis are compared to the target values as shown in

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Fig.11-13. The target values are $f1^*$, $f2^*$ and $f3^*$ in Fig.7 which are the reference data or training data to have trained the neural network. One hundred and seventy patterns are arranged in 10 separate curves base on the value of a as shown in the Fig.8 shows the first natural frequency $f1$ is monotonously increasing as the crack location moves from the clamped end to the free end when the crack depth $a1=a2$ is kept constant. On the other hand, the second and the third natural frequencies oscillate under the same situation as shown in Fig.9 and Fig.10.

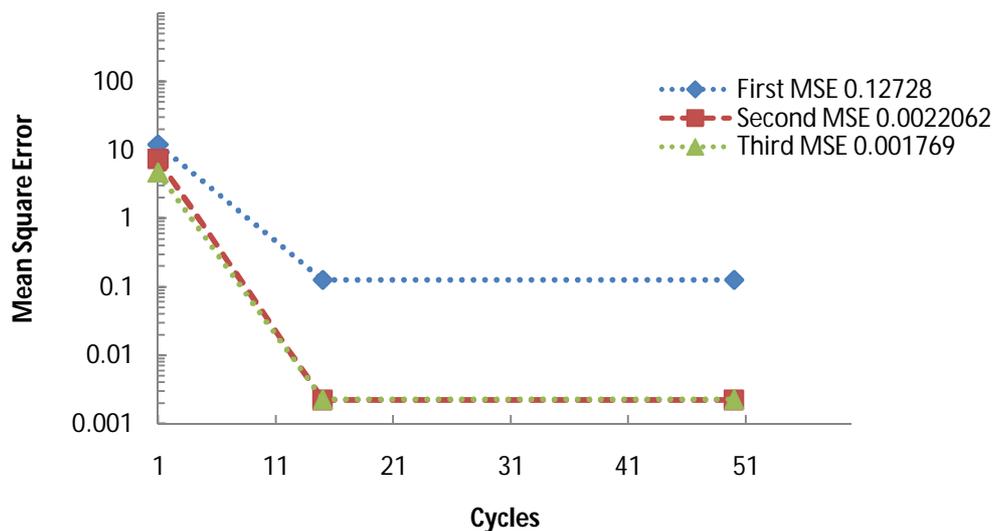


Fig.14: Neural network output

IX. CONCLUSION

The frequency of the cracked cantilever beam decreases with increase in the crack depth for the all modes of vibration. For same amount of material cantilever beam of I cross-section has more dynamic stability than beam of rectangular cross section. Feed-forward multi-layer neural networks trained by back-propagation are used to learn the input (the location and depth of a crack)-output (natural frequencies) relation of the structural system. From neural network training, the first natural frequency $f1$ is monotonously increasing as the crack location moves from the clamped end to the free end when the crack depth $a1=a2$ is kept constant. On the other hand, the second and the third natural frequency oscillate under the same situation. The first MSE is 0.12728, second MSE is 0.0022062 and third MSE is 0.001769. A neural network for the cracked structure is trained to approximate the response of the structure by the data set prepared for various crack sizes and locations. Training data to train the neural network are properly prepared. Multiple Regression Analysis is also carried for the data obtained from the Modal analysis to learn the relation between natural frequencies and crack location and crack depth. ANN is the more powerful tool than MRA and it predict the cack location and depth to natural frequencies and vice-versa.

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