Damage Analysis of an Inclined Cracked Curved Beam Using ANFIS

Shraddha Lohar and Prases K. Mohanty

Abstract As the damage in the structures grows, failure rate increases rapidly causing weakening of structures which leads to early failure of the structures. Hence, advance identification of damages in structures should be addressed immediately. This paper presents an intelligent technique for damage identification in a curved inclined cracked beam based on vibration signatures. Vibration analysis of the cracked curved beam is carried out using ANSYS© software. The natural frequencies and mode shapes are computed by varying crack severities and crack locations. The results dictate that the vibration parameters are changed for different crack severities and crack locations. These parameters are given as input to adaptive neuro-fuzzy inference system (ANFIS) to predict the damage characteristics for the cracked beam. The results reveal that the proposed intelligent controller could be deployed to locate and quantify the damage in any cracked structure.

Keywords Curved beam · Inclined crack · Finite element analysis (FEA) · Natural frequency · ANFIS

1 Introduction

Structural integrity is the structure capacity to carry loads without undergoing damage. Loss in the structural integrity is the major reason for structural damage. The weak structures, faulty designs, fatigue, etc. cause the structural integrity loss. One of the reasons for the structural damage is crack present in the structures. The crack initiation starts at the points where stress concentration is present, causing the start of the damage in the structures. And when the load varies with respect to time, crack develops. Due to which, early recognition of crack present in the structures is mandatory to eliminate these abrupt breakdowns of the structures. Out of all structures, one of the significant basic structural elements used in variety of day-to-day applications is 'curved beam'. Presence of fault like crack in the curved beam causes

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changes in natural frequency, amplitude response and vibration mode shapes of the beam.

Recent times, many studies are focused on the fault diagnosis of structures, in which crack diagnosis is also an important issue in recent years. Krawczuk et al. [1] investigated circular arches with clamped–clamped end boundary condition and effect of open edge crack on the circular arch. Viola et al. [2] studied thin and thick circular arches with different cross-sections and a single crack. He investigated effect of in-plane vibration on the same. Cerii et al. [3] studied effect of vibration on circular arches and found the dynamic characteristics of circular arches with and without damage. Yang et al. [4] studied free in-plane vibration of general curved beams using finite element method. Chen [5] studied non-prismatic curved beam and found out of plane vibrations for the same. Zare [6] studied simply supported curved beam with crack present in it and analyzed it with analytical and experimental methods. Many heuristics techniques are implemented for diagnosis of damage in cracked structures. Prawin et al. [7] found the damages in the structures with the help of single sensor measurement technique. A damage detection technique was used for the first time to detect location of the crack by Das et al. [8] which was based on zero strain energy node concept accomplished an artificial neural network to predict the position of the crack as well as severity of the crack in a fixed cantilever beam with crack. They used first three relative natural frequency along with mode shape as input to the ANN controller inorder find the damage parameters. Mehrjoo et al. [9] performed a fault detection by inverse set of rules to estimate the damage intensities of joins in truss bridge structure using backpropagation neural network method. From literature survey, it is investigated that identification of open inclined edge crack in curved beam structures using ANFIS has not previously been studied for vibration analysis. ANFIS takes the advantages of the neural network and fuzzy logic.

2 Objective of the Proposed Research

The FEA modeling along with simulations of beam is carried out using software ANSYS© 14.5 [10]. The software SolidWorks 2017 [11] is used to develop the curved beam model. The inclined edge crack depth must be taken as less than otherwise equal to the half of the beam thickness [12]. Starting with the left end support of the simply supported beam, relative angular crack position varies from 0.005 to 0.95. And also relative crack depth varies 0.1–0.5. By using ANSYS© software, the models of curved beam with simple supports by varying relative locations and severities are simulated.

Figure 1 indicates the simply supported curved beam model with an inclined open edge crack, for RCL = 0.21 and $\theta = 35°$, and Fig. 2 indicates the magnified view of inclined open edge crack with crack opening 0.8 mm and crack depth 3 mm. Later, the computed natural frequencies using FEA are given as inputs to the ANFIS model to predict location and quantify the damage in cracked beam.

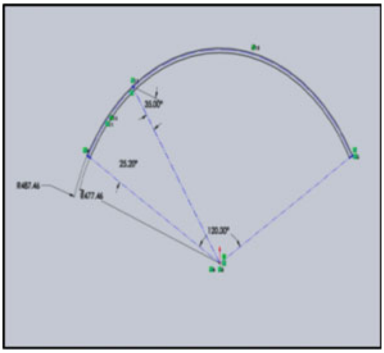

Fig. 1 Curved beam of Ø = 120° with inclined crack at 25.20°, $\theta = 35°$, RCL = 0.21 and $a = 3$ mm

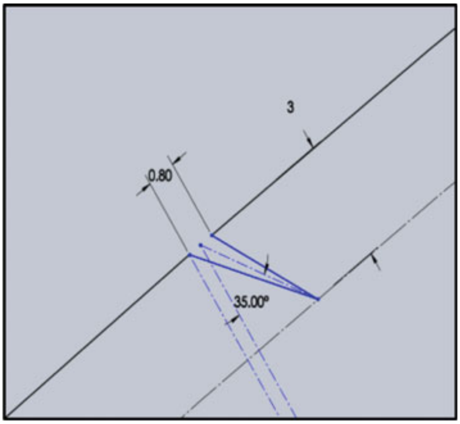

Fig. 2 Magnified view of an inclined edge crack

3 Theoretical Analysis

The curved beam with simple supports as well as with loading condition is used to create beam model with open edge crack. The model generation can be achieved with the help of local flexibility approach based on linear fracture mechanics. In beam present crack location, flexibility influence co-efficient (i.e., local compliance, herein S_{ij}) is given by [13];

$$(Sij) = \frac{\partial ui}{\partial Pj} = \frac{\partial^2}{\partial Pi \partial Pj} \int_0^a G(a)\mathrm{d}a \tag{1}$$

where $G(a) = \frac{\partial u}{\partial a}$ strain energy rate, u = strain energy, a = variable with respect to crack depth.

$$J = \frac{1 - \nu}{E}(K11 + K12)^2 \tag{2}$$

where K_{11} and K_{12} = stress intensity factors of opening of crack.

The inversion compliance matrix is used to derive the local stiffness matrix which is written as,

$$K = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}^{-1} = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \tag{3}$$

4 Finite Element Analysis (FEA) of the Cracked Curved Beam

The FEA simulations of inclined open edge crack as well as un-cracked curved beam with simple supports are carried out using ANSYS© software. From the analysis, natural frequencies along with the consequent mode shapes at various crack locations and severities of crack are computed. The specifications of a cracked curved beam of the current analysis are as shown below,

Opening angle of the curved beam (ϕ) = 120°.

Curved beam cross-sectional depth (d) = 10 mm.

Curved beam cross-sectional width (w) = 14 mm.

Relative crack location (RCL) = 0.005–0.95.

Relative crack severity (RCS) = 0.1–0.5.

Figures 3 and 4 indicate the FEA model for the curved beam with simple supports and the magnified details of the crack edge meshing during FEA analysis.

Figures 5, 6 and 7 show the 1st, 2nd and 3rd mode of vibrations of the curved beam with a relative crack severity of 0.3 and relative location at 0.21. These modes of vibrations demonstrate the distortions occurring in the curved beam due to the rotational and translational displacements.

Also it shows the effect of crack on the mode shapes of vibrations.

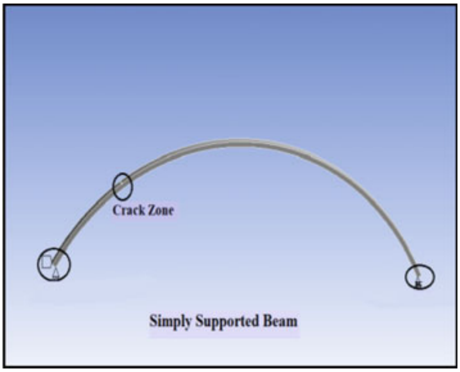

Fig. 3 Curved beam having simple supports with inclined edge crack at a = 3 mm and RCL = 0.2

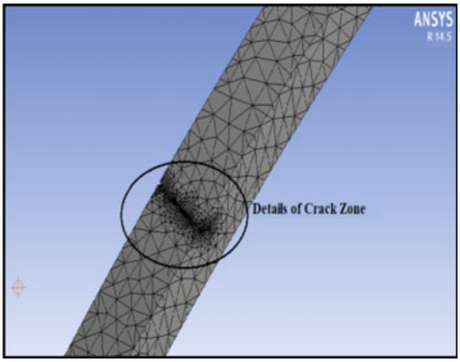

Fig. 4 Magnified details of the meshing at an inclined edge crack zone

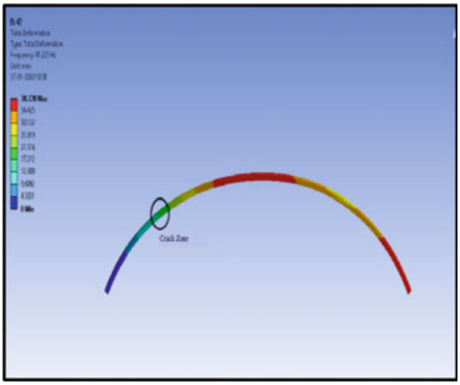

Fig. 5 1st mode shape of curved beam with simple supports for crack at RCS = 0.3, RCL = 0.21 and $\theta = 35°$

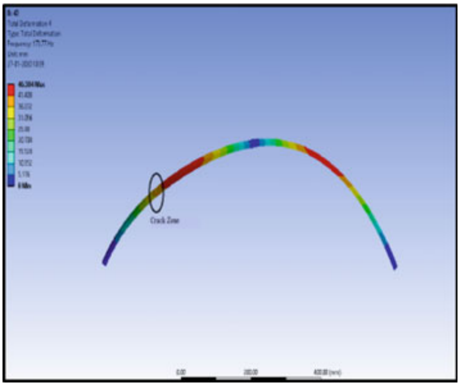

Fig. 6 2nd mode shape of curved beam with simple supports for crack at RCS = 0.3, RCL = 0.21 and $\theta = 35°$

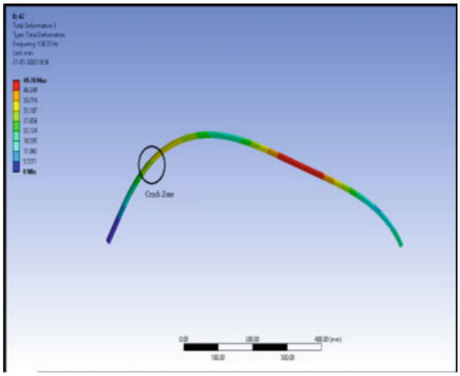

Fig. 7 3rd mode shape of curved beam with a simple supports for crack at RCS = 0.3, RCL = 0.21 and $\theta = 35°$

5 Architecture of ANFIS for Damage Detection in Curved Cracked Beam

The ANFIS is a hybrid system which combines the learning ability of neural network and human reasoning ability of fuzzy inference system [14]. The proposed system has the strength to solve complex problems. The function of each layer of ANFIS is explained in [14].

The proposed ANFIS model was framed with three input parameters and two output parameters as shown in Fig. 8.

The main objective of the proposed model is to set a relationship among input and output parameters. The data extracted from FEA was divided into two groups such as training and testing data sets, and 80% of the total data were used as training data and remaining 20% was used for testing data. The ANFIS model was trained with total 1000 data sets. The generalized bell membership function with three membership function for each input and hybrid optimization method was selected in ANFIS model. It has been noticed that after 200 iterations the training data sets became produce steady mean square error (MSE).

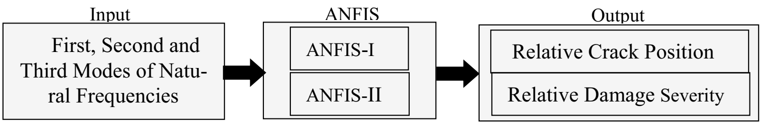

Fig. 8 Proposed ANFIS model for damage identification

6 Result and Discussions

Architecture of ANFIS is used for the dynamic behavior modeling of the curved beam. Figures 9 and 10 show the ANFIS model with absolute error for crack severity and crack locations where 80% of the data set is used for training and remaining 20% for testing and validating.

The results for simply supported curved beam with inclined crack by varying location of crack and severities using FEA and ANFIS model are tabulated in Table 1. Figures 9 and 10 provide the results about mean square error (MSE) between target and outputs on the basis of the topology of the ANFIS. It has been indicated that ANFIS model estimates accurately the damage parameters to actual data. The table shows both FEA and ANFIS outputs are in close proximity with each other which indicates crack identification accuracy in the ANFIS testing process.

As the depth of the crack increases, initially natural frequencies of the beam increases. But as crack location changes from left end of the beam to right end, after

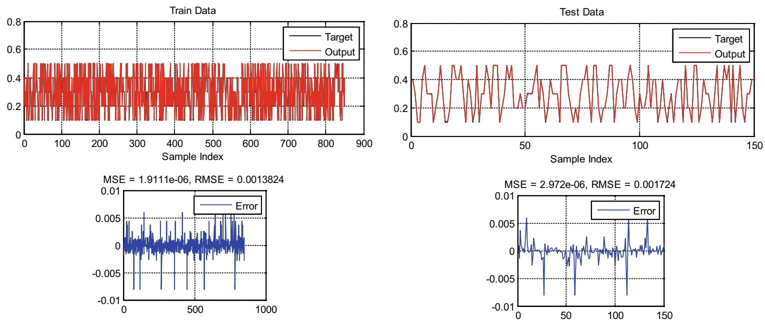

Fig. 9 ANFIS model with absolute error for crack severity

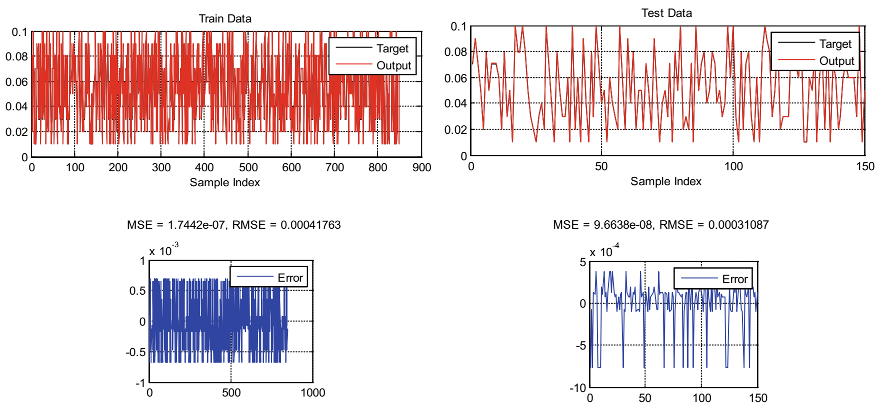

Fig. 10 ANFIS model with absolute error for crack location

Table 1 Sample of FEA and ANFIS analysis comparison results of cracked beam

Sr. No.	Input			Output			
	1st relative natural frequency	2nd relative natural frequency	3rd relative natural frequency	Relative crack location		Relative crack severity	
				FEA	ANFIS	FEA	ANFIS
1	0.997744	0.999484	0.998324	0.005	0.0049	0.025	0.02501
2	0.997986	0.999534	0.998629	0.01	0.099	0.05	0.0499
3	0.998229	0.999584	0.998934	0.015	0.014	0.075	0.07501
4	0.998447	0.999634	0.999162	0.02	0.0199	0.1	0.1009
5	0.998641	0.999684	0.999391	0.025	0.0249	0.125	0.12499
6	0.998836	0.999717	0.999543	0.03	0.029	0.15	0.1501
7	0.999005	0.999767	0.999695	0.035	0.0349	0.175	0.17502
8	0.999151	0.9998	0.999848	0.04	0.0399	0.2	0.1990
9	0.999296	0.999834	0.999924	0.045	0.0451	0.225	0.22499
10	0.999418	0.999867	0.99999	0.05	0.0501	0.25	0.25011
11	0.997744	0.999484	0.998324	0.055	0.0549	0.275	0.27501
12	0.997986	0.999534	0.998629	0.06	0.0609	0.3	0.299
13	0.998229	0.999584	0.998934	0.065	0.06501	0.325	0.32501
14	0.998447	0.999634	0.999162	0.07	0.0699	0.35	0.3499
15	0.998641	0.999684	0.999391	0.075	0.07501	0.375	0.37498
16	0.998836	0.999717	0.999543	0.08	0.08001	0.4	0.3997
17	0.999005	0.999767	0.999695	0.085	0.085003	0.425	0.4249
18	0.999151	0.9998	0.999848	0.09	0.0899	0.45	0.4501
19	0.999296	0.999834	0.999924	0.095	0.095001	0.475	0.47502
20	0.999418	0.999867	0.99999	0.1	0.1003	0.5	0.4991

certain location natural frequency decreases and cycle will go on till the formation of first and second modes of vibration of the curved beam as shown in Figs. 11 and 12.

Compared to the first and second natural frequency, third natural frequency also shows the similar frequency variation. Firstly, frequency increases as variation in the location of crack starting from left end of the beam to right end. After particular location, frequency will be minimum and process repeats forming three modes of vibration. Minimum frequency implies that impact of the crack at that point will be less. This variation is indicated as in Fig. 13.

As the natural frequency and mode shapes are the parameters dependent on each other. Hence, with the change in natural frequency, amplitude of vibration also changes.

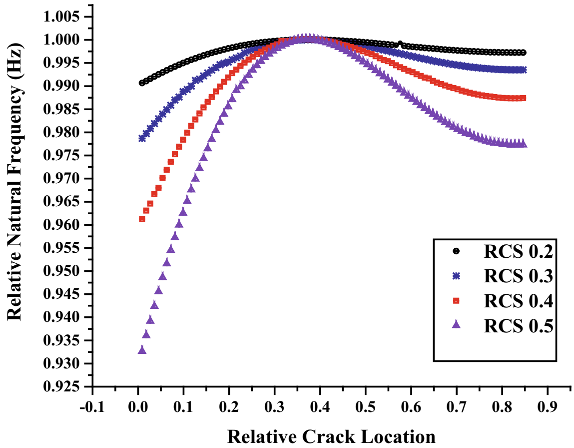

Fig. 11 Relative 1st mode of natural frequency versus relative crack locations

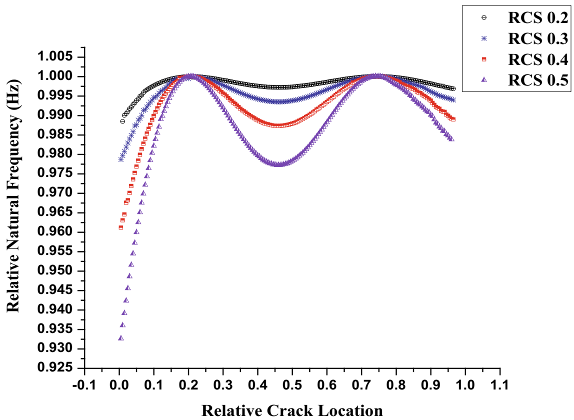

Fig. 12 Relative 2nd mode of natural frequency versus relative crack locations

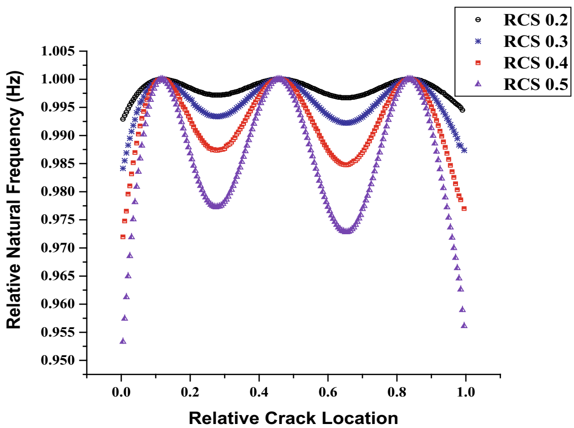

Fig. 13 Relative 3rd mode of natural frequency versus relative crack locations

7 Conclusion

The current investigation of simply supported curved beam with inclined crack concludes that:

- Natural frequency of the curved beam varies as the severity of crack as well as the location of crack varies.
- At invariable crack severity, as the location of the crack varies from left end of the beam to the right end, initially natural frequency increases up to certain location of the crack and again decreases, and cycle repeats forming respective mode shapes.
- At invariable crack location, as the depth of crack increases, natural frequency of curved beam decreases and amplitude of curved beam increases.
- By knowing natural frequencies, ANFIS architecture identifies crack location as well as crack depth with close proximity with FEA.
- Fault diagnosis of the complicated dynamic structures with multiple cracks would be considered for future work. Many dynamic structures contain multiple cracks in it.

Acronyms and Nomenclature

ϕ	Opening angle of the simply supported curved beam.
d	Thickness of the curved beam.
L	Inner arc length of the curved beam.
a	Crack depth.
w	Cross-sectional width of the curved beam.
α	Angular position of crack from left end of the beam.
RCS	Relative crack severity $\left(\frac{a}{d}\right)$.
RCL	Relative crack location $\left(\frac{\alpha}{\phi}\right)$.
θ	Crack inclination angle of curved beam.

References

1. Krawczuk M, Ostachowicz W (1997) Natural vibrations of clamped-clamped arch with an open transverse crack. J Vib Acoust 119:145
2. Viola E, Tornabene F (2005) Vibration analysis of damaged circular arches with varying cross-section. SID 1(2):155–169
3. Cerri MN, Dilena M, Ruta GC (2008) Vibration and damage detection in undamaged cracked circular arches: experimental and analytical results. J Sound Vib 314:83–94
4. Yang F, Sedaghati R, Esmailzadeh E (2008) Free in-plane vibration of general curved beams using finite element method. J Sound Vib 318:850–867
5. Chen C-N (2008) DQEM analysis of out-of-plane vibration of non-prismatic curved beam structures considering the effect of shear deformation. Adv Eng Softw 39:466–472

6. Zare M (2018) On crack detection in curved beams using change of natural frequency. J Vibroeng 20(2):1–19
7. Prawin J, Lakshmi K, Rao ARM (2019) A novel vibration based breathing crack localization technique using a single sensor measurement. Mech Syst Sig Process 122:117–138
8. Das H, Parhi DR (2009) Applications of neural network for fault diagnosis of cracked cantilever beam. In: World congress of nature and biologically inspired computing. Coimbatore, pp 1303–1308. Article No. 5393733
9. Mehrjoo M, Khaji N, Moharrami H, Bahreininejad A (2008) Damage detection of truss bridge joints using artificial neural networks. Expert Syst Appl 35:1122–1131
10. ANSYS© Release 14.5, Inc. Engineering simulation software
11. SolidWorks (2017) 3D design software—Dassault systems
12. Nandwana BP, Maiti SK (1997) Modelling of vibration of beam in presence of inclined edge or internal crack for its possible detection based on frequency measurements. Eng Fract Mech 58(3):193–205
13. Tada H, Paris PC, Irwin GR, Tada H (2000) The stress analysis of cracks handbook, vol 130. ASME Press, New York
14. Jang J-SR, Sun CT, Mizutani E (1997) Neuro-fuzzy and soft computing: a computational approach to learning and machine intelligence. Prentice-Hall, Upper Saddle River, NJ