
Crack Identification in a Structural Beam Using Regression and Machine Learning Models

Vikas KHALKAR *

*Department of Mechanical Engineering, Gharda Institute of Technology, Lavel, India,
vikas_khalkar@rediffmail.com*

Arul MOSHI

*Department of Mechanical Engineering, JKKN College of Engineering and Technology,
Vattamalai, Komarapalayam, India, moshibeo2010@gmail.com*

Jyoti BORDE

*Department of Computer Engineering, Gharda Institute of Technology, Lavel, India,
India, jvkhalkar@git-india.edu.in*

Raman BANE

*Department of Computer Engineering, Yashwantrao Bhonsale College of Engineering,
Sawantwadi, India, ramanbane@gmail.com*

Lalitkumar JUGULKAR

*Department of Mechanical Engineering, Rajarambapu Institute of Technology
Islampur, Sangli, India, lmjugulkar@rit-india.edu*

S BASKAR

*Department of Automobile Engineering, Vels Institute of Science, Technology and
Advanced Studies, Chennai, India, baskar133.se@velsuniv.ac.in*

* Author to whom correspondence should be addressed

Abstract: - A manufacturing fault causes a defect consisting of a crack in the structure. Identification and classification are essential challenges in scientific research because cracks can lead to catastrophic system failure. Structural fitness tracking aims to diagnose and predict structural fitness. A complete crack detection method based on free vibration is widely used to find potential cracks in systems. However, bending stiffness methods are limited in predicting the crack parameters. Therefore, the bending stiffness approach has been used in the present work to determine the crack locations and depth in the cantilever beam. A dead weight was attached to the beam's free end, and two dial gauges were used. A gauge was attached to the free end of the beam to measure the free-end deflection. Another dial indicator was installed near the crack to measure the static deflection at the crack. Numerical and experimental analyses were performed on 25 cracked specimens to measure the static deflection and stiffness at two points. Regression models were developed for the crack parameters to predict them without the need for numerical and experimental analyses. Also, the ANN model was developed for the same purpose to relate the considered input and output variables. The crack depth and location results obtained from the regression and machine learning models are consistent with the actual values. The crack parameters were predicted using static two-point bending stiffness values as input, and the results were encouraging. Therefore, the static two-point bending stiffness approach may be widely used to detect future cracks in more complex structures.

Keywords: - Bending stiffness, Static deflection, ANN, Regression models, Dial gauges, ANSYS.

1. INTRODUCTION

The presence of a crack affects the mode shapes, natural frequencies, static deflection, and damping coefficient in beam-like structures. For a few decades, non-destructive methods for locating cracks in structures have relied on alterations in the physical

properties. Using deflection measurements, Naik [1] developed a technique for checking the defects in lengthy pipelines. The stiffness of a spinning spring model closely mirrored the crack was calculated using fracture mechanics. The long pipes not only supported boundary conditions, but they also had

cantilevers. Experiments using steel and aluminium pipes demonstrated the potency of the suggested strategy. Theoretical and experimental crack site predictions were in good agreement. The efficiency of a static deflection technique for inclined edge fracture diagnostics in a prismatic cantilever beam was demonstrated by Pansare and Naik [2]. Rotational springs were used to show how the inclined edge fracture made the beams flexible. They employed twenty-one mild steel specimens for the experimental studies. The experimental static deflection results provided precise fracture site estimates. Using the measurements of the damage-induced fluctuations in the static deflection of the beam under a specific loading condition, Caddemi and Morassi [3] had located the numerous open cracks in a beam. A comparable linear spring connecting the two neighboring beam segments simulated each break. In their research work, many open cracks in a beam were found using measurements of differences in the static deflection of the beam caused by damage under specific load conditions. Each break was simulated by a similar linear spring connecting the two adjacent beam segments. The pertinent requirements on the static measurements were presented and addressed for non-uniform beams with particular ideal boundary conditions, enabling the precise detection of the damage. The inverse analysis provided accurate closed-form representations of the position and severity of the fractures in terms of the observed data. It was based on an explicit description of the crack-induced change in the deflection of the beam under a particular load distribution. Comparative static testing on a steel beam with localized flaws supported the theoretical conclusions.

Tufisi et al. [4] calculated the damage severity for the closed and open transverse fractures in beam-like structures using deflection under the weight of the undamaged and damaged beams. They validated the results by comparing the damage severity assessed using the stochastic hill climbing (SHC) approach with the severities indicated by the expert simulation tool. Kumar and Singh [5] looked at border distortion about wavelet scale and measurement resolution. The appropriate wavelet scale was selected based on the fracture localization and wavelet coefficient smoothness. Isomorphism was used to show how measurement resolution affects signal extension. The photographic approach was used to achieve the high-resolution measurement of the beam deflection. Panasare et al. [6] looked at the cracked cantilever beam for the static analysis. The researchers used the ANSYS Mechanical 16 simulation to investigate the cracked cantilever beam for static deflection. The static deflections that were obtained and those that

were measured were compared. Furthermore, results were obtained from the generated reliable FEA model. Tufisi et al. [7] had suggested an analytical data creation method. This information is required to train the random forest model (RF), which monitors the structural health of the structures. The RF model was trained using normalized natural frequencies from multiple damaged samples. It was discovered that the RF model predicts how the structure will behave when cracks are still visible towards the cantilevered end. Ostachowicz [8] presented the method of analysis of the effect of two open cracks upon the frequencies of the natural flexural vibrations in a cantilever beam. Two types of cracks were considered: double-sided, occurring in the case of cyclic loadings, and single-sided, which is the principle that occurs as a result of fluctuating loadings. Cawley and Adams [9] described the method of non-destructively assessing the integrity of structures using measurements of the structural natural frequencies. It is shown how measurements made at a single point in the structure can be used to detect, locate, and quantify damage. Rizos et al. [10] studied the flexural vibrations of a cantilever beam with a rectangular cross-section having a transverse surface crack extending uniformly along the width of the beam. From the measured amplitudes at two points of the structure vibrating at one of its natural modes, the respective vibration frequency, and an analytical solution of the dynamic response, the crack location can be found, and depth can be estimated with satisfactory accuracy. Liang et al. [11] proposed a method that has practical applications in the detection of crack location and quantification of damage magnitude in a uniform beam. Their approach, which uses rotational massless springs in the beam element as a mechanical model, can be applied to structures under simply supported or cantilever boundary conditions. Khatir et al. [12] present a methodology based on non-destructive detection, localization, and quantification of multiple damages in simple and continuous beams and a more complex structure, namely a two-dimensional frame structure. The proposed methodology makes use of the Firefly Algorithm and Genetic Algorithm as optimization tools and the Coordinate Modal Assurance Criterion as an objective function. The results show that the proposed combination of the Coordinate Modal Assurance Criterion and Firefly Algorithm or Genetic Algorithm can be easily used to identify multiple local structural damages in complex structures. Sutar et al. [13] investigated the transverse crack in a cantilever beam by developing a Neural network-based controller. The input parameters to the controller are the relative divergence of the first three natural frequencies, and

the output parameters are relative crack depth and relative crack location in dimensionless forms.

Random forest (RF) and artificial neural network (ANN) were recommended by Gillich et al. [14] as two machine learning techniques that might be used as search tools in their study. Their databases offer damage scenarios for a prismatic cantilever beam with a single crack and favorable and unfavorable border circumstances. Two steps were taken to detect the crack. A rough damage location was first determined using networks trained for scenarios involving the entire beam. A specialized network trained for the beam area where the break had previously been found was used to evaluate that. For both lab testing and simulations, they could precisely identify the crack site and severity using the two machine learning techniques. The errors were less than 0.6% about the positioning of the crack, which was the practitioners' primary objective. Due to these accomplishments, they concluded that the suggested damage assessment in conjunction with the machine learning methodology is sound and dependable. The two machine learning algorithms could detect the crack site and severity for lab testing and simulations. Tufisi et al. [15] proposed a model for detecting transverse cracks in support beams, which can be a part of more complex structural systems. The structure's relative frequency variations were first used to look for damage. The required modal parameters were assessed using the authors' original method. A multi-stage optimization process based on the stiffness loss experienced by the affected structure was used to precisely pinpoint the locations of possible cracks. The study's conclusions showed how the suggested model can assess the damage in beam-like structures, including its presence and location. Based on the investigation's findings, Tufisi et al. [16] developed an analytical method for gathering the information necessary to train a Random Forest model (RF) to carry out the SHM task of locating and assessing the severity of transverse fractures in beam-like structures. The relative frequency shifts (RFS) for various damage scenarios were determined using the novel methodology, and the generated data was used to train the RF model. The results showed that the RF model can discover the defect and determine the precise location and depth of the transverse cracks if the transverse fracture is situated where the beam is subject to the most incredible bending stress. A massless rotational spring of finite length could be positioned there to imitate a crack [17]. The findings demonstrated that by combining the suggested Coordinate Modal Assurance Criteria with a Firefly Algorithm or Genetic Algorithm, various local structural problems in complex buildings can be

swiftly found. Because visual inspection of fractures and flaws is worthless and frequently not worth considering, non-destructive testing (NDT) techniques like thermography, ultrasonic testing, X-ray diffraction, etc., are used to forecast damage to structures. These techniques, however, cost time and money. As a result, it is advised that workable alternatives be created. The paper is organized considering the various sections, i.e., theoretical analysis, finite element modeling and analysis, experimental analysis, database generations, regression modeling, artificial neural network modeling and analysis, results and discussions, and conclusions, after the introduction section.

From the literature review, it was found that there is a vast research scope in the field of the detection of cracks in beams. For crack detection, the conventional techniques focus mainly on using natural frequencies and mode shapes. From the literature survey, the authors did not find a single paper in which two-point bending stiffness was used as one of the ways for crack detection. This motivated the authors to do crack detection in a cantilever beam using bending stiffness as a primary criterion. Hence, this paper attempts to use the two-point bending stiffness as a primary criterion to predict the crack depth and locations in a cantilever beam. The predicted crack parameters using the Regression and ANN models were validated against the experimental results and found promising. These good agreements with the results showed the effectiveness of the two-point bending stiffness approach.

1.1. Material and geometric properties of the beam

The material properties and geometric properties of the steel cantilever beams are given in this sub-section.

Material properties: density (ρ) = 7810 kg/m³, Young's modulus (E) = 2.17101 x 10¹¹ N/m², Poisson's ratio (μ) = 0.3

Geometric properties: The length of the beam (L) and cross-sectional area are 0.4m and 0.016 x 0.016 m², respectively; ' I ' is the moment of inertia of the beam.

1.2. Design of experiments and crack configurations

Scientists and engineers can utilize the design of experiments (DOE) method to conduct systematic and efficient investigations into the link between many input parameters and response (output) variables. This research study considers major

influencing input parameters at five levels, i.e., crack location and depth. It means that 60 mm, 120 mm, 180 mm, 240 mm, and 300 mm crack locations have been considered. Moreover, at each location, crack depths varied from 2 mm to 10 mm at an interval of 2 mm. Based on the Taguchi technique, the L_{25} orthogonal array has been formed for the input parameters ranges, and the combination of the various parameters corresponding to the twenty-five experimental runs is presented in Table 1. Table 1 also presents various cracked cases' numerical and experimental bending stiffness. The two stiffness values (K_1 and K_2) were considered dependent variables. The global stiffness (K_I) and stiffness at the crack (K_2) were considered in a cracked cantilevered beam. The crack location and depth (L_1 and a) were considered independent variables.

2. THEORETICAL ANALYSIS

A schematic of a cracked cantilevered beam is shown in Figure 1. Furthermore, a cracked cantilever beam is represented by two complete beam segments joined by a torsional spring when the force is ignored, as shown in Figure 2. Dimarogonas et al. [23] derived the torsional stiffness (K_T) equation that characterizes the crack. The torsional stiffness of the fragmented beam is represented in equation (1).

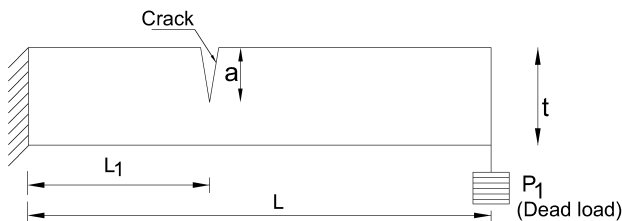


Figure 1. A cracked cantilever beam carries a point load at the free end

$$K_T = \frac{EBt^2}{72\pi(L-L_1)^2(1-\mu^2)\Phi} \quad (1)$$

where, B and t are the width and thickness of the beam respectively.

L_1 and L are the crack's distance from the fixed end and the beam's length, respectively.

P_1 is the dead load applied at the free end.

The function Φ is given by

$$\begin{aligned} \Phi = & 0.629 \left(\frac{a}{t}\right)^2 - 1.047 \left(\frac{a}{t}\right)^3 + 4.602 \left(\frac{a}{t}\right)^4 - \\ & 9.975 \left(\frac{a}{t}\right)^5 + 20.295 \left(\frac{a}{t}\right)^6 - \\ & 32.993 \left(\frac{a}{t}\right)^7 + 47.041 \left(\frac{a}{t}\right)^8 - \\ & 40.693 \left(\frac{a}{t}\right)^9 + 19.6 \left(\frac{a}{t}\right)^{10} \end{aligned} \quad (2)$$

where, a is the crack's depth.

The open-edged cracked beam stiffness (K_I) or global stiffness can be computed by

$$K_1 = \frac{K_T K_I}{K_T + K_I} \quad (3)$$

The stiffness of an intact (K_I) or un-cracked cantilever beam is computed using equation (4),

$$K_I = \frac{3EI}{L^3} \quad (4)$$

The theoretical stiffness of an open-edged cracked beam is presented in the Table 3.

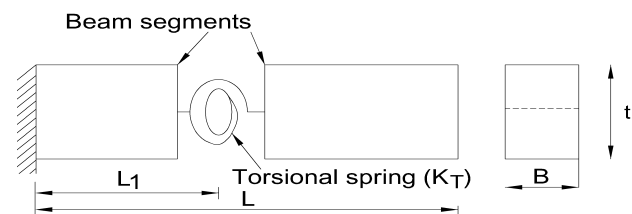


Figure 2. A cracked cantilever beam stiffness model

3. FINITE ELEMENT MODELING AND ANALYSIS

The beam with an assumed open crack was simulated using the ANSYS 12.1 finite element program. The block command was used to help build volumes with the necessary dimensions. Similar to this, the main volume of the model was modified to generate a triangular-shaped volume where it was needed. The required three-dimensional crack model was then generated by deducting the triangular volume from the main volume. Solid 186 elements [19-20] from the ANSYS element library were used to mesh the model. At the left end of the beam, there was no room for rotation or movement [24]. Cantilevered boundary conditions [21] were consequently employed. A static point load of 50 N was applied to the beam's free end to cause elastic deformation in the bending mode. The deflections at the crack and the free end of the cantilever beam are shown in Figure 3.

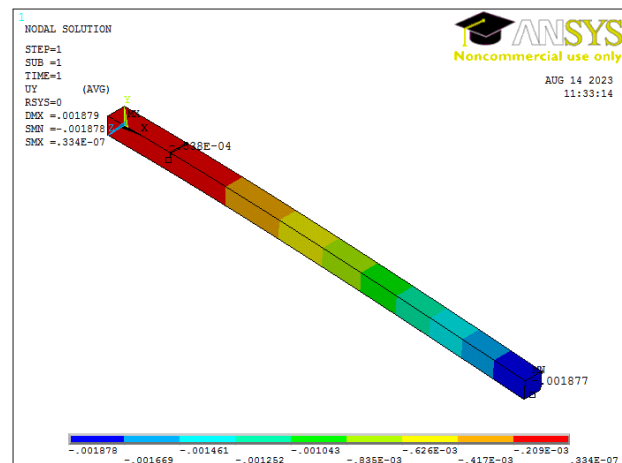


Figure 3. The two-point static deflection of a cracked cantilever beam

4. EXPERIMENTAL ANALYSIS

Two-point static deflection measurements were used to find the cracks in cantilever beams. A 50 N dead load was applied at the beam's free end to get the elastic deformation at the free end and the crack in the bending mode. The dial gauges were used to measure the static displacements at the free end and the crack in the beam. Figure 4 displays the same device's schematic. A picture of the actual experimental setup is found in Figure 5. The arrangement comprises a specimen holder, an EN 31 cracked specimen, and a dead load. Dial indicators (Made: Mitutoyo; one micron least count) were used with stands. Out of twenty-five cracked cases, the deflection at the free end and the crack are given for one case, i.e., crack location 60 mm, crack depth

10 mm, the found experimental deflection at the free end (δ_1) was 1.382 mm, and the deflection at the crack (δ_2) was 0.02867 mm.

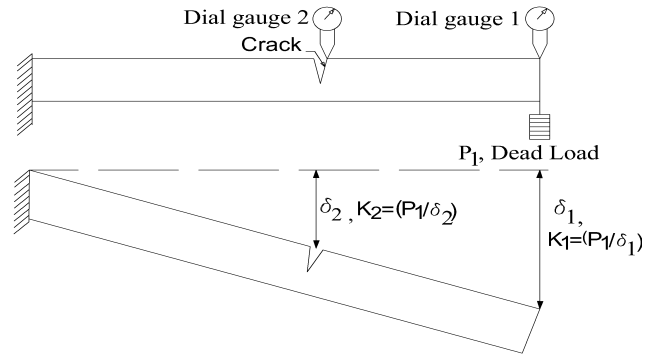


Figure 4. Schematic representation of a two-point static deflection measurement

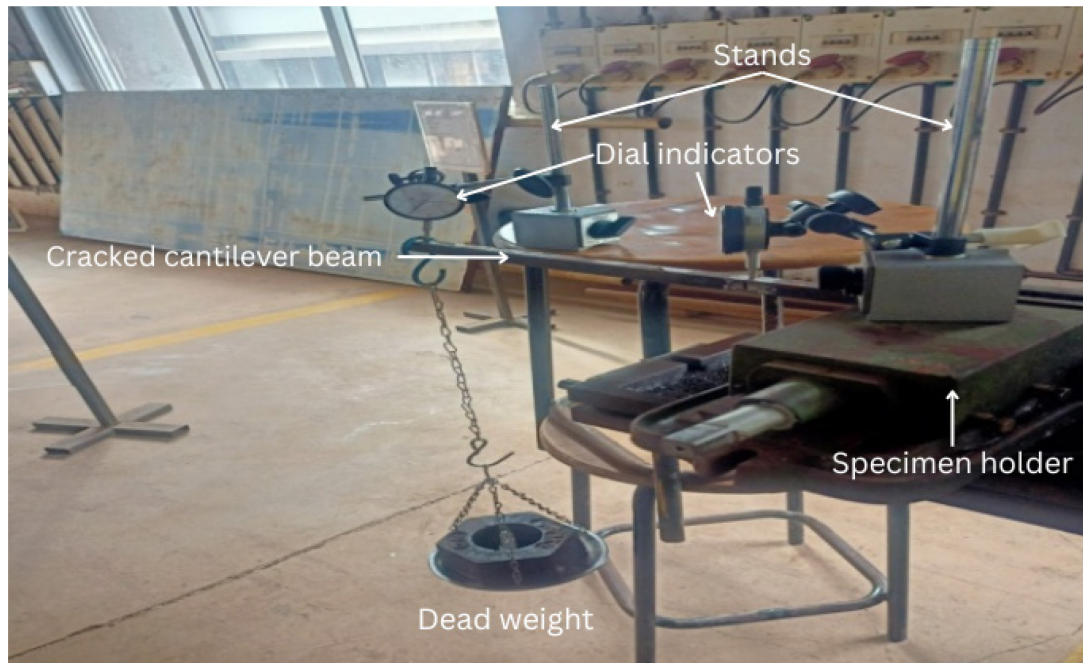


Figure 5. Experimental setup

The procedure for measuring the static deflections was as follows: This research employed the static deflection measurement on the cracked cantilever beams at two specific locations. First, one dial indicator was positioned at the free end of the beam, and another was placed at the crack. Then, a load of 50N was applied at the free end of the cantilever beam, causing the beam to elastically deform in the vertical plane. As a result, the dial indicator at the free end provided the free end deflection, while the one at the crack gave the displacement at the crack of a cantilever beam.

The global stiffness (K_1) and the localized stiffness (K_2) at the crack were calculated considering the crack's static deflections, i.e., δ_1 and δ_2 , respectively. Hence, the stiffness values K_1 and K_2 were used as

input parameters for damage detection in a cantilever beam.

5. DATABASE GENERATIONS

Because of the known crack severity, a database consisting of shifts in bending stiffness was required to train the inverse algorithm. As analytical expression for the vibration of the cracked beam is complicated and time-consuming, the required database is generated with the help of a numerical and experimental analysis. FE simulation and experimental analysis were conducted on all the beam models with different sizes and crack locations. The numerical and experimental datasets of bending

stiffness were leveraged to develop the ANN and regression models. In this endeavor, a comprehensive range of twenty-five different cracking scenarios were meticulously considered. The static deflection at the free end and the crack were measured and taken into account for all the cracked cases. Furthermore, the global bending stiffness (K_1) and stiffness at the crack (K_2) were determined using the formula as

shown in Figure 4. The two-point bending stiffness values (K_1 and K_2) were used as the inputs to the ANN and regression models, with the crack location and depths (L_1 and a) as outputs. The regression model demonstrated an excellent polynomial fit to the data. The bending stiffness dataset, based on the numerical and experimental analysis, is presented in Table 1.

Table 1. Numerical and experimental stiffness results obtained for the proposed experimental plan

Sr. No.	Crack location, L_1 (m)	Crack depth, a (m)	Numerical stiffness, K_1 (N/m)	Numerical stiffness, K_2 (N/m)	Experimental stiffness, K_1 (N/m)	Experimental stiffness, K_2 (N/m)
01	0.060	0.002	55126.79	1766784	55115.85	1767034.21
02	0.060	0.004	53276.51	1763668	53270.83	1764851.22
03	0.060	0.006	49825.61	1760563	49850.45	1761245.55
04	0.060	0.008	44345.9	1757469	44342.36	1758495.29
05	0.060	0.010	36153.29	1742160	36151.20	1743411.65
06	0.120	0.002	55309.73	460829.5	55295.60	460519.65
07	0.120	0.004	53995.68	460676.6	54004.14	460409.40
08	0.120	0.006	51546.39	460672.4	51564.94	460193.28
09	0.120	0.008	47438.33	460668.2	47434.28	460006.99
10	0.120	0.010	40683.48	458715.6	40714.62	459242.25
11	0.180	0.002	55432.37	215982.7	55447.86	216141.44
12	0.180	0.004	54644.81	215968.7	54630.54	216132.10
13	0.180	0.006	53050.4	215959.4	53047.87	216078.86
14	0.180	0.008	50301.81	215945.4	50306.16	216042.45
15	0.180	0.010	45330.92	215517.2	45322.29	215912.77
16	0.240	0.002	55555.56	129032.3	55559.69	129031.26
17	0.240	0.004	55126.79	129027.3	55123.02	129024.93
18	0.240	0.006	54259.36	129025.6	54253.35	129018.27
19	0.240	0.008	52687.04	129022.3	52685.43	129010.28
20	0.240	0.010	49701.79	128866	49692.40	128964.36
21	0.300	0.002	55617.35	88028.17	55633.01	88032.82
22	0.300	0.004	55463.12	88026.62	55465.02	88031.11
23	0.300	0.006	55126.79	88025.07	55115.37	88030.49
24	0.300	0.008	54495.91	88021.97	54481.31	88027.08
25	0.300	0.010	53219.8	87950.75	53206.38	88012.98

6. REGRESSION MODELING

A regression analysis was made using Design Expert 13.0 software to obtain the functional relationship between the independent and dependent variables of the proposed study in the form of algebraic equations. This research study proposes a correlation model between the bending stiffness and crack parameters, i.e., crack location and depth, as a forward approach. It is given in equation (5).

$$K = f(L_1, a) \quad (5)$$

' K ' is the bending stiffness of the cracked beam
' L_1 ' is the distance of the crack from the cantilevered end

' a ' is the crack depth of the beam.

$$f(L_1, a) - K = 0 \quad (6)$$

When global bending stiffness was considered, the equation (6) will be as follows

$$f(L_1, a) - K_1 = 0 \quad (7)$$

Similarly, when the bending stiffness at the crack was considered, the equations (6) will be as follows.

$$f(L_1, a) - K_2 = 0 \quad (8)$$

An inverse approach to crack detection is proposed in this work K_1 and K_2 are the stiffness plotted against the crack parameters, i.e., crack location and depth. The global stiffness (K_1) and stiffness (K_2) at the crack were used to obtain the correlation model for the curve fitting.

Only two equations were required to find two unknown crack parameters, i.e., crack location and depth. Based on the non-linear relationship between crack parameters and stiffness, a non-linear

polynomial curve fitting was used for two equations considering the ' K_1 ' and ' K_2 ' stiffness. Equations (9) and (10) were developed using the numerical data set. Similarly, equations (11) and (12) were developed using the experimental data set. The numerical and experimental data set of bending stiffness values are presented in Table 3. The regression models

$$56029.93658 - 7604.66446L_1 - 1.30970 * 10^5 * a - 2.14347 * 10^5 * L_1 * a + 66558.42752 * L_1^2 - 1.2226 * 10^8 * a^2 - 6.18143 * 10^6 * L_1^2 * a + 9.24786 * 10^8 * L_1 * a^2 - 1.17203 * 10^5 * L_1^3 - 1.14098 * 10^{10} * a^3 - K_1 = 0 \quad (9)$$

$$4.40077 * 10^6 - 5.84578 * 10^7 * L_1 - 3.24169 * 10^6 * a + 2.83346 * 10^7 * L_1 * a + 2.63499 * 10^8 * L_1^2 + 1.69736 * 10^8 * a^2 - 1.03804 * 10^8 * L_1^2 * a + 1.54853 * 10^9 * L_1 * a^2 - 3.88659 * 10^8 * L_1^3 - 3.07722 * 10^{10} * a^3 - K_2 = 0 \quad (10)$$

$$55963.58886 - 6872.21815 L_1 - 1.15018 * 10^5 * a - 2.82909 * 10^5 * L_1 * a + 63276.96214 * L_1^2 - 1.23464 * 10^8 * a^2 - 6.28421 * 10^6 * L_1^2 * a + 9.31555 * 10^8 * L_1 * a^2 - 1.10358 * 10^5 * L_1^3 - 1.14106 * 10^{10} * a^3 - K_1 = 0 \quad (11)$$

$$4.40287 * 10^6 - 5.85148 * 10^7 * L_1 - 2.63821 * 10^6 * a + 2.77512 * 10^7 * L_1 * a + 2.63824 * 10^8 * L_1^2 + 6.23266 * 10^7 * a^2 - 1.02272 * 10^8 * L_1^2 * a + 1.51891 * 10^9 * L_1 * a^2 - 3.89217 * 10^8 * L_1^3 - 2.39209 * 10^{10} * a^3 - K_2 = 0 \quad (12)$$

To determine the locations and depths of cracks in a cantilever beam, equation (9) and equation (10) were used. The numerical bending stiffness (K_1) and stiffness at the crack were used (K_2) and were substituted with equation (9) and equation (10), respectively, to predict the crack depth and the locations in a cracked beam using a numerical data set. Then, equations (9) and (10) were solved simultaneously using a Microsoft Excel solver to predict the crack location and depth in a cantilever beam. Similarly, to determine the locations and depths of cracks in a cantilever beam, equation (11) and equation (12) were used. The experimental bending stiffness (K_1) and stiffness at the crack were used (K_2) and were substituted in equation (11) and equation (12), respectively. Microsoft Excel solver was used to solve the simultaneous equations, i.e., equations (11) and (12).

In order to predict the crack characteristics of a cracked cantilever beam, equations (9), (10), (11), and (12) were applied. Regression analysis and Design Expert software were used to generate the third-order correlation models shown in equations (9), (10), (11), and (12). Correlation model reliability is commonly assessed using R-squared values. If the R-squared value is close to 1, then the data and derived correlation models suit the data well. The built-in correlation models described in equations (9), (10), (11), and (12) were found to have R-squared values of 0.9997, 0.9955, 0.9999, and 0.9953 respectively in the current experiment. The reliability of the created correlation models is shown by the R-squared values, which are close to 1.

developed using the numerical bending stiffness values are given in Equation (9) and Equation (10), respectively. Similarly, the regression models developed using the experimental bending stiffness values are given in Equation (11) and Eq. (12), respectively.

Using the numerical data set, equations (9) and (10) forecast the positions and sizes of cracks in a cantilever beam. Using the experimental data set, equations (10) and (11) also estimate the location and depth of the cracks that will appear in a cantilever beam.

7. ARTIFICIAL NEURAL NETWORK MODELING AND ANALYSIS

The depth and location of cracks in a beam are evaluated and predicted using artificial neural networking (ANN). The analytical work's findings are consistent with what was learned during training [18, 22]. The "nntool" tool uses the intended inputs and outputs, or targets, imported into the MATLAB workspace. A neural network's structure is depicted in Figure 6. In this case, a typical three-layered Feed Forward Back Propagation (FFBP) neural network comprises three input neurons, nine hidden neurons, and two output neurons (Figure 6). Table 2 contains a list of an artificial neural network's hyperparameters. Figure 7 depicts the feed-forward, backward-propagation neural network. While the fracture position and depth were considered output parameters, the bending stiffness at the free end and the crack were considered an input parameter. Levenberg Marquardt serves as the training function, while MSE, LEARN GDM, and tansig serve as the performance, adaptive learning, and transfer, respectively. Figures 8 and 9 display the regression plot for training, validation, and testing. The

experimental and numerical datasets were used to produce the regression curve that can be seen in Figures 8 and 9. It displays how well the actual results match the projected statistics.

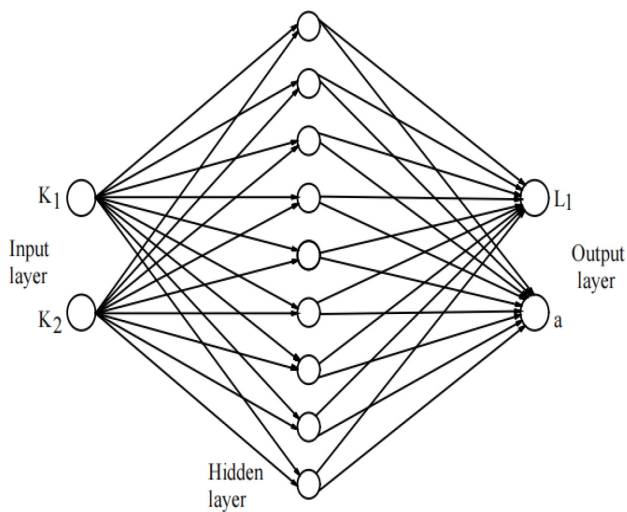


Figure 6. Architecture of ANN

Table 2. Hyper-parameter of Artificial Neural Network

Sr. No.	Input parameters for training	Values
01	Learning rate	0.1
02	Number of epochs	1000
03	Number of nodes in input layer	02
04	Number of neurons in the hidden layer	9
06	Number of nodes in output layer	02
07	Goal	Zero

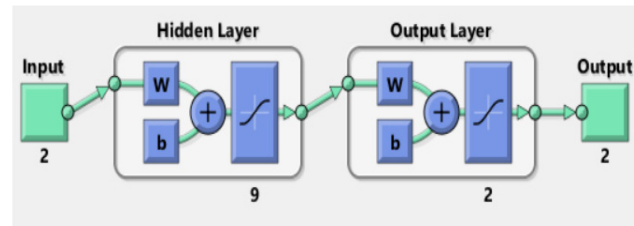


Figure 7. Feed forward back propagation neural network

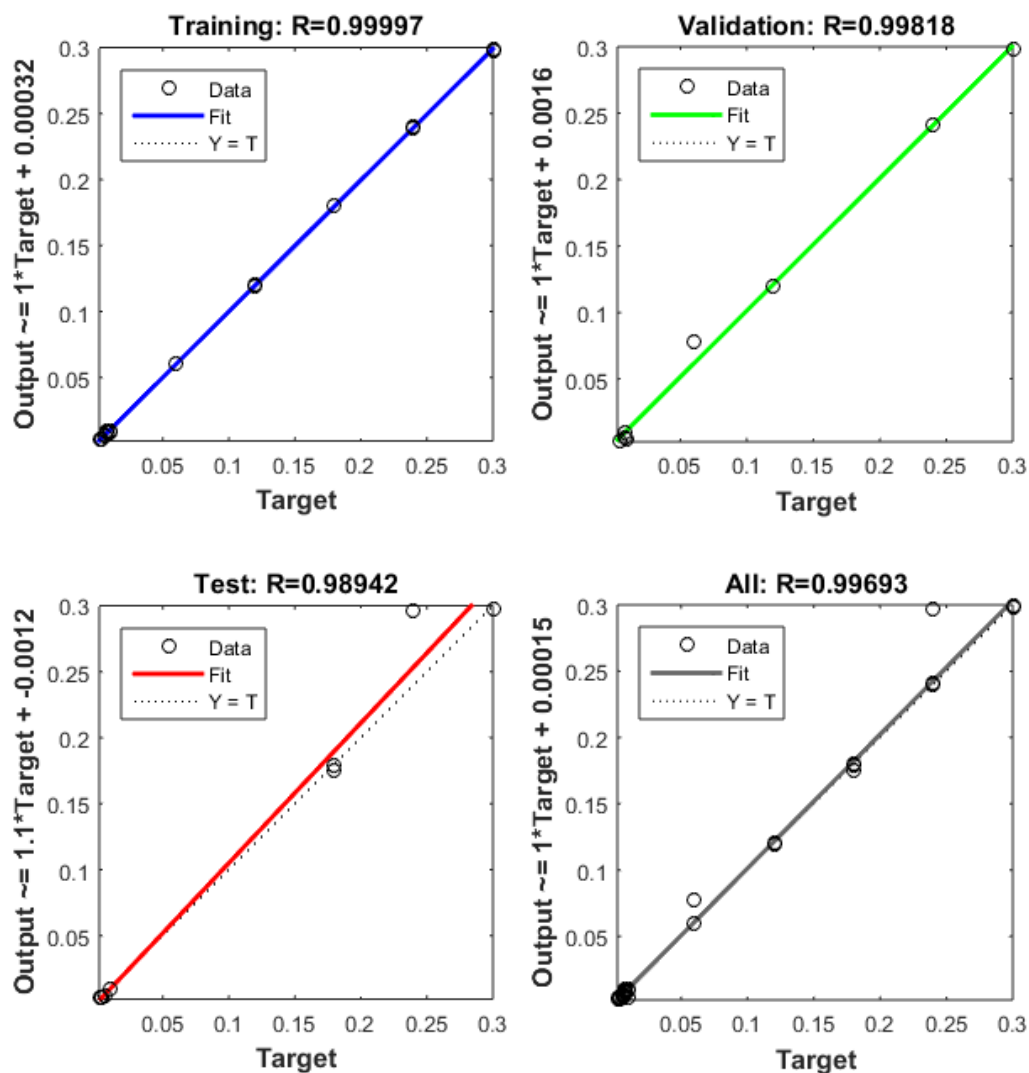


Figure 8. Regression plot based on numerical data set

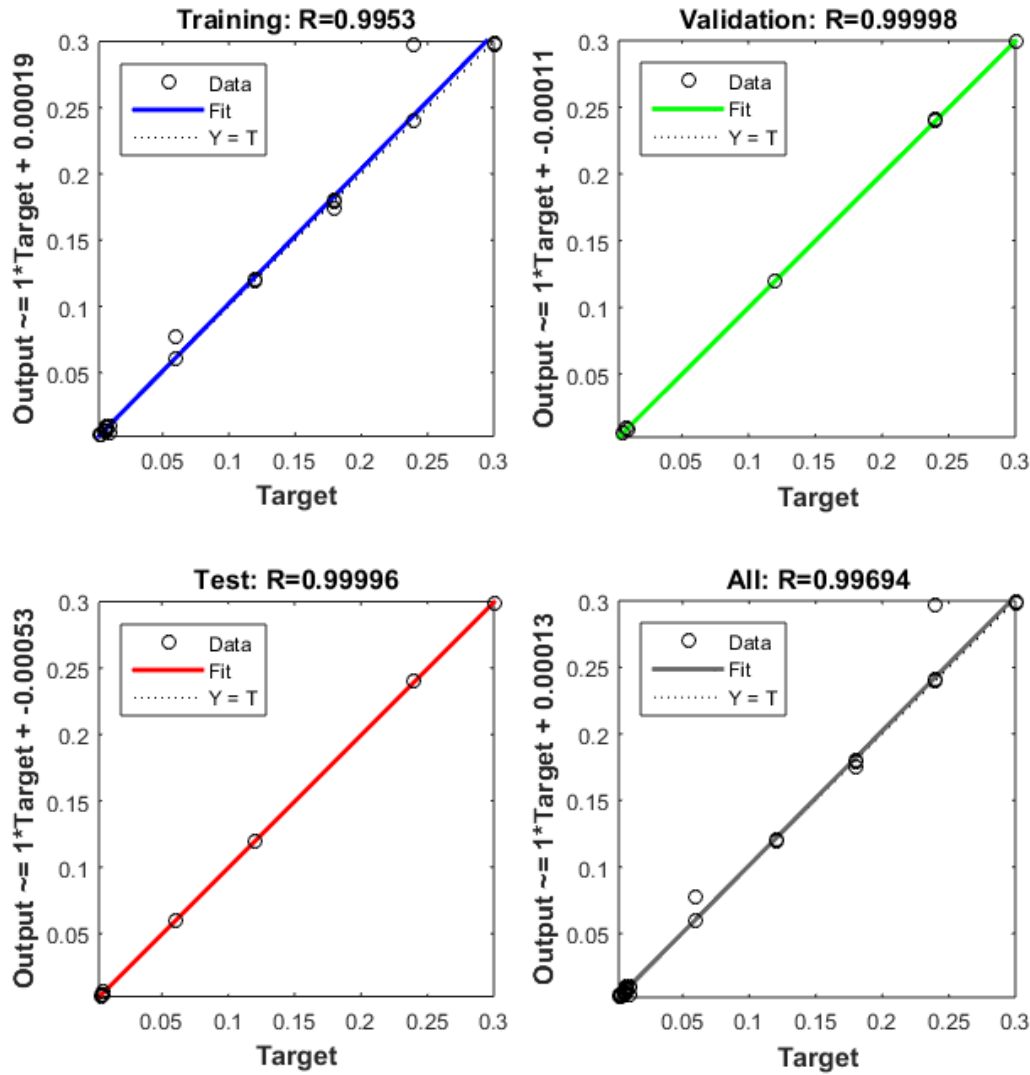


Figure 9. Regression plot based on experimental data set

8. RESULTS AND DISCUSSION

In order to check the correctness of the approach to the numerical modeling and experimental analysis, the bending stiffness of cracked cases of beams was determined using the theoretical method. The global bending stiffness (K_I) calculated using the various methods is in good agreement and is presented in Table 3. This study investigates the bending stiffness of a cracked cantilever beam with different crack depths and locations experimentally and numerically.

Figures 10 and 11 show a significant relationship between the independent variables (crack location and crack depth) and the dependent variables (bending stiffness). Furthermore, Figure 10 shows that the global bending stiffness decreases as crack depth increases at any unique location in the beam. As the depth of the crack increases, strength is

reduced. Figure 11 shows that at constant crack depth, the beam's global bending stiffness increases as the crack's distance increases from the cantilevered end. The crack nearer to the fixed end of the beam reduces the beam stiffness significantly compared to the crack at the free end of the cantilever beam. As a result, as the fracture moves further from the fixed end of the beam, the global bending stiffness increases. Thus, it is shown that the depth and location of the crack affect the bending stiffness. The two-point bending stiffness (global stiffness and stiffness at the crack) was a vital component of this experiment for identifying the cantilever beam's fracture characteristics. The creation of regression and ANN models was also made possible by the utilization of experimental and numerical datasets. The positions and depths of cracks have been predicted using the regression and ANN models, and the anticipated values are contrasted with the actual fracture features. Tables 4 to 7 present the findings about the same.

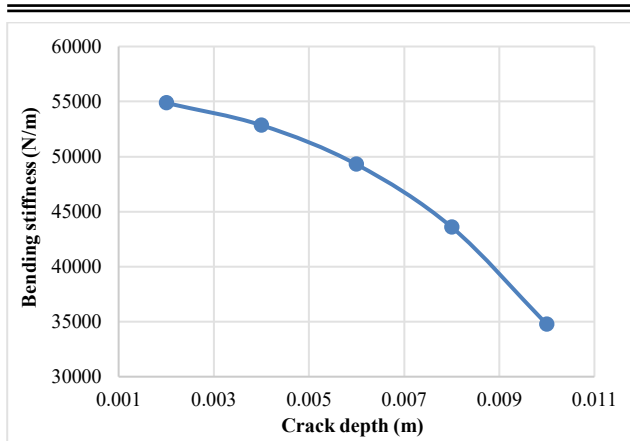


Figure 10. Variation in bending stiffness with respect to crack depth; 60 mm crack location from the cantilevered end

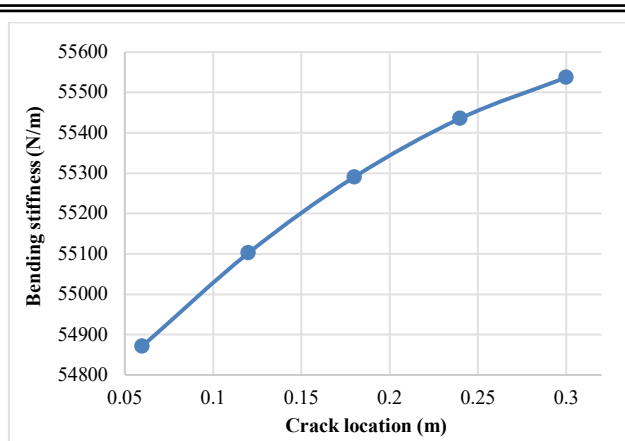


Figure 11. Variation in bending stiffness with respect to crack location at constant crack depth

Table 3. Cantilever beam global bending stiffness (K_1)

Sr. No.	Crack location, L_1 (m)	Crack depth, a (m)	Stiffness K_1 (N/m) Theoretical method	Stiffness K_1 (N/m) Numerical method	Stiffness K_1 (N/m) Experimental method	% error (Theoretical and numerical)	% error (Theoretical and experimental)
01	0.060	0.002	54871.65	55126.79	55115.85	0.4628	0.4431
02	0.060	0.004	52851.59	53276.51	53270.83	0.7976	0.7870
03	0.060	0.006	49290.35	49825.61	49850.45	1.0743	1.1236
04	0.060	0.008	43586.39	44345.9	44342.36	1.7127	1.7048
05	0.060	0.010	34754.42	36153.29	36151.20	3.8693	3.8637
06	0.120	0.002	55102.17	55309.73	55295.60	0.3753	0.3498
07	0.120	0.004	53704.52	53995.68	54004.14	0.5392	0.5548
08	0.120	0.006	51157.61	51546.39	51564.94	0.7542	0.7899
09	0.120	0.008	46842.91	47438.33	47434.28	1.2551	1.2467
10	0.120	0.010	39522.56	40683.48	40714.62	2.8536	2.9279
11	0.180	0.002	55290.45	55432.37	55447.86	0.2560	0.2839
12	0.180	0.004	54413.60	54644.81	54630.54	0.4231	0.3971
13	0.180	0.006	52770.64	53050.4	53047.87	0.5273	0.5226
14	0.180	0.008	49847.10	50301.81	50306.16	0.9040	0.9125
15	0.180	0.010	44440.00	45330.92	45322.29	1.9654	1.9467
16	0.240	0.002	55435.59	55555.56	55559.69	0.2159	0.2234
17	0.240	0.004	54966.33	55126.79	55123.02	0.2911	0.2843
18	0.240	0.006	54067.38	54259.36	54253.35	0.3538	0.3428
19	0.240	0.008	52402.26	52687.04	52685.43	0.5405	0.5375
20	0.240	0.010	49082.05	49701.79	49692.40	1.2469	1.2283
21	0.300	0.002	55536.92	55617.35	55633.01	0.1446	0.1727
22	0.300	0.004	55352.59	55463.12	55465.02	0.1993	0.2027
23	0.300	0.006	54993.52	55126.79	55115.37	0.2418	0.2211
24	0.300	0.008	54308.46	54495.91	54481.31	0.3440	0.3173
25	0.300	0.010	52861.39	53219.8	53206.38	0.6734	0.6484

Table 4. Prediction of crack location using the regression and ANN model based on numerical data set

Sr. No.	K_1 (N/m)	K_2 (N/m)	L_1/L (Actual)	L_1/L (Regression)	% Error	L_1/L (ANN)	% Error
01	51786.64	1762115	0.06	0.05947	0.88	0.06	0.00
02	47370.91	1758706	0.06	0.05945	0.92	0.06	0.00
03	54794.52	460678.8	0.120	0.1227	-2.25	0.1208	-0.67
04	52966.1	460674.5	0.120	0.1227	-2.25	0.1171	2.42
05	51894.14	215954.7	0.180	0.1525	15.28	0.1745	3.06
06	48239.27	215940.7	0.180	0.1523	15.39	0.2074	-15.22
07	54265.54	178486	0.200	0.161	19.50	0.1782	10.90
08	51188.49	178433.1	0.200	0.161	19.50	0.1746	12.70

Table 5. Prediction of crack location using the regression and ANN model based on experimental data set

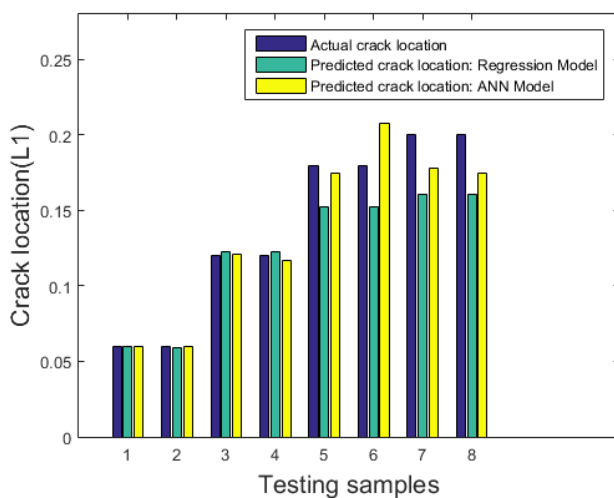
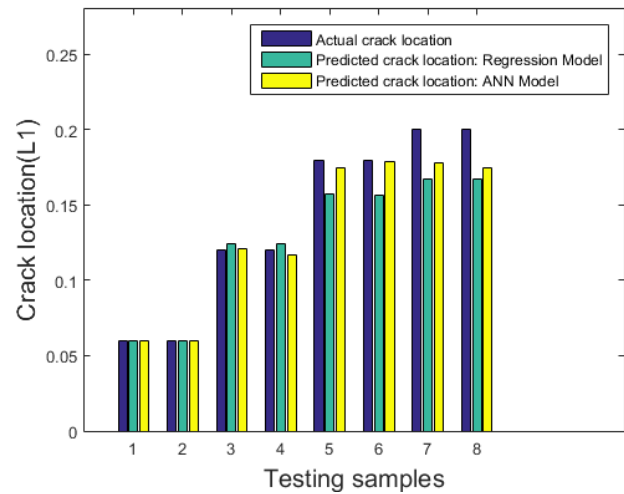
Sr. No.	K_1 (N/m)	K_2 (N/m)	L_1/L (Actual)	L_1/L (Regression)	% Error	L_1/L (ANN)	% Error
01	51772.27	1764309	0.06	0.05959	0.69	0.06	0.00
02	47307.27	1762158	0.06	0.05953	0.79	0.06	0.00
03	54787.5	460456	0.120	0.124	-3.23	0.121	-0.83
04	52965.26	460566.3	0.120	0.124	-3.23	0.117	2.50
05	51874.65	216052.7	0.180	0.157	14.65	0.1745	3.06
06	48233.68	215982.7	0.180	0.1564	15.09	0.179	0.56
07	54269.55	178484.1	0.200	0.167	19.76	0.1781	10.95
08	51188.49	178433.1	0.200	0.167	19.76	0.1746	12.70

Table 6. Prediction of crack depth using the regression and ANN model based on numerical data set

Sr. No.	K_1 (N/m)	K_2 (N/m)	a/t (Actual)	a/t (Regression)	% Error	a/t (ANN)	% Error
01	51786.64	1762115	0.005	0.005044	-0.88	0.0049	2.00
02	47370.91	1758706	0.007	0.007023	-0.33	0.0072	-2.86
03	54794.52	460678.8	0.003	0.002922	2.60	0.0028	6.67
04	52966.1	460674.5	0.005	0.005024	-0.48	0.0039	22.00
05	51894.14	215954.7	0.007	0.0064	8.57	0.009	-28.57
06	48239.27	215940.7	0.009	0.0083	7.78	0.01	-11.11
07	54265.54	178486	0.005	0.00424	15.20	0.0043	14.00
08	51188.49	178433.1	0.008	0.00698	12.75	0.0099	-23.75

Table 7. Prediction of crack depth using the regression and ANN model based on experimental data set

Sr. No.	K_1 (N/m)	K_2 (N/m)	a/t (Actual)	a/t (Regression)	% Error	a/t (ANN)	% Error
01	51772.27	1764309	0.005	0.005051	-1.02	0.0049	2.00
02	47307.27	1762158	0.007	0.007044	-0.63	0.0071	-1.43
03	54787.5	460456	0.003	0.00295	1.67	0.0028	6.67
04	52965.26	460566.3	0.005	0.005043	-0.86	0.0039	22.00
05	51874.65	216052.7	0.007	0.00645	7.86	0.009	-28.57
06	48233.68	215982.7	0.009	0.00839	6.78	0.0099	-10.00
07	54269.55	178484.1	0.005	0.0044	12.00	0.0043	14.00
08	51188.49	178433.1	0.008	0.0072	10.00	0.0099	-23.75

**Figure 12.** Predicted crack locations using ANN and regression model at different crack depth ratio based on a numerical dataset**Figure 13.** Predicted crack locations using ANN and regression model at different crack depth ratio based on an experimental dataset

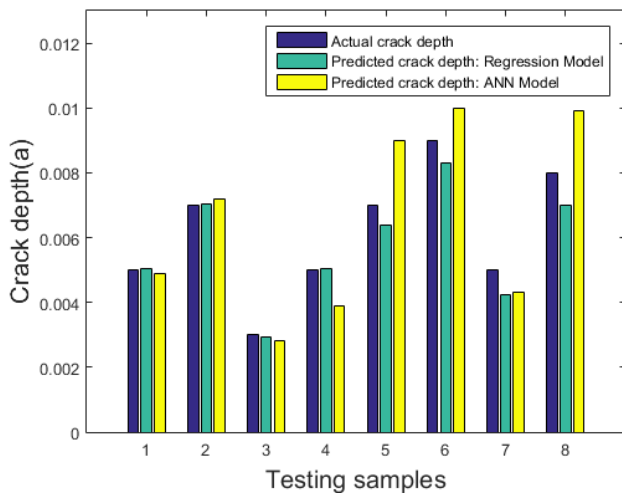


Figure 14. Predicted crack depth using ANN, and regression models at different crack location ratios based on a numerical data set

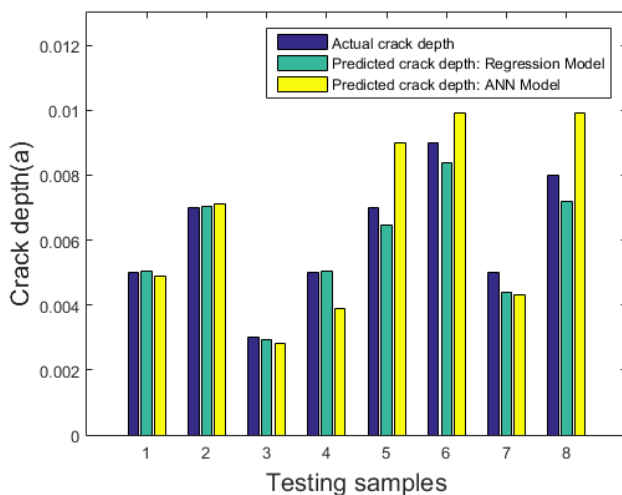


Figure 15. Predicted crack depth using ANN, and regression models at different crack location ratios based on an experimental data set

Figures 12 and 13 show the actual and predicted crack locations using the numerical dataset and experimental data set. Similarly, Figures 14 and 15 show the actual and predicted crack depths using the numerical dataset and experimental data set. From Figs. 12 to 15, it is clear that the regression and ANN models give good predictions for the crack depths and locations in cantilever beams. Based on the numerical dataset, it is found that the regression and ANN models give average errors of 9.386 and 5.621 to predict the crack locations, respectively. Similarly, based on the experimental data set, it is found that the regression and ANN models give average errors of 9.65 and 3.825 to predict the crack locations, respectively. Based on the experimental dataset, it is found that the regression and ANN models give average errors of 6.07 and 13.87 to predict the crack depths, respectively. Similarly, based on the experimental dataset, it is found that the regression

and ANN models give average errors of 5.102 and 13.55 to predict the crack depths, respectively. Hence, it is clear that the two-point bending stiffness approach (inverse method) leads to good predictions regarding the crack parameters in a cantilever beam. The regression model results based on the numerical dataset showed that the mean square error for the crack location (L_I) and crack depth (a) were 0.0005725 and 0.00000030964, respectively. Based on the ANN model results from the numerical dataset, the mean square error for the crack location (L_I) and crack depth (a) were 0.0002388 and 0.0000013, respectively. The regression model results based on the experimental dataset showed that the mean square error for the crack location (L_I) and crack depth (a) were 0.00041204 and 0.0000002104, respectively. Based on the ANN model results from the experimental dataset, the mean square error for the crack location (L_I) and crack depth (a) were 0.0001457 and 0.0000012725, respectively. The regression model gives comparatively better predictions for the crack depths than the ANN model. On the other hand, the ANN model gives better predictions for predicting the crack locations than the regression models.

9. CONCLUSIONS

The proposed study uses a Two-point bending stiffness approach to predict the crack depth and location in the cantilever beam. It was observed that the presence of transverse cracks changes the bending stiffness of the beams. Two-point bending stiffness values were used as inputs for the regression and the ANN models. Crack location and depth were considered to be the output responses. The concluding remarks are drawn herewith:

- The two-point bending stiffness approach gives good results for predicting the crack depth and the crack location in a cantilever beam (inverse crack detection problem).
- The theoretical, experimental, and numerical results for the bending stiffness are encouraging and valid. The maximum percentage error for the global bending stiffness between theoretical and numerical methods is 3.8693. Similarly, the maximum percentage error for the global bending stiffness between the theoretical and experimental methods is 3.8637
- Regression and ANN models based on the numerical and experimental data sets give good results in predicting the crack parameters, i.e., crack depth and locations.
- The regression and ANN model results show that the two-point bending stiffness method is

a viable, non-destructive method for crack detection in structures, i.e., the cantilever beam.

- Based on the estimation of mean square errors, the regression model gives comparatively better predictions for the crack depths than the ANN model. On the other hand, the ANN model gives better results for predicting the crack locations than the regression models.
- The cracked beam's global bending stiffness increases as the crack's distance increases from the cantilevered end to the free end.
- The global bending stiffness decreases as the depth of the crack increases at a constant crack location.

REFERENCES

- [1] Naik, S.S., Crack detection in pipes using static deflection measurements. *Journal of the Institution of Engineers: Series C*, Vol. 93, No.3, 2012, pp. 209– 215.
- [2] Pansare, S.S., and Naik, S.S., Detection of inclined edge crack in prismatic beam using static deflection measurements, *Sadhana academy proceedings in engineering sciences*, Indian academy of sciences, 2019, pp. 1-7.
- [3] Caddemi, S. and Morassi, A., Detecting Multiple Open Cracks in Elastic Beams by Static Tests, *Journal of Engineering Mechanics*, ASCE, Vol.137, 2011, pp. 113-124.
- [4] Tufisi, C., Rusu, C., Gillich, N., Vasile, M., Hamat, C.O., Gillich, G., Sacarea, C., Gillich, G., Determining the Severity of Open and Closed Cracks Using the Strain Energy Loss and the Hill-Climbing, *Applied Science*, Vol.12, 2022, pp.1-18.
- [5] Kumar, R. and Singh, S.K., Crack detection near the ends of a beam using wavelet transform and high-resolution beam measurement, *European Journal of Mechanics – A/Solids*, Vol.88, 2021.
- [6] Pansare, S., Warhatkar, H.N. and, Naik, S.S, Estimation of static deflection in beam with crack using FEA, *Solid State Technology*, Vol. 63, No. 6, 2020.
- [7] Tufisi, C., Rusu, C., Gillich, G., Locating transverse cracks in prismatic beams using random forest method and the frequency drop, *Applied Science*, Vol. 12, 2022, pp.1-18.
- [8] Ostachowicz, W.M., Krawczuk, M., Analysis of effects of crack on frequencies of a cantilever beam. *Journal of Sound and Vibration*, Vol.150, No. 2, 1991, pp. 191-201.
- [9] Cawley, P., and Adams, P.D., The location of defects in structure from measurements of natural frequencies. *Journal of Strain Analysis*, Vol. 14, No.2, 1979, pp. 49-57.
- [10] Rizos, P.F., Aspragathos, N., and Dimarogonas, A.D., Identification of crack location and magnitude in a cantilever beam from the vibration modes. *Journal of Sound and Vibration*, Vol. 138, 1990, pp. 381-388.
- [11] Liang, R.Y., Choy, F.K., and Hu, J., Detection of cracks in beam structures using measurements of natural frequencies. *Journal of Franklin Institute*, Vol. 328, 1991, pp. 505-518.
- [12] Khatir, A., Tehami, M., Khatir, S., and Wahab, M.A, Multiple damage detection and localization in beam-like and complex structures using co-ordinate modal assurance criterion combined with firefly and genetic algorithms, *Journal of Vibroengineering*, Vol.18, No. 8, 2016, pp. 5063-5073.
- [13] Sutar, M.K., Patnaik, S., and Rana, J., Neural Based Controller for Smart Detection of Crack in Cracked Cantilever Beam, *Materials Today: Proceedings*, Vol. 2, No. 4-5, 2015, pp. 2648-2653.
- [14] Gillich, N., Tufisi, C., Sacarea, C., Rusu, C.V., Gillich, G., and Praisach, Z., Ardeljan, M., Beam Damage Assessment Using Natural Frequency Shift and Machine Learning, *Sensors*, Vol. 22, 2022, pp. 2-23.
- [15] Tufisi, C., Gillich, N., Ardeljan, M., Paun, R.L., Rusu, V., and Gillich, G., A Cost Function to Assess Cracks in Simply Supported Beams with Artificial Intelligence, *Romanian Journal of Acoustics and Vibration*, Vol.18, NO. 1, 2021, pp. 46-52.
- [16] Tufisi, C., Rusu, V., and Gillich, G., Locating Transverse Cracks in Prismatic Beams Using Random Forest Method and the Frequency Drop, *Romanian Journal of Acoustics and Vibration*, Vol. 18, NO. 2, 2021, pp. 119-125.
- [17] Gope D, Gope P.C., Thakur A., Application of artificial neural network for predicting crack growth direction in multiple cracks geometry. *Applied Soft Computing*, Vol. 30, 2015, pp. 514-528.
- [18] Elshafey A.A, Dawood N, and Marzouk H., Crack width in concrete using artificial neural networks. *Engineering Structures*, 52: 676-686. Vol. 52, 2013, pp. 676-686.
- [19] Khalkar, V., Oak, P., Hariharasakthisudhan, P., Moshi, A., Jugulkar, L.M., and Bane, R.R., Crack detection in a cantilever beam using correlation model and machine learning approach, *Romanian Journal of Acoustics and Vibration*, Romanian Society of Acoustics, Vol. 19, NO. 2, 2022, pp. 121- 133.
- [20] Khalkar, V., Hariharasakthisudhan, P., Logesh, K., Moshi, A., Borade, J.G., and Kalamkar, R.R., Some studies verify the applicability of free vibration method of crack detection in a composite beam for different crack geometries, *Romanian Journal of Acoustics and Vibration*, Romanian Society of Acoustics, Vol. 20, NO. 1, 2023, pp. 30-41.
- [21] Khalkar, V., and Logesh, K., The effect of crack geometry on mode shapes of a cracked cantilever beam, *Australian Journal of Mechanical Engineering*, Vol. 20, NO. 4, 2020, pp. 1-12.
- [22] Probst P., and Boulesteix A.L., To tune or not to tune the number of trees in random forest, *Journal of Machine Learning Research*, Vol. 18, NO. 1, 2017, pp. 6673-6690.
- [23] Dimarogonas A, Paipetis S and Chondros T Analytical methods in rotor dynamics. *Dordrecht*, Springer, 2013.
- [24] Jarali, O.A., Logesh, K., Khalkar, V., and Hariharasakthisudhan, P., Vibration based delamination detection in Fiber Metal Laminates Composite Beam, *Romanian Journal of Acoustics and Vibration*, Romanian Society of Acoustics, Vol. 20, NO. 1, 2023, pp. 48-58.