

CRACK EFFECT ON THE NATURAL FREQUENCY OF COMPOSITE BEAM: FINITE ELEMENT ANALYSIS WITH EXPERIMENTAL STUDY

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Abstract

Cracks in structural elements can significantly affect their dynamic behaviour and lead to detrimental consequences. This study investigates the influence of cracks on the natural frequency of a laminated beam under free vibration, employing a combination of finite element method (FEM) analysis and experimental work. The numerical computation is done using ABAQUS simulation software by developing a comprehensive FEM model that accurately represents the laminated beam's mechanical behaviour, considering material anisotropy, geometry and crack propagation. The finite element model is validated through experimental tests conducted on both intact and cracked laminated beam specimens. The experimental setup utilizes Fast Fourier Transform (FFT) analyzer high-precision measurement tool to obtain accurate natural frequency values. The parametric study is conducted to analyze the impact of crack location, size, and orientation on the laminated beam's natural frequency. The FEM simulations reveal that the presence of cracks leads to a reduction in natural frequency, indicating a decrease in structural stiffness. The extent of frequency reduction is found to be influenced by crack characteristics and their proximity to critical locations within the beam. The experimental investigations corroborate the FEM findings, highlighting the consistency between numerical predictions and actual measurements.

Keywords: Transverse Crack, Laminated Beam, Free Vibration, FFT Analyzer

Introduction

The layering arrangement allows laminated composites to achieve a unique combination of strength, stiffness, and lightweight characteristics making them ideal for applications in industrial field as well as in applied engineering where high-

performance materials are required. Based on their applicability and performance, composites are widely engaged in different engineering applications ranging from aerospace, mechanical to civil infrastructures (Awad *et al.*, 2012; Ye *et al.*,

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2021; Jaturonlux and Ratanawilai, 2023). However, the presence of cracks in laminated composites can significantly compromise their structural integrity and performance. Cracks introduce stress concentrations, which can lead to local stress amplification that can cause the crack to propagate, leading to ultimate, structural failure. Furthermore, cracks can influence the dynamic behaviour of laminated composites. They can cause changes in the natural frequencies, damping characteristics, and vibration modes of the structure. These alterations in dynamic properties can impact the performance and stability of the laminated composite under different operating conditions. Understanding the effects of cracks on laminated composites is crucial for ensuring the safety and reliability of composite structures. Since vibration analysis is an efficient mode of structural analysis, efforts were made aiming to quantify the crack-induced changes in mechanical properties, develop crack growth models, and devise strategies for crack detection in the threshold of vibration and subsequently reviewed (Hajianmaleki and Qatu, 2013; Gayen *et al.*, 2019). The vibration quantification provides an efficient non-destructive tool to analyze the structural behaviour and state of functionality and thus, significant research attention was paid to cracked metallic (Kisa and Gurel, 2007; Khalkar and Ramachandran, 2018), composite plate (Bachene *et al.*, 2009; Sadiq *et al.*, 2021), and shell (Googarchin and Moazzez, 2019; Eyvazian *et al.*, 2020) structures.

The excellent structural applicability of laminated composites attracts more research studies pertaining vibration exploration and subsequently reflected through notable research works (Malekzadeh and Vosoughi, 2009; Rafiee *et al.*, 2017; Carrera *et al.*, 2020; Das and Sahu, 2022) in past two decades. Cracks can alter the stiffness and strength properties of the laminated composite. The presence of cracks disrupts the load transfer mechanisms between the layers, affecting the overall mechanical response of the composite (Singh and Talreja, 2008). This can result in reduced stiffness, increased flexibility, and decreased load-bearing capacity. Keeping in view the wide applicability of composite laminates in weight-sensitive structures has ranging aerospace, mechanical, and civil structural fields, the issue of delamination was widely addressed by researchers (Kashtalyan and Soutis, 2000; Della and Shu, 2007; Mukhopadhyay *et al.*, 2018). In spite of the extensive potential research significance the laminated cracked beams possess in the practical applied sectors, the quantity of researches is limited in regards to the analysis of vibration characteristics.

Within the framework of local compliance, Kisa and Gurel (2005) performed the dynamic response analysis of unidirectional graphite/epoxy composite beams with single transverse open crack employing finite element method (FEM). To facilitate the response of vibration analysis of a beam with multi-cracked, double or centrally cracked, the evaluation of local compliance will enable to effectively govern the stiffness matrix of cracked beam element (Papadopoulos, 2004). Kim and Kim (2003) investigated the free vibration behaviour of rotating composite beams with a breathing crack using FEM. Extending to multiple cracks, Kisa (2004) explored the free vibration behaviour of unidirectional graphite/epoxy beam through FEM in conjunction with component mode synthesis method. In order to explore matrix crack effects, Pawar (2011) investigated the stochastic property degradation of anisotropic thin-walled composite laminate beams due to matrix cracks. Employing shear correction in line with first order analysis, Daneshmehr (2013) presented the FE solution to analyze the influence of multiple cracks on composite beams coupled with torsion and bending for cantilever boundary conditions under vibration. The matrix crack effects on the mechanical and vibration properties of the cross-ply composite beam through analytical solutions are extensively studied by Birman and Byrd (2003). Fan and Wang (2017) demonstrated the influences of matrix-crack on the vibration response of laminated composite beam (LCB) with carbon nanotube (CNT) using finite element analysis.

The complexity involved in fabricating the LCB and assigning cracks at different positions makes the experimental vibration analysis on cracked composite beams a challenging issue. Furthermore, the stacking sequence plays an important role for mechanical behaviour analysis (Palani *et al.*, 2023) which elevates the complexity. Thus, limited experimental studies dealing with free vibration of composite cracked beams are available in open literature (Karaagac *et al.*, 2009; Das and Sahu, 2020; Sahu and Das, 2020). Crack identification from dynamic structural analysis using frequency signatures gained more research attention over crack effect analysis concerning structural health monitoring. In this context, vibration-based crack detection engaged through different methods are widely addressed (Yang *et al.*, 2009; Das *et al.*, 2021; An *et al.*, 2022).

Conclusively, the literature study places of interest the significance of dynamic analysis of laminated composites and states that the free vibration attributes in interaction with crack-like complex damage scenarios are not discovered to

their optimal extent and remains a significant scientific research issue. Furthermore, the literature broadly explains the utilization of different numerical techniques for free vibration analysis but, largely silent about the follow-up experimental validations. Accentuating this novelty, a concerted experimental and numerical research is carried out in present study. The theoretical analysis is done in FEM-based ABAQUS FE simulation software and the experiments are performed using a vibration FFT analyzer. The crack depths, crack location along with the fiber orientation and boundary conditions are the parameters considered for studying the variations in frequency responses of laminated composite beams.

Mathematical Modelling

The geometrical signatures length (L), width (b) and thickness (h) for an LCB with rectangular cross-section is shown in Figure 1. The crack positions are defined at L_1 , L_2 from the left end and the depth of the transverse crack is denoted as 'a'. The cracked beam model can be extended to multiple cracks located at $L_3, L_4 \dots L_i$.

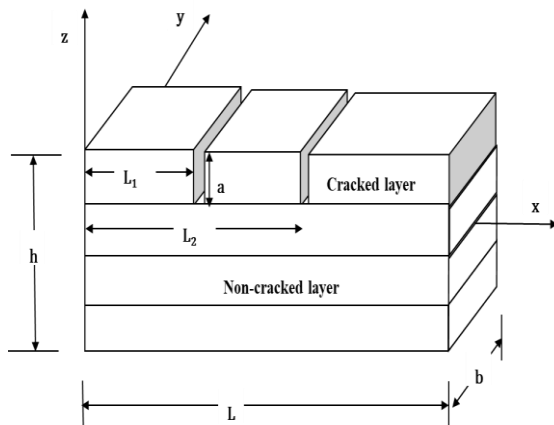


Figure 1. Cracked LCB with geometry and coordinates

To study the effects of cracks on the natural frequencies, an infinitesimal element of LCB encompassing the cracked region can be identified for study for governing the local compliance matrix adequately as demonstrated in Figure 1. Within this frame of reference, the local compliance matrix for the element is written as:

$$c_{ij} = \frac{\partial^2}{\partial P_i \partial P_j} \int_A (D_1 \sum_{n=1}^6 K_{In}^2 + D_2 \sum_{n=1}^6 K_{IIIn}^2 + D_{12} \sum_{n=1}^6 K_{Ii} \sum_{n=1}^6 K_{IIIn} + D_3 \sum_{n=1}^6 K_{IIIn}^2) dA \quad (1)$$

Where

'A' is the cracked surface area and D_1 , D_2 , and D_{12} are the material parameters coefficients (Tada *et al.*, 2000) and expressed as:

$$D_1 = -0.5 \bar{b}_{11} \text{Im} \left(\frac{\mu_1 + \mu_2}{\mu_1 \mu_2} \right)$$

$$D_1 = 0.5 \bar{b}_{11} \text{Im}(\mu_1 + \mu_2)$$

$$D_{12} = \bar{b}_{11} \text{Im}(\mu_1 \mu_2) K_I K_{II}$$

$$D_3 = 0.5 (\bar{b}_{44} \bar{b}_{55})^{\frac{1}{2}}$$

The stress intensity factors K_I , K_{II} , and K_{III} are accounted for crack modes I, II, and III respectively (Tada *et al.*, 2000). ' $\bar{b}_{ij}$ ' accounts for the local compliance of composite material and the characteristic equation roots are μ_1 and μ_2 (Kim and Kim, 2003).

The crack simulation in ABAQUS follows this concept of inverting the local compliances to get the stiffness matrix of cracked element and subsequently cracked beam stiffness is evaluated. Kisa, (2004) did the crack modelling for a 2-noded three degrees of freedom (DOF) composite beam and the stiffness matrix is presented as the inverse of compliance matrix as:

$$K_C = \begin{bmatrix} [C]^{-1} & -[C]^{-1} \\ -[C]^{-1} & [C]^{-1} \end{bmatrix}_{(6 \times 6)} \quad (2)$$

Now in line with Kisa (2004), the above equation can be improvised to any degrees of freedom per node. Now, the cracked laminated beam stiffness matrix is given by,

$$[K_{cbe}] = [K_e] - [K_{crack}] \quad (3)$$

The governing eigenvalue equation for LCB with crack is

$$[K_{cbe}] = [K_e] - [K_{crack}] \quad (4)$$

Where,

$[K]$ = cracked laminated beam stiffness matrix (Global)

$[M]$ = cracked laminated beam Mass matrix (Global)

Ω = Frequency

$\{\Delta\}$ = vector degrees of freedom (Global)

Finite Element Simulation

A linear beam FE model is erected in ABAQUS platform for recording the simulation results. In the event, the pre-processing commenced with developing the laminated beam and assigning the elastic moduli to each individual layer. Post assigning of material properties, assembling is done and the crack signatures are defined. The pre-processing step is followed by analysis which entails fixing boundary conditions, suitable mesh size selection and crack simulation. The analysis is then followed by post-processing where the modal analysis is performed and the simulated results for eigen frequencies are recorded. According to the ABAQUS documentation, using a well-structured mesh composed of hexahedral elements (C3D8R) often yields a solution of comparable accuracy while being more cost-effective. This is supported through the reflections observed by previous notable research work (Yardimoglu, 2010). Moreover, in the developed finite element modelling, a 3-point integration scheme is implemented, reducing computational costs when compared to other type of element. Additionally, dividing the mesh into sections is simpler with the 8-noded isoparametric element than with the other type of element. Thus, this research work is attempted adopting a C3D8R brick element for modal simulation. The mode shapes and numerical modal frequencies from the ABAQUS domain are presented in Figure 2.

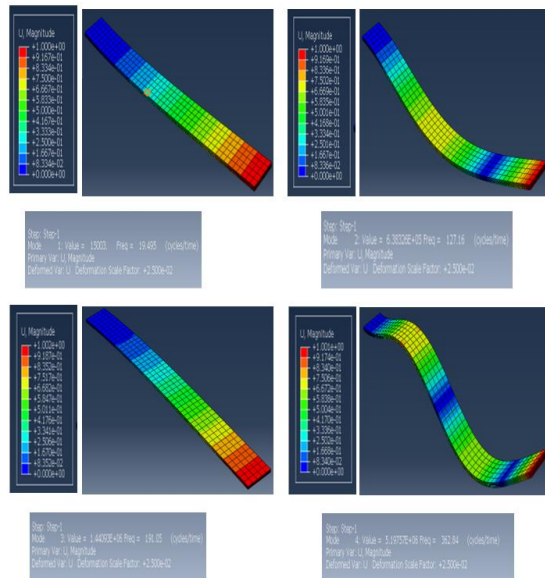


Figure 2. Mode shapes and frequencies using ABAQUS

Experimental Programme

Composite carbon/epoxy beam Fabrication

Towards free vibration experiments, carbon/epoxy LCB samples were prepared in line with many investigators (Das and Sahu, 2020). The “Owens-Corning” carbon fibers (WR 360/100) are procured and employed for specimen preparation. The bi-directional woven carbon fibers are cut into specified sizes for the preparation of laminated plates samples from which the beam samples were extracted. The fabrication process was followed the identical path as observed by previous experimental studies (Das and Sahu, 2020). Following these studies, the adhesive matrix prepared with fusion of epoxy (Lapox L-12, Atul Pvt. Ltd., India) with hardener (K-6, Atul Pvt. Ltd., India) as matrix using a proportion of 90:10 to laminate the carbon fibers. For the present investigation, the composite laminate is prepared for 8-fabric layers. The produced LCB samples in intact and cracked condition are shown in Figure 3. The beam geometries are measured with the help of a Vernier caliper and found as 250 mm, 25 mm, and 2.1 mm for length (L), breadth (b), and thickness (h) respectively. The dimension of the beam was measured using a Vernier calliper and repeatability is ensured through measurement 3-times, and taking average of that measurement.

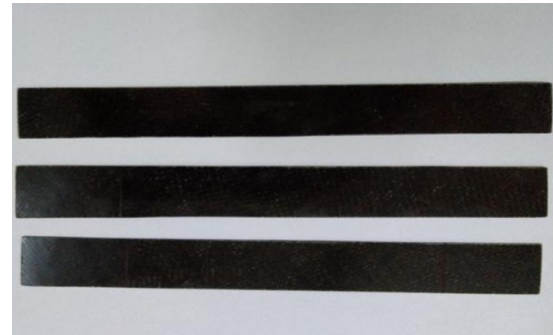


Figure 3. Coefficient Sparse Matrix A_y by $D_y \rightarrow$ Synthesis $\rightarrow$ Reconstructed Image in style S_y

Carbon/epoxy LCB material elastic constants from tensile test

The intact carbon/epoxy LCB samples are placed in hydraulic servo-electric universal testing machine (UTM) set-up INSTRON 8862 in order to acquire the elastic moduli (Figure 4). The tensile test engagement was carried out as per the guidelines

by ASTM-D3039/D3039M-14 (2008). The Bluehill universal software compatible with INSTRON 8862 is employed and the material properties for the LCB are reflected in Bluehill platform. During the tensile testing, the Bluehill platform gives the stress-strain curve in real time and the elastic moduli ' E_{11} ' and ' E_{22} ' are recorded and the rigidity modulus ' G_{12} ' is estimated in line with the empirical formulation provided by Jones (2018).

$$G_{12} = \frac{1}{\frac{4}{E_{45}} - \frac{1}{E_1} - \frac{1}{E_2} + \frac{2\nu_{12}}{E_1}} \quad (6)$$



Figure 4. Carbon/epoxy LCB put under tensile test using INSTRON 8862

The tensile test is conducted using three beam specimens in the INSTRON 8862 universal testing machine (UTM), adhering to the ASTM-3039/D 3039M-14 guidelines. The Bluehill universal software, compatible with INSTRON, is utilized to record the output data of the tensile test. The display unit presents the average of the three values for the elastic modulus. The material properties for the laminated carbon/epoxy beam as produced from the tensile testing are $E_{11} = E_{22} = 40.96$ GPa, $E_{45} = 11.26$ GPa, $\nu_{12} = \nu_{13} = \nu_{23} = 0.3$, $G_{12} = G_{13} = G_{23} = 3.11$ GPa and mass density (ρ) = 1676.19 kg/m³.

Free vibration experiments

Modal testing can be employed as an effective non-destructive analysis tool for dynamic exploration of structures including cracked composite beams. For the free vibration test, different beam samples are used with varying crack locations and depths, all with the desired boundary

condition attained through a pre-fabricated iron frame exclusively built to achieve the support conditions. To excite the samples, a modal impact hammer is used, and the Pulse software displayed the results in the form of an average of five consecutive frequency response functions (FRF). During the tests, the modal hammer, a Bruel and Kjaer 2302 model equipped with an internal force sensor, transmitted the excitation to the samples, while an accelerometer (Bruel and Kjaer 4507) attached to the surface of the beam near the crack received the signals (Figure 5). The experimental work observed a linear relationship between the input and output, supporting the reliability of the governed results. Overall, the findings indicate that the test setup and methodology were effective in obtaining accurate and consistent results for the free vibration characteristics of the LCB samples.

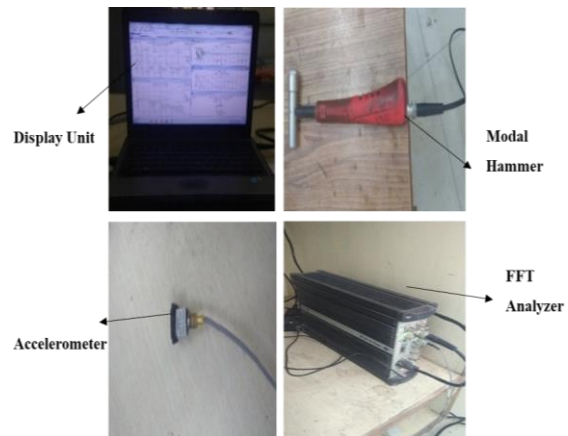


Figure 5. Complete set-up for experimental analysis

The weight of the sensor (Bruel and Kjaer 4507) used in the present study is 4.8 gm and compared to the weight of the composite beam, the sensor weighs only 5.1% which has insignificant effect on natural frequencies. Based on this, the present study does not consider the effect of the weight of sensors.

Results and Discussion

LCB vibration responses are recorded from free vibration test and beam simulation in ABAQUS for an 8-layered woven roving laminated carbon/epoxy beam with transverse open cracks and presented with respect to different parameters. In view of analysis, the results are grouped as

- Comparison of present FE results with previous studies.
- Numerical and Experimental results for different parameters.

Comparison of present FE analysis with Previous studies

The precision and proficiency of the present FE modelling through ABAQUS are validated with regard to previous studies. The vibration frequencies cracked cantilever composite beam are recorded through ABAQUS platform in the equal domain of material properties and boundary condition as performed by Kisa (2004) and summarized in Table 1. The geometry and material details are:

length= $L = 1000\text{mm}$, width = $b = 25\text{ mm}$ and thickness = $h = 5\text{ mm}$ for a relative crack depth $=a/h = 0.2, 0.4$ and 0.6 located at $0.1L$ from fixed end. $E_m = 2.756\text{ GPa}$, $E_f = 275.6\text{ GPa}$, $\nu = 0.3$, $G_m = 1.036\text{ GPa}$, $G_f = 114.8\text{ GPa}$, $\rho_m = 1600\text{ Kg/m}^3$, $\rho_m = 1900\text{ Kg/m}^3$.

Table 1. First natural non-dimensional frequency comparison for clamped-free LCB with varying fiber-orientations and an open crack ($L_1/L = 0.1$ from clamped end)

Fiber orientation	a/h	Kisa (2004)	Present results
0°	0.2	0.9773	0.9625
	0.4	0.9046	0.91
	0.6	0.7526	0.75
15°	0.2	0.9812	0.9733
	0.4	0.9861	0.9093
	0.6	0.7849	0.77
30°	0.2	0.9876	0.9836
	0.4	0.9477	0.9377
	0.6	0.8429	0.83

The expression for evaluation of non-dimensional natural frequency as per the formula:

$$\lambda = \left(\frac{\rho A}{E_3 I} \right)^{\frac{1}{2}} L^2 \omega \quad (7)$$

Where ' λ ' is noted as the non-dimensional natural frequency and the dimensional eigen frequency is represented by ' ω '.

Numerical and Experimental Results

The frequencies of vibration of cracked LCB, computed through ABAQUS platform and experimental analysis are studied with respect to the following parameters for LCB:

- Effect of lamination layers
- Effect of boundary condition

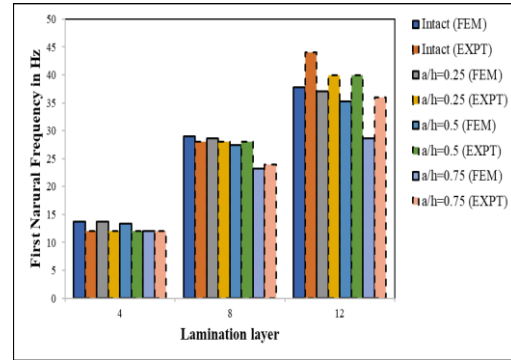


Figure 6. First mode frequency for CF carbon/epoxy LCB concerning lamination layers with varying RCD (a/h)

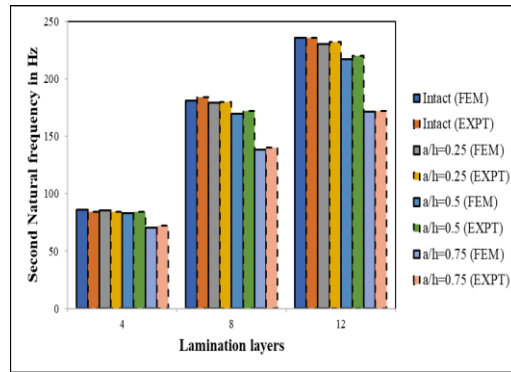


Figure 7. Second mode frequency for CF carbon/epoxy LCB concerning lamination layers with varying RCD (a/h)

Effect of lamination layers on the natural frequencies of LCB

The effect of multiple transverse cracks on the frequencies of free vibration concerning different lamination layers are presented in Figure 6 and Figure 7. Three types of carbon/epoxy LCB with 4-layer, 8-layer, and 12-layer were prepared confirming the beam depths 1.1 mm, 2.1 mm, and 2.9 mm respectively with 0° fiber orientation. Three cracks positioned at $0.25L$, $0.5L$, and $0.75L$ with relative crack depths (RCD) of 0.25, 0.5, and 0.75 considering Clamped-Free (CF) support condition. From the graphical curve in Figure 6, first mode frequency of 8-layered beam jumps about 110% than 4-layered LCB and falls about 40% less than 12-layered LCB. Similar observations are noticed from the summarizations in Figure 7 for all crack depths and locations concerning second natural frequency. It can be predicted from the illustrations that the frequency variation is significant from 4-layered LCB to 8-layered LCB and less for 8-layered LCB to 12-layered LCB. In this context, in

view of greater accuracy in fabrication with ambient duration, ease of lamination, and lower computational cost, current research employed 8-ply carbon/epoxy LCB for further parametric study regarding crack analysis.

Effect of boundary conditions on the frequencies of cracked composite beam

In this section the effects of different boundary conditions on the frequencies of vibration in existence of cracks is presented. In this context, the vibration study is thrust on three boundary conditions namely, cantilever or Clamped-Free (CF) and Simply Supported (SS). The elucidation of the results for above boundary conditions are discussed in following subsections.

(a) Free vibration of cracked carbon/epoxy LCB with CF boundary condition

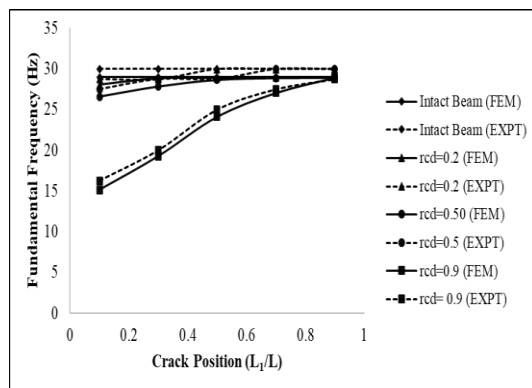


Figure 8. First mode frequency variation for CF carbon/epoxy LCB concerning crack locations with varying RCD (a/h)

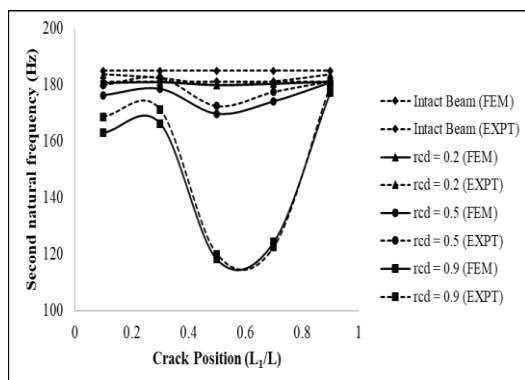


Figure 7. Second mode frequency variation for CF carbon/epoxy LCB concerning crack locations with varying RCD (a/h)

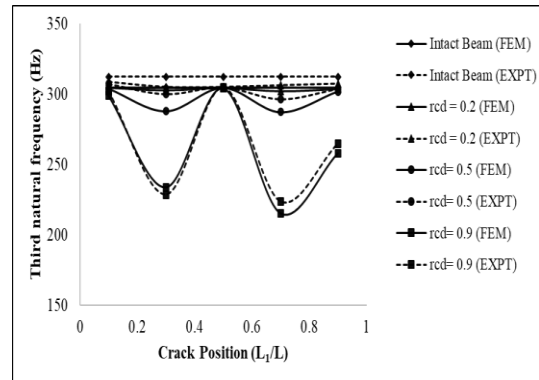


Figure 10. Third mode frequency variation for CF carbon/epoxy LCB concerning crack locations with varying RCD (a/h)

The variations in first, second and third natural frequencies with respect to different crack locations (L_1/L) concerning RCD are presented in Figure 8 – Figure 10. The crack positions are engineered selectively at 0.1L, 0.3L, 0.5L, 0.7L and 0.9L by means of a hacksaw. In similar way, the crack depths assigned to each position are 0.2h, 0.5h and 0.9h. Now observing the frequency shifts, Figure 8 indicates that at the crack location 0.1L the fundamental frequency reduced by 3.3%, 8.3% and 47.7% at a/h 0.2, 0.5 and 0.9 than the fundamental frequency of intact carbon/epoxy LCB. Analyzing for second natural frequency illustrated in Figure 9, the reduction with respect to Intact beam observed in the range of 0.19% to 9.88% for above crack signatures. But at 0.5L, the second natural frequency exhibits maximum reduction quantifying 0.6%, 6.2% and 34.8% for 0.2, 0.5 and 0.9 crack depths respectively. The trends are recorded for third natural frequency as demonstrated in Figure 10 where the reduction is recorded in a range from 0.2% to 29.32% considering all crack locations and depths. The maximum reduction is realized at 0.3L and 0.7L. Furthermore, the cracked natural frequencies at far end resembles as that of natural frequencies of intact LCB. Similar observations are also reflected in the numerical modal analysis by Kisa (2004).

(b) Free vibration of cracked carbon/epoxy LCB with SS boundary condition

The experimental and simulated frequency results are summarized in Figure 11 through Figure 13 for first, second and third natural frequencies of cracked carbon/epoxy LCB concerning SS boundary condition. The observations from Figure 11 are

showing equal magnitudes at $0.1L$ and $0.9L$, and also for $0.3L$ and $0.7L$ for any crack depth and maximum reduction in the fundamental frequency occurs at $0.5L$. Quantifying, the reduction is measured 2.9%, 8.07% and 40.93% correspond to 0.2, 0.5 and 0.9 crack depths respectively. Analyzing for second natural frequency, the Figure 12 shows that a maximum reduction of 47.12% is recorded at $0.3L$ and $0.7L$ for a crack depth of 0.9 whereas, at mid-span of the SS carbon/epoxy LCB almost no change in frequency is observed. Moving on to Figure 13, the trend shows maximum reduction realized at $0.1L$ and $0.9L$ quantifying 26.2%.

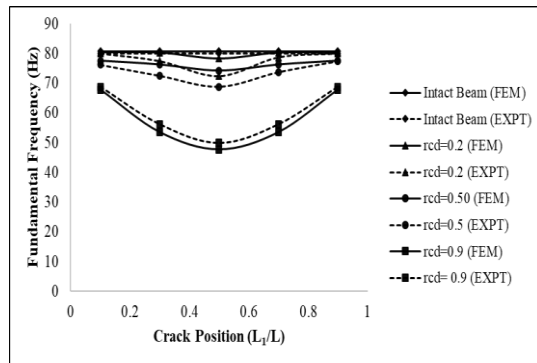


Figure 11. First mode frequency variation for SS carbon/epoxy LCB concerning crack locations with varying RCD (a/h)

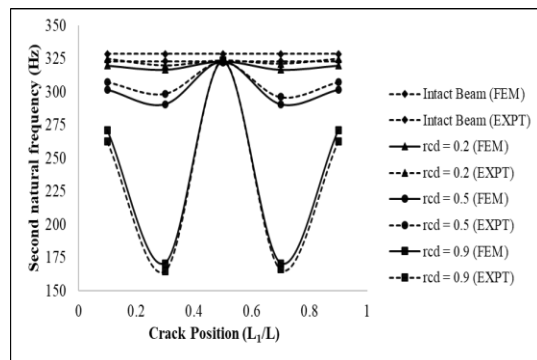


Figure 12. Second mode frequency variation for SS carbon/epoxy LCB concerning crack locations with varying RCD (a/h)

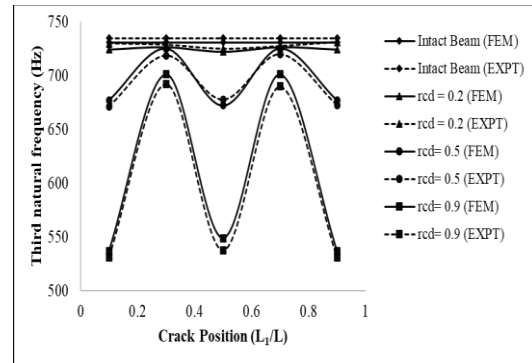


Figure 13. Third mode frequency variation for SS carbon/epoxy LCB concerning crack locations with varying RCD (a/h)

(c) Free vibration of cracked carbons/epoxy LCB with CC boundary condition

The crack effect study shifted to CC case where the both ends of the beam is clamped restraining the translation and rotation. The experimental and FE predictions towards this analysis is summarized in Figure 14, Figure 15 and Figure 16 for first, second and third natural frequencies respectively. It is evident from the graphical summarization that the maximum reduction in natural frequencies occur when the crack is placed at central span of the LCB for any relative depth of crack. Observing the frequency shifts from Figure 11, maximum variation is recorded at crack position of $0.5L$ quantifying a reduction of 49.5% for a crack depth of $0.9h$ in fundamental frequency than the fundamental frequency of intact beam. Figure 12 and Figure 13 follows similar trends in frequency reduction for higher modes and exhibit a maximum reduction of 49.52% and 46.56% for 2nd and 3rd mode vibration respectively with respect to intact beam when the crack signature is defined at $0.5L$ with 0.9 relative crack depth. It can also be realized from the illustrations that apart from $0.9h$ crack depth, the crack location $0.5L$ exhibits more reduction in natural frequencies with respect to relative crack depths 0.2 and 0.5 compared to the crack located at all other positions. In line with this observation similar reflections can be found in previous works

(Karaagac *et al.*, 2009; Daneshmehr *et al.*, 2013; Sahu and Das, 2020) towards supporting the outcomes.

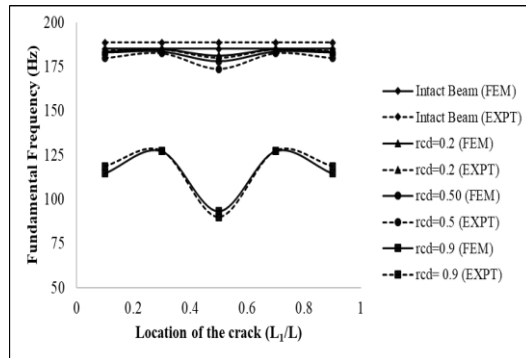


Figure 14. First mode frequency variation for CC carbon/epoxy LCB concerning crack locations with varying RCD (a/h)

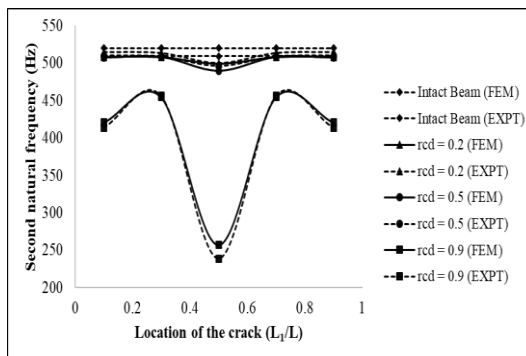


Figure 15. Second mode frequency variation for CC carbon/epoxy LCB concerning crack locations with varying RCD (a/h)

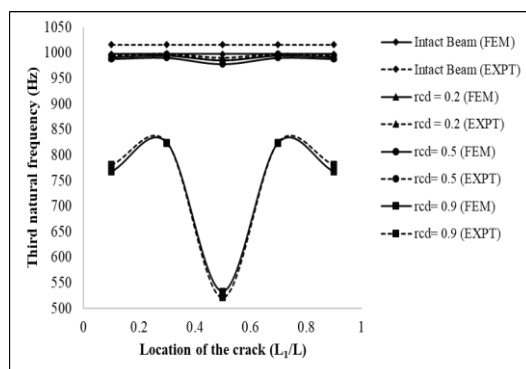


Figure 16. Third mode frequency variation for CC carbon/epoxy LCB concerning crack locations with varying RCD (a/h)

Conclusions

In this study, the frequency-based crack effect analysis is done for carbon/epoxy LCB with respect to different beam parameters. From the concerted efforts through experimental and finite element modal analysis, ensuing conclusions are made.

- The utilization of frequency data for crack detection in beams has proven to be a valuable and effective approach. The analysis of frequency response provides valuable insights into the structural behaviour and can serve as a sensitive indicator of crack presence and severity.

- The FE simulated results imply close resemblance with the results from free vibration experiments.

- For the Clamped-Free composite beam, minimum reduction in vibration frequency is observed and the maximum percentage reduction in natural frequency is experienced for the crack nearer to the fixed support.

- Clamped-Clamped laminated cracked composite beam displays higher frequencies as compared to the simply supported and Clamped-Free beam due to restraint at edges.

- Significant variations in frequencies of vibration are observed for greater crack depth.

- Cracks located near the clamped support exhibit maximum reduction in natural frequency for any particular crack depth.

The findings of this study provide valuable insights into the dynamic behaviour of laminated structures implied with crack or crack-like structural irregularities. The combination of FEM analysis and experimental work offers a comprehensive understanding of the influence of crack on frequencies and enhances the accuracy of predictions in practical engineering applications. The outcomes of this research can assist in assessing the structural integrity of laminated beams and guide effective maintenance and repair strategies to mitigate the detrimental consequences of cracks.

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