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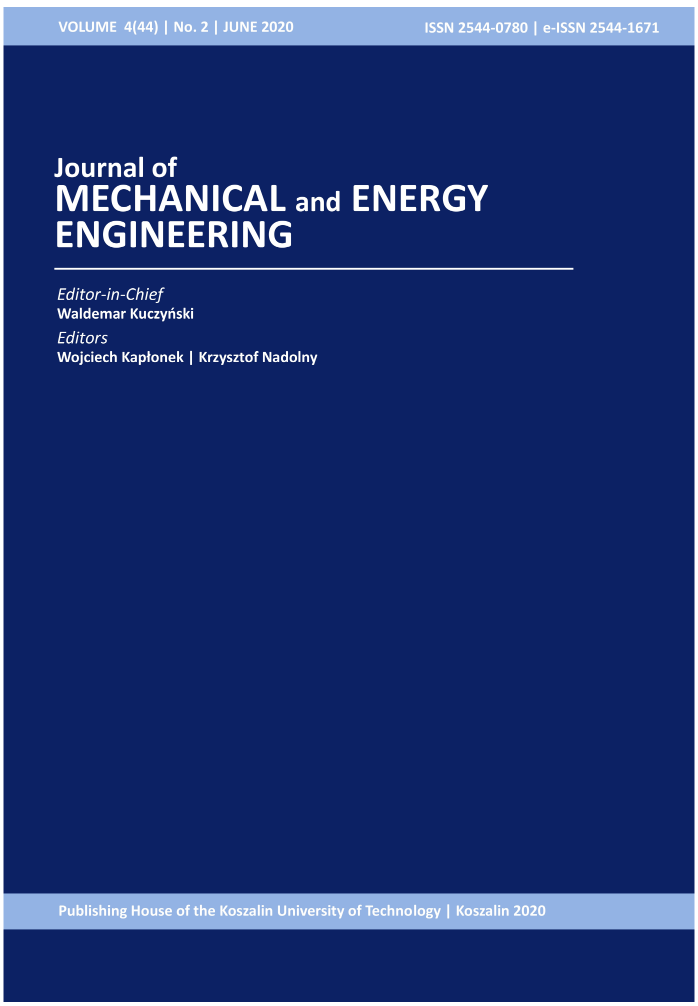

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RESIDUAL LIFE ESTIMATION OF HEALTHY AND CRACKED COMPOSITE BEAM USING EXPERIMENTAL AND NUMERICAL MODAL ANALYSIS METHODS

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Abstract: Preventive maintenance is beneficial to minimize unexpected breakdowns in industries with continuous production. Composite structures are used for naval applications like ship hulls and marine propellers. In most of the industries, composite structural health analysis using experimental and numerical model are available for damage detection and estimate the residual life of composite beams. The present work is focusses on identification of damage and estimate residual life of composite healthy and cracked beams. Free vibrational analysis is carried out on composite beam made of Glass fiber reinforced polymer (GFRP) with a different crack orientation. A Fast Fourier Transform (FFT) spectrum analyzer associated with engineering data management (EDM) software utilized for experimental analysis to detect presence of damage in cracked composite beam. Finite element method (FEM) software called Analysis of composite pre/post (ACP) available in ANSYS R3 is used to compare the natural frequency results of healthy composite beam with cracked composite beam with different ply orientations. For validation of numerical modal evaluation, the consequences acquired from ANSYS R3 Finite element analysis (FEA) software are in comparison with experimental results received by impact hammer method. The fatigue life of a damaged composite beam is estimated the use of "Hwang and Han's" fatigue life equation.

Keywords: E-glass/Epoxy fiber, composite healthy beam, composite cracked beam, Mode shape, Natural frequency, FFT Analysis, Crack location, ACP (pre& post).

1. INTRODUCTION

Structural health monitoring is a concept of identifying damage location and strategizing its characteristics in engineering structures. In other words, health monitoring of machine elements or structures is procedure wherein certain methodologies are executed for the discovery of damage, location. These parameters vary between damaged and undamaged structures. Crack formation due to repetitive loads ends in fatigue of the structure. Hence crack detection plays an essential position in structural health monitoring programs. There is different non-destructive testing methods such as flaw detection C-scan are available for earlier damage detection in composite structures. But they are very expensive, time-consuming and some of them are difficult to implement for complex structures such as aircrafts, railway tracks, long columns, and long pipelines in power plants. Vibration testing has become a standard procedure for fault diagnosis in many applications. Due to the excellent mechanical properties, fiber reinforced composites are widely utilized in industry. Many fatigue specimens for fiber reinforced composite substances had been advanced, and can be classed into three categories: fatigue existence models based at the comparing three models, S-N curves are base for fatigue lifestyle evaluation in fiber strengthened composite structure. Too many fatigue experiments are necessary to devise S-N curves that is time consuming. Multi-axial fatigue life prediction can reduce time because of composite anisotropy and make contact with between the composite systems. Sufficient quantity of literature was available on fatigue behavior of GFRP epoxy composite substances. Equation is further simplified by strain failure criterion for realistic application.

2. LITERATURE REVIEW

From existing literature, it is evident that both experimental and numerical models are available to detect damage and estimate residual life in structure Pratibha [1] said an experimental modal analysis to discover crack place and size in cracked composite beam the usage of their first three natural frequencies in FFT analyzer. These results are validated with natural frequencies received from finite element technique in ANSYS software. Santiuste [2] tested the impact of experimental parameters namely wide variety of layers, fiber orientation and boundary situations at the natural frequency of woven fiber composite plate using FFT analyzer. [3, 4] they as investigated on natural frequency characteristics of quasi isotropic carbon fiber reinforced polymer (CFRP) with containing different hole location specimens. Decrease of the specimen natural frequencies based on increase number of holes and size. Cui [5] numerical study on modal frequency behaviour and structural dynamics of combining composite turbine blade. Pushparaj [6] analyzed the influence of hybridization, matrix fabric and fiber orientation on modal frequencies of GFRP and CFRP composites and also studied the mode shapes using experimental and computational procedures at different fiber volume fractions [7]. Chaudhari [8] performed modal analysis on isotropic right triangular composite plate made of materials like rubber, plastic and fiber reinforced polymers (FRP). The experimental results are compared with that obtained from fem analysis. More [9] compared finite element analysis and experimental modal analysis to detect damage in fiber reinforced composites and non-composite structures. Sharayu [10] calculated natural frequency of different modes of a cantilever beam analytically and experimentally to find the effect of fiber orientation and aspect ratio of woven fiber composite plates in free-free boundary condition. Reddy [11] performed analytical studies on four different materials of transmission shaft in rear wheel drive automobile. They designed drive shaft in ANSYS ACP and in comparison natural frequencies of various substances the use of ANSYS static structural. Vader [12] evaluated changes in natural frequencies of cracked composite beam both experimentally and numerically. They conducted experiments to find frequencies in cracked beam using vibration analyzer with data acquisition system. They also modelled cracked structure in harmonic response module of ANSYS workbench and found to be close with experimental results. Stevan [13] developed a powerful and reliable computational approach for residual life estimation of cracked aircraft structural additives with recognize to fracture mechanics and the modal frequency of the cantilever beam will increase while the crack orientation with appreciate to the transverse axis is increased. Xe [14] conducted on vibration characteristics of woven fiber composite beam with different thickness is prepared by mixing of fiber volume fraction and epoxy resin curing ratio. The results observed from the experimental, strength depends on the fiber volume fraction and resin area in composite beam. Kale [15] studied on natural frequency characteristics of combined titanium alloy with CFRP turbine blade. Equal composition of material more stiffness and increases the weight of blade. [16] Studied about the residual strength of glass composite beam with the influence of impact strength, beam width and nose geometry of experimental specimens. The residual strength lower value at prepare the charpy nose compare to the hemispherical nose impactor. Prenil [17] predicative study on strength and failure analysis of modern composite turbine. Strength depend upon fiber orientation and layer stacking sequence order. Syayuthi [18] investigation of fatigue behavior of glass fiber reinforced epoxy composite material under different stress ratio. The fatigue behaviour majorly depend upon the variation of load and stress ratio. Wei [19] predict the fatigue life based on different ply angles and lay up order to sequence in-plane, longitudinal and transverse shear directions of composite plate.

3. EXPERIMENTAL ANALYSIS

The natural frequency of healthy composite beam with consider the relation of rotary inertia, shear deformation and damping.

Fig. 1. Experimental analysis of E-Glass fiber beam

The natural frequency of healthy composite beam with consider the relation of rotary inertia, shear deformation and damping. For vibrational center line of beam due to the component of displacement 'V 'and point of function x, and time't' [20]:

$$EI\frac{\partial^4 V}{\partial X^4} + \rho A\frac{\partial^2 V}{\partial t^2} = 0. \quad (1)$$

With harmonic function of time consider as:

$$V(x,t) = V(x)\,sin(\omega t - a). \quad (2)$$

From equation (1) and (2):

$$\boldsymbol{\lambda^4 = \frac{\rho A\omega^2}{EI}}, \quad (3)$$

$$\frac{d^4 V}{dx^4} + \lambda^4 V = 0, \quad (4)$$

$$V(x) = B_1 \sinh \lambda x + B_2 \cosh \lambda x + B_3 \sin \lambda x + B_4 \cos \lambda x \,. (5)$$

The Eigen value (λ) for composite beam at first three modes:

$$(\lambda_1 L) = 1.875, \quad (6)$$

$$(\lambda_2 L) = 4.694, \quad (7)$$

$$(\lambda_3 L) = 7.855, \quad (8)$$

$$\omega_r = (\lambda_r{}^2)\sqrt{\frac{EI}{\rho A}}; (r = 1,2,3). \quad (9)$$

An experimental modal investigation is performed on healthy composite beam for validation of numerical analysis carried using ANSYS ACP. One end of the composite healthy and crack beam of size 300×50×3 mm is tightly fixed with the assistance of bench vice without damage the thickness of composite beam. Natural frequency test is carried out on healthy and cracked composite beam using impact hammer, accelerometer and FFT analyzer. Basically frequency range of composite material near to 1000 Hz.As per setting available in FFT analyzer, 1440 Hz only available near to 1000 Hz. Frequency range is selected from 0 to 1440 Hz. The impact hammer sensitivity value is 10 mv/g and accelerometer sensor sensitivity is 9.6 mv/g. The output channel is connected to the computer. An accelerometer is placed at the selected locations and initial excitation is given by the impact hammer and the output signal is saved in FFT analyzer. The data from FFT analyzer is transferred to EDM software for post processing of test results generated from equation 1-9. Figure 1 shows the experimental setup of E- Glass fiber beam for natural frequency test. Figure 2 shows modal frequencies of healthy composite beam. Figure 3 shows modal frequencies of an inclined cracked composite beam. Figure 4 shows modal frequencies of a longitudinal cracked composite beam. Figure 5 Shows modal frequencies from FFT analyzer for a transverse cracked composite beam. Table 1 represents experimental natural frequency data from FFT spectrum analyzer at crack location 150 mm from the fixed end.

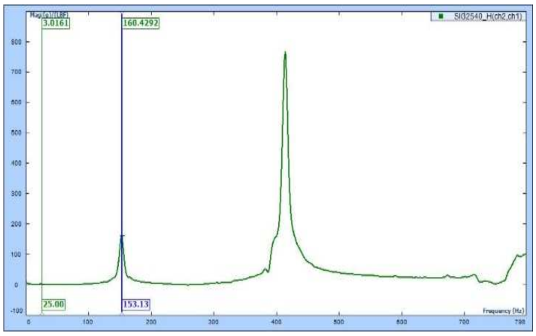

Fig. 2. Modal frequencies of healthy composite beam

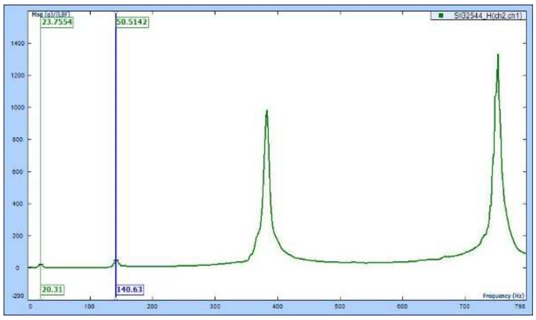

Fig. 3. Modal frequencies of an inclined cracked composite beam

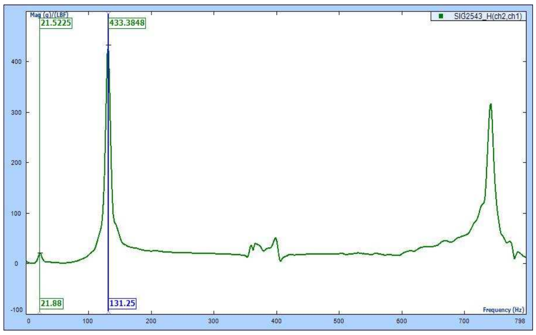

Fig. 4. Modal frequencies of an longitudinal cracked composite beam

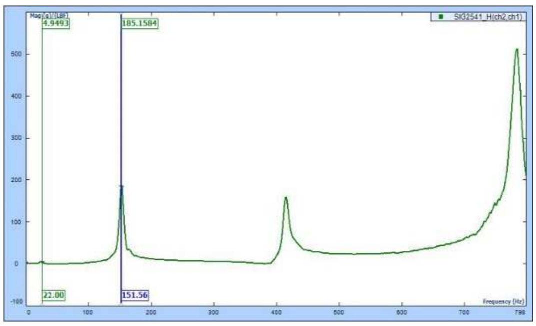

Fig. 5. Modal frequencies of an transverse cracked composite beam

Tab. 1. Experimental natural frequency data from FFT analyzer at crack location 150 mm from the fixed end

Mode	Healthy beam *[Hz]*	Inclined crack *[Hz]*	Longitudinal crack *[Hz]*	Transverse crack *[Hz]*
1	25.00	20.31	21.88	22.00
2	153.3	140.8	131.25	151.56
3	418.2	396.2	392.14	401.26

4. NUMERICAL ANALYSIS

Modal analysis is performed using FEM software called ANSYS R3 2019 workbench to get first three modal frequencies of a healthy and cracked composite beams. A modal analysis used for determine the vibrational analysis of the composite beam. Figure 6 shows methodology for prediction of modal frequencies of a healthy and cracked composite beam using ANSYS ACP. In ACP preprocessing mode represent in block "A", composite beam geometry and a mesh, the boundary conditions and composite definitions are applied to composite beam in the pre-processing stage. After preprocessing data connect to input of solver block "B". In the post-processing mode block "c", after a completed solver and the transfer of the post-processing results can be evaluated. In this ANSYS ACP analysis blue lines indicated that data can be shared in between blocks and pink line mean data should be transfer one block to another block represent in Figure 6. Composite beam was modelled with 0/90 layups. Total 9 bi-directional layers of each 0.2 mm are used to model the composite beam. Table 2 shows specification of E-Glass composite beam and Table 3 shows the material behaviour of E-Glass composite material with epoxy used in the present modal analysis on healthy and cracked composite beam. After comparison it is confirmed that hexahedral elements generates more accurate results when compared with tetrahedral elements. Hexahedral element was used to generate the mesh for healthy and cracked composite beam. The mesh was converged with element size of 2 mm. Figure 7 and 8 shows the orientation of fiber in composite beam and direction of layers in E-Glass composite beam respectively.

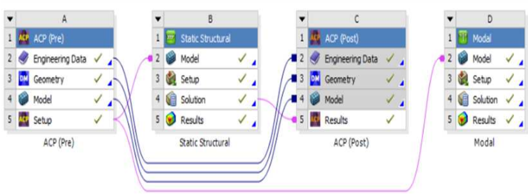

Fig. 6. Methodology for estimation of modal frequencies using ANSYS ACP

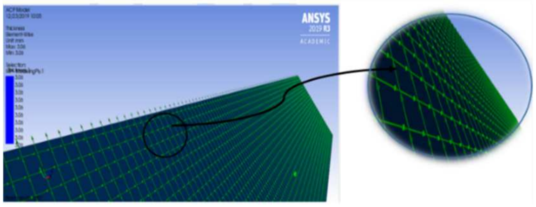

Fig. 7. Fiber orientation in composite beam

Table 4 shows the natural frequencies of healthy composite beam. Figure 9 and 10 shows the mode shapes of healthy and cracked composite beam respectively. Mode shapes cracked composite beam are changed when compared with healthy composite beam. So mode shapes also can be used to find the cracks present in the beam. Auto scale used to show the deformation in each mode. In red and blue colour indication in mode shape of both healthy and cracked composite are maximum and minimum deformation respectively. Table 5 depicts the results of first three natural frequencies of longitudinal crack, transverse crack and inclined crack with respect to change of crack location.

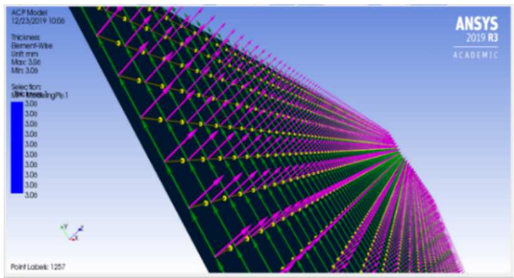

Fig. 8. Direction of layers in E-Glass composite beam

Tab. 2. Specification of E-Glass composite beam

Parameters	Value
Total length	300 mm
Width	50 mm
Thickness	3.05 mm
No of layers	9
Type of fiber	E-Glass fiber (0.2 mm thickness)
Types of matrix	Epoxy resin (LY556)& Hardener(HY951)
Direction of ply	(0/90)

Tab. 3. Material behaviour of E-Glass composite beam

Material properties	Value
Young's modulus (E_x)	35125 MPa
Young's modulus (E_Y)	6450 MPa
Young's modulus (E_Z)	6450 MPa
Shear modulus (G_{xy})	2436 MPa
Shear modulus (G_{yz})	1696 MPa
Shear modulus (G_{zx})	2436 MPa
Poisson's ratio (ν_{xy})	0.223
Poisson's ratio (ν_{xz})	0.223
Poisson's ratio (ν_{yz})	0.372

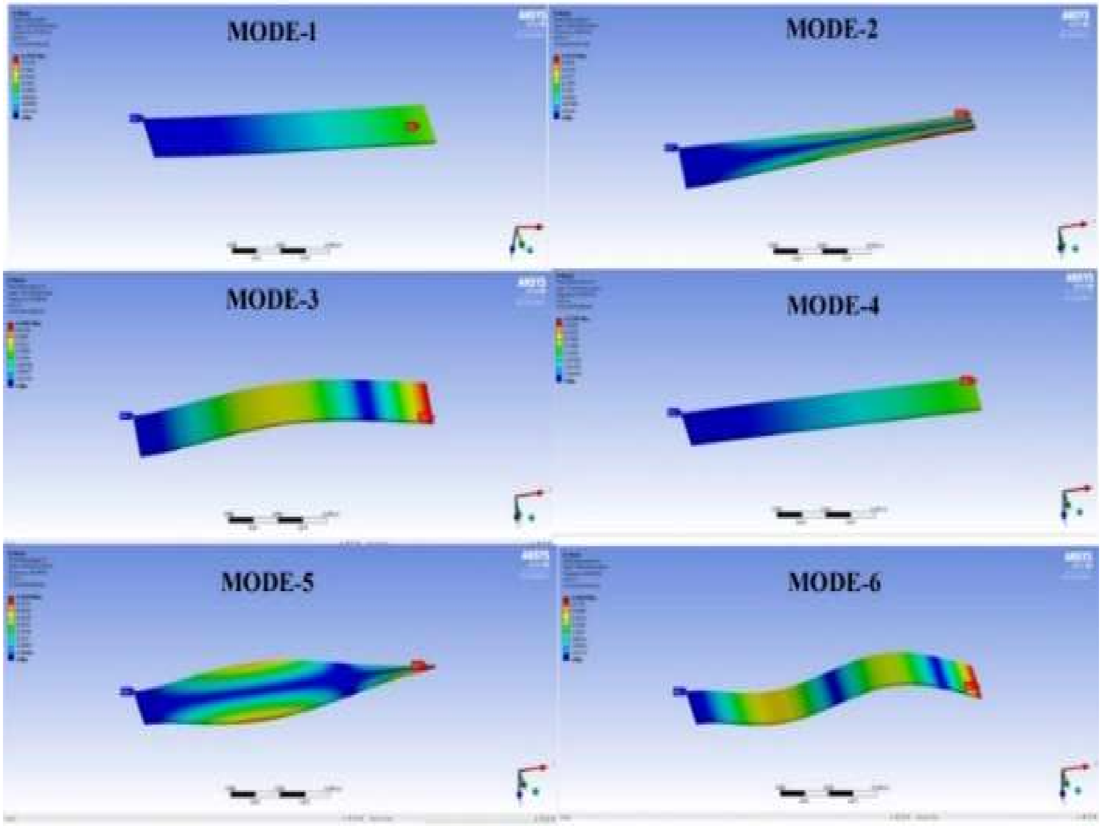

Fig. 9. Mode shapes for healthy composite beam

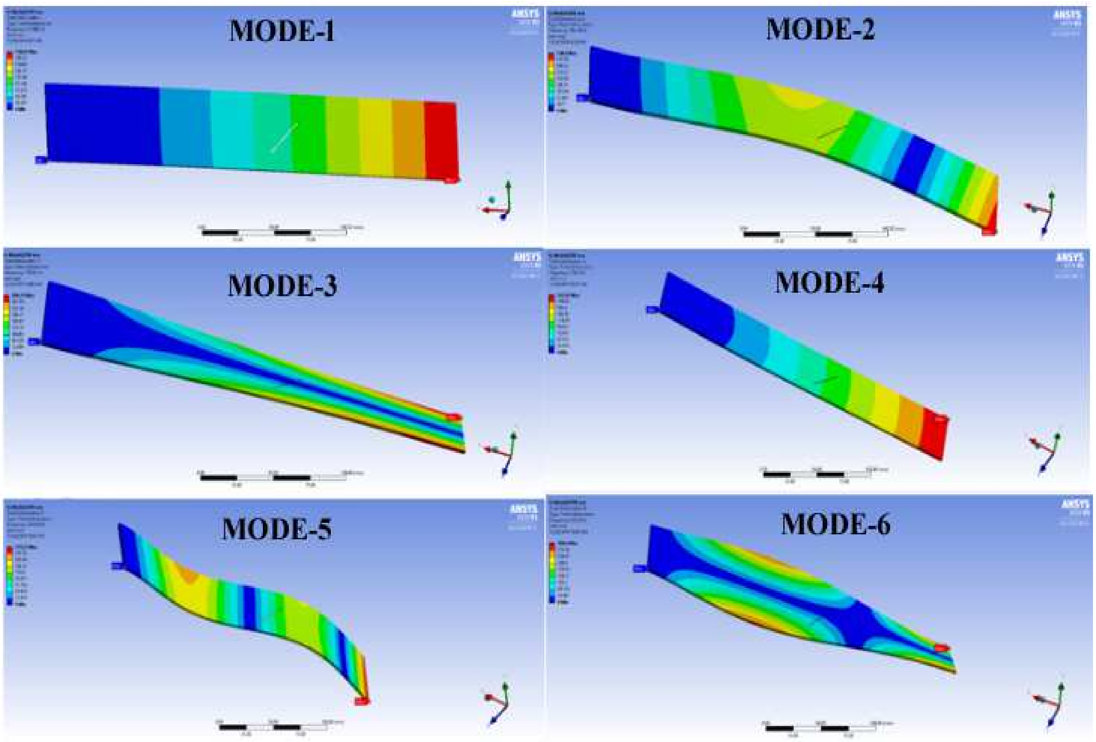

Fig. 10. Mode shapes for cracked composite beam

Tab. 4. Natural frequency of cracked composite

Crack location [mm]	Longitudinal crack *[Hz]*			Transverse crack *[Hz]*			Inclined crack *[Hz]*		
	f_1	f_2	f_3	f_1	f_2	f_3	f_1	f_2	f_3
50	21.83	148.68	170.61	23.89	149.94	170.68	21.83	148.68	170.63
100	23.66	146.27	169.70	23.93	149.94	170.82	22.79	145.84	170.66
150	23.77	145.38	170.14	23.94	149.86	171.00	23.49	138.88	170.98
200	23.86	145.39	170.56	23.96	149.78	171.19	23.85	141.49	171.31
250	23.98	148.37	171.21	23.99	149.81	171.43	23.99	148.44	171.58

Tab. 5. Natural frequencies of healthy composite beam

Mode shape number	Modal frequency *[Hz]*
1	24.802
2	130.22
3	169.59
4	309.39
5	364.15
6	522.49

5. RESULTS AND DISCUSSIONS

FFT modal analysis is used for conducted composite healthy beam and different types of inclined, longitudinal, and transverse cracked beams. Damage present in the composite beam can be identified by change of natural frequency between healthy and cracked composite beam. First three frequencies are sufficient to estimate the damage present in the cracked composite beam. The natural frequency is majorly influenced by crack direction and crack area from fixed side of composite beam. In the present study crack is generated at distance of 200 mm from the fixed end in the composite beam. Figure 11 shows the comparison of modal frequencies obtained from FFT modal analysis. From figure 11, it was observed that natural frequency of healthy composite beam is greater than cracked beams. Figure 12 shows comparison between the modal analysis of composite healthy beam. From the figure 12 shows comparison between the experimental and numerical healthy beam. From the figure 12 clearly shows that the maximum percentage of error is 9.486 %. Figure 13 shows comparison between the experimental and numerical composite cracked beam. From the figure 13 clearly shows that the maximum percentage of error is 3.286 %. From the figure 12, third modal frequency of composite beam (418.2 Hz) is same as fifth modal frequency (364.15) of Table 5.

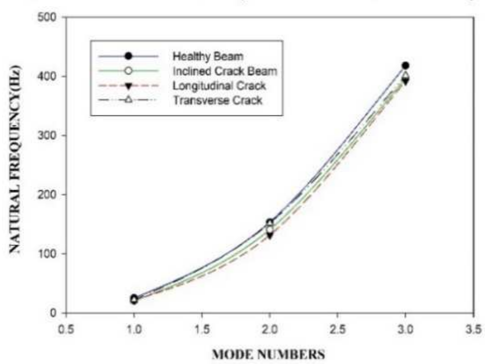

Fig. 11. Comparison of modal frequencies

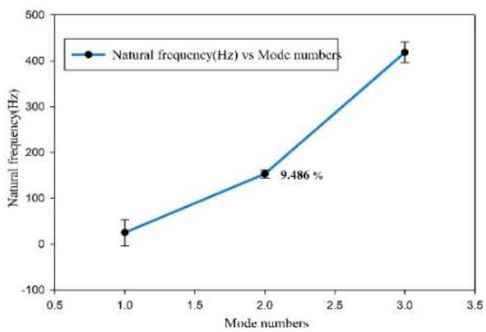

Fig. 12. Comparison between the modal analysis of composite healthy beam

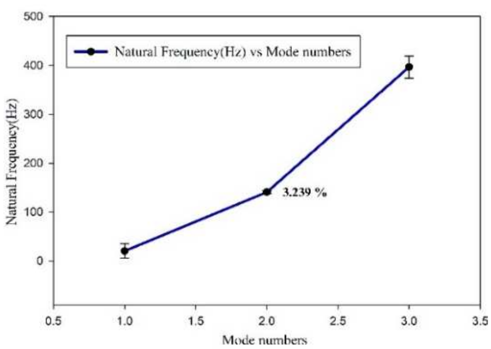

Fig. 13. Comparison between the modal analysis of composite cracked beam

5.1. Residual Life Criteria and S-N Curves

The equation used for determine the residual life of composite beam [21]. The figure 14 shows the S-N curve generated for healthy E-Glass composite beam using Eqs.5

Hwang and Han's relation:

$$N = \left(B(1-r)\right)^{\frac{1}{c}}, \quad (10)$$

where: B = 10.33 and C = 0.14012.

Applied stress level (r) is ratio of maximum stress to ultimate tensile stress [MPa] of composite beam:

$$\boldsymbol{\sigma}_{max} = \frac{6fl}{bt^2}. \quad (11)$$

A load of 1000 N is applied on the residual life of composite beam. Residual life of healthy composite beam, inclined composite cracked beam, longitudinal composite cracked beam and transverse cracked composite beam calculated using Hwang and Han's equation 10 and 11. Residual life of healthy composite beam is 15.72×10^6 cycles, inclined composite cracked beam is 12.04×10^6 cycles, longitudinal composite cracked beam is 15.46×10^6 cycles and transverse composite cracked beam is 11.04×10^6 cycles

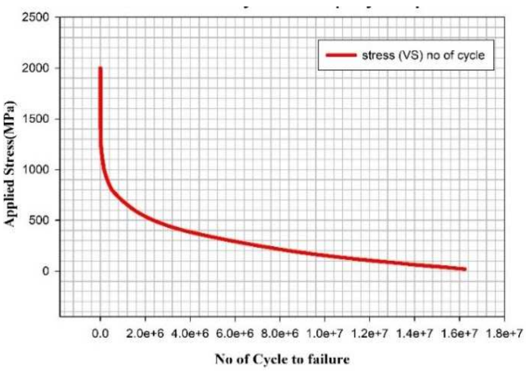

Fig. 14. S-N curve for healthy E-Glass composite beam

6. CONCLUSIONS

Residual life of healthy and cracked composite beam are estimated using experimental and numerical modal analysis methods.

1. A good correlation is observed between experimental and numerical modal analysis results.
2. The natural frequency of the E-Glass composite beam is directly proportional to stiffness of the composite beam i.e. high modal frequency reflects that high stiffness of composite beam
3. The natural frequency of a composite beam decreases when crack orientation increased to fixed end position.
4. The numerical results are validated for natural frequency of composite beam with benchmark solutions of Pushparaj et al. [6] and found to be in decent agreement with maximum percentage of deviation 17.89%.
5. To enhancement in first modal frequency at crack constant crack location 150 mm from the fixed end (from 23.49 Hz to 23.94 Hz) occurs at the different crack orientations.
6. From the analysis of residual life estimation of different crack orientation beams it was found that transverse cracked beam has least residual life when compared with longitudinal crack and inclined cracked beam.

From the numerical analysis using ANSYS R3 2019 workbench it was found that the residual life of healthy composite beam is 15.72×10^6cycles, longitudinal composite cracked beam is 15.46×10^6cycles, inclined composite cracked beam is 12.04×10^6cycles and transverse composite cracked beam is 11.04×10^6cycles.

Nomenclature

Symbols

A – cross sectional area of beam, mm^2
E – young's modulus, Mpa
f – applied force, N
f_1 – first modal frequency, Hz
f_2 – second modal frequency, Hz
f_3 – third modal frequency, Hz
I – moment of inertia, mm^4
L – Length of beam, mm
N – failure cycles
r – stress level ratio
t – thickness of beam, mm
V – displacement of component, mm

Greek letters

ρ – density of composite beam, kg/mm^3
σ_{max} – maximum stress, Mpa
ω - circular frequency value
λ – eigen value

Acronyms

ACP – Analysis of composite pre/post
CFRP – Carbon Fiber Reinforced polymers
EDM – Engineering Data Management
FEA – Finite Element Analysis
FEM – Finite Element Methods
FFT – Fast Fourier Transform
GFRP – Glass Fiber Reinforced polymers

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