JOURNAL OF ACOUSTICS AND VIBRATION RESEARCH (JAVR)
ISSN: XXXX-XXXX
VOL. 1, ISSUE 1, 2023, 27 – 40

Damage Detection of Carbon Fibre Reinforced Polymer Cantilever Beam Using Modal Analysis of Structural Vibration

Loo Kai Xen[1], Khairil Anas Md Rezali[1*], Mohd Zuhri Mohamed Yusuf[1] & Azmi Mohammad Hassan[1]

[1]Sound and Vibration Research Group, Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor Darul Ehsan, Malaysia

*Corresponding email: khairilanas@upm.edu.my

ABSTRACT

Research in structural health monitoring is becoming intense because it is used for detecting and preventing failures and damages in structures or systems. The characteristics for detection of failures or damages depends on many factors such as methods of detection, types of material and structures. Carbon fiber composite has become common nowadays, used in many mechanical structures. Carbon fiber composite is light, and strong (high tensile strength per weight) but it is also brittle, thus preventing it from fail before it occurs is needed to be done to make sure it is always in good condition. The aim of this project was to investigate the effect of damage location, severity, and number of damages on the natural frequencies of the carbon fiber composite cantilever beam. The natural frequencies were acquired using vibration modal analysis on the carbon fiber composite cantilever beam. A model of carbon fiber beam was developed in ANSYS with the material defined by the results from a tensile test. The model was then optimized and validated by comparing the natural frequencies of the beam predicted by ANSYS with those acquired experimentally. Once validated, simulations were conducted with artificial damages created in ANSYS based on three common damage parameters which were damage location, severity of damage, and number of damages. It was found that natural frequencies of the beam structure reduced with increasing severity of damage, increasing location distance from the free end of the cantilever beam to the damage position, and increasing the number of damages. It was concluded based on the study that the damage in cantilever beam can be detected through modal analysis of structural vibration including classifying the number of damages, location, and severity. These findings will help industry in planning maintenance, reduce downtime and improve product quality.

Article History

Received: 09/09/2022

Revised: 07/04/2023

Accepted: 16/04/2023

Published: 03/05/2023

Keywords: composite damages; modal analysis; vibration in composite

INTRODUCTION

Typical parameters that one would examine during a vibration exposure on a structure would be the natural frequencies and its mode shapes [1,2,3]. These two parameters can be acquired by conducting a modal analysis of structural vibration. A damage in a composite structure, for example, due to a localized crack or yield, can cause a change in the natural frequencies and its mode shapes [4,5]. This method of damage detection is classified as a highly sensitive non-destructive technique (NDT) and being practiced in the engineering industry. Additionally, this method had become a preferred choice because of its measurement flexibility and reduced cost [6]. The research about this technique is intense because it allows damage to be detected in structures offsite and continuous without having to apply any synthetic damage to the structure and preventing them before failing.

A damage structure is expected to have natural frequencies at a lower frequency than the one without damage [7,8,9]. It is also expected that the displacement or amplitude of the structure during vibration exposure, to be either increased or decreased [7,8,9]. The percentage change in the natural frequencies and its mode shaped of a damage composite structure may be influenced by several factors such as the geometry of the structure [10], the size of damage [10], the location of the damage on the structure [11], the fiber or composite matrix, and the number of delamination [12].

For two structures with the same geometry, the one made of greater modulus of elasticity will produce natural frequencies at a greater frequency than a structure made of lower modulus of elasticity. This is because that the material with greater modulus of elasticity has greater stiffness than the other [13,14]. In the event of damage in a structure, the stiffness of the structure is compromised, and due to this, the natural frequencies will occur at a lower frequency than the undamaged structure. Study conducted previously has found that by imposing 50% reduction of the modulus of elasticity, the reduction in the frequency mimics the reduction in the damaged cantilever beam [7]. Natural frequency shifted by up to 40% for I cross-section beam with 1 damage and over 40% for the same beam with 2 damages [10]. On the other hand, the significant shift in natural frequency is found to be less for rectangular cross-section with natural frequency changes of less than 1.5% regardless the mode of vibration [10].

Damage due to local delaminated composite beams can be detected based on the change in the mode shape [12]. Typically, the composite delamination damage will induce local flexibility, hence the natural frequencies decreased [12]. This behaviour also applied to localized crack composite damage, and natural frequencies tended to decrease with an increase in crack size [16]. The damage location on a plywood can be observed using Mode Shape Squares (MOSS). Furthermore, the location of damage is detected by using Mode 1, Mode 2, or combination of modes for single damage condition (MOSS). On the other hand, the position of damage can also be determine using natural frequency change ratio [7]. A delaminated composite beam will cause change in the natural frequencies at it is expected to occur at high frequencies [17,18]. The difference in the outcomes of those studies indicated that the technique requires more studies in the detection and classifying the damage and this requires large database with comparisons and/between composite variations [19].

Composite beams damage based on the location and size of damage, as well as multiple damage, is detected by using modal curvature-based detection method [20,21,22]. In this method, the damage location can be identified because the composite beams with damages have a decrease in the corresponding bending stiffness at the damage position, with curvature modal difference at this position severely affected [21,23]. By systematically studied the changes in the natural frequencies and mode shapes through modal curvature change rate, the method has shown to be a reliable indicator of varied damage in composite structures [20]. The mutation of curvature mode difference can be used for the detection of presence, location, and size of damage [21,24]. This study was pre-motivated by the findings of previous studies in using modal analysis for structural vibration to detect failures. In many studies mentioned previously, the damage detection can be conducted and found to be a success. However, applying the same method in reality, can be difficult because the damage magnitudes for every case are not quantified systematically. The use of artificial intelligence algorithm such as artificial neural network (ANN) can help this [25,26,27] but the method still requires data to train the algorithm. The data needs to be reliably representing damage cases as suggested previously [19].

The objective of this study was to investigate the effect of location of damage, damage severity, and number of damages on the natural frequencies on the carbon fiber polymer composite cantilever beam using Ansys simulation software. Two experiments were conducted, a tensile test, and a random spectral test, to provide data for the validation of the model in Ansys. Later, damage was applied on the geometry by imposing reduction in modulus of elasticity. Damages applied were based on the location, severity, and number of damages. The effect of damage variables as mentioned, towards changing of natural frequencies is further discussed in this paper.

METHODS

Preparation of specimen

Carbon fiber fabric (BH-T300-3K-P240) with a thickness of 0.33 mm and resin were used to prepare a carbon fiber composite beam. The beam specimen was fabricated using hand lay-up process. The carbon fiber was lay layer-by-layer (about 15 layers), with Isophtalic Resin R-280-P applied in-between using a roller. Once the thickness has been achieved (about 5 mm), a weight was applied on top of the specimen to remove air bubbles trapped during the fabrication process. After curing, the specimen was cut accordingly with final dimension as shown in Table 1.

Table 1. Specimen dimension

Thickness (mm)	Length (mm)	Width (mm)
4.99	705	25.59

A tensile test was conducted on the carbon fiber specimen to determine its tensile properties. The tensile strength was required for the validation study of Ansys Finite Element Model in the later part of this study. The size of the tensile specimen was fabricated according to the ASTM standard, which is dog-bone shape (Figure 1). Samples dimension for tensile test are shown in Table 2.

Table 2. Specimen dimensions

Sample	Width, W (mm)	Thickness (mm)	Area, A (mm^2)
1	12.927	2.90	37.4883
2	14.250	2.98	42.4650

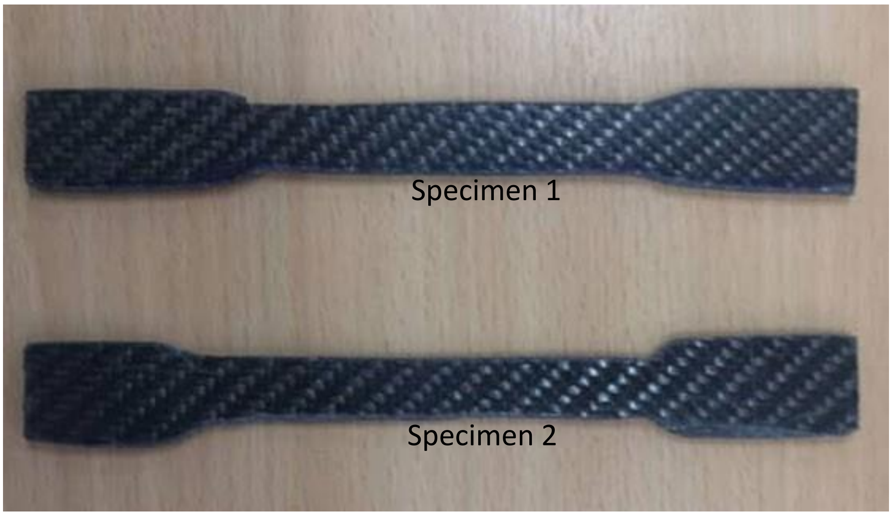

Figure 1. The fabricated test specimen for Tensile Test

The tensile test was conducted using Universal Testing Machine Instron 3382 with a crosshead displacement of 2 mm/min. The Young's modulus and Poisson's ratio for carbon fiber, respectively were calculated by using the formula as follow:

$$\text{Young's Modulus}, E = \frac{FL}{Ae} \tag{1}$$

Where *F* is the tensile force, *L* is the length of the neck of the specimen, *A* is the cross section area at the neck area and *e* is the strain.

$$\text{Poisson's ratio}, \nu = -\frac{\Delta W/W}{\Delta L/L} \tag{2}$$

Where the *w* is the width and *L* is the length of the neck of the specimen.

Random vibration spectral test

Spectral test was conducted on the specimen to acquire the natural frequencies of the beam as shown in Figure 2. The beam was secured on to a vibrator (TIRA TV 51120-M) at one end with the other end is free so as to simulate a cantilever beam setup. An accelerometer (Dytran 3097A2) was placed at the free end of the beam to measure acceleration of the beam. The vibrator is connected to an amplifier and then to a data acquisition box (LMS). A random vibration was then generated by the vibrator. The stimulus has a frequency range of 5 to 300 Hz. The sample was acquired at 4096 Hz with spectral resolution of 0.5 Hz. This experiment was conducted only on undamaged carbon fiber polymer beam.

SIMULATIONS

Model Validation

This study employed Ansys software to carry out the finite element analysis. A carbon fiber beam model was inserted to the software with dimension as in Table 1. The model has fixed boundary condition at one end and free boundary condition at the other end. The element size was set at 2.5 mm. The model was validated using data from experiment explain in Section 2.3 for the undamaged condition.

Damage Application

This study employed damage cases based on location of damage, severity, and number of damages. To do this, the model was divided into 20 points to represent the location on the beam as shown in Figure 3. Each position has a length of about 35 mm.

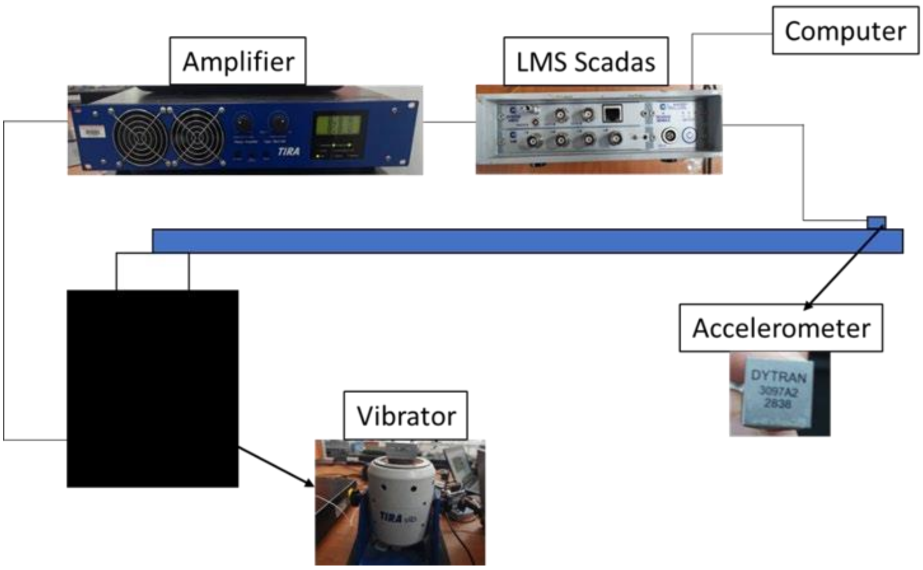

Figure 2. Schematic diagram of the equipment setup for spectral analysis test

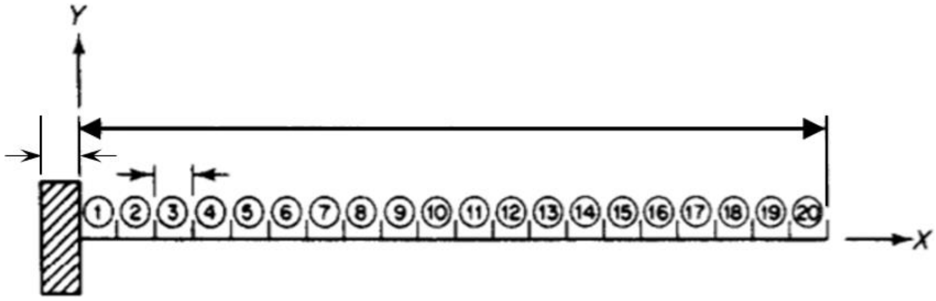

Figure 3. Cantilever beam divided into 20 points to represent location

To simulate the damage, a reduction in the Young's modulus, *E* (as suggested by Tan *et al.,* 2018) was applied on the model at a damage location. Table 3 showed the details of the condition simulated based on damage location (L1-L3), damage severity (S1-S3) and number of damages (N1-N3). Severity at each element was calculated and also shown in the Table 2.

Table 3. Damage variables based on damage location (L1-L3), damage severity (S1-S3) and number of damages (N1-N3).

Damage case	Applied damage				
	Number of damages	Element location 1	Element location 2	Element location 3	Severity at each element (ΔE/E)
Undamaged	-	-	-	-	0
L1	1	5	-	-	-0.5
L2	1	10	-	-	-0.5
L3	1	15	-	-	-0.5
S1	1	10	-	-	-0.25
S2	1	10	-	-	-0.5
S3	1	10	-	-	-0.75
N1	1	15	-	-	-0.5
N2	2	10	15	-	-0.5
N3	3	5	10	15	-0.5

RESULT AND DISCUSSION

Tensile test

Figure 4 shows the tensile test of carbon fiber reinforced polymer composite. As expected, both samples exhibited brittle failure with a similar trend of load-displacement traces. It is observed that Sample 1 (lies at 390 MPa) has greater ultimate tensile strength than Sample 2 (330 MPa) before a sudden drop of stress. This is due to the composite is losing its capability to hold the given loading. Both samples exhibited maximum stress for elasticity at 200 MPa, however they are having a different strain which were at 0.01 and at 0.015 for Samples 1 and 2, respectively. The Young's Modulus and Poisson's ratio for both samples are shown in Table 4 and Table 5. The average Young's Modulus value for the carbon fiber beam was 24.6 GPa while the Poisson's ratio was 0.25. It is observed that the carbon fiber composite facing a catastrophic failure horizontally, which is a common failure for composite material.

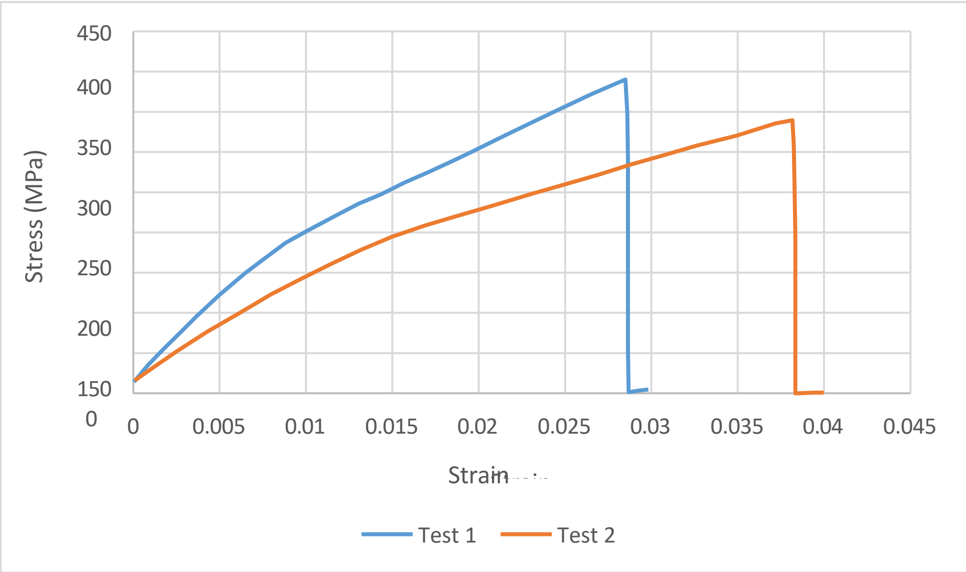

Figure 4. Tensile test of carbon fiber polymer reinforced beam

Table 4. Young's Modulus of Elasticity for both samples.

Sample	Maximum force at linear elasticity, F (N)	Extension at linear elasticity, e (mm)	Young's modulus, *E* (MPa)
1	5174.05	0.62	24307.40
2	4422.37	0.40	25296.16
Mean			24554.09

Table 5. Poisson's ratio of carbon fiber

Sample	Width, W (mm)	ΔW (mm)	Gauge length, L (mm)	ΔL (mm)	Poisson's ratio, ν
1	12.93	-0.09	106.95	3.05	0.24
2	14.25	-0.09	97.58	2.42	0.25
Mean					0.25

Spectral Testing

Figure 5 shows the amplitude and phase of the cantilever beam for the spectral testing of the cantilever beam. It was observed that there were four natural frequencies found which occurred at 7.39 Hz, 43.87 Hz, 134.85 Hz, and 264.16 Hz.

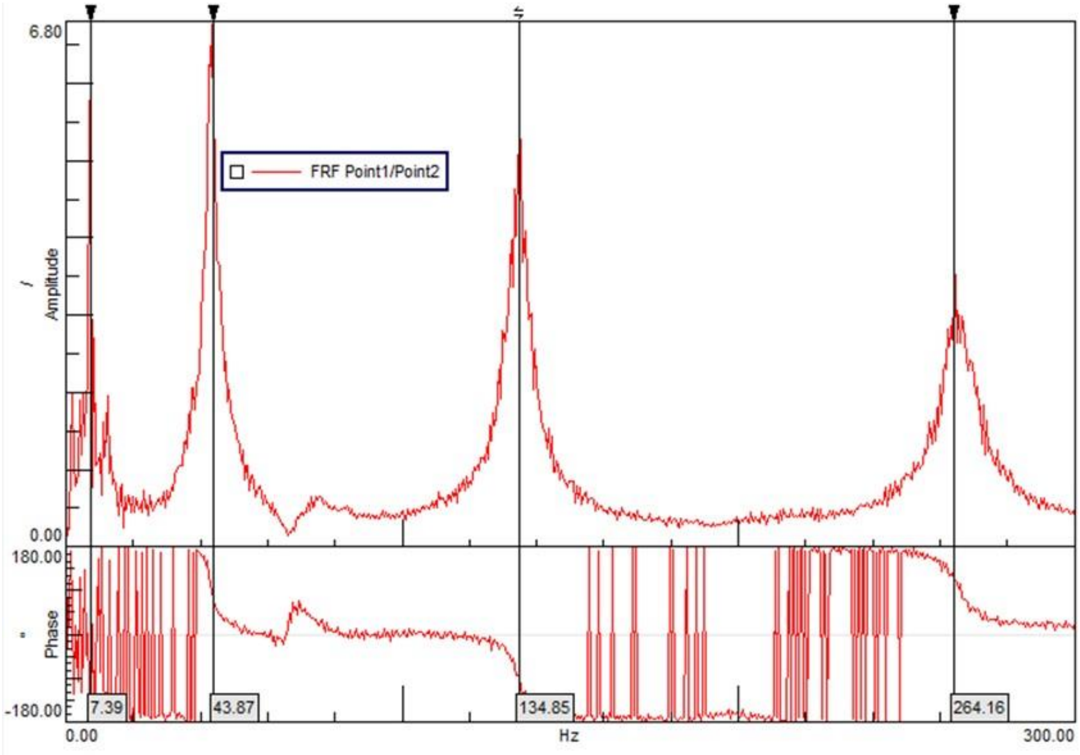

Figure 5. Amplitude and phase versus frequency for the spectral testing of the cantilever beam

Model Validation Test

Model of undamaged cantilever beam was developed and exported to Ansys Software for validation process. The first four modes and natural frequencies were acquired from the simulation. The natural frequencies were compared to the one acquired experimentally and are shown in Table 6. The percentage difference between the natural frequency measured experimentally and simulation was found to be at 1.08%, 4.44%, 4.89%, and 4.9% difference for Mode 1, 2, 3, and 4, respectively. The largest difference of natural frequency occurrence found to be at Mode 4 which has 12.95 Hz difference between experimental and simulation results. Based on the percentage difference in frequency which were less than 5%, the model can be accepted representing the actual beam as suggested by Randy et al., 2013.

Table 6. Natural frequencies of the first four modes for experiment and simulation

Mode number	Natural frequency, f (Hz)		Percentage difference, $\left(\frac{f_s - f_e}{f_e}\right) \times 100$ (%)	Difference in frequency magnitude, $f_s - f_e$ (Hz)
	Experimental, f_e	Simulation, f_s		
1	7.39	7.31	1.08	-0.08
2	43.87	45.82	4.44	1.95
3	134.85	128.25	4.89	-6.60
4	264.16	251.21	4.90	-12.95

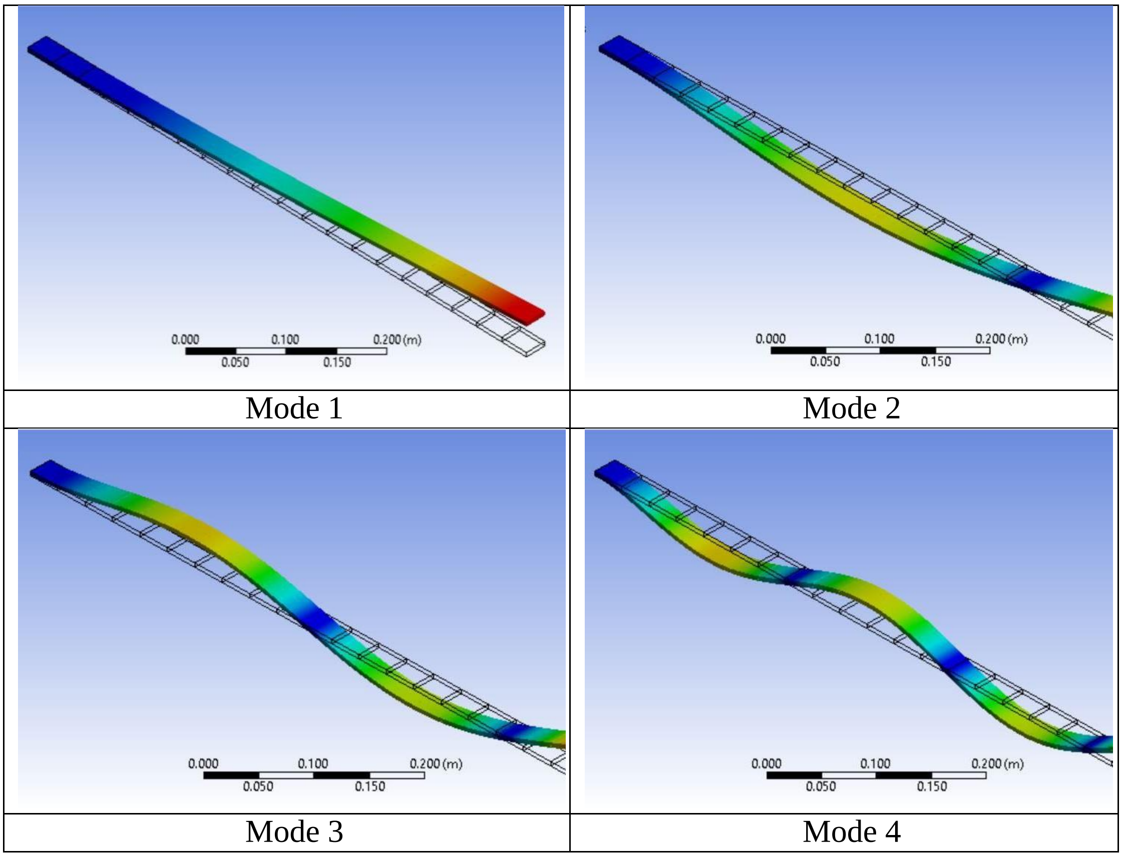

Figure 6. First four mode shapes for undamaged carbon fiber beam

Effects of location of damage on the natural frequencies

The natural frequencies for various damage cases have been obtained and shown in Table 6. It can be observed that as the distance between damage position and the fixed end position of cantilever beam changes, the natural frequency for respective mode changes. The percentage difference between undamaged case and damage case (Table 7) for Mode 1 increased with decreasing distance between the damage position and the fixed end position (also shown in Figure 7). However, for Mode 2, 3, and 4, the percentage changes are either increased or decreased as the distance between the damage position and the fixed end position increased. This finding suggests that if one would like to identify the location of damage along a cantilever beam, the changes in the natural frequency for Mode 1 can provide useful information of the location of damage. The changes can be up to 5% and as low as 0.5% for Mode 1.

Effects of damage severity on the natural frequencies

The simulation predicted that as the severity of the damage increases, the natural frequencies for all four modes decreased (Table 7). However, the largest change in natural frequency was found to be for Mode 2, and followed by Mode 4, 1, and 3 as shown in Figure 8. However, this may be since the damage was applied at the middle of the beam and as shown previously in Section 3.3, Mode 2 of the beam has larger amplitude of displacement in the middle of the beam for undamaged case.

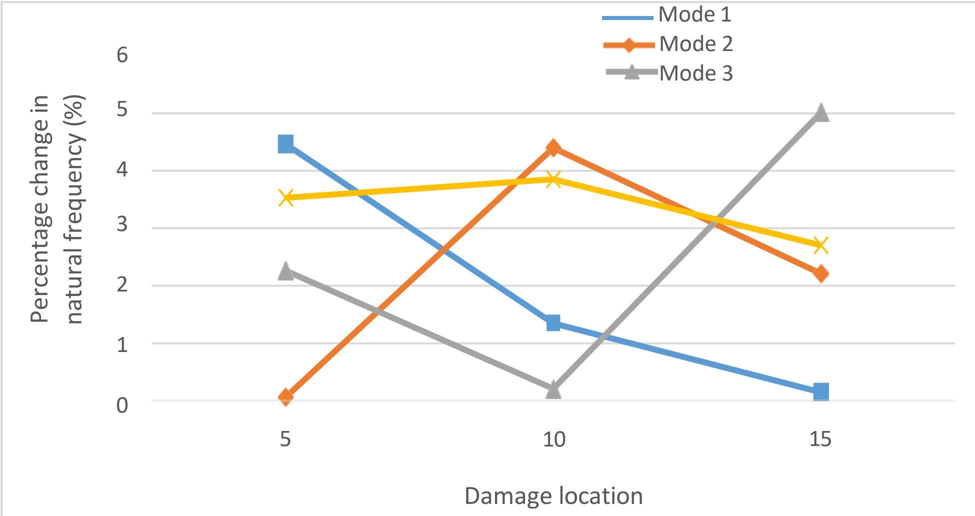

Figure 7. First four mode shapes for undamaged carbon fiber beam

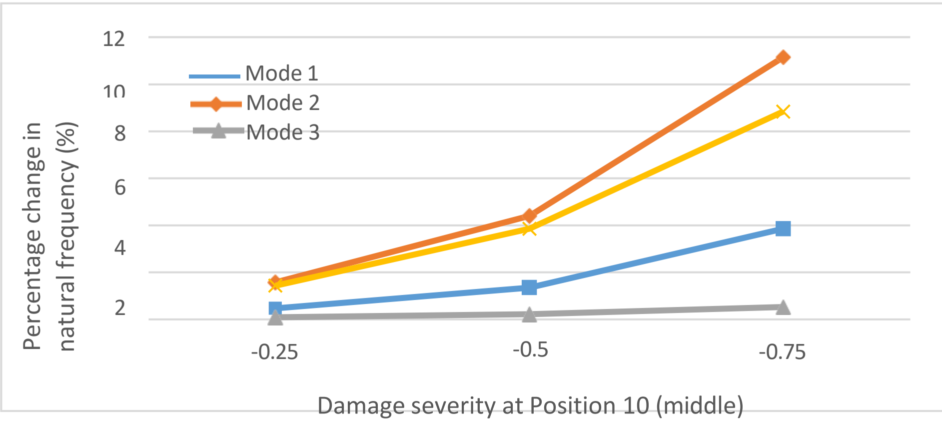

Figure 8. Percentage change in natural frequency based on number of damages

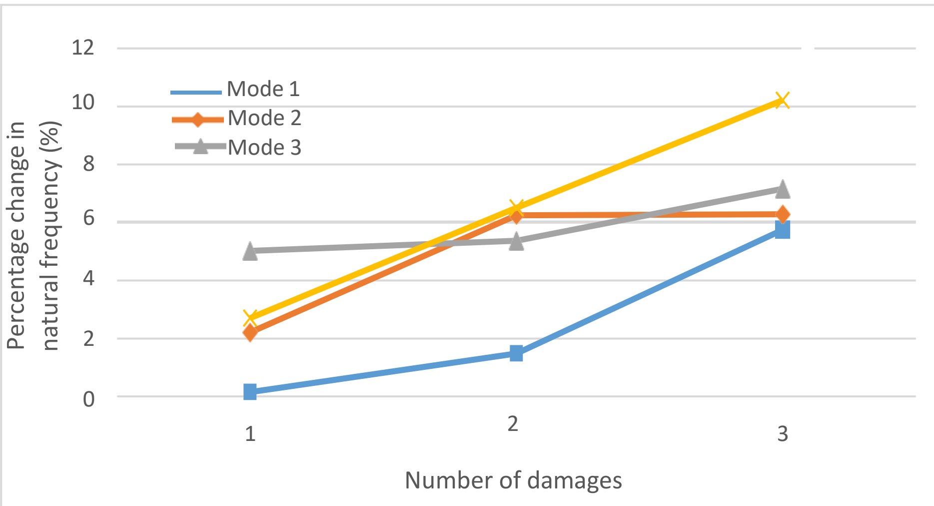

Figure 9. Percentage change in natural frequency based on number of changes

Effects of damage severity on the natural frequencies

Increasing number of damages on a cantilever beam will increase the natural frequency as shown in Table 7. Mode 4 was found to be the most sensitive mode as the number of damages increases (Figure 9).

Table 7. Natural frequencies for 1st mode – 4th mode based on damage cases.

Type of damage	Damage case	Natural frequency, f (Hz) Mode 1	Mode 2	Mode 3	Mode 4
NA	Undamaged	7.3138	45.824	128.27	251.25
Location	L1	6.9874	45.795	125.37	242.38
	L2	7.2150	43.809	128.00	241.57
	L3	7.3027	44.812	121.84	244.45
Severity	S1	7.2795	45.103	128.16	247.64
	S2	7.2150	43.809	128.00	241.57
	S3	7.0317	40.713	127.60	229.03
Number of damages	N1	7.3027	44.812	121.84	244.45
	N2	7.2053	42.962	121.39	234.90
	N3	6.8936	42.947	119.09	225.59

DISCUSSION

The ANSYS simulations were carried out to predict the changes on natural frequencies when damages were introduced. The model was successfully developed with material specifications defined from results of tensile test. The model was then validated with the results from spectral testing.

This study suggests that the best mode in detecting damage based on damage location was Mode 1 even though all modes affect the natural frequencies (Table 8). For a cantilever beam, the mode shape for Mode 1 deflected the most at the free end. The shear stress is larger at position closer to the fixed end compared to the free end. When damage is introduced closer to the fixed end of the beam, the higher stress will produce changes in the natural frequency, larger than the one at the free end of the beam.

Severity of damaged can be detected through modal analysis method. In this study, Mode 2 was found to be the most sensitive with the changes of damage severity. However, as mentioned previously, this could be due to the mode shape for Mode 2 having larger displacement in the middle of the beam compared to other position.

The percentage change in natural frequency for Mode 4 increased linearly with increasing number of damages. As shown in Figure 6, the mode shape for Mode 4 has three large deflection position and the introduction of number of damages of 3 in this study could potentially made the Mode 4 the most reliable mode to detect number of damages.

Table 8. Percentage change of natural frequency based on various damage cases.

Type of damage	Damage case	Element location	Severity at each element ($\Delta E/E$)	Number of damages	Percentage change in natural frequency, $\left(\frac{f_d - f_u}{f_d}\right) \times 100$ (%)			
					Mode 1	Mode 2	Mode 3	Mode 4
Location	L1	5	-0.5	1	4.4628	0.0633	2.2609	3.5303
	L2	10	-0.5	1	1.3509	4.3973	0.2105	3.8527
	L3	15	-0.5	1	0.1518	2.2084	5.0129	2.7065
Severity	S1	10	-0.25	1	0.4690	1.5734	0.0858	1.4368
	S2	10	-0.5	1	1.3509	4.3973	0.2105	3.8527
	S3	10	-0.75	1	3.8571	11.153	0.5223	8.8438
Number of damages	N1	15	-0.5	1	0.1518	2.2084	5.0129	2.7065
	N2	10, 15	-0.5	2	1.4835	6.2456	5.3637	6.5075
	N3	5, 10, 15	-0.5	3	5.7453	6.2784	7.1568	10.213

CONCLUSIONS

All three factors studied which were the location of damage, the severity of damage, and the number of damages can affect the natural frequencies.

For the effects of damage location, the natural frequencies changes as the distance of damage from the damage position to fixed end position changes. However, it was found that Mode 1 can provide better detection of damage location because the natural frequencies occurred at lower frequencies than the undamaged one.

For the effects of severity of damage, all modes detected larger percentage change in natural frequency with larger damage severity. Mode 2 was found to be the most sensitive mode when the damage position was at the middle of the beam.

For the effects of number of damages, the natural frequencies were found to be most sensitive in Mode 4 with respect to the increase in the number of damages.

REFERENCES

[1] Cawley, P., and Adams, R. D. “A vibration technique for non-destructive testing of fibre composite structures”. Journal of Composite Materials. 13(2), 161–175 (1979).

[2] Rucevskis, S., Janeliukstis, R., Akishin, P., and Chate, A. “Mode shape-based damage detection in plate structure without baseline data.” Struct. Control Health Monit., 23: 1180– 1193.

[3] Negru, I., et al. "Natural frequency changes due to damage in composite beams." Journal of Physics: Conference Series. Vol. 628. No. 1. IOP Publishing, (2015).

[4] Fan, W., & Qiao, P. “Vibration-based Damage Identification Methods: A Review and Comparative Study.” Structural Health Monitoring, 10(1), 83–111 (2011).

[5] Ravi Prakash Babu, K.; Raghu Kumar, B.; Narayana, K.L.; Mallikarjuna Rao, K. “Multiple crack detection inbeams from the differences in curvature mode shapes.” J. Eng. Appl. Sci. 10, 1701–1710 (2015).
[6] Huiwen Hu, Bor-Tsuen Wang, Cheng-Hsin Lee, Jing-Shiang Su, “Damage detection of surface cracks in composite laminates using modal analysis and strain energy method.” Composite Structures, 74-4, (2006)
[7] Pandey, A. K., Biswas, M., and Samman, M. M. “Damage detection from changes in curvature mode shapes”, Journal of Sound and Vibration. 145(2), 321–332 (1991).
[8] Kim, J.T., Ryu, Y.S., Cho, H.M., and Stubbs, N. “Damage identification in beam- type structures: frequency-based method vs mode-shape-based method”. Engineering Structures. 25(1), 57–67 (2003).
[9] Fan, W. and Qiao, P. “Vibration-based damage identification methods: a review and comparative study”. Structural Health Monitoring: An International Journal. 10(1), 83–111 (2010).
[10] Praisach Z., Gillich, G. R., and Birdeanu E. D. “Considerations on natural frequency changes in damaged cantilever beams using FEM.” Latest Trends on Engineering Mechanics, Structures, Engineering Geology. 214-219 (2010)
[11] Tracy J. J., Pardoen G. C. “Effect of delamination on the natural frequencies of composite laminates.” Journal of Composite Material. 23, 1200–15 (1989).
[12] Shen M. H. H., Grady J. E. “Free vibration of delaminated beams.” AIAA J 30, 1361–70 (1992).
[13] Altintas, Gökhan. Effect of Material Properties on Vibrations of Nonsymmetrical Axially Loaded Thin-Walled Euler-Bernoulli Beams. Mathematical and Computational Applications Vol. 15, no. 1, p. 96–107 (2010).
[14] Dominick Rosato, Donald Rosato, “3 - Design Parameter, Plastics Engineered Product Design,” Elsevier Science, 161-197 (2003).
[15] R.M. Gadelrab, “The Effect of Delamination nn the Natural Frequencies of a Laminated Composite Beam,” Journal of Sound and Vibration, 197-3, (1996)
[16] Missoum Lakhdar, Djermane Mohammed, Labbaci Boudjemâa, Abdeldjebar Rabiâ, Moudden Bachir, Damages Detection in a Composite Structure by Vibration Analysis, Energy Procedia, 36, (2013)
[17] Diaz Valdes, S. H., and Soutis, C. “Delamination detection in composite laminates from variations of their modal characteristics.” Journal of Sound and Vibration. 228(1), 1–9 (1999).
[18] Pardoen GC. “Effect of Delamination on the Natural Frequencies of Composite Laminates.” Journal of Composite Materials.;23(12):1200-1215 (1989).
[19] Zou Y., Tong L., Steven G. P. “Vibration-based model dependent damage (delamination) identification and health monitoring for composite structures. A review.” Journal of Sound and Vibration. 2, 357–78 (2000).
[20] Dawari V. B., and Vesmawala G.R. “Modal Curvature and Modal Flexibility Methods for Honeycomb Damage Identification in Reinforced Concrete Beams. Procedia Engineering.” 51, 119-124 (2013)
[21] Meihong H., Tao Y., and Yu D. “Non-destructive identification of composite beams damage based on the curvature mode difference.” Composite Structures 176: 178- 18 (2017).

[22] Govindasamy M, Kamalakannan G, Kesavan C, Meenashisundaram GK. “Damage Detection in Glass/Epoxy Laminated Composite Plates Using Modal Curvature for Structural Health Monitoring Applications.”, Journal of Composites Science, 4(4):185 (2020).

[23] Hamey, Cole S., et al. "Experimental damage identification of carbon/epoxy composite beams using curvature mode shapes." Structural Health Monitoring, 333-353.3.4 (2004)

[24] Pooya S. M. H., Ali Massumi. “A novel and efficient method for damage detection in beam-like structures solely based on damaged structure data and using mode shape curvature estimation.” Applied Mathematical Modelling. 91, 670-694 (2021).

[25] Okafor A. C., Chandrashekhara K, Jiang Y. P. “Delamination prediction in composite beams with built-in piezoelectric devices using modal analysis and neural network.” Smart Materials and Structures. 5:338 (1996).

[26] B.J, M., & M.R, P. (2021). Damage detection and classification for sandwich composites using machine learning. Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2021.10.088"

[27] Bao, X., Wang, Z., Fu, D., Shi, C., Iglesias, G., Cui, H., & Sun, Z. (2022). Machine learning methods for damage detection of thermoplastic composite pipes under noise conditions. Ocean Engineering, 248(February),110817. https://doi.org/10.1016/j.oceaneng.2022.110817