Journal of Solid and Fluid Mechanics (JSFM), 14(5): 1-5, 2025

Shahrood University of Technology

Journal of Solid and Fluid Mechanics (JSFM)

DOI: 10.22044/jsfm.2025.14931.3884

Manufacturing Engineering of Iran

Fractography and Non-Destructive evaluation of fatigue damage in GFRP composites using natural frequency

Pouya Valizadeh[1], Ahad Zabett[2,*], Jalil Rezaeepazhand

[1] Ph.D. Student, Ferdowsi University of Mashhad, Sun Air Research Institue, Department of Mats. Sci. and Eng., Mashhad, Iran
[2] Assoc. Prof., Ferdowsi University of Mashhad, Sun Air Research Institue, Department of Mats. Sci. and Eng, Mashhad, Iran
[3] Prof., Ferdowsi University of Mashhad, Smart and Composite Structures Lab, Department of Mech. Eng., Mashhad, Iran

*Corresponding author: Ahad Zabett – Email: ahad@um.ac.ir

Received: 08/19/2024 Revised: 09/07/2024 Accepted: 10/2026/2024

Abstract

Residual strength is considered as an indicator of damage accumulation and used in life prediction models. The relation between the residual strength and the modal parameters has been studied and reported. Results showed that with damage accumulation over fatigue cycling, a 20% decrease in residual strength (from 415 to 330MPa) corresponded to a 12% decrease in natural frequency (from 30.5 to 27 Hz). Fracture surfaces of fatigued specimens showed different failure micro-mechanisms for different maximum fatigue stress levels. The first mode of natural frequency not only followed the changes of residual strength with damage accumulation but also could reflect the structural changes and alteration of failure micro-mechanisms at different stress levels. This paper focuses on how varying fatigue stress levels affect the failure micro-mechanisms and the relationship between these damages, residual strength and natural frequency. At lower maximum stress levels, more failure micro-mechanisms were activated and the changes in the first mode of natural frequency were more pronounced. This suggests that natural frequency is sensitive enough to detect different fatigue micro-mechanisms and could be used as a non-destructive parameter for fatigue damage assessment.

Keywords: Fatigue damage; Fractography, Fiber-reinforced Polymer Composite, Natural Frequency; Residual Strength.

1. Introduction

Fatigue is a primary cause of unexpected failure in components under mechanical loading. Wind turbine rotor blades are subjected to both static and dynamic loads from wind and gravity and are particularly vulnerable to fatigue damage [1,2]. Given the high production costs and the severe consequences of premature failure, ensuring operational reliability by predicting the life of these blades is critical [3]. Recent researches have been increasingly focused on developing analytical and numerical models to predict fatigue life in composite structures, aiming to reduce experimental testing and costs. One widely used approach for predicting fatigue damage in wind turbine blades is based on residual strength [4], which monitors the reduction in ultimate tensile strength to estimate remaining life. Broutman and Sahu (1972) [5] introduced a linear strength degradation model, later validated by Wahl [6], demonstrating that both linear and nonlinear models provide more accurate fatigue life predictions compared to traditional methods.

A variety of non-destructive damage detection methods (many of which are based on modal responses) have been coupled with destructive fatigue tests to provide more reliable and cost-effective life prediction models. In these approaches, changes in modal parameters are often linked to stiffness degradation, allowing for damage zone detection using response history tables [7]. Gibson [8] introduced modal testing for evaluating the mechanical properties of composite materials. Moreover, changes in modal parameters, such as natural frequencies and damping ratios, have been used as indicators of fatigue damage in composites. Some recent studies [9-18] have used modal analysis for damage detection. Changes in modal parameters, such as natural frequencies and damping ratios, are often correlated with structural stiffness reduction and are used to predict the location and extent of fatigue damage. Modal testing offers a fast and cost-effective way to assess the mechanical properties of composite materials during design and manufacturing.

To date, no studies have investigated the prediction of residual strength during fatigue loading using modal parameters, such as natural frequency and damping ratio, for cross-ply GFRP laminates. In this study, glass fiber-reinforced polymer (GFRP) composites were subjected to fractographic analysis at high and low stress levels of fatigue loading. Dynamic mechanical thermal analysis (DMTA) was used to estimate the glass transition temperature and assess the viscoelastic properties of the samples. Modal tests were conducted before and after fatigue loading, with fatigue damage expressed as a percentage of fatigue life. A significant correlation was found between residual strength, fatigue damage, and changes in natural frequency, offering new insights into fatigue life prediction in composite materials.

2. Materials and experiments:

2.1. Materials and fabrication:

E-glass stitched fabrics of 0° and 90° orientations, with a layer thickness of 0.3 mm were used. These fabrics were impregnated with a very low-viscosity epoxy resin, Axson Technologies EPOWIND® EPOLAM 2040, mixed with EPOLAM 2047 hardener with a ratio of 100:32, suitable for the vacuum infusion process. Laminates with dimensions of 500 × 500 × 2.1 mm³ and a stacking sequence of $[0/90]_7$ were fabricated using the Vacuum Assisted Resin Transfer Molding (VARTM) process at Sun Air Research Institute, Ferdowsi University of Mashhad.

2.2 Modal Analysis

Modal analysis was conducted employing a data acquisition system with Fast Fourier Transform analyzing software on residual strength rectangular samples according to ASTM D3479 [19]. The modal test was conducted using an impact hammer (TL-IH01-0.2KN) as a source of excitation equipped with a force transducer. The impact was applied on the opposite side of the accelerometer using a light vibration accelerometer, GT-AP2037 and the vibration responses were collected. The responses of both the accelerometer and hammer were measured and analyzed for 5 excitation repeats. All data were analyzed with ME scope VES/v5.1 software with a multi-channel signal analyzer. FRF was plotted and the first mode of modal parameters was extracted.

The modal analyses were performed twice on each sample. First-run modal analysis was conducted on all residual strength samples before the CA fatigue test. Second-run modal analysis was performed on the residual strength specimens after a specified number of fatigue cycles. To do this, the fatigue test was interrupted and the sample was subjected to modal analysis with the same conditions as the first-run modal analysis. The excitation point and the location of the vibration transducer were marked in the first-run test and employed for the best results in the second-run measurement.

2.3 Residual Strength Tests

Residual strength tests were performed to determine the tensile strength of materials after a given number of load cycles, quantifying the effect of fatigue damage according to ASTM D3479 [19] at a stress ratio (R) of 0.1 and test frequency of 8 Hz based on GL recommendations [20] for a given number of cycles, then the fatigue test is interrupted and the static tensile test is performed on the cycled sample. Fatigue tests were performed at two stress levels of 55% and 43% of the ultimate tensile strength. The residual strength test was then conducted at various fatigue loading stress levels, corresponding to 5%, 10%, 15%, 20%, 35%, 50%, and 70% of the sample's fatigue life. To estimate the life of material at any stress the SN curve obtained from a previous study by the authors [21] was used.

2.4 Fractography:

Fractography of the composite fatigued samples was done by a Leo-1450 VP scanning electron microscope.

2.5 Dynamic Mechanical Thermal Analysis (DMTA):

Dynamic mechanical thermal analysis was conducted to estimate the glass transition temperature (Tg) and assess the viscoelastic properties of the material according to ASTM D7028 [22] using a DMA-Tritron, Triton 2000.

3. Discussion and results:

The experimental results demonstrated that key physical and mechanical properties, including fiber density, void content, tensile strength, and the SN curve (fatigue behavior) of the composite sheets, were accurately measured and reported [21]. Fracture surface analysis after fatigue loading at high and low stress levels showed minimal void content, consistent with the GL standard [23], confirming the quality of the manufacturing process.

Microstructural analysis by SEM revealed that at the higher stress fatigued samples, fiber breakage was the dominant failure mechanism, while at the lower stress fatigued samples, matrix cracking and fiber pull-out were more evident. The observations are consistent with fatigue damage mechanisms described by Reifsnider's theory [24], indicating that at lower stress levels, more complex failure modes, such as fiber-matrix debonding and delamination, had time to develop.

In the fatigue tests, the low heat transfer rate of the GFRP composites causes a temperature raise at higher loading frequencies. Local temperature increase could affect the fatigue behavior and lead to early failure. Dynamic mechanical thermal analysis (Figure 1) identified the glass transition temperature (Tg) at 80.8°C, with no significant creep damage below 60°C. Thus, fatigue damage was the primary factor influencing results, and the modal and residual strength tests were not affected by temperature, at which the tests were performed.

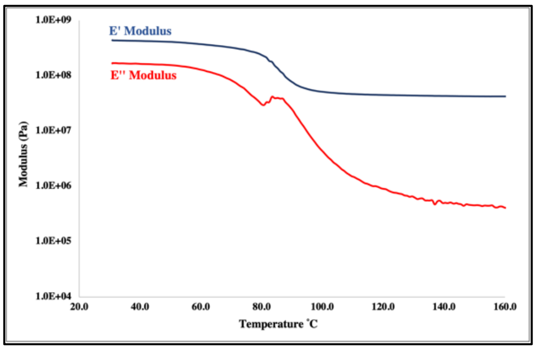

Figure 1 - Dynamic mechanical thermal analysis of GFRP including the storage and loss modulus.

The results of the first mode's natural frequency and damping ratio from the modal tests, along with residual strength data are shown in Figure 2 and 3. Comparing the effect of fatigue damage on natural frequency and damping ratio at two stress levels: 55% (high stress) and 43% (low stress) of tensile strength (Figure 4), no significant changes were observed in natural frequency at 55% stress, but at 43%, both the median and mean natural frequency increase as the number of cycles decreases. This suggests that natural frequency is more sensitive to fatigue damage at lower stress levels (higher number of cycles), while at higher stress levels (fewer number of cycles), these changes are not noticeable.

The fractography supports the finding of modal analysis, showing diverse failure micro-mechanisms at lower stress levels, where natural frequency changes are more pronounced. Thus, natural frequency can serve as a non-destructive indicator of fatigue damage. However, no significant trend was observed in the damping ratio for either stress level. Cao et al. [25] and Tournour et al. [26] identified damping percentage as a highly sensitive indicator of structural damage in materials. However, our research did not find a significant correlation between damping ratios and the fatigue properties. The effect of fatigue damage at different stress levels on residual strength was compared. The results show that residual strength decreases as fatigue damage increases for both stress levels, while data variability also increases.

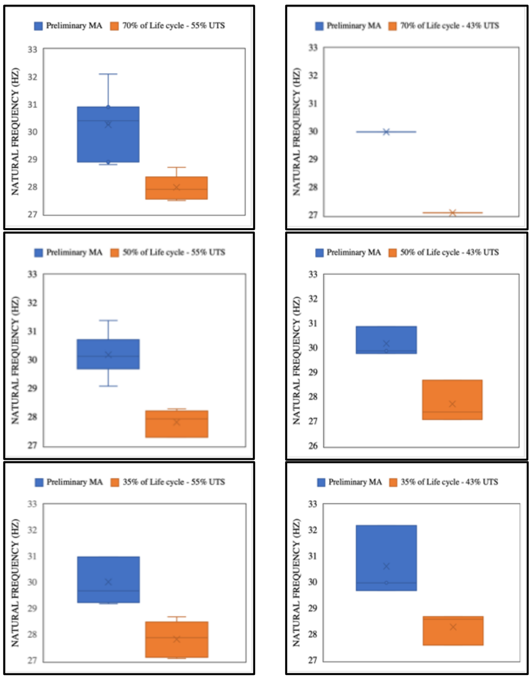

Figure 2- Natural frequency variation before and after fatigue damage at two fatigue stress levels of 55 and 43%.

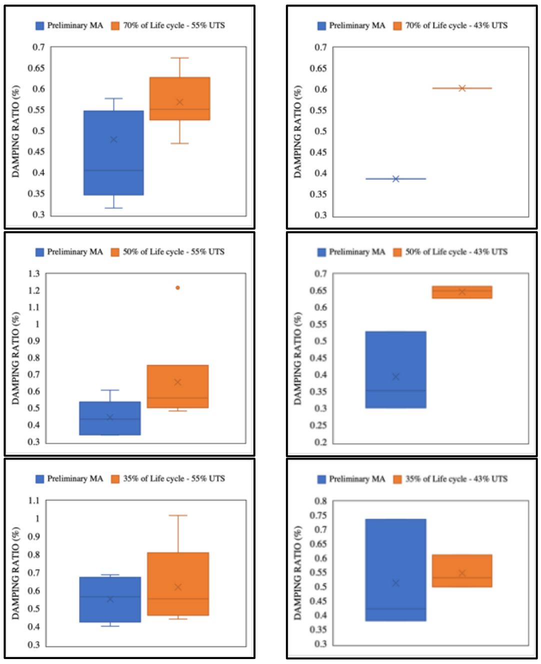

Figure 3- Damping ratio (%) variation before and after fatigue damage at two fatigue stress levels of 55 and 43%.

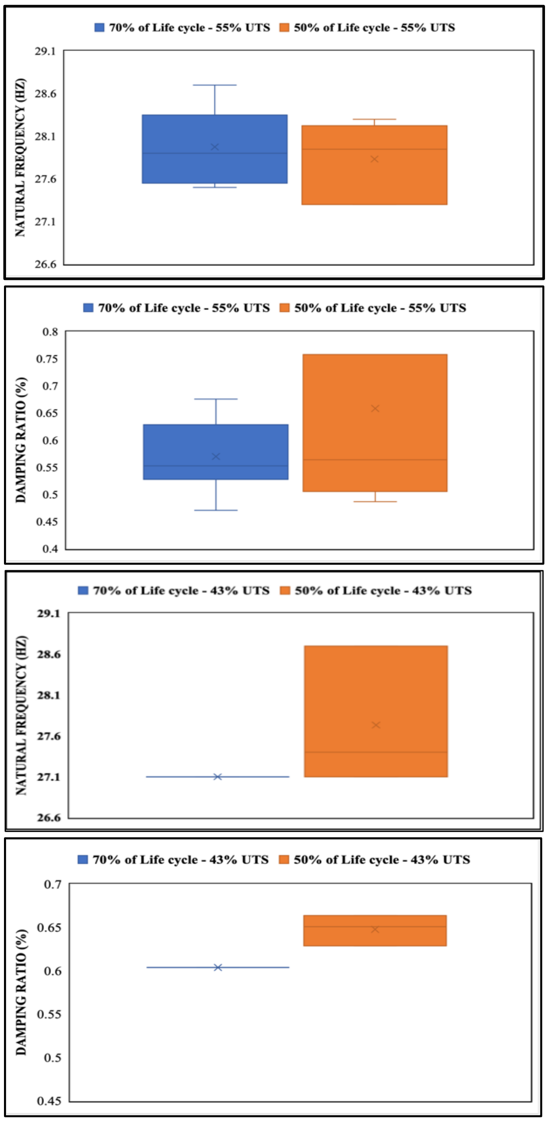

Figure 4 – Modal analysis of samples at two fatigue stress levels for two different fatigue life.

The reduction in residual strength, natural frequency, and damping ratio with fatigue damage at early stage of life is attributed to matrix and fiber/ matrix interface properties like matrix micro cracking, delamination and fiber/ matrix debonding. A clear decreasing relationship between the residual strength and the natural frequency, as shown in Figure 5, suggests that natural frequency can be used as a non-destructive indicator of fatigue damage as proposed by Gibson [27].

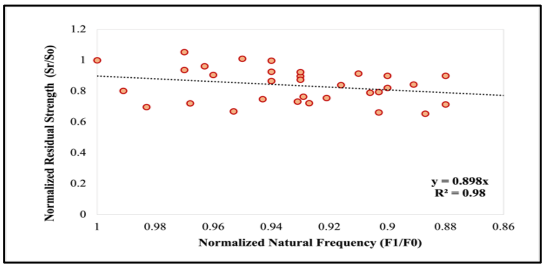

Figure 5 - Normalized natural frequency versus normalized residual strength.

4. Conclusions

- Low-stress fatigue resulted in more distinct damage micro-mechanism damages compared to high-stress fatigue.
- Dynamic thermomechanical analysis showed that the reduction in mechanical properties was not due to the viscoelastic behavior of the composite matrix in the performed experimental condition.
- Decreasing correlation of natural frequency with fatigue damage at low-stress fatigue levels was statistically significant, making it a reliable non-destructive indicator. The damping ratio did not show a meaningful correlation with damage.
- A clear decreasing relationship between relative residual strength and relative natural frequency was observed, with a 20% drop in residual strength corresponding to a 12% reduction in natural frequency.

5. References

[1] Yang B, Sun D (2013) Testing inspecting and monitoring technologies for wind turbine blades: *A survey*. *Renew Sustain Energy* Rev 22:515-526.

[2] Kong C, Taekhyun Kim DH, Sugiyama Y (2006) Investigation of faitigue life for a medium scale composite wind turbine blade. *Int. J. Fatigue* 28:1382-1388.

[3] Lio Y, Mahadevan S (2005) Probabilistic fatigue life prediction of unidirectional composite laminates. *Compos Struct* 69:11-19.

[4] Westphal T, Nijssen RPL (2014) Fatigue life prediction and strength degredation of wind turbine rotor blade composites: Validation of constant amplitude formulations with variable amplitude experiments. *J Physics: Conference Series* 555.

[5] Tsai SW (2012) Composite Materials: Testing and Design. Editor: *ASTM STP* 497.

[6] Wahl NK (2001) Spectrum fatigue lifetime and residual strength for fiberglass laminates. *PhD Thesis*. Montana state university.

[7] Stinchomb WW (1986) Nondestructive evalution of damage accumulation processes in composite laminates. *Compos Sci Technol* 17:343-351.

[8] Ronald F Gibson (2000) Modal vibration response mesurements for characterization of composite materials and structures. *Compos Sci Technol* 60:2769-2780.

[9] Purekar Ashish S, Lakshmanan Kodanate A, Pines Darryll J (1998) Detecting delamination damage in composite rotorcraft flexbeams using the local wave response. *Proceedings of the SPIE* 3329. 523-535.

[10] Valdes SHD, Soutis SC (1999) Delamination detection in composite laminates from variations of their modal charactristics. *J Sound Vib* 228:1-9.

[11] Rotem A (1988) Residual strength after fatigue loading. Int *J Fatigue* 10:27-31.

[12] Bedewi NE, Kung DN (1997) Effect of fatigue loading on the modal properties of composite structures and its utilization. *Compos Struct* 37:357-361.

[13] Zou L, Tong L, Steven GP (2000) Vibration-based model-dependent damage (delamination) identification and health monitoring for composite structures—a review. *J Sound Vib* 23:357-378.

[14] Kim H (2003) Vibration-based damage identification using reconstructed FRFs in composite structure. *J Sound Vib* 259:1131-1146.

[15] Kessler SS, Spearing SM, Atalla MJ, Cesnik CES, Soutis C (2002) Damage detection in composite materials using frequency response method. *Compos part B* 33:87-95.

[16] Moon TC, Kim HY, Hwang Wb (2003) Natural frequency reduction model for matrix dominated fatigue damage of composite laminates. *Compos Struct* 62:19-26.

[17] Damir AN, Elkhatib A, Nassef G (2007) Prediction of fatigue life using modal analysis for grey and ductile cast iron. *Int J Fatigue* 29:499-507.

[18] Abo-Elkhier M, Hamada AA, El-Deen AB (2014) Prediction of fatigue life of glass fiber reinforced polyster composites using modal testing. *Int J Fatigue* 69:28-35.

[19] ASTM D3479/ D3479M (2002) Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials. *West Conshohocken: ASTM International.*

[20] Roundi W, Mahi AE, Ghar AE (2017) Experimental and numerical investigation of the effects of stacking sequence and stress ratio on fatigue damage of glass/epoxy composites. *Compos Part B: Engineering* 109:64-71.

[21] Valizadeh P, Zabett A, Rezaeepazhand J (2024) Investigating the relationship between natural frequency and residual strength and stiffness of cross-ply laminate under cyclic loading. *Polym int*. online (DOI 10.1002/pi.6682).

[22] ASTM D7028 (2015) Standard Test Method for Glass Transition Temperature (DMA Tg) of Polymer Matrix Composites by Dynamic Mechanical Analysis (DMA). *West Conshohocken: ASTM International.*

[24] Reifsnider KL (1990) Damage and Damage Mechanics in Fatigue of Composite Material. *Edn. Elsevier* B.V. 11-77.

[25] Cao MS, Sha GG, Gao YF, Ostachowicz W (2017) Structural damage identification using damping: a compendium of uses and features. *Smart Materials and Structures* 26:1-14.

[26] Tournour M, Treviso A, Genechten BV, Mundo D (2015) Damping in composite materials: properties and models. *Composites Part B* 78:144-152.

[27] Gibson RF (2000) Modal vibration response measurements for characterization of composite materials and structures. *Compos Sci Tech* 60:2769-2780.