Fatigue life prediction of CFRP composites in plane bending by modal analysis

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Abstract. This is investigation of the fatigue behaviour of carbon fiber reinforced polymer laminates under various angles of deflections of cantilever beam in bidirectional (R=-1) plane bending. The Unidirectional 45\degree carbon fiber oriented CFRP composite were tested at different cantilever bending angles at frequency of 8 Hz. The non- destructive modal testing is conducted to evaluate reduction in structural stiffness in fully reversed plane bending in terms of natural frequency. The modal test at specific intervals is conducted by interrupting the fatigue test. The curve fitting technique for prediction of fatigue life over experimental analysis is used to formulate behaviour of CFRP in plane bending fatigue. It is shown that A Non-destructive Testing method (Modal Test) can be applied for the fatigue life estimation of CFRP laminates. The natural frequency reduction model is able to represent the overall reduction in stiffness due to fully reversed plane bending fatigue.

1. Introduction

Carbon Fiber Reinforced Polymer (CFRP) has various applications in aerospace, aeronautical, automobiles and sports goods due to their comparatively high strength, low specific weight and varieties in the types as per the applications than polymers, metals, alloys and foams etc. During its service life, it is subjected to different types of fatigue loading, especially plane bending fatigue failure occurs often. The fatigue performance of CFRP composites is still a big concern. A. Mohamed Ansar et al. [1] presented work on fatigue analysis of both aluminium and glass fiber reinforced composite material under vibrating or oscillating bending force. B. M. Faisal et al. [2] estimated the mechanical static and dynamic properties like S-N curve and fatigue limit of aluminium alloy and fiber glass-polyester composite material under static and fully reverse bending dynamic test (R= -1) and he found that the life cycles are significantly less for glass polyester composite than that for aluminium alloy at the same applied stress level. Bryan Harris [3] claimed that the fatigue phenomenon in composites is quite a complex one and need to be investigated for different parameters such as fibre orientation, thickness, type of fibre, matric etc. M. Abo-Elkhier et al. [4] investigated the capability of experimental modal analysis to characterize and quantify the fatigue behaviour and to determine modal parameters of glass fiber reinforced polyester laminated composite cantilevered beam by interrupting Plane bending fatigue tests at different fatigue life ratios (n/N\textsubscript{f}). Also curve fitting technique was used to correlate modal parameters to fatigue life. The value of damping ratio is more noticeable than the value of frequency. The extent of fatigue damage determines the damping ratio which indicates the fatigue life ratio at lower mode. T.ae-Chul Moon et al. [10] proposed the natural frequency reduction model for the composite laminates with matrix dominated fatigue damage. A
flexural stiffness reduction model was also suggested for estimation of residual flexural properties. Farhad Adel et al. [11] applied modal testing for analysing the dynamic behaviour of hybrid composite/aluminium joints. A. N. Damir et al. [12] used the modal analysis for prediction of fatigue life of gray and ductile cast iron in rotating bending fatigue. Rui-Jie Wang et al. [13] estimated the fatigue damage for spot welded joints in terms of changes in natural frequency. It is seen that the natural frequency reduction model is a better technique for fatigue life estimation to present the overall stiffness reduction model. M M Shokrieh et al. [5] studied the effect of adding graphene nanoplatelets on mechanical properties of epoxy resin under flexural bending stress at displacement-controlled bending loading and different displacement amplitudes at room temperature. He observed the improvement in fatigue life of epoxy resin by addition of graphene nanoplatelets. P. K. Dash et al. [6] investigated that the residual strength of the cyclic stressed bidirectional CFRP produced significant stress reduction with respect to increased number of cycles and increased value of cyclic stress. Pritam. V. Kulkarni et al. [7] presented work on the development of fatigue testing set up for the fatigue life estimation of CFRP in plane bending with different orientation (0-degree, 45 degree and 90 degree) and suggested modal testing (NDT) for estimation of fatigue life. Raif Sakin et al. [8] tested aluminium alloys with different rolling direction to obtain tensile and fatigue characteristics at high and low cycle fatigue region by static and deflection-controlled plane-bending fatigue tests under fully reversed loading. H. Dong et al. [9] studied non-linear degradation in both the strength and stiffness through residual strength and stiffness models by fatigue theory to predict the fatigue life, residual strength and residual failure envelope of fibre reinforced composite laminates under multidirectional loadings.

In this paper the application of Non-destructive modal testing is analysed to predict fatigue life of CFRP composites under fully reversed plane bending fatigue (R= -1). The plane bending fatigue test interrupted by modal tests (Bump test) is conducted to analyse the behaviour of CFRP composites under bidirectional fatigue loading. An experimental Modal analysis is conducted to study modal parameters of cantilever structure under plane bending fatigue cycles. The reduction in stiffness of cantilever structure in terms of natural frequency is studied and a fatigue life prediction model is presented.

2. Experimental Analysis

2.1. Material Properties

The unidirectional 45° carbon fiber oriented T700/ HY3544 carbon/epoxy resin composite laminates is used. The material properties in GPa of selected CFRP are shown in table 1. The specimens for static flexure and tensile testing were prepared according to ASTM D 7264 and D 3039 respectively.

Table 1. Material Properties of CFRP

| E_{11} | E_{22} | E_{33} | G_{12} | G_{13} | G_{23} | \nu_{12} | \nu_{13} | \nu_{23} |
|-------|-------|-------|-------|-------|-------|--------|--------|--------|
| 123   | 8.3   | 8.3   | 4.8   | 4.8   | 2.84  | 0.3    | 0.3    | 0.46   |

2.2. Static tensile testing

Static tensile and three points bending flexural test is conducted on UTM. There are five specimens were tested to obtain peak load, ultimate strength, maximum displacement and deflection of CFRP under tensile and flexure loading as shown in table 2.

Table 2. Static Test Results of 45° CFRP

| Test | Thickness (mm) | Width (mm) | CS Area (mm²) | Peak Load (N) | Ultimate Strength (N/mm²) | Maximum Displacement (mm) | Maximum Deflection (mm) |
|------|----------------|------------|---------------|---------------|---------------------------|---------------------------|-------------------------|
|      |                |            |               |               |                           |                           |                         |
2.3. Plane bending fatigue test

The dog bone shaped test specimens were prepared as per the guidance given by Japanese standard, JIS Z2275. The dimensions of the specimen in mm are shown in figure 1.

![Figure 1. Test specimen](image1)

The fully reversible plane bending fatigue test was carried out on plane bending fatigue test machine at stress ratio R = -1 and frequency of 8Hz on 45° fibre orientated CFRP laminates as shown in figure 2. There are five test specimen were tested at ±8°, ±10° and ±12° of angle of bending to obtain reduction in strength of cantilever structure.

![Figure 2. Plane bending Fatigue testing machine](image2)

2.4. Modal test

The modal test was carried out by interrupting fatigue test at specific number of cycles (n) to obtain frequency response i.e. Natural Frequency ($f_n$). The figure 3 shows experimental setup for this test. The FFT analyser and instrumented impact hammer (Piezoelectric sensor) was used to obtain natural frequency of test specimen at each stage of fatigue test. Five test specimens were tested for each level as shown in figure 4.

![Figure 3. Modal Testing Setup](image3)
3. Results and Discussions

3.1. Stiffness reduction model

Fatigue tests were conducted up to $10^6$ numbers of cycles ($N_f$) at constant angle of bending and reduction in stiffness at each specified number of cycles was obtained. Five specimens were tested at each bending angle. The results are shown in table 3. The percent reduction in stiffness shows failure of specimen. Failure of Work piece at 12° of bending angle at 400000 numbers of cycles is shown in figure 5. The plot of Stiffness (K) verses Normalized Number of Cycles ($n/N_f$) at different angle of bending is shown in figure 6.
It was observed that quadratic equation is nicely fitted to experimental data. The quadratic equation at each angle of bending is given below:

For $12^\circ$

\[ y = 0.7x^2 - 4.2x + 5.3 \]  
(1)

For $10^\circ$

\[ y = 0.8x^2 - 2.8x + 5.3 \]  
(2)

For $8^\circ$

\[ y = 0.4x^2 - 1.8x + 5.3 \]  
(3)

Where, $y =$ Stiffness N/mm (K)

\[ x = (n/N_f) \]

3.2. Frequency reduction model

The formation of frequency reduction model obtained by modal analysis indicates overall reduction in stiffness due to fatigue loading. The graph of Natural Frequency verses Normalised number of cycles at different angle of bending is mentioned in figure 7. The quadratic equations obtained by curve fitting technics are given below.

It was observed that quadratic equation is nicely fitted to experimental data. The quadratic equation at each angle of bending is given below:

For $12^\circ$

\[ y = 0.7x^2 - 4.2x + 5.3 \]  
(1)

For $10^\circ$

\[ y = 0.8x^2 - 2.8x + 5.3 \]  
(2)

For $8^\circ$

\[ y = 0.4x^2 - 1.8x + 5.3 \]  
(3)

Where, $y =$ Stiffness N/mm (K)

\[ x = (n/N_f) \]
For 12°
\[ f_n = 46x^2 - 116x + 112 \]  \hspace{1cm} (4)

For 10°
\[ f_n = 23x^2 - 52x + 103 \]  \hspace{1cm} (5)

For 8°
\[ f_n = 15x^2 - 36x + 100 \]  \hspace{1cm} (6)

Where, \( f_n \) = Natural Frequency (Hz)  
\( x = n/ N \) = Normalised Number of cycles

The Comparative results of reduction in stiffness as well as natural frequency of CFRP are shown in table 3.

| Angle of Bending | Number of Cycles (n) | Load at peak point (N) | Stiffness (N/mm) | Natural Frequency (Hz) | % Reduction in Stiffness | % Reduction in Natural Frequency |
|------------------|----------------------|------------------------|-----------------|------------------------|--------------------------|----------------------------------|
| ±8°              |                      |                        |                 |                        |                          |                                  |
| 0                | 24                   | 5.31                   | 100.6           |                        |                          |                                  |
| 200000           | 23                   | 5.09                   | 92.3            |                        |                          |                                  |
| 400000           | 21                   | 4.65                   | 87.3            |                        |                          |                                  |
| 600000           | 20                   | 4.42                   | 83.9            |                        |                          |                                  |
| 800000           | 19                   | 4.20                   | 80.8            |                        |                          |                                  |
| 1000000          | 18                   | 3.98                   | 77.7            |                        |                          |                                  |
| ±10°             |                      |                        |                 |                        |                          |                                  |
| 0                | 30                   | 5.30                   | 108.1           |                        |                          |                                  |
| 200000           | 27                   | 4.77                   | 90.7            |                        |                          |                                  |
| 400000           | 25                   | 4.42                   | 85.7            |                        |                          |                                  |
| 600000           | 22                   | 3.89                   | 81.0            |                        |                          |                                  |
| 800000           | 20                   | 3.53                   | 77.3            |                        |                          |                                  |
| 1000000          | 19                   | 3.36                   | 71.3            |                        |                          |                                  |
| ±12°             |                      |                        |                 |                        |                          |                                  |
| 0                | 36                   | 5.33                   | 115.2           |                        |                          |                                  |
| 100000           | 29                   | 4.29                   | 81.5            |                        |                          |                                  |
| 200000           | 23                   | 3.40                   | 67.2            |                        |                          |                                  |
| 300000           | 17                   | 2.51                   | 49.0            |                        |                          |                                  |
| 400000           | 12                   | 1.78                   | 40.9            |                        |                          |                                  |

4. Conclusions
Based on the experimental load and frequency reduction models by modal test, following conclusions can be derived:

1. The testing for modal parameters is best Non-destructive fatigue life prediction method which can be useful to estimate fatigue behavior of CFRP laminates in plane bending fatigue.

2. The Reduction in Natural frequency and strength is depends on angle of bending of CFRP laminated.

3. As there is no complete fracture of 45° fiber oriented CFRP laminates so a natural frequency reduction model will be the appropriated approach to prediction fatigue life in plane bending.

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