PREDICTION OF FATIGUE LIFE OF COMPOSITE LAMINATES USING LASER ULTRASONIC METHOD

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ABSTRACT

Composite laminates suffer from fatigue damages under cyclic loads and can display quite notable property degradation during the process. Stiffness degradation is one of the most utilized to characterize fatigue damages. However, stiffness measurement in real applications remains a challenge. Since the stiffness degradation also directly affects the velocity of the ultrasonic wave that propagates inside the structure, it is reasonable to use the wave velocity to assess the damage levels and further predict the residual life. In a multi-layer laminate, dispersive matrix cracks, delamination and fibre breakage are usually considered to be the main causes of decrease in stiffness. In this paper, a stiffness/velocity degradation model based on the three damage mechanisms is proposed to characterize the fatigue damages in GFRP composite laminates using Lamb wave velocity measured with laser ultrasonic method. Life predictions were also made with a residual velocity criterion, multiple prediction points were chosen to evaluate the model's ability of early stage life prediction. The prediction results were compare to experimental data where overall good agreement was obtained.

1 INTRODUCTION

Composite materials are wildly used nowadays due to its high specific stiffness and strength. Although composite materials were once understood to not suffer from fatigue damages under cyclic loads, it has now been well established that they also degrade due to fatigue damages and would finally lead to failure. It is therefore of great importance to be able to inspect the accumulated fatigue damages inside composite materials and predict the residual life. However, due to the complexity of composite materials' constitutions, it is often difficult to truly evaluate its damage state in detail. Multiple kinds of fatigue damages such as matrix cracks, interfacial debonding, fibre pull-out, fibre breaks and many other minor damages exist simultaneously to make the characterization of specific damages extremely difficult.

One common method to evaluate the overall damage state of composite laminates is to use its residual stiffness [1-3], which is a macroscopic result of the presence of all the inner micro damages. One practical issue of this method is the difficulty in measuring stiffness of structures with real applications. Traditionally mechanical measurements of stiffness such as tensile test requires mount and dismount of measured components. Also, the measurement is usually not non-destructive that it could induce new unwanted damages to the structure. However, the measurement can also be conducted using non-destructive methods such as using Lamb wave. This method is based on the fact that the stiffness of the material is related to the velocities of ultrasonic wave propagation inside the material, which is referred to as Lamb wave in the case of a plate. Meanwhile fatigue damages in composite materials are micro damages, the scale of which is much smaller than the typical wavelength of Lame wave thus the ultrasonic wave would not interact with a specific damage and the plate can still be regarded as homogenous in terms of Lamb wave propagation. If the stiffness degrades due to the presence of fatigue damages, the Lamb wave velocity will decrease correspondingly. Therefore, it is possible to use Lamb wave velocities to characterize the fatigue damages inside composite laminates.

In this work, an explicit solution of 0-frequency S_0-mode velocities is obtained, based on which a velocity degradation model is also proposed. The velocity degradation model is directly derived from a shear-lag approximation model and a modified Paris law, thus giving the damage model an underlying

physical sense. Experiments were then conducted to validate the effeteness of the proposed method. Furthermore, fatigue life prediction was also conducted using a residual velocity criterion.

2 WAVE MODES AND FREQUENCY SELECTION

Lamb wave phase velocities are highly dispersed and a typical phase velocity dispersion curve of Lamb wave propagating in composite laminates is illustrated in Fig. 1. There are generally multiple Lamb wave modes existing simultaneously in plates and the number of modes increase with the frequency. The propagation characteristics of Lamb waves are sensitive to the changes in materials' properties, which can be caused by damages.

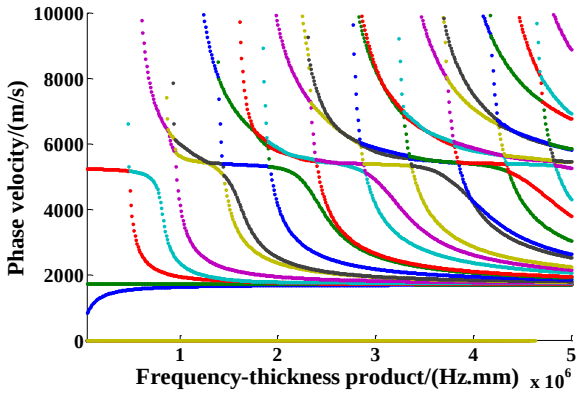


Figure 1: Typical dispersion curve of composite laminates

The Lamb wave velocities in anisotropic materials can be obtained by several methods such as global matrix method, semi-analytic finite element (SAFE) method etc. Those methods all use the materials' properties (density and elastic parameters) to generate a dispersion curve diagram, where the wave velocities change with the frequency. In order to use lamb wave velocities to characterize the materials' properties, however, a reverse relation is needed where materials' properties can be obtained by wave velocities. Zhao et al. [4] used a genetic algorithm to solve the inverse problem to obtain all nine stiffness coefficients of composite laminates. Although this method can provide all the elastic parameters of a laminate, the calculation process takes a long time and the velocities in multiple directions are required. Since most of the traditional residual stiffness models only utilize the stiffness along loading direction, the velocity that is most sensitive to this stiffness is chosen to characterize the fatigue damage. Considering the low frequency range of the S_0-mode, which is also known as extension mode where the wave length is much longer than the thickness of the laminate and particles inside move in a way much similar to that under tensile load. At 0-frequency, the ratio of wave length over thickness approaches infinity and the wave velocity can be obtained as follow:

$$v_p^{f_0,S_0} = \sqrt{\frac{E_x}{(1-v_{xy}v_{yx})\rho}} \tag{1}$$

Eq. 1 indicates that the 0-frequency phase velocity of S_0-mode is purely decided by the axial elastic module, the two in-plane Poisson's ratios and the density of the material. Considering that all damages take place under fatigue loads are micro damages and would not notably change the density of the material and phase velocity is insensitive to the changes of Poisson's ratio [4, 5], a damage factor is thus defined as following to assess the level of damages.

$$D = 1 - \frac{E_x}{E_0} = 1 - \left(\frac{v_x}{v_0}\right)^2 \tag{2}$$

where v_0 is the phase velocity measured from pristine condition while v_x is the one measured from damaged condition.

3 STIFFNESS/VELOCITY DEGRADATION MODEL

Among all the damages that might occur under cyclic loads, matrix transverse crack is the one that is mostly heavily studied [5-8]. The reason is probably because it is the main cause of stiffness degradation in the first two stages of then typical three-stage stiffness degradation curve as shown in Fig. 2. Although most of the stiffness is usually lost in the third stage because of fiber damages, that stage is short, unstable, difficult to observe and dangerously close to the final collapse of structures thus it is not taken into consideration in this work. However, this does not mean no fiber damage is considered here. In our experiments, one distinct phenomenon we observed is a relatively large stiffness/velocity loss after the very first load cycle. Meanwhile, fiber breakage is also clearly audible during loading of that cycle. In case of mechanical tensile test, the stiffness loss in first several cycles can be caused by multiple factors other than fiber damages such as relaxation of the grips or slippery between the grips and specimens. However, due to the nature of wave velocity measurement, these factors would not affect the wave velocity, which is one of the advantages of using Lamb wave velocity. Therefore, based on the fact that the loss is in both stiffness and velocity, we think it is reasonable to attribute this to fiber damage. Thus, the aforementioned damage factor is further divided into damage factor for fiber damage and damage factor for matrix cracks and delamination:

$$D_f = 1 - \frac{E_{x1}}{E_0}; \quad D_m = 1 - \frac{E_x}{E_{x1}} \tag{3}$$

where E_{x1} is the stiffness/velocity measured right after firs load cycle, E_0 is the pristine stiffness and E_x is the stiffness/velocity measured after E_{x1}, D_f is damage factor for fiber damage and D_m is damage factor for both matrix cracks and delamination.

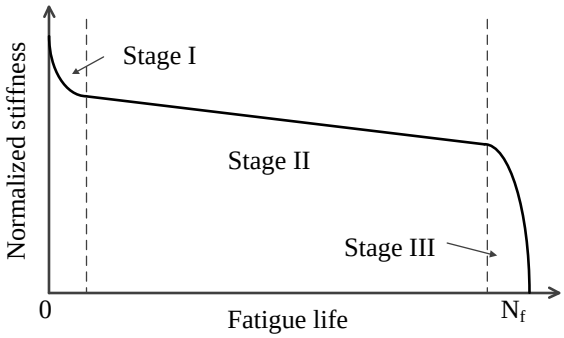


Figure 2: A typical trend for composite stiffness degradation

3.1 Fiber damage

As previously mentioned, majority of fibre damage happens in the third stage which is not considered here. The rest of fibre damage, as a simplification, is considered only to take place in the first load cycle. Therefore, the fibre damage in this model is basically static non-evolutional damage and is characterized by Eq. 3.

3.2 Matrix cracks

Matrix cracks as the main cause to the stiffness/velocity degradation during the first two stages is regarded as the core mechanism in the model. The stiffness reduction caused by matrix cracks is heavily studied and several existing models can be utilized such as shear-lag model [5,6] and variation model [9]. A simplification for shear-lag model is proposed here to obtain energy release rate (ERR) for formation of new matrix cracks using only information from wave velocity measurement. The calculated ERR is then combined with a modified Paris law to get the matrix crack density increase rate, which then can be used to calculate the new residual stiffness after a certain amount of cycles. The proposed simplification is as follows:

$$D_{mc} = 1 - \frac{E_x}{E_1} = D_c(1 - e^{-c\rho_c}) \tag{4}$$

where ρ_c is the crack density, c is a material parameter, D_{mc} is a damage factor for matrix cracks only and D_c is an estimation based on the typical value of the residual stiffness at the end of the second fatigue stage. Fig. 3 shows a comparison between the proposed approximation, a typical shear-lag model and a linear approximation.

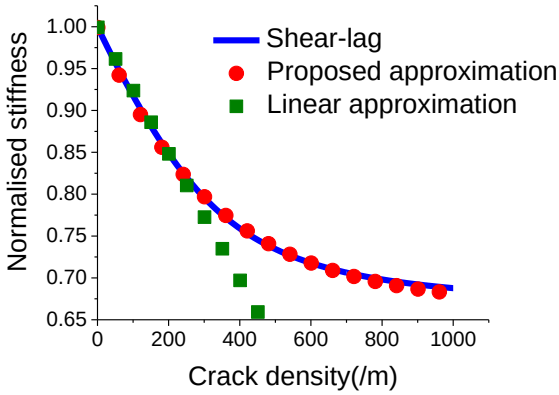


Figure 3: Comparison of a shear-lag model to proposed approximation and linear approximation

Combing the above approximation and Eq.3 the ERR for formation of new cracks can be obtained as [10]:

$$G = \frac{B\sigma_x^2}{2\rho_c}\left(\frac{1}{E_x(2\rho_c)} - \frac{1}{E_x(\rho_c)}\right) = \frac{\sigma_x^2 D_{mc}(D_c - D_{mc})}{\log\left(\frac{D_c}{D_c - D_{mc}}\right)(D_c - 2D_cD_{mc} + D_{mc}^2)(1 - D_{mc})} \tag{5}$$

where B is material related parameter, σ_x is the maximum applied stress, D_{mc} is damage factor for matrix cracks.

3.3 Delamination

Delamination in this paper is considered as subordinate to matrix cracks since it mainly initiates from matrix cracks and causes relatively less stiffness reduction compared to matrix cracks [11]. Therefore, a simple relation is proposed to characterize delamination damage, D_{dela}:

$$D_{dela} = \alpha D_{mc} \tag{6}$$

Thus, D_m becomes:

$$D_m = D_{dela} + D_{mc} = (1 + \alpha)D_{mc} \tag{7}$$

3.4 Damage evolution model

Now with the ERR for formation of new matrix cracks and delamination being subordinate to matrix crack, we can obtain the evolutional part of the stiffness/velocity degradation model. Using a modified Paris law model:

$$\frac{d\rho_c}{dN} = C(\Delta G)^m \tag{8}$$

and Eq.4, we have:

$$\frac{dD_{mc}}{dN} = \frac{dD_{mc}}{d\rho_c}\frac{d\rho_c}{dN} = c(D_c - D_{mc})C(\Delta G)^m \tag{9}$$

combined with Eq.5, we have:

$$\frac{dD_{mc}}{dN} = A(D_c - D_{mc})\left[\frac{\sigma_x^2(1-R^2)D_{mc}(D_c - D_{mc})}{\log\left(\frac{D_c}{D_c - D_{mc}}\right)(D_c - 2D_cD_{mc} + D_{mc}^2)(1 - D_{mc})}\right]^m \tag{10}$$

where

$$A = C[c(Bc)^m] \tag{11}$$

Eq. 11 indicates that the two unknown parameters from Eq. (4) and Eq. (5) are not necessarily required, instead, parameter A can be obtained directly by fitting experimental data which includes both c and B in addition to Paris parameter C. A closed-form solution for Eq. (10) is hard to obtain, thus a cycle-to-cycle finite difference method is used to solve the differential equation. Put the stiffness loss caused by three damage mechanisms together, the total damage factor after *N+1* cycle is then:

$$D_{total}^{N+1} = 1 - \left(1 - D_f\right)\left[1 - (1+\alpha)\left(D_{mc}^{N} + \frac{dD_{mc}}{dN}\right)\right] \tag{12}$$

The last equation contains two main terms. The first one is the fiber damage factor D_f, which is a static one that would not evolve through cycles. The second one is the damage factor for matrix cracks and delamination and its cycle-increment. This term is the evolutional part of the stiffness/velocity degradation model.

4 EXPERIMENTAL SETUP

Controlled experiments were conducted to validate the degradation model, several GFRP laminate specimens were tested in interrupted tests where fatigue tests were stopped after a certain amount of cycles so wave velocity measurement can be conducted. The wave velocity was measured using a laser ultrasonic method, where an AE sensor was attached to one end of the specimen before experiments and a laser beam scanned the middle area of specimens after each interval to generate ultrasonic waves. Signals picked up by the AE sensor were then used to obtain a position-time diagram where wave velocity can be measured [12]. A schematic for experimental setup is shown in Fig. 4.

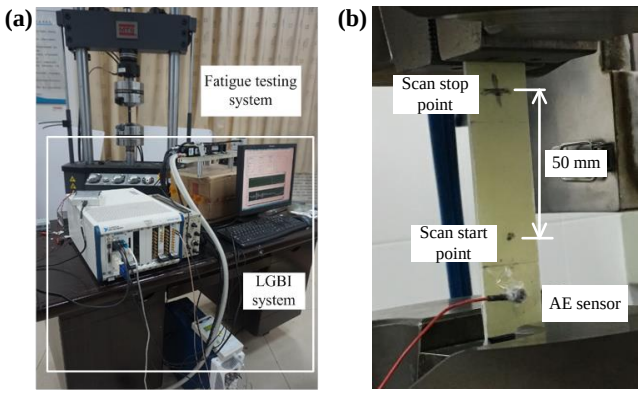


Figure 4: Experimental setup for fatigue test (a) two main systems (b) scanning area and the AE sensor position

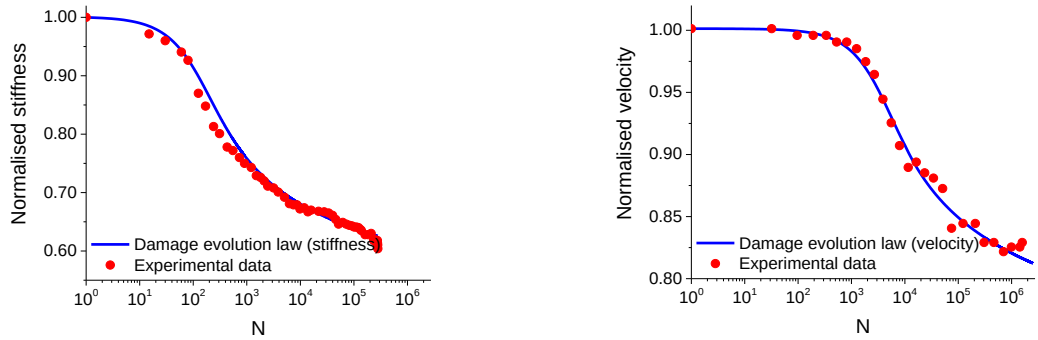
5 FATIGUE DAMMAGE CHARACTERIZATION

Specimens with two different lay-ups of $[45/0/-45/90]_{2s}$ and $[0/90_3]_{2s}$were tested. The basic material parameters are listed in Table 1.

Lamina properties	
$E_1 = 43.16\text{GPa}$	$\mu_{12} = 0.31$
$E_2 = 10.81\text{GPa}$	$G_{12} = 4.85\text{GPa}$
Nominal ply thickness=0.106mm	

Table 1: Lamina properties for tested specimens

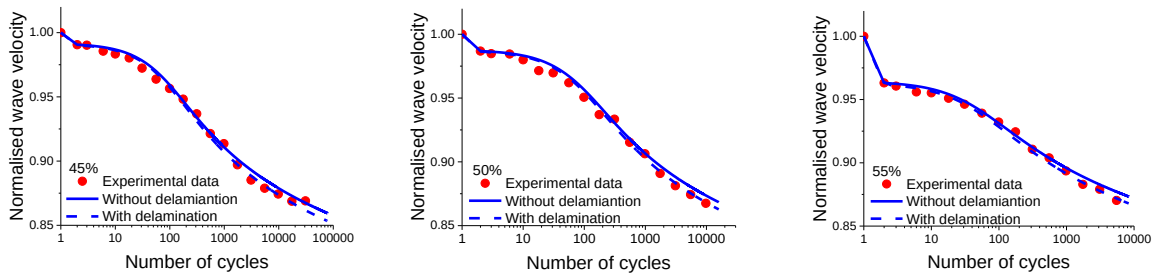
The tensile strength of the cross-ply laminates was tested in a tensile test to be 314.89MPa and the strength of the quasi-isotropic laminates to be 463.0MPa. Two stress levels were chosen for cross-play laminates to be 45% of the tensile strength which is 141.70MPa and 80% of the initial crack stress level which is 102.08MPa. As for the quasi-isotropic laminates, three different stress levels of 45%, 50% and 55% of the ultimate tensile strengths were tested.



(a) (b)

Figure 5: Fatigue damage characterization of cross-ply laminates (a) 141.70MPa in terms of stiffness (b) 102.08MPa in terms of velocity

Fig. 5 shows the characterization results for the cross-ply laminates, the experimental data in Figure. 5(a) is in stiffness, a very short-period stage 3 can be seen at the end of the experiment, apart from this the model has good agreements with experiments. In Figure. 5(b), experimental data is described in velocity, no clear sigh of stage 3 is observed and the proposed model fits well with the experimental data. Generally, the proposed stiffness/velocity degradation model successfully characterizes the fatigue damage evolution in cross-ply GFRP laminates in terms of both stiffness and Lamb wave velocity.



(a) (b) (c)

Figure 6: Fatigue damage characterization of quasi-isotropic laminates (a) 45% severity (b) 50% severity (c) 55% severity

Fig. 6 shows the characterization results for the quasi-isotropic laminates, compared to the results from cross-ply laminates a notable difference is the stiffness loss after the first load cycle. In cross-ply laminates, no such phenomenon is observed. The reason is probably because of the applied stress being much higher in quasi-isotropic laminates than in cross-ply laminates due to the much higher tensile strength for quasi-isotropic laminates. As a result, the fiber damage factor in quasi-isotropic laminates is utilized to reflect this phenomenon while in cross-ply laminates the fiber damage factor is zero. Other than this, the characterization results also show good agreement with experimental data.

6 FATIGUE LIFE PREDICTION

The ultimate purpose of the characterization of fatigue damage using Lamb wave is to predict residual lives of structures by means of Lamb wave inspections. For this to be achieved the proposed stiffness/velocity degradation model is combined with a failure criterion to test its ability for accurate prior prediction of residual lives. In this case, a residual Lamb wave velocity criterion similar to the residual stiffness criterion is incorporated to predict fatigue life. Firstly, a threshold value for residual Lamb wave velocity is obtained from stiffness/velocity degradation model for every tested specimen. The reason why a numerical value is used instead of a real one is because it is extremely difficult to obtain the actual residual wave velocity right before a structure's final failure in experiments, not mentioning in real applications. Meanwhile due to the success of characterization with the proposed damage model, the residual velocity from which should be a good estimation. The prediction results are listed in Table 2, where fairly good accuracy can be seen considering the usual large scatters in fatigue tests.

Specimen No.	Threshold value	Predicted life	True life	Error (%)
E1	0.861955	31900	78397	-59.31
E2	0.862253	29500	50378	-41.44
E3	0.861332	18000	15993	12.56
E4	0.861328	18100	16018	13.00
E5	0.862292	5030	8352	-39.76
E6	0.860468	19400	8235	135.59
E7	0.861052	7230	5212	38.74

Table 2: Summary of predicting fatigue life

To further test the proposed model's ability to predict residual life in early service stage, four extra prediction points for two selected specimens E2 and E3 are chosen. Each prediction point means the prediction is made with all the information before that point. Since the last data point from experiments are both around 60% of the total life for the two selected specimens, the prediction point of 60% is the point where all the experimentally measured information is utilized. It should be noted that the interrupted point during experiments are not evenly distributed, prediction point does not necessarily mean the number of experimental data points.

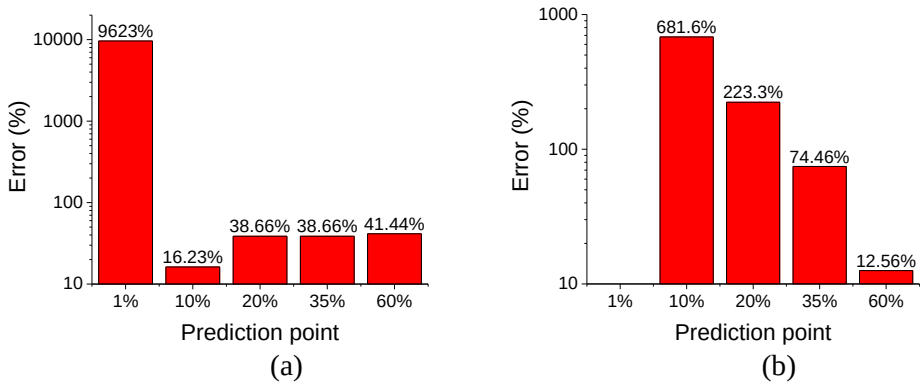


Figure 7: Error evolution with increased inspected information (a) E2 (b) E3

From Fig. 7, it can be seen that with only information from the first 1% of specimens' total life span, predictions made deviates severely from the true life, which is not surprising considering the limited information known of the specimen at this stage. By the increase of information, the accuracy of prediction generally gets better, however, in the first selected specimen, the best accuracy was achieved

in the 10% prediction point. The reason for this is probably because of the fact that prediction is made in the second stage, where the stiffness decrease rate is quite small and since the wave velocity is generally the square root of stiffness. The decrease rate for velocity in this stage is even smaller, therefore, any small fluctuation in velocity might cause quite large prediction differences. This makes the prediction rely heavily on a continuously accurate wave velocity measurement.

7 CONCLUSIONS

This paper proposed a stiffness/velocity degradation model that is constructed mainly on matrix cracks propagation. In addition, some effects caused by delamination and fibre damage is also included. The proposed model successfully characterizes the accumulated fatigue damages in composite laminates in terms of both stiffness and Lamb wave velocity in both cross-ply laminates and quasi-isotropic laminates. The Lamb wave velocity is measured through a laser ultrasonic method, which combines with the proposed degradation model gives good correlation between numerical predictions and experimental data. Furthermore, a residual velocity criterion is incorporated to give predictions of residual lives of laminates with only the measured velocity information from laser ultrasonic method. Predicted results indicate that the accuracy is generally good considering the usual large scatters observed in fatigue experiments, however, this method is heavily affected by the wave velocity measurement accuracy due to the small degradation rate. Further development regarding failure criteria is still needed for more robust life predictions.

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