ICCM 23

SHANGHAI JIAO TONG UNIVERSITY

A STUDY ON THE EFFECT OF LAMINATE TAPER ON DAMAGE MECHANISMS IN COMPOSITE LAMINATES

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BIOGRAPHY

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Mr Jin is a doctoral candidate at the School of Mechanical Engineering at Shanghai Jiao Tong University in China. His research interests the design, analysis, and validation of composite structures. In particular, he specializes in fatigue fracture mechanics issues in composite structures. He has authored many research publications in international journals and conferences.

[1] **Jin L**, Chen Y, Tang X, et al. A numerical study on damage characteristics in composite tapered laminates under cyclic loading with different stress ratios. ***Composite Structures*, 2023**: 116777.

[2] **Jin L**, Chen Y, Zhang J G, et al. A study on the effect of delamination defects on damage mechanisms in composite tapered laminates. ***ICCM*, 2023**.

[3] **Jin L**, Chen Y, Wang Z J, et al. Investigating the Influence of Ply-drop Groups Interactions on Damage Mechanisms in Tapered Composite Laminates. ***AIAA*, 2023**.

[4] Chen Y, **Jin L**, Tang X, et al. Dynamic response of a composite fan blade excited instantaneously by multiple MFC actuators. ***Aerospace*, 2022**, 9(6): 301.

Content

01

INTRODUCTION

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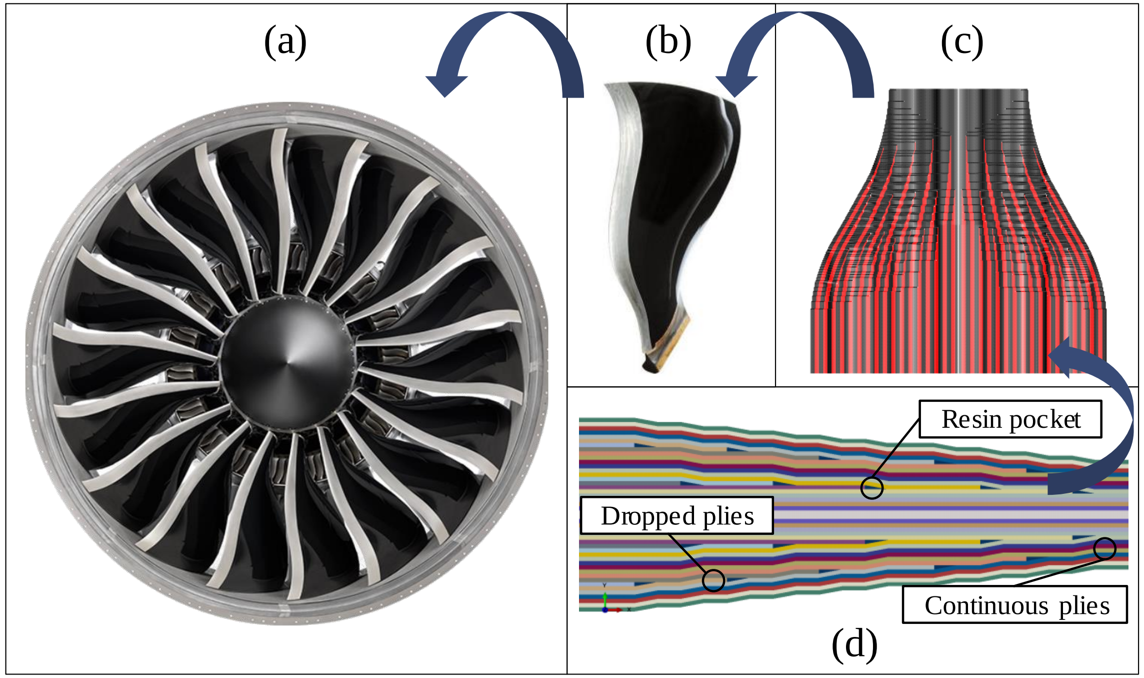

《Advisory Circular》

- This establishes the **damage growth**, **strength**, **failure location**, **and failure mode and mechanism** of the components. The damage tolerance discussion focuses on propeller blades, but may be applied to any composite propeller component.
- Applicants should conduct material testing to determine material properties, including the impact of **defects**, **manufacturing parameters**, **pollution**, **environmental effects**, **operational damage** during the blade's lifecycle, and changes in material performance during service.

—— Quoted from 《AC No: 35.37-1B》 and 《CCAR 33.15》

Current research lacks in several aspects

- Static strength analysis is typically conducted only for specific laminate structures, with limited involvement in the study of dynamic characteristics under cyclic loading.
- The dynamic characteristics and dynamic strain of weak-link are not taken into account, and there is limited involvement in determining the optimal laminate design from the perspective of damage tolerance.

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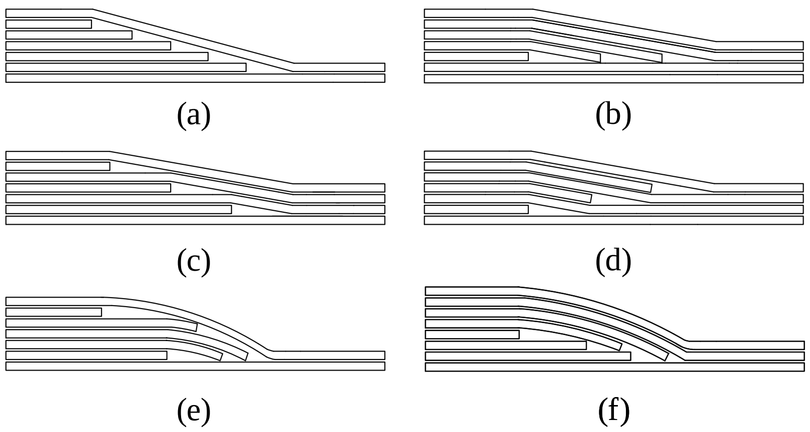
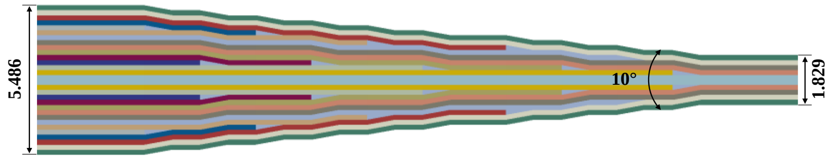
LAMINATE MODELLING

LAMINATE MODELLING

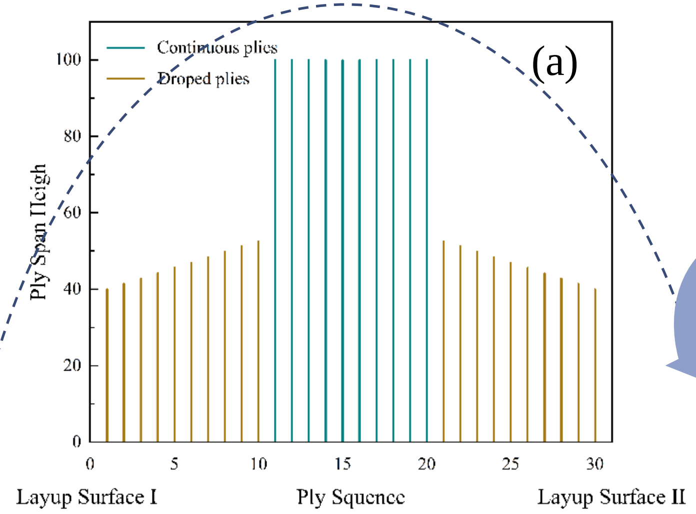
➢ Laminate design



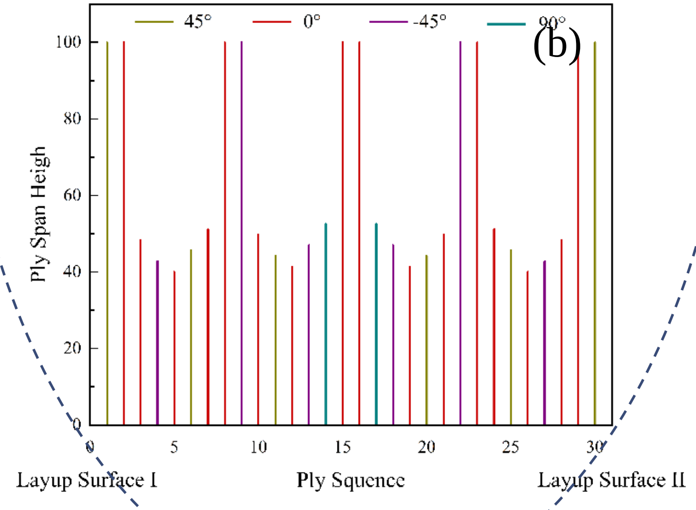
Layup styles of (a) staircased-grouped, (b) overlapped-grouped, (c) staircased-dispersed, (d) overlapped-dispersed. (e) other and (f) bamboo shoots shell



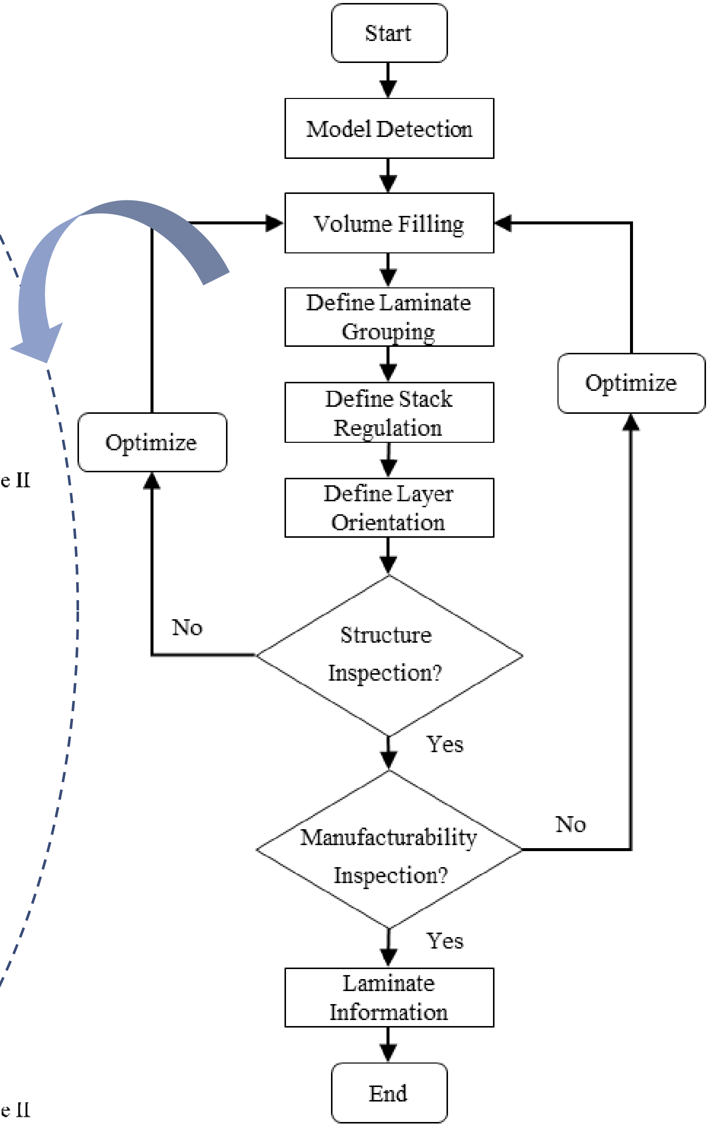
Tapered composite laminate



Original ply stacking sequence



Optimized ply stacking sequence



Flowchart of composite laminate design

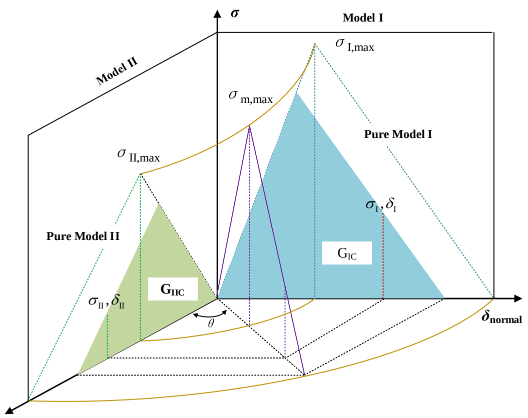
03

DAMAGE ASSESSMENT

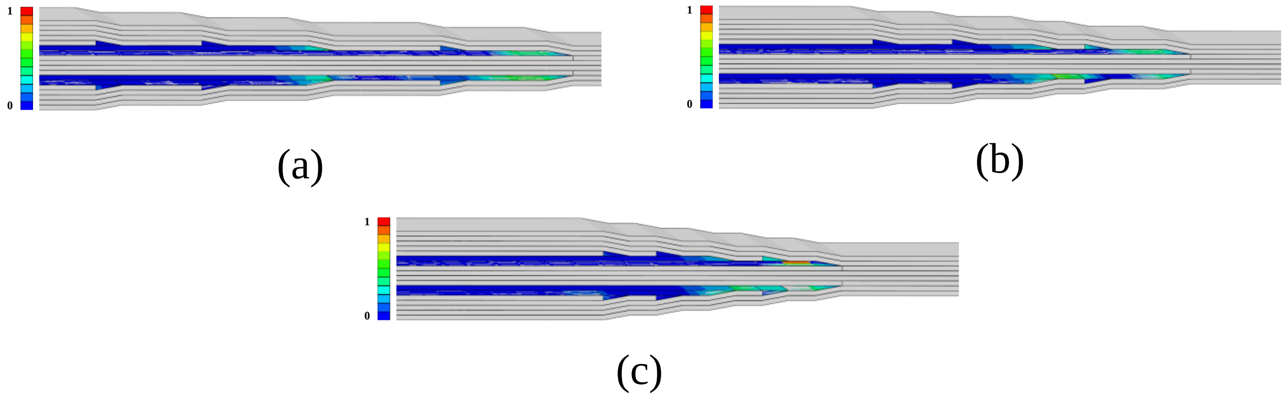
➢ Static damage assessment

Regarding monotonic loading, interlaminar behavior is described by a bi-linear traction-separation cohesive formulation, which describes static damage initiation status in this section.

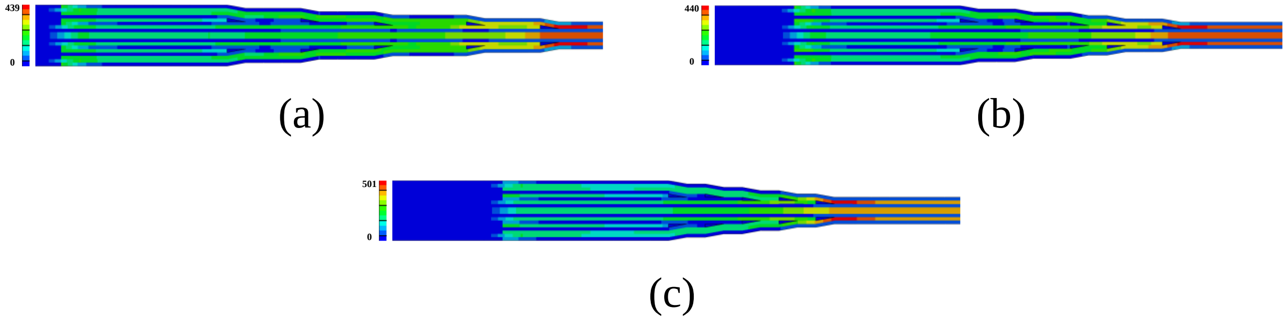
$$\left(\frac{\langle\sigma_n\rangle}{N_{\max}}\right)^2+\left(\frac{\langle\sigma_s\rangle}{S_{\max}}\right)^2+\left(\frac{\langle\sigma_t\rangle}{T_{\max}}\right)^2=1$$



A Schematic plot of traction-separation cohesive criteria

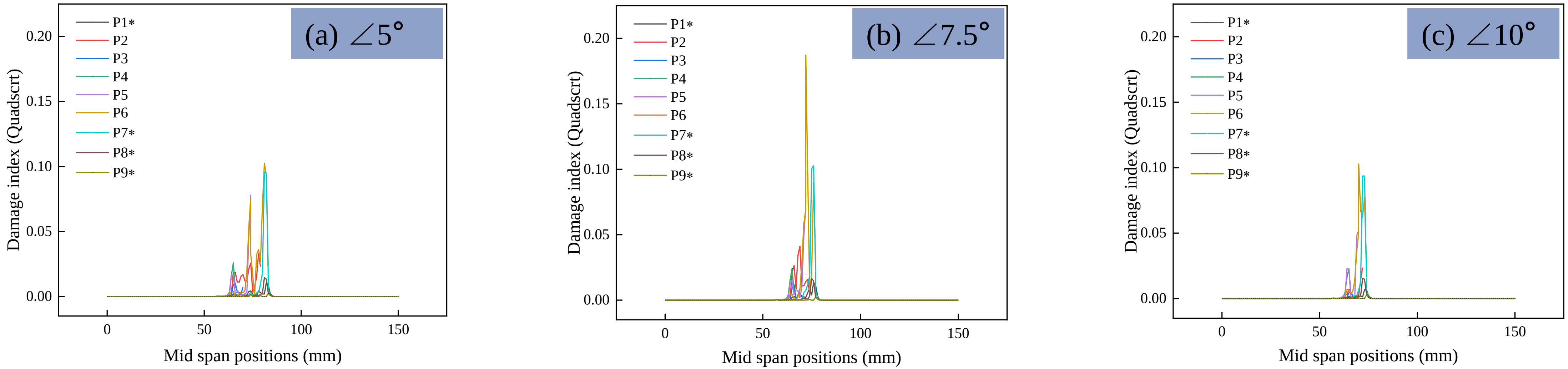


Comparisons of static damage index contour of (a) 5° tapered laminate, (b) 7.5° tapered laminate and (c) 10° tapered laminate



Comparisons of a stress contour plot of   direction under monotonic loading of (a) 5° tapered laminate, (b) 7.5° tapered laminate and (c) 10° tapered laminate

➢ Static damage assessment



Comparisons of damage index between (a) 5° tapered laminate, (b) 7.5° tapered laminate and (c) 10° tapered laminate

The results show

- ➢ It can be seen that all of the maximum value of damage index in continuous cohesive element plies in three tapered laminate are approximately equal, but the maximum value of damage index in dropped cohesive element plies is different. Therefore, it indicates the maximum value of damage index in dropped cohesive element plies is more sensitive to taper angle change.
- ➢ It can also be seen that the range of stress distribution can increase with the decrease of the taper angle, which indicates the interaction of adjacent layers can be stronger. And another factor is that the stress can be more concentrated as the taper angle increase. These reasons ultimately lead to the highest damage index of 7.5° tapered laminate in dropped cohesive element plies in three tapered laminates.

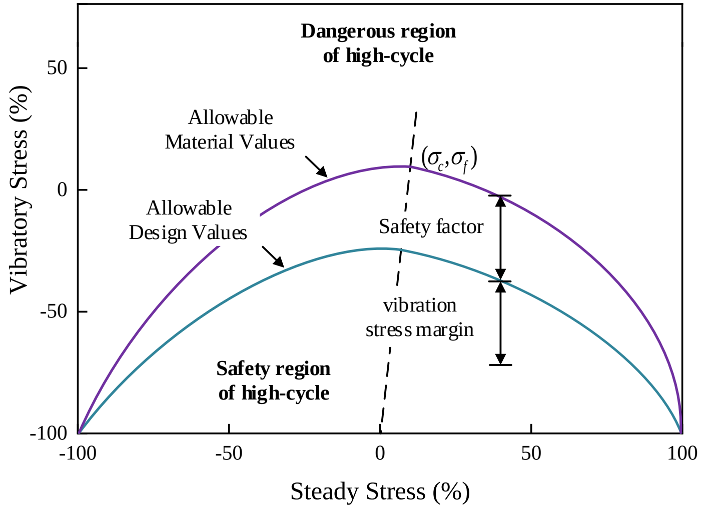
Dynamic damage assessment

The high-cycle fatigue weak-link can be located and predicted, based on the constant life diagram of composite laminate, when the following equation is satisfied

$$\begin{cases} \sigma_{a,j} = \dfrac{\sigma_{f,j}}{\sigma_{c,j} - \sigma_{st,j}}\left(\sigma_{s,j} - \sigma_{st,j}\right), & \sigma_{c,j} \le \sigma_{s,j} \le \sigma_{st,j} \\ \sigma_{a,j} = \dfrac{\sigma_{f,j}}{\sigma_{c,j} + \sigma_{st,j}}\left(\sigma_{s,j} + \sigma_{sc,j}\right), & -\sigma_{sc,j} \le \sigma_{s,j} \le \sigma_{c,j} \end{cases}$$

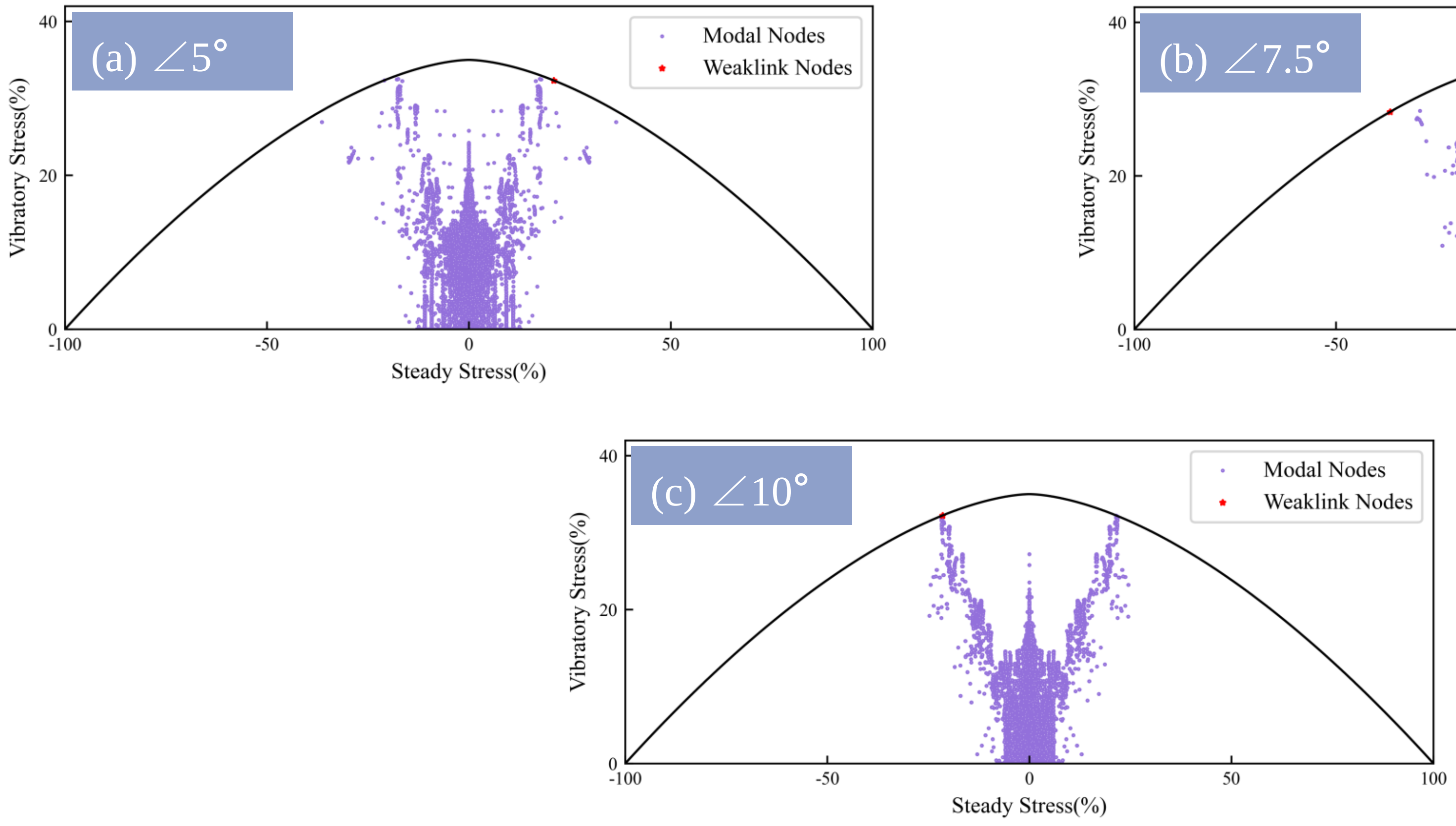
The weak-link zone corresponds to the position, where the vibration stress margin is zero, when the following equation is satisfied

$$\eta_{\sigma}^{m}\left(i,j\right) = 1 - \frac{\beta_{i,j}^{m}}{\beta_{\max,j}^{m}}$$



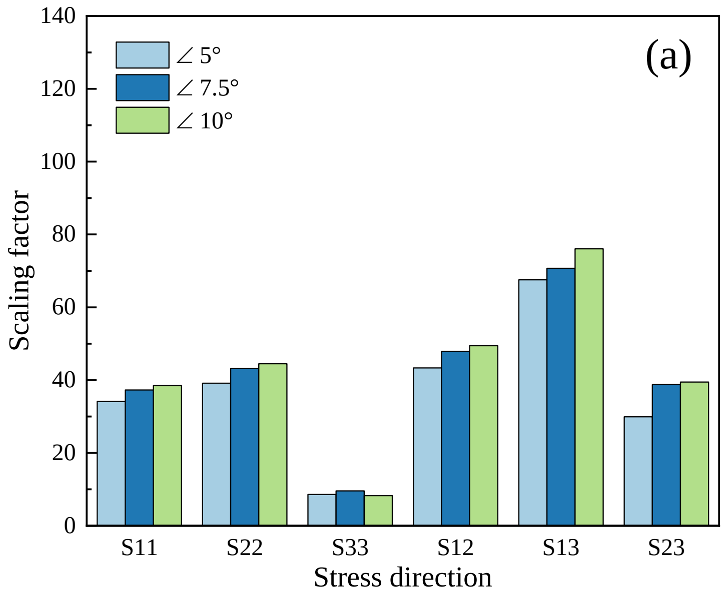
A schematic plot of the constant life diagram of composite laminate

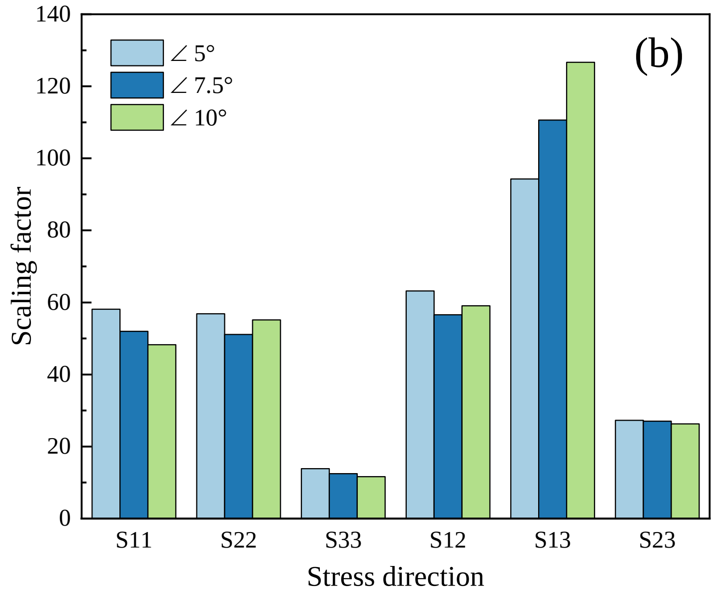
➢ Dynamic damage assessment



Comparisons of distribution of first-order flexure vibration stress margin on all nodes with S13 direction

➢ Dynamic damage assessment





Comparisons of damage index of different static stress of (a) 1kN and (b) 5kN

The results show

- All of the maximum value of the scaling factor is the direction S13 of with different steady stress in three taper angles laminates. The scaling factor value increases as the taper angles increase in the direction of with different steady stress, which indicates interlaminar shear stress along the longitudinal orientations reaches its fatigue failure first, and also explains the reason why interlaminar failure is easier to break.

04

FATIGUE BEHAVIOUR

➢ Interlaminar behavior

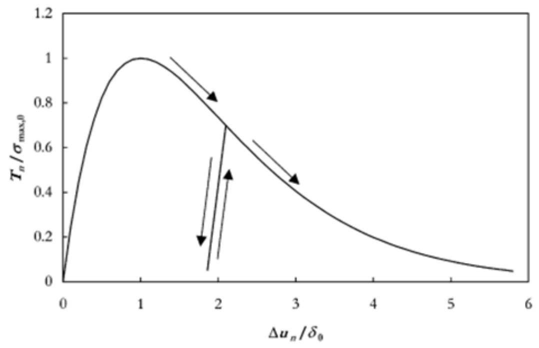
The delamination behavior was investigated based on the constitutive equation with a cyclic cohesive interface model approach in this study, which allows a more detailed investigation of the failure criteria used to model the delamination failure described by a cyclic traction-separation cohesive formulation.

$$\int_V s:\delta F dV - \int_{S_{in}} T\cdot\ \delta\Delta u dS = \int_{S_{out}} T_{out}\cdot\ \delta u dS$$

The evolution equation for damage with a cyclic cohesive interface model approach based on the above requirements, which is written as

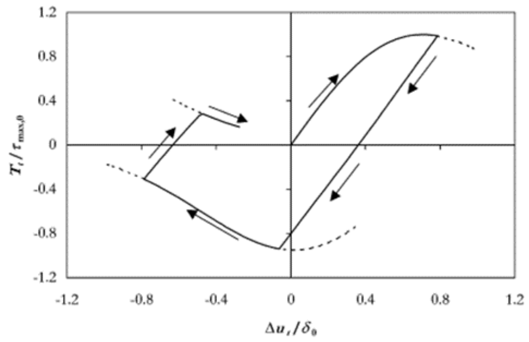
$$\dot{D}_c = \frac{|\dot{u}_\Sigma|}{\delta_\Sigma}\left[\frac{T}{\sigma} - C_f\right]\psi\left(u_\Sigma - \delta_0\right),\ \dot{D}_c \geq 0 \qquad D = \int \max\left(\dot{D}_c, \dot{D}_m\right) dt$$

(a)

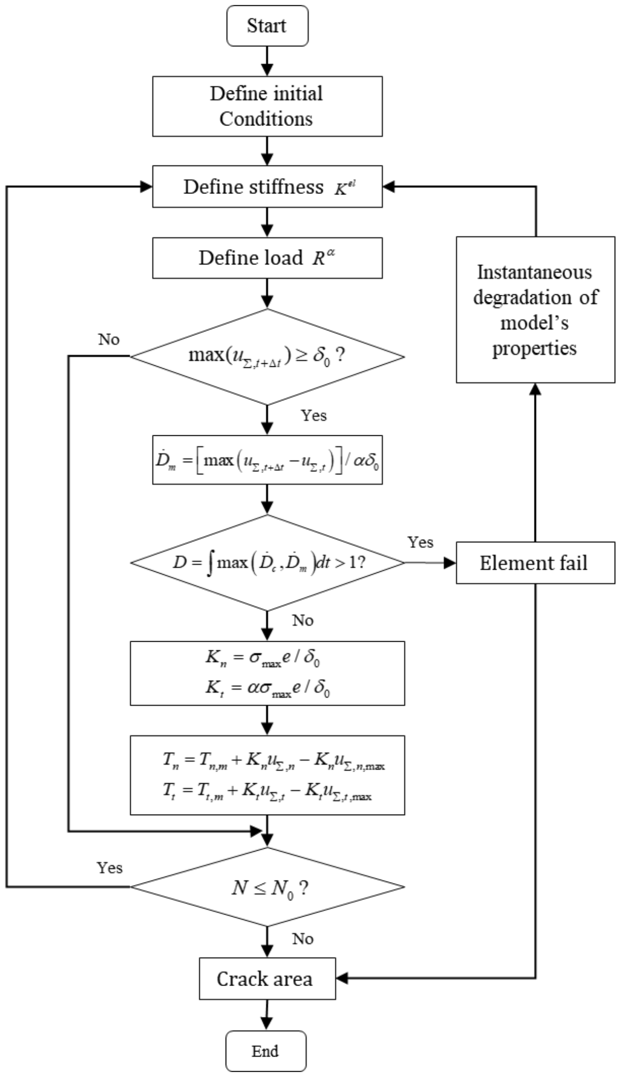


Normal separation behavior including unloading and reloading

(b)



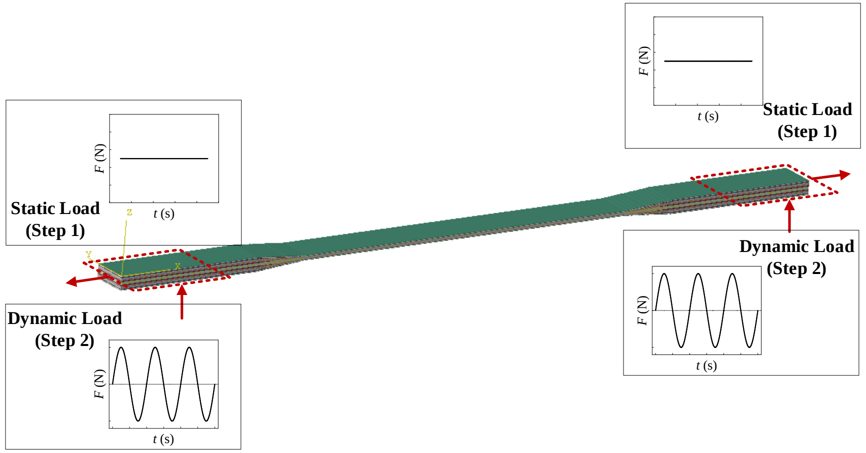
Shear separation behavior including unloading and reloading



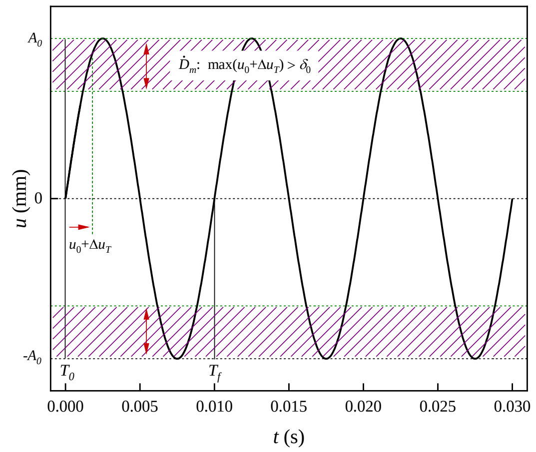
Flowchart of cyclic cohesive interface model

FATIGUE BEHAVIOUR

➢ Prediction of fatigue crack growth



(a) A schematic plot of the loading of fatigue behaviour of the tapered laminate



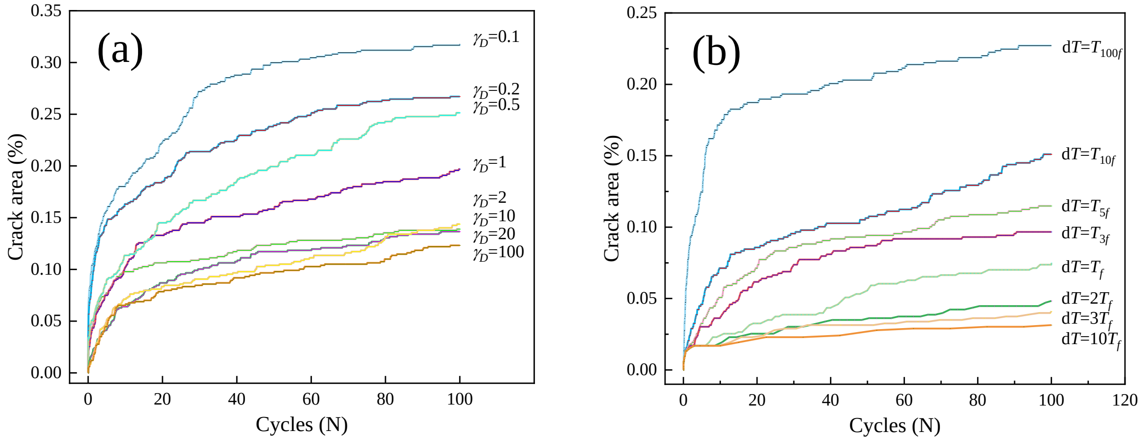
(b) Damage increment under amplitude of sinusoidal cyclic displacement

The results show

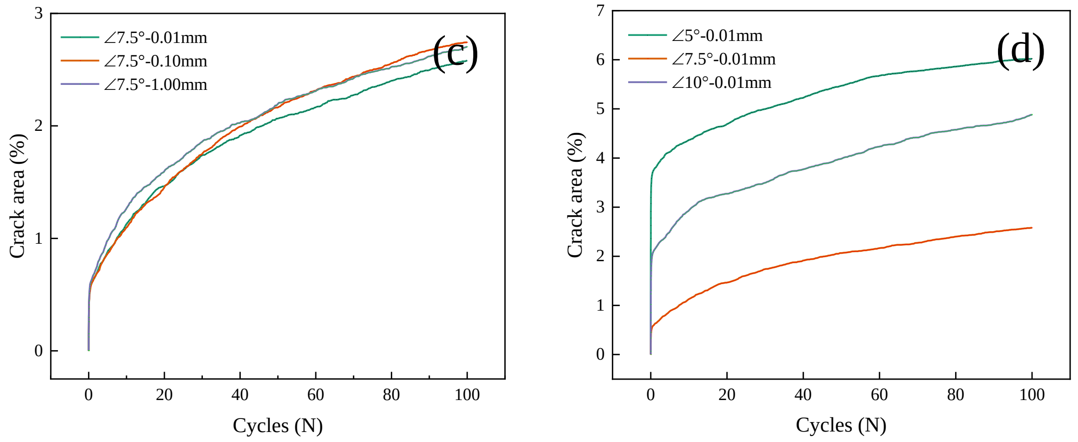
- The effect of time increment with different sampling frequencies on fatigue crack growth was investigated to reveal the internal mechanism better. As shown in Fig. (b), the time increment defined as one cycle of the dynamic load is a distinct dividing line for others. The less time increment is, the more damage accumulation is, which indicates fatigue crack growth rates is faster.

FATIGUE BEHAVIOUR

➢ Prediction of fatigue crack growth



The effect of (a) time increment and (b) coefficient of damage on fatigue behaviour under amplitude of sinusoidal cyclic displacement



Comparisons of the behaviour of fatigue behaviour with the different dynamic loads

The results show

- ➢ The less time increment is, the more damage accumulation is, which indicates fatigue crack growth rates is faster. Furthermore, the more coefficient of damage is, the more damage accumulation is, which indicates fatigue crack growth rates also is faster.
- ➢ Some features: (1) the crack growth rate only slightly increases as the taper angles increase, which indicates the range of the taper angles is not quite sensitive to the crack growth rate; (2) in the early stage of crack growth, the percentage of the crack area from large to small is 7.5°, 10°, 5°. One of the reasons is that the range of stress distribution can increase with the decrease of the taper angle, and the interaction of adjacent layers can be stronger, which results in the initial value of the cumulative damage being larger, and it fatigues failure first.

05

CONCLUSION

CONCLUSION

01

This study focuses on the interlaminar fatigue behavior of different taper angles laminates with a "bamboo shoots shell" shape under cyclic loading with varying stress ratios. The study proposes a novel tapered composite material layer design criterion, which shows that the laminate structure meets the composite laminate design criterion, has rational dropped plies and transition and is more manufacturable.

A dynamic damage assessment method based on the classical constant life diagram model is proposed to predict the high-cycle fatigue weak-link zone.

02

A smaller taper angle leads to a wider range of stress distribution and stronger interaction between adjacent layers, while a larger taper angle results in more concentrated stress. The reason why tapered laminates with a smaller taper angle are more prone to fatigue failure is the stronger interaction between adjacent layers and the larger range of stress distribution. This leads to a higher initial value of cumulative damage and ultimately results in earlier fatigue failure.

The key to the issue is how to balance the damage caused by the tapered angle is very important based on the weak-link location.

THANKS