MESOSCALE LAMINA FATIGUE DAMAGE MODEL FOR FIBER-REINFORCED POLYMER COMPOSITE LAMINATES

AZISYAHIRAH AZIZAN

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Faculty of Engineering
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DEDICATION

To *Mak & Abah*

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ABSTRACT

Carbon fiber-reinforced polymer (CFRP) composite laminates used as load-bearing structures, such as skin of aircraft wings and wind turbine blades, are likely to experience fatigue loading. The resulting complex stresses could cause fatigue damage in the laminas in the form of matrix cracking, interface delamination, and fiber fracture. The prediction of the reliability of these structures requires an accurate constitutive damage model of the composite material. However, the previous available damage models are based on stress control condition and limited to low cycle fatigue loading conditions. In this respect, the research proposes and examines a new universal damage-based material fatigue model of unidirectional lamina. The mesoscale model incorporates the observed degradation of the lamina strength and stiffness properties in defining the material damage under cyclic loading conditions. Hashin's stress-based criteria for damage under monotonic loading are extended and used to describe the fatigue damage accumulation process. The normalized model is employed to describe the fatigue degradation of the strength and stiffness properties. The model acknowledges the effects of mean stress on the damage and fracture process. It is observed that the shear strength of the CFRP composite lamina is the first to degrade when compared to other properties. The predicted fatigue damage evolution characteristics are examined for a typical material point in the CFRP composite lamina throughout the fatigue loading. For this purpose, a finite element (FE) model of a CFRP composite laminate plate with a through central hole is subjected to tension-tension cyclic stressing ($\kappa = 0.1$) in transverse fiber direction. Since cycle-by-cycle life calculations are impractical given the large number of anticipated fatigue cycles involved, a load-cycle block sequence is introduced to address the computational efficiency of the fatigue life prediction routine. The number of load cycles represented by each block is dictated by the rate of the property degradation. The size of a load cycle block is determined by the residual property curve that exhibits the shortest fatigue life, N_f under the operating fluctuating load cycles. Nonlinear characteristic evolution of the fatigue damage with the applied stress cycles is demonstrated. The critical level of the fatigue damage, determined based on the total dissipated energy of fracture, denotes the nucleation of the fatigue crack through the separation of the material point. From the case study, with the operating stresses of ${\sigma_{22}}^{max}$=18.85 MPa and ${\tau_{12}}^{max}$=1.30 MPa, the accumulated matrix tension fatigue damage at the critical point reaches $g_{MT} = 1.0$ after $n^d = 1.93\times10^3$ cycles have elapsed. The collection of the separated material points throughout the applied fatigue cycles represents the propagated fatigue crack. The calculation routine is readily implemented in any standard FEA software for damage-based fatigue life prediction of fiber-reinforced polymer (FRP) composite laminate structures. The unified fatigue damage model developed in this thesis is significant for industrial sectors, dealing with FRP composite design, fabrication, reliability prediction, and failure analysis of load-bearing structures.

ABSTRAK

Lapisan komposit polimer yang diperkuat dengan gentian karbon (CFRP) yang digunakan sebagai struktur penahan beban, seperti kulit sayap pesawat dan bilah turbin angin, cenderung untuk mengalami kelesuan. Tegasan kompleks yang terhasil boleh menyebabkan kerosakan akibat kelesuan dalam lapisan lamina dalam bentuk keretakan matriks, pelekangan antara muka, dan keretakan gentian. Ramalan kebolehharapan struktur komposit ini memerlukan model konstitutif kerosakan yang tepat. Walau bagaimanapun, model kerosakan yang tersedia sebelum ini adalah berdasarkan keadaan kawalan tegasan dan terhad kepada keadaan pembebanan kelesuan kitaran rendah. Dalam hal ini, penyelidikan mencadangkan dan meneliti model baru semesta kelesuan bahan yang dibangunkan berasaskan kerosakan dari ekaarah lamina. Model skala meso menggabungkan penurunan kekuatan lamina dan sifat kekukuhan yang diperhatikan dalam menentukan kerosakan bahan dalam keadaan pembebanan berkitar. Kriteria Hashin yang berdasarkan tegasan di bawah pembebanan berkitar dikembangkan dan digunakan untuk menggambarkan proses penumpukan kerosakan akibat kelesuan. Model ternormal digunakan untuk menggambarkan penurunan sifat kekuatan dan kekukuhan akibat kelesuan. Model ini merangkumi kesan tegasan min terhadap proses kerosakan dan kepatahan. Telah diperhatikan bahawa kekuatan ricih pada CFRP komposit lamina adalah yang pertama merosot jika dibandingkan dengan sifat lain. Ciri-ciri evolusi kerosakan kelesuan yang diramalkan diperiksa pada titik tertentu pada bahan dalam lamina CFRP komposit sepanjang pembebanan kelesuan. Untuk tujuan ini, model FE dari plat CFRP komposit lamina berserta lubang pada tengah plat dikenakan tegasan tegangan-tegangan berkitar (κ= 0.1) pada arah melintang gentian. Oleh kerana pengiraan jangka hayat kitaran demi kitaran tidak praktikal memandangkan bilangan besar kitaran kelesuan yang terlibat, urutan blok kitaran beban diperkenalkan untuk menangani kecekapan rutin komputasi untuk ramalan jangka hayat akibat kelesuan. Jumlah kitaran beban yang ditunjukkan oleh setiap blok ditentukan oleh kadar penurunan sifat kekuatan bahan. Blok kitaran beban ditentukan oleh baki kekuatan bahan dengan jangka hayat terpendek (N_f) di bawah bebanan kelesuan. Evolusi tidak lelurus menggambarkan kerosakan akibat kelesuan dengan kitaran tegasan yang berlaku ditunjukkan. Tahap kritikal kerosakan kelesuan, ditentukan berdasarkan jumlah tenaga patah yang hilang, menunjukkan penukleusan retak akibat kelesuan. Daripada kajian kes di bawah operasi tegasan ${\sigma_{22}}^{max}$= 18.85 MPa dan ${\tau_{12}}^{max}$= 1.30 MPa, kerosakan kelesuan dalam bentuk tegangan matriks terkumpul pada titik kritikal memenuhi persamaan $g_{MT} = 1.0$ selepas melalui n^d=1.93 $\times 10^3$ kitaran. Pengumpulan titik bahan yang terpisah sepanjang kitaran kelesuan yang berlaku mewakili retakan akibat kelesuan tersebar. Rutin pengiraan mudah dilaksanakan dalam mana-mana perisian standard FEA untuk ramalan yang tepat bagi jangka hayat bahan daripada struktur komposit polimer lamina bertetulang gentian (FRP) akibat kelesuan. Model kerosakan bersatu akibat kelesuan yang dibangunkan dalam tesis ini adalah penting untuk sektor perindustrian yang berkaitan dengan industri pembuatan FRP komposit, fabrikasi dan analisis kegagalan struktur penahan beban.

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LIST OF ABBREVIATIONS

3D	-	Three-dimensional
AFP	-	Automated fiber replacement
ASTM	-	American Society for Testing and Materials
ATL	-	Automated tape laying
CDM	-	Continuum damage mechanics
CFRP	-	Carbon-fiber reinforced polymer
CTRM	-	Composite Technology Research Malaysia
CZM	-	Cohesive zone model
FE	-	Finite element
FEM	-	Finite element modeling
FRP	-	Fiber-reinforced polymer
GFRP	-	Glass-fiber reinforced composite laminates
HLU	-	Hand lay-up
RFI	-	Resin film infusion
RP	-	Reference point
RTM	-	Resin transfer molding
SC8R	-	8-node hexahedron, general-purpose, finite membrane strains element
UAV	-	Unmanned aerial vehicle
UD	-	Unidirectional
UHMW	-	Ultra-high molecular weight polyethylene
VIP	-	Vacuum Infusion Process

LIST OF SYMBOLS

d_{FC} - Damage indicator in fiber damage under compression under quasi-static loading.

d_{FT} - Damage indicator in fiber damage under tension under quasi-static loading.

d_{MC} - Damage indicator in matrix damage under compression under quasi-static loading.

d_{MT} - Damage indicator in matrix damage under tension under quasi-static loading.

E - Young's modulus

$\hat{E}$ - Normalized stiffness

$\hat{E}_{11}$ - Normalized longitudinal stiffness

$\hat{E}_{22}$ - Normalized transverse stiffness

G - Shear modulus

g_{FC} - Damage indicator in fiber damage under compressive fatigue loading.

g_{FT} - Damage indicator in fiber damage under tensile fatigue loading.

g_{MC} - Damage indicator in matrix damage under compressive fatigue loading.

g_{MT} - Damage indicator in matrix damage under tensile fatigue loading.

$\hat{G}_{12}$ - Normalized shear stiffness

n - Number of cycles

$\hat{N}$ - Normalized number of cycles

N_f - Number of cycles to failure

P_{cyclic} - Cyclic load

P_{max} - Maximum load

P_{min} - Minimum load

κ - Stress-ratio

R - Residual strength

$\hat{R}$ - Normalized strength

S_1 - Interface shear strength for sliding shear mode

S_2 - Interface shear strength for tearing shear mode

S^L - Longitudinal shear strength

S^T - Transverse shear strength

$\hat{S}^L$ - Normalized longitudinal shear strength

$\hat{S}^T$ - Normalized transverse shear strength

T - Interface tensile strength

U_x - Displacement in x-axis

U_y - Displacement in y-axis

U_z - Displacement in z-axis

UR_x - Rotation about x-axis

UR_y - Rotation about y-axis

UR_z - Rotation about z-axis

X^C - Longitudinal compressive strength

X^T - Longitudinal tensile strength

$\hat{X}^C$ - Normalized longitudinal compressive strength

$\hat{X}^T$ - Normalized longitudinal tensile strength

Y^C - Compressive tensile strength

Y^T - Transverse tensile strength

$\hat{Y}^C$ - Normalized transverse compressive strength

$\hat{Y}^T$ - Normalized transverse tensile strength

α - Contribution of shear stress to the fiber tension mode of failure

γ - Shear strain

ε - Strain

ε_f - Strain to failure

σ - Nominal, true or Cauchy stress tensor

σ^a - Amplitude stress

σ^m - Mean stress

σ^{max} - Maximum stress

τ - Shear stress

ν - Poisson’s ratio

χ - Life parameter

CHAPTER 1

INTRODUCTION

1.1 Research Background

FRP composite material is used for applications in various industries, such as aeronautical, automotive, marine, and advanced engineering applications. This is due to the high strength-to-weight ratio of FRP composite that makes them desirable for structural applications than conventional material. In the aerospace and automotive industries, the aim can be accomplished by substituting metal-based alloys with lighter materials such as carbon fiber-reinforced polymer (CFRP) composite. This may explain the significant increase in the use of CFRP composite material which is less than 20% in 1987 (A320), to over 50% in 2013 (A350 XWB) [1]. Besides, FRP composite material provides corrosion resistance in the marine environment and therefore requires less maintenance. Nowadays, racing powerboats such as superyachts made of composite are becoming more common for long-lasting performance and safety. The 48M Supersport is the largest superyacht constructed out of FRP composite which the fuel efficiency is optimized by 50% due to weight reduction[2]. Apart from that, CFRP composites provide design flexibility through the sequencing of pre-impregnated laminates for tailored strength and stiffness properties in particular loading directions. Thanks to these advantages, the wind industry is growing rapidly during the last half of the twentieth century and continues to grow to meet the demand for larger wind turbine rotor blades.

The fact that could not be avoided is that the composite components are subjected to different loading types, both static and fatigue, as well as the harsh operating environment. This necessitates investigations, particularly into fatigue and fracture analysis of the structure. Fatigue is the most frequent cause of structural failures and should be accounted for in any structural design process. In fact, in the last decades, fiber-reinforced polymer (FRP) composite has attracted increasing attention, especially in fatigue [3]. Under fatigue loading conditions, the FRP composite laminate simultaneously experiences multiple damage mechanisms, including intra- and interlaminar. The laminate consists of plies of the lamina and the interfaces between the laminas. In order to reduce the complexity, the effect of fatigue loading is treated separately in laminas and interfaces. Therefore, it is of paramount importance to understand the mechanism associated with fatigue damage and introduce a predictive model to predict the damage in FRP composite laminate.

Fatigue damage models are necessary to be well developed by adapting the damage mechanics approach to predict damage development in the laminated composite structure during service lifetime. In the FRP composite laminates, the development of damage is depicted through the degradation of material properties. However, the variety of laminate design configurations makes it impractical to determine degradation properties through experimentation alone. Thus, it is more desirable to predict the material performance during fatigue loading conditions by modeling behavior in response to the applied load. An accurate fatigue damage model for the laminated composite could facilitate design improvement of FRP composite structure. The fatigue model should be able to predict the fatigue behavior of the laminate for any layup configuration for structural reliability assessment.

Consequently, this research work complements the development of damage-based fatigue model for FRP composite laminates. The emphasis is on the fatigue failure of the laminas. The fatigue model of the interfaces is being addressed separately. Ultimately, the fatigue damage model for lamina and interface is implemented in the reliability prediction of FRP composite laminates, where the interaction of interface and lamina damage is captured under general loading conditions.

1.2 Statement of Research Problem

The damage development during fatigue loading conditions in a FRP composite lamina is predicted using a damage model. In this study, the unified damage model is developed based on the degradation of mechanical properties of the material. The evolution of fatigue damage is described through the degradation of fracture energy. The modeling concept for the FRP composite laminates has been studied and available the open literature [4, 5] based on stress controlled condition. However, the approach presented in this thesis is illustrated for constant displacement during the fatigue loading. It follows that the effect of damage is observed through the level of stress diminishing during the loading cycles. In addition, in a multidirectional laminate, the significant failure mechanism is addressed by the competition between the weak interfaces and continuously degrading matrix properties of the lamina. The approach is to address the issues separately. In this study, the damage-based fatigue model is developed for the quantitative and physically-based description of fatigue damage development of the lamina. Developing a unified damage model allows a better prediction of fatigue behavior of the laminate, particularly for the lamina. Such model caters for the damage prediction in any layup configuration of the laminates. Since the model is accounts for the non-linear properties degradation, an incremental calculation procedure is introduce to address the accumulated damage throughout the fatigue loading. This approach addresses the central question of *"How to correctly and efficiently predict the reliability and failure response of CFRP composite lamina under cyclic loading condition."*

1.3 Research Objectives

This research aims to develop a new damage-based fatigue model of unidirectional FRP composite lamina. The specific objectives are:

(a) To establish characteristic residual properties of the lamina due to fatigue loading conditions.

(b) To develop a new damage model for fatigue of UD lamina based on cyclic property degradation.

(c) To quantify the characteristic evolution of the lamina damage under cyclic loading conditions

1.4 Scope of Study

The scopes of study cover the following:

1. Lamina damage model is developed based on equivalent UD lamina at mesoscale.
2. Mechanical destructive tests are conducted on CFRP composite lamina $[0°]_S$ for properties extraction. The tests are conducted according to American Society for Testing and Materials (ASTM) standards. These tests are conducted at room temperature and laboratory air/humidity environment under static loading.
3. Property degradation modes are developed. Test data in item *2* are used in the model.
4. Incremental fatigue damage is calculated based on load cycle-block approach.
5. Fatigue damage evolution characteristic is illustrated through a case example of 16-ply CFRP composite laminate with a straight-through hole. Computational efficiency is considered in fatigue damage calculations. This would be practical in addressing reliability of composite structures.
6. FE simulation using SIMULIA Abaqus ver. 6.12 commercial software.

1.5 Significance of the Outcomes

The degradation of residual fatigue properties dictates the fatigue damage accumulation in the FRP composite lamina. The properties degradations are obtained through the normalization of residual properties to the static properties. Thus, the developed methodology can be extrapolated to any set of properties for carbon-based FRP composite under various stress ratios without reproducing the experimental tests. In addition, the methodology can be adopted for any FRP composite laminate layup configuration. Due to the high number of fatigue cycles involved, a load-cycle block approach is introduced to address the efficiency issue in fatigue damage prediction. The establishment of methodology and predictive model will fulfill the industrial requirement, especially reducing the number of experimental tests. This is significant for all industrial sectors, including aerospace, automotive, marine, and advanced engineering applications.

1.6 Thesis Layout

All chapters in this thesis had been arranged to establish a model for predicting fatigue damage in FRP composite lamina. The methodology for predicting the fatigue lamina damage was explained in this thesis. Therefore, the content of each chapter had been specified to explain the objectives and scope of the research as follows.

Chapter 1 describes a summary background of composite laminates. Then the problem statement, scope, and objectives of the research are defined. The limits of what this study is restricted to are being highlighted.

Chapter 2 summarizes previous researchers' findings and literature regarding CFRP composite laminates properties and behavior under static and fatigue loading. This includes the previous research on related static and fatigue damage models for FRP composite laminate. A review of existing damage models for cyclic loading applications is presented to bring the reader up to date with the current literature on the topic.

Chapter 3 details about research methodology of the current work. A methodology on process of constructing the new lamina fatigue damage model is explained. The foundation of extracting fatigue degradation properties through quasi-static tests is elaborated. The details on the finite element (FE) simulation for the case study are described.

Chapter 4 describes the characteristic of the cyclic degradation properties. The normalized strength approach is adapted in order to obtain properties degradation for fatigue loading. Also, the applicability of this method for carbon-based material is presented in this chapter. As a result, nine normalized properties degradation curves are generated, including residual strength and stiffness properties.

Chapter 5 elaborates the extended theory for the lamina damage model for CFRP composite laminates under cyclic loading conditions. A set of new fatigue damage criteria is proposed to predict damage specifically in a FRP composite lamina. The characteristic of the damage model for lamina damage is explained here.

Chapter 6 discuss the fatigue damage evolution in CFRP composite lamina based specific case study. The newly developed fatigue damage model for the lamina is explained through the numerical value resulted from the case study. Detailed analysis of damage calculation is given in this chapter. The energy-based concept is used to discuss the evolution of fatigue damage to nucleation at a material point.

Chapter 7 summarizes the main conclusion related to the methodology to obtain the damage parameters and the newly extended lamina damage model under cyclic damage conditions. The main contributions that have been addressed in the form of research objectives were concluded in this chapter. Additional work was recommended for further advanced research.

REFERENCES

1. Airbus. Flying Ahead 2016, April 28 [Available from: https://www.airbus.com/content/dam/corporate-topics/financial-and-company-information/airbus-ra-2015-en-03.pdf.]
2. García-Espinosa J, Salinas R. FIBRESHIP objectives and concept. 2016.
3. Vassilopoulos AP. The history of fiber-reinforced polymer composite laminate fatigue. International Journal of Fatigue. 2020;134:105512.
4. Krüger H, Rolfes R. A physically based fatigue damage model for fibre-reinforced plastics under plane loading. International Journal of Fatigue. 2015;70:241-51.
5. Brod M, Dean A, Rolfes R. Numerical life prediction of unidirectional fiber composites under block loading conditions using a progressive fatigue damage model. International Journal of Fatigue. 2021;147:106159.
6. Henry A. McLaren: Formula 1 Racing Team: Haynes Pub.; 1999.
7. Davies P, Rajapakse YD. Durability of composites in a marine environment: Springer; 2014.
8. Seo H-S, Jang H-Y, Lee I-W, Choi H-S. Development of 33feet Class America's Cup Training CFRP Sailing Yacht for Marine and Leisure Applications. Composites Research. 2015;28(1):15-21.
9. Jang H, Lee I, Seo H. Effectiveness of CFRP rudder aspect ratio for scale model catamaran racing yacht test. Journal of Mechanical Science and Technology. 2017;31(9):4109-17.
10. Airbus. [Available from: https://www.airbus.com/]
11. Boeing. [Available from: https://www.boeing.com/]
12. Selvaraju S, Ilaiyavel S. Applications of composites in marine industry. Journal of Engineering Research and Studies. 2011;2(2):89-91.
13. Selvaraju S, Ilaiyavel S. Applications of composites in marine industry. J Eng Res Stud, II. 2011:89-91.

14. Stewart R. Wind turbine blade production–new products keep pace as scale increases. Reinforced Plastics. 2012;56(1):18-25.

15. Ong C-H, Tsai SW. The use of carbon fibers in wind turbine blade design: a SERI-8 blade example. Sandia National Labs., Albuquerque, NM (US); Sandia National Labs …; 2000.

16. Ennis BL, Kelley CL, Naughton BT, Norris B, Das S, Lee D, et al. Optimized Carbon Fiber Composites in Wind Turbine Blade Design. Sandia National Lab.(SNL-NM), Albuquerque, NM (United States); 2019.

17. Zhang Q, editor The" Black Revolution" of Sports Equipment: Application of Carbon Fiber Reinforced Plastics (CFRP). Applied Mechanics and Materials; 2014: Trans Tech Publ.

18. Kaiser R. Technology Assessment of Advanced Composites. Phase 1. Applied Enginerring Resources Inc. Santa Barbara CA; 1978.

19. Chang R, Dai W, Wu F, Jia S, Tan H. Design and manufacturing of a laminated composite bicycle crank. Procedia Eng. 2013;67:497-505.

20. Elkington M, Bloom D, Ward C, Chatzimichali A, Potter K. Hand layup: understanding the manual process. Advanced manufacturing: polymer & composites science. 2015;1(3):138-51.

21. Dirk H-JL, Ward C, Potter KD. The engineering aspects of automated prepreg layup: History, present and future. Composites Part B: Engineering. 2012;43(3):997-1009.

22. Hashim S, Nisar J. An investigation into failure and behaviour of GFRP pultrusion joints. International journal of adhesion and adhesives. 2013;40:80-8.

23. Al Mahmood A, Mobin A, Morshed R, Zaman T. Characterization of glass fibre reinforced polymer composite prepared by hand layup method. American journal of bioscience and bioengineering. 2017;5(1):8.

24. Chaple A, Khedakar S, Dharmadhikari S, Chaple N. Newly developed automatic lay-up process for manufacturing of FRP sheets. Int J Comput Eng Res. 2013;3(3):92-7.

25. Blumenfeld L. Flight Airworthiness Support Technology (FAST). 2013, Jun.

26. Gooch JW. Encyclopedic dictionary of polymers: Springer Science & Business Media; 2010.

27. Heimbs S, Nogueira A, Hombergsmeier E, May M, Wolfrum J. Failure behaviour of composite T-joints with novel metallic arrow-pin reinforcement. Composite Structures. 2014;110:16-28.

28. Goren A, Atas C. Manufacturing of polymer matrix composites using vacuum assisted resin infusion molding. Archives of materials Science and Engineering. 2008;34(2):117-20.

29. Van Oosterom S, Allen T, Battley M, Bickerton S. An objective comparison of common vacuum assisted resin infusion processes. Composites Part A: Applied Science and Manufacturing. 2019;125:105528.

30. Hoebergen A, Holmberg J. Vacuum infusion. Materials Park, OH: ASM International, 2001. 2001:501-15.

31. Koloor S, Khosravani MR, Hamzah R, Tamin M. FE model-based construction and progressive damage processes of FRP composite laminates with different manufacturing processes. International Journal of Mechanical Sciences. 2018;141:223-35.

32. Dutton S, Kelly D, Baker A. Composite materials for aircraft structures: American Institute of Aeronautics and Astronautics; 2004.

33. Chae HG, Choi YH, Minus ML, Kumar S. Carbon nanotube reinforced small diameter polyacrylonitrile based carbon fiber. Composites Science and Technology. 2009;69(3-4):406-13.

34. Kaw AK. Mechanics of composite materials: CRC press; 2005.

35. Gunes O. Failure modes in structural applications of fiber-reinforced polymer (FRP) composites and their prevention. Developments in Fiber-Reinforced Polymer (FRP) Composites for Civil Engineering: Elsevier; 2013. p. 115-47.

36. Kelly G, Hallström S. Strength and failure mechanisms of composite laminates subject to localised transverse loading. Composite structures. 2005;69(3):301-14.

37. Rosen BW. Tensile failure of fibrous composites. AIAA journal. 1964;2(11):1985-91.

38. Tagarielli V, Minisgallo G, McMillan A, Petrinic N. The response of a multi-directional composite laminate to through-thickness loading. Composites science and technology. 2010;70(13):1950-7.

39. Mangalgiri P. Composite materials for aerospace applications. Bulletin of Materials Science. 1999;22(3):657-64.

40. Adden S, Horst P. Damage propagation in non-crimp fabrics under bi-axial static and fatigue loading. Composites Science and Technology. 2006;66(5):626-33.

41. Lafarie-Frenot M, Henaff-Gardin C. Formation and growth of 90° ply fatigue cracks in carbon/epoxy laminates. Composites Science and Technology. 1991;40(3):307-24.

42. Quaresimin M, Carraro P. On the investigation of the biaxial fatigue behaviour of unidirectional composites. Composites Part B: Engineering. 2013;54:200-8.

43. Yokozeki T, Aoki T, Ishikawa T. Fatigue growth of matrix cracks in the transverse direction of CFRP laminates. Composites science and technology. 2002;62(9):1223-9.

44. Kaminski M, Laurin F, Maire J, Rakotoarisoa C, Hémon E. Fatigue damage modeling of composite structures: the onera viewpoint. AerospaceLab. 2015(9):p. 1-12.

45. Herup EJ, Palazotto AN. Low-velocity impact damage initiation in graphite/epoxy/nomex honeycomb-sandwich plates. Composites Science and Technology. 1998;57(12):1581-98.

46. Silberschmidt VV. Dynamic deformation, damage and fracture in composite materials and structures: Woodhead Publishing; 2016.

47. Miyano Y, Nakada M, Ichimura J, Hayakawa E. Accelerated testing for long-term strength of innovative CFRP laminates for marine use. Composites Part B: Engineering. 2008;39(1):5-12.

48. Nakada M. Accelerated Testing Methodology for Life Prediction of Polymer Composites. Wiley Encyclopedia of Composites. 2011:1-11.

49. Reifsnider K, Jamison R. Fracture of fatigue-loaded composite laminates. International Journal of Fatigue. 1982;4(4):187-97.

50. Schulte K. Stiffness reduction and development of longitudinal cracks during fatigue loading of composite laminates. Mechanical characterisation of load bearing fibre composite laminates. 1985:36-54.

51. Van Paepegem W, Degrieck J. A new coupled approach of residual stiffness and strength for fatigue of fibre-reinforced composites. International Journal of Fatigue. 2002;24(7):747-62.

52. Lasn K. Evaluation of Stiffness and Damage of Laminar Composites. 2015.

53. Koloor S, Tamin M, editors. Effects of lamina damages on flexural stiffness of CFRP composites. Proceedings of the 8th Asian-Australasian Conference on Composite Materials; 2012.

54. Koloor R. SS Simulation Methodology for Fracture Processes of Composite Laminates Using Damage-Based Models. Department of design and applied mechanics, faculty of mechanical engineering: Universiti Teknologi Malaysia, Johor; 2016.

55. Zhang W, Zhou Z, Scarpa F, Zhao S. A fatigue damage meso-model for fiber-reinforced composites with stress ratio effect. Materials & Design. 2016;107:212-20.

56. Lee J-W, Allen D, Harris C. Internal state variable approach for predicting stiffness reductions in fibrous laminated composites with matrix cracks. Journal of Composite Materials. 1989;23(12):1273-91.

57. Pagano N, Pipes RB. The influence of stacking sequence on laminate strength. Journal of composite materials. 1971;5(1):50-7.

58. Bailey J, Curtis P, Parvizi A. On the transverse cracking and longitudinal splitting behaviour of glass and carbon fibre reinforced epoxy cross ply laminates and the effect of Poisson and thermally generated strain. Proceedings of the Royal Society of London A Mathematical and Physical Sciences. 1979;366(1727):599-623.

59. Wicaksono S. Fracture of laminated panels in tension. Mechanical and aerospace engineering. 2009:90-102.

60. Azzi V, Tsai S. Anisotropic strength of composites. Experimental mechanics. 1965;5(9):283-8.

61. Tsai SW, Wu EM. A general theory of strength for anisotropic materials. Journal of composite materials. 1971;5(1):58-80.

62. Hashin Z. Failure criteria for unidirectional fiber composites. Journal of applied mechanics. 1980;47(2):329-34.

63. Hashin Z, Rotem A. A fatigue failure criterion for fiber reinforced materials. Journal of composite materials. 1973;7(4):448-64.

64. Yamada S, Sun C. Analysis of laminate strength and its distribution. Journal of composite materials. 1978;12(3):275-84.

65. Hart-Smith L. A new approach to fibrous composite laminate strength prediction. 1990.

66. Chang F-K, Chang K-Y. A progressive damage model for laminated composites containing stress concentrations. Journal of composite materials. 1987;21(9):834-55.

67. Shahid I, Chang F-K. An accumulative damage model for tensile and shear failures of laminated composite plates. Journal of Composite Materials. 1995;29(7):926-81.

68. Rahimian Koloor SS, Karimzadeh A, Yidris N, Petrů M, Ayatollahi MR, Tamin MN. An Energy-Based Concept for Yielding of Multidirectional FRP Composite Structures Using a Mesoscale Lamina Damage Model. Polymers. 2020;12(1):157.

69. Koloor R. Simulation Methodology for Fracture Processes of Composite Laminates Using Damage-Based Models. Department of design and applied mechanics, faculty of mechanical engineering: Universiti Teknologi Malaysia, Johor; 2016.

70. Barenblatt GI. The mathematical theory of equilibrium cracks in brittle fracture. Advances in applied mechanics. 7: Elsevier; 1962. p. 55-129.

71. Ungsuwarungsri T, Knauss WG. The role of damage-softened material behavior in the fracture of composites and adhesives. International Journal of Fracture. 1987;35(3):221-41.

72. Cui W, Wisnom M, Jones M. A comparison of failure criteria to predict delamination of unidirectional glass/epoxy specimens waisted through the thickness. Composites. 1992;23(3):158-66.

73. Davila C, Camanho P, editors. Analysis of the effects of residual strains and defects on skin/stiffener debonding using decohesion elements. 44th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference; 2003.

74. Davila C, Jaunky N, Goswami S, editors. Failure criteria for FRP laminates in plane stress. 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference; 2003.

75. Abdullah M. Delamination damage of carbon fiber-reinforced polymer composite laminates under cyclic shrear-induced loading conditions: Universiti Teknologi Malaysia; 2018.

76. Beaumont PW. The Structural Integrity of Composite Materials and Long-Life Implementation of Composite Structures. Applied Composite Materials. 2020;27(5):449-78.

77. Gamstedt EK, Andersen SI. Fatigue degradation and failure of rotating composite structures-Materials characterisation and underlying mechanisms. 2001.

78. Wicaksono S, Chai GB. A review of advances in fatigue and life prediction of fiber-reinforced composites. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications. 2013;227(3):179-95.

79. Degrieck and J, Van Paepegem W. Fatigue damage modeling of fibre-reinforced composite materials. Appl Mech Rev. 2001;54(4):279-300.

80. SENDECKYJ GP. Life prediction for resin-matrix composite materials. Composite materials series. 4: Elsevier; 1991. p. 431-83.

81. Vassilopoulos AP, Manshadi BD, Keller T. Influence of the constant life diagram formulation on the fatigue life prediction of composite materials. International journal of fatigue. 2010;32(4):659-69.

82. Whitworth H. A stiffness degradation model for composite laminates under fatigue loading. Composite structures. 1997;40(2):95-101.

83. Zhang Y, Vassilopoulos AP, Keller T. Stiffness degradation and fatigue life prediction of adhesively-bonded joints for fiber-reinforced polymer composites. International journal of fatigue. 2008;30(10-11):1813-20.

84. Shokrieh MM. Progressive fatigue damage modeling of composite materials. PhD Thesis. 1996;Department of Mechanical Engineering, McGill University, Canada.

85. Philippidis T, Passipoularidis V. Residual strength after fatigue in composites: Theory vs. experiment. International Journal of Fatigue. 2007;29(12):2104-16.

86. Shokrieh MM, Lessard LB. Progressive fatigue damage modeling of composite materials, Part II: Material characterization and model verification. Journal of Composite materials. 2000;34(13):1081-116.

87. Tserpes KI, Papanikos P, Kermanidis T. A three-dimensional progressive damage model for bolted joints in composite laminates subjected to tensile loading. Fatigue & Fracture of Engineering Materials & Structures. 2001;24(10):663-75.

88. Montesano J, Chu H, Singh CV. Development of a physics-based multi-scale progressive damage model for assessing the durability of wind turbine blades. Composite Structures. 2016;141:50-62.

89. Hack M, Carrella-Payan D, Magneville B, Naito T, Urushiyama Y, Yamazaki W, et al. A progessive damage fatigue model for unidirectional laminated composites based on finite element analysis. Frattura ed Integrità Strutturale. 2018;12(46):54-61.

90. Jen M-H, Lee C-H. Strength and life in thermoplastic composite laminates under static and fatigue loads. Part I: Experimental. International journal of fatigue. 1998;20(9):605-15.

91. Jen M-HR, Lee C-H. Strength and life in thermoplastic composite laminates under static and fatigue loads. Part II: Formulation. International journal of fatigue. 1998;20(9):617-29.

92. Philippidis T, Vassilopoulos A. Fatigue strength prediction under multiaxial stress. Journal of Composite Materials. 1999;33(17):1578-99.

93. Reifsnider K, Gao Z. A micromechanics model for composites under fatigue loading. International Journal of Fatigue. 1991;13(2):149-56.

94. Fawaz Z, Ellyin F. Fatigue failure model for fibre-reinforced materials under general loading conditions. Journal of composite materials. 1994;28(15):1432-51.

95. Paramonov YM, Kleinhof M, Paramonova AY. A probabilistic model of the fatigue life of composite materials for fatigue-curve approximations. Mechanics of composite materials. 2002;38(6):485-92.

96. Mandell JF, Samborsky DD. DOE/MSU composite material fatigue database: test methods, materials, and analysis. Sandia National Labs., Albuquerque, NM (United States); 1997.

97. Shokrieh MM, Lessard LB. Progressive fatigue damage modeling of composite materials, Part I: Modeling. Journal of composite materials. 2000;34(13):1056-80.

98. Zhang W, Zhou Z, Zheng P, Zhao S. The fatigue damage mesomodel for fiber-reinforced polymer composite lamina. Journal of Reinforced Plastics and Composites. 2014;33(19):1783-93.

99. Chou PC, Croman R. Residual strength in fatigue based on the strength-life equal rank assumption. Journal of Composite Materials. 1978;12(2):177-94.

100. Chou P, Croman R, editors. Degradation and sudden-death models of fatigue of graphite/epoxy composites. Composite Materials: Testing and Design (Fifth Conference); 1979: ASTM International.

101. Huston R. Fatigue life prediction in composites. International journal of pressure vessels and piping. 1994;59(1-3):131-40.

102. Epaarachchi JA, Clausen PD. An empirical model for fatigue behavior prediction of glass fibre-reinforced plastic composites for various stress ratios and test frequencies. Composites Part A: Applied science and manufacturing. 2003;34(4):313-26.

103. Yao W, Himmel N. A new cumulative fatigue damage model for fibre-reinforced plastics. Composites science and technology. 2000;60(1):59-64.

104. Hahn HT, editor Fatigue behavior and life prediction of composite laminates. Composite materials: testing and design (fifth conference); 1979: ASTM International.

105. Revuelta D, Miravete A. Fatigue damage in composite materials. International applied mechanics. 2002;38(2):121-34.

106. Payan J, Hochard C. Damage modelling of carbon/epoxy laminated composites under static and fatigue loads. 2002.

107. Hahn H, Kim RY. Fatigue behavior of composite laminate. Journal of Composite Materials. 1976;10(2):156-80.

108. O'Brien TK, Reifsnider KL. Fatigue damage evaluation through stiffness measurements in boron-epoxy laminates. Journal of composite materials. 1981;15(1):55-70.

109. Lian W, Yao W. Fatigue life prediction of composite laminates by FEA simulation method. International Journal of Fatigue. 2010;32(1):123-33.

110. Pfanner D. Zur Degradation von Stahlbetonbauteilen unter Ermüdungsbeanspruchung: VDI-Verlag; 2003.

111. Biner S, Yuhas V. Growth of short fatigue cracks at notches in woven fiber glass reinforced polymeric composites. 1989.

112. Owen M, Bishop P, editors. Prediction of static and fatigue damage and crack propagation in composite materials. AGARD Specialists Meeting on Failure Modes of Composite Mater With Organic Matrices and Their Consequences on Design 12 p(SEE N 75-23698 15-24); 1975.

113. Bergmann H, Prinz R. Fatigue life estimation of graphite/epoxy laminates under consideration of delamination growth. International journal for numerical methods in engineering. 1989;27(2):323-41.

114. Dahlen C, Springer GS. Delamination growth in composites under cyclic loads. Journal of Composite Materials. 1994;28(8):732-81.

115. Feng X, Gilchrist M, Kinloch A, Matthews F, editors. Development of a method for predicting the fatigue life of CFRP components. Proceedings of the International Conference on Fatigue of Composites; 1997.

116. Ogin S, Smith P, Beaumont P. Matrix cracking and stiffness reduction during the fatigue of a (0/90) s GFRP laminate. Composites Science and Technology. 1985;22(1):23-31.

117. Harris B. Fatigue behaviour of polymer-based composites and life prediction methods. AIB-Vinçotte Leerstoel. 1996;2.

118. Knight N, editor Factors influencing progressive failure analysis predictions for laminated composite structures. 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 16th AIAA/ASME/AHS Adaptive Structures Conference, 10th AIAA Non-Deterministic Approaches Conference, 9th AIAA Gossamer Spacecraft Forum, 4th AIAA Multidisciplinary Design Optimization Specialists Conference; 2008.

119. Khan AI, Venkataraman S, Miller I. Predicting fatigue damage of composites using strength degradation and cumulative damage model. Journal of Composites Science. 2018;2(1):9.

120. Nakai-Chapman J, Park YH, Sakai J. Implementation of progressive failure for fatigue based on cycle-dependent material property degradation model. Multiscale and Multidisciplinary Modeling, Experiments and Design. 2021;4(1):41-50.

121. Hinton M, Soden P. Predicting failure in composite laminates: the background to the exercise. Composites Science and Technology. 1998;58(7):1001-10.

122. Hinton M, Kaddour A, Soden P. Predicting failure in fibre composites: Lessons learned from the World-Wide Failure Exercise. Technical Papers-Society of Manufacturing Engineers-All Series-. 2002.

123. Highsmith AL, Reifsnider KL. Stiffness-reduction mechanisms in composite laminates. Damage in composite materials: basic mechanisms, accumulation, tolerance, and characterization: ASTM International; 1982.

124. Sendeckyj G. Fitting models to composite materials fatigue data. Test methods and design allowables for fibrous composites: ASTM International; 1981.

125. Radhakrishnan K. Fatigue and reliability evaluation of unnotched carbon epoxy laminates. Journal of composite materials. 1984;18(1):21-31.

126. Halpin JC, Jerina KL, Johnson TA. Characterization of composites for the purpose of reliability evaluation. Analysis of the test methods for high modulus fibers and composites: ASTM International; 1973.

127. Broutman L, Sahu S, editors. A new theory to predict cumulative fatigue damage in fiberglass reinforced plastics. Composite materials: Testing and design (second conference); 1972: ASTM International.

128. Daniel I, Charewicz A. Fatigue damage mechanisms and residual properties of graphite/epoxy laminates. Engineering Fracture Mechanics. 1986;25(5-6):793-808.

129. Reifsnider KL, Stinchcomb W. A critical-element model of the residual strength and life of fatigue-loaded composite coupons. Composite materials: fatigue and fracture: ASTM International; 1986.

130. Adam T, Dickson R, Jones C, Reiter H, Harris B. A power law fatigue damage model for fibre-reinforced plastic laminates. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 1986;200(3):155-66.

131. Shokrieh MM, Lessard LB. Multiaxial fatigue behaviour of unidirectional plies based on uniaxial fatigue experiments—I. Modelling. International Journal of fatigue. 1997;19(3):201-7.

132. Shokrieh MM, Lessard LB. Multiaxial fatigue behaviour of unidirectional plies based on uniaxial fatigue experiments—II. Experimental evaluation. International journal of fatigue. 1997;19(3):209-17.

133. Totry E, Molina-Aldareguía JM, González C, LLorca J. Effect of fiber, matrix and interface properties on the in-plane shear deformation of carbon-fiber reinforced composites. Composites Science and Technology. 2010;70(6):970-80.

134. Adam T, Fernando G, Dickson R, Reiter H, Harris B. Fatigue life prediction for hybrid composites. International Journal of Fatigue. 1989;11(4):233-7.

135. Adam T, Gathercole N, Reiter H, Harris B. Fatigue life prediction for carbon fibre composites. Advanced Composites Letters. 1992;1(1):096369359200100106.

136. Gathercole N, Reiter H, Adam T, Harris B. Life prediction for fatigue of T800/5245 carbon-fibre composites: I. Constant-amplitude loading. international Journal of Fatigue. 1994;16(8):523-32.

137. Chen D, Sun G, Meng M, Jin X, Li Q. Flexural performance and cost efficiency of carbon/basalt/glass hybrid FRP composite laminates. Thin-Walled Structures. 2019;142:516-31.

138. Brod M, Just G, Jansen E, Koch I, Rolfes R, Gude M, editors. Simulation of the fatigue damage behavior of carbon composites under consideration of manufacturing induced residual stresses. Proceedings of the 7th International Conference on the Fatigue of Composites; 2018.

139. Khan A, Venkataraman S, Miller I. Predicting fatigue damage of composites using strength degradation and cumulative damage model. Journal of Composites Science. 2018;2(1):9.

140. Turon A, Camanho PP, Costa J, Dávila CG. An interface damage model for the simulation of delamination under variable-mode ratio in composite materials. 2004.

141. Van Paepegem W. The cycle jump concept for modelling high-cycle fatigue in composite materials. Fatigue of Textile Composites: Elsevier; 2015. p. 29-55.

142. Llobet J, Maimí P, Essa Y, de la Escalera FM. A continuum damage model for composite laminates: Part III-Fatigue. Mechanics of Materials. 2021;153:103659.

143. Van Paepegem W, Degrieck J, De Baets P. Finite element approach for modelling fatigue damage in fibre-reinforced composite materials. Composites Part B: Engineering. 2001;32(7):575-88.

144. Botkin M, Johnson N, Simunovic S, Zywicz E. Crashworthiness simulation of composite automotive structures. Lawrence Livermore National Laboratory, Livermore, CA; 1998.

145. Majamäki J, editor Impact simulations of a composite helicopter structure with MSC. Dytran. URL: http://www mscsoftware com/events/aero2002/abstracts/pdf/p00701a pdf) MSC-f Worldwide Aerospace Conference & Technology Showcase, Toulouse, France; 2002.

146. Kong C, Park H, Lee H, Lee J. Design of natural fiber composites chemical container using resin flow simulation of VARTML process. Int J Mater Mech Manuf. 2014;2(3):256-60.

147. Maia LG, De Oliveira PHIA. A review of finite element simulation of aircraft crashworthiness. SAE Technical Paper; 2005. Report No.: 0148-7191.

148. Lenzi L. Analysis of the rear impact-absorption structure of a racing car: Politecnico di Torino; 2020.

149. Melani A, Khare R. Finite Element Modelling and Free Vibration Analysis of RC Shell & Spatial Structures for Seismic Evaluation. 2019.

150. Karakoti A, Tripathy P, Kar V, Jayakrishnan K, Rajesh M, Manikandan M. Finite element modeling of natural fiber-based hybrid composites. Modelling of Damage Processes in Biocomposites, Fibre-Reinforced Composites and Hybrid Composites: Elsevier; 2019. p. 1-18.

151. Baker AA. Composite materials for aircraft structures: AIAA; 2004.

152. Jones RM. Mechanics of composite materials: CRC press; 2018.

153. Li C, Ellyin F, Wharmby A. A damage meso-mechanical approach to fatigue failure prediction of cross-ply laminate composites. International journal of fatigue. 2002;24(2-4):429-35.

154. Reifsnider KL. The critical element model: a modeling philosophy. Engineering Fracture Mechanics. 1986;25(5-6):739-49.

155. Sørensen BF, Goutianos S, Mikkelsen LP, Fæster S. Fatigue damage growth and fatigue life of unidirectional composites. Composites Science and Technology. 2021;211:108656.

156. Sun Q, Zhou G, Meng Z, Guo H, Chen Z, Liu H, et al. Failure criteria of unidirectional carbon fiber reinforced polymer composites informed by a computational micromechanics model. Composites Science and Technology. 2019;172:81-95.

157. Krause D. A physically based micromechanical approach to model damage initiation and evolution of fiber reinforced polymers under fatigue loading conditions. Composites Part B: Engineering. 2016;87:176-95.

158. Okabe T, Imamura H, Sato Y, Higuchi R, Koyanagi J, Talreja R. Experimental and numerical studies of initial cracking in CFRP cross-ply laminates. Composites Part A: Applied Science and Manufacturing. 2015;68:81-9.

159. Drzal L, Madhukar M. Fibre-matrix adhesion and its relationship to composite mechanical properties. Journal of materials science. 1993;28(3):569-610.

160. Theocaris PS. The mesophase concept in composites: Springer Science & Business Media; 2012.

161. McCartney L. Analytical models of stress transfer in unidirectional composites and cross-ply laminates, and their application to the prediction of matrix/transverse cracking. Local mechanics concepts for composite material systems: Springer; 1992. p. 251-82.

162. Nairn JA. Exact and variational theorems for fracture mechanics of composites with residual stresses, traction-loaded cracks, and imperfect interfaces. International Journal of Fracture. 2000;105(3):243-71.

163. Pitkethly M, Favre J, Gaur U, Jakubowski J, Mudrich S, Caldwell D, et al. A round-robin programme on interfacial test methods. Composites Science and Technology. 1993;48(1-4):205-14.

164. Sencu R, Yang Z, Wang Y, Withers P, Soutis C. Multiscale image-based modelling of damage and fracture in carbon fibre reinforced polymer composites. Composites Science and Technology. 2020:108243.

165. Zheng H, Zhou C, Yuan Y. Meso-scale finite element modeling of moisture diffusion in 3D braided composite. International Journal of Heat and Mass Transfer. 2019;129:862-72.

166. Mohammadi B, Olia H, Hosseini-Toudeshky H. Intra and damage analysis of laminated composites using coupled continuum damage mechanics with cohesive interface layer. Composite Structures. 2015;120:519-30.

167. Standard A. D3039 “Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials”. Annual Book of ASTM Standards. 2000.

168. Llobet J, Maimi P, Mayugo J, Essa Y, de la Escalera FM. A fatigue damage and residual strength model for unidirectional carbon/epoxy composites under on-axis tension-tension loadings. International Journal of Fatigue. 2017;103:508-15.

169. Michel SA, Kieselbach R, Martens HJ. Fatigue strength of carbon fibre composites up to the gigacycle regime (gigacycle-composites). International journal of fatigue. 2006;28(3):261-70.

170. Zhou S, Wu X. Fatigue life prediction of composite laminates by fatigue master curves. Journal of Materials Research and Technology. 2019;8(6):6094-105.

171. Awerbuch J, Hahn H. Off-axis fatigue of graphite/epoxy composite. Fatigue of fibrous composite materials: ASTM International; 1981.

172. Brunbauer J, Pinter G. Effects of mean stress and fibre volume content on the fatigue-induced damage mechanisms in CFRP. international Journal of Fatigue. 2015;75:28-38.

173. Hashin Z. Failure criteria for unidirectional fiber composites. 1980.

174. S.A RBS. [Available from: www.RegalPTS.com/Jaure.]

LIST OF PUBLICATIONS

1) Azizan A, Israr HA, Tamin MN. Effect of Fiber Misalignment on Tensile Response of Unidirectional CFRP Composite Lamina. Journal of Advanced Research in Applied Sciences and Engineering Technology. 2018;11(1):23-3