EFFECT OF SHEAR STRESS ON FATIGUE LIFE OF COMPOSITE LAMINATES

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Keywords: *Composite laminates, micromechanics of failure (MMF), fatigue life, constituents, stress ratio, damage parameter*

Abstract

The effect of complex stress state is not properly taken into account for determining the fatigue life of thin-walled structures made of composite materials like wind turbine blade. Fatigue life predictions, as per state-of-the-art design codes like IEC 61400-1 and GERMANISCHER LlOYD (Part 1), account only for normal stresses, neglecting the contribution of shear stresses. This is due to either misconception or lack of experimental data and theoretical models. Many mechanical tests are required to fully characterize the composite laminates made of various materials and having different layup sequences under many load combinations of in-plane stress tensor components. A micromechanics based fatigue life prediction of composite laminates under multi-axial loading was developed that can take care of complex stress state. In order to reduce number of tests, a methodology was presented in this paper to predict fatigue life of composite laminates based on fatigue life of constituents, i.e. the fiber, matrix and interface, using micromechanics of failure (MMF). For matrix, the equivalent stress model which is generally used for isotropic materials was employed to take care of multi-axial fatigue loading. For fiber, a maximum stress model considering only stress along fiber direction was used. Critical plane model was introduced for the interface of the fiber and matrix. The modified Goodman approach was utilized to take into account the mean stress effect. In order to validate the proposed methodology, the fatigue life of three different GFRP laminates, UDT [90°], BX [±45°]S and TX [0°2/±45°]S, was examined experimentally. The predictions are compared with the experimental data, and are shown in good agreement. A comprehensive implementation example is also presented for the case of wind turbine rotor blade composite laminates. An initial estimate on the effect of neglecting shear stresses in fatigue life calculations is provided based on predictions. It is concluded that in wind turbine blade GFRP laminates, shear stresses have an important contribution in reducing fatigue life.

1 Introduction

Fiber reinforced laminated composites have been used in many structural applications because of their superior specific properties compared with metals. Typical modern composite structures include aeronautical vehicles, ships, wind turbine blades, flywheels, pressure vessels, helipads, Clock Tower in KSA, and sporting goods. Fiber reinforced composites consist of fibers and visoelastic matrix. With the increase of loads and changes in environmental conditions, the damage grows and progresses until ultimate failure of structures. The stress state in composite structural elements, either in the form of thin or moderately thick shell construction, can be assumed plane, i.e. composed of two normal components and an in-plane shear component of the stress tensor. The composite structures should be stiff enough to resist deformations and strong enough for long term operation in service under particular stress state. Fatigue failure of composite materials has been widely discussed in the literature by the researchers during the past two decades [1-5].

Hashin and Rotem [3] presented a simple fatigue failure criterion expressed in terms of S-N curves obtained by uniaxial cyclic testing of unidirectional specimens.

Energy-based criteria incorporate both stresses and strains. In this approach, the damage is related to input energy which cannot give any information about failure mechanism [6, 7].

Several researchers [8, 9] have investigated fatigue damage response of polymer composites based on reduction of composite stiffness as the number of fatigue cycles increased. Mayes and Hansen [10] proposed a muti-continuum theory (MCT) in which phases averaging of micro-level stresses is applied to each constituent. This micromechanical approach effectively includes changes in constituent level properties. However, since they used volume averaged micro stresses, it is difficult to distinguish failure location either in fiber or matrix or interface and, also, incorporating damage degradation in fatigue analysis.

Due to the large variety of laminates resulting from numerous materials, lay-ups and stacking sequences, and loading conditions, it is uneconomic to determine fatigue life curves for any degree of generality by experiments only. Most of fatigue life assessment methods used to estimate the experimental results was empirically approximated by phenomenological theories which cannot prove its absolute validity and universal generality.

In this paper, a general methodology based on micromechanics of failure (MMF) approach is presented for fatigue life prediction of composite laminates. The methodology is based on fatigue life of constituents, i.e. the fiber, matrix and interface. A wide range of experimental fatigue data of composite laminates are used to validate the proposed methodology. The predictions based on the MMF based fatigue model agree very well with the experimental results.

2 Theory and Methodology

2.1 Micromechanics of Failure (MMF) Approach

The composite structures are made from composite laminates. The Fig. 1 shows the Micromechanical approach to evaluate fatigue life of composite structure. This approach is divided into two parts, namely Macro Stress Analysis and Micro Fatigue Analysis. In Macro Stress Analysis, macroscopic stresses are calculated on the composite laminates under varying external mechanical and thermal loads using finite element method (FEM). In addition, on-axis macro ply stresses are calculated using Classical Laminate Theory (CLT) or FEM. In Micro Fatigue Analysis, micro model is employed to calculate stresses in fiber, matrix, and interface. These six components of stresses, varying with time, depend on micro model. From these stress components, effective stress is calculated which, also, is a function of time. The Modified Goodman diagram is used to take care of mean stress effects. For particular mean and amplitude of effective stress cycles, damage index is calculated. Finally, Linear Damage Accumulation rule, i.e., Miner's Rule is used to give fatigue damage for all varying stresses with different means and amplitudes.

2.2 Macro and Micro Stresses

Composite laminates are subjected to time vary ing load. These causes in-plane loads and in-plane m oments, expressed also as function of time, in lamina tes. Then using FEM or CLT, on-axis macro stresses are calculated on each ply. Micro stresses in fiber, matrix, and interface are calculated from on-axis ply macro stresses using Micro-mechanics. For this, diff erent micro unit cell models are available. Unidirecti onal (UD) composite ply micro model depends on fi ber arrangement. It consists of square array (SQR) or hexagonal array (HEX). These unit cell models can simulate the behavior of entire UD [11, 12]. There is another choice for micro model based on Multi-Con tinuum Theory (MCT) that defines stress and strain s imply as average over unit cell model [13]. Micro str esses at any arbitrary point within fiber and matrix c an be obtained using these models which vary over f iber and matrix. $M_{ij}^{(f,m,i)}$, stress amplification factor (SAF) gives relation between macro-micro stresses. $A_j^{(f,m,i)}$, stress amplification factor for temperature in

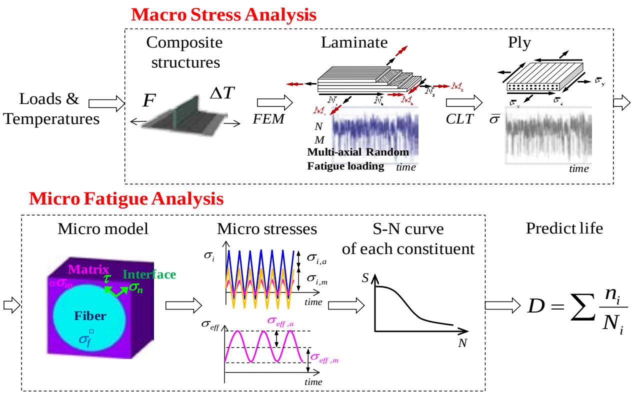

Fig. 1 MMF based fatigue life prediction procedure for composite laminates

crement. A direct finite element analysis was performed to determine stress amplification factors.

2.3 Fatigue Life Prediction Models

Three different models were employed for each constituent. Figure 2 shows all these models. For Fiber, Maximum Stress Model is used. Critical Plane Model is incorporated for fiber/matrix interface. For matrix, Equivalent Stress Model is used. Originally, this model is for isotropic material and matrix in composites has also isotropic characteristics. This model is also take care of multiaxial fatigue. This formulation depends on isotropic matrix tensile and compressive strength characteristics. Various multiaxial fatigue life prediction models have been proposed in the past decades. But, Equivalent Stress Model seems to perform better than the von Misses criteria and others [14]. Therefore, in this paper, Equivalent Stress Model is adopted. Figure 5 shows schematically Equivalent Stress Model. The six components of the varying stress is converted into amplitude $\sigma_{eq,a}$ and mean $\sigma_{eq,m}$ values of equivalent stress as expressed in Equation (1). Here, β is the ratio of the uniaxial compressive yield stress (C) to the uniaxial tensile yield stress (T), i.e., $(\beta = C/T)$.

$$\sigma_{eq,a}^{(m)} = \frac{(\beta-1)I_{1,a} + \sqrt{(\beta-1)^2 I_{1,a}^2 + 4\beta\sigma_{VM,a}^2}}{2\beta}$$
$$\sigma_{eq,m}^{(m)} = \frac{(\beta-1)I_{1,m} + \sqrt{(\beta-1)^2 I_{1,m}^2 + 4\beta\sigma_{VM,m}^2}}{2\beta} \qquad (1)$$

Although, fiber is anisotropic material and fatigue behavior is very much dependent on direction. But in analysis, only maximum stress in fiber direction is considered.

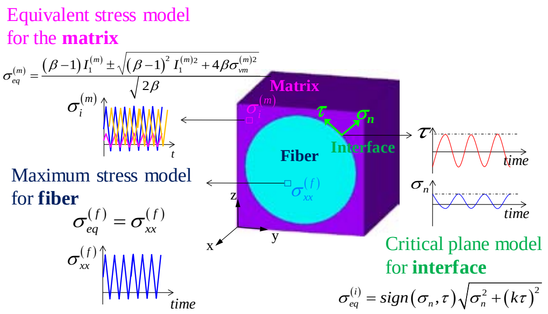

Fig. 2. MMF based fatigue life prediction models

For fiber/matrix interface, Critical Plane Model is used. The interface failure is governed by normal and shear stress components. Figure 6 shows determination of equivalent stress at interface. From this, amplitude and mean stress as a function of time is calculated.
Modified Goodman equation is used to include mean stress effect. This equation includes amplitude, mean, tensile and compressive stress of the material, as expressed in Equation (2).

$$\sigma_{eff} = \frac{\sigma_{eq,a}\sqrt{TC}}{\frac{T+C}{2} - \sqrt{\sigma_{eq,m} - \frac{T-C}{2}}} \qquad (2)$$

Fatigue life prediction needs to model damage accumulation in the general case of external variable amplitude loading. The common approach for such a model is a cycle-by-cycle summation of a damage parameter, D, where fatigue failure is defined as a critical value of the damage sum. A linear fatigue damage accumulation rule proposed by Palmgren and Miner is given by the relation.
The cumulative damage factor is equal to or greater than 1 is considered as fatigue failure. This relation is most popular because of its simplicity. Damage index is calculated for each constituent, i.e., fiber, matrix and interface, based on their respective fatigue failure criterion. The damage will be the one that has maximum value. Generally, matrix fails first. Then, using progressive failure to find final fatigue failure of ply, and hence laminates. Thus, micromechanics approach used to predict fatigue failure of composite laminates from constituent failure. Also, failure mode can easily be distinguish, either matrix or fiber or interface failure.

3 Experiments and Results

The resin system used in this study is Hexion MGS RIM 135 (L135i) epoxy and Hexion MGS RI MH 134 hardener with the mixing ratio of 10:03. Resin Specimens were fabricated by curing resin for 18 hours at 60°C. For epoxy tensile and compressive characterization, ASTM D 638 and ASTM D 695, respectively, guidelines were followed. Three different Woven Composite Laminates of E-glass with the same epoxy as above were used. The E-glass/Epoxy laminates were UDT [90°], BX [±45°]s and TX [0°2/±45°]s. Similarly, laminates tensile and fatigue proper

ties were characterized by ASTM D 3039 and AST M D 3479, respectively. In order to reduce uncertain ty in test results, all tests (tensile and fatigue) were c onducted on the same test machine. The static speci mens were loaded to failure with a speed of 1 mm/m in. All fatigue tests were performed at stress ratio of 0.1. The load levels for fatigue tests were from 50-8 0% of static strength.
The results of static tests are shown in Table 1.

Table 1 Material properties of epoxy and laminates; Mean value (Standard Deviation)

	Young's modulus (GPa)	Tensile strength (MPa)	Compressive strength (MPa)
Epoxy	3.35(0.41)	67.7(1.1)	73.8(1.2)
UDT	13.07(0.26)	35.1(2.8)	-
BX	22.3(5.12)	111.6(5.2)	-
TX	26.55(0.82)	464.2(39.6)	-

The summary of fatigue test results is given in Table 2.

Table 2 Summary of fatigue test results

	Maximum stress (MPa)	Number of cycles to failure
Epoxy	54.6	1008, 1476, 1237
	47.8	8713, 3981, 5012
	41.0	39811, 50119, 25119
UDT	28.1	32232, 45516, 39406
	24.6	98597, 63433, 46923
	21.1	225647, 229270, 225957
BX	78.1	3138, 3227, 2364
	67.0	17702, 20398, 24428
	55.8	262711, 292423, 315449
TX	325.0	2475, 1389, 1487
	278.5	5595, 5152, 6027
	232.1	13361, 18918, 14619

4 Verification of Life Prediction Methodology

Fig. 3 shows test results of UDT, BX, and TX along with the predictions from micromechanics of failure. This shows that predictions made by HEX and SQR unit cell models are in good agreement with test results. UDT [90°] prediction is based on matrix failure mode. Also, in BX [±45°]s, the failure mode observed is matrix, which is exactly the real behavior of this laminate. In case of TX, the initial fatigue failure is [±45°] which is matrix dominant. The final fatigue failure is [0°], i.e., fiber breakage. The test results of TX also match well with the predictions. This shows that the micromechanics of failure approach predict not only matrix dominant laminate failure but also catches well fiber dominant laminate behavior.

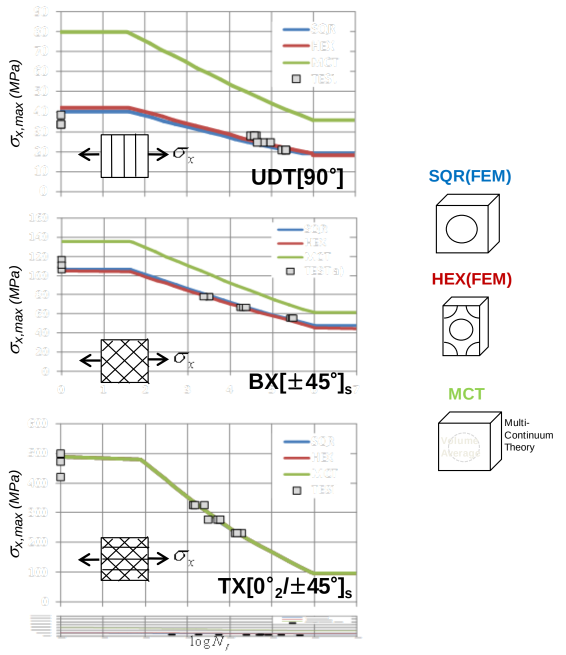

Fig. 3. Fatigue life prediction of the UDT, BX and TX

5 Structural Applications: Wind Turbine Blade Laminates

A case study was carried out to highlight implication of MMF based fatigue life prediction methodology for a realistic application of composite wind turbine blade structure. Wind turbine blade can be analyzed as typical beam-like structure as described by state-of-the-art design codes [15, 16]. The reason to make this assumption about the blade as beam-like structure is that blade behaves like a beam in whole. Also, the equivalent beam can produce results with reasonable accuracy and with an ease which design engineers prefer. The computation time is also greatly reduced comparing to the 3D shellconstructed FEM model. The investigated blade has shell and spar/web type structure. There exist flanges and stiffeners as well. Shell and spars are assumed to carry only shear stresses, and flanges and stiffeners are assumed to carry only axial stresses. A 35 m GRP wind turbine rotor blade, for which detailed finite-element models, material properties and design load case (power production at rated wind speed) definitions were available [17, 18], was analyzed for this case study. The investigated blade consists of different types of E-glass/Epoxy composites: BX [±45°]s, and TX [0°2/±45°]s. The TX is used in the shell structure along with PVC core. BX and PVC core is used in shear webs. The reason of using PVC core is to avoid local buckling. From FEM analysis, it is found that the in-plane shear load N6 is varying from 0.5% to 65% of in-plane normal load N1at different locations of wind turbine blade like on outer skin and shear webs. The shear stress is of comparable magnitude to the axial stress in areas such as the shear webs and leading/trailing edges of the rotor blade, as shown in Figure 12. An example is given in Fig. 4 where the resulting stresses in the transition section of a 35m wind turbine blade under typical loading during power production are presented [18].

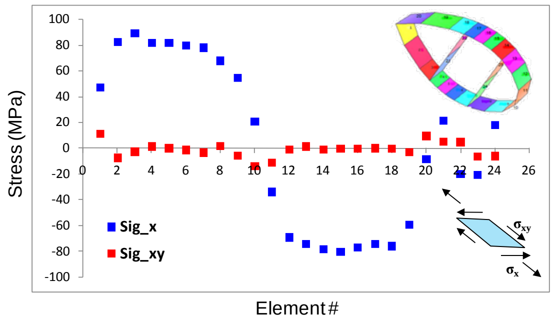

Fig. 4. Typical stress state at the transition section for a 35m blade

As these elements of blade are placed in the confined region, edge effect will not occur and, therefore, Classical Laminate Theory (CLT) is appropriate to calculate on-axis macro ply stresses. The fatigue life calculations by the state-of-the-art design codes [15, 16] are limited by the considering only in-plane normal stress resultant component in the blade axis direction. Although, shear stress levels in thin walled structures are often negligibly small, but it has an effect on the strength and life of the composite structures. The life prediction methodology as described earlier is used in this section to show the effect of in-plane shear stress resultant in defining service fatigue life of wind turbine rotor blade laminates.

For the purpose of comparison, stress ratio 'R' is kept constant which is -1. Also, with R = -1, there is no mean stress effect that will make the conclusion straightforward. Also, for ease of calculations, sinusoidal cycling is considered. Assuming that the stacking sequence of multilayer element is same as considered in this study, i.e., TX [0°2/±45°]s. The MMF based life prediction with and without contribution of in-plane shear stress component yields impressive results in reducing fatigue life. The results are presented in Fig. 5. In this layup considered, number of cycles is drastically reduced when in-plane shear stress resultant is considered. This shows that life is over estimated when only axial stress component N1 is taken in the life analysis. Interesting to note that for these calculations, as shown in Fig. 5, shear stress component N6 has magnitude say about 60% of the axial (longitudinal) normal stress component N1 (this value is at shear web) but life is over estimated by a factor of 19 at some load level like 250 MPa.

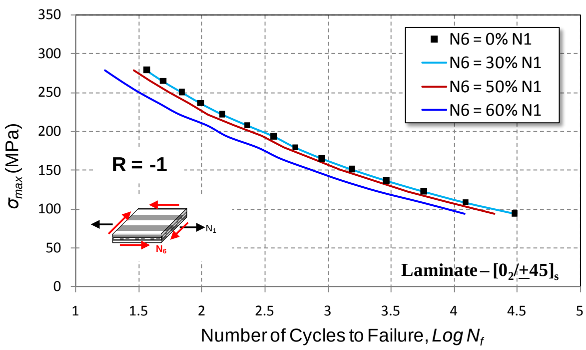

Fig. 5. Fatigue Life Curves with and without Shear Component

6 Conclusion

In this study, a new methodology for fatigue life prediction of composite laminates based on Micromechanics of Failure is presented. This methodology is based upon behavior of the constituents, i.e., fiber, matrix, and interface. The model determines the fatigue failure of composites by considering failure of constituents in Micromechanical analysis.

This unified fatigue prediction model has been successfully applied to predict fatigue lives of different laminates under cyclic tension considering various combinations of fiber angles. For this, various test performed on three different laminates, UDT, BX, and TX. The current approach predicts very well the test data.

In addition, the main data needed for fatigue analysis of composite laminates is material properties of matrix, fiber and interface. Once such constituents properties is established, then by using Micromechanics of Failure model the number of experiments to characterize the material properties of a composite laminates of any layup and under any stress ratio can be minimized. Therefore, the Micromechanics of Failure model is potentially a valuable tool for fatigue design.

Finally, a case study of fatigue life prediction of composite wind turbine rotor blade is considered to demonstrate application of MMF based life prediction approach to the real structural application. A parametric study of life prediction with and without considering in-plane shear stress resultant was performed. Results indicate that the in-plane shear stress has an effect on life and it reduces life drastically. It was concluded that the life is reduced by 19 times with respect to situation where only the in-plane axial normal stress component was used in calculations.

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