# Fatigue prediction of composite components based on failure mechanisms

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## 1 Summary

A model for fatigue prediction in composite laminates is presented. It is an adaptation of a previously existing damage model for quasi-static loading that is able to account for various physical damage mechanisms. As a result of a special two-step model formulation, damage mechanisms can be tracked individually and their effect in terms of stiffness degradation can be modeled. For more complex fatigue load collectives, damage from different mechanisms can be accumulated individually, which poses a significant advancement compared to simple rain-flow counting normally used for metal fatigue. Comparison to experimental results shows good correlation for matrix-dominated failure in a variety of laminates and load levels tested. As a post-processing tool using ply-level stress data from FEM analyses, the model can be applied efficiently for structural analysis of composite components.

## 2 Introduction

Predicting fatigue life of laminated composites remains a difficult challenge in the verification of composite components. Initially, fatigue assessment was relying heavily on laminate level coupon testing. Modern prediction methods consider the accumulation of damage on the ply level, with the advantage of being applicable to more general laminate stackings. The accuracy of current fatigue models, however, is still limited due to the complexity of damage and failure processes occurring in hierarchical structures such as composite laminates. For static loading, it has been found that accurate failure prediction requires the consideration of individual failure mechanisms and capturing the load redistribution due to local stiffness degradation caused by the gradual failure process. In this contribution, a generally applicable fatigue damage model for predicting fatigue life and anisotropic stiffness degradation in a ply caused by matrix dominated failure mechanisms is presented.

## 3 Modeling Method

The fatigue damage model is based on an existing damage model for quasi-static loading developed previously by Schuecker et al [1,2]. The general modeling concept is sketched in Fig. 1. It features a two-step procedure using (1) a damage evolution function to account for the increase of damage as a function of the maximum load in load history and (2) a micromechanics-based method to compute the effect of damage on ply stiffness depending on the current loading situation (i.e. the current ply stress state). For fatigue loading, the damage evolution function has been modified to increase with the number of cycles, $n$ (for a given stress amplitude), rather than with the stress state, $\boldsymbol{\sigma}$, used for static loading. By using a ply-based approach in combination with classical laminate theory (CLT), the load redistribution within the laminate stack due to a stiffness change individual plies is automatically accounted for to yield the stiffness change of the whole laminate.

Using this mechanism-based two-step procedure, on the one hand, provides the possibility to track different damage mechanisms individually – an information which can subsequently be used for separate accumulation of each damage mechanism in complex fatigue load collectives. On the other hand, it permits to account for the unilateral effect which leads to stiffness recovery in a ply if the load during a fatigue cycle changes such that already existing cracks close – an effect which is expected from a physical point of view and has been observed experimentally by Brunbauer et al. [3]. To predict the crack orientation in a ply for a given stress state, the Puck failure criterion [4] is used.

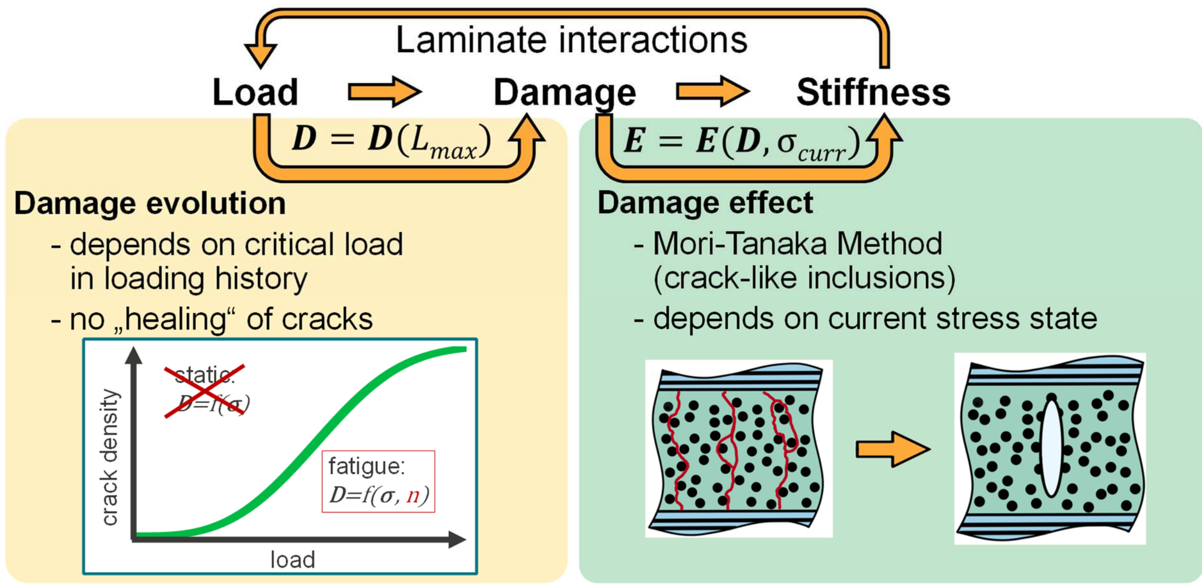


Fig. 1: Two-step modeling concept with a distinct separation of damage evolution and damage effect.

## 4 Comparison to experimental data

For the model development, a special highly instrumented testing procedure has been developed to evaluate possible measures for damage detection and quantification, including intermittent quasi-static stiffness evaluation, temperature measurement, acoustic emission, and a camera for recording trans-illuminated images of the specimen surface [5]. An image processing tool “CrackDect” [6] has been developed and published as open source software to obtain crack density curves from the images. Several angle-ply laminates as well as UD-specimens and a special “embedded” 90° specimen were tested at various load levels referenced to the corresponding static strength of the critical ply.

It has been shown, that the predicted stiffness degradation based on crack densities correlates well with measured data, as illustrated in Fig. 2a for a ±45° angle-ply laminate [7]. It was also found, however, that the dissipated energy obtained from hysteresis evaluation of the experimental data is significantly higher for some laminates (Fig. 2b) [5]. This is attributed to differences in the micro-mechanical crack development under shear-dominated loading compared to that under transverse tension (Fig. 2c). While this distinction is not that important for static load cases, it has a curucial impact on fatigue prediction. Since under cyclic loading the hysteretic heating in shear dominated conditions subsequently leads to premature failure, this effect needs to be accounted for in fatigue life prediction. Therefore, an additional distinction of failure mechanisms following the model by Carraro et al [8] has been implemented in the fatigue damage model.

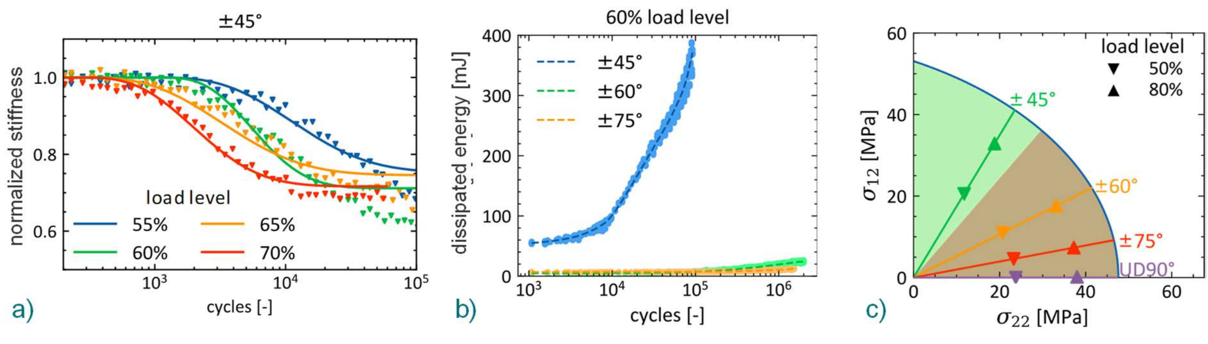


Fig. 2 (adapted from [9]): Change in axial stiffness of a ±45° angle-ply laminate at various load levels normalized to its initial stiffness – model (solid lines) vs. experiments (data points) (a); dissipated energy obtained from hysteresis evaluation of experimental data (b); ply stress states for the laminates investigated plotted for in-plane shear vs transverse tension stress (c).

Since the model is formulated on the ply level, it can be transferred to any laminate layup once it has been calibrated. A comparison of the model prediction to experimental results for a multi-axial laminate in terms of stiffness degradation of the whole laminate is plotted in Fig. 3a, which shows good agreement until close to ultimate failure. Note, that ultimate failure mechanisms like delamination and fiber failure are not accounted for in the model, which is the reason for the discrepancy in the stiffness drop close to ultimate failure of the specimens. Since the whole progression of damage is modeled, it is now also possible to generate a series of SN-curves for a laminate corresponding to specific stages of its fatigue life. In Fig. 3b, this is shown by example of a ±45° laminate with SN-curves for damage onset and ultimate failure, respectively. Note, that for this angle-ply layup, last ply failure coincides with ultimate failure.

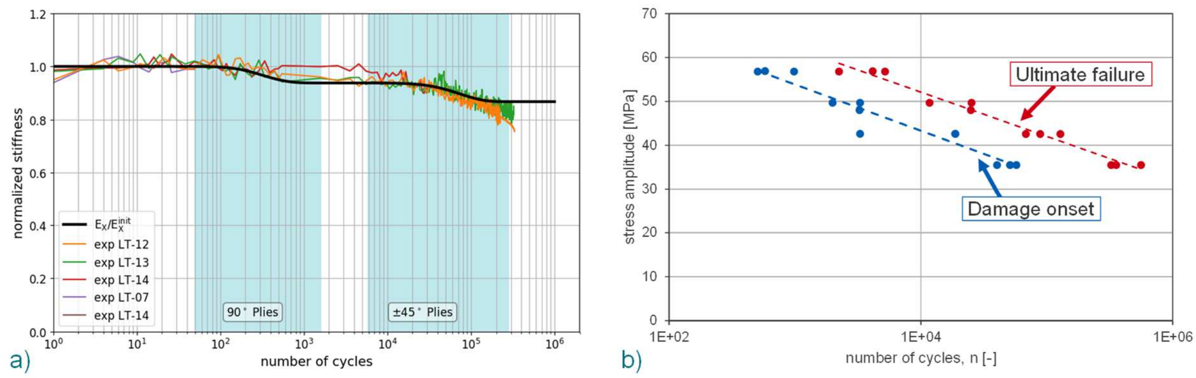


Fig. 3: Change in axial stiffness of a multiaxial laminate with $[0/45/90/-45/0]_S$ layup normalized to its initial stiffness – model vs. experiments (a); SN-curves for damage onset and ultimate specimen failure for a ±45° specimen (b).

## 5 Conclusions

The current work presents a fatigue model based on physical failure mechanisms for predicting the stiffness degradation and fatigue life of composite laminates subjected to cyclic loading. Because of the specific modeling concept, different types of damage can be accumulated individually for evaluating complex load collectives. Furthermore, the unilateral effect, leading to stiffness recovery due to crack closure and frictional effects, is accounted for.

Comparison to experimental data shows, that a more detailed distinction of damage mechanisms is necessary in fatigue damage compared to static loading in order to properly capture the effects of increased energy dissipation due to internal friction on the microscopic scale. This friction leads to a significant reduction of fatigue life under shear-dominated loading conditions. Properly accounting for these effects in the early loading history is essential to finally predict ultimate failure under fatigue loading conditions, which is usually caused by global delamination or fiber failure. Furthermore, the tracking of damage progression provides the means to generate separate SN-curves for intermediate characteristic damage states in addition to the usual SN-curve for ultimate failure.

For application on component level, the model is used as a post-processing tool for stress data from FEM-analyses and is currently being implemented as an additional feature in the commercial fatigue software FEMFAT. As an additional option, future versions are planned to offer the possibility to feed back the reduced stiffness data into the FEM models at certain intervals to be able to assess the effect of global load redistribution within a component during fatigue life.

## 6 Acknowledgement

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