Damage accumulation and stiffness degradation in composite laminates

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Doctoral Thesis

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Abstract

Composite laminates due to their high strength and stiffness to weight ratio are widely used in different load carrying structures. In order to obtain high stiffness laminates with complicated lay-up are used. Laminates during the service are subjected to complex thermo-mechanical loading that causes damage accumulation. In the presented thesis damage accumulation in layers with fiber orientation transverse to the loading direction is studied. The first mode of damage is matrix cracking or so called transverse cracking. In some cases such damage is catastrophic for structures, for instance, it can cause leakage in pressure vessels and therefore it is not permissible. On the other hand, in structures where only stiffness is the main concern this damage will cause certain stiffness degradation but it can be accepted at some extent. In order to design structure properly it is necessary to understand the damage process and to predict the level of degradation of mechanical properties.

In presented thesis transverse cracking initiation on a fiber/matrix level is investigated and fiber/matrix interface strength that influences this process is discussed. Testing methods, such as single fiber fragmentation, pullout and transverse cracking in cross-ply laminates are used to characterize and grade fiber/matrix interface strength. Analysis of obtained results show that testing of model composites can lead to wrong conclusions due to unfulfilled assumption used in data analysis.

The measure of damage level in laminates containing 90°-layer is crack density in those layers. With increasing of crack density in transverse layers elastic properties of whole laminate are decreasing. Analytical models are developed in order to predict the level of elastic properties degradation. Models originally obtained for cross-ply laminates (shear lag, variational) are adapted for more general lay-up of laminates \([S,90_n]\), where \(S\) can be any balanced sub-laminate. Closed form expressions to calculate elastic properties changes as a function of crack density are derived. These models are verified by comparing prediction with experimental results.

Since crack density is increasing with applied load, complete model that describes elastic property degradation must contain damage evolution modeling. In this work damage evolution modeling is performed by Monte-Carlo simulation. In order to perform analysis whole specimen is divided in small elements and properties that define failure of each element are assigned according to the two parameter Weibull distribution. Failure of the element is considered as an appearance of new crack. Two approaches that use different failure criteria are executed. First approach uses strength failure criteria and, therefore, strength to each element of the 90°-layer is assigned. Second approach uses fracture mechanics criteria and fracture toughness defines failure of each element. Cross-ply laminates are used as a reference and their experimental damage evolution data are used to obtain Weibull parameters. These parameters are considered as material properties and used to model damage evolution in laminates with other lay-ups than cross-ply. Experimental data for \([\pm\theta/90_\ell]\) laminates are used to verify correctness of this procedure. Influence of the thickness of 90°-layer on damage evolution is also analyzed.

Data obtained from modeling of elastic properties changes as a function of crack density and simulation of damage evolution for laminates with \([\pm\theta/90_\ell]\) lay-up show that models do not work with satisfactory accuracy for some \(\theta\). Therefore detailed study of laminates containing off-axis layers is performed in this study. The results show that degradation of the shear modulus occurs in those layers during the loading. Degradation of the shear modulus influences longitudinal modulus of the whole laminate as well as stress distribution in 90°-layer. It explains inaccuracy of prediction of stiffness reduction and damage evolution simulation in laminates with off-axis layers. To complete the prediction of stiffness reduction with increase of applied load this phenomenon also should be included in model and is considered as a future work by author.
Introduction

Composite laminates due to their high strength and stiffness to weight ratio are widely used in different load carrying structures. Laminates with complicated lay-up are used in order to obtain high stiffness. During the service laminates are subjected to complex thermomechanical loading that causes damage accumulation. The first mode of damage is matrix cracking or so called transverse cracking. In some cases such damage is catastrophic for structures. For instance, it can cause leakage in pressure vessels and, therefore, it is not permissible. On the other hand, in structures where only stiffness is the main concern this damage will cause certain stiffness degradation but at some extent it can be accepted. In order to design structure properly it is necessary to understand the damage process and to predict the level of degradation of mechanical properties.

The most studies of transverse cracking in multidirectional laminates are performed on cross-ply laminates (0°-layer as outer layer and 90°-layer inside) subjected to uniaxial tensile loading (see Fig. 1a). As a result of such loading transverse cracking occurs (see Fig. 1b).

![Fig. 1. Cross-ply laminate (a) subjected to uniaxial loading and (b) resulting damage.](image)

Important characteristic of cross-ply laminate is the first cracking strain that indicates at which extent laminate can be loaded without introducing damage. After that limit is reached damage is progressing during further increase of load. The measure of damage is crack density in 90° layer. The investigation of transverse cracking can be separated in two stages: initiation of transverse cracking and damage accumulation.

The initiation of transverse cracking is only briefly discussed in the presented thesis and the main part of the thesis is focused on developing models to predict damage evolution in multidirectional laminates and stiffness degradation due to damage accumulation.

**Crack initiation**

There are two mechanisms for crack initiations that are discussed in literature: crack initiation from matrix fracture and crack initiation from fiber/matrix interface failure. Based on his own experience the opinion of the author of this thesis is that cracks are initiated from interface failure. As a result of it multiple debonding between fibers and matrix occurs. Then those debonds are connected and transverse crack is formed. As an illustration transverse crack in glass fiber/vinyl ester system is presented in Fig. 2a. Picture from carbon fiber/epoxy bundle loaded in transverse direction is shown in Fig. 2b.
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Fig. 2. Transverse crack initiation from fiber/matrix interface failure.

Picture of transverse crack (Fig. 2a) shows that this crack is following path around the fibers that verifies the statement about crack formed from debonds. Picture of one carbon fiber (Fig. 2b) shows that fiber is clean and no matrix is attached to it after failure. It indicates poor adhesion and, most probably, source for crack initiation. It should be noted that author is not drawing this conclusion for any fiber/matrix system and in some cases initiation mechanism, probably, can be different. Therefore, initiation of cracking from matrix fracture can not be completely ruled out for all composite systems. Probably, in some case matrix fracture can occur very close to the fibers and can be misinterpreted as an interface failure. In order to verify this statement very careful in-situ observation of cracking process must be performed.

Assuming that crack is initiated on the interface one should be able to characterize and compare interface properties of the different fiber/matrix systems. Model composites are widely used for this purpose [1]. Single fiber fragmentation test is one of the most used methods to characterize fiber/matrix interface. There are studies that investigate interface strength dependence on matrix properties [2,3]. It is shown that even if matrix is very tough and has very high strain at failure it does not show dramatic improvement in strain of transverse failure [2]. Another study [3] also obtains similar results by showing that even if ultimate shear stress developed in matrix is considerably varied interfacial shear strength is not affected that much.

It should be noted that interfacial properties are not only affected by chemical composition of matrix and fiber sizing but also by manufacturing procedure, namely curing cycle of resin. Even if specimens with different resins are produced with the same curing cycle it does not completely eliminate this effect. Different matrices have different thermal expansion coefficient and in single fiber (SF) specimens different residual stresses are developed. Usually resin has higher thermal expansion coefficient than fiber and, therefore, fiber in SF specimen is compressed even before the mechanical test. In data reduction these residual stresses as well as chemical shrinkage of matrix are usually taken into account. It is more difficult to account for radial compressive stress to which fiber is subjected to due to the thermal shrinkage and mismatch in fiber/matrix Poisson’s coefficients during the test. This radial stress can greatly affect data from the SFFT test, because frictional forces between fiber and matrix are strongly dependent on it. Therefore in Paper I of this thesis investigation of fiber/matrix interface was performed using the same type of resin (vinyl ester). Only fiber coating and fiber diameter was varied (the same type of glass fibers were used in all cases). On one batch of fibers, in order to obtain a very different fiber/matrix interface, vinyl ester compatible sizing was applied.
In this paper test results from model SF composite were compared with test of real scale cross-ply laminate. One can argue that these tests can not be directly compared because of different failure modes: Mode I crack propagation in cross-ply laminate and Mode II in SFFT. The aim of investigation was not to compare directly values from those tests but characterize fiber/matrix interface by different methods and see if SFFT can be used to substitute macro test of cross-ply laminate where stress state in matrix is very different from SF specimen. The results of this study showed that in case of cross-ply laminate the strain at which first transverse crack developed differs very much between two different fiber coatings. This indicates that fiber/matrix interface in case when vinyl ester compatible sizing was used is much tougher than another one. In contrary, the data from SFFT indicated only minor improvement in interface properties.

There are two different ways to process experimental data from SFFT. One method is the most frequently used: Kelly-Tyson model (or based on it Shear Lag model) that gives interfacial shear strength [3]. Another is based on linear fracture mechanics approach and gives interface fracture toughness [4]. Both these methods assume that interface has failed and parameters that are used there are critical fiber fragment length and debond length. Optical observation of SF specimen showed that interface did not fail in case of strong bonding and matrix crack developed instead. This explains why SFFT leads to wrong conclusions and indicates only a small difference between interface properties of the studied systems.

Paper I of the presented thesis showed influence of interface properties on transverse cracking initiation stage and indicated problems and limitations of the tests of model composites to characterize fiber/matrix interface.

Crack evolution and stiffness degradation

After the initiation phase extensive crack evolution takes place. Due to damage accumulation stiffness of the damaged layer as well as stiffness of the whole laminate is decreasing. This problem usually is solved in two steps: modeling the stiffness degradation at given crack density and modeling the damage evolution as a function of increasing load. Successfully solving these two problems powerful tool for design of composite structures would be obtained. Therefore, during the last two decades the transverse cracking problem in laminates has been studied extensively. In most cases the analysis is limited by cross-ply lay-up. The simplest task is to predict the extent of degradation of laminate elastic properties for situation when a certain crack density is given [5-10]. A large variety of approaches has been used: different modifications of shear lag model [5], variational models based on minimisation of complementary energy [6-8], continuum damage mechanics approach [9] and numerical methods, for example, based on FE analysis [10]. In [11] the listed analytical models have been generalised to describe more complex case - stiffness reduction due to 90°-layer cracking in laminates where the 0°-layer is replaced by an orthotropic sub-laminate. In Paper II of presented thesis this approach is used employing most of existing models for property degradation prediction in cross-ply laminates and adapting them for more generalised lay-up. Closed form expressions for longitudinal modulus and Poisson’s ratio changes are derived for [S,90n]s laminates. These expressions contain only elastic properties and geometry of 90°-layer and sub-laminate as well as crack density in 90°-layer. The accuracy of developed models is verified by comparing prediction with experimental data for [±?/904], GF/EP laminates.

Exact expressions for thermo-elastic properties of damaged laminates expressed through average crack opening displacement were derived by P. Gudmundson in [12,13]. An approximate explicit expression for average COD was obtained considering a row of parallel
cracks in an infinite homogeneous medium. The effect of anysotropic neighbouring layers is not described right in the approximate solution. The accuracy of the approximate solution was verified comparing with FE results in [12].

L.N. McCartney [14,15] derived inter-relationships between thermo-elastic constants of damaged laminate and showed that knowing the damage dependence for only one parameter we can predict the dependence for the rest of thermo-elastic constants. He has developed a very accurate numerical algorithm for stress state calculation in a laminate element between two cracks. In the specimen width direction generalised plane strain is assumed allowing also the edge rotation if the laminate is unbalanced.

As it was mentioned before, the engineering problem faced in design is the stiffness dependence on the load level. To solve this problem data about crack density increase due the loading must be available. Crack density curve for each particular laminate lay-up may be determined experimentally. However, this process is very time consuming and relying to this approach in modelling we loose all advantages of theoretical prediction. An application of a reliable damage accumulation model that includes certain fracture information for the considered material would be significantly more efficient. However, the damage evolution modelling has been much less successful.

Deterministic approach, that ignores the fact that the transverse cracking is a progressive damage, predicts appearance of many transverse cracks simultaneously when the first transverse cracking strain is reached [16,17]. The deviation of the crack density curve from vertical is due to the crack interaction only. In many analytical models (for example, Hashin’s model [6]) the interaction is overestimated and that leads to apparent agreement with test data. This approach was used by Nairn [11,17] in fracture mechanics failure analysis of cross-ply laminates based on Hashin’s variational stress model. To describe the high crack density region a fitting factor was introduced accounting for statistical distribution of crack spacing [17]. The model was applied to intermediate crack density data to determine the critical strain energy release rate for many composite systems.

Deterministic $G_c$ was used also in [18] to model transverse cracking using fracture mechanics approach and utilising approximate COD’s and more accurate ones obtained from fitting FE results.

The statistical nature of failure properties was emphasised in several papers [19-25]. P.W.M. Peters developed several routines [20-23] to obtain Weibull parameters for strength distribution from transverse cracking data. Monte-Carlo simulation of the transverse cracking process is only one of them. In [23] this approach was applied using shear lag model stress analysis. Unfortunately, different Weibull parameters were required in order to fit data for laminates with different 90-layer thickness.

It should be noted that all above fracture mechanics models are based on through-the-thickness flaw concept. The concept of “effective flaws” was introduced by A.S.D Wang [25] assuming that they have normal distribution of location and size. In this approach 5 constants (including the critical strain energy release rate $G_c$) are available to fit the experimental crack density data. Monte-Carlo simulation of the cracking evolution was performed using FE stress analysis in generalised plane strain formulation. The crack propagation was considered in layer thickness direction only. But this scenario rather corresponds to the crack initiation phase than to propagation.

It is more reasonable (and convenient) to start the growth analysis with through-the-thickness flaw and to describe its propagation in the specimen width direction. This assumption is used in presented thesis and damage evolution is modelled by two methods that use different failure criteria. One method employs strength approach and maximum stress criteria is used. Another approach uses energy approach and failure criteria is based on linear elastic fracture mechanics. In both approaches a concept of statistical distribution of failure
properties along the specimen is introduced. This concept reflects the fact that the material in
the front of a propagating crack may have varying failure properties resulting from distributed
microflaws. This approach was used by Ochiai et. al. [23] assuming Weibull strength
distribution and performing stress analysis by shear lag model and by L.N. McCartney [14,15]
assuming normal $G_c$ distribution and using his powerful stress calculation code.

In Paper III, IV transverse cracking is modelled by Monte-Carlo simulation in
strength formulation. The drawbacks of the strength approach are well known, for instance
this approach can not predict effect of the thickness of 90-layer on cracking strain. However,
it is convenient to use. The range of validity of the strength approach was evaluated and the
basic problems exposed. The axial stress distribution in a unit between two cracks of arbitrary
length, needed for strength analysis, was calculated using analytical models (shear lag, Hashin’s) and FE calculations.

In the Paper V the transverse cracking problem is addressed using for damage
accumulation Fracture Mechanics approach. The whole analysis is based on an opening
displacement of transverse crack (COD) normalised with respect to the far field strain. First,
closed form expressions for thermo-elastic properties of damaged laminate are derived. Apart
from material thermo-elastic properties and geometry they contain only crack density and
COD. A power law based on FE parametric analysis is suggested to describe the COD
dependence on constituents stiffness and layer thickness ratio. Crack closure technique is used
to calculate the energy release due to cracking. Monte-Carlo simulation in incremental strain
controlled loading is used to model the transverse cracking process.

In the presented thesis Weibull parameters for strength or $G_c$ distribution in 90°-
layer are assumed to be material properties. This is one of the important differences between
presented thesis and most of other studies that model damage evolution by assuming in 90°-
layer some kind of statistical distribution of failure properties that depends on the particular
lay-up. In the present work Weibull parameters are obtained from the best fit between
simulation and experimental data for reference laminate. As a reference laminate cross-ply
laminate is chosen. The same parameters are used to simulate damage evolution in all other
lay-ups.

It was noted that models for stiffness degradation and damage simulation don’t
perform with acceptable accuracy for a certain configuration of the sub-laminate. Since 90°-
layer was always the same in all tested laminates it was concluded that sub-laminate
mechanical response during loading is different than assumed in models. Model assumes that
sub-laminate layers are intact and therefore its elastic properties remain constant. Detailed
study of laminates containing off-axis layers is performed in Paper VI of this thesis. This
study shows that damage also accumulates in off-axis layers. Most probably this damage is
microcracking on the fiber/matrix level. In-plane shear modulus of those layers decreases as a
consequence of it. It results in decrease of longitudinal modulus of sub-laminate and
longitudinal modulus of whole laminate as well. This can explain inaccuracy in prediction of
stiffness changes. Stress distribution in 90-layer changes due to more compliant sub-laminate
and therefore damage evolution can not be predicted with acceptable accuracy either. In the
presented study on damage evolution these effects are not taken into account but are suggested
as a future work by the author.
References

EFFECTS OF FIBRE COATING (SIZE) ON PROPERTIES OF GLASS FIBRE/VINYL ESTER COMPOSITES

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Abstract

Effects of fibre coating (size) on transverse cracking has been investigated. Two glass fibre/vinyl ester model composites were studied, denoted CA and NoCA and based on different size compositions. Various single fibre tests were found unable to quantify the interfacial failure of CA since the interface never failed. The CA size consisted of a film former and a methacrylsilane coupling agent whereas the NoCA size contained no coupling agent. The study reveals limitations with single fibre composite tests for fibre/matrix combinations with high interfacial toughness.

Cross-ply laminates based on NoCA demonstrated significantly inferior transverse cracking toughness as compared with CA laminates. Composites based on commercially sized glass fibre were also investigated and they performed almost as poorly as the NoCA material, demonstrating large potential for improvement in commercial composites. Results further indicate that the remarkable transverse cracking toughness of the CA material stems partly from strong fibre/matrix adhesion but also from high ductility of the matrix region close to the fibre surface.
ANALYTICAL MODELING OF STIFFNESS REDUCTION IN
SYMMETRIC AND BALANCED LAMINATES
DUE TO CRACKS IN 90° LAYERS

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Abstract

Stiffness reduction in [S,90_n]_s, symmetric laminates, containing orthotropic sub-laminates (S) and with cracks in 90°-layer, is analyzed. Closed form expressions relating stiffness changes to the transverse crack density are derived. They contain only material properties, laminate geometry and stress perturbation function that is proportional to normalized average crack opening displacement.

Stress distribution models (shear lag, based on variational approach, FEM) are adopted for [S,90_n]_s configuration and used to calculate the stress perturbation function. Predictions are compared with experimental data for [±θ, 90_d]_s, θ = 0,15,30,40 GF/EP laminates. Generally FEM slightly underestimates stiffness reduction whereas both used variational models lead to similar results, slightly lower than experimental. Even shear lag model may be successfully used if the shear lag parameter is first obtained from fitting test results for cross-ply laminate of the same material.

Keywords: polymer matrix composites (PMCs), thermo-mechanical properties, transverse cracking, laminates, crack.
DAMAGE EVOLUTION MODELING IN MULTIDIRECTIONAL LAMINATES AND THE RESULTING NONLINEAR RESPONSE

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Abstract

Stiffness reduction in [S,90\textdegree]_s symmetric laminates, containing orthotropic sub-laminates (S) is analyzed as a function of crack density in 90\textdegree layer. Closed form expressions relating stiffness changes to the transverse crack density are used to compute stiffness changes due to accumulated damage. Weibull strength distribution of 90\textdegree layer is assumed and Shear Lag and Hashin’s models are used for calculation of stress distribution in 90\textdegree layer with cracks. Weibull parameters are obtained from experimental data for [0\textdegree, 90\textdegree]_s laminate and then used for other lay-ups. Strength approach and Monte-Carlo simulation is used to estimate damage evolution in 90\textdegree layer and crack density as a function of applied strain is obtained. It is used to predict stiffness changes in [S,90\textdegree]_s laminates as a function of applied strain. Predictions are compared with experimental data for [\pm\theta, 90\textdegree]_s, \theta = 0,15,30,40 GF/EP laminates. Comparison shows fairly good agreement between prediction and experimental.

Keywords: laminates, damage evolution, stiffness reduction, Weibull distribution, transverse cracking, Monte-Carlo simulation.
NONLINEAR RESPONSE DUE TO DAMAGE EVOLUTION IN MULTIDIRECTIONAL LAMINATES

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Abstract

Damage evolution in form of transverse cracks in 90° layer of [S,90n], laminates due to increasing applied strain is modelled using Monte-Carlo simulation. In the used strength based approach the whole 90° layer of the specimen is divided in to a large number of small elements and the strength is assigned to each element according to Weibull distribution. Parameters of distribution are obtained by fitting for a certain reference cross-ply material the simulated crack density curve to the experimental curve. The obtained parameters are considered as material properties and used to predict the cracking evolution in laminates with different outer layer S and the same 90° layer. Needed stress distributions are obtained using FE results or analytical models. Agreement with test results is good as long as the cracked 90° layer thickness is not changed but, as expected, becomes worse for thinner 90° layer. In order to describe stiffness reduction due to increasing load the predicted crack density curves are used as an input in expressions relating stiffness to crack density.

Keywords: laminates, mechanical properties, transverse cracking, analytical modelling, FEA, statistical methods.
FINITE ELEMENT MODELING OF TRANSVERSE CRACKING AND RESULTING INELASTIC BEHAVIOR OF LAMINATES

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Abstract

Closed form expressions are derived for stiffness reduction in \([S,90_n]\), laminates due to transverse cracking in 90-layers. Provided normalized average crack opening displacement is known, expressions contain only crack density, geometrical parameters and elastic constants of layers. The average COD dependence on the constraint effect of adjacent layers and crack spacing is analyzed using FEM in plane stress formulation. It is found that the out-of-plane elastic constants have a very limited effect on COD. Simple power law relating average COD to elastic and geometrical parameters is derived. The obtained power law and the developed methodology is successfully used to predict the reduction of thermo-elastic properties of \([\pm \theta/90_4]\) laminates.

The crack closure technique and Monte-Carlo simulations are used to model the damage evolution: 90-layer is divided into a large number of elements and \(G_c\) to each element is assigned according to Weibull distribution. The experimental crack density versus strain curve for \([0_2/90_4]\), cross-ply laminate is used as a reference configuration to determine parameters in Weibull distribution.

Damage evolution in \([S,90_4]\), laminates is modelled and results are in good agreement with test data for glass fibre/epoxy laminates containing sub-laminates with \(\pm \theta\) layers only. The 90-layer thickness effect on damage evolution is discussed in strength and fracture mechanics formulation.
**DAMAGE IN COMPOSITE LAMINATES WITH OFF-AXIS PLIES**

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Abstract

Damage in off-axis plies of composite laminates is studied by examining the configuration $[0/\pm \theta_s/0_{\theta_s}]_s$ with $\theta = 25, 40, 55, 70$ and $90$ subjected to tensile loading in the axial direction. It is found that for the values of $\theta$, where the stress in the off-axis plies normal to the fibers is tensile, ply cracks lying along fibers initiate and increase in number, while for other $\theta$ values the plies do not undergo this damage, as expected. However, the overall laminate elastic moduli are found to change also for the $\theta$ values where no ply cracks exist. It is postulated that a shear-induced degradation of the off-axis plies is responsible for the observed laminate moduli changes. The prediction of changes in these moduli by using the ply shear modulus measured on $[\pm \theta_s]_s$ appears to support this postulate. For the case of moduli changes caused by ply cracks the recently proposed synergistic damage mechanics approach is applied. The implications of the findings of this work on a class of continuum damage mechanics formulations proposed in the literature are discussed.