On mechanical modeling of composite materials

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Preface

The work presented in this thesis was carried out at the Department of Solid Mechanics, Royal Institute of Technology (KTH), Stockholm, Sweden in four distinct occurrences stretching from May 1997 to May 2010.

During the first part of this thesis, between May 1997 and September 2000, I was employed at KTH as a full-time doctoral student; my supervisor, Assoc. Prof. Jonas Neumeister, is acknowledged for initiating the first two research projects of this thesis and for guiding me through problems related to elasticity and fiber failures in composite materials.

In January 2005, after working a few years in the industry, I initiated an industrial research project between KTH and Infineon Technology Sweden AB. This project dealt with the mechanical behavior of solder joints. At that time, I became an industrial doctoral student under the supervision of Prof. Peter Gudmundson. My former Swedish and German Infineon managers Håkan Sjödin and Heinz Pape, respectively, are gratefully acknowledged for actively supporting and financing this project, which nonetheless abruptly ended in March 2006 when Infineon Technology closed down its activity in Sweden and laid off all the employees.

In September 2006, after working a few months at Sony Ericsson Mobile Communication AB, I initiated another industrial research project with KTH dealing with the mechanical behavior of polymers. Again, I became an industrial doctoral student but this time under the supervision of Assoc. Prof. Jonas Faleskog. This project appeared to be much more intricate than expected and I am grateful for the many hours spent discussing the implementation of large strain plasticity in Finite Element programs. The enthusiastic support of my former manager at Sony Ericsson, Leif Brunström, was greatly appreciated but unfortunately could not prevent the project to suddenly end when Sony Ericsson closed down its development activity in Stockholm and laid off all the employees in February 2009.

As a result, I came back to KTH in March 2009 where I was offered a position as a full-time doctoral student in order to complete the Sony Ericsson polymer project and to apply some of the
results to paper mechanics. Prof. Sören Östlund and Assoc. Prof. Mikael Nygård are greatly acknowledged for allowing this financial support through BiMaC Innovation.

I am also indebted to Assoc. Prof. Bengt Sundström and Prof. Mårten Olsson for the numerous Solid Mechanics related questions I have asked them over the years and that they always answered patiently and accurately. Finally I would like to thank Hans Öberg for help with experiments and Bengt Möllerberg for specimen manufacturing.

Last but not least I want to thank my present and former colleagues at KTH, Infineon and Sony Ericsson for all the nice moments we have shared during these thirteen years.

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Etienne Bonnaud
List of appended papers


Introduction

1. Background
As the name implies, composite materials are made up of different constituents: in their simplest form, a stiffer reinforcement surrounded by a softer matrix. Such combinations allow to achieve overall properties which are at least the sum of the individual properties.
Natural composite materials have existed in numerous forms for a long time. Wood, for example, consists of cellulose fibers (strong in tension) embedded in a lignin matrix (resisting compression).
Manufactured composite materials appear early in mankind history mainly for construction purposes but have recently been the focus of intensive scientific research. As a result, industrial composite materials are now extensively used in several applications such as vehicles, sport equipments and microelectronics.
Usually, distinction is made between microcomposites, like alloys, where two different phases are finely dispersed into one another and macrocomposites, like metal reinforced concrete beams, made up of two distinct materials. In the following only macrocomposites will be considered.
A very large variety of composite materials can be designed depending, among others, on the matrix material, the reinforcement material and the reinforcement shape. Over the years, three main matrix material groups have emerged: polymer resins, metals and ceramics.
Among polymer resins, due to their relatively simple manufacturing processes, thermosetting polymers are today predominantly used. For numerous every day applications, simpler and cheaper resins (like polyester and epoxy resins) are sufficient, whereas for more specific applications, where chemical resistance, higher temperature or fire resistance is a concern, more advanced and more expensive resins (like vinylester, polyimids and phenolic resins) are necessary. Nonetheless, and despite the necessity of high pressure and high temperature during injection, thermoplastic polymers are becoming more and more popular for applications where toughness matters: several sailing boat constructors have for example begun to manufacture hulls in polypropylene.
Relatively light metal matrices are of interest for applications where high loadings need to be sustained but for which, weight and toughness are a concern. Possible candidates are for example
aluminum and tin. By reinforcing metal matrices, increased yield, tensile, creep or fatigue strengths can be achieved.

Finally, ceramic matrices (like for instance silicon carbide: SiC) are almost exclusively used in high technology applications within the nuclear or space industry, where very high temperature resistance is of interest; they are unfortunately relatively expensive to manufacture.

In order to provide a strengthening effect, reinforcement materials should obviously have a relatively higher stiffness and strength than the matrix material. A new trend for low cost composites is to use vegetal fibers (like linen, hemp or wood) which apart from being cheap are also ecological and biodegradable; nonetheless for more technically advanced applications, glass, aramid (Kevlar), carbon, metal and ceramic are still most widely used. The shape of reinforcement can vary a lot and mainly depends on the sought mechanical properties: particles, short fibers (whiskers) aligned or randomly dispersed, aligned long fibers or long fibers woven in a roving; see Fig. 1 where different types of reinforcement are illustrated (reproduced from [1]).

Figure 1: Schematic illustration of different reinforcements, a) particles, b) whiskers, c) long fibers.

To summarize, three main groups of materials (metals, ceramics and amorphous) are commonly used to manufacture composites and can serve both as matrix material and as reinforcement material, either in connection with another material from the same group (steel fibers in aluminum...
matrix, glass fibers in polymer matrix) or with a material from another group (ceramic particles in a metal matrix).

One of the main reasons behind the development of composites is the possibility to produce materials combining low weight and high stiffness. As already mentioned, reinforcement materials are stiffer than matrix materials but they also happen to have higher density. In order to achieve high stiffness while keeping low weight, stiffness is only enhanced in the directions where it matters. Assuming known in advance, both intensities and directions of the loads to be experienced by the composite material allows, at the conception stage, to accordingly place the right amount of reinforcement material in the right directions. This concept is precisely the ground for a noteworthy group among long fiber reinforced composites: laminates in which plies or laminae (where fibers are all aligned in the same direction) are glued together at angles determined from the presumed future loads. The laminate presented in Fig. 2 is stiffest in the $x$-direction, approximately half less stiff in the $y$-direction and considerably less stiff in the $z$-direction, in which the load is primarily carried by the matrix material.

![Figure 2: Schematic of a $0^\circ/90^\circ/0^\circ$ laminate where fibers in the top and the bottom laminae are aligned with the $x$-direction while fibers in the intermediate lamina are aligned with the $y$-direction.](image)

Furthermore, additional features not at all contained in any of the two constituents can be achieved through such combinations. When it comes to energy consumption at fracture for example, a desirable property in many applications (the more energy absorbed by a car structure during a
collision, the less violent its impact for the driver), energy is not only consumed by fibers and matrix fracture but also by fiber debonding and delamination.

Averaged mechanical properties are often sufficient when evaluating strains and displacements at the laminate level. However, stress responses require a more detailed level of refinement meaning that properties need to be averaged at more internal levels. In a composite panel for example, possible levels are: laminate, lamina, woven roving, bundle of fibers, individual fiber and resin levels. Studying failure initiation in a laminate is a typical case when detailed stress fields are essential. The main concern is to assess stresses in levels where failure is likely to occur and once a constituent has broken to evaluate the consequences at other levels, e.g. the laminate level. The study of the mechanics of composites therefore involves a two way analysis: global loading results in local stresses and possible damage, which in turn affects the global behavior of the laminate. However a fully comprehensive mechanical model for fiber composites would contain a huge number of parameters, namely all pertinent properties of each constituent and all pertinent properties of each interface between different levels. Studying composite structures must therefore be restricted to certain aspects, for example applying a load at a given level and investigating the response at the level immediately below. Again, the common approach is to study separately the different phenomena involved by isolating certain components of a certain level. Eventually, such studies will lead to a better understanding of the overall behavior.
2. Summary of the appended papers

The work presented in this thesis touches upon different aspects of the mechanical behavior of composite materials. The first article presents a new method to calculate stresses and strains in a laminate. The second and third articles deal with fiber failures. The fourth and fifth articles focus on matrix behavior (metallic matrix and polymer matrix). Finally, the sixth article is an application of the polymer matrix model to paper material.

Paper A

Stress analysis in laminates gives very different results when performed at the laminate or at the lamina level as the homogenized and individual layer properties markedly differ. In the approach chosen here, complete determination of the stress field requires the computation of four constants in each layer; therefore conventional methods solving simultaneously for all the unknowns lead to tedious calculations and multilayered laminates are usually modeled by a few layers resting on a rigid foundation or an elastic half-plane of homogenized mechanical properties. Here, instead, the laminate is modeled by the replication of the first $q$ layers up to infinity (see Fig. 3).

Figure 3: Laminate structure with identical blocs of $q$ different layers.
As there of course does not exist any laminate of infinite extent, this again is an approximation but which appears to be better than the previously mentioned ones. Say that stresses are to be calculated in a 100 layers composite. The layers of main interest are the ones close to the loaded region where stresses are likely to be high. Usual methods would take into account the first two layers and approximate or even disregard the influence of the 98 others. Here, the 100 layers are all exactly modeled as layers and only the boundary conditions on the 100th differ from reality. According to the Saint Venant’s principle, the further from the region of interest approximations are made, the less they matter, which obviously makes an approximation on the 100th layer better than an approximation on the second layer. Furthermore this method allows to reduce the number of unknowns to four, namely the four coefficients characterizing the first layer onto which loads are applied. Coefficients in other layers of interest can subsequently be determined by simple matrix multiplication. Stress results from the multilayered model are presented and compared to stresses from the homogeneous material [2].

**Paper B and Paper C**

As previously mentioned, fibers in laminates are always aligned in a specific direction and often gathered in groups like in woven rovings, see Fig. 4 (reproduced from [1]).

![Figure 4](image)

**Figure 4**: Details a) of a woven roving (top view) and b) of several neighboring fiber bundles (cross section).

Nevertheless, the simple fiber bundle model already contains many interesting features of material degradation. In the model studied here (see Fig. 5), fibers are detached from the composite
structure, clamped at both ends and submitted to the same increasing load. All intact fibers are furthermore assumed to carry an equal load throughout the degradation process (true global load sharing assumption).

![Figure 5: Fiber bundle model with mass attached \( m \) and viscous damper \( \eta \). Applied displacement and measured force are noted \( x \) and \( F \), respectively.](image)

Noticeable is that fibers usually break in small groups called bursts: the force lost in a newly broken fiber overloads the remaining ones and possibly causes the rupture of further weak fibers (see Fig. 6). Burst occurrences during the failure process obviously depend on the fibers themselves through their statistical strength distribution. What however does not depend on the fiber strength distribution is the mutual relation between bursts of different sizes \( \Delta \) summed up over the entire failure process \( D_\Delta \). The burst size distribution is therefore said to be universal as its shape is independent of the fiber properties. Moreover, in an assumed massless bundle, this distribution follows a power law that gives a straight line in a log-log diagram, see [3] for details. Here, in an attempt to improve modeling of damage progression, additional effects as inertia and damping are taken into account. Their consequences on burst size distributions are investigated: distributions are shown to remain universal but with notably altered shapes for small burst sizes (see Fig. 7).

Inertia increases the number of large bursts to the detriment of small ones; combined inertia and damping are shown to render an intermediary case between the ones with and without inertia. Nevertheless, all distributions approach a straight line of same slope for larger burst sizes.
Figure 6: Bundle force response to applied strain; the true curve is jagged whereas the overall curve is monotonously increasing and decreasing.

Figure 7: Burst size distributions $D_\Delta$ as a function of burst sizes $\Delta$. Inertia and damping modify the burst size distribution for small bursts.
Paper D

In order to characterize the global mechanical behavior of composites, knowledge of the mechanical behavior of the matrix is essential: as being the interface with the surroundings, the matrix material is naturally the first to experience loads or impacts.

The first step in experimentally characterizing materials and particularly metals is usually to conduct a tensile test. As simple as it is, this test gives important information about the elastic and the plastic behavior. For metals featuring little viscosity, the transition between the elastic and the plastic regimes is easy to establish. The constant slope of the elastic part of the curve gives the elasticity modulus and the not necessary constant slope of the plastic part of the curve gives the elasto-plastic modulus; this modulus is generally associated to hardening (isotropic and/or kinematic). When viscosity effects are not negligible (as for soft metals or metals relatively close to their fusion temperature) it is difficult to establish a clear elastic-plastic transition and more advanced numerical methods to estimate material parameters are necessary. Furthermore, in that case, the rate at which load is applied matters and gives considerable differences in stress levels.

Here, non-linear isotropic hardening plasticity combined with the Perzyna viscoplastic model was assumed; results from curve fitting are presented in Fig. 8.

![Figure 8: Monotonic stress strain curves at different strain rates (0.2/s, 1/s, 5/s): experiments (dotted line) and model predictions (solid line).](image)

Figure 8: Monotonic stress strain curves at different strain rates (0.2/s, 1/s, 5/s): experiments (dotted line) and model predictions (solid line).
The second step consists in studying the behavior at unloading and subsequent compressive loading to, if necessary, split isotropic hardening into isotropic and kinematic hardenings. The stress level at which plasticity sets in during unloading or compression loading indicates the ratio between the two hardening contributions. As developed in [4], a simple Melan-Prager kinematic hardening law only gives realistic results when used with linear hardening. For non-linear hardening, the Armstrong and Fredrick model should be used instead. Results from this model again combined with the Perzyna viscoplastic model are shown on Fig. 9. Another aspect contained in this study is the numerical implementation of this material model into the commercial Finite Element code LS-Dyna [5]. This implementation is valid for small strains but large rotations and follows a Backward-Euler scheme. As an application, results from drop test experiments in electronics are presented.

![Cyclic stress strain curves at 0.2/s: experiments (dotted line) and model predictions (solid line).](figure9.jpg)

**Figure 9**: Cyclic stress strain curves at 0.2/s: experiments (dotted line) and model predictions (solid line).

**Paper E**

In this paper, focus is shifted towards polymer matrix materials. The mechanical model used is described in [6] and different methods for its numerical implementation in the Finite Element code Abaqus Explicit [7] are presented.
In contrast to the vast majority of metals, the true stress-true strain curve is not monotonously increasing, see Fig. 10a. The force-displacement curve (or engineering stress-engineering strain curve) does present a maximum when necking sets in but, provided the polymer is not brittle, subsequently remains fairly constant (and low) as necking propagates along the whole length of the specimen, see Fig. 10b.

![Figure 10:](image)

The reason for this behavior is to be found in the microstructure of polymers. When submitted to loading, polymer chain segments (delimited by chain entanglements) first withstand deformation but eventually rotate causing the rupture of weaker bonds as well as an increase of the free volume, which results in micro-shear banding and softening. Subsequently, when polymer chains are more or less aligned with the load, covalent bonds are directly stretched which results in an increasing stiffness.

The material model presented in [6] is based on a solid thermodynamical fundament. It is developed within the hyperelastic and the multiplicative split frameworks and is therefore valid for large strains and large rotations. Consequently, time integration algorithms should also be valid for large deformations, meaning that objectivity should be ensured within every integration.
Three different objective algorithms (explicit, fully implicit and forward gradient) are presented here and the influence of increasing the size of the time steps on the stability within an explicit dynamic framework is investigated. Figure 11 shows results for the explicit and fully implicit cases.

![Figure 11](image)

**Figure 11**: Algorithm results; uniaxial tension; Cauchy stress vs. Hencky strain. a) Explicit: number of time steps: 800, 900...1800 and b) Fully implicit: number of time steps: 10, 20, 40, 80, 160, 320. The vertical scale is only valid for the for lowest curve; all subsequent curves are translated upwards 10 MPa for clarity.

As expected, the explicit algorithm is very sensitive to the number of time steps: fewer/larger time steps lead to increasing instability (conditional stability). On the contrary, the fully implicit algorithm stability is not affected by the number of time steps (unconditional stability).

**Paper F**

As an application, the polymer matrix model is used to describe paper material. Polymers and papers should show comparable mechanical behaviors as they share similar structures where chains and fibers respectively lie in a network and interact with each other at entanglement points. Stiffness of paper fibers vary with a number of properties but mainly with fibril orientation, see Fig. 12 replotted from [8]. Appropriate choice of material parameters in the polymer model allows to reproduce this dependency, see Fig. 13.

Once the behavior of single fibers is captured, micromechanical network modeling strategy is used to study the influence of fiber properties on global paper properties.
**Figure 12**: Experimental uniaxial tension test of single fibers with different fibril angles.

**Figure 13**: Computed uniaxial tension test of single fibers with different fibril angles.
3. Conclusions

A complete model for composite materials would involve so many different aspects and phenomena that it would be very difficult to handle. Consequently, analyses are restricted to investigations of certain behaviors at particular levels.

The influence of elastic properties of (infinitely) many layers on detailed stresses is investigated analytically and the method is shown to reduce to the computation of only four coefficients. Statistical analysis of fiber bundles results in very predictable behaviors, which can be described with only two parameters. The behavior of matrix material is modeled analytically and implemented in Finite Element codes for numerical simulations. Here, the number of parameters is only an experimental concern and barely affects the computational running time; high number of material parameters is therefore generally preferred as it leads to increased accuracy.

Hopefully, such findings will facilitate forthcoming efforts to improve material description of composite materials.

References


