

Experimental and Numerical Multi Scale Analysis of Fiber Reinforced Composites

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Dedicated to my parents Erwin and Christiane Stier

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Abstract

Increasing energy costs necessitate efficient lightweight constructions particularly in the fields of mobility and transport. For these applications, tailorable materials like fiber reinforced plastics (FRP) are gaining more and more importance. However, the characterization and experimental validation of advanced numerical composites analysis techniques is challenging. A significant outstanding quandary is in regards to the proper, or most beneficial, scale on which the constitutive damage model defining the mechanical response of the material should function. The prediction of the global FRP weave response, particularly when exceeding the linear elastic regime, is only possible if the internal structure is taken into account. Thus, different scales need to be considered.

Treating the composites as fully homogenized via the macro scale approach is computationally efficient, but, since the physics induced by the intrinsic structure are lost, it is extremely challenging to devise a predictive model on this scale. In contrast, the meso scale approach, wherein the composite tows are treated as effective anisotropic materials, will always be more computationally expensive. It further requires a complex damage model to handle the extreme anisotropy of the tow material, with its directionally dependent multiple damage mechanisms. Advantageous is the better physical representation of the internal structure. The material model suitable for the tows needs to be fully characterized which can be done by verified micro scale analysis techniques. The micro scale approach, involving modeling the composite to the scale of the constituents (i.e. fiber and matrix materials) enables use of simpler models and avoids ad-hoc coupling rules for the various damage components. However, this approach can be very computationally demanding, and often, the constituent scale data best suited for characterizing the damage model are unavailable.

In this dissertation, the hierarchical multi scale method is applied to predict the mechanical response of a carbon fiber reinforced plastics plain weave composite. The validity of the method is verified by comparison of the numerically obtained material response with experimental data at all scales. The advantages and limitations of this technique are discussed. An anisotropic damage material model which is required for this approach, is presented. It is shown that it is suitable to describe the material behavior of the constituents of the micro scale as well as unidirectional composites.

Zusammenfassung

Steigende Energiekosten erfordern besonders im Mobilitäts- und Transportwesen effiziente Leichtbaukonstruktionen. Für solche Anwendungen werden faserverstärkte Kunststoffe immer wichtiger. Allerdings sind die Herausforderungen bei der Charakterisierung und Validierung neuer numerischer Kompositanalysemethoden sehr groß. Eine weitere wichtige Fragestellung betrifft die Zwickmühle, auf welcher Skala das Konstitutivgesetz das die mechanische Antwort der Werkstoffe beschreibt am geschicktesten eingesetzt werden soll. Die Vorhersage von gewobenen Faserverbundwerkstoffen, besonders im nichtlinearen Bereich, ist nur dann möglich, wenn die intrinsische Struktur des Materials berücksichtigt wird. Deshalb müssen mehrere Skalen in Betrachtet werden.

Behandelt man das Komposit als homogenes Material, durch den numerisch effizienten Makroskalenansatzes, gehen die physikalischen Zusammenhänge, hervorgerufen durch die Mikrostruktur, verloren, was die Komplexität für prädiktive Materialmodelle enorm steigert. Dahingegen fordert der Mesoskalenansatz, bei dem das Roving als effektives Material behandelt wird, erhöhten numerischen Aufwand. Ausserdem wird ein komplexes Schädigungsmodell benötigt um die starke Anisotropie des Rovings mit den richtungsabhängigen Schädigungsmechanismen abbilden zu können. Die genauere physikalische Darstellung der internen Struktur ist vorteilhaft. Das Materialmodell, das zur Beschreibung des Rovings herangezogen wird, muss vollständig charakterisiert werden. Die Charakterisierung kann mittels verifizierter mikromechanischer Analyse erfolgen. Auf der Mikroskala, die das Material auf der Ebene der Konstituenten (Faser und Matrix) beschreibt, können einfachere Materialmodelle verwendet, und die willkürliche Annahme über die Interaktion der Schädigungsmechanismen vermieden werden. Leider ist diese Methode mit großem numerischem Aufwand verbunden, und die Materialparameter der Konstituenten oft nicht bekannt.

In dieser Dissertation wird der hierarchische Mehrskalensatz herangezogen, um das mechanische Verhalten eines Kohlenstofffaser leinwandgewebeverstärkten Komposites vorherzusagen. Die Gültigkeit der Methode ist durch experimentellen Abgleich auf jeder Skala verifiziert. Die Vorteile und Grenzen der Methode sind erläutert. Das für die Methode benötigte anisotrope Schädigungsmodell ist dargestellt. Es wurde gezeigt, dass das Materialmodell sowohl für die Konstituenten als auch für das unidirektionale Komposit geeignet ist.

Contents

Contents

List of Figures

List of Tables

Abbreviations

1	Introduction	1
1.1	Motivation	1
1.2	Overview of Composite Analysis Methods	4
1.2.1	Single Scale Methods	4
1.2.2	Multi Scale Methods	5
1.2.3	Experimental Techniques	8
1.3	Outline of the Dissertation and Applied Methods	10
1.3.1	Experimental Work	11
1.3.2	Numerical Work	12
2	Experimental Work	15
2.1	Experimental Setup	15
2.2	Determination of Material Parameters	17
2.2.1	Constituents	17
2.2.1.1	Carbon Fiber	17
2.2.1.2	Matrix Material	20
2.2.2	Production Process of the Composite Material	26
2.2.3	Unidirectional Composites	30
2.2.3.1	0° UD Tensile Tests	30
2.2.3.2	90° UD Tensile Tests	35
2.2.3.3	±45° UD Tensile Tests	42
2.2.4	Woven Composites	45
2.2.4.1	0°/90° Plain Weave Tensile Tests	48
2.2.4.2	+45°/−45° Plain Weave Tensile Tests	54
2.3	Microscopic Analysis	58
2.3.1	UD Composites	62
2.3.2	Woven Composites	68
2.4	Conclusions	70

3	Anisotropic Damage Material Model	73
3.1	Introduction	73
3.2	Material Modeling	74
3.3	Damage Interaction	78
3.4	Integration Algorithm	80
3.5	Parameter Discussion	81
3.6	Conclusion	85
4	Micro Scale Analysis of Unidirectional Composites	87
4.1	Introduction	87
4.2	Generation of the Unidirectional Composite RVE	89
4.3	Periodic Boundary Conditions	94
4.4	Numerical Homogenization using FEA	98
4.5	Convergence of the RVE	104
4.6	Linear Elastic Micro Mechanics	114
4.7	Continuum Damage Mechanics at the Micro scale	116
4.8	Conclusion	150
5	Meso Scale Analysis of Woven Composites	151
5.1	Introduction	151
5.2	Generation of the Plain Weave RUC	152
5.3	Linear Elastic Meso Mechanics	156
5.4	Continuum Damage Mechanics at the Meso Scale	162
5.5	Conclusion	190
6	Summary, Conclusions and Outlook	193
A	Complete Set of Neat Resin Experimental Data	197
B	Complete Set of Unidirectional Composite 0° Experimental Data	205
C	Complete Set of Unidirectional Composite 90° Experimental Data	213
D	Complete Set of Unidirectional Composite $\pm 45^\circ$ Experimental Data	221
E	Complete Set of Woven Composite $0^\circ/90^\circ$ Experimental Data	229
F	Complete Set of Woven Composite $+45^\circ/-45^\circ$ Experimental Data	235
	Bibliography	241