

**EUSMAT**

**European School of Materials**

**DocMASE**

**Doctorate in Materials Science and Engineering**

**Status Report**

Mechanics of extreme thin composite layers for aerospace applications

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# Acronyms

|  |  |
| --- | --- |
| **DocMASE** | Doctoral Program in Materials Science and Engineering |
| **EUSMAT** | European School of Materials Science and Engineering |
| **EEIGM** | École Européenne d'Ingénieurs en Génie des Matériaux |
| **CAE** | Computer Aided Engineering |
| **CF** | Carbon Fiber |
| **CZM** | Cohesive Zone Model |
| **EP** | Glass Fiber |
| **FEM** | Finite Element Method |
| **GF** | Glass Fiber |
| **LEFM** | Linear Elastic Fracture Mechanics |
| **RVE** | Reference Volume Element |
| **UD** | Uni-Directional |
| **VCCT** | Virtual Crack Closure Technique |

# Introduction

This report is intended to be a brief introduction to the project *Mechanics of Extreme Thin Composite Layers for Aerospace Applications* and a summary of recent developments. The project is carried out in the framework of the *Doctoral Program in Materials Science and Engineering (DocMASE)* of the *European School of Materials Science and Engineering (EUSMAT)*, co-supervised by Prof. Zoubir Ayadi of the *École Européenne d'Ingénieurs en Génie des Matériaux (EEIGM, Université de Lorraine)* and Prof. Janis Varna of Luleå tekniska universitet.

The structure of this report is explained in the following. Firstly, an introduction to the rationale motivating the project is provided: the scope of the work is put into perspective in the contemporary debate on sustainable development and the current trends in the transport industry, with a focus on the aerospace sector. A few concepts are introduced to provide the technical foundations of the problem. The objectives of the project are then presented and briefly described. Subsequently, recent developments are summarized. In presenting them, a functional approach is followed: the overall activity is split into functional areas, for which objectives, tasks and corresponding level of completion are reported.

# Project’s rationale and background

Social and political awareness for a renovation in industrial practices towards a reduction of their health, societal and environmental impact are nowadays increasing across the globe (see for example [8]). New fiscal policies have been put into place, elevating the costs of running unsustainable businesses through taxes and fines. Transportation has answered the call mainly through two different but related strategies: the adoption of alternative energy sources and the improvement of fuel efficiency. Driven by the increased costs derived from its extensive use of fossil fuels, the aerospace sector has been a pioneer in these efforts in recent years. From a technical standpoint, both strategies depend strongly on the adoption of novel structures and materials capable of significant reductions in weight, and thus in consumption, without compromising safety and structural integrity.

Carbon and Glass Fiber Reinforced Polymers (CFRP and GFRP, respectively) hold the promise of lighter and robust structures, due to their high stiffness to density ratio. Furthermore, the development in very recent years of the spread tow technology has allowed increased savings in terms of weight. Originally developed by Kawabe of Fukui Technology Center, the spread tow technology allows the original tow of 12k or 24k fibers to spread along its width, reducing its thickness to values around 0.02 mm or less (see [1] and [2] for a producer’s recent press releases). Extremely thin plies can thus be produced. When used in cross-ply, angle-ply or quasi-isotropic laminates, thin plies show a significant increase in their resistance to fracture, as found in [3]. This phenomenon, already known in literature (see [4] for one of the first accounts on the topic) from experimental observations, has been known as the in-situ or thin-ply effect. Unfortunately, as the organizers of the Third World Wide Failure Exercise (WWFE-III) point out ([5] and [6]), neither a clear physical understanding nor a reliable analytical or numerical model exist on the mechanisms governing the failure of thin ply laminates. It implies that damage propagation inside such laminates cannot be reliably predicted, leaving room for the possibility of sudden collapse or onset of instabilities. Such lack of knowledge hampers the effective exploitation of the phenomenon, as it cannot be quantified in the design phase with an admissible level of uncertainty (see [7] for details on certification and airworthiness).

# Objectives and areas of activity

The research project focuses on the study of the thin-ply effect. The focus of this doctoral thesis is analyzing and understanding the mechanisms governing the onset and propagation of damage in extremely thin carbon- and glass- fiber composite plies. It aims to the development of reliable analytical and numerical models for the analysis and design of structures made of this kind of material.

The activities conducted under the framework of the project can be classified into a few different functional areas. This is an abstraction helpful in the presentation of the project’s developments on one side, and as well a pragmatic frame of mind to increase the daily productivity on the other side. For each functional area, different objectives can be laid out and a set of tasks can be identified for the successful completion of each objective.

The project work is thus divided into the functional areas described in the following.

1. *Administration:* it refers to all activities related to public bureaucracy, academic administrative duties, travel planning and organization, application and inscription to events and similar.
2. *Project planning and management:* as the doctoral project is projected to extend for 4 years and involves people located in different countries, planning and management assume an important role. This category comprises all activities from the selection of best practices to the creation or adoption of tools for their effective implementation.
3. *Literature review and analysis:* knowing the state of the art in the field is of fundamental importance in a research project. Its study and the implementation and use of tools for its analysis represent the core of this functional unit.
4. *Experimental activity:* it involves all tasks related to the preparation, conduction and data-analysis of real-world (physical, mechanical, chemical) tests.
5. *Analytical modeling:* it comprises all activities related to mathematical modeling, where algorithmic reduction or discretization are not the main focus.
6. *Numerical simulation:* it refers to the tasks related to the ideation, development, conduction and analysis of numerical simulation.
7. *Reporting and dissemination of results:* activities concerning the writing and redaction of internal and external reports, presentations, papers, theses, books, blogs and websites.
8. *Learning and professional development:* as part of the doctoral track, learning and professional development are not only suggested activities, but mandatory ones. Courses, seminars, webinars, on-line courses, MOOCs and all other activities related to learning and professional development lie in this category.

# Summary of developments

## Administration

### 4.1.1 Goals

1. Formalise doctoral student status.
2. Formalise doctoral researcher status

### 4.1.2 Tasks’ overview

|  |  |  |  |
| --- | --- | --- | --- |
| **Description** | **Goal(s)** | **Status** | **Completion (reached or foreseen)** |
|  |  |  |  |
| Preparation of personal documents for working contract preparation | 2 | Done | End Sep./ beg. Oct. ‘15 |
| Preparation of documents for inscription to Swedish doctoral school | 1 | Done | Mid-Oct. ‘15 |
| Preparation of documents for inscription to French doctoral school | 1 | Done | Nov. ‘15 |
| Inscription to French doctoral school | 1 | Done | End Nov. ‘15 |
| Creation of university account | 1/2 | Done | End Nov. ‘15 |
| Set-up of office pc | 2 | Done | End Nov. ‘15/Beg. Dec . ‘15 |
| Submission of doctoral school’s documents for working contract preparation | 2 | Done | End Nov. ‘15 |
| Contract received | 2 | Done | Beg. Jan. ‘16 |
| Preparation of documents for inscription to French social security | 2 | Done | Mid Jan./Beg. Mar. ‘16 |
| French social security number received | 2 | Done | End Mar. ‘16 |
| French social security card (carte vitale) received | 2 | Pending | End Apr. ’16? |
|  | **Note:** | It depends on public administration. | |
|  |  |  |  |

Table 1: Administration task's overview

## Project planning and management

### 4.1.1 Goals

1. Identify, adopt, practise and improve a strategy for effective management of daily work aimed towards the successful completion of a research project under the constraints described in the following.
2. Medium-term project life-span (4 years).
3. Multiple assignments to be fulfilled from different stakeholders (reported in brackets): develop mathematical/physical models and numerical simulations, produce results, report and publish (research group, supervisors); learn, attend courses, seminars, etc. ..., acquire ECTS credits (doctoral school); collaborate, network, teach, join side projects/activities, join professional associations (personal, professional development); earn a living, manage household, balance work/life time (family).
4. Not all tasks and objectives are well-defined from the beginning, but unfolds as the projects evolves.
5. Supervisors and research groups are located in different countries and travel on a regular basis.
6. Supervisors, researchers, administrative staff come or live in different countries: cultural differences and barriers, which might cause misunderstandings.
7. Identify, learn and regularly use (mostly software) tools to practice the adopted strategies.
8. Identify shortcomings of adopted tools, design and implement solution(s).

### 4.1.2 Tasks’ overview

|  |  |  |  |
| --- | --- | --- | --- |
| **Description** | **Goal(s)** | **Status** | **Completion (reached or foreseen)** |
|  |  |  |  |
| Learning principles of waterfall and agile project management methodologies | 1 | Done | Dec. ‘15 |
| Adoption of agile-based strategy | 1 | Done | Beg. Jan. ‘16 |
| Identification and adoption of tools to practise the strategy, now used daily (such as degreed, github, cloud9, sharelatex, ...) | 2 | Done | Dec. ‘15/Jan. ‘16 |
| Ideation of a software tool to overcome shortcomings of available ones | 3 | Done | End Feb./Beg. Mar. ‘16 |
| Development of research-oriented web-based management tool | 3 | In progress | Mar. ‘17 |
|  | **Note:** | Side project. Only a fraction of time (10% or less) is devoted to it. | |
|  |  |  |  |

Table 2: Project planning and management tasks' overview

## Literature review and analysis

### 4.1.1 Goals

1. Identify the main actors, peers and stakeholders in the field of thin ply fibre composite laminates in present-day academic and industrial world.
2. Get acquainted with the state-of-the-art of research activities on thin ply mechanics.
3. Study previous results on scaling in fracture mechanics with a focus on fibre composite laminates.
4. Collect previous works on analytical modelling and numerical simulation on the micromechanics of fibre-matrix de-bonding.
5. Develop, test and apply tools for collection and thematic analysis of large scientific literature datasets.

### 4.1.2 Tasks’ overview

|  |  |  |  |
| --- | --- | --- | --- |
| **Description** | **Goal(s)** | **Status** | **Completion (reached or foreseen)** |
|  |  |  |  |
| Studied PhD theses of previous group members | 2 | Done | Oct. ‘15 |
| Literature search for papers on thin ply mechanics. | 2 | Done | Oct. ‘15 |
| Study of papers. | 2 | Done | End Oct./Beg. Nov. ‘15 |
| Identification of institution of researchers who published the papers previously searched. | 1 | Done | End. Oct./Beg. Nov. ‘15 |
| Creation of a map reporting the different actors retrieved from the literature available. | 1 | Done | Beg.-Mid. Nov. ‘15 |
| Literature search and study on scaling in fracture mechanics | 3 | Done | Mid Dec. ‘15/ Mid Jan’ 16 |
| Literature search and study on micromechanics of fibre-matrix de-bonding | 4 | Done | Mid March ‘16 |
| Develop python code to scrape scientific literature databases | 5 | In progress | End May/Beg. Jun. ‘16 |
| Build a dictionary for use in thematic analysis | 5 | In progress | May ‘16 |
| Develop python code to perform thematic analysis | 5 | Planned | Sept./Oct. ‘16 |
|  |  |  |  |

Table 3: Literature review and analysis tasks' overview

## Experimental activity

No experimental activity is currently planned or foreseen.

## Analytical modeling

### 4.1.1 Goals

1. Develop tools to efficiently perform dimensional analysis of physical models.
2. Perform dimensional analysis of developed micromechanical model.

### 4.1.2 Tasks’ overview

|  |  |  |  |
| --- | --- | --- | --- |
| **Description** | **Goal(s)** | **Status** | **Completion (reached or foreseen)** |
|  |  |  |  |
| Review of Buckingham’s theorem | 1 | Done | Feb. ‘16 |
| Review and improvement of Mathematica program for dimensional analysis | 1 | In progress | End April ‘16 |
| Creation of a Mathematica package | 1 | Planned | End April ‘16 |
| Dimensional analysis of micromechanical model of fiber-matrix de-bonding | 2 | Planned | End April ‘16 |
|  |  |  |  |

Table 4: Analytical modeling tasks' overview

## Numerical simulation

### 4.1.1 Goals

1. Develop micromechanical model to study fibre-matrix in thin plies.
2. Develop tools for parametric model and mesh creation.
3. Develop code for test and debug of the model.
4. Develop code for large-scale parametric study of the model.

### 4.1.2 Tasks’ overview

|  |  |  |  |
| --- | --- | --- | --- |
| **Description** | **Goal(s)** | **Status** | **Completion (reached or foreseen)** |
|  |  |  |  |
| Model ideation and definition | 1 | Done | End Nov. ‘15/Beg. Dec. ‘15 |
| Mesh generation prototype in Matlab, for testing | 3 | Almost completed | Beg. April ‘16 |
| Graphical User Interface Prototype in Mathematica | 3 | Almost completed | Beg. April ‘16 |
| Mesh generation prototype in C++, for parametric study | 2/4 | In progress | Beg./Mid May ‘16 |
| Graphical User Interface Prototype in Qt4/C++, for stand-alone platform-independent deployment | 2 | In progress | Beg./Mid May ‘16 |
| Parametric study pipeline in C++ | 4 | Planned | End May ‘16 |
| Abaqus template input file | 2/3/4 | Almost completed | Beg. April ‘16 |
| Automatic html report generation | 4 | Planned | End Apr. ‘16 |
| Automatic latex report generation | 4 | Planned | End Apr. ‘16 |
|  |  |  |  |

Table 5: Numerical simulation tasks' overview

### 4.1.3 Introduction to the numerical model

In order to start probing the mechanics of thin ply composites from a numerical standpoint, a Reference Volume Element (RVE) model is developed for subsequent numerical simulations with the Finite Element Method (FEM).

The RVE is 2-dimensional and it is supposed to be taken from a [90°] ply inside a cross-ply laminate. The element lies inside the [90°] ply on a plane parallel to the [0°] direction of the laminate (global x-direction) and to the across-the-thickness direction of the laminate itself (global z-direction). Three different specifications of the RVE are developed: a simple single element made up by a fiber inside a square matrix domain; the latter element bounded by [0°] plies on the upper and bottom side; a periodic pattern constituted by the single RVE tiled in a 3 x 3 2D array.

The discretization of the geometry and the consequent mesh generation is performed by means of a custom-developed application written in C++ for stand-alone platform-independent deployment and in Matlab for fast prototyping and testing. Such choice has been motivated by the need of generating a parametric structured grid of quadrilateral elements capable of adapting to the curved geometry of the problem. Furthermore, as mesh geometry and size could affect significantly the final result of simulations, full control on the discretization process is fundamental for reliable numerical results. Hence the choice of developing a custom algorithm for the discretization step instead of using the ABAQUS FEA CAE interface. The main reason is the fact that numerical simulations of fracture mechanics are strongly dependent on mesh size and characteristics; thus it is better to have direct knowledge and control of the mesh generation process instead of leaving it to ABAQUS algorithms, which work as "black boxes" and are thus not so easily customizable. Furthermore, based on author’s experience, building a custom parametric mesh using ABAQUS FEA input file syntax is certainly possible but quite cumbersome and rigid. Hence the choice of C++/Matlab, as it allows for flexibility and, if needed, custom-made features.

The main output of the C++ code is an ABAQUS FEA input file; using a C++ script, the all process can be streamlined and automatized allowing parametric studies to be performed. A Graphical User Interface (GUI) is created in Mathematica for prototyping and in Qt4/C++ for final deployment. Automatic latex and html report generation capabilities are included to simplify the reporting and publishing process at a later stage.

In order to accommodate a grid of quadrilateral elements in a curvilinear geometry, the RVE geometry is split into different regions and a few parameters are introduced in order to control the outcome of the discretization process. The creation of multiple regions is important to control the localization of irregularities and elements’ deformation. These can be in fact greatly reduced and smoothed out but not completely removed. Thus, transition zones are created in order to prevent irregularities to appear close to the fiber/matrix interface, where the fracture process takes place. The geometry is topologically transformed and discretized using transfinite interpolation and elliptic smoothing.

As the problem is 2-dimensional and in plane-strain, ABAQUS FEA elements CPEG4 (2D bi-linear plane strain elements) and CPEG8 (2D bi-quadratic plane strain elements) are chosen. CPEG8 are considered in addition to CPEG4 because only quadratic elements can capture curvature effects, as they might be present at a circular interface. Comparison of results from the same set-up with the two different elements could show the presence (or absence) of curvature effects on the fracture process. Furthermore, the choice of CPEG4 and CPEG8 allows for a direct comparison with the work presented in [1]. Numerical simulations are then conducted with the Finite Element Method (FEM) using the commercial CAE software ABAQUS FEA. Two different analyses are conducted: a Linear Elastic Fracture Mechanics (LEFM) study and Cohesive Zone Model (CZM) approach.

## Reporting and dissemination of results

### 4.1.1 Goals

1. Provide reports on completed, on-going and planned activity
2. Provide reports on achievements.
3. Publish articles.
4. Create and maintain a website for public dissemination of the results of the research project.

### 4.1.2 Tasks’ overview

|  |  |  |  |
| --- | --- | --- | --- |
| **Description** | **Goal(s)** | **Status** | **Completion (reached or foreseen)** |
|  |  |  |  |
| Project summary for inscription to doctoral school EMMA | 1 | Done | Nov. ‘15 |
| Project report for EMJD commission | 1 | Done | Nov. ‘15 |
| Report on micromechanical model ideation | 1/2 | Done | Dec. ‘15 |
| Slides on micromechanical model ideation | 1/2 | Done | Dec. ‘15 |
| Status report | 1 | Done | End Mar. ‘16 |
| Creation of website | 4 | Done | Oct. ‘15 |
| Creation of user-account system | 4 | Planned | Jun./Jul. ‘16 |
| Start publication of material in restricted area | 4 | Planned | Aug. ‘16 |
| Start publication of material in public area | 4 | Planned | Aug ‘16 |
|  | **Note:** | The website is a side project. Only a fraction of time (10% or less) is devoted to it. | |
|  |  |  |  |

Table 6: Reporting and dissemination of results tasks' overview

## Learning and professional development

### 4.1.1 Goals

1. Deepen the theoretical knowledge in the project field.
2. Acquire the technical know-how to accomplish the project’s objectives.
3. Widen the understanding and awareness of current trends/novelties/problems in affine fields.
4. Improve useful skills for present and future professional life and development (communication skills, business skills, etc. ...).

### 4.1.2 Tasks’ overview

|  |  |  |  |
| --- | --- | --- | --- |
| **Description** | **Goal(s)** | **Status** | **Completion (reached or foreseen)** |
|  |  |  |  |
| MOOC on *Corporate Social Responsability (CSR) and Value Creation* by Audencia Nantes Business School | 4 | Done | End Nov. ‘15/End Dic ‘15 |
| Webinar *Landscape and the City* by Architectural Record-Continuing Education Center | 3 | Done | Beg. Jan. ‘16 |
|  |  |  |  |

Table 7: Learning and professional development tasks' overview

# References

1. *Ntpt plays key role in thin ply research for aerospace* [press release]. April 2015.
2. *Ntpt makes world’s thinnest prepreg even thinner* [press release]. June 2015.
3. *Thin ply composites: experimental characterization and modeling*, September 2014.
4. J. E. Bailey A. Parvizi. *On multiple transverse cracking in glass fibre epoxy cross ply laminates.* Journal of Materials Science, Volume 13, Issue 10, pp 2131-2136, October 1978.
5. A. S. Kaddour, M. J. Hinton, S. Li, and P.A. Smith. *Damage theories for fibre reinforced polymeric composites: the third world-wide failure exercise (WWFE-III).* In 16th International Conference on Composite Materials, July 2007.
6. A. S. Kaddour, M. J. Hinton, S. Li, and P.A. Smith. *Damage prediction in polymeric composites: up-date of part (a) of the third world-wide failure exercise (WWFE-III).* In 18th International Conference on Composite Materials, August 2011.
7. R. Minter. *Certification and continued airworthiness issues for composite structures.* In ICAS Biennal Workshop, September 2011.
8. D. Ozik. *Design for sustainability.* MIT Course Notes, 2006.
9. Miguel Herráez et al. *Transverse cracking of cross-ply laminates: A computational micromechanics perspective.* In: Composites Science and Technology 110 (2015), pp. 196–204. issn: 0266-3538. doi:10.1016/j.compscitech.2015.02.008.