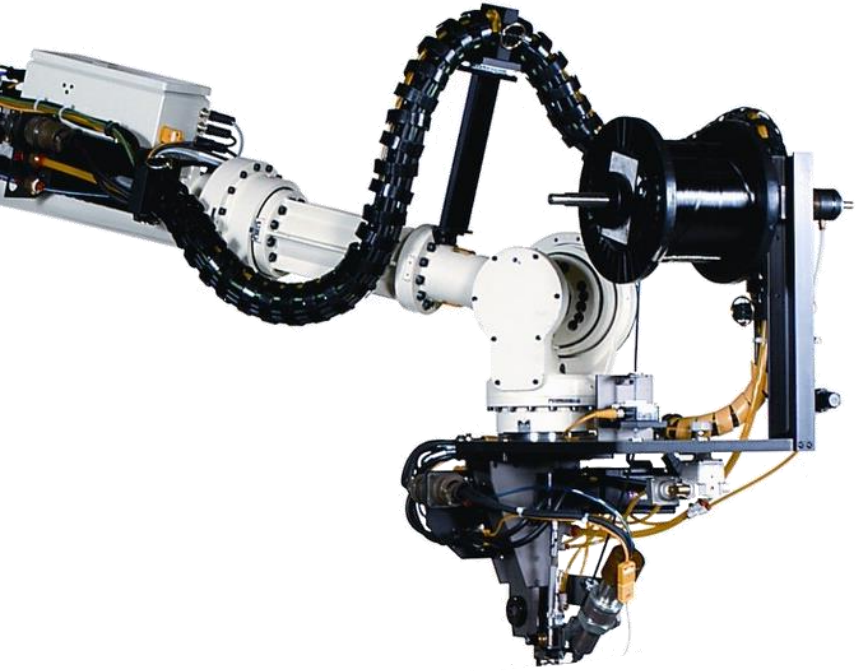


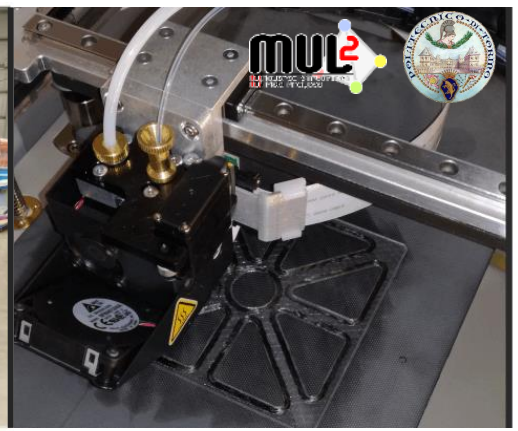
A new paradigm to re-engineering printed composites

PRE-ECO

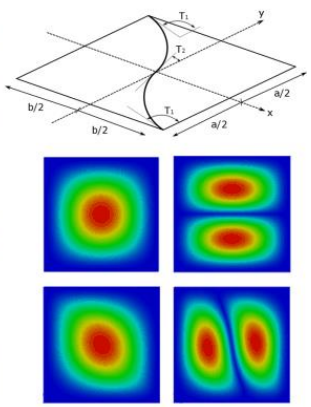
Alfonso Pagani
Politecnico di Torino

"PRE-ECO will fill the gap between design and additive manufacturing, providing the engineering community with new variable-angle tow (VAT) composites that are expected to change the design paradigms."





Brooks et al., JFS, ***2019***

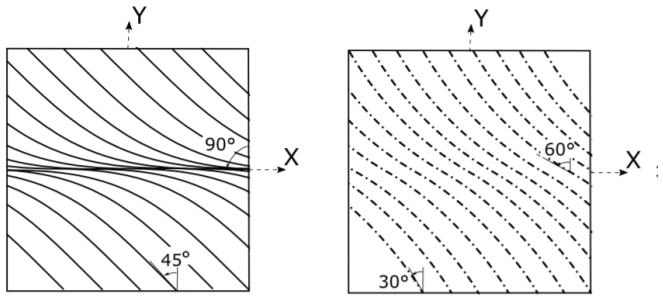


Used for step 2 interview

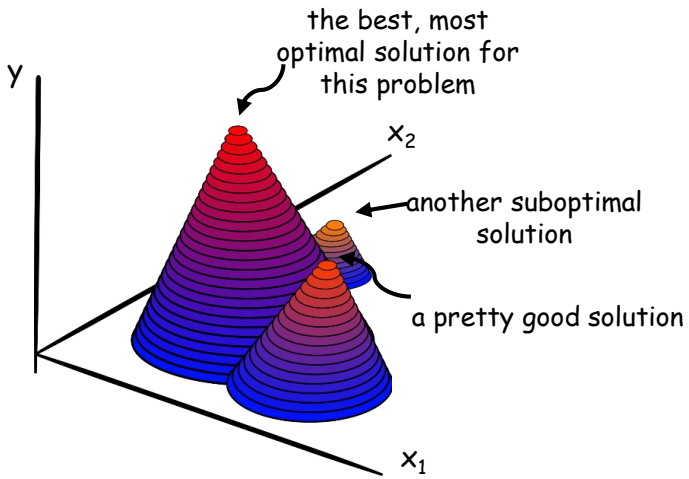
Challenges

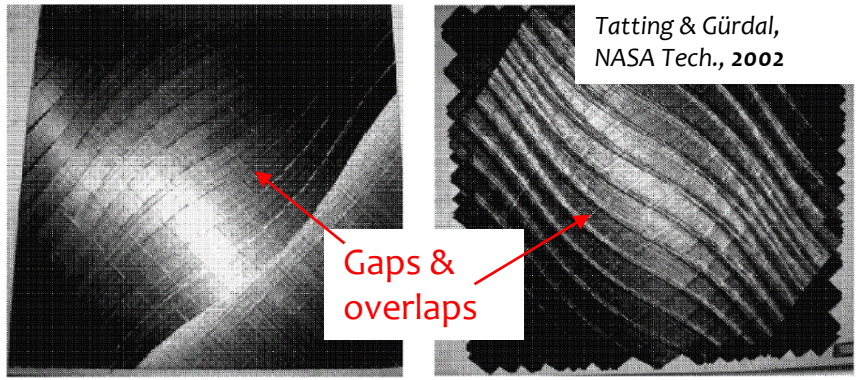
"Design of VAT structures is based on assumptions that substantially modify the nature of the problem itself and extremely shrink the design space ."





Viglietti et al., COMB, **2018**

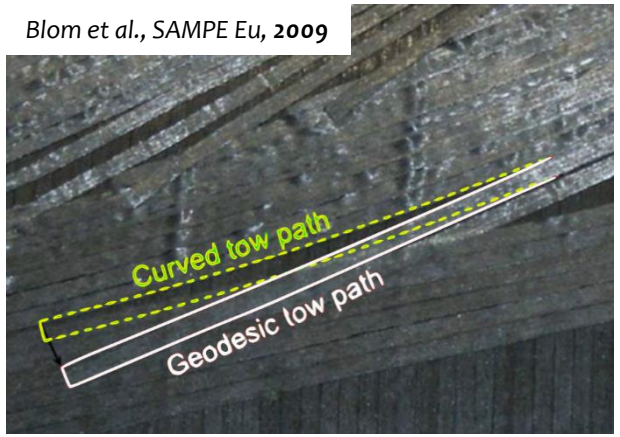


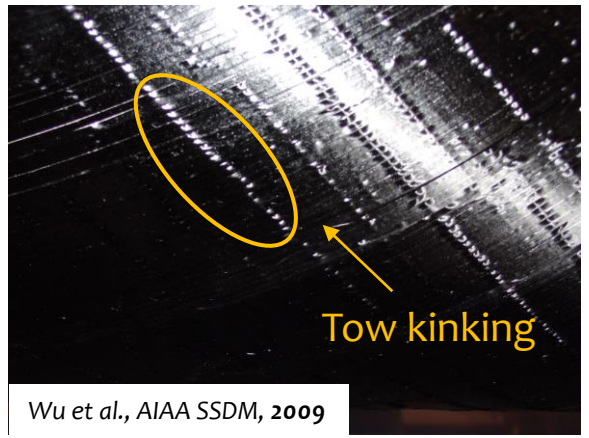


Tatting & Gürdal, NASA Tech., **2002**

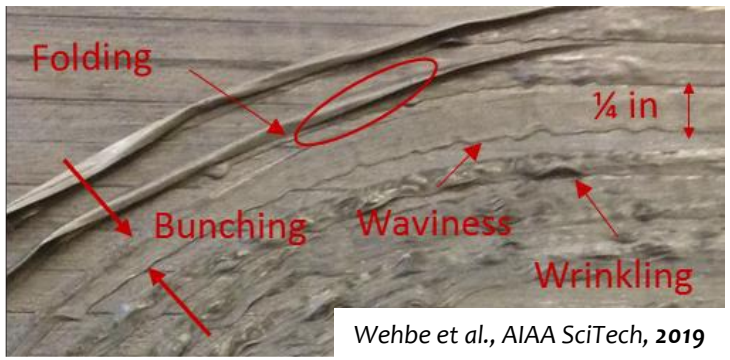
- ✓ Propagation of defects through the scales.
- ✓ Damage tolerance.
- ✓ Scaling issue; structure vs coupon.
- ✓ Manufacturing signature.

Blom et al., SAMPE Eu, **2009**

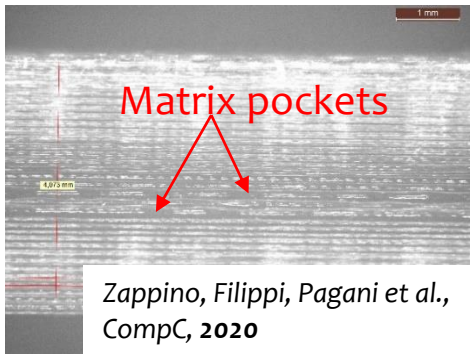




Wu et al., AIAA SSDM, **2009**

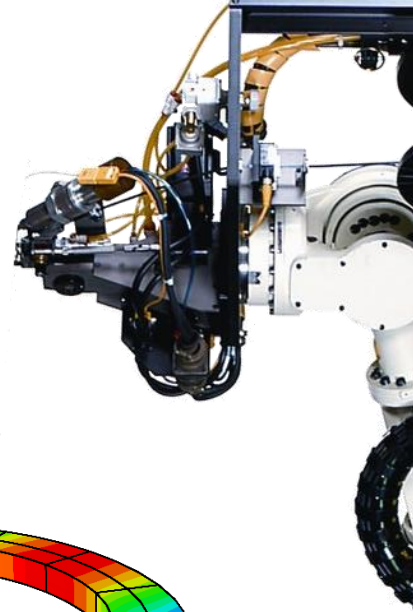


Wehbe et al., AIAA SciTech, **2019**



Zappino, Filippi, Pagani et al., CompC, **2020**

Methodology



Multi-scale simulation tools

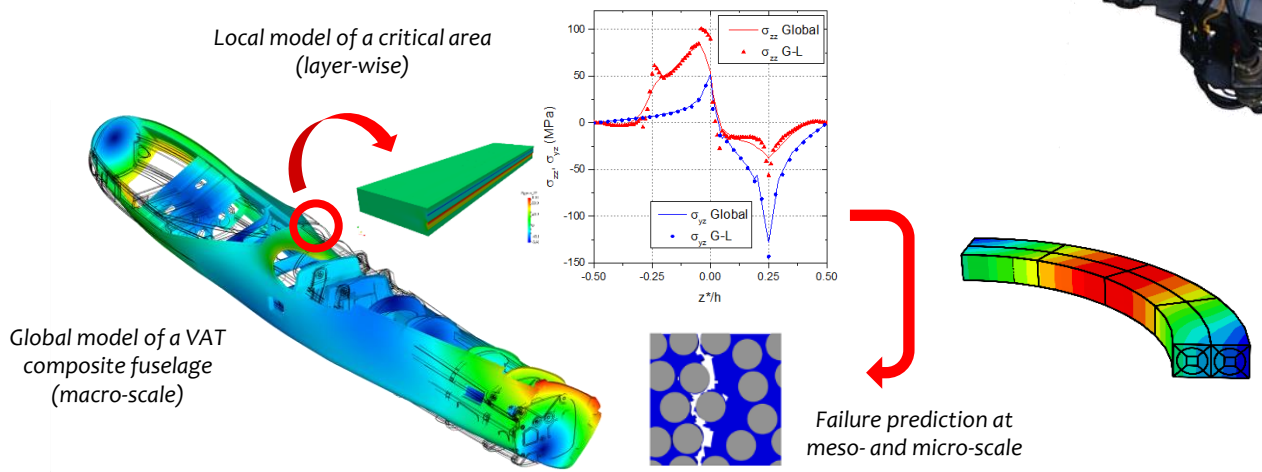
Unified formulation of theories of structures

Micro-mechanics

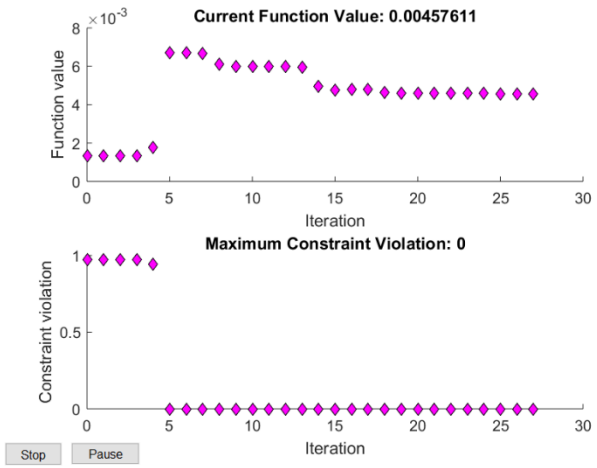
Layer-wise models

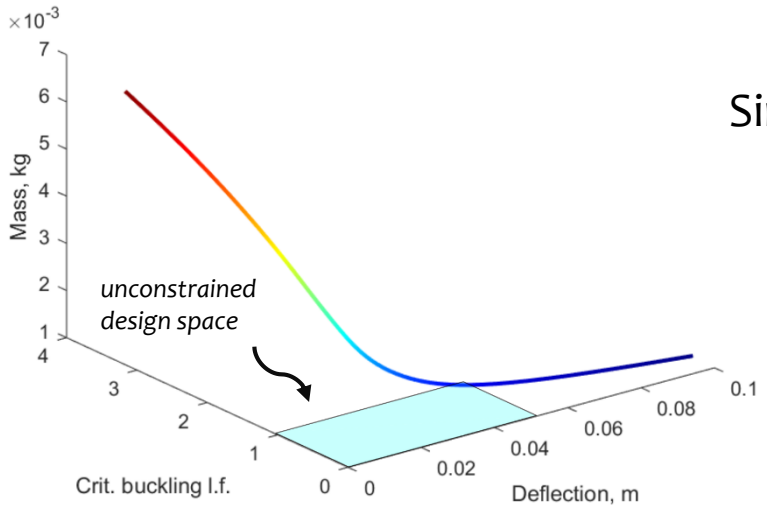
Failure mechanisms and stress distribution

WP1 SRA PhD1



dM, DP, C, G, Pagani, CMAME, ***2018***





Design for manufacturing

Single- and multi-step optimization algorithms

Genetic algorithms

Minimum weight design

Manufacturability and defect tolerance

PhD2 PD1 **WP2**

Used for step 2 interview

Methodology, cont'd

Metamodelling

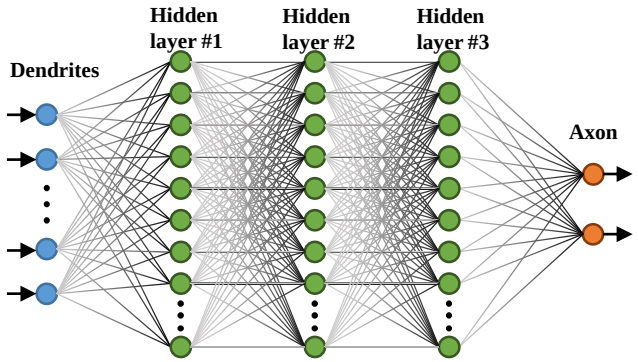
Artificial intelligence

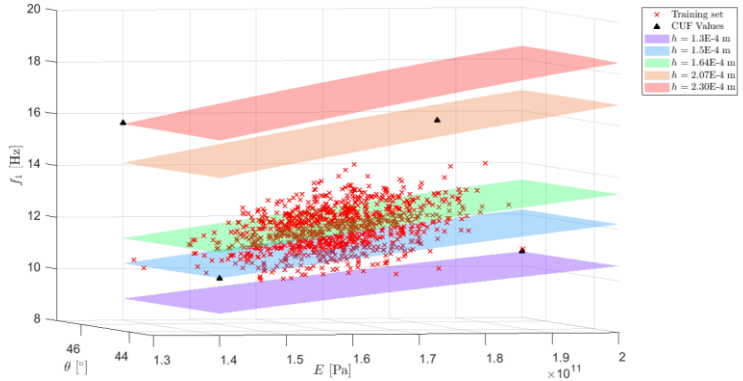
Hybrid data (simulation & test)

Sensitivity analysis

Defect quantification and propagation

WP3 PD2 PhD3





Pagani et al., ICMAMS, ***2019***

ALFONSO PAGANI (PI), JUNE 2019

Assistant prof. @ PoliTO, Visiting ass. @ Caltech.

PhD in Fluid-dynamics (PoliTO); **PhD in Aeron. Eng.** (CityU London).

Supervisor of 2 post-doc and 9 PhD students.

Co-author of 70 peer-reviewed Journal papers (**20 as leading author**) on **mechanics of advanced materials and structures**.

H-index Scopus: 17; WoS: 16; Google Scholar: 20.

Top 150 most cited scientist in Europe in Mechanical Eng., Structural Eng., and Mechanics of Materials (2013 to 2018, SciVal).

POLITECNICO DI TORINO (hosting Inst.)

Admin. support; Computer cluster; Manufacturing and testing instr. (FDM 3D printer, DIC, INS. testing machine, portable vibration acquisition system, elect. microscope, etc.)

Current research team: PI + 2 ppl.

Research team if PRE-ECO is granted: PI + 6 ppl.

Senior R. Ass. – Multiscale models & co-supervision
PD1 – Optimization
PD2 – AFP & Manufacturing/testing
PhD1 – Meso- and micro-mechanics
PhD2 – Defect analysis and sensitivity/constr.
PhD3 – Surrogate models



Used for step 2 interview

Project network

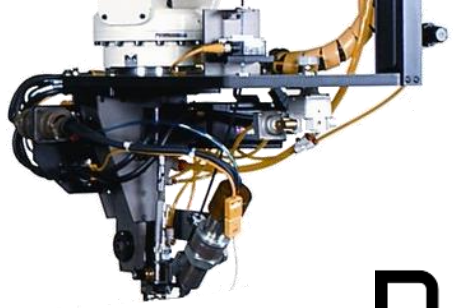
Politecnico di Torino
- ✓ Multi-scale mechanics
- ✓ Global-local
- ✓ ITN Marie-Courie FULLCOMP Network (ENSAM, ACCIS Bristol, Purdue, Swansea)

California Institute of Technology
- ✓ Additive manufacturing
- ✓ Application to vibration suppression systems
- ✓ Bio-engineering

Industry and Research Labs
- ✓ Coriolis Composites
- ✓ 3D@UniPV

ITEA
- ✓ VMAP– Virtual Material Modelling in Manufacturing
- ✓ Data exchange
- ✓ Networking

NAFEMS
- ✓ Member of the Italian Steering Committee
- ✓ Dissemination and comunication



PRE-3CO

Cost-effective computational models for VAT printed composites with unexplored **multi-scale** capabilities.

Developing new methodologies for the virtual (defect tolerant) **design** accounting for manufacturing signature.

Enabling **new technologies** for bio-materials and periodic structures (e.g., noise suppression, metamaterials, etc.)

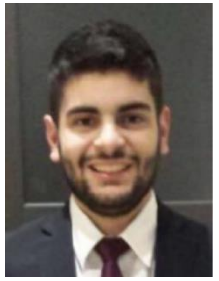
The PRE-ECO Team



Alfonso Pagani
Principal investigator
Global/local & Multi-scale failure models, Non-linear multi-physics

Matteo Filippi
Assistant professor
Meta-materials & Wave propagation, Rotor-dynamics, Composites





Riccardo Augello
Post-Doc
Non-linear mechanics, Non-local elasticity, Vibration correlation

Alberto R. Sanchez-Majano
PhD student
Uncertainty analysis, Machine learning & Evolutionary optimization



MUL² @ PoliTO



www.mul2.com

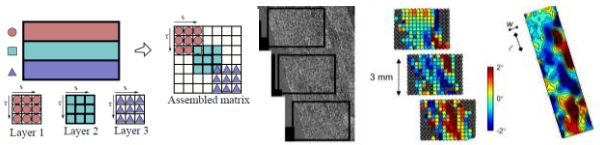
ERC-NSFC Collaboration

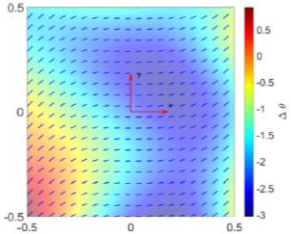
Prof. Chao Zhang
Northwestern Polytechnical University
Department of Aeronautical Structure Eng.

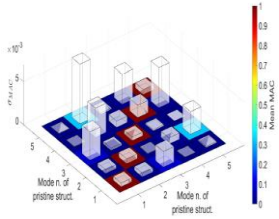
Preliminary results

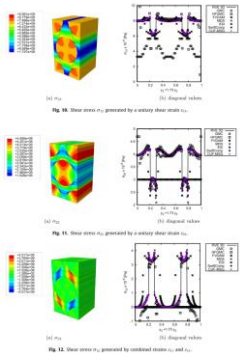
Multi-scale uncertanty analysis by CUF-based multi-scale models

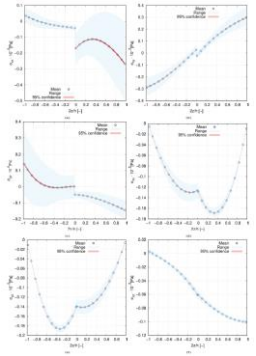
$$\boldsymbol{u}(x,y,z) = F_\tau(x,z)\mathbf{u}_\tau(y) = F_\tau(x,z)N_i(y)\boldsymbol{q}_{\tau i}$$
$$\tau = 1,\dots,M \quad \text{and} \quad i = 1,\dots,n$$







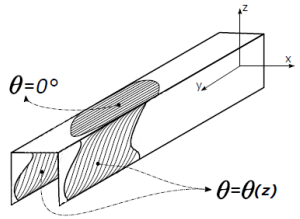


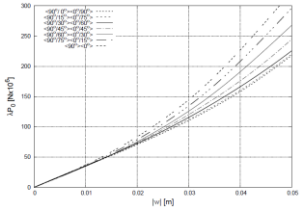


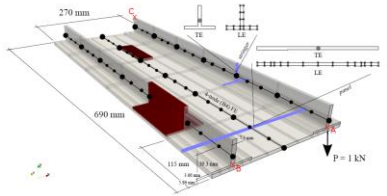
A. Pagani, A.R. Sanchez-Majano, Composites Part C, 4:100091.

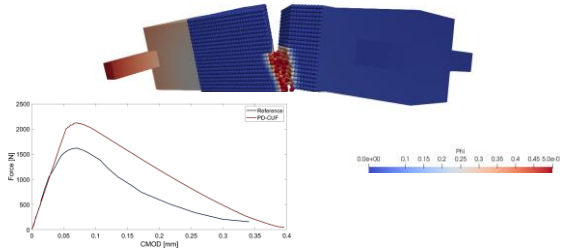
A. Pagani, A.R. Sanchez-Majano, Mechanics of Advanced Materials and Structures. In Press.

Nonlinear analysis, including large-deflection response and fracture







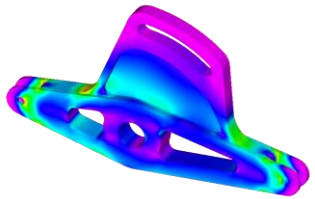


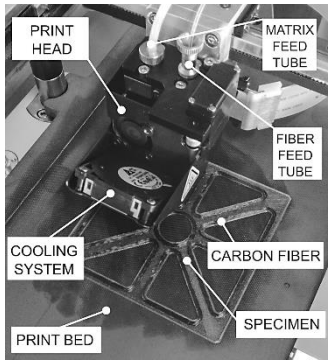
A. Viglietti, M. Filippi, A. Pagani, E. Zappino, E. Carrera, Static analyses of VAT composites via geometrically nonlinear variable kinematic FEs.

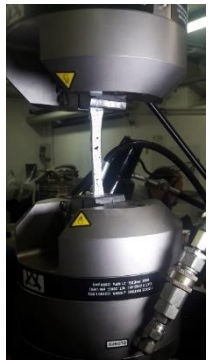
A. Pagani, E. Carrera, International Journal for Numerical Methods in Engineering, 121(22): 5066-5081.

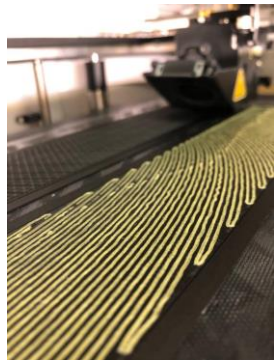
3D printed fibre-reinforced structures



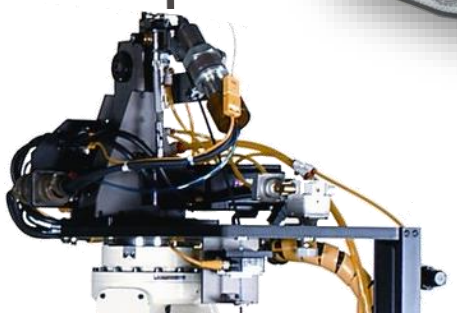








E. Zappino, M. Filippi, A. Pagani, M. Petiti, E. Carrera, Experimental and numerical analysis of 3D printed open-hole plates reinforced with carbon fibers, Composites Part C, 22:100007.



More info on www.pre-eco.eu & www.mul2.com

Proposal writing

Form A
- ✓ General info
- ✓ Administrative data
- ✓ Budget
- ✓ Ethics
- ✓ Call specific questions

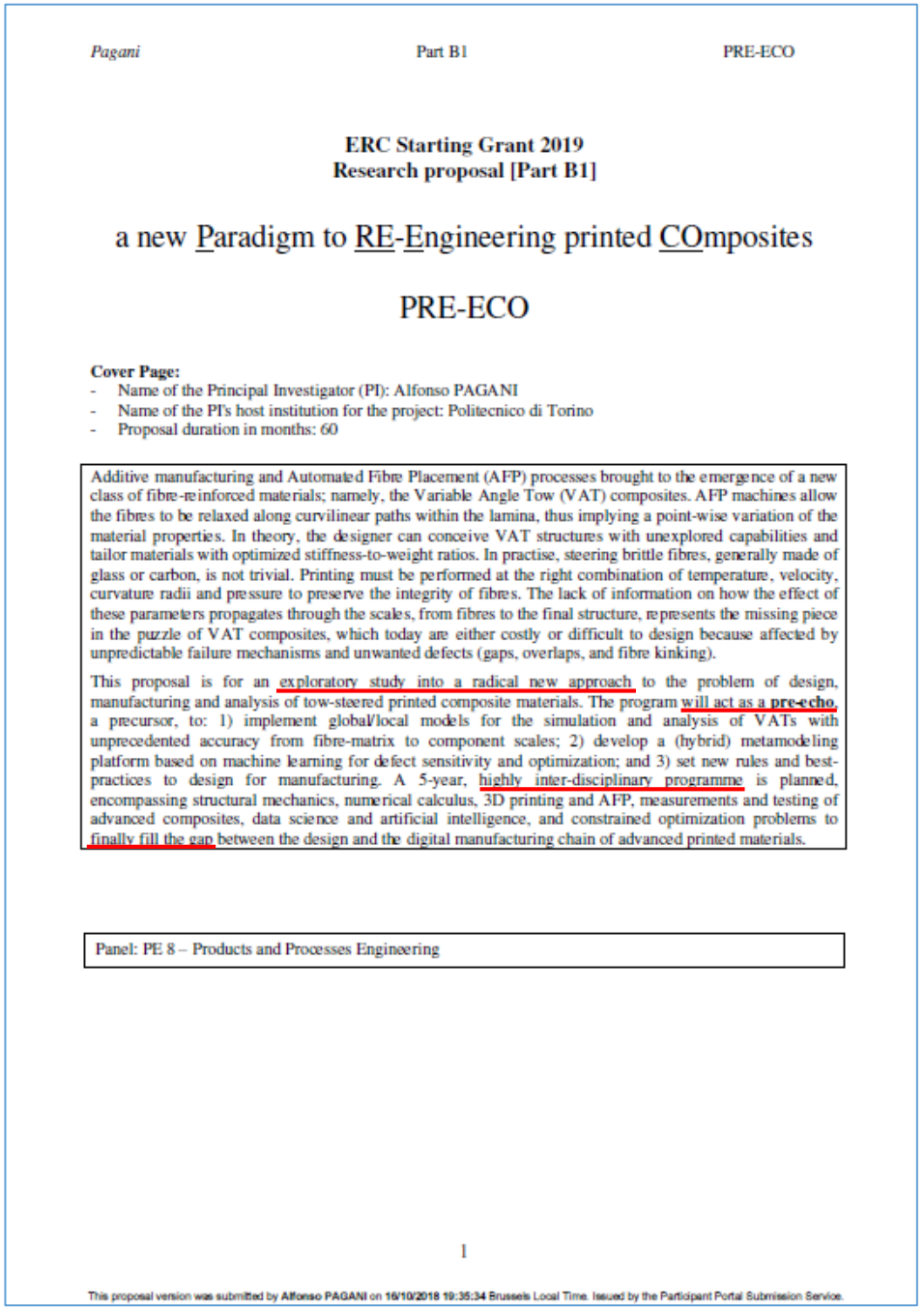
Part B1
- ✓ Cover Page
- ✓ Extended synopsis (section a) → 5 pp excluding references
- ✓ PI profile, CV (section b)
- ✓ Funding ID
- ✓ Track record (section c)

5 pp

Part B2
- ✓ State-of-the-art and objectives (section a)
- ✓ Methodology (section b)
- ✓ Resources, including project costs (section c)

15 pp excluding references

Am I ready?
Where do I start?
How long does it take to write a good proposal?



Pagani Part B1 PRE-ECO

ERC Starting Grant 2019
Research proposal [Part B1]

a new Paradigm to RE-Engineering printed COmposites

PRE-ECO

Cover Page:
- Name of the Principal Investigator (PI): Alfonso PAGANI
- Name of the PI's host institution for the project: Politecnico di Torino
- Proposal duration in months: 60

Additive manufacturing and Automated Fibre Placement (AFP) processes brought to the emergence of a new class of fibre-reinforced materials; namely, the Variable Angle Tow (VAT) composites. AFP machines allow the fibres to be relaxed along curvilinear paths within the lamina, thus implying a point-wise variation of the material properties. In theory, the designer can conceive VAT structures with unexplored capabilities and tailor materials with optimized stiffness-to-weight ratios. In practise, steering brittle fibres, generally made of glass or carbon, is not trivial. Printing must be performed at the right combination of temperature, velocity, curvature radii and pressure to preserve the integrity of fibres. The lack of information on how the effect of these parameters propagates through the scales, from fibres to the final structure, represents the missing piece in the puzzle of VAT composites, which today are either costly or difficult to design because affected by unpredictable failure mechanisms and unwanted defects (gaps, overlaps, and fibre kinking).

This proposal is for an exploratory study into a radical new approach to the problem of design, manufacturing and analysis of tow-steered printed composite materials. The program will act as a **pre-echo**, a precursor, to: 1) implement global/local models for the simulation and analysis of VATs with unprecedented accuracy from fibre-matrix to component scales; 2) develop a (hybrid) metamodeling platform based on machine learning for defect sensitivity and optimization; and 3) set new rules and best-practices to design for manufacturing. A 5-year, highly inter-disciplinary programme is planned, encompassing structural mechanics, numerical calculus, 3D printing and AFP, measurements and testing of advanced composites, data science and artificial intelligence, and constrained optimization problems to finally fill the gap between the design and the digital manufacturing chain of advanced printed materials.

Panel: PE 8 – Products and Processes Engineering

1

This proposal version was submitted by Alfonso PAGANI on 16/10/2018 19:35:34 Brussels Local Time. Issued by the Participant Portal Submission Service.

Part B1

Both B1 and B2 are submitted together on the same deadline, however, only the B1 form is reviewed at Step 1 by 3-4 selected review panel members.

Extended synopsis

- ✓ 5-page limit for this section represents a great challenge…
- ✓ Address the state-of-the-art in the field, while highlighting the knowledge gaps that you want to address.
- ✓ Explain the motivation and the project's objectives, followed by the selected methodology.
- ✓ Novelty, high-risk, high-gain, non-incremental, investigator-driven and (potentially) hypothesis-driven research project.

PANEL COMMENT: […] The panel agrees that the proposed research on Variable Angle Tow (VAT) composites and identified applications has important potential impact. The proposed unified theory formulation and simplifications for modelling are promising and will speed up the virtual numerical experimentation and calculations. The PI made a clear presentation and provided very convincing answers. The panel concluded that the proposed project is innovative and involves high risk with potential for high gains.

Section a: Extended Synopsis of the scientific proposal

PRE-ECO (a new Paradigm to RE-Engineering printed COmposites) is an ambitious project that aims at setting **new methodologies and optimum design standards for composite structures obtained through additive manufacture processes** and 3D printing. Namely, the primary objective is substituting, in a unified framework and industry oriented way, the currently available analysis and simulation tools **for exploiting in a full manner the unveiled possibilities coming from this new technology** (Liu, et al., 2018).

a-1. Introduction to scientific challenges of printed composite materials

Due to their advantageous characteristics, composite materials continue to attract interest from modern industry. As a matter of fact, composite structures show high stiffness-to-weight and strength-to-weight ratios, which make them good candidates for advanced applications and substantial weight saving, which is a major concern in many engineering fields. In contrast, it is undoubtedly clear that the design of composite structures adds new degrees of freedom (design variables and parameters) that were unavailable and, hence, unexplored in the case of metallic components (Liu, et al., 2018). Moreover, the availability of new technologies, such as additive manufacturing, allows for **going beyond the classical design rules, thus leading the designer to find innovative and more efficient solutions than ever** (Lukaszewicz, Ward, & Potter, 2012). The use of the AFP (automated fibre placement) technology, in particular, brought to the emergence of a new class of composite materials; namely, the **Variable Angle Tow (VAT) composites**. In fact, a modern AFP machine allows the fibre (i.e. the tow) to be placed along a **curvilinear path within the constitutive lamina thus implying a point-wise variation of the material properties (stiffness, strength, etc.), see Figure 1**. Although the utilisation of VAT laminates considerably increases the complexity of the design process (mainly due to the large number of design variables involved within the problem), on the other hand it leads the designer to conceive non-conventional solutions characterised either by a considerable weight saving or enhanced mechanical properties when compared to classical solutions.

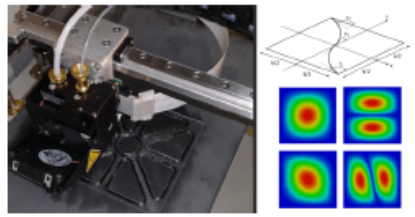


Figure 1 Printing carbon-nylon VAT composite plates by Fused Deposition Modelling (FDM), Politecnico di Torino.

The concept of VAT is not new although. In their pioneering work, Hyer and Lee (Hyer & Lee, 1991) demonstrated that fibres with curvilinear paths can be exploited to improve stress distribution in the presence of holes. Since then, several studies have shown the capabilities of VAT composite laminates to **increase the buckling loads, aeroelastic response, load redistributions and provide optimal solutions with maximum weight saving**. Recent studies from NASA, see for example (Stanford & Jutte, 2016), have shown that the combined use of curved stiffeners and composite VAT panels may result into a structural weight saving of aircraft wings of about 20 per cent. Nevertheless, as a matter of fact, the use of VAT composites in real engineering applications is nowadays limited. **Two unresolved, scientific challenges shrink the applicability of printed composites**; i.e.

1) **Modelling.** Most of the theoretical studies, which have been carried out about tow steered laminates during the last two decades, are based on investigation tools that were originally developed for classical straight fibres composites or, even worse, for metallic structures (Ribeiro, et al., 2013). **Mechanics of VAT composites is still in its infancy. Currently, we have no theories and simulation tools able to predict the mechanical behavior of printed composites** through the different scales, from the global scale and deposition layer to the fibre scale.
2) **Limitations of printing processes.** Automated Tape Laying (ATL) and Automated Fibre Placement (AFP) are the two leading technologies that are employed today to manufacture VAT composites from unidirectional prepregs (Lukaszewicz, Ward, & Potter, 2012). The effect of the manufacturing issues, regardless of the technology employed for production, is constant throughout the practical applications of VAT laminates. Nonetheless, **best-practises for design and a systematic characterization of the defects caused by additive manufacturing processes are still missing.**

Clearly, re-engineering is needed to bridge VAT composites from theoretical studies to real-life products. In this context, an advanced modelling technique, which is developed *ad-hoc* for this new class of materials and integrating the limits of the modern technology is the *missing piece* in the digital manufacturing chain of VAT composites.

This proposal version was submitted by Alfonso PAGANI on 18/10/2018 19:35:34 Brussels Local Time. Issued by the Participant Portal Submission Service.

Part B1

Curriculum vitae

- ✓ The ERC is an investigator-driven grant which focuses great attention on the PI's excellence.
- ✓ Fellowships and awards, leading capabilities (supervising students, etc.), show evidence of independence.
- ✓ Why me, Why now?

Early achievements track-record

- ✓ Direct or schematic.
- ✓ Show 5 papers and describe your contribution.
- ✓ Invited talks, research impact…

Funding ID

- ✓ Show relation/continuation, but not superimposition.

REVIEWER COMMENT: The PI has performed excellent research and has all necessary expertise for carrying out the proposed research.

REVIEWER COMMENT: The PI's main contribution is on structures and simulations with most of his papers with multiple authors and a senior author.



Pagani Part B1 PRE-ECO

Section b: Curriculum vitae

PERSONAL INFORMATION

Family name, First name: Pagani, Alfonso
Identifiers: ORCID (0000-0001-9074-2558), Researcher ID (P-7157-2015), Scopus (55744911900)
Date of birth: 13 – May – 1987
Nationality: Italy
URL for web site: www.mul2.com

EDUCATION

2016 MPhil/PhD in *Aeronautical Engineering*
School of Mathematics, Computer Science & Engineering, City University of London, UK.
2015 PhD in *Fluid-dynamics*
Dipartimento di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Italy.
2011 Laurea Magistrale 110/110 summa cum laude (MSc degree)
Aerospace Eng., Dip. di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Italy.
2009 Laurea di I livello 110/110 summa cum laude (BSc degree)
Eng., Dip. di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Italy.

IOUS POSITIONS

rofessor of Aerospace Structures and Design
nto di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Italy.
esearch fellow
nto di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Italy.

WARDS

cientific Habil. for the role of *Associate Professor of Aerospace Engineering*.
holar, School of Aeronautics and Astronautics, Purdue University, USA.
holar, Laboratoires i2m, ENSAM, Bordeaux, France.
student award (in fluid-dynamics) received from Politecnico di Torino, Italy.
award, 8th ACAM, Melbourne, Australia.
holar, RMIT University, Melbourne, Australia.
p for the *Analysis of composite space structures*, Politecnico di Torino, Italy.
ll's Award for the best student paper, ICCS17, Porto, Portugal.
holar, Universidade do Porto, Portugal.
p for *Non-linear numerical simulations of autofrettage*, Politecnico di Torino.
holar, City University of London, UK.
gia Award, Associazione ex Allievi del Politecnico di Torino, Italy.
d Ben Omega Petrazzini Grant, Accademia delle Scienze di Torino, Italy.

ADUATE STUDENTS AND POSTDOCTORAL FELLOWS

rvisor of 2 postdocs
nto di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Italy.
rvisor of 1 PhD student in Mech. Eng.
nto di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Italy.
isor of 1 PhD student in Aerosp. Eng.
es i2m, ENSAM Bordeaux.
isor of 5 PhD students in Mech. Eng.
nto di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Italy.
rvisor and co-supervisor of 21 MSc and BSc students in Aerosp. Eng.
nto di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Italy.

ES

for the postgraduate course ''Structural analysis and design of leaf springs'',
stra, Italy.

8

y Alfonso PAGANI on 16/10/2018 18:36:34 Brussels Local Time. Issued by the Participant Portal Submission Service.

Pagani Part B1 PRE-ECO

Section c: Early achievements track-record

RECENT (FIVE) PUBLICATIONS

1. A. Pagani, E. Carrera (2018) ``Unified formulation of geometrically nonlinear refined beam theories'', Mechanics of Advanced Materials and Structures, Vol. 25 no.1, pp. 15-31.
2. A. Pagani, E. Carrera (2017) ``Large-deflection and post-buckling analyses of laminated composite beams by Carrera Unified Formulation'', Composite Structures, Vol. 170, pp. 40-52.

In these two works, I extended the Carrera unified formulation to deal with geometrical nonlinear analysis of solid and thin-walled structures. Then, the model was applied to the large displacements and rotations analysis of composites. The method was demonstrated to be very accurate in the description of the stress states at the layer level (meso-scale) in nonlinear regimes.

In this paper, I formulated the dynamic stiffness matrix of arbitrarily refined theories of structures in a hierarchical manner. The method, which is as unique in the literature and numerically exact, was used to measure the vibration characteristics of laminated plates. The theory was validated via experimental tests conducted with the help of Embraer S.A.

3. A. Pagani, E. Carrera, J.R. Banerjee, P.H. Cabral, G. Caprio, A. Prado (2014) ``Free vibration analysis of composite plates by higher-order 1D dynamic stiffness elements and experiments'', Composite Structures, Vol. 118, pp. 654-663.

INVITED PRESENTATIONS AND SEMINARS

2016 Invited Lecturer, ``Second generation of theories of structures: applications to laminates'' presented during Prof. Wenbin Yu couse ``Mechanics of structure genome'', The Neil Armstrong Hall of Engineering, Purdue University, November 10.
2015 Invited Lecturer, School for Young Scientists ``Mathematical Modelling and Computer Simulation of Technical Systems'', Tambov, Russian Federation, 26-28 October.
2013 – 2018 Speaker at more than 25 International Conferences.

RESEARCH IMPACT

Co-author of 60 articles (**19 as leading author, 1 w/o PhD supervisors**) in International peer-reviewed Journals, 75 abstracts and contributions in Conference Proceedings, 3 guest editorials, 2 book chapters, 2 PhD theses, and 1 patent.

Year range: 2013 to 2018 Data source: Scopus, up to 24 Aug 2018

71
number of publications by authors of Pagani, Alfonso

SCHOLARLY OUTPUT

Share of publications of Pagani, Alfonso that are among the most cited publications worldwide

28 (39.4%)
number of publications in the top 10% most cited publications worldwide

OUTPUTS IN TOP CITATION

Part B2

The B2 form is the main document that the external experts will review, in addition to the B1 form.

State-of-the-art and objectives

- ✓ Enhance the presentation of the project proposal with any visual elements: colours & bold characters to attract attention, balance paragraphs, keep visual consistency…
- ✓ Use subsections: a1 Introduction, a2 state-of-the-art and open issues, a3 objectives of PRE-ECO,…
- ✓ Draft the text as if you were presenting your research to your scientific peers.

REVIEWER COMMENT: Additive manufacturing, advanced composite material and multiscale simulation/design are all frontier topics. […] Even though it is a very ambitious goal, but if successful, it will address the needs in multiple industries and advance the understanding of composites and design sciences.

REVIEWER COMMENT: The topic of the proposal is interesting and worth investigating. The objectives are ambitious, even overambitious […]



Pagani Part B2 PRE-ECO

a-2. State-of-the-art and open issues

Since 1985, when Airbus for the first time utilized composite materials for the primary airframe with a series production of the carbon/epoxy fins of the A310, considerable progress in advanced composite technologies has been made, see the comprehensive text by Niu (Niu, 1992). Nowadays, **fibre composites are widely used for both aeronautics and space applications**, such as solar arrays, antennas, optical platforms, satellites and supports for cryogenic tanks (Bansemir & Haider, 1998). In this domain, **VAT and related additive manufacturing processes are the technologies that promise to let composites to take one step forward.**

The fibre-reinforced composites commonly adopted in various engineering disciplines are multi-layered structures. Each layer is in general characterized by fibre tows arranged in straight paths and immerged into an epoxy matrix. The variability of stiffness is traditionally obtained by appropriately designing the stacking sequence of the laminate. The idea behind VAT is to have an increased freedom in the tailoring of the material properties: the fibres in

Pagani Part B2 PRE-ECO

applications. Also, neural networks have already been proposed in the recent past for structural analysis, design, and verification. Nonetheless, the recent research and outcomes in this field - such as, deep learning, reinforcement learning, etc. - provide confidence for further developments in this direction. As an example, in a recent work (Pagani & Carrera, 2018), it was demonstrated that – under certain conditions – it is possible to use **machine learning** and vibration analysis to detect damage location and severity in multi-damaged, multi-component aerospace structures with a relative error rate lower than 1% for 98% of the test cases. The algorithm developed, see Figure 10, was able to solve complex inverse problems in fractions of a second. Direct numerical simulations would take hours or even days to complete such task.

During PRE-ECO program, AI will be combined with multi-scale advanced CUF models, by using a data-driven, bottom-up approach based on experiments to conduct unexplored analyses about defect sensitivity of tow-steered, printed composite laminates.

Testing will play a fundamental role and will be aimed at solving open issues in the field. First, the effects of overlaps and tow-drops will be investigated, because general rules and conclusive results are still missing. Furthermore, the robustness of VAT manufacturing in off-design operating conditions and consequences on defects will be studied. Finally, the effect of parameters on the manufacturing process will be quantified. All these **investigations, combined with AI and numerical modelling, will help us to provide design rules and best-practises which are not available yet for VAT printed composites.** Ad-hoc optimization constrains will be formulated as well and used in design for manufacturing as per *scientific pillar number 2*.

Figure 11 In-plane shear strain measurements during composite wing-up bending t

Experiments will combine classical investigation tools and innovative techniques for defects, displacement-load curves, quasi-static failure mechanisms, buckling loads example, **Digital Image Correlation (DIC)** will be employed in PRE-ECO for parameters and in-plane strains of VAT laminated subjected to in-plane and out-of-pl non-contact, optical methodology that employs tracking and image registration techn and 3D measurements of changes in images. This method is used to measure full fi displacements and superficial strains. Compared to strain gages and extensom information gathered about the fine details of deformation during mechanical tests This technology has been employed recently by the applicant and co-workers fo measurements of a (straight-fibre) composite wing (Pagani, et al., 2018), see Figure 1 on tow-steered printed composites provide confidence in this direction.

***Expected goal:** PRE-ECO will result into a robust and efficient simulation and design printed composites with unprecedented predictive capabilities to face technical iss engineering, including aerospace, bio-mechanics, and material science. Furthermor scientific pillar will have their own distinct impact. The advanced structural models will provide a physically consistent formulation for the multi-scale analysis of printed unveil new optimization algorithms for heterogeneous and anisotropic structures, procedures and full manufacturing constraints set. Finally, pillar 3 will be of pive*

arbon-nylon parts obtained by Fused Deposition
g (FDM) at the Department of Mechanical and
Aerospace Eng., Politecnico di Torino.

makes use of the Composite Filament Fabrication
eously both thermoplastic material and continuous
printer has two extruder heads; one to print plastic
d us **to relax fibres along curvilinear paths, so as**
***ctionality* to the structure, or to alleviate stress**

neering work, Hyer and Lee (Hyer & Lee, 1991)
loited to improve stress distribution in the presence
bilities of VAT composite laminates to increase the
ns and provide optimal solutions with maximum
tions about real-life potential applications of VAT

Pagani Part B2 PRE-ECO

scaled and simulaneusly employed, for example, in large optimization algorithms, in failure evaluation and delamination analysis at layer interface, and in stress evaluation at fibre-matrix level or fibre micro-buckling at micro-scale, see Figure 6.

Extension of CUF to deal with multi-scale analysis of VAT composite will require a number of challenges to be faced. These include, but are not limited to, in-plane integration of continuously varying material elastic coefficients, formulation of the problem statements in curvilinear coordinates to accommodate curved fibre paths, and development of proper algorithms for global/local and variable-kinematics theories.

Design for manufacturing. The problem of (optimally) designing a VAT laminate is intrinsically a multi-scale design problem. To formulate the problem of the optimum design of a VAT composite in the most general way, the designer should take into account the **full set of design variables (geometrical and material) governing the behaviour of the structure at each characteristic scale (micro-meso-macro)**. Up to now, no general rules and methods exist for the optimum design of VAT laminates. The few works that can be found in literature always make use of some simplifying hypotheses and rules to get, in an easy and fast way, a solution. Often, such assumptions and rules have not a precise physical and technological justification. Besides, they substantially modify the nature of the problem itself and extremely shrink the design space leading only to suboptimal solutions.

The main limitations and drawbacks characterizing the vast majority of the studies on optimal design of VAT laminates are:

1. *the use of linear functions for representing the fibre path (which significantly reduces the design domain);*
2. *the lack of a multi-scale approach for dealing with the optimum design problem of VAT laminates – see the first scientific pillar of PRE-ECO;*

Part B2

Methodology

- ✓ Methodology: work packages & tasks?
- ✓ Implementation, integration.
- ✓ Describe your embedded research network.
- ✓ Risk analysis: high-gain / fail-safe project!

REVIEWER COMMENT: The PI detailed the steps to be followed in each proposed activities and provided comprehensive relevant literature review and justification.

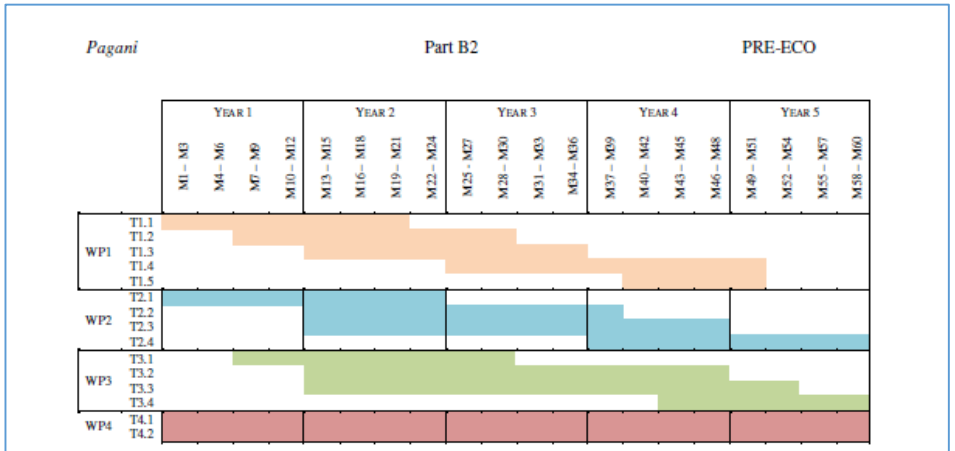
REVIEWER COMMENT: A sparse risk analysis is presented. The research methodology is appropriate. The working arrangements are clearly structured, detailed and well thought through.

Resources (including project costs)

- ✓ In kind contributions free of charge.
- ✓ External experts.

REVIEWER COMMENT: The proposed timescales, resources and the PI commitment are adequate.

REVIEWER COMMENT: there is no […] justification why the aimed research requires 3 PhD students, 2 postdocs, 1 senior scientist plus 70% of the time of the PI.



Pagani Part B2 PRE-ECO

	YEAR 1				YEAR 2				YEAR 3				YEAR 4				YEAR 5			
	M1 – M3	M4 – M6	M7 – M9	M10 – M12	M13 – M15	M16 – M18	M19 – M21	M22 – M24	M25 – M27	M28 – M30	M31 – M33	M34 – M36	M37 – M39	M40 – M42	M43 – M45	M46 – M48	M49 – M51	M52 – M54	M55 – M57	M58 – M60
WP1	T1.1 T1.2 T1.3 T1.4 T1.5																			
WP2	T2.1 T2.2 T2.3 T2.4																			
WP3	T3.1 T3.2 T3.3 T3.4																			
WP4	T4.1 T4.2																			

Table 1 Gantt chart of PRE-ECO project.

b-3. An embedded research project

PRE-ECO will be embedded into an existing collaboration network, including:

- *Sensitivity analysis and metacomposites. Prof. Sondipon Adhikari, Swansea University.*
- *…alifornia Institute of Technology.*
- *…tiers ParisTech.*
- *…rsity.*
- *…Limerick University.*

10 by Popular Science Magazine (2010) will act …gram and will be hosted in Politecnico di Torino. … materials science, condensed matter physics, and …vestigation on metacomposites and defect analysis …

…orino. The research group has an own computing … GHz, 128 GB RAM) which will be used for large …ntation for manufacturing and testing include: 1) a …on-glass-Kevlar fibre materials with build volume …icron; 2) a DANTEC DYNAMICS digital image …r full-field quasi-static measurements of superficial … system for the acquisition of sound and vibrations; …nd testing.

…ndustrial interest will be manufactured by using

Pagani Part B2 PRE-ECO

the full set of design variables intervening at each scale.

2. Second-level problem. The goal is the determination of the **optimum lay-up of the laminates** composing the structure meeting the optimum combination of their material and geometrical parameters provided by the first level of the strategy. At this stage, the design variables are the layer orientations, and the designer can add some additional requirements, e.g. constraints on the elastic behaviour of the laminate, manufacturability constraints, strength and damage criteria, etc.

Tasks

Task 2.1 – Implementation of a multi-level strategy based on ESL parameters and invariants for optimum design of VAT composites. Task 2.2 – Use of NURBS or spline basis functions for obtaining a continuous point-wise variation of the laminate invariant parameters (first-level) and the fibres orientation angle within each layer (second-level). Task 2.3 – Employment of refined structural multi-scale models at both first- and second-level phases of the optimum design strategy for taking into account higher-order effects and increasing the space of the optimization problem. Task 2.4 – Formulate a proper mathematical formalization of the manufacturability constraints linked to printing processes.

Expected scientific outcomes

• Systematic formulation of additive manufacturing constraints related to tow kinking and wrinkling, gaps, overlaps, jagged boundaries, tow-drops, course edges and minimum cut length (MCL). • Development of a multi-level algorithm for optimum design of VAT composite laminates based on multi-scale models with unprecedented simulation capabilities.

Persons involved

PI (12MM), Senior research fellow (12MM), Postdoc #1 (12MM), PhD #2 (36MM)

WP3 – Surrogate modelling and testing

Main challenges

This work package has two main objectives. The first one is to **manufacture and test advanced composite specimens with curved fibres** (carbon, Kevlar, glass, and active fibres possibly). Manufacturing will be made by using and already available 3D printing machine, which has two degrees of freedom (extruder heads can move only along the plane coordinates) and makes use of fused deposition modelling, see Figure 3. Six-axes printing of composites will be possible by developing, modifying and opportunely programming an **opensource robot**, such as the 11-kg e.DO® robot by COMAU which is shown in Figure 13. ***Further VAT thermoset structures of industrial interest will be manufactured via AFP with the courtesy of third parties which are interested to the project*** *(Figure 1).*

Results from experimental tests will be combined with results from simulations as the second objective of WP3 to **develop a metamodeling technique based on AI**. Thus, by using neural networks and Monte Carlo analyses, response surfaces will be built for defect sensitivity analysis. Based on observations, overlaps, gaps, tow-drops, jagged boundaries, course edges and MCL will be investigated for developing a formal paradigm of manufacturing constraints for optimization (see WP2) and for evaluating the consequ… on structural response over the various scale lengths, from micro- to macro-scale (see … **best-practises and guidelines for printed composites.**

Tasks

Figure 13 O… program fo…

b-2. Implementation

Figure 14 shows the implementation and the integration of the work packages. Furthermore, the work schedule of PRE-ECO is summarized in the **Gantt chart** in Table 1.

In WPs 1 and 3, we will develop the backbone of PRE-ECO project; i.e., the multi-fidelity, multi-scale simulation tools and the metamodeling algorithms encompassing experimental tests, respectively. These work packages, also, represent the critical aspects of the work program as they **bring innovative and unexplored approaches for the analysis and design of tow-steered printed composite structures.** Although independent, outcomes from WPs 1 and 3 will be then integrated into WP2 – in which an advanced optimization algorithm based on a multi-level procedure and eventually on a genetic formalism will be developed – to finally give a hybrid, virtual platform to design for additive manufacturing. As a consequence, **current technological limitations of additive manufacturing machines will be hopefully overcome; new rules and best-practises that are expected to push the use of printed composite materials into a new era will be unveiled.**

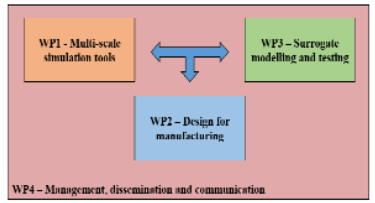
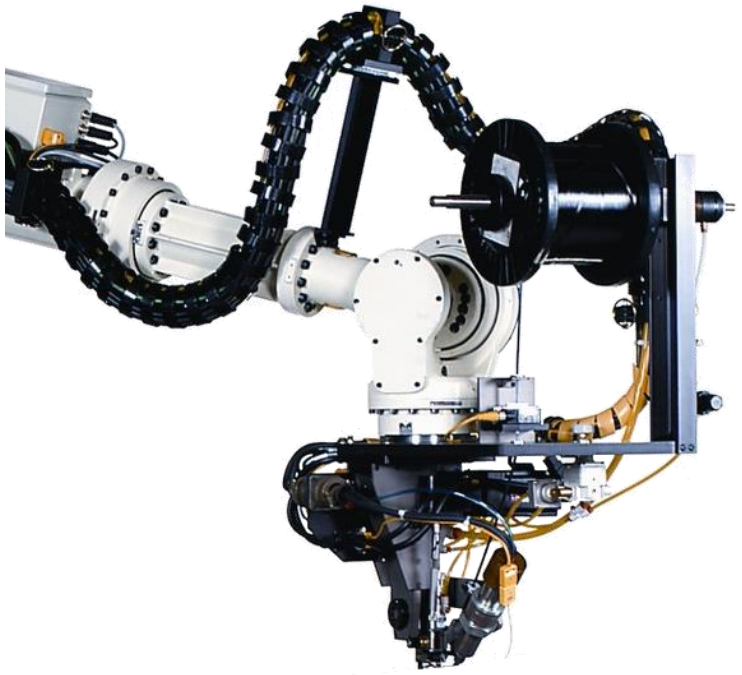


Figure 14 Implementation of the work packages.

12



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