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Content

1. SUMMARY

The NewFrac Global Research Plan is composed of the Individual Research Projects (IRP) plans for the Early Stage Researchers (ESRs) composing the network. The overall development of individual investigations is described in this deliverable.

2. GENERAL OBJETIVES AND TECHNIQUES

The current trend to implement a fast design-virtual testing and manufacturing cycle, automation, and data exchange in manufacturing technology will require highly efficient and reliable failure-predictive computational tools for an accurate prediction of fracture and damage phenomena but the current modeling tools are insufficient for failure prediction in heterogeneous systems with high level of complexity.

The overarching objective of the NEWFRAC network is a high-level training of a new generation of creative, entrepreneurial and innovative **early-stage researchers (ESRs)** through the development and engineering applications of a new modeling framework focused on the prediction and analysis of multi-field fracture phenomena in heterogeneous engineering systems at different scales.

The main research objective of the NEWFRAC network is the development of a new modeling and simulation framework for the fracture mechanics optimization of high-level technological products involving heterogeneous systems (materials and structures), employed in engineering fields of strategic societal and scientific impact, ranging from renewable energy production systems to biological hard tissues.

The NEWFRAC network will integrate two recent strategies of high impact for fracture modeling: **Finite Fracture Mechanics (FFM)** and a variational approach to fracture referred to as **Phase Field (PF)** approach, as well as novel methodologies for a consistent hybridization of strategies. These strategies will enable simulation of complex fracture phenomena in different engineering applications which was difficult to achieve using previous methods.

These techniques will be extended to deal with fracture in heterogeneous materials across multiple length scales and including multi-field effects. This main objective will be achieved through the two following Specific Objectives:

- Obj. 1) To make a significant step forward on the key issues in FFM and PF, that will allow developing general computational tools able to solve complex fracture problems described above.
- Obj. 2) To confront these computational tools with challenging real-world fracture problems and applications which will provide the necessary feedback to upgrade these computational tools to obtain really predictive tools, which are robust, reliable and efficient, and thus useful in strategic industrial sectors.

While **Work Package WP4** with secondments and internships in academy are aimed at accomplishing Specific Objective 1, **Work Package WP5** with secondments and an internship in industry and a hospital are aimed at accomplishing Specific Objective 2.

3. METHODOLOGIES

This scientific achievement will be carried out by training future experts, who will assimilate the required capacities and competences of analysis under the guidance of reputed researchers and professionals. To achieve these targets, **NEWFRAC will support 13 Early Stage Researchers (ESRs)** who will be trained to conduct a breakthrough research in fracture modelling engaging interdisciplinary academic and industrial activities. The NEWFRAC network has an ideal composition, providing an excellent environment and training program for future professionals in failure analysis in engineering systems.

The training plan is split into 5 **Work Packages (WPs)** as illustrated in Fig 1. The research and technical activities are concentrated in WP4 and WP5, which are focused on the development of tools for the study of multi-field, multi-scale and/or multi-material failure processes (WP4) and applying these methods to provide solutions to challenging industrial problems (WP5). These two WPs will solve wide-ranging interconnected fundamental issues of fracture modelling, with a flow of procedures and codes developed in WP4 towards WP5, while open problems found in solution of industrial problems will serve as an inspiration for new developments in WP4.

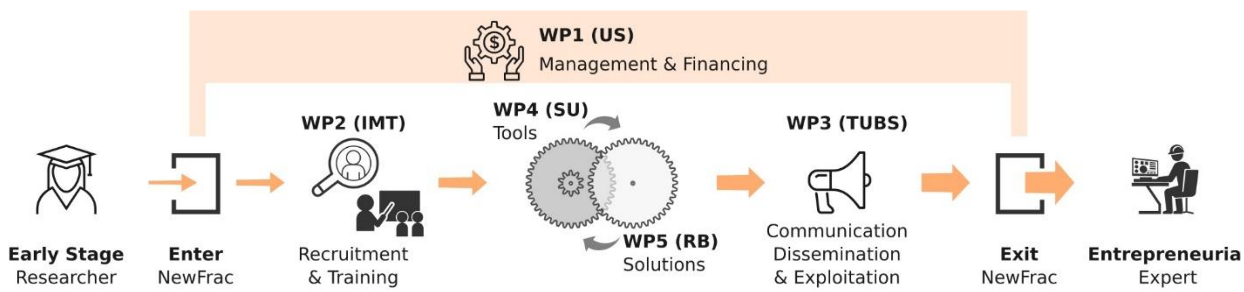

Figure 1. Work Packages Illustration

4. WORK PACKAGE 5

The objective of this Work Package 5 **"Innovative solutions to fracture problems in Energy, Health and Transport"** is the application of novel fracture techniques Coupled Criterion of Finite Fracture Mechanics (CCFFM or simply FFM) and Phase Field (PF) to the study of promising solutions that have been presented in the last decade for the enhancement of new materials and the understanding of the fracture behaviour of complex materials.

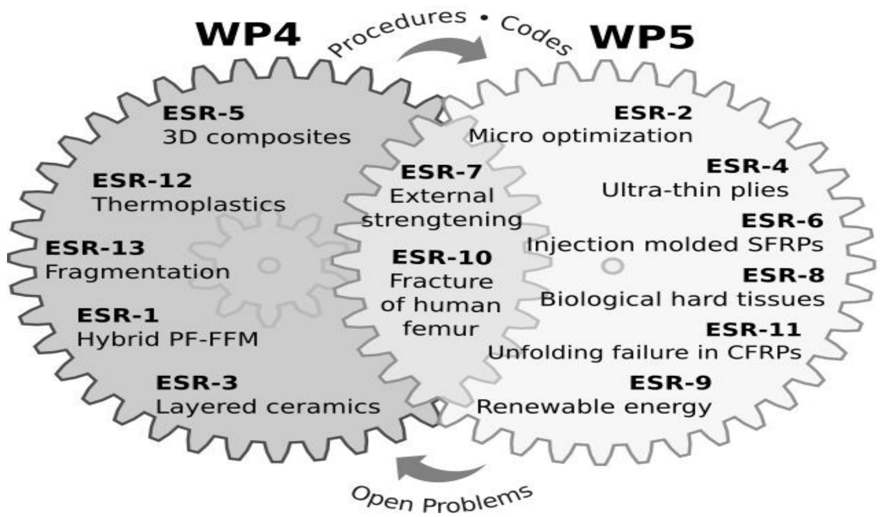

Figure 2. Individual Research Projects (IRPs) relation to Work Packages 4 and 5 (WP4 and WP5)

For composites the objective is the improvement of the mechanical response of composite structures in service with:

- The use of ultra-thin plies to inhibit the presence of transverse cracks
- The incorporation of thermoplastic-based polymeric matrices in the new composite definitions
- The implementation of bio-mimetic specimens using Additive Layer Manufacturing (ALM) techniques and structured interfaces using carbon nanotubes to improve mechanical performance against interlaminar failure.
- The use of LFRP sheet to strengthen stone/concrete arches and to prevent tensile crack growth within stone/concrete.

For biomaterials, the aim is the development of the ability to predict the behaviour of human bone. This is a complex biological tissue that may fail under a fall on the side or outstretched arms in the elderly. These failures, causing proximal femur or humerus fractures, are hardly predicted nowadays, and widely acceptable failure criteria exist in the biomechanical community. In an attempt to formulate a coupled micro-macro validated failure law of the proximal femur and humerus, CCFFM at the micro scale will be employed for the fracture initiation at the trabecular micro level (at the intertrabecular joints), and combined with a macro phase-field model that drives the propagation of the fracture and is related to the micro level.

For ceramics, innovative solutions to improve their low fracture toughness are necessary. Their very low fracture toughness often causes spontaneous brittle failure of the component or system. Contrary to metals, crack propagation in brittle materials such as ceramics is usually catastrophic, due to the lack of plastic deformation. Increasing strength in ceramics can be attained by reducing the size of these critical defects and introducing compressive residual stresses at the surface. However, significant reduction of strength variability cannot be achieved with the classic approaches. With the use of CCFFM and PF, the goal is to understand how cracks propagate in layered ceramics and to develop new ceramics with increased fracture toughness.

In addition, in the context of renewable energy applications, innovations are proposed, with special focus on photovoltaics and solid oxide fuel cells. These problems are characterized by coupling of multiple fields (thermal, electrical, mechanical, chemical fields) in statics and dynamics.

The Lead Beneficiary of this Work Package (WP5) is **Robert Bosch (RB)** and the main participants are Universidad de Sevilla (US), Sorbonne Université (SU), Politecnico di Torino (POLITO), Eidgenoessische Technische Hochschule Zürich (ETH), University of Porto (FEUP), IMT School for Advanced Studies Lucca (IMT), Tel Aviv University (TAU) and Foundation for the Research Development and Application of Composite Materials, Airbus Group (FIDAMC).

This Work Package involves eight Individual Research Projects (IRP) for eight Early Stage Researchers (ESRs) along the main participants, whose research plans are described in the sequel. The principal tasks of this WP and the description of role and work of partner within to them is structured at Table 1.

ESRs-Task Relation					
WP	Task Number	Task Description	ESR Collaborating	Lead Institution	Participant institutions
WP5	*5.01*	Development of new bioinspired tougher composites	**ESR-2**	US	ETH, BOTTERO
	5.02	Study of ultra-thin solutions in aeronautical composite laminates	**ESR-4**	FEUP	US, FIDAMC
	5.03	Innovative solutions to the fracture of injection molded SFRPs	**ESR-6**	RB	ETH, SU, US
	5.04	Advances in the reinforcement of FRP externally strengthened curved beams	**ESR-7**	POLITO	ETH, FIDAMC
	5.05	Simulation of biological anisotropic hard tissues	**ESR-8, ESR-10**	TAU/ETH	ETH, SU, RB, TAU
	5.06	Multi-scale and multifield applications for renewable energy problems	**ESR-9**	IMT	US, CUBICOFF
	5.07	Analysis of the failure mechanisms involved in the unfolding problem	**ESR-11**	FIDAMC	US, POLITO

Table 1. Principal WP5 tasks details

5. WORK PLAN – WP 5

Principal task of WP4 relation to Individual Research Projects (IRP) descriptions:

a. Task 5.01: Development of new bioinspired tougher composites.

This task will be principal related to ESR-2 at individual research project (IRP) "Toughening composites by micro and meso structural optimization". The lead beneficiary of this IRP is Universidad de Sevilla (US) in collaboration with Eidgenoessische Technische Hochschule Zürich (ETH) and BOTTERO.

The aim of this ESR project is to investigate the reduction of the flaw sensitivity of engineering composites by the optimization of their micro and meso structures as well as the geometric definition of their interfaces. The complex microstructures in biomaterials have been known for decades but its replication at an industrial scale was anti-economic with the traditional fabrication procedures. However, the recent development of new fabrication techniques, with some similarities with the biological procedures, opens new opportunities. One of these fabrication techniques is Additive Layer Manufacturing (ALM) which is applied to an industrial scale. Thus, the specific objective of this ESR project is the development of new materials and joints with lower flaw sensitivity inspired by biological materials and compatible with the new fabrication techniques. The microstructural design will be addressed by the combination of the observation of biological materials and the development of an optimization strategy based on genetic and related algorithms. The genetic algorithm will be based on the use of FFM and PF to test flaw sensitivity in order to create a new generation of microstructures.

ESR-2 will deal with multiscale analysis to enhance optimization range. For this aim, ESR-2 will collaborate with ESR-4, 6, 8, 9, 10 and 12, also working on multiscale modelling, by interchanging procedures and codes. Especially, ESR-2 will benefit from the expertise in microstructure of bones gained by ESR-8.

Expected results from this research project are:

1. Bibliographic revision: toughening mechanisms in biological materials, their evolution and current and future limitations of new fabrication techniques.
2. A new approach and computational tool to optimize micro- and meso-structures and structural joints based on the combination of genetic and related optimization algorithms, FFM and PF.
3. Design of a new composite microstructure, meso-structure or structural joint that fulfils certain criteria of flaw sensitivity and fabrication efficiency.
4. Fabrication and test of new designs to validate the methodology.
5. Adaptation of the new methodology to the industrial environment. These results will show the advantages of the methodologies and computational tools developed.

Planned secondment for ESR-2:

Scdmt	Months	Location	Comments
1	Month 12-17	ETH	Training in fracture mechanics in biomaterials
2	Month 35-38	BOTTERO	Adaptation and application of the computational tools developed in the advanced glass industry.

Table 2. ESR-2 Secondments

ESR-2 will be registered in the Doctoral Program in Mechanical Engineering and Management of the International Doctoral School. In addition to network-wide training, ESR-2 will receive an extensive hands-on training in: Biomechanics, including fracture mechanics in biological materials; New fabrication techniques in composites; Structural optimization techniques. ESR-2 will be enrolled in complementary courses in US and ETH.

b. Task 5.02: Study of ultra-thin solutions in aeronautical composite laminates.

This task will be principal related to ESR-4 at individual research project (IRP) "Fracture of LFRP ultra-thin ply laminates in aeronautical applications". The lead beneficiary of this IRP is University of Porto (FEUP) in collaboration with Universidad de Sevilla (US) and Foundation for the Research Development and Application of Composite Materials, Airbus Group (FIDAMC).

Ultra-thin ply composite laminates are the product of a novel manufacturing technology that produces laminates with higher longitudinal compressive and in situ strengths, higher resistance to delamination events and higher laminate tensile and compressive strengths. However, failure mechanisms in this novel material-type are not completely understood up to now, neither are the most appropriate analysis methods to represent these mechanisms. For instance, the choice of the constituent materials (reinforcing fibres and matrix) and ply size effects become particularly important due to ply thinness, which can be as low as 0.015 mm (i.e. 2-3 fibre diameters).

On the other hand, macro-mechanical homogenization is much easier to achieve in ultra-thin ply laminates due to a finer ply dispersion; hence, their mechanical behaviour is suitably represented by a homogenized quasi-brittle material model at the coupon and sub-component levels. The aim of this project is to understand the failure mechanisms and fully exploit the load bearing capacities of ultra-thin ply laminates by means of the development of novel numerical techniques integrating FFM and PF approach of fracture in the most efficient way. These modelling strategies will be set up at different scales of analysis. Micro-mechanical analysis will provide more comprehensive understanding with regard to the potential sources of damage (matrix breakage, fibre-matrix decohesion, delamination, among others), as well as the prospective propagation paths, and allow the study of constituent and ply size effects. Additionally, macro-mechanical modelling strategies will be employed to predict the macroscopic response of ultra-thin ply coupons and structures. Special attention will be devoted to investigating geometrical effects and loading states in specimens with stress concentrations and holes, which are of relevant practical importance in the aeronautical and aerospace industries.

ESR-4 will interact with ESR-1 to take advantage of the tools for FFM and PF analysis of anisotropic materials under general stress states and with ESR-13 to extend the FFM and PF analysis of ultra-thin ply laminates to dynamic test cases. Additional collaborations with ESR-2, ESR-6 and ESR-12 concerning the development of multiscale approaches of fracture of anisotropic materials and with ESR-3, ESR-7, and ESR-11 by interchanging procedures, codes and common perspectives in the analysis of fracture of different multi-layered composites are expected. It is also expected that ESR-4 will collaborate with ESR-12 in the definition of robust characterization techniques for advanced composite systems across the scales (from the constituent materials to the multi-layered composites), and to validate the developed models in an industrial context.

Expected results from this research project are:

1. Development and validation of FFM and PF models for the analysis of ultra-thin ply laminates at the micro- and macro-scales.

2. Development of micro-mechanical models of ultra-thin ply composites for the study of constituent and ply size effects.
3. Development of an efficient framework for the analysis of the mechanical response and failure of aeronautical coupons and structures suitable of application in an industrial context.

ESR-4 planned secondments:

Scdmt	Months	Location	Comments
1	Month 10-15	US	Formulation and numerical implementation of the FFM and PF strategies
2	Month 24-27	FIDAMC	Training in ultra-thin ply laminates applied in the aeronautical sector and transfer of the computational tools developed to these laminates.

Table 3. ESR-4 Secodments

ESR-4 will be included in a double doctoral degree agreement between FEUP and US. In addition to network-wide training, ESR-4 will receive an extensive hands-on training in: Advanced analysis of composite materials and anisotropic elasticity; Damage Mechanics in layered composite materials; Implementation of FFM and PF; Experimental techniques for characterizing ultra-thin ply laminates; Design, sizing, stress and failure analysis of aeronautical structures. ESR-4 will be enrolled in complementary courses in FEUP and US.

c. Task 5.03: Innovative solutions to the fracture of injection molded SFRPs.

This task will be principal related to ESR-6 at individual research project (IRP) "Multiscale modeling of fracture processes in injection molded SFRPs". The lead beneficiary of this IRP is Robert Bosch (RB) in collaboration with Eidgenoessische Technische Hochschule Zürich (ETH) and Sorbonne Université (SU).

Components made of SFRP are typically manufactured via injection molding. Hereby, the resulting local microstructural configuration of the composite, i.e. the spatial arrangement of the fibers, highly influences the deformation and failure behaviour of the macroscopic component. Later in the application, products are exposed to harsh environments and severe operational loads. Aiming at the development of products with high reliability requirements in a time- and cost-efficient manner, simulation methods with high accuracy predictions and efficient adaption routines are becoming increasingly important.

To achieve this, robust multiscale techniques must be established that contain elements of virtual material testing where a large portion of the required experiments are transferred to the virtual or numerical world. Clearly, this requires a model on the microscopic scale that captures all relevant failure mechanisms like fiber fracture, cavitation fracture at fiber tips, and matrix fracture. In this context, PF models for fracture are promising approaches, as they can be employed to describe highly complex fracture processes in very complicated 3D microstructures. With precise microscopic models at hand that are validated with non-standard microscopic experiments, numerous simulations are performed with highly efficient Fast Fourier Transformation (FFT) solvers. In line with concepts of data-driven modeling strategies, effective material laws for the macroscopic component scale are derived based on closed form approaches or on modern model order reduction techniques which are fed by the previously performed microstructural simulations.

The 1st objective of this ESR project is to deliver variational-based robust PF models for fracture that can be employed to predict damage progression on the microstructural level for complex operational loads. In order to achieve this, experiments on the microscale of the composites will be carried out to make the main failure mechanisms visible and to motivate the specific PF modeling approaches. Having the microscopic model at hand, the 2nd objective of this ESR project is the derivation of a suitable effective model that can be employed for component simulations that are performed with commercial FEM packages.

For the development of high accuracy PF models of fracture, a close methodological link exists between ESR-6, 3, and 10. In order to tackle the problem of bridging the different length scales, ESR-6 will collaborate with ESR-2, 3, 4, 8, 9, 10 and 12.

Expected results from this research project are:

1. New PF models for fracture are derived to predict damage mechanisms on the microscale.
2. Non-standard experimental techniques on the microscale are established to validate the PF models.
3. Data-driven effective models for the macroscopic scale are derived that can be used for a component simulation.

ESR-6 planned secondments:

Scdmt	Months	Location	Comments
1	Month 12-16	US	Specific training in recent advances in PF modeling of fracture for cyclic fatigue loading
2	Month 23-27	FIDAMC	PF modeling of the temperature- or moisture-induced transition from brittle to ductile fracture in polyamide-based thermoplastic composites

Table 4. ESR-6 Secondments

ESR-6 will be enrolled as doctoral student in the Department of Mechanical and Process Engineering at ETH and in complementary courses of his/her choice at ETH and SU. ESR-6 will also be a member of the international Bosch PhD program (380 PhD-students), which promotes interdisciplinary and intercultural exchange, and offers courses to enable innovative training regarding entrepreneurial behaviour. The exchange in the program is promoted by a yearly PhD conference organized by the PhD network and supported by the senior management of Bosch. Furthermore, workshops, PhD-and job fairs are held regularly. Training in advanced modeling and simulation techniques are available in the research group 'Design and Dimensioning of Components, Prediction of Lifetime, Process Simulation for Plastics Engineering'.

d. Task 5.04: Advances in the reinforcement of FRP externally strengthened curved beams

This task will be principal related to ESR-7 at individual research project (IRP) "Debonding of the reinforcement in LFRP and FRCM externally strengthened beams". The lead beneficiary of this IRP is Politecnico di Torino (POLITO) in collaboration with Eidgenoessische Technische Hochschule Zürich (ETH) and Foundation for the Research Development and Application of Composite Materials, Airbus Group (FIDAMC).

Externally reinforced structures are composite structures where the heterogeneity is due to the application of an external reinforcement to an existing structure in order to restore it or to increase its bearing load. The main objective of this ESR project is the analysis of the delamination of the external reinforcement in rectilinear and curved beams strengthened by thin Long Fiber Reinforced Polymer (LFRP) or Fiber Reinforced Cementitious Matrix (FRCM) composite. The problem has a great relevance since external bonding of Fiber Reinforced Composites is nowadays a common practice in strengthening of existing structures in general and in restoring of stone and masonry arches in particular.

Furthermore, among the different failure mechanisms of strengthened structures, the reinforcement debonding is probably the most important one to be investigated because of his typical brittle and catastrophic character. A first goal of the project is to develop an analytical approximate solution for the interfacial stresses between the structure and the reinforcement, under different mechanical and thermal loading conditions. A second goal is the application of LEFM, FFM and its comparison with the numerical solution of the problem by means of the Cohesive Crack Model (CCM). A third goal is to understand the effect of cyclic loads by assessing the fatigue behavior of LFRP-to-concrete joints.

ESR-7 will strongly interact with ESR-4, 7,11,12 and 13 dealing with layered structures. Especially, ESR-11 will benefit from the analytical results by ESR-7, while ESR-7 will exploit the knowledge acquired by ESR-13 about FFM and dynamics to assess the strength of FRP-reinforced structures under impact loads.

Expected results from this research project are:

1. A deeper understanding of the edge debonding and intermediate-crack induced debonding mechanisms, gathering information about how to design the external reinforcement of beams to prevent failure. The study is expected to clarify the essential differences in behaviour between joints with flat and curved substrates and between reinforcements made by LFRP and FRCM during debonding.
2. To develop analytical formulae, under suitable simplifying assumptions, providing the load causing debonding that will be useful in engineering practice. A good agreement between CCM and FFM approaches is expected. A successful comparison between the FFM and the CCM solutions would be an important goal since FFM would provide a useful tool for preliminary sizing of externally strengthened structures, limiting the use of the computationally expensive CCM to the final stage in the structural design.

ESR-7 planned secondments:

Scdmt	Months	Location	Comments
1	Month 12-17	ETH	Training about the unfolding problem in curved laminates
2	Month 35-38	FIDAMC	Industrial applications of the tools developed for challenging unfolding problems in curved laminates used in CFRP aeronautical structures

Table 5. ESR-7 Secondments

ESR-7 will be registered in the PhD Program in Civil and Environmental Engineering of ScuDo the Doctoral School at POLITO. ESR-7 will be enrolled in complementary courses of his/her choice in POLITO, in Structural engineering and Applied mathematics and physics, among others. The host department, the Department of Structural, Building and Geotechnical Engineering at the Politecnico di Torino, holds excellent expertise in Structural and Fracture Mechanics.

e. Task 5.05: Simulation of biological anisotropic hard tissues.

This task will be related to two Individual Research Projects (IRPs), ESR-8 "Fracture in biological anisotropic hard tissues (human bones)" and ESR-10 "PF modeling of fracture in the human femur".

- **e.1) ESR-8 "Fracture in biological anisotropic hard tissues (human bones)"**

ESR-8 IRP lead beneficiary is Tel Aviv University (TAU) in collaboration with Eidgenoessische Technische Hochschule Zürich (ETH), Sorbonne Université (SU) and Robert Bosch (RB).

The main objective of this IRP is to perform experiments on bone tissues at micro and macro scales, learn to use a micro-CT scanner and apply a digital image correlation (DIC) system for the measurements of displacements and strains, formulate a failure initiation criterion for trabecular bone, and verify and validate it by application of a high order Finite Element Analysis (FEA).

ESR-8 focusses on the FFM and PF models and interacts strongly with ESR-10. It is expected that ESR-8 will benefit from ESR-2 that deals with micro-macro analysis, a relevant topic to the analysis of bone fracture. Vice versa, ESR-2 will also benefit from the expertise gained by ESR-8. ESR-8 will also collaborate with ESR-4, 6, 9 and 12 working on multiscale analysis by interchanging procedures and codes.

The expected results of this projects are:

1. A set of experimental results of the trabecular bone at the micro-scale.
2. FFM model for failure initiation at trabeculae intersections.
3. Determination of experimental failure load in cortical and trabecular bone.
4. Connections between micro-scale fracture and PF model at the macro scale.
5. A failure model for trabecular bone at the micro-macro level validated by experimental observations at the organ level.

Planned secondments:

Scdmt	Months	Location	Comments
1	Month 13-15	SU	Discussion of the experimental results at the micro scale
2	Month 25-27	ETH	Training in PF models and developing a macro failure propagation law in the framework of a PF model at the macro scale based on the experimental data at the micro scale
3	Month 35-38	RB	Apply the developed procedures to fracture problems in other hierarchical materials

Table 6. ESR- 8 Secondments

ESR-8 will be registered in the Program PhD in Engineering at TAU. Prof. Zohar Yosibash is the chairman of the PhD Committee of the Faculty of Engineering at TAU. In addition to network-wide training, ESR-8 will be enrolled in advanced courses at the graduate level on solid mechanics, FE methods, and biomechanics of bones at TAU. ESR-8 will be part of Prof. Zohar Yosibash's group. This group is known for its international expertise in bone mechanics (both experimental and computational). Prof. Yosibash is an expert and one of the initiators of the FFM concept with Prof. Leguillon, and internationally known for his expertise in high order FEA. An internship is planned at Sourasky Medical Center in Tel Aviv (M11) for training in clinical aspects of bone fracture and to apply the developed procedures to problems of clinical practice.

- **e.2) ESR-10 “PF modeling of fracture in the human femur”.**

ESR-10 IRP lead beneficiary is Eidgenoessische Technische Hochschule Zürich (ETH), in collaboration with Tel Aviv University (TAU) and Robert Bosch (RB).

ESR-10 will work at the development, implementation and testing of a PF model for fracture of anisotropic biological tissues, with specific reference to the human bone, especially to the proximal part of the femur. First, ESR-10 will develop a suitable energy functional to account for anisotropic effects and for asymmetry between tension and compression, investigating the mathematical properties of different options and carrying out both homogeneous and localization analyses. ESR-10 will thus develop the macroscopic anisotropic PF model, carry out the theoretical analysis and numerical implementation phases, and test the model on simple geometries before extending it to the geometry of the proximal part of the femur.

Subsequently, ESR-10 will work in cooperation with ESR-8 to formulate a scale transition procedure between the microscale, where ESR-8 will have developed local fracture initiation criteria based on FFM, and the macroscale, where crack propagation will be described. Again, in cooperation with ESR-8 ESR-10 will carry out numerical simulations of the experiments performed by ESR-8 to validate the developed tools.

ESR-10 will work with ESR-8 on the formulation of a scale transition procedure. ESR-10 will also interact with ESR-8 in the comparison of numerical simulation results with experimental results. ESR-10 will also collaborate with ESR-4, 6, 9 and 12 working on multiscale analysis by interchanging procedures and codes.

Expected results of this IRP are:

1. A family of PF models for anisotropic materials with asymmetry between tension and compression.
2. A specific PF model for fracture of the human femur.
3. An experimentally validated computational multiscale framework for fracture in the human femur.

Planned secondments:

Scdmt	Months	Location	Comments
1	Month 13-15	TAU	Discussing, developing and implementing the micro-macro scale transition procedure
2	Month 25-27	TAU	Validation of the computational framework against experiments performed
3	Month 35-38	RB	Developing and implementing scale transition procedures and validation of modeling approach.

Table 7. ESR-10 Secondments

ESR-10 will be enrolled as doctoral student in the Department of Mechanical and Process Engineering at ETH. ESR-10 will be a member of the graduate school at the ETH. Specific training in advanced modelling and simulation techniques as well as training of PF modelling of fracture will be arranged at the group of Prof. De Lorenzis, where extensive know-how and experience on this topic is available

f. Task 5.06: Multi-scale and multifield applications for renewable energy problems.

This task will be related to Individual Research Project (IRP) ESR-9 "Multi-field and multi-scale modeling of fracture for renewable energy applications". The lead beneficiary of this IRP is IMT School for Advanced Studies Lucca (IMT) in collaboration with Universidad de Sevilla (US) and CUBICOFF.

Fracture mechanics of materials for renewable energy applications (photovoltaics, solid oxide fuel cells, etc.) is a fundamental tool to assess the reliability and the durability of these technologies. From the modeling point of view, the study of these problems is challenging due to the simultaneous presence of multiple fields, often strongly coupled together. In this regard, there is room for innovation in terms of development of novel FEM software that can be incorporated into existing FEM tools for industrial simulation and virtual material testing. To make advancement in this research, a deep knowledge on numerical analysis and FEM procedures, with a strong background on the physical-mathematical formulations of the multi-field phenomena is required. Therefore, advanced training on these topics is original and highly relevant for the realization of a new class of specialized analysts to be employed in research and development departments of companies.

ESR-9 will intensively collaborate with ESR-3, 5 and 12 working on multi-field modeling in the PF approach as well. ESR-9 will also benefit from the computational procedures developed for a novel treatment of anisotropy in the PF approach by ESR-1, 4, 8, 10 and 12. Eventually, ESR-9 will interchange the computational procedures developed for multiscale modeling using the PF approach to fracture with ESR-2, 4, 6, 8, 10 and 12.

Expected results for this project are:

1. Computational procedures for the PF approach implemented in FEM research/commercial software, like FEAP/ABAQUS. The developed routines will be delivered as open source codes, to foster their exploitation in academy and industry.
2. Specific applications focused on reliability and durability of materials for renewable energy applications, for their virtual testing and design of innovative solutions.

Planned secondments:

Scdmt	Months	Location	Comments
1	Month 10-15	US	Computational implementation of PF procedures and comparison with the FFM formulation
2	Month 35-38	CUBICOFF	Testing the computational tools developed on fracture problems in glass pipelines in solar thermal collectors

Table 8. ESR-9 Secondments

ESR-9 will be included in a double doctoral degree agreement between IMT and US. In addition to network-wide training, ESR-9 will receive extensive hands-on training in Computational Fracture Mechanics methods (for applications to problems characterized by multiple fields, very important in renewable energy applications: mechanical, thermal, electrical, chemical fields), Partial Differential Equations (in the presence of strong nonlinearities induced by fracture and with multiple fields, requesting sequential or monolithic numerical procedures for their effective solution and simulation). Specific training at IMT will regard the knowledge of intellectual property rights (IPR) and their protection, with special focus on patenting. This will be achieved via a series of specific courses on IPR, available at IMT Lucca in the framework of the activities of the Joint Technology Transfer Office (JoTTO) of IMT, Scuola Superiore Sant'Anna, Scuola Normale Superiore and IUSS Pavia.

g. Task 5.07: Analysis of the failure mechanisms involved in the unfolding problem.

This task will be related to Individual Research Project (IRP) ESR-11 "Analysis of the failure mechanisms associated to the unfolding failure in CFRP profiles". The lead beneficiary of this IRP is Airbus Group (FIDAMC) in collaboration with Politecnico di Torino (POLITO) and Universidad de Sevilla (US).

Unfolding failure consists of a delamination produced in curved composite laminates when they are loaded under a bending moment which tries to open the curvature. This failure is typically associated to the interlaminar normal stress (INS) characterized by the interlaminar tensile strength (ILTS). The ILTS is generally obtained by a four-point bending test. The four-point bending test applied to the curved composite laminates causes a thickness-dependence of the ILT S with the thickness of the specimens. Several authors have associated this dependency to manufacturing defects or porosity, but results are not conclusive.

The aim of this project is to analyse numerically and experimentally the failure mechanisms involving the unfolding failure in order to demonstrate a novel idea of unfolding failure associated to intralaminar stresses instead of the INS. Preliminary analyses of existing experimental results (facilitated by an external company) have shown a good agreement with this new hypothesis. The study will be based in a set of new experimental results specifically oriented to observe the effect of the intralaminar failures. Since failure is catastrophic and difficult to be precisely observed, the experimental results will be complemented by numerical simulations, using FEM models, in which crack onset will be determined using FFM, and crack propagation (including possible migration from layers to interfaces and vice-versa) will be simulated with PF. Correlation between experimental and numerical results will provide important proof of the existence of this novel failure mechanism.

ESR-11 will collaborate with ESR-3, 4, 7, 12 and 13 dealing with layered curved structures. Especially, ESR-11 will benefit from analytical results by ESR-7, and the PF formulation employed in ESR-3 for ceramics will be adapted by ESR-11 for composite structures.

Expected results for the project are:

1. Carry out an experimental test campaign to demonstrate the validity of a new hypothesis to explain the unfolding failure of certain curved laminates.
2. Predict the critical load that causes the onset of the unfolding failure (according to the proposed failure mechanism) using FFM and Finite Element models.
3. Simulate the delamination process after the onset, using PF and FEM models, to prove that multiple delamination is unstable appearing after the initial intralaminar failure.
4. Develop a new failure criterion that includes the traditional concept of unfolding failure with the new idea of failure mechanism, to define an accurate procedure to characterize experimentally the ILTS suppressing the thickness-dependency and in order to predict the unfolding failure with high confidence.

Planned secondments:

Scdmt	Months	Location	Comments
1	Month 10-15	US	Training in advanced numerical modelling of the problem and support for the performance of the experimental tests
2	Month 24-27	POLITO	Development of semi-analytical models providing the critical load for debonding onset in curved composite beams by means of CCFFM

Table 9. ESR-11 Secondments

ESR-11 will be registered in the Doctoral Program in Mechanical Engineering and Management of the International Doctoral School at US. ESR-11 will be enrolled in complementary courses of his/her choice in US. FIDAMC and the US hold wide expertise in the calculation and analysis of the unfolding failure through a previous PhD collaboration project, which lays the groundwork on the unfolding analysis and supplies efficient calculation tools, which will provide an excellent framework for the development of the ESR-11 project. Furthermore, FIDAMC provides outstanding facilities for the manufacturing and preparation of the specimens for the experimental tests, and the US has wide experience on numerical simulations in failure propagation.

6. CONCLUSIONS

This Overall Research Plan describes in detail the general objectives of Work Package 5. It summarizes all the Individual Research Projects (IRP) of ESRs related to Work Package 5, focusing on the specific objectives to be achieved and on the methodologies and techniques to be used by these ESRs. This Overall Research Plan has been updated to consider the results of the presentations and discussions we had at our first extended Webinar (four 2-hour sessions) on November 2020.