PHD SUBJECT PROPOSITION

Title:
Investigating the mechanisms governing the long-term mechanical performance of type IV composite pressure vessels

PhD advisors:
Federica Daghia – Director (federica.daghia@ens-paris-saclay.fr)

Industrial contact:
Denis Espinassou (Denis.Espinassou@cetim.fr)
Suzanne Laik (Suzanne.Laik@cetim.fr)

Context:
This PhD thesis is proposed in the context of a long-standing collaboration between the academic PhD advisor, expert in the modelling and simulation of damage and failure of polymer matrix composites, and CETIM, a technical centre providing industries with expertise on the design, manufacturing and testing of composite structures, including composite pressure vessels.
As such, the PhD student will spend most of his/her time in the academic laboratory, but regular meetings and discussions with CETIM will be organized.

Keywords: Composite pressure vessels, Damage mechanisms, Fatigue, Multiscale modelling

Description:
Hydrogen mobility solutions require storage systems capable to withstand high pressures and multiple loading cycles over the course of many years. Type IV pressure vessels, that is carbon fibres composite structures with an internal polymer liner, are currently used in industry due to their excellent strength to weight ratio. However, experiments have shown that burst pressure can decrease significantly after a vessel has been subjected to cyclic loading, resulting in significant subcritical damage. Understanding and predicting the evolution of the burst pressure of vessels due to damage cumulated over time is a key industrial challenge to ensure safety and define monitoring, maintenance and repair strategies.

The mechanical response and damage evolution of composite pressure vessels is controlled by its strong hierarchical organisation at different scales, from the fibre/matrix constituents (~10^{-5} m), through single tows, winding patterns, local composite layups, to the overall structure (~1 m). A robust design ensures that final burst pressure is brought about by failure of the carbon fibres, while subcritical damage mechanisms associated to cycling and ageing generally affect the polymer matrix through modification of its mechanical properties and/or the appearance of cracks within and between tows.

While its stiffness and strength are much lower than those of the fibrous reinforcement, the polymer matrix enables load transfer between the reinforcement elements. Understanding and quantifying the way such subcritical damage mechanisms affect load redistribution at different scales, and thus modify the long-term mechanical performance of such structures, is the subject of this PhD thesis. More specifically, load redistribution at different scales will be investigated through modelling and simulation. Information on the damage present within the structure and its burst pressure will be obtained through observations and tests associated to a different PhD work, focused on inspection and structural health monitoring of both new and aged pressure vessels.

Single tows of polymer matrix composites display higher values and lower variability in longitudinal tensile strength than tow consisting of dry fibres, but their properties worsen when the polymer properties are affected by temperature or the presence of damage [Hochard *et al*, 2014]. This first level of load redistribution will be investigated through models including statistical fibres' properties and different possibilities of redistribution between them [Murthy *et al*, 2010]. Experimental characterisation of such effects can be carried out at this scale via tensile tests on flat specimens or tubes, pre-damaged by applying temperature or transverse mechanical loads.

Layups involving tows with different fibres directions can efficiently withstand multiaxial loadings in the local tangent plane, with the fibres of each layer contributing to the overall stiffness and strength thanks to the overall "plate-like" kinematics of the assembly. Depending on the layup and loading conditions, the transverse and shear properties of a given ply can provide a significant contribution to the stiffness and strength of the stack: in these cases, matrix damage in a ply is directly visible at the scale of the stack, for instance in the extreme case of a $[+45/-45]_{ns}$ layup under uniaxial tension [Ladevèze et Le Dantec, 1992]. In layups involving at least three different fibres directions and optimised for specific multiaxial loadings, the evolution of transverse and shear properties is generally not visible at the scale of the stack. However, transverse cracks within plies and local delaminations could still affect the local load sharing by modifying the "plate-like" kinematic of the stack. These aspects will be investigated through simulations involving discrete descriptions of some transverse cracks and delaminations, to analyse their effect on local kinematics and load sharing between tows. A first level of simulations will involve simplified layups with uniform fibres' orientations at different heights of the stack. Then, the effect of the local winding pattern will be explored by introducing local damage in the extremely detailed geometric and mechanical model developed by [Landron *et al*, 2026].

At the structural scale, damage and failure often develop in the vicinity of specific geometric features, such as free edges, notches, holes, … Although most of these features are absent in pressure vessels, different zones of the structure have different local loadings and stacking sequences, as well as some specific features, like curvature discontinuities and ply drops, which can induce bending in a structure mostly working in a membrane regime. Different subcritical damage evolution in different zones within the structure can lead to a change of failure mode, which could lead to a decrease in the burst pressure.

The systematic exploration and quantification of the changes in the redistribution mechanisms at different scales should enable us to provide a clear explanation for the evolution of burst pressure for vessels in service, as well as to define appropriate ways to account for this in the design, maintenance and end of life prediction of such structures.

References:

Hochard C, Miot S, Thollon Y, Fatigue of laminated composite structures with stress concentrations, *Composites: Part B* 65:11-16 (2014).

Ladevèze P, Le Dantec E, Damage modelling of the elementary ply for laminated composites, *Composites Science and Technology* 43(3):257-267 (1992).

Landron G, Rassineux A, Bovet C, Fagiano C, Hirsekorn M, Baranger E, Espinassou D, Geometric validation of a tape scale meshing tool for hydrogen tank modeling, *International Journal of Hydrogen Energy* 220:154170 (2026).

Murthy PLN, Phoenix SL, Grimes-Ledesma L, Fiber breakage model for carbon composite stress rupture phenomenon: theoretical development and applications, *NASA Technical Memorandum 215831* (2010).

PhD student profile:

- A Master Diploma (or equivalent) in Mechanical or Civil or Materials Engineering
    - A solid knowledge of Structural mechanics, Material modelling, Numerical modelling (finite elements)
- Proficiency in English and/or French (oral and written)
- Motivation for research and autonomous work
- Interest for experiments
- Experience with Matlab and/or Abaqus is a plus