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Big and smart experimental databases for mechanical model calibration: development of an automatized solution

PhD position at IRDL – LORIENT, France

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PhD topic

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General framework. Materials are key technology enablers and may become rare and very expensive in the future, thus encouraging massive light-weighting of structures though keeping the safety of the users [1]. This duality leads to the use of materials with always higher and higher mechanical properties. Nowadays, the mechanical design of a novel part or structure should make a smart use of materials, choosing ones with very high strength in specific areas and high ductility and/or elasticity in other areas. Such a design requests an intensive knowledge of the mechanical properties and accurate models to represent the materials in finite element simulations, replacing the real material with a virtual one, and fast and reliable calibration procedures to adjust the material parameters [2].

Characterizing the mechanical behavior of materials is an essential step for the further use of such materials. Though tensile test is certainly the oldest one [3] and still the most widely used, both in academy and industry, the knowledge of the mechanical behavior must be enlarged to other mechanical states, like simple shear, plane strain tensile tests, biaxial tension, tensile type loading with high triaxiality ratios [4,5,6]. Within a phenomenological approach, the number of necessary tests to obtain a full database for model calibration is around 50-80 tests, including repeatability. Such a task is huge and corresponds to around 1 person.month for the mechanical testing itself and 0.5 person.month for the model calibration, and demands qualified engineers with different skills. It is certainly a limitation to the widespread use of complex mechanical models in numerical simulations.

AutoMeCal project. The subject of this PhD takes place within the AutoMeCal project, for Automated Mechanical Lab' and Model Calibration with financial support from the French National Research Agency (ANR), for 4 years starting in 2024. The aim of this project is to create an automated and intelligent tool where the input is a chosen new material and the output is the calibrated model, i.e., the optimized set of parameters for a given phenomenological model, that is accurately representative of the mechanical behavior of the material. This project is limited to thin sheet metal products, as used in automotive (steel and aluminium alloys) and electronic (copper alloys) industries. **The research challenges are the automated mechanical testing itself, for several mechanical states, and the robustness of the**

automated model calibration and validation. Figure 1 gives an illustrated overview of the tool to be designed within the AutoMeCal project.

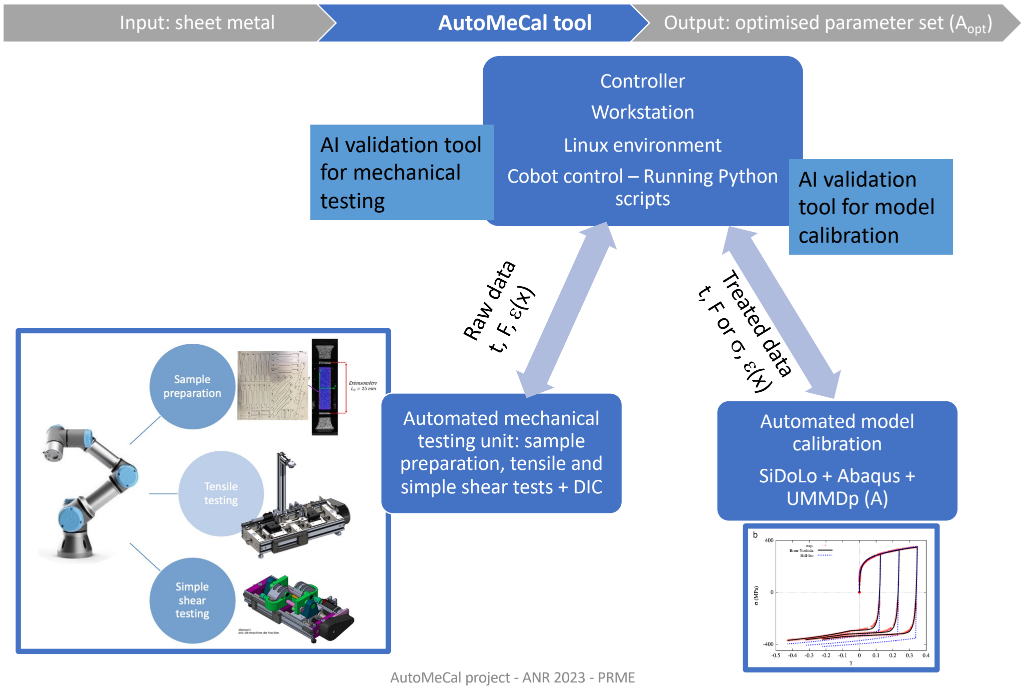

Figure 1: schematic illustration of the AutoMecal project, with the 2 main units, i.e., mechanical testing with Digital Image Correlation (DIC) and model calibration, managed by the controller, as well as the data flow.

Mechanical characterization of materials has received increasing attention due to the need of precise input data to computational analysis software, based on a representation of the mechanical behavior through constitutive equations and material parameters. A finite element software uses complex material constitutive models and its success reproducing the real behaviour is largely dependent on the capability of these models to reproduce the material behaviour and on the material parameters. The representation of the mechanical behaviour of materials through complex/sophisticated constitutive models required for the use of simulation software, presents two major challenges/difficulties: (i) the identification of a large number of parameters, and (ii) the quality and amount of information and number of the experiments performed. To speed up the characterization, automated mechanical testing has been developed for several decades, and solutions with cobots are available to customers [7] or developed within an academic environment [8]. A very recent alternative to circumvent the limitations of standard testing is the use of experiments that induce heterogeneous strain states in the specimen, and which can be measured through full-field experimental techniques such as Digital Image Correlation (DIC) and later processed with a suitable full-field inverse technique such as the Finite-Element Updating Method (FEMU). Therefore, the definition of the virtual material can be divided into three pillars, which can be understood as necessary steps of the process: (i) material testing, including the mechanical tests (either homogeneous or heterogeneous ones), experimental and numerical techniques to acquire and reconstruct the kinematic fields; (ii) constitutive models, used to describe different phenomena of material behavior; and (iii) inverse methodologies, employed in the identification of the material parameters governing the constitutive models. Each pillar has already been investigated previously and the aim of the AutoMeCal project is to bring automation in the mechanical testing and in the calibration steps, to create a direct link between the chosen material as an input and the optimized parameter set for a chosen model as an output.

Aims of the PhD. The development of the automated mechanical testing itself, for a uniaxial tensile loading and quasi-homogeneous tests, and the robustness of the automated model calibration is the research hypothesis of the PhD. It is therefore related to mechanical engineering and design, material mechanical behavior, mechanical modelling, inverse methods for material parameters identification and robotization. Two main steps are planned: the first one is related to the automation of the test itself and the second one to the calibration step.

Methodology. Performing a mechanical test corresponds to several tasks, which control, and accuracy are decisive in the repeatability and the quality of the output data. Replacing a human operator by an automated one requires several mechanical adaptations of the grips, especially to take the sample, settle it in the machine and remove it. The feasibility a IRDL has already been established, using a cobot (of brand Universal Robot) and a machine designed by the French company MatAndSim[1], which software is developed within Linux environment. The MatchID[2] solution for DIC has been chosen, as it proves to be open to line commands, and it brings tools to quantify the quality of the measure as well as filters to make a reliable comparison with finite element calculations. The cobot is programmed to control the machine and a digital camera and acts as a master. The first goal of the PhD is to develop a robust robotized mechanical testing unit. It should be emphasized that, performing a mechanical test today, in the field of plasticity at large strains, with DIC measurement, is a qualified task that requests a dedicated training and a clear and accurate procedure. Indeed, the quality of a test is still highly dependent on the operator. The quality of the test is validated by plotting the evolution of some raw data. A skilled operator can obtain rapidly repeatable and reliable results and the technical issue is to transfer this knowledge into an automatic procedure, based on an artificial intelligence (AI) tool for test validation, with some basics elements to check, as the quantified gap between load-strain data for tests performed under the same conditions, the initial slope deviation from a known Young's modulus, … This tool, as well as the fully automated calibration process, represent the scientific issues to be solved. Repeatability of the mechanical behavior should also be considered, it is usually investigated by repeating the same test under the same condition at least 3, and sometimes up to 5, times. Only the sample is changed from one test to the other. Then, an automatic selection of a unique representative test, to add to the database, is performed. This selection will be based on basics criteria like the closeness of the output signals of the representative test to all the others. This validation corresponds to the implementation of the skills and knowledge of a human operator into an automated process.

The second step is dedicated to model calibration based on inverse methodology. The validation of the calibration process is a key point. Indeed, today, the human operator validates the optimized parameter based mainly on visual inspection (data plotting) and by checking local minima of the cost function of the optimisation process. A tool based on AI will be developed, built from the know-how of the team. This tool will use indicators from the optimisation process (cost function values, rate of convergence, closeness of the material parameters to the constraints, …) to validate the calibration. Finally, results obtained from a known material, already tested and for which a mechanical model is already calibrated, will be compared with results obtained in a fully automated way, starting from the blank sheet, and ending up with the parameter set.

Societal issues related to the project. Energy transition may well become materials transition, as electrification of vehicles or the use of wind turbines are demanding large amounts of raw materials, such as copper [1]. More than ever, materials are these "technological key enablers in societal challenges". A way of living, manufacturing, consummating should be related at each step to energy sobriety and therefore, in the field of transportation, vehicle lightening and scrap reduction. A way towards such a sobriety is the extensive use of virtual mechanical design of forming processes and structural parts, to increase their efficiency and decrease their weight. The robustness and reliability of such a design depends strongly on the accuracy of the material mechanical model and more specifically on the choice of appropriate constitutive equations with accurate identification of the parameters for the chosen material.

The impact of the PhD project is presented in relation to the United Nation Sustainable Development Goals or SDGs [13]. Goal 9 is related to industry, innovation, infrastructure. Defining a virtual material in

[1] https://www.matandsim.fr/
[2] https://www.matchid.eu/

an efficient and robust way is an essential milestone for virtual design and eco-production of parts made of thin metallic sheets. Creating a database of optimized parameter sets, for given materials and constitutive equations, in a controlled and automatic way from the input (the material) to the output (the parameter set) is a huge contribution to the Industry 4.0, as the quality of the input data to numerical simulation is essential to the robustness and accuracy of the numerical predictions.

Goal 12 is dedicated to responsible consumption and production. As stated previously, energy transition may become materials transition and promoting high quality virtual materials will contribute to the virtual mechanical design and decrease the prototyping of parts, and therefore the consumption of materials. Moreover, the material suppliers, though they have significantly improved the repeatability of the mechanical properties and dimensional features, still provide a rather large range of accepted properties. Moreover, the rupture properties are not characterized. This type of variations can lead to a shift between acceptable products to non-acceptable ones, when changing the material batch. An automated solution for both material testing and model calibration gives the possibility to investigate virtually, and thus rather rapidly, any impact of a variation of the mechanical properties from one batch to the other. In industry, this could represent a significant decrease of wasted materials and therefore to eco-production practices, well in line with Goal 12.

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Practical details

The PhD student will be located at IRDL (UMR CNT 6027, https://www.irdl.fr/), in Lorient.
Skills: mechatronics, mechanics of materials, numerical simulation with Abaqus, constitutive equations in anisotropic plasticity, experimental mechanics, mechanical design, fine instrumentation, automatization, programming in Python
Language skills: very good level in English (writing of papers and oral presentation) ascertained by the results of a test.
Starting date: 01/10/2024 - Duration: 36 months
To apply: send a CV and a motivation letter (with people to contact for recommendation) to Sandrine Thuillier, email address **sandrine.thuillier@univ-ubs.fr**