An aeronautics and space-oriented research group

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research

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The Clément Ader Institute's (ICA) Composite Materials and Structures research group (UMR CNRS 5312) was set up in 2010 after the Institute was created by decree in July 2009. The group conducts transversal research on materials, processes and structures, with a strong focus on numerical and experimental aspects.

Fig. 1: The Roctool process

The ICA works in a wide range of research fields, targeting applications in the aeronautics and space sectors, as well as transportation and energy.

Materials and processes

Understanding and modelling thermokinetic and thermomechanical phenomena in manufacturing processes

The group's material and process research activities focus on the characterization and modelling of:

- the polymerization kinetics of organic matrices (thermoset and thermoplastic) and inorganic matrices;
- the thermomechanical degradation kinetics of matrices, reinforcements and the fibre-matrix interface, together with their impact on the properties of materials;
- the crystallization of thermoplastic polymers (morphology and kinetics) and the influence of reinforcements and fillers on crystallization.

The purpose of this research is to gain a better understanding of the physicochemical phenomena governing the use of composites in order to optimize the polymerization/crystallization conditions of matrices during the manufacture and processing of prepregs and composites. This work focuses mainly on high-performance aeronautical matrices, such as Class 180 epoxy resins or thermostable PEEK and PPS matrices.

Study and modelling of resin flow in fibrous reinforcements

The group's work on resin flow in fibrous reinforcements focuses on modelling resin flow in liquid composite moulding processes and determining the material parameters related to the permeability and compressibility of woven reinforcements. The variability of reinforcements and its effect on their permeability are among the main topics considered from an experimental and numerical point of view.

Resin flow is studied in various configurations, such as woven, knitted or mat preforms for thermoset and thermoplastic organic/inorganic matrices. This work generally aims at predicting mould filling times and/or resin front kinetics and optimizing them according to the polymerization cycles of resins.

Multiphysics analysis and functionalization of composite materials

To propose reliable numerical models, test benches were developed/adapted to determine the anisotropic thermal conductivity of composite materials by inverse analysis. This work, carried out in collaboration with ICA's Measurement research group, is based on original approaches using non-contact measurement by infrared thermography. The other part of the work, related to thermal and electrical properties, consists in preparing and characterizing functionalized matrices in order to improve the properties of composites. As the aim is to meet the needs of the aerospace industry regarding conductivity issues, the studies focus on thermoset and thermoplastic matrices functionalized by nanometric particles. On the thermal side, a hybrid composite material consisting of a polymer matrix doped with micro- and nanoparticles and reinforced with long pitch carbon fibres was developed in order to significantly increase thermal conductivity. On the electrical side, another example is the design of a thermoplastic PEEK/carbon fibre/carbon nanotube (CNT) matrix composite without compatibilizing agents. The goal is to produce a PEEK/carbon laminate with through-the-thickness electrical properties, enhanced by the incorporation of CNT.

More generally, these efforts are part of the functionalization of materials using a nanoscale phase, particularly via an aligned carbon nanotube forest, which is intended to improve the impact response or the thermal or electrical conductivity through the thickness of composite materials. Work is currently underway to integrate nanotube mats grown either on a substrate or directly on carbon fabrics, or by liquid or pre-impregnated processes.

The research work then consists in characterizing the processing properties, the microstructure and the different interface scales, and determining the mechanical properties of the composite over a broad spectrum of stresses (static and dynamic).

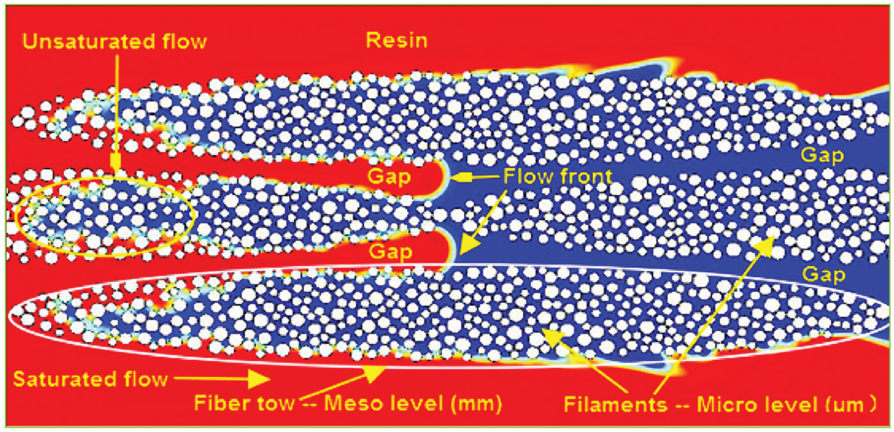

Fig. 2: Simulation of resin flow in a 3D reinforcement at different scales

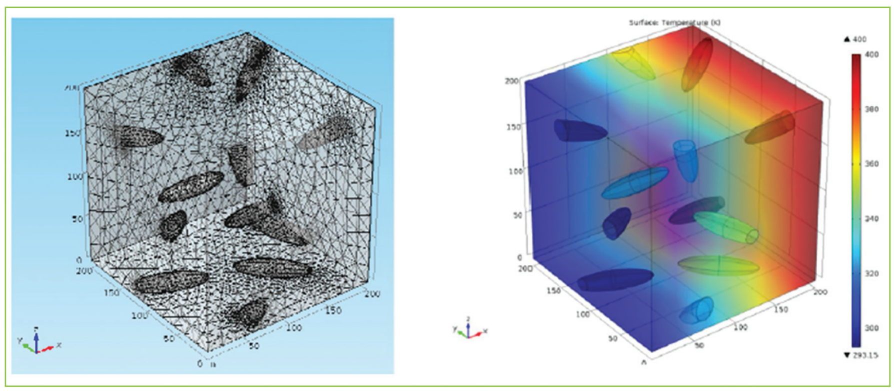

Fig. 3: Modelling thermal conductivity in a doped composite material

Modelling thermal and electrical transfers in functionalized matrices requires the use of models at the microscopic scale. This work aims to improve the understanding of size, dispersion and orientation effects in order to optimize the morphologies of composites and to enhance homogenized approaches.

In processes using radiating sources (infrared emitters), the prediction of thermal fields requires the development of advanced numerical models taking radiation heat exchange into account.

The research work thus led to the development of radiative transfer modelling using ray throw approaches. Initially developed for packaging applications, the models were progressively improved and adapted to composite applications (epoxy curing and preform heating in a stamping process).

Processes and structures

Understanding and modelling variability sources in composite structures

Various sources of variability within composite structures were analysed, in particular with regard to the measurement of spatial variations of "topological" quantities and material quantities. These include spatial variations in ply thicknesses, strand orientations or the matrix ratio, during and after the manufacturing process. A mathematical modelling of these spatial variations was proposed based on statistical studies of the different parameters that control these mathematical laws. Three examples of applications associated with these developments are particularly noteworthy:

- Prediction of residual curing strains of a laminated plate generated by "topological" variabilities;
- Prediction of the stiffness dispersion of a composite beam in 3-point bending;
- Prediction of the localization variability

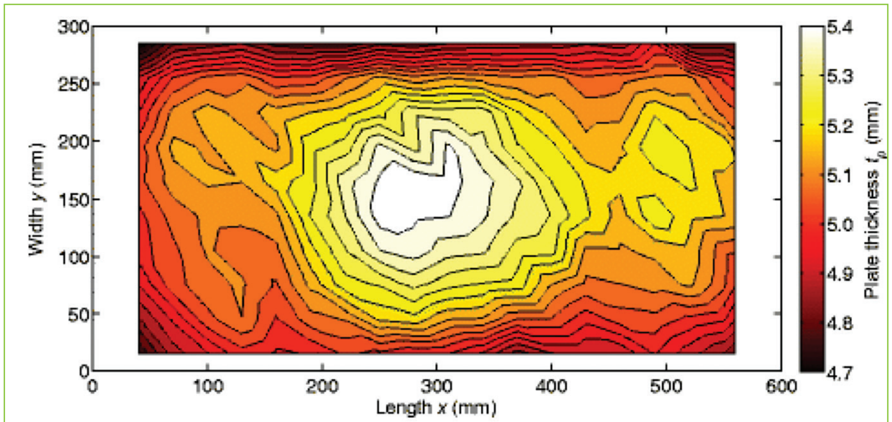

Fig. 4: Example of ply thickness spatial evolution

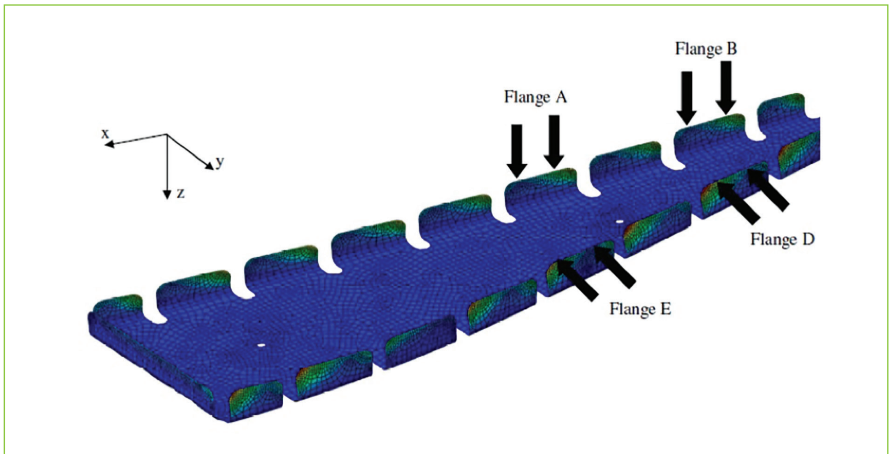

Fig. 5: A350 rib spring-back computation

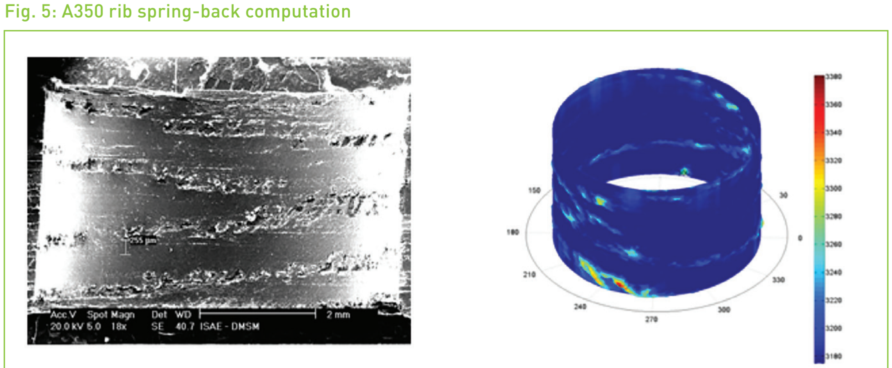

Fig. 6: Hole roughness analysis to define drilling quality indicators

of a laminated plate's failure zones under complex stresses (technological evaluators).

Analysis and modelling of shape defects generated during the manufacture of composite structures

During the manufacture of laminated composite structures, many physicochemical and thermomechanical phenomena are at work and can produce unwanted deformations of the resulting parts.

A thermochemical modelling of the polymerization process was conducted to predict, among other things, overshoots during the polymerization of a thermoset resin for a thick composite.

On another level, a semi-empirical thermomechanical spring-back model was developed and recently applied to a large part: the A350 rib in the framework of CORAC – these two studies are used to predict the spring-back of bonded stiffeners.

Analysing the links between manufacturing/machining parameters and mechanical strength

When machining composite materials, the main problem is the choice of criteria for the qualification of machined surfaces. The current industrial criteria (for example, the average roughness Ra, Rp, etc.) do not appear to be relevant for composites. In this context, it is interesting to study the influence of the microstructure (such as the presence of thermoplastic nodules between the plies) and the conditions in which the composite is manufactured and cured on machining quality.

In particular, the surface defects and the extent of delamination during machining (drilling and milling) were analysed. In addition, the influence of processes (drilling or trimming) on the defects and the mechanical resistance under static or fatigue conditions is studied. New machining quality indicators, such as the bearing surface, were proposed and their links with the mechanical resistance were established.

Composites machining

The anisotropic and highly abrasive nature of reinforcements, together with the heterogeneity of composite structures, makes machining delicate. Moreover, for economic reasons, one-shot drilling of hybrid materials (composite/aluminium, composite/titanium, etc.) is a very complex machining operation that damages the materials. As a result, the ICA studies on the machining of composite materials and multi-materials [2] mainly focus on:

- the understanding of surface creation mechanisms in relation to material removal processes (orthogonal cutting, drill, bit and orbital drilling, and high-pressure abrasive water jet cutting);
- in situ measurement of the drilling temperature by instrumentation at the core of cutting tools using Bragg grating optical fibres;
- the analysis of machined surfaces to improve the life of bolted structures;
- analytical and numerical modelling of the conditions in which delamination appears at the exit of the hole (drill and bit), taking thermomechanical phenomena into account;
- multiscale modelling of material removal mechanisms and induced defects.

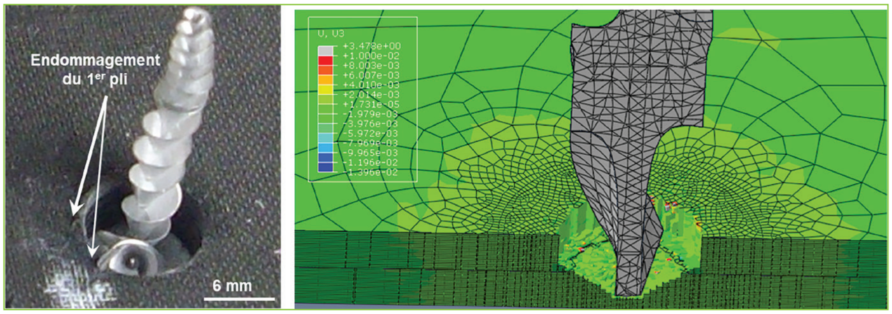

Fig. 7: Chip formation analysis (left) during CFRP/Ti multi-material drilling (simulation on the right)

Structures and modelling strategies

Short fibre injection

The ICA has been working on the development and validation of solutions for injected polymer materials, with their properties induced by the injection process. A behaviour law with damage (CDM) was proposed, which takes the microstructural parameters related to the process into account and is "implementable" in an industrial finite element code.

Its applications are dedicated to the dimensioning of composite parts injected with PEEK thermoplastic matrices reinforced with short carbon fibres, e.g., the calculation of a helicopter door hinge.

The ICA has also been working on the injection of PEEK resin reinforced with carbon fibres as part of industrial projects and/or PhD theses. Some outcomes of these projects are already in use.

As an extension of these studies, work is underway on the recycling of carbon fibres to re-use them in various forms (mats, short fibre granules) in thermoplastic matrices.

This work contributes to the creation of an industrial recycling sector in the Occitanie Region.

Modelling strategies

For the past twenty years, the research of ICA professors has specifically focused on the development of strategies to model the damage and fracture scenarios of composite structures. Three main strategies were developed [3].

The first one is the Diffuse Damage Model (DDM), which combines the continuum damage mechanics laws for mechanical damage with cohesive zones. Due to the general nature of implementable laws, the DDM can be applied to many standard materials and problems, such as impact for example. It was recently used to size CFRP or SiC-SiC junctions. It is also interesting for bearing issues.

The second strategy is the Discrete Ply Model (DPM), which is based on a mesh that follows the orientations of the unidirectional plies, on cohesive zones, on a fragile rupture in matrix cracking driven by the adjacent volume elements and on a fibre break taking strain energy release rates into account. It has the advantage of being based on only 13 mechanical parameters, which can be obtained easily. It was successfully applied first to out-of-plane problems such as low-velocity/low-energy impact, edge impact, compression after impact or pull-through. Initially developed for out-of-plane problems, the discrete character of the model proved relevant to model splitting, thus making it possible to deal with problems such as hole failure, scale effects and large cuts under complex stress.

The third strategy is based on semi-continuous modelling used for frontal or razing impact problems on helicopter blades. Bars are used to model the fibres and volumes (for solid glass/epoxy UD) or plates (for woven plies) to model the resin. Specific elements are developed (i) to find the static characteristics and (ii) to model the damage observed at the strand scale. Specific cohesive elements were recently developed, together with approaches to recover the bending stiffness of a fabric considering the actual weaving geometry. These models have reached a high level of confidence and are now validated for certification purposes.

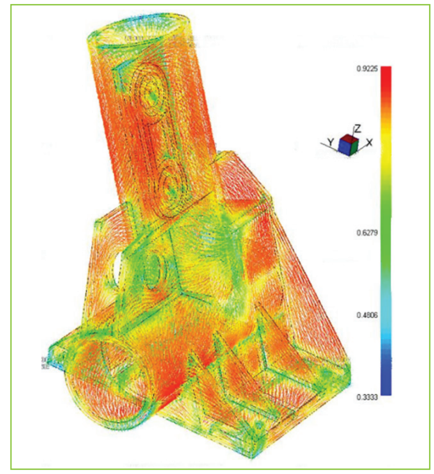

Fig. 8: Simulation of short fibre injection in a complex part (aircraft fitting)

In general, these modelling strategies and other, more specific ones were developed and used to respond to many application problems covering the whole field of composite structures:

- Impact and residual behaviour after impact, damage tolerance, large cuts, shields;
- Crash modelling, energy absorption mechanisms;
- Fatigue;
- Sandwich structures: nonlinear analysis, impact, inserts, modelling of foam or honeycomb cores;
- Junctions, Z-pinning, stitching;
- Structural details: unfolding, stiffener debonding, post-buckling;
- Repairs;
- Optimization of composite structures.

Wood-based eco-structures

An emerging topic in the group is the study of new wood-based structures. Sandwich structures using birch/poplar/okoumé plywood cores and aluminium, fibreglass, flax or carbon skins were manufactured and studied experimentally and numerically under static loading, impact and compression after impact. These structures showed very interesting specific and economic characteristics and studies will now focus on assembly and crash issues.

Experimental methods and means

Complex loading

The Institute uses a modular multiaxial

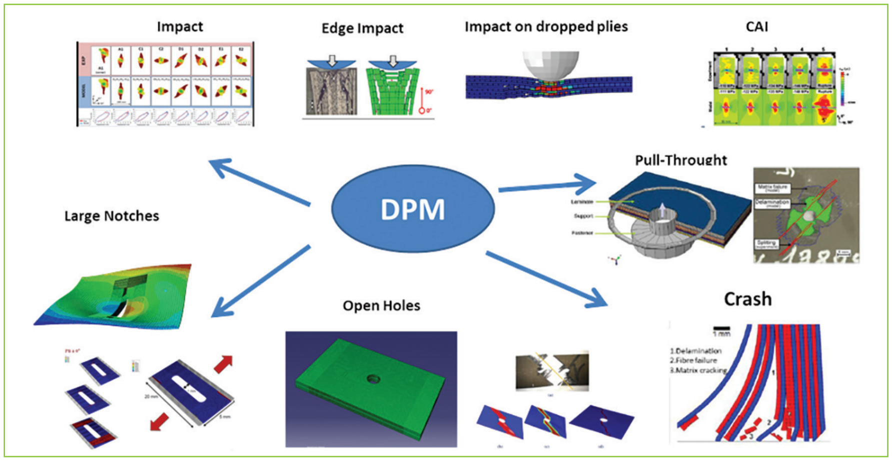

Fig. 9: DPM modelling

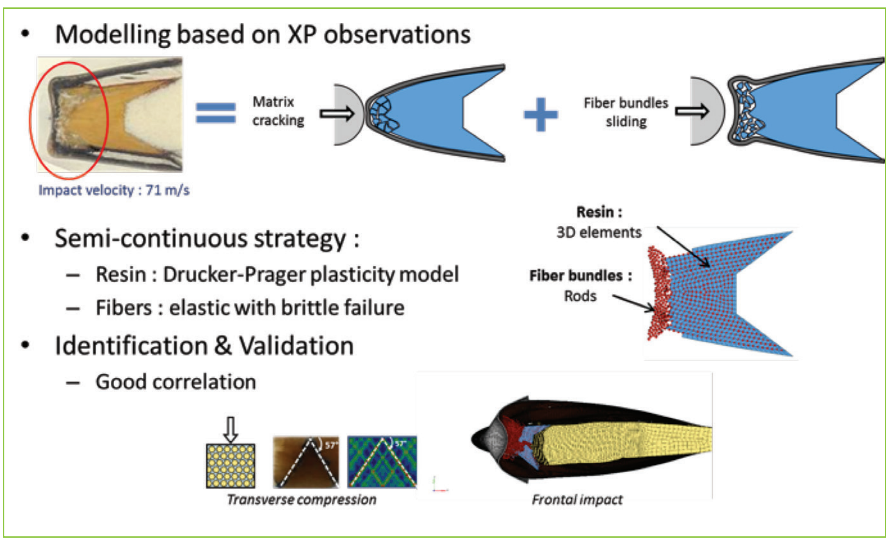

Fig. 10: Semi-continuous modelling for frontal impact of rotor blades

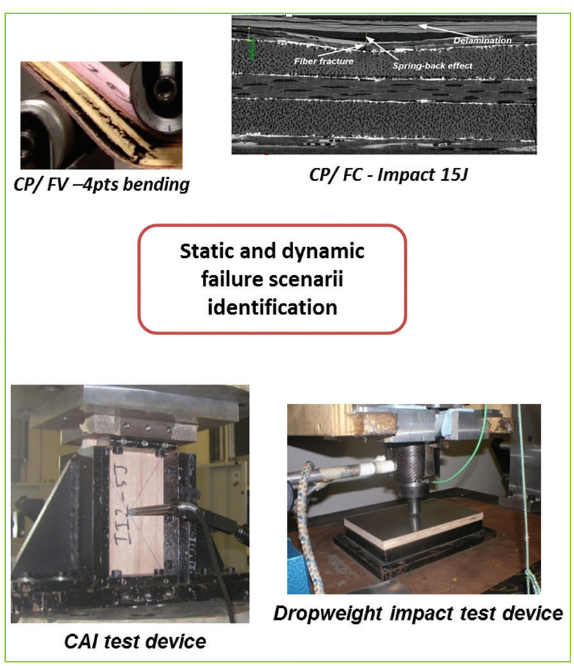

Fig. 11: Analysis of wood-based structures

beam frame supporting multi-instrumented technology evaluators. This frame is a quadripod used to apply loading (six components) to a specimen with dimensions typically of the order of 600 mm by 450 mm for a thickness up to 15 mm. This tool is used, for example, for the experimental evaluation of the complex static stress behaviour of a 16-step elliptical step-lap repair. An Astrid ANR project entitled BLAST is underway to extend the technology evaluator concept to situations of blast vulnerability of composite fuselages and to analyse the over-protective behaviour of light armoured floors, considering the manufacturing conditions.

As part of the Vertex collaborative project, funded by ANR [4] and led by the ICA, a test bench reproducing the stresses (tensile, compression, shear and internal pressure) and the boundary conditions of aeronautical composite structures was developed. The stresses can reach several thousands of N/mm for a pressure of 1.6 bar with a zone of interest of 400x400 mm^2. A specific measurement methodology was developed in collaboration with the ICA MICS group. A cluster of six cameras is used for near-field and far-field measurements, coupled with a so-called FE-DIC method. The regularization of the finite element optical measurement field allows an improved test/calculation dialogue by direct export of nodal displacements (translations and/or rotations) to the finite element models.

Measuring methods and specific tests

As part of the "Strategic Thematic Actions" (ATS) IDEX UNITI Initiatives for Excellence projects, the WAALS project for "Wide analysis of interactions between polymer links and structural loads" focuses on the in-depth investigation of an adhesive placed between two composite substrates: epoxy matrix and long carbon fibres. WAALS is led by the ICA and involves detecting the presence of altered zones within an adhesive that is free of defects detectable by CND techniques and whose interfaces are functionalized by low-pressure plasmas. A first family of markers was chosen for X-ray detection within the adhesive. A second family was used to introduce local warm-ups by magnetic induction to induce localized stress. A reference numerical model was used for a comparison with the measurements related to the particle displacements observed by X-ray associated with the altered areas in the adhesive. It was established that the perimeter of a mechanical weakening zone and its abatement factors with respect to a reference value can be detected.

Another work focuses on the continuous monitoring of composite structures at different scales throughout their life cycle. The structures and, when possible, their tools and means of production, are instrumented to determine the influence of the various process parameters and materials and the associated variabilities. Bragg optical fibre was used to study residual curing stresses in the current or singular zone of composite parts and to investigate tool-part interactions through work for several PhD theses considering different manufacturing (autoclave, filament winding, etc.) and machining (drilling) processes.

An infrared thermography analysis method was developed to measure energy restitution rates during compression of the carbon plies, among other things. This method was patented and is the subject of a dissemination action via TTT (Toulouse Tech Transfer).

Many tests were developed as part of recent research work, including an experimental delamination propagation method in Mode I and II under gigacyclic fatigue that is based on the structural resonance of the specimen and allows the use of frequencies up to 400 Hz. An original Mode III measurement method (edge ring crack torsion test, ERCT) was proposed and extended to the study of mixed modes I + II + III.

For staircase repairs of carbon/epoxy composite primary structures by structural bonding, the conditions of use of the infrared thermography technique were evaluated. This situation is not usual given the subtle nature of the thermal behaviour difference between the constituent parts of the assembly zone (parent part and carbon-epoxy patch), which constitutes the main problem when capturing the response. As part of a collaboration with ENI Tarbes' industrial engineering laboratory, an original experimental procedure was developed, allowing numerical modelling physically consistent with the thermal problem and demonstrating good agreement between the measured and calculated temperature fields. This work proposes and opens up ways to modify the intrinsic thermal properties of a joint using additives with an infrared signature that makes it possible to identify the staircase area and its geometrical defects more clearly.

Fig. 12: The Vertex test rig

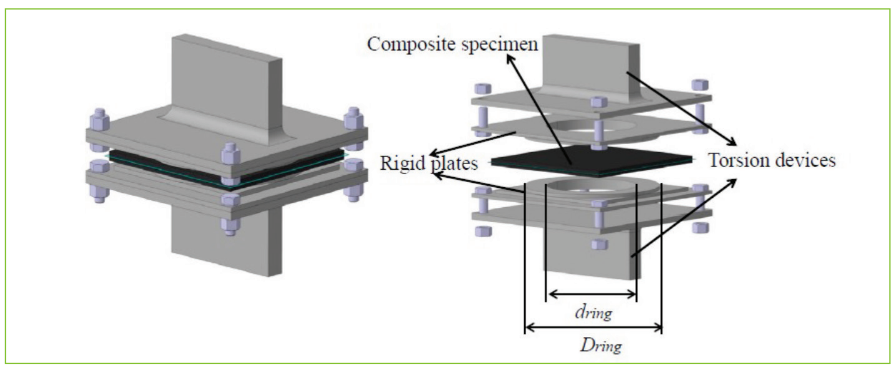

Fig. 13: Edge ring crack torsion test (ERCT)

Fig. 14: STIMPACT platform gas guns

Dynamic testing

The Clement Ader Institute, in partnership with Airbus and IRT Saint Exupéry, developed the STIMPACT dynamic testing platform on its premises. The platform is equipped with three gas guns covering a wide range of impacts up to 500 g and 800 m/s [5]. The institute also has several drop towers up to 5000 J. A new machine owned by Airbus Central R&T is currently being installed for dynamic material testing and crash tests up to 35,000 J on structural parts. ◻

More information:
www.institut-clement-ader.org

Focus

The Composite Materials and Structures (MSC) research group was set up in 2010 following the creation of the Clément Ader Institute by decree in July 2009. Its presence in the structure of the Clément Ader Institute results from the history of contributions by professors Daniel Gay and Jean-Jacques Barrau since the 1980s, and from the need and the will to highlight the specificities of research on composite structures and materials. Today, the group comprises 28 permanent members from all the funding members of the Clément Ader Institute (Paul Sabatier University, INSA Toulouse, Institut Mines Telecom Albi-Carmaux and ISAE-Supaéro) and from ICAM. The group currently has 44 doctoral students. Its field of research covers all areas and scales of composite structures, from the study of constituent materials and their development to structural issues. One of the group's specificities is the strong links developed with the aerospace industry over the years. Recent statistics show that 62% of the subjects treated are related to aeronautical issues and 50% are directly funded by the industry – from very small businesses to large industrial groups. The quality of ICA's research was recognized by the CNRS at the beginning of 2016 and ICA is now part of the UMR CNRS 5312 joint research unit. The MSC group is developing many partnerships, both nationally and internationally, and has been involved in many French and European collaborative projects. Among its 100 most recent publications [1], 23% were co-signed with French laboratories and 25% with foreign colleagues.

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