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Experimental and Numerical Simulation Strategies for the Prediction of the Macroscopic Behavior and Rupture of Structural Materials under Fast Dynamic Loadings

The presented research works have been done at ONERA – The French Aerospace Lab, in collaboration with many academic and industrial partners. They are aimed at improving the safety and protection of passengers and crew in aircraft transport, thanks to an increased resistance of structures and decrease of high energy impacts vulnerability. This paper gives an overview of recent progress made in the experimental and numerical fields to better predict the dynamic behavior and strength of primary structure materials. In this frame, the particular questions of the mechanical characterization and numerical modeling of behavior and damage laws, of crack initiation and propagation, and of failure (be it ductile or fragile) are addressed. The described results concern both bulk materials (e.g., metals) and structured materials (e.g., composite laminates), at the macroscale level for the former and mesoscale level for the latter.

Introduction

One of the main missions of ONERA – The French Aerospace Lab, is to perform applied research in the Aeronautic and Space fields, for military and civil applications. The ONERA researchers of the Materials and Structures Scientific Branch are interested in Material Sciences (to produce knowledge and models), in Process and Technologies (to mature the readiness level of innovations) and in Applied Mathematics (to develop the numerical tools that will integrate fundamental concepts into new aircraft concept design). The works in this paper, performed in the ONERA Aeroelasticity and Structural Dynamics Department, contribute to the achievement of these objectives.

The design and manufacturing of structures is one of the main skills of the airframe and engine industry: any aircraft or spacecraft is a propelled vehicle, the first requirements of which include lightness and mechanical strength. These basic properties are directly linked to their constitutive materials. Due to specific application requirements (civil transport, space, defense, etc.), a large variety of properties, and hence performance-driven aerospace materials, must be studied and developed. Among the most common material properties are the weight, mechanical stiffness and strength, thermal stability and durability (ageing and fatigue), but more exotic ones should also be considered, such as stealth and conductivity or, also recently, environmental ones, etc. Metallic and organic matrix composite materials are both massively, but not solely, used today in the aircraft, rotorcraft, power plant, missile and spacecraft industry. One of the research objectives discussed hereafter consists, on the one hand, in studying their properties and, on the other hand, in developing knowledge and numerical models that will help the European industry to design, size and optimize improved or innovative flying structures of the next decades. From this perspective, the increase in the use of composite materials (especially organic matrix based ones) and their hybridization with metals seems inevitable, despite all of the processing and modeling difficulties that this trend still presents. This challenge cannot be viably addressed without the structural design question being considered as a whole. Obviously, material weight and mechanical stiffness cannot be separated from structural dynamics issues (hence aeroelastic coupling, fatigue vibrations, acoustic nuisance, etc.). The material thermal and mechanical strength cannot be separated from structures life-expectancy, damage tolerance and vulnerability issues. Finally, the material manufacturing and assembling processes cannot be dissociated from aerospace structure design optimization, reliability and safety issues.

Consequently, the ONERA research activities in the material and process fields are closely connected to taking into account the operational environment of the final structures. In particular, this paper describes a research that is mainly aimed at improving structural safety for crew and passengers, by increasing the mechanical strength against highly dynamic and high-energy harmful situations (either intentional or accidental). Such situations may of course also suddenly and definitely reduce the aircraft exploitation expectancy below that expected by initial design durability considerations. The research topics concern the understanding and prediction of the dynamic behavior and rupture of materials relative to structure bearing loads, such as impacts, crashes, or even explosions. These topics are not specific to Aeronautics and Space, they are more broadly of interest for Defense (Land, Marine, etc.), and also remarkably for Civil Transport (crashworthiness). Nevertheless, aerospace specificities exist here, arising from the use of different kinds of materials and processes, or simply because of different threats that must be considered (e.g., bird strike, hail impact, ditching, etc.). Compared to other industry sectors, these threats also differ in their range of load parameters (impact speeds and energy levels). In any case, fast dynamic structural analysis using Finite Elements Methods (FEM) has been greatly developing over the past decades in the aerospace industry, with ONERA being involved in many developments and with all of the previously mentioned impact scenarios being studied, such as bird strike [26] and hail impact [34], as well as flying stones, tires or fragments, or crashworthiness [11] [13] [14], ditching [37] and hydrodynamics in the fuel tanks [9] [12] [15] [39].

In order to study such events using numerical simulation codes, increasingly more complex material models are required for metals and composites, in order to take their highly non-linear and rupture dynamic behaviors into account. The authors will not discuss the numerical methods (basically natural finite elements, but possibly extended-FE or particle based methods when a complex numerical description of rupture is required), the numerical formulations (mainly Lagrangian, but not solely when very large material transformations are considered), or the resolution algorithms (explicit in this case, to solve transient regimes due to wave propagation equations in continuum media, parallel, etc.) in this paper. They will also not discuss the numerical simulation of other mechanical problems involved, such as contact, friction, heat, etc.). Let us just say that the standard numerical tools used to perform fast dynamic structural analysis are not a priori energy conservative, stable or convergent and that their predictive capabilities are not necessarily and sufficiently linked to the material model accuracy or the mesh size. Concerning rupture, it is also important to understand that the point here is not to simply predict its appearance, but rather to simulate its propagation within a large structure until a transferred part of the impact energy is internally (deformation) or kinetically (fragmentation) dissipated or accommodated. In the end, a relevant material behavior and rupture model for explicit structural finite element simulations must be understood as a compromise between model accuracy (meaning complexity) and calculation efficiency (CPU cost and robustness). This is the reason why the development of enhanced dynamic material models available in fast dynamic structural tools is still often performed separately to their quasi-static counterparts. It also explains why these dynamic models mostly cope with the macroscopic or mesoscopic material responses, and why they were historically empirical ones. More phenomenological models are proposed today in the explicit code library, which can sometimes be thermodynamically based (French school), but none of them are yet physically or mechanistically based on the purely material sense.

These material models still require characterization tests to identify their mechanical parameters. Now, in these studied impacted structures, the strain and strain rate range is a broad continuum, with areas experimenting very high levels of both, where location phenomena occur, for instance at impact points or in singular parts (because of the geometry and/or assembly [22] [23] [27] [28] [38]). The experimenter then faces several difficulties to answer the numericist who wants to run his model. The first is that no unique standard and universal dynamic testing machine exists to cover the previously mentioned large strain and strain rate ranges: the experimenter needs to have several testing machines available in the lab and to be skilled in their use, mainly hydraulic machines and Hopkinson bars here for the subsonic range of impacts considered [20] [21]. Second, while performing dynamic testing can be considered to be quite easy, the difficulty lies in succeeding to obtain proper results from it that will definitely and objectively enable the intrinsic behavior parameters of the tested material to be characterized. Third, due to the destructive nature of these tests (up to rupture) and the possible model complexity (e.g., in the case of damageable anisotropic and unsymmetrical composite materials), the experiment plan can become very large, with highly expert exploitation work being needed: the characterization issue for such models can eventually become questionable with respect to the modern aircraft development cycle, including cost and time ("too many tests kill testing").

This paper introduces some basic concepts to properly deal with these difficulties and points out some noticeable recent developments concerning experimental and numerical strategies, which will contribute to the improvement of the material and structure dynamic resistance prediction capabilities in the aerospace domain. It focuses more specifically on the characterization and modeling of macroscopic (e.g., for bulk metals) and mesoscopic (e.g., for OMC composite laminates) dynamic material behaviors, including some aspects related to crack initiation, propagation, and rupture.

The first part of the paper presents specificities and inherent difficulties in the use of dynamic jacks and small size test specimens to characterize the dynamic behavior of materials, compared to the use of quasi-static machines and normalized specimen geometry at lower strain rates. The second part of the paper discusses the measurement, the signal processing and the exploitation of the data that will be used to identify material model parameters under dynamic loadings, for non-linear behaviors (stress/strain curves). In particular, solutions that can be used to solve various issues, such as vibratory noise and inhomogeneity of experimental responses in space (in the specimen) and in time (during the test) are described. While the two previous parts of the paper address metallic and composite materials as well, the third focuses only on organic matrix composite materials, which are very fashionable at the moment in the aeronautical sector and hence at ONERA. These composite materials, which are by nature heterogeneous and anisotropic, associating polymeric matrices and various fiber reinforcements, exhibit very complex behaviors, which are non-linear, damageable, viscous and highly dependent on temperature and that turn out to be a modeling challenge compared to metallic materials under dynamic loadings. Last, general conclusions and some research outlooks conclude the paper.

Presentation of the medium speed dynamic testing machines and associated experimental protocols

The topic of interest here concerns the characterization and identification of non-linear material models in the [1.10^{-3} s^{-1}, 1.10^{+4} s^{-1}] medium range of strain rates. Let us recall that the main objective of the proposed experiments is theoretically to perform uniaxial

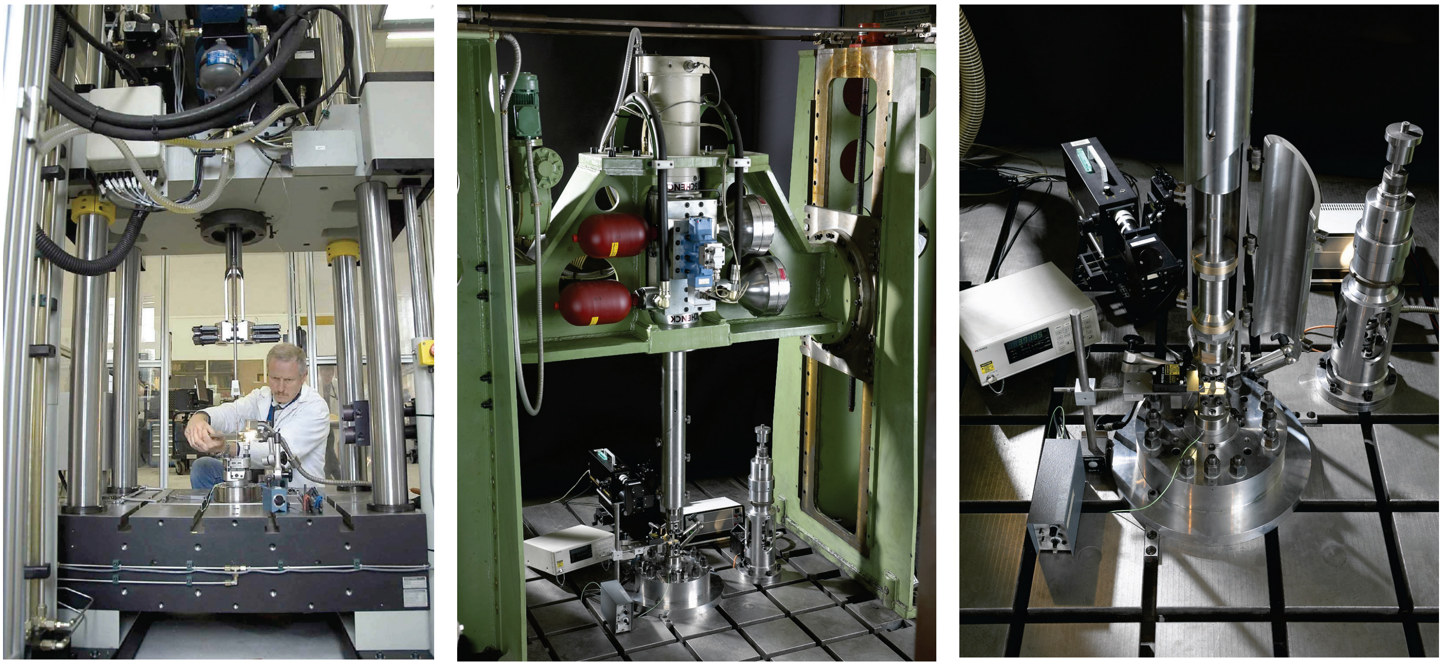

Figure 1 - INSTRON Hydraulic Jack (on the shelf, left), SCHENCK hydraulic machine (specific design, middle) and ONERA Titanium test rig developed for the SCHENCK facility (right)

load tests, monotonous from rest to rupture, tension and/or compression, at constant strain rate. One could think that such uniaxial mechanical tests at non "extreme" speeds would be perfectly mastered today, which is only true for the lowest "quasi-static" speeds in the range (a few mm/mn, up to 10^{-1} s^{-1}) with normalized test protocols being available even, and only true for long-used and known materials. This is not the case for higher test speeds (over 1 m/s and 1 s^{-1}) and for many of the modern aircraft materials. As the reader will see, apart from the mechanical limitations of the available testing machines, other causes explain the persisting difficulties to obtain test results that would allow the dynamic characterization of intrinsic material behavior and rupture model parameters: among these, the possible influence of the sample geometry on the "material" response, the difficult introduction of perfectly controlled dynamic loads into these samples, a more "miserable" instrumentation in terms of dynamic measurements compared to static ones, and a need for very rigorous data acquisition, treatment and exploitation. Some of these points will be discussed hereafter, together with some solutions currently being studied at ONERA and other research labs.

Nothing will be said about electro-mechanical testing machines, which are generally used to perform quasi-static normalized material characterization tests. The important point to be aware of is that they can be used to properly study – with some care being taken – strain rates from 10^{-4} up to 10^{-1} s^{-1}. They enable the lower range of strain rates reachable using hydraulic jacks to be overlapped. These hydraulic jacks comprise a large hydraulic framework, in which the operating jack, the test rigs (needed for load introduction and load measurement) and the material sample can be found. The size of the framework limits the testing capabilities, in terms of jack displacement range, test rig dimensions and hence of the size of material samples. The hydraulic system may directly accelerate the jack or part of the framework to which the jack is connected. Note that the weight (inertia) and stiffness of the various fixed and mobile parts have a decisive influence on the final performances of the test facility. The ONERA hydraulic jacks (INSTRON and SCHENCK respectively) have the following general capabilities: 250 and 300 mm displacement range, 10 m/s and 20 m/s maximum operating speeds, and maximum applied loads of 50 kN and 80 kN. Nevertheless, the maximum capabilities are rarely reached during tests. According to the test speed, the jack velocity V_{jack} is controlled in a closed or open loop manner. The hydraulic power being limited, such a speed instruction may be difficult to maintain when the load or speed limits of the testing machine are challenged ($P \# FV$, where P is the hydraulic power available, F is the applied load and V is the imposed velocity).

In order to perform dynamic tension tests (compression tests can be done, but they raise supplementary difficulties, e.g. samples buckling, etc.), a groove/wings concept has been proposed, each part of it being fixed respectively to the moving jack and the clamped sample, in order that the groove can be set in motion and reach the targeted velocity before it impacts the wings end to load the sample. It is then necessary to design and set up such a specific mechanical system, with its weight, stiffness, gaps and vibration modes (figure 1). An optimization work is required to prevent this new mechanical system from degrading the original dynamic characterization capabilities of the testing machine [20]. The different parts of the test rigs used at ONERA are often designed and validated using finite element analysis and made of Titanium in order to minimize their weight and maximize their stiffness, obtaining Eigenfrequencies that are high enough to be eliminated (filtered) more easily without losing information about the material sample response itself.

From the displacement speed theoretically imposed to the sample, it is possible to calculate the engineering strain rate using (1):

$$\dot{\varepsilon} = \frac{V_{sample}}{l_{free}} \qquad (1)$$

where V_{sample} is the test speed imposed to the sample and l_{free} is the deformable length of the sample (between the grips, if the grip is perfect). As a first approximation, if the imposed test speed is assumed to remain constant and the sample elongation (and deformation) is assumed to be small during the dynamic test before rupture, it is easy

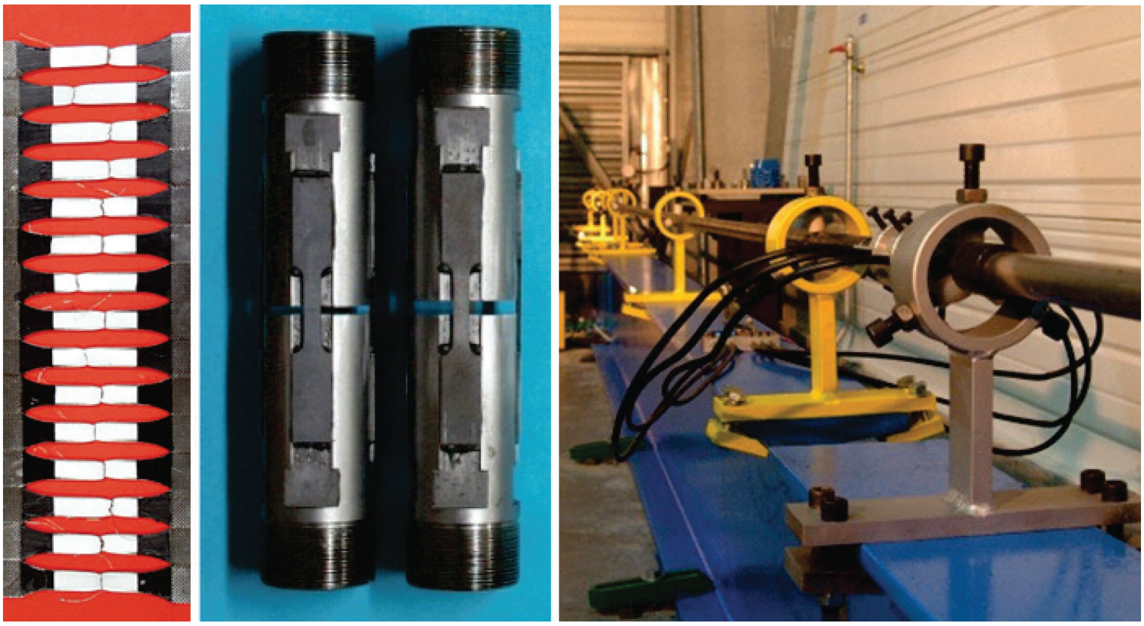

Figure 2 - Deformation of metallic specimens (middle) up until rupture using the optical extensometer technique (left) and tensile Hopkinson bars (right)

to plan experiments that enable the strain rate sensitivity of the material response to be characterized for various constant strain rates, just by playing with the sample free lengths and imposed velocities. The necessary hypothesis for this is to assume that the strain and strain rate fields are homogeneous over the free length of the specimen.

By the way, though the various parts of the hydraulic machines are made very massive and stiff, some of them, such as the beams and jack (figure 1) can become deformed, or the hydraulic control may struggle to maintain the imposed speed when very high loads are developed. The contact between the groove and the wings (that is to say, between the jack and the sample) can also be temporarily lost when the highest test speeds are challenged (inertia effects, bounces, vibrations). Thus, it can turn to be very difficult to really loop on the instantaneous velocity of the jack that would give a constant strain rate test at the material specimen level. This is why it is generally necessary (usually above 1 m/s) to measure the specimen deformation by a direct and ad-hoc experimental technique, in order to detect and deal with any deviation from the expected rate. As will be seen later, specific measurement techniques are used today quite as a standard to obtain accurate dynamic strain data for the free length of tested specimens: gauge extensometry, optical extensometry and, more recently, digital image correlation techniques.

Given an imposed test speed, it is evident that the strain rate that will develop in a material test depends on the sample free length. Many works are underway that concern the definition of the relevant specimen geometry for dynamic material testing (figures 2 and 3). These specimens are usually symmetrical, with smaller free lengths and working sections than standard material specimens, and depend on the tested materials, of course.

With a specific geometry, the ONERA hydraulic testing machines enable elastic strain rates of about 10^{+2} s^{-1} to be reached, for non-normalized 10 to 20 mm free-length specimens. In order to obtain these accurately, both the gauge and optical extensometry techniques are used; in addition, the gauge extensometry is always used to obtain the Poisson coefficient, if required. In the case of perfect (homogeneous) localization of a nonlinear material response across the specimen section over a smaller length area than the specimen overall free length, the use of more costly specific strain gauges (e.g., 0.6 mm grids, 20% strain capability and high cut-off frequency) enables higher measured strain rate levels to be obtained compared to the elastic regime (for instance, when plasticity develops in metallic specimens).

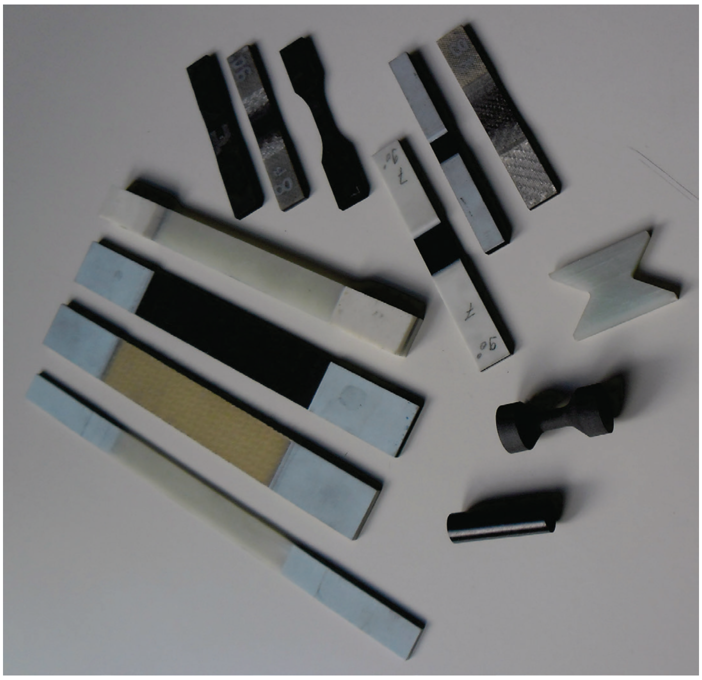

Figure 3 - Examples of specimen geometry for composite tension, compression and shear tests with hydraulic jacks

Strain rates of up to 500 s^{-1} have been obtained with such test protocols and the ONERA hydraulic testing machines. An important point to mention here concerns the care that must be taken when using such small specimen geometry: geometry effects and/or scale effects can take place that can dodge the results and prevent the intrinsic material

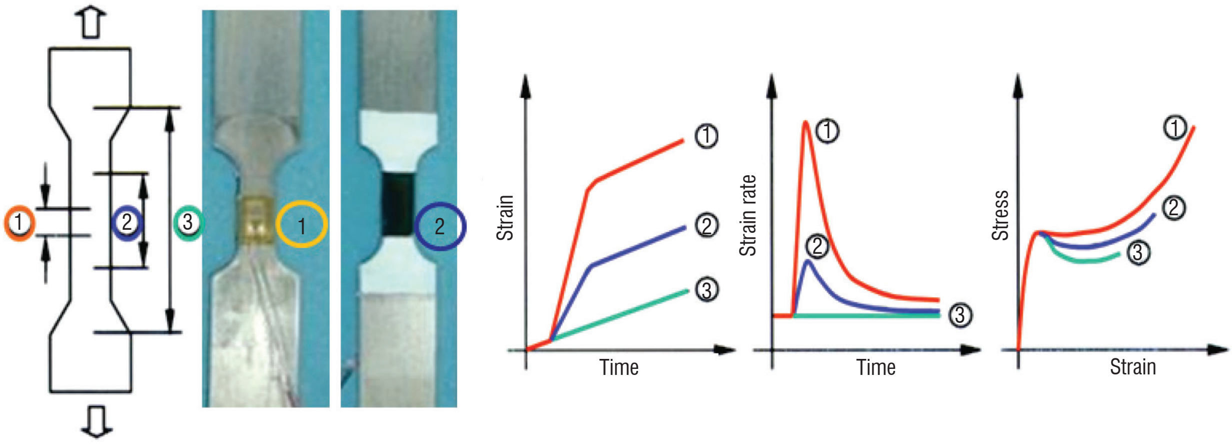

Figure 4 - Illustration of various strain acquisition methods on tensile specimens by (1) strain gauge, (2) optical extensometer, (3) hydraulic jack/grip displacement and influence on results with regard to strain/time, strain rate/time and stress/strain curves

behavior from being obtained. It is thus highly recommended to check that the dynamic specimen geometry gives, at low strain rates, the same results as those obtained with the quasi-static normalized geometry. A satisfying dynamic geometry can reasonably be obtained that way, when the elastic material data are compared. It is far more difficult when highly non-linear material behaviors are studied [4].

In order to study material behaviors for strain rates over the previously mentioned limits, Hopkinson bars systems [10] have historically been used, which can provide access to a range of strain rates from 10^{+3} s^{-1} to 10^{+4} s^{-1}. Given the plentiful papers dealing with Split Hopkinson Bars – as opposed to hydraulic jacks – in the literature, nothing will be said in this paper concerning this kind of dynamic testing machine, but rather about the fact that small specific specimen geometries are also required (thus with possible geometry and scale effects), which means that it is also highly recommended to check that the test results obtained at lower Hopkinson bars strain rates are consistent with those obtained at higher hydraulic jacks strain rates, or to adapt the test protocols to obtain these [20] [40]. Note also that, inversely to hydraulic jacks, compression tests with Hopkinson bars are easier to perform than tension tests (due to gripping difficulties): for sample geometries or materials with clear unsymmetrical tension/compression responses, additional care must be taken before extrapolating test results from both hydraulic jacks and Hopkinson bars.

Mechanical measurements and exploitation methods for the dynamic characterization of materials

The establishment of the existing relation between stress and strain in a given material during a dynamic test is desired. Several questions must systematically be considered, which consist in the measurement validity (nature, acquisition and exploitation), their objectivity (no influence of the instrumentation and protocol on the measured data) and accuracy (known measurement uncertainties). Stress is commonly calculated as the ratio between the applied load force and the working section of the material specimen. In order to obtain the dynamic load measured, piezoelectric load cells are generally used (a single one is enough when mechanical equilibrium is assumed for the specimen at each time during the test, otherwise, two should be used to measure forces at both ends of the sample and then subtract them to obtain the resultant one). Such a load cell (a uniaxial Kistler 9031A for instance at ONERA, with 80 kHz Eigenfrequency, 60 KN load measurement capacity and 6.10^{+9} N/m stiffness) should be pre-stressed under compression to be used for tensile tests. This means that the mechanical test rig dynamics become complicated, with heavy and stiff parts being added again. Note that the force measurement in this case is diverted away from the material specimen itself (clamping grips are set between the specimen and the load cells): the force and the strain signals must be shifted synchronously if the Young modulus value is sought, which can be a tricky point in dynamic testing if poor care is taken in this respect. The load cell must be regularly calibrated and possible drifts must be taken into consideration (e.g., thermal drifts). Other load measurement techniques have been proposed, for instance using staged specimen geometry with a strain gauge being placed in an elastic response area of the sample. Such a technique is of interest when the linear behavior of the tested material is known and the nonlinear behavior is studied. Then, the main load cell drawback (measurement of all the dynamics of the test rig and mean) is eliminated, with a supplementary cost however (extra specimen manufacturing and strain gauge instrumentation costs).

The most commonly proposed dynamic mechanical tests remain classical, in the sense that they are supposed to be statically determined: together with the assumption that the mechanical equilibrium of the specimen is fulfilled during tests, uniaxial stress and plane strain hypotheses are made, hence homogeneous deformation can be measured at one point along a specimen section, by strain gage for instance. In order to face some limitations concerning the strain range that can be measured with strain gauges (even the “large deformation” ones are limited to an elongation of about 20%, or the glue fails prior to the gauge), the preferred technique used today in many test labs consists in using fast optical extensometers (e.g., a 500kHz cut-off frequency Rudolph type one, with a 0.01 μm resolution for a 10 mm displacement, at ONERA). Such an apparatus enables the evolving distance between test cards (e.g. black & white patterns set on the sample) at very high speeds to be measured. An average strain can then be measured between the test cards, up until the specimen rupture (figure 4).

Finally, the objective would be to obtain stress/strain material responses by decades of strain rates, under tension and compression loadings. Figure 5 shows that it is not always possible to obtain such a detailed characterization, some strain rates being not accessible

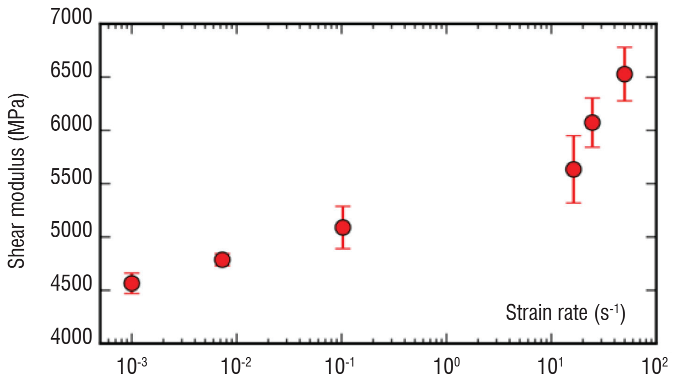

Figure 5 - Dynamic characterization test results: influence of the strain rate on the T700GC/M21 shear modulus obtained with +/-45° tensile Rosen tests

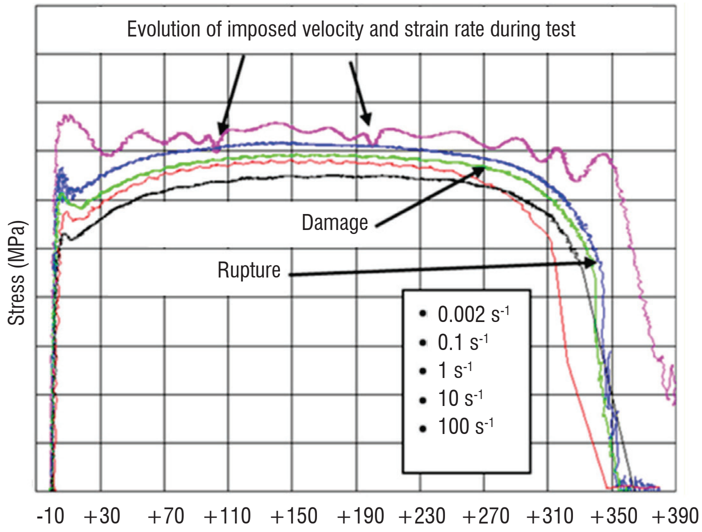

Figure 6 - Dynamic characterization test results: damageable visco-plastic behavior of steel according to strain rate

(here 1. s^{-1}) because of the various phenomena mentioned before (pumping mode, loss of contact, etc.), occurring according to the tested material (T700GC/M21 here), which cannot be predicted before the tests are done. It is nevertheless possible to see in the same figure that such a decade characterization reveals a transition effect that would have been completely ignored if only test results at the lowest and highest strain rates were sought (by means of a quasi-static normalized test or Split Hopkinson bars tests, for instance).

Figure 6 also shows that the strain rate obtained with hydraulic jacks (here performed on metallic XES steel) can vary a lot during tests at the limit capacity of the testing machine. Recent works have thus attempted to derive benefit from this undesired fact: given that the changing strain rate is calculated throughout the test, the test result is plotted in a 3D space (stress, strain and strain rate). Using a specifically designed experiment plan, a surface response can be established in this 3D space, a set of test curves being fitted by an appropriate (polynomial) mathematical function. Thus, a simple projection of this mathematical 3D surface onto constant strain rate planes gives the corrected stress/strain curves at true constant strain rates, which can then be used to characterize the strain rate dependency parameters of the material model. Once the exploitation toolbox has been implemented, the need to perform constant strain rate tests ceases [29] [32].

Another measurement technique makes it possible to use and exploit dynamic tests that do not fulfill the previously mentioned academic hypotheses (here uniaxial stress and plane strain), which are otherwise necessary to characterize material behaviors. It relies on the measurement of strain fields over the sample surface, instead of punctual strains at gauge locations. This technique has been made far easier with the development of the (stereo) digital image correlation technique; digital images can be recorded now at high frame rates, with high resolution, using new generation high-speed digital cameras (e.g., Photron, 12500 f/s, up to 1024x1024 pixels, at ONERA). This technique still requires highly skilled experimenters today, with long preparation (pattern deposition, calibration) and long exploitation times. However, statically determined tests are no longer required, which means that non-standard specimens of various geometries can be used, with inhomogeneous and multi-axial stress, strain, strain rate fields spreading through the sample during the tests (figure 7), up to rupture [1] [19] [36]. It also enables the true boundary conditions to be checked, as well as the way in which the load is progressively introduced into the samples.

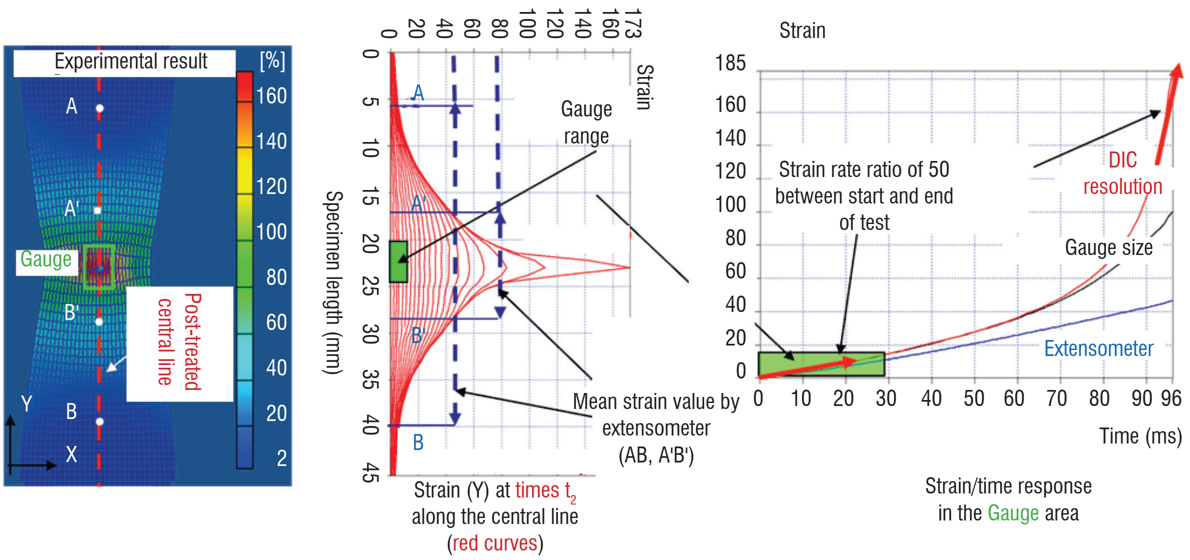

Figure 7 - Example of strain and strain rate fields obtained during an average 10.s^{-1} tensile test on a metallic specimen, using the digital image correlation technique (GOM system)

The test instrumentation with strain field measurement obtained using the digital image correlation (DIC) technique, together with non-statically determined tests, considerably increases the current capabilities of dynamic material characterization with hydraulic jacks and even Split Hopkinson Bars. Such tests deliver a huge amount of qualitative information and quantitative data and make it possible to cover a large local strain rate range with a single test, as well as to reach higher strain rates than with traditional protocols. Due to the tremendous progress in digital high speed camera technology, new exploitation methods (there is a family of them) are proposed today to identify complex non-linear dynamic behavioral, damage and rupture material models, as possible alternatives compared to traditional direct methods [25], or inverse ones by Finite Element Model Updating for instance (which will not be discussed in this paper, because they are not specific to the dynamic problem). One of these methods, currently studied at ONERA, is the Virtual Field Method, to which the authors would like to simply refer to [33].

Models for the dynamic behavior and rupture of organic matrix composites

The paper only discusses meso-macro models, which cannot yield insight into experiments at the material level, but rather only at the structural level. They would thus provide a better understanding of the global dynamic behavior of large components, when various areas of the structure undergo a large variety of strain and strain rate ranges, which may modify the ruin phenomenology and chronology when strain rates are taken into account. On the other hand, these meso-macro models cannot be fully representative of the physical mechanisms that develop at the material micro-structural level: an experimentally based calibration, or at least a verification step, should then always be done to clearly establish their confidence domain with regard to predictive capabilities.

Concerning organic matrix composites (whatever the fibers), these prove to be particularly complex (much more than metallic bulk materials) to study in their non-linear behavioral domain, because of well-known scale effects [30] and because of anisotropic and unsymmetrical mechanical properties that the specimen geometry can accentuate [6] [14]. As far as material characterization is concerned, scale effects are often claimed to appear when less than 4 composite plies of UD tape or fabric materials are used in the laminated test specimens (for thin ply composites of the aerospace kind). However, the use of a more than four-ply Representative Elementary Volume of materials for laminated test specimens often leads to difficulties with respect to the load and stiffness capabilities of the traditional hydraulic testing machines, especially when Carbon Fiber Reinforced Plastics are studied in their fiber direction. Specific preparation is sometimes necessary (dogbone specimens, use of tabs) to avoid non-linear mechanisms and the development of failures in the load introduction area (between grips) [11] [17] rendering test results useless for material characterization purposes. Due to these various reasons, the homogeneity of strains in the composite specimen section (be it profiled or not) should again be carefully assessed. Another difficulty arises, due to the development of new generations of composites by the industry, e.g., 3D interlocks, the dynamic characterization of which is a veritable headache for experimenters, with the same but greatly amplified difficulties. Last, let us say that while great care is needed in the manufacturing of the specimens (curing, machining, etc.) and the setup of the test specimens (tightening, alignment, etc.) to achieve acceptably repeatable test results in terms of stress/strain dynamic behavior of organic matrix composite materials, their dynamic rupture is very dispersive and far more so than for metallic materials, which is something that is currently not being properly dealt with in regard to the modeling question.

A large variety of dynamic behavior laws, linear or non-linear, already exists to deal with the various materials of interest for aerospace applications: visco-elastic, visco-plastic, visco-elasto-plastic-damageable, etc. However, one can see in the literature that the behavior and dependency on the load speed of a given material can lead to different models, according to the strain and strain rate ranges considered, for instance when small strains and very low speeds (creep), or large strain and high speeds (impacts) are studied. This for a very simple reason: a full spectrum model, developed at the smallest material scale, would cause the number of its parameters to increase so much that not only would the difficulties mentioned in the previous chapter (in terms of characterization) become inextricable, but also the resolution of such complex equations within an explicit simulation of a large structure would be unacceptable for any user. Nevertheless, the growing computing capabilities make it possible to progressively increase the complexity of dynamic material models, taking of course into account the research work done in the quasi-static, more experimentally friendly, domain. As mentioned in the introduction, this paper only deals with possibly physically justified behavioral material models, at best phenomenological ones, written at the macroscale or mesoscale material levels.

Concerning organic matrix composite materials, recent works have extended an existing spectral visco-elastic formulation [31] developed for creep analysis, to high load speed solicitations. In a first step, a bi-spectral model was proposed for a T700GC/M21 composite tape material, to represent the different influence of the load speed on the shear modulus observed during creep and high speed material tests [3], this difference is explained by the existence of two families of elastic viscous mechanisms in the organic matrix constituent, having two very different sets of characteristic times. These two families were easily revealed and justified thanks to the physical β-transition of the M21 resin. In the second step, the use of the well-known time-temperature equivalence in polymers enabled an extension of the bi-spectral model to a large range of room temperature to be proposed (see Figure 8). These proposals were confirmed by experiments [5] and the new visco-thermo-elastic model parameters were identified on a [-100°C, +20°C] temperature range and a [10^{-5} s^{-1}, 10^{+2} s^{-1}] strain rate range [7]. Eventually, Berthe's model, with only 3 more parameters than the original creep model, enables the dynamic elastic response, at ambient temperature, of T700GC/M21 composite material from 10^{-5} s^{-1} up to 10^{+4} s^{-1} to be described. Note that the research also benefitted from interesting technological progress over several years in field measurements and fast infrared thermography digital cameras [8] [16]. The current research in the community is mainly focused now on the study and modeling of visco-damage in composite materials, at the mesoscale (ply) level, meaning here the effects of load speed on the damage evolution law (mainly in the matrix phase, in the DDR team).

Parallel to these works on the behavior of organic matrix composite materials, the modeling of delamination in composite laminates, especially epoxy resin and carbon fiber based ones, constitutes a singular field of research in the aerospace domain.

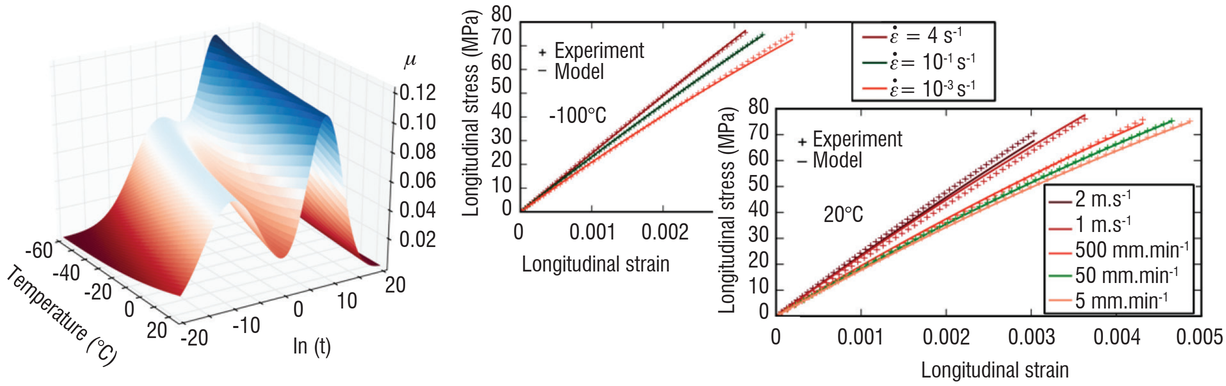

Figure 8 - Representation of Berthe's bi-spectral visco-elastic model with temperature dependency (left) and comparison of its shear response with dynamic tests at various temperatures for T700GC/M21 tape material (right)

These very tough but brittle materials – such as T700GC/M21 – are known to be fragile under impact, with delamination being a very favored degradation mode of the structure integrity in case of out-of-plane dynamic solicitation. Here again, the epoxy resin is directly involved in the degradation process, amorphous polymers being known to become brittle after curing.

The main trend to predict delamination by FEM simulations consists today in using Cohesive Zone Models [2], which rely on a local approach to model rupture in solids. Phenomenologically speaking, for epoxy resin composites, CZM enables the crazing mechanism in polymers to be described, during which molecular chains organize into fibrils to resist, by exerting a cohesive stress σ_{coh} against the interlaminar crack opening. The fibrils stretch until they reach a critical elongation δ_c and then break after having dissipated an amount of internal energy that can be related to the material toughness and its energy release rate, which are both fundamental quantities in the linear rupture mechanics theory (figure 9).

The dynamic rupture of epoxy resins under impact is combined with a local heating around the crack tip, which propagates very rapidly, and several works [24] [38] have shown that the energy release rate of vitreous polymers depends on the crack speed $\dot{a}$. As many studies have revealed, the material viscosity in the crazing zone is responsible for this important local heat at the crack tip and the thermal phenomenon can be assumed to be adiabatic when the crack propagates very fast. When the T_f temperature in the active zone becomes close to the glassy transition temperature T_g, noticeable changes appear in the crazing mechanism that modifies the dynamic toughness of the material. It has been previously observed that other transition mechanisms – which can also be associated with characteristic temperatures and relaxation times – already exist below the T_g temperature and can influence the dynamic behavior of the T700GC/M21 composite material. Thus, in order to characterize the influence of the crack speed on the energy release rate of a delamination crack, Joudon proposed to develop a 3-point bending test protocol. Hence the setup, initiation and propagation of a Mode I crack in a thick epoxy HexPly M21resin specimen would be studied. Indeed, in the case when a straight, stable and constant speed crack propagation is obtained, it is possible to characterize the material toughness, energy release rate and dependency on the crack speed (figure 10).

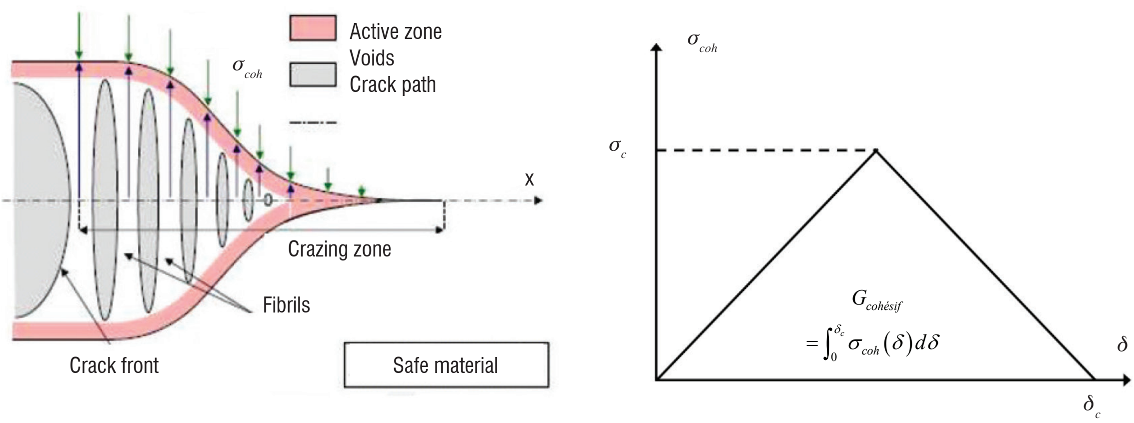

Figure 9 - Illustration of crazing phenomenon in amorphous polymers (left) and standard bilinear cohesive zone model (right)

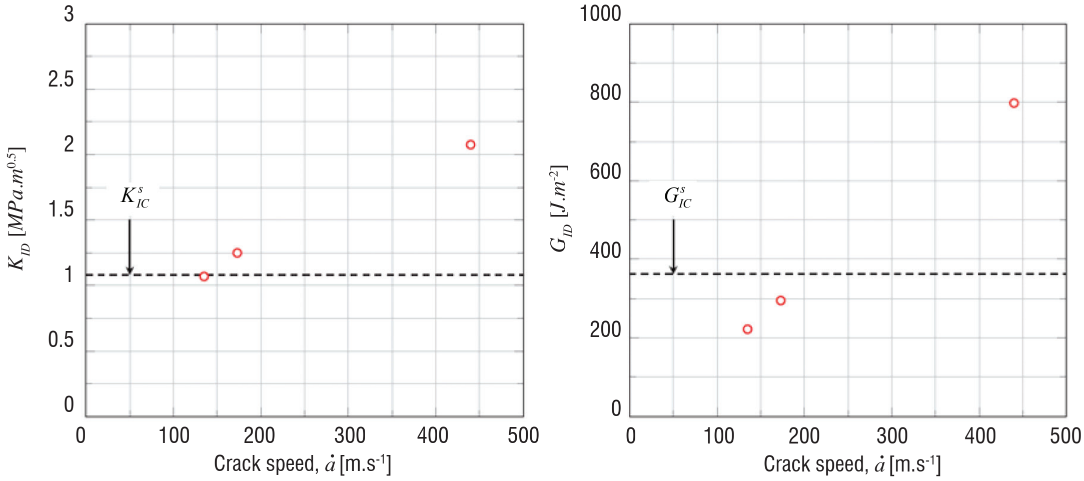

Figure 10 - Influence of crack velocity on the Mode I stress intensity factor K_{ID} and energy release rate G_{ID} for the epoxy M21 resin

It is thus possible to propose CZM formulations that depend on the crack speed, for example using a phenomenological expression (2) of the dynamic energy release rate G_{ID} close to that proposed by Zhou in [41]:

$$G_{ID}(\dot{a}) = G_{IC}^d + G_0.\ln\left(\frac{c_R}{c_R - \dot{a}}\right) \quad (2)$$

where G_{IC}^d is a (dynamic dependent) parameter for crack initiation, G_0 is a constant parameter for crack propagation and c_R is the Rayleigh waves celerity.

Concerning M21 resin, Joudon managed to identify (in his PhD work) – using dynamic tests performed at 1 m/s on notched and pre-cracked specimens - the following values for the proposed model: G_{IC}^d = 48.5 J/m², G_0 = 1080.25 J/m², with c_R = 873 m/s. The questions of the dependency of the crack set up (σ_{coh}) and of the initiation of the propagation (G_{IC}^d) on the load speed are currently being studied in the DDR lab, together with the question of the influence of temperature on cohesive zone models.

Conclusions

In the case of dynamic testing, several testing means are used to characterize material models, which cover a broad range of strain rates. This means that it is necessary to make sure that the delivered test results are consistent throughout the tested domain. This can be done by designing tests in such a way that the partial strain rate range overlaps are reached between the various testing machines (quasi-static electro-mechanical testing machine, hydraulic jacks and Hopkinson bars). When new materials are developed, it is often necessary to adapt the capabilities of existing testing machines and protocols, and the consistency of results must again be checked. Indeed, the experimental characterization of the dynamic behavior of materials is a tricky exercise, with many difficulties along the path. No normalized dynamic test protocol exists yet today that would make it a routine, while the aerospace industry need for nonlinear dynamic material models has been increasing for many years. The associated characterization costs also increase directly with the number of tests in the experiment plan and indirectly with the associated preparation and exploitation times needed by highly skilled experimenters to perform these tests. This can be a really dissuasive factor for the industry to invest in research in this field. Given this fact, many research works are presently aimed at developing methods and techniques that would make such dynamic characterization tests easier and cheaper, and would enable at least best practices, if not standardization of such dynamic material tests, to be achieved. The development of new digital image technologies (visible, thermo or tomography), together with digital image correlation techniques, probably constitutes a real opportunity to achieve such a difficult objective.

Concerning the modeling of material behaviors and rupture to predict the structure response to high energy dynamic solicitations, the main research topics remain very pragmatically focused on the development of phenomenological material models at the mesoscale or macroscale levels: an exaggeration of the model complexity not only cannot be justified with respect to the level of complexity and accuracy of the other mechanical models involved in high energy impact simulations (contacts, friction, heating, etc.), but also would be unusable in terms of implied CPU costs for complex structural analysis in the industry context. Nevertheless, more traditional problems, such as creep or fatigue analysis, developing at lower load speeds and for lower strain ranges, are dynamic in essence and the influence of the loading rate on the material behaviors for this range of dynamic solicitations has been studied for a long time, at the smallest material scale. If the corresponding models cannot be directly and simply transferred to explicit fast dynamic simulation codes as they are, they still constitute a very interesting and relevant basis, in terms of understanding and justification, for the progressive development of less empirical, more phenomenological, and hence more predictive, material behavior models for fast dynamics. This is clearly the path that the ONERA research teams have been exploring for many years now ■

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Acronyms

ASDS (Aeroelasticity and Structural Dynamics Department)
CFRP (Carbon Fiber Reinforced Plastic)
CZM (Cohesive Zone Models)
DDR (Design and Dynamic Resistance)
DIC (Digital Image Correlation)
FEM (Finite Element Method)
OMC (Organic Matrix Composite)
ONERA (Office National d'Etudes et de Recherches Aérospatiales)
REV (Representative Elementary Volume)

Nomenclature

$a, \dot{a}$	crack length, crack velocity
c_R	celerity of Rayleigh waves
δ	crack opening (Mode I)
δ_c	critical crack opening
ε	strain
$\dot{\varepsilon}, \dfrac{d\varepsilon}{dt}$	strain rate
F	force
G	energy release rate
G_{ID}	critical energy release rate
G_{ID}^{s}	critical static energy release rate
G_{IC}^{d}, G_0	parameters of the dynamic energy release rate model
K_{ID}	dynamic stress intensity factor
K_{IC}^{s}	critical static stress intensity factor
l_{free}	free length of the material sample
P	power
σ	stress
σ_c	critical stress
σ_{coh}	cohesive stress
T_f	temperature at the crack tip
T_g	glassy transition temperature
V	speed
V_{jack}	speed imposed to the hydraulic jack
V_{sample}	speed applied to the material sample

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