

E. Deletombe, D. Delsart
(ONERA)

E-mail: eric.deletombe@onera.fr

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Highly-Nonlinear and Transient Structural Dynamics: a Review about Crashworthiness of Composite Aeronautical Structures

This paper is a bibliographic review dealing with composite aircraft and rotorcraft crashworthiness. The paper focuses on structural aspects of large composite aircraft or rotorcraft parts (fuselage parts, barrels or larger parts). Material topics, such as the experimental characterization and numerical modelling of the dynamic behavior of composite materials, of composite joints (details) and of energy-absorbing components (elementary parts) are mentioned but not discussed in detail. More information about this topic can be found, for instance, in another bibliographic review. The first section of the paper deals with work performed in various labs since the early '90s. The second section describes the global strategy of the French Aerospace Lab in the matter of studying composite aircraft or rotorcraft crashworthiness over the same period, following a quite different strategy. Lessons learnt from all of these works are discussed in detail, which can be derived into best practices for young engineers or researchers working in this field. Indeed, the complexity of the composite materials, and hence the structure behavior under crash conditions, is so great (due to potentially very versatile rupture behaviors) that great care must be taken when studying their crash response. As a conclusion of the review paper, the need for a numerical/experimental building-block approach up to the barrel level is clearly evidenced, which should not be done without well-assessed V&V (verify and validate) strategies for the virtual part of the process.

Introduction

Aviation is one of the safest public transport modes today. To reach such performance, aircraft safety mainly relies on experience feedback and on a set of constantly evolving rules that concern the flying products and operations. In the course of events that punctuate the aeronautics history, aircraft certification rules progressively improved. This is especially the case in the field of crash and survivability, which is identified as a specific topic, for instance, in the CS25 (large civil aircraft) document, and where highly-nonlinear and transient structural dynamics is concerned.

An advisory international group – which Airbus Aircraft was involved in – was set up in the USA in the early 2010s by the FAA, to address the question and identify beneficial research activities in the field of civil aircraft crashworthiness. Among the initial objectives of this advisory group, one could find: (1) the evaluation of the interest and feasibility of future regulation evolutions, (2) the

standardization/harmonization of (absolute) crash performance criteria for whole aircraft or parts of it, some of them being still quite de-correlated from the others, (3) the validation and standardization of the building-block approach used for the aircraft static design demonstration, as an acceptable way forward to deal with crash certification, and (4) the consideration of more representative crash scenarios, in particular, at the full-scale level.

In parallel, some European aircraft manufacturers also proposed to the French CORAC organization (Council for Civil Aviation Research) to unite efforts in order to also better cover possible future regulation evolutions in the domain of crash safety. A transverse "Crash and Survivability" theme was introduced in 2013 within the CORAC overall roadmap. Once completed, the results of the discussions were presented to the French DGAC (French General Civil Aviation Directorate), which defined clear objectives for such research: (1) to analyze the full-aircraft numerical simulation to better cover the crash domain (to avoid a costly experimental approach), and (2) to develop

and standardize advanced experimental means of characterization for nonlinear material models from quasi-static to dynamic loadings, to optimize and reduce the number, types, and costs of required tests. Considering these objectives, several themes of transversal interest for the various European aircraft and rotorcraft manufacturers have been identified, which have an upstream, general and prospective character. The French DGAC then contracted the French Aerospace Lab (ONERA) to conduct some of these research studies for the benefit of the aeronautic community as a whole, meaning to increase its capability to better understand, analyze and improve the aircraft behavior in the event of crash situations (which is the purpose of this review paper).

The four-year PHYSAFE 2015-2019 research project funded by the French DGAC is straight online with the transverse CORAC "Crash and Survivability" roadmap. It is aimed, on the one hand, at experimentally studying and characterizing various phenomena that may have a noticeable influence on aircraft passenger safety in the event of a crash. On the other hand, it is aimed at developing the numerical finite-element code capabilities to predict the crash response of composite aircraft structures and their consequences in terms of passenger survivability. The corresponding research activities are being conducted by ONERA according to the following general line of research: (1) the development of test means and facilities to characterize the dynamic behavior, rupture and abrasion of composite aircraft primary structure materials, (2) the study and development of dynamic behavior and rupture models for organic matrix composite materials and crashworthiness numerical analysis.

This paper is a bibliographic review dealing with composite aircraft and rotorcraft crashworthiness. Its main objective is to contribute to the definition and dissemination of best practices in designing such aircraft. It complements a previous bibliographic report and paper [31] limited to work on metallic aircraft crashworthiness [1][31]. Since general questions, besides the nature of the materials used to design the aircraft, were already discussed in more or less detail in these previous report and paper (standards, test means, seats and dummies, numerical methods, etc.), this paper only focuses on the structural aspects and composite structures. It also only focuses on large composite aircraft or rotorcraft structures (fuselage parts, barrels or larger parts): specific topics, such as the experimental characterization and numerical modelling of the dynamic behavior of composite materials, composite joints (details) and energy-absorbing components (elementary parts), can be found elsewhere, e.g., [2][3][4][33][34]. A review of the work performed in other labs is presented and analyzed in the second part of this paper. In the third section, the expertise of the ONERA Design and Dynamic Resistance research unit is summarized to shed light on the global strategy of the French Aerospace Lab in the matter of studying composite aircraft or rotorcraft crashworthiness.

Literature Review on Composite Aircraft and Rotorcraft Crashworthiness

Compared to the crashworthiness of metallic airframes [1][31], research work on composite structures appeared later in the open literature, in the '90s. Concerning the experimental works, the same crash test facilities and philosophies as those previously used for the metallic airframes were naturally used, without any real modification of the test facilities being necessary. Although the FE explicit codes were really starting to spread, hybrid tools were already well developed

and used – combined with a component-based testing approach – to study the crashworthiness of full-scale aircraft or rotorcraft structures, and all the more preferred for composite structure analysis, since the complexity of composite material behaviors and their potentially associated FE computing costs were high compared to those of metals. A first set of reviewed papers gathers those that dealt with such hybrid models for composite structures, one way or another. Hybrid models (based on component test results) were first used by Jackson *et al.* [5] to study the crash behavior of a general aviation composite aircraft section (Lear Fan). A first simplified structural model (added masses set on seat rails instead of seats and passengers) was developed (no laminate description or material data available in the paper) for the initial aircraft design: a quasi-static crush test was used to determine the ground and underfloor spring characteristics to be used in the hybrid model, and the composite material rupture criterion was calibrated according to the crash test result. A retrofitted design was then studied (this time with seats and dummies) with the initial underfloor structure being replaced by composite energy-absorbing beams (Kevlar and foam-based sandwiches). Again, a post-test hybrid model was developed with (1) the composite frame stiffness being first calibrated using a preliminary quasi-static linear elastic analysis, and (2) the non-linear hybrid spring characteristics, being characterized through a quasi-static crush test of the underfloor structure. The same composite material rupture criterion as that used for the first version of the model was used, making it possible to obtain the rupture of the composite frames as in the test (the underfloor energy-absorbing structure remained undamaged during the crash test). A third model was then proposed (without any test being done) to evaluate a new design concept for the fuselage section, where the composite frame integrity was ensured *a priori* by design. Here, the underfloor energy-absorbing composite sandwich structure virtually turned to crush properly, which increased the crash performance of the structure compared to the two previous cases. One of the first reported purely FE crash simulations of a composite aircraft structure was performed by Vincente *et al.* [6]. It was limited to a coarse FE model of a composite commuter sub-floor structure, which was later compared to the full-scale crash test result performed within the framework of the EU project CRASURV [7]. To limit the computing costs for the full structure, the authors' choice was to use simple shell elements and calibrated nonlinear isotropic material models based on FE simulations of tests performed on simple parts and components, in a way very similar to that of the previous hybrid approach. The material models needed to be seriously calibrated again once the full-scale test results were known, to reach a good correlation level. In the same period, a MSC-DYTRAN FE model of a Sikorsky composite helicopter underfloor structure was developed by Lyle *et al.* [8], starting from an existing NASTRAN model (initially developed for structural dynamic analysis). The size of the crash FE model was constrained by the CPU costs, which were targeted to be less than 1 day: important assumptions and simplifications in the FE description of the complex underfloor keel beams (geometry, materials, etc.) then needed to be done. With the idea of combining hybrid and FE methods, the crash-model loading conditions were deduced from both the full scale Sikorsky crash test result and the associated KRASH [32] hybrid model of the helicopter. The crash simulation was simplified, using a falling mass (representing the remaining helicopter mass, except for the subfloor) onto the subfloor FE model, with a kinetic energy (and hence velocity) estimated from the crash test and KRASH numerical results. Since no dynamic crash data were locally recorded during the test relative to this subfloor structure, only a post-mortem analysis (maximum crush displacement) was proposed for comparison and discussion of the MSC-DYTRAN dynamic numerical results.

The lessons learnt from this first set of papers are as follows: Jackson *et al.* proved in [5] that hybrid models can be efficient, but need many test results at the component level – as for metallic airframes – to be used properly. If the materials used are not dependent on the strain rate (e.g., aluminum and quasi-isotropic carbon fiber laminates) quasi-static tests are enough to build the hybrid model of the airframe. However, composite energy-absorbing underfloor structures cannot be properly designed if the load introduction scenario is misunderstood, with the risk of the driving energy-absorbing mechanisms not developing/ triggering as wanted. The use of rigid added masses instead of deformable (with complex kinematics) seats and passenger/dummy systems to design the underfloor structure was proven to lead to the overestimation of local input inertial loads, which can then lead to unwanted experimental ruin modes. By using the FE method in the same way as the hybrid one (model development based on sub-component testing), the results in [6] also prove that the building-block approach cannot be applied with confidence whatever the numerical tool when excessively simple models are used for composite structures and highly-nonlinear crash behaviors. Lyle *et al.* list several difficulties concerning the FE model development and study of the crash behavior of composite aircraft (helicopters) in [8]. First, only partial information and a partial description can be derived straightforwardly from standard structural dynamics FE models (e.g., NASTRAN) into crash FE models, and a significant effort is then needed to achieve a satisfying FE crash model. Starting from a CAD (geometry) model would have lessened the effort, using, for instance, the NASTRAN data cards just to obtain some of the composite laminates and material parameters. Second, a full-structure physical crash test alone with KRASH numerical analysis appear to be of limited interest to validate the FE crash models and explicit codes (applied here to the subfloor structure only). Since component tests have been performed to develop the KRASH model crush springs, some of these tests (even the static ones) could have been used (with great care, see the previous paragraph) in a Building-Block-like Approach, to progressively assess the subfloor FE crash model and then increase confidence in the FE dynamic numerical result analysis. The inverse path, starting from the top of the pyramid of experiments to assess numerical tools for intermediate level structural components, clearly seems not to be the appropriate way to proceed.

Among a second set of papers dealing with crashworthiness and FE methods, Fasanella *et al.* presented a full-scale crash test and post-test numerical simulation of a composite helicopter with its landing gears [9]. A coarse FE model and a simple composite material model were used. The results of the test and numerical simulation were analyzed and quantitatively compared up to 150 ms, in terms of filtered accelerations at several locations. The experimental local accelerations had, somehow, quite different shapes, here and there, whereas the numerical ones had more similar (harmonic) shapes, but the acceleration orders of magnitude were correctly predicted. The tail break (observed in the physical test) seemed not to be predicted well, but the acceleration response was anyway mainly driven by the dynamic response of the landing gears, which was almost properly modelled. Fasanella *et al.* retried the same work in [10], meaning that the post-test simulation of the Sikorsky ACAP helicopter full-scale crash test, with the main effort of the work being this time dedicated to propose an engineering methodology that would permit the full crash test event to be computed more efficiently (CPU costs). Besides the fact that a still quite coarse mesh (7,350 finite elements, developed from a NASTRAN model (thus needing to track and remesh areas with very small FE elements) was used to model

the helicopter airframe, a simplified landing gear modelling methodology was proposed. To save more CPU time, the simulation was split into two phases: in the first step (45 ms, during which the rear landing gears only interact with the ground) the helicopter FE model was forced to behave rigidly, and final positions and initial velocities of all of its nodes were recorded. These data were then used in the second step as initial input data to start a flexible-model crash simulation (with gravity being taken into account), to be able to capture the tail break (as known from the test), to simulate the contact (no friction was modelled) of the main helicopter body with the ground and the final deformation of the subfloor structure. As previously mentioned, in terms of crash analysis, no dynamic data were experimentally available/recorded to compare with local subfloor dynamic numerical responses: the test and simulation were again globally compared through post-mortem observations, to major event chronology recorded by videos, and dynamic data from accelerometers (60 Hz filtered) located at some floor, engine, gear and bulkhead locations. Following this work, due to the cost of full-scale structure crash tests, and considering the previously described limitations in numerical simulations, Jackson *et al.* proposed a crashworthy composite fuselage design strategy in [11] based on a concept definition step (starting from engineering and analytical considerations), followed by a 1/5th scale model manufacturing and testing step to select best EA concepts. The performance of the final selected concept was then extrapolated to the full scale using scaling rules and simple empiric static material laws. The scale-model test results were also used to assess numerical FE (MSC-DYTRAN) tool capabilities (post-test). The full-scale manufacturing and crash testing of the selected concept was performed in following works [12], where Jackson *et al.* studied the improved full-scale composite general aviation fuselage section concept (selected among 5 possibilities), both experimentally (2 drop tests) and numerically (using MSC-DYTRAN). The fuselage concept was based on a protective composite sandwich shell (cabin), together with an energy-absorbing subfloor structure partly made of Rohacell foam blocks. A coarse FE crash model (18,250 shell elements) was developed with different nonlinear material behavior laws (with rupture criteria) being used for the E-glass composite material and Rohacell foam. Carbon fiber composite laminates and sandwich foam cores for the protective fuselage shell were modelled as linear elastic. All of the different parts were modelled as perfectly bonded (no possible debonding). Gravity was not taken into account in the simulation, with just the initial velocity (kinetic energy) being applied. The same cabin fuselage shell was used for two drop tests (0° and 15° roll angles), with only the subfloor part, including the Rohacell foam, being replaced after the first test (0°). The results of this 1st test (both experimental and numerical) were quite satisfying and comparable. The structure behaved as predicted, except that the experienced G-levels were higher than expected from the 1/5th scale study, and all the more for the FE model, which seemed to be stiffer than the physical structure (a small debonding developed within the cabin sandwich shell during the test, which could not be simulated). This damage was not repaired before the second test (15°), during which major ruptures occurred in the cabin shell. The large difference between this second test and its FE simulation was then explained not to be due to the change in test conditions (15°), but rather to the initial damage after the 1st physical test, which was missing in the virtual test. In the continuity of these works, Fasanella *et al.* studied the numerical simulation (30,000-finite-element model) and comparison with the test of a new crashworthy fuselage demonstrator, including composite parts and Rohacell foam in its underfloor structure for business jet or helicopter airframes (#2 m fuselage

diameter) [13]. The crash test was performed on a rigid surface, and the attention was paid to the comparison with the simulation in terms of several filtered acceleration measurements at rail positions, and several dummy pelvis acceleration and lumbar load measurements. The main energy-absorbing concepts introduced in the tested fuselage section were Rohacell foam blocks in the subfloor part, and energy-absorbing seats in the cabin. The other parts of the structure (stiff fuselage section and floor) were made of a sandwich material (no frames or beams) with glass-epoxy face sheets and Rohacell core, which was expected to keep safe (almost no energy absorbed there). Thus, the sandwich material was modelled using shell elements for the composite sheets (simple bi-linear elastic-plastic behavior), and brick elements for the Rohacell core (linear elastic behavior). The order of magnitude of the predicted acceleration levels was quite good, with noticeable differences being nevertheless pointed out. No detailed analysis of the damage and rupture of the composite skins (2nd order influence on accelerations compared to the Rohacell blocks and energy-absorbing seats) was given in the paper. The same composite structure was used again by Fasanella *et al.* (several demonstrators were manufactured) to compare test (and numerical) results for vertical impacts on rigid surface, soft soil (sand) and water [14]. The composite material in the 30,000-FE simulations was still simply modelled using a linear orthotropic elastic material law, and laminated shell elements were used, because of the first-order influence of Rohacell material on the nonlinear response of the very specific tested structure (as proven in the previous works). Filtered acceleration results were compared between tests and simulations with a quite good agreement.

In this second set of papers, as shown by Fasanella *et al.* in [9] [10], coarse FE models can be used to predict the crash response of full structures, even composite ones, if the driving phenomena are global ones (e.g., the landing gear response) and not local ones (sub-component ruptures). Due to the coarse model used to describe the sub-floor structure, and due to missing dynamic local information (only few post-mortem comparisons are given) it is difficult in these papers to conclude whether deviations compared to the test results stem from modelling approximations/inaccuracies or from other FE model limitations. Following the same general idea, the deterministic design (stiff and strong frame/fuselage/cabin design, no windows, etc.) with no joints, etc., proposed by Jackson *et al.* in [11] prevents complex damage/failure modes to develop during tests: simple elastic static composite material models are then enough to properly catch the fuselage response using FE models. Thanks to such a well-controlled scenario, an energy-absorbing concept can be selected among others (using 1/5th scale models), with a FE model comparison with the test being done, which only requires a sufficiently accurate absorber model to be used in the FE structure model to achieve a very satisfying comparison with the experiment (e.g., accelerations at floor level, in several locations). Considering the study of the full scale demonstrator of the selected 1/5th concept [12], the interesting results come from the first test/simulation comparison. First, the scaling exercise (from 1/5th to 1/1th) seems pretty successful, except for the added lead mass (which has been overestimated and turned out to be the reason for the G-levels that were 20 percent higher than expected). These higher G-levels can be the reason for the unexpected damage to the cabin shell structure during the first test (which then deviated from the initial deterministic design scenario and had a dramatic consequence for the second test). Pre-test simulations would probably have helped to detect and to correct this deviation. Whatever the case, the post-test simulations show that the local damage and

ruin phenomena cannot be captured (very few comments about this) because of the use of excessively simple nonlinear material models and rupture criteria and – above all – the perfect bonding model without rupture set between the various parts of the structure. Note that it was reported that, although gravity is not taken into account, the simulation results can miss the contribution of potential energy (which may be non-negligible even for the crash response of a light-weight structure). The second design described by Fasanella *et al.* in [13] is again made in order for no composite failure to occur along the stiff composite cabin fuselage and floor. With such a deterministic design, as long as the crushing behavior of the underfloor Rohacell foam blocks and energy-absorbing seats are properly modelled, the main collapsing phenomena can be captured and the accelerations and dummy loads well predicted, even with a quite coarse FE model (30,000 elements). Last, for the different studied cases presented by the major contributors to this field in [14], impacts on rigid surfaces are shown to be the most severe ones (higher acceleration levels), but this conclusion could possibly be contradicted if horizontal velocities are considered, with plowing forces (soft soil or water) probably changing the crash scenario and results. In order to achieve a good agreement with the tests, the sand and foam materials must be accurately modelled, especially their rate-dependent behavior (foam), their zero Poisson ratio (sand), and their unloading dissipative "crushable" behavior (nonlinear hysteresis), if one wishes to avoid any non-physical rebound in the simulation. Last but not least, the use of quite coarse FE models – once validated with some full-scale crash tests – proves in the end to be acceptable for numerical parametric crash justifications (in the sense that hybrid models were).

Then, very few works were reported in the literature after these works by Fasanella, Jackson, and Lyle *et al.* until recent years. In 2012, Zou *et al.* published a purely numerical study of the crash performance of a hybrid metallic/composite fuselage section [15]. The only composite part of the virtual fuselage section was its skin (given thickness); all of the other parts were made of aluminum. The parametric study focused on the influence of the metallic strut angle and section on the crash performance of the fuselage section, according to an academic vertical crash condition. The behavior of the composite material was modelled as orthotropic elastic brittle (multi-layered shell elements) behavior with no possible energy absorption (in the skin). No test result was available/presented to be compared with the numerical simulations in this paper. In 2013 (about 10 years after Fasanella's last paper), Heimbs *et al.* presented this time a building-block-type exercise, including the comparison of dynamic test results and numerical simulations of composite parts of different increasing complexity: from simple plates and riveted T-joints up to complete frames [16]. Although the numerical simulations fitted well for simple plates, noticeable differences appeared when more complex structural tests were studied. The differences were claimed to be due to complexities that could still not be properly tackled by numerical FE methods: boundary conditions, load-introduction issues, etc. Note that the paper did not comment about the possible nonlinearity or strain rate sensitivity of the composite materials, since very simple (elastic brittle) material models were used (quasi-isotropic laminates). The numerical tool was then used to compute the macroscopic behavior (super-element) of some details that could not be accurately represented in a full 2-frame composite barrel structure, which was then crash-simulated. The lack of experimental results at the barrel scale prevented any estimation of the error propagation in the FE model (from coupons to full scale) to be made. The last of the series of papers reviewed here, a CFRP composite (sandwich design) fuselage response was investigated by

Sturm *et al.*, with respect to crashworthiness [17]: the development of a "plastic" hinge in the airframe has been identified for a long time as a key and favorable mechanism in the crash response of metallic commercial airframes. The purpose was, here again, to study composite integral (sandwich) fuselage concepts (no frame) that could develop such hinges at pre-determined locations, in order to ensure a satisfying crash scenario (proper load introduction in struts and energy-absorbing components). The studied concept was based on a honeycomb core trigger to pre-determine hinge locations. Experimental and numerical works were done separately: a FE numerical model at the fuselage level was used to identify the load (compression and bending) conditions to be supported by a fuselage panel under crash situations. These loads were used to design the experiment at the sandwich panel level. The numerical tool was also used to perform a parametric sensitivity study about the core trigger concept efficiency, with only the honeycomb core being modelled (not the CFRP skins). Then, different sandwich solutions were fabricated and tested. No comparisons were made in the end in this paper between sandwich panel test results and simulations.

Among this last set of more recent works, Zou *et al.* [15] has shown that the composite part (only the skin in this paper) has very little influence on the crash scenario of the hybrid metallic/composite fuselage design that is numerically studied (the crash performance is controlled by the metallic parts, including the struts). In reality, true manufacturing would rely on setting up many riveted fasteners (which are not modelled in this virtual test): the EU TIM-CRASH project results in 1995 [18] suggested that devil key rupture mechanisms might be in such structural details in terms of crash behavior even of metallic structures. All the more as like recently shown by Heimbs *et al.* [16], despite many improvements in the FE explicit codes in terms of computing costs and modelling accuracy (finite elements, material models, etc.) the building-block approach for composite structures is still not straightforward when the crash simulation of composite airframe structures (prediction or simply justification) is concerned: numerical models still have to be assessed/calibrated by tests at every level of the design pyramid. Last, Sturm *et al.* once more remind the composite structure designers that the crash response of a full airframe needs to be studied experimentally in the end, since unpredicted rupture in the fuselage frame, for instance, would clearly endanger survivability [17]. In that sense, these works are complementary to those of Fasanella *et al.*

ONERA Background in Crashworthiness of Composite Aeronautical Structures

Composite rotorcraft crashworthiness is a particularly important topic at ONERA, insofar as military helicopter structures must fulfill crash specifications: indeed, Airbus Helicopters chose many years ago to develop a full composite combat helicopter because of the weight benefits and marine environment specificities. In [19][20], research works aimed at improving the crash resistance of the Tiger helicopter (thanks to the use of composite underfloor energy-absorbing sinewave beams) are presented, with the ONERA CRD Research Unit being involved in the '90s in the development and validation of a FE model (Radioss) of the central composite section of the helicopter, including the main rotor mass, the weapon supporting wings, the fuel tanks and the under-floor energy-absorbing components. The overall objective of the research was, in fact, to assess modeling methodologies for the prediction of composite helicopter crashworthiness

and to demonstrate the feasibility of calculations for full-scale structures. Compared to other research teams and at that time, ONERA took the gamble and made the choice to develop very detailed FE crash models from the very beginning of its involvement in this field (no hybrid methods/models). For the Tiger case, the works led to the definition of a FE model that was finally made up of 180,000 shell elements (see Figure 1) and 60,000 volume elements (mainly for the fuel), which means ten times more than the models used by Fasanella *et al.* In order to evaluate the prediction capability of such a model, experimental data obtained from a crash test conducted on the considered section in 1998 at the GEAT (French crash test center, now DGA TA) were available for comparison with the numerical results. Various kinds of data were recorded at various points of the structure, including acceleration measurements on the main additional masses (rotor, wing weapons, etc.), gauges on structural panels, and pressure measurements in fuel tanks.

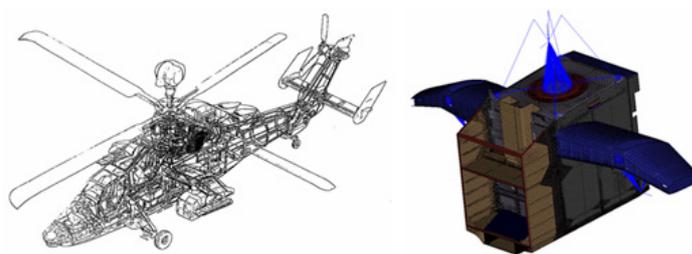


Figure 1 – Broken view (left) and FE model (right) of the Tiger central composite structure

Besides the intrinsic difficulty of modeling composite structures, the major issue in simulating such a complex event was, in the fact, that the structural ruin mechanisms are strongly interdependent. These mechanisms essentially concern the in or out-of-plane loading of unsymmetrical sandwich panels, the resistance of riveted or bounded assemblies, the crushing of energy-absorbing components and finally, the response of the fuel tanks (the structure included 2 flexible fuel tanks partly filled by more than 1 ton of fuel, representing three quarters of their total capacity). The latter point appeared to be one of the most influential phenomena in the ruin scenario, since the expansion and increase of pressure in the tanks directly control the out-of-plane loading of the structural panels and the vertical loading of the composite underfloor beams. Two methods were mainly investigated in order to evaluate which would be the most appropriate to correctly model the pressure load transfer to the panels and under-floor beams: several methods were analyzed (which is not the purpose of this paper) with some of them yielding satisfactory results in terms of robustness, CPU costs and correlation with experimental results. This point being solved, a very fine mesh size (4x4mm multi-layered shell elements) and a new composite material law developed and validated in the Radioss code were used to model the composite energy-absorbing components. The material model – describing the composite material at the ply level – is orthotropic with a rate dependent yield stress and nonlinear behavior, and proposes a set of rupture criteria to describe the different material failure modes (tension, compression, maximum dissipated energy, etc.). Using these advanced functionalities and after a calibration step based on subcomponents test comparisons, the simulated energy-absorbing underfloor structure turned out to correctly approach the global deformation of the physical under-floor system during the test, with a progressive crushing of the trapezoidal and sine-wave

beams obtained (see Figure 2). Finally, the calculations conducted at a full-scale level (including fuel tanks) achieve a satisfactory level of prediction with an acceptable computational cost.

The next steps in the 2000s focused on the dynamic characterization and modelling of composite riveted joints, since in the previously described FE simulations, kinematic relations (tied interfaces) were mostly used to model the assembly of the various parts of the fuselage structure. Other works done by ONERA in the field of helicopter crashworthiness have dealt with ditching situations: the most recent numerical formulations proposed to deal with fluid/structure interactions were, here again, analyzed to establish the current numerical capabilities of explicit commercial codes (e.g., Radioss). For instance, a Euler/Lagrange coupling interface implemented in the Radioss code was evaluated to cope with the modelling of fluid/structure interactions [21] (see Figure 3).

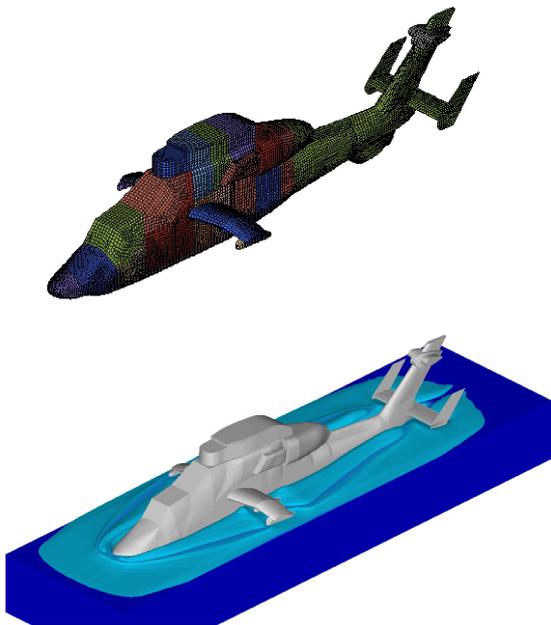


Figure 3 – FE model of a full-scale rigid helicopter model (up) and ditching simulation (vertical and horizontal speed) using Radioss CEL formulation – final stage: 300ms (bottom)

From the works presented in [19][20] it was proven that the explicit FE codes could be used to study crashworthiness for very complex composite structures (C3-C4 composite helicopter structure). However, a lot of preliminary works were necessary before such a satisfying result (French reports) could be achieved. These preliminary works started in 1993 with the numerical simulation of the crash behavior of underfloor composite beams using state-of-the-art

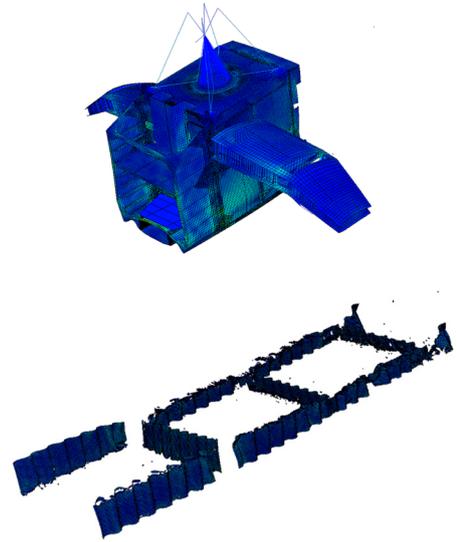


Figure 2 – Global response of the composite airframe (up) and final crushing state of composite underfloor beams (bottom)

models and FE tools and continued till 1998 with the dynamic characterization of composite materials and the development and identification of enhanced composite material laws for brick and shell [7] elements. The final successful exercise constituted the required demonstration before the industry partner started to develop its skills and to use this kind of FE explicit tool for composite helicopter crashworthiness analysis.

In the field of composite commercial aircraft, the objectives of the EU CRASURV project (1997-2000) [7] were to develop the technology for the design of composite airframes (commuter and large transport aircraft) with maximum safety with respect to potentially survivable crash scenarios. ONERA first contributed to the dynamic characterization of composite materials, and the development and identification of a dynamic material law for composite multi-layered shell elements [22]. The new material law implemented in the Radioss explicit FE commercial code was verified, and applied to the post-test simulation of a sub-cargo floor composite structure (half-moon), which was previously drop-tested at the French DGA-TA test center (see Figure 4) [23][24]. Note that separate reports are dedicated in the PHYSAFE project to the various topics of the dynamic bulk behavior characterization and modelling of Organic Matrix Composite (OMC) materials [2][4].

ONERA also used its test facilities (crash tower, hydraulic jack) [1] [31] in the EU CRASURV project for the crash-testing of sub-cargo floor energy-absorbing components [22] and the dynamic testing of composite riveted joint specimens manufactured by other partners. A summary of the ONERA CRASURV works is presented in [25].



Figure 4 – Various crash tests of composite components and corresponding FE simulations (EU CRASURV)

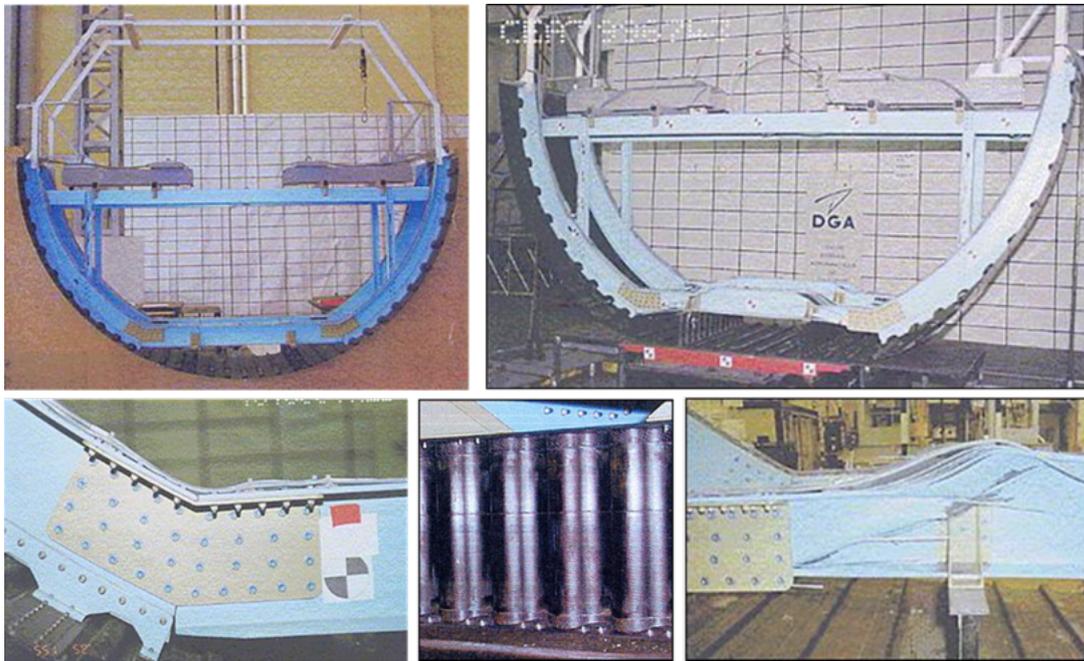


Figure 5 – EU CRASURV composite A/C half-fuselage demonstrator before and after the crash test (DGA TA test center)

Despite the experimental-numerical Building-Block Approach, which was implemented up to the half-moon component level and followed by a crashworthy pre-test numerical simulation of the designed composite half-fuselage structure, the physical test of the composite half-fuselage demonstrator did not quite go as expected, with the cargo-floor beams breaking before the sinewave energy-absorbing beams started to crush and then failed to absorb any energy. The passenger composite floor beams remained safe, but the measured "passenger" acceleration levels exceeded 50 Gs (unsurvivable conditions). The explanation proposed for this unpredicted behavior was the embrittlement of the 2-part cargo floor beam junction in the metallic riveted fastener area (see Figure 5), where the rupture initiated (these fasteners were not taken into account in the numerical simulation of the final proposed composite half-barrel design). In the end, the test

results revealed that the composite frames and main floor beams should have been reinforced (safety coefficient taken compared to the numerical design, which would have meant an extra mass penalty), in order to ensure that the energy-absorbing components would behave as expected. After the EU CRASURV project ended, a feedback (retour d'expérience, REX) study was funded by the French DGAC (Civil Aviation General Directorate) [26][27], in order to precisely analyze the reasons why the EU CRASURV FE simulations failed to predict the composite half-fuselage final crash test result (see Figure 6) although the FE models of the half-moon structures had been properly calibrated (see Figure 4). The exercise mainly consisted in a numerical sensitivity study dealing with different parameters, such as the mesh size, laminate description, riveted joint models (kinematic constraints or beam-spring finite elements), the nonlinear material law and its

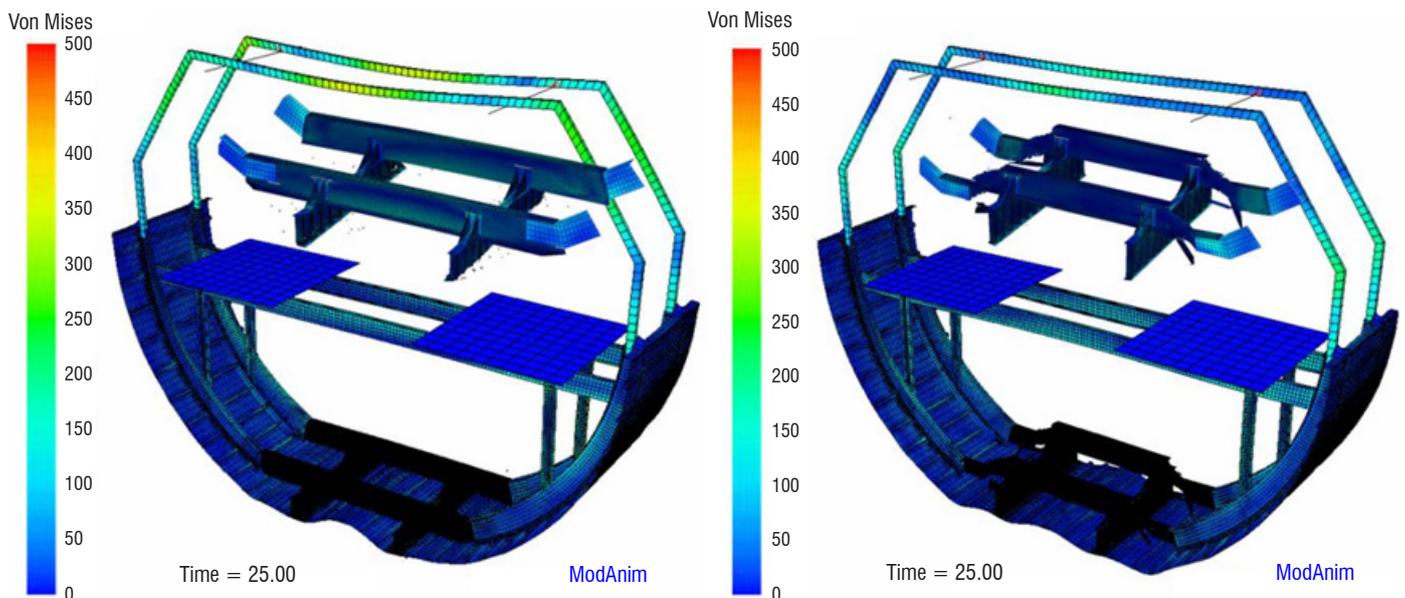


Figure 6 – Illustration of various numerical ruin scenarios obtained during the parametric REX study for the EU CRASURV fuselage structure, with either the crushing of the sinewave beams (left) or the rupture of the cargo beam (right)

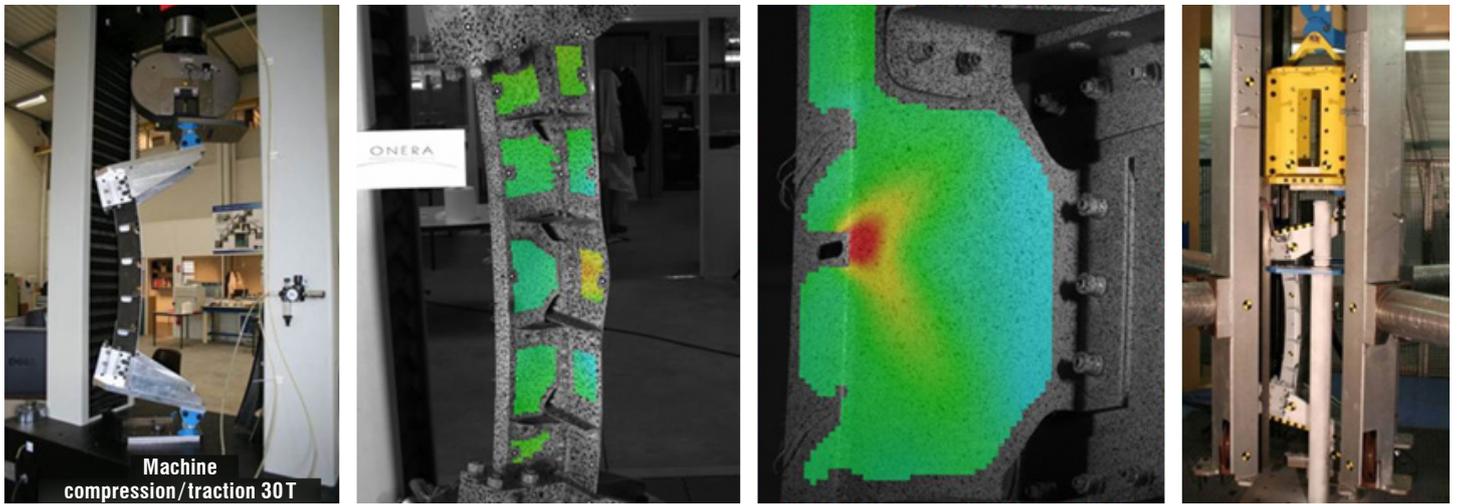


Figure 7 – Static (left) and dynamic (right) compression/bending tests on composite A/C fuselage frames with stereo-DIC analysis (middle) of the overall strain field (with zoom on the crack-starter area)

rupture criteria, and the introduction of some missing design details, such as, for instance, the "brackets" at the top and bottom of the sinewave beams. The objective of the study was to investigate their numerical influence on the global structural ruin mode and the rupture – or lack of it – of the composite sinewave beams and/or cargo floor beams (see Figure 6).

Concerning the EU CRASURV project, as already mentioned, despite the various developments and the (possibly too simple/quick) Building-Block Approach followed up to the half-moon composite structure, the pre-test FE simulations failed to predict the composite half-fuselage final crash test result. In the end, these results proved the higher-than-expected complexity of composite structure crash problems, where representative load transfer and boundary conditions between the various components of the full composite structures must be properly represented in the sub-component test program. Then, it was shown in the DGA funded REX study that all of the "numerical parameters" studied in [26][27] have an influence on the composite half-barrel structural ruin mode one way or another. However, the final conclusion of this REX study was that it was possible – whatever the value of the other parameters – to cover a large spectrum of ruin modes – including that observed during the physical test – just by "playing" with the ultimate rupture criteria of the composite multilayered shell elements in the various parts (frame, beam, sinewave) of the composite structure (see Figure 6). Last, as shown in [23][24] during the EU CRASURV project and also in [26][27] during the final REX study, post-test simulations based on knowledge-driven calibration of the ruin mode and scenario can yield a satisfying comparison with physical tests, but no certainty can be claimed that empirical (and not physically justified) calibrations could be predictive of higher level structures in the pyramid or different crash conditions (e.g., roll angle, forward velocity, etc.). It also means that any blind-test simulation based design should be decided only after a large parametric numerical study, leading at the end only to acceptable ruin scenarios, whatever the values of the uncertain parameters (in the CRASURV case: the ultimate rupture criterion of the multilayered shell elements).

From 2006 onwards, following this philosophy, ONERA took part in a series of national studies funded by the French Institutions and AIRBUS-DLR-ONERA (ADO) collaborative projects funded by AIRBUS industry. The objective of these works was to propose, study with FE crash codes, design and test different concepts that would lead to deterministic failure modes in composite fuselage frames under vertical crash conditions. The first step was to search for mechanical load transfer concepts that would guarantee a more robust crushing initiation process of the energy-absorbing beams. Within the ADO projects, the second idea was to study the possibility of introducing "kinematic joints" [17] and "crack starters" in the composite fuselage frames (to mimic plastic hinges found in metallic frames) that would fail at a prescribed load level and location, in order to avoid rupture in unexpected/unwanted areas, and would redistribute the loads in an appropriate way onto the crush/energy-absorbing components. Static (hydraulic machine) and dynamic (crash tower) tests were performed by ONERA to study the efficiency of such "crack starter" concepts (see Figure 7). The Digital Image Correlation technique was used to record more information (displacement and strain fields) from the tests, to improve analysis.

In this ADO project, a final A/C black fuselage demonstrator (half-moon) was finally designed and manufactured by AIRBUS Germany, numerically studied by the DLR and tested at the ONERA crash tower. The testing at the ONERA crash tower of this half-moon full composite sub-cargo structure representative of possible new-generation CFRP (carbon fiber reinforced polymer) commercial aircraft is presented in [28]. The demonstrator was based on a single aisle aircraft geometry and comprised 2 Integrated Cargo Units (ICU) equipped with Triggered Tube Segments (TTS) dedicated to energy absorption and CFRP stringer-stiffened skin. The crash concept was based on an integrated structural design, which used the "bend-frame-concept" where the cargo cross-beam acts as a bend frame and withstands the dynamic loads introduced by the TTS components. The testing configuration – loading system and instrumentation – was defined on the basis of numerical analysis performed by the DLR at the fuselage section level. For this purpose, a kinematic model with a 2-frame typical fuselage section and ICUs involving the "bend-frame" concept was numerically simulated,

with the main objective of identifying the loading conditions that apply at specific sections, notably those surrounding the ICU-frame coupling areas where the test fixtures were to be implemented. Since the outcomes of these numerical works show that bending/compression loading, at a specific ratio, must be targeted as a priority, the loading system accordingly designed by ONERA thus consisted of articulated rigs holding both ends of the demonstrator (see Figure 8). The testing was performed with the ONERA-Lille crash tower at 6.7m/s impact velocity, with a 1050 kg trolley mass. The acquisition system comprised a total of 48 channels, including force sensors (6), strain gauges (36), displacement laser sensors (5) and an accelerometer (1). In addition, 4 high-speed cameras were implemented to visualize the rupture phenomena likely to develop during the crash test. Finally, the compact half-moon structure was successfully tested.

About 15 years after the EU CRASURV project, the ADO project test results in 2016 confirmed the simulated and expected crash scenario (representative load transfer and boundary conditions for the half-moon composite structure have been numerically studied and the test rig has been designed according to the numerical results), with the bending of the composite half-moon sub-cargo cross-beams and the resulting progressive crushing of the TTS components. However, it should be noted that, in order to ensure the expected crash scenario, the beams and frames surrounding/supporting the energy absorption components had to be quite heavily reinforced, thus notably increasing the final mass of the structure. The first crack starter concepts (ply drop-off, notches, holes, etc.) were also abandoned because they penalized the static design (mass), and because of the difficulty in achieving truly predictive rupture simulations.

Last, very recently, the EU SMAES project (2010-2014) focused on the study of the ditching behavior of business jets and commercial aircraft [29]. Part of the ONERA work was dedicated to the testing

and modelling of composite fuselage sub-structures (business jets), and more specifically to the buckling and crushing behavior of these sub-structures [30]. In order to make the tests more representative of ditching ones without having to deal with water wells or pools, an original concept was proposed with the use of substitute calibrated honeycombs (distributed pressure load with a prescribed peak pressure) instead of water (see Figure 9). Thanks to this, static and dynamic tests with different honeycombs (tailored compression strength) could be performed, to mimic the effect of different impact speeds (corresponding to different hydrodynamic pressures). Digital cinematography and an image correlation technique were used to globally instrument and analyze the tests. The different experiments have been modelled: most of the experimental data were correctly predicted by the FE models for the different loading conditions (compression, bending, and crushing on honeycomb). The global force displacement response was well predicted, as well as those of the strain gauges (located on the structure outside the area where non-linear geometrical and material phenomena develop).

Conclusions

Due to the more recent introduction of composite CFRP materials in primary fuselage structures, less works concerning crashworthiness of composite aircraft or rotorcraft are reported in the open literature compared to metallic ones. Nevertheless, these works benefited from more recent advances in the experimental and numerical fields, with more expertise having been built and confidence gained thanks to metallic studies.

The same building-block strategy was used as for metallic structures, but combining more experimental and numerical results (especially explicit FE simulations). Hybrid models were still used at the

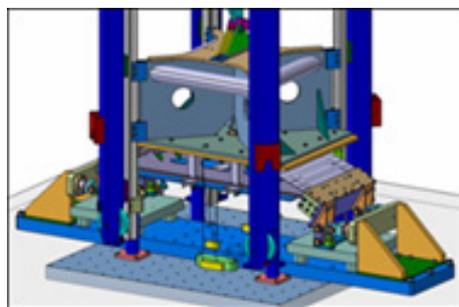


Figure 8 – Drawing of the dynamic test rig set up on the 2mx2m test floor of the ONERA crash tower (left) and picture of the AIRBUS composite crashworthy Sub-Cargo demonstrator before testing (right)



Figure 9 – Pictures of the ONERA test protocols used during the EU SMAES project for static buckling (left) and to mimic crash tests on water (ditching) using equivalent dynamic tests with calibrated honeycombs (right)

beginning of the composite story, but it rapidly gave way to explicit FE ones, especially in the design process, compared to the justification – to not mention the certification – process.

However, the complexity of the composite materials and the component behavior under crash conditions proved to be so high (and their rupture behavior so versatile, for instance, with respect to the way in which the external and internal loads and inertial forces are applied, with respect to the boundary conditions, etc.) that only two appropriate procedures were quickly established:

- either concentrating (thanks to a "simple" and robust design) the nonlinear absorbing and rupture mechanisms in pre-determined parts or components of the structure (e.g., parts made of more simple and less versatile metallic or foam materials), and designing the composite parts to keep completely safe of any rupture,
- or by increasing the complexity of the composite material laws and numerical FE models (leading to much greater FE models than those used for metallic structures), and by performing enough parametric studies by varying as many relevant parameters as possible to check their influence on the structural ruin scenario.

In the first case, hybrid or quite simple FE models (tens of thousands of finite elements) in a "coarse" building block philosophy can be used to calculate key criteria and support crash justifications, either together with composite fuselage barrel crash tests (e.g., for the Boeing B787) or with hybrid metallic/composite fuselage barrel FE crash simulations (e.g., for the Airbus A350). In this case, quite simple elastic composite material models and rupture criteria can be used. Note that scale models were even used in more prospective research works to partly reduce the experimental costs.

In the second case (e.g., the latest versions of the Airbus A350 aircraft), more steps in the test pyramid are needed (up to large full-scale components, such as half-moon sub-cargo floor structures if not full barrels), together with the development of clearly specific (different from the FE models used for standard static or dynamic analysis, e.g., using NASTRAN) and detailed (hundreds of thousands of finite elements) explicit FE models. Indeed, the FE codes still have many limitations and generally raise supplementary difficulties related, for instance, to (1) the need for complex nonlinear material models and rupture criteria, (2) the need for assessment of simplifications (e.g., joints) and approximations (e.g., geometry) and (3) the demonstration of numerical robustness and accuracy, etc. In this case, a much larger number of mechanical tests (including dynamic ones) also has to be performed, to identify the composite material law parameters and calibrate them at the composite detail level: this point is key for (and then is to be the subject of) the PHYSAFE research project, since no standards exist as yet for the dynamic mechanical characterization of composite materials and elementary joint behavior and rupture (including delamination).

In both cases, the need for an experimental and/or numerical building-block approach up to the full barrel level is evidenced, as well as an even more elaborate V&V (verification and validation) process for the numerical crash simulations, compared to metallic fuselage designs. In the end, the (exponential) complexity of FE crash simulation validation from the composite material level up to that of the composite structures still seems to be higher today than possibly expected initially. The intrinsic composite material behavior (and model) is not the only difficult point to be solved, in particular, since it cannot be as simply de-correlated from its "structural" environment in FE crash simulations as one would wish (e.g., materials that behave differently once they are used in structural details that cannot yet be modelled in the FE crash simulation for FE size limitations) ■

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AUTHORS



Eric Deletombe is Director of Scientific Industrial and Institutional Outreach for Northern France, and Senior Scientist (PhD supervision accreditation by the Valenciennes University) in the Materials and Structures Department at ONERA (The French Aerospace Lab). He was Head of the "Structural Design and Dynamic Resistance" Research Unit at the French Aerospace Lab (Office National d'Etudes et de Recherches Aérospatiales) from 1999 till 2009. He started work at ONERA in 1990 (having graduated from Sup'Aéro in 1988) as a Research Engineer, to work on modelling the crash behavior of metallic aircraft structures. His key research topics are: Metallic and Composite Materials, Joints, Behavior, Damage and Rupture, Transient Dynamic Loads (crash, impacts, etc.), and Fluid/Structure Interactions (HRAM, etc.).



David Delsart graduated from the Ecole Centrale de Lille in 1994. He then graduated from the University of Sciences and Technologies of Lille (with a Post-graduate diploma in Mechanics, in 1994). He has worked as a Research Engineer at ONERA in the Design and Dynamic Resistance Research Unit since 1997, specializing in the dynamic characterization of materials and assemblies, and in the development of dynamic mechanical models and Finite-Element explicit modelling (Radioss, Abaqus, and Europlexus). He is the manager and the person technically in charge of the ONERA/DLR/AIRBUS-Helicopters joint research program on the crashworthiness/vulnerability of helicopter structures.