Survey of aircraft structural dynamics non-linear problems and some recent solutions

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ABSTRACT

Structural dynamics is a key discipline in aircraft design and certification. The realm of structural dynamics includes problems in which structure flexibility is important, such as dynamic loads (landing, taxi, gust, turbulence...), but it also includes other areas like environmental vibration or impacts technology. This is closely related with its sister discipline Aeroelasticity.

Linearity has been the cornerstone assumption in aircraft design engineering solutions. In the past, linearity allowed to solve many structural dynamics problems that otherwise would have been unaffordable. Nowadays, the necessity of highly optimised structures, combined to an increase of computer power, has made this assumption to be reconsidered.

This paper presents a wide survey on non-linear topics in structural dynamics and the way they have been solved at EADS-CASA (Airbus military) in the past 25 years. Although the paper has been mainly focused on numerical simulation using the Finite Element Method technique, component tests and full aircraft tests are also presented.

The non-linear structural dynamics topics presented herein are categorised in two main lines of work. Within each one, several aspects will be addressed:

1. Dynamic ground loads:
   - taxi loads
   - dynamic landing
2. Impacts technology:
   - bird strike
   - crashworthiness
   - wheels-up landing
   - ditching
   - ice impacts
   - blade loss
   - vulnerability

The paper concludes with lessons learned in these 25 years and challenges that must be solved in the near future.

1.0 INTRODUCTION: 25 YEARS OF NON-LINEAR STRUCTURAL DYNAMICS AT CASA

CASA, Construcciones Aeronauticas S.A. acronym, is the largest aircraft manufacturer in Spain. CASA was founded by the outstanding businessman José Ortiz Echagüe on 3 March 1923. José Ortiz Echagüe was not only the Spanish Aeronautical Industry founder, but he also founded the Spanish automotive company SEAT. In addition, he got a great artistic reputation as photographer, field in which he invented a number of techniques and produced

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Figure 1. Left: Poster of a recent Ortiz Echagüe Exhibition at Valencia Contemporary Museum in summer 2009.
Right top: the CASA CN-235 aircraft; a best seller in light military transport aircraft.
Right bottom: the EADS-CASA A330-MRTT Tanker with air refuelling boom: winner of five recent tanker contests around the world.

several sets of photographs that are still frequent in museum exhibitions (Fig. 1)

After a wide and successful trajectory as an independent company, CASA merged into the European group EADS on 2 December 1999. CASA activities continued inside EADS in the Military Transport Aircraft Division (MTAD). As from 15 April 2009 EADS-CASA was integrated into Airbus, now named Airbus Military.

Dynamic ground loads, in particular taxi, were the first incursions in non-linear structural dynamics problems in CASA. The need of certifying the CN-235 aircraft for operating in unpaved surfaces was the main motivation. A technology project was launched in the mid 80s intending to simulate the coupled system of non-linear landing gear with a linear aircraft structure. The developed software code was validated using flight tests. The project concluded successfully with a suitable methodology for taxi loads simulation[1]. The same methodology –with minor enhancements– was afterwards applied on C-295[2] and recently on A400M.

Some years later the state of the art allowed to step forward in non-linear ground loads with the fully coupled landing-gear-to-aircraft solver for dynamic landing. The main difference with taxi code was the inclusion of landing gear normal modes also in the solution. These normal modes are needed to simulate the landing gear spin-up and spring-back effects that are essential for a dynamic landing proper simulation. This technique was introduced in CASA at the beginning of this decade and it is being successfully put into practice on A400M aircraft.

Impacts technology is an inherent non-linear discipline. Both, the impactor and the impacted structure are subjected to large deformations beyond the linear regime. During an impact, the involved materials may reach its plasticity region and even rupture conditions. The wide spread use of the explicit FE technique allows tackling this type of problems. The first two impact problems addressed in CASA were bird strike and crashworthiness.

Bird strike numerical simulation was used for the Airbus A340 Horizontal Tail Plane leading edge design and optimisation in the early 90s[3]. At that moment, this component was CASA responsibility. The exercise was a complete success. The simulation results reduced the number of specimen tests to a minimum and proved that the achieved structural weight was an optimum. In 1994, numerical simulation was also used to demonstrate the EF-2000 fighter slats structural integrity against three successive bird impacts[4]. As the author is concerned, this was the first time Airworthiness Authorities accepted a simulation as an acceptable means of qualification of an aeronautical structure against bird strike.

CASA participated in the European funded research project Crashworthiness from 1993 to 1996. This project was instrumental in the validation of numerical tools for aeronautical metallic structures impacts simulation[5] and created a group of engineers at the European industry that worked together for many years in the

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subsequent research projects CRASURV (devoted to composites)[6] and CRAHVI (devoted to high velocity impacts).

Since then, impacts technology applications in CASA have been multiplied: simulations such as impacts against water for the CN-235 US coast guard version ditching certification; ice impact to protect the A400M engine nacelle; A400M blade loss; missile fragments impacts against fuel filled structures under maneuver loads for the EF-2000 fighter aircraft vulnerability studies … These are only some examples of a technology that has grown up following the same company evolution pace.

Due to space-limit reasons, non-linear Aeroelasticity is not part of this paper. However, it has to be said that CASA has been also very active on that matter during the past 25 years. Non-linear aerodynamics treatment using CFD codes, especially in the transonic regime has been both subject of research (EU projects UNSI and TAURUS) and application[7]. Non-linear normal modes have been considered in large and very flexible structures[8] and also measured in Ground Vibration Tests (GVT) like the A400M recent GVT[9] (October 2008).

The rest of the paper will show a detailed technical overview of CASA two lines of research in non-linear structural dynamics that have been briefly introduced in this section: Ground loads and Impacts.

2.0 DYNAMIC GROUND LOADS: NON-LINEAR RESPONSE TO DYNAMIC LANDING AND TAXI USING FULLY COUPLED LANDING/GEAR (L/G) – AIRCRAFT (A/C) SOLUTION

2.1 Taxi loads analysis

2.1.1 Introduction

Military transport aircraft are required to operate in unpaved runways. The landing gear (L/G) and the aircraft (A/C) shall withstand taxi loads that appear in such type of exigent operations. Taxi loads computation on L/G and on aircraft structure requires coupled analysis of a L/G non-linear model with the A/C linear dynamic model. To obtain meaningful numerical simulations, the coupled model results should be matched to a comprehensive set of aircraft taxi tests.

Taxi loads analysis has been structural dynamics engineers object of study for many years and is currently a well-established practice in industry. One of the first general use computer programs was the TAXI code[10] developed for the US Air Force in 1973 and used – for instance – to compute the dynamic aircraft response to bomb damage repair. AGARD conference devoted to aircraft dynamic response to damaged and repaired runways that was held in Brussels 1982 provided excellent papers[11] that still have current validity.

At the end of the 80s, CASA developed in-house software[1] to tackle the non-linear analysis in time domain resulting from the non-linear L/G with linear aircraft structure coupled model taxiing at constant speed over a surface of prescribed roughness. Many improvements have been added to that code since then, based on component tests and full-scale tests. Essentially, the code uses the normal modes obtained from any Finite Element Method (FEM) commercial software (like MSC/NASTRAN). Non-linear model of the L/G kinematics and L/G components like tyres, shock absorbers (S/A), etc. is included.

The process to derive a suitable numerical model to simulate aircraft taxi loads requires a significant effort from the analyst and can be split in the following steps:

- development of a taxi loads software tool.
- complete aircraft taxi test specifications, test performance and test results analysis.
- matching numerical model to test results.
- tool and matched numerical model industrial application to determine the runway roughness in which the aircraft is able to operate.

2.1.2 Problem statement

Dynamic loads due to taxi in unpaved or uneven runways can be the sizing cases for some L/G and A/C structure pieces or elements. They can also limit aircraft operation on this type of runways. The non-linearities present in the L/G constitute the main difficulty in these loads determination. These non-linearities are related with its kinematics and with some of its components elastic characteristics. The coupled system of equations that defines the aircraft-landing gear system movement is a non-linear system that should be solved numerically in an iterative process in the time domain.

The development of a software tool to solve this problem was done in EADS-CASA at the end of the 80s following the most general way to state it[10,11]. The aircraft structure is considered a linear system, its movement and deformation are governed by a set of equations formulated in modal coordinates. The L/G equations of motion keep all the kinematic non-linearities and the elastic non-linearities of tyres and shock absorbers, considering as rigid all the structural components that constitute the landing gear. These two systems coupling leads to a system of L/G equations of motion that takes into account its non-linear behaviour and its interaction with a flexible structure. The aircraft equations of motion in modal coordinates are:

$$[GM]\{\ddot{x}\} + [GS]\{x\} = [\emptyset]^T\{F_0\} + [\emptyset]^T\{F_{t/a}\} \quad \ldots(1)$$

where: $\{x\}$ is the modal generalised coordinate, [GM] is the matrix of generalised mass, [GS] is the matrix of generalised stiffness, [Ø] is the modal matrix, $\{F_0\}$ are the external forces and $\{F_{t/a}\}$are the forces applied by the L/G on the aircraft. The term $\{F_0\}$ allows including terms such as gravity, aerodynamic forces, engine thrust, brakes, etc.

The landing gear is considered like a mechanism of rigid elements on which the tyres, shock absorbers and the rest of the aircraft structure are acting. The L/G elements mass characteristics are represented by lumped masses with their corresponding inertial moments. The equations of motion are derived from the Lagrange equations, obtaining the following system in matrix form:

$$[\mathbf{TM}]\{\ddot{q}\} = [\mathbf{V}_r]\{F_r\} + [\mathbf{V}_a]\{F_a\} + \{F_{a/t}\} + [F_c] \quad \ldots(2)$$

where: $\{q\}$ represent the landing gear geometric co-ordinates, [**TM**] is the matrix of generalised masses, $[\mathbf{V}_r]$ is the tyre forces geometric transformation matrix, $\{F_r\}$ are the tyre forces, $[\mathbf{V}_a]$ is the shock absorber forces geometric transformation matrix, $\{F_a\}$ are the shock absorber forces, $[F_c]$ are non-linear terms in q and q and $\{F_{a/t}\}$ are the interaction forces aircraft-landing gear.

The system matrices (2) have a non-linear dependence on the degrees of freedom that define the L/G position $\{q\}$. The L/G elements large displacements (as a mechanism), as well as the kinematics relationship between $\{q\}$ and the tyres and shock absorbers deformations, do not allow to linearise those terms. The force produced by those elements depends, in non-linear form, on its deformation and, in the shock absorber case, on the deformation speed. The set of co-ordinates which define the L/G movement $\{q\}$, are divided in two groups, $\{q_d\}$ and $\{q_i\}$ depending on if they are dependent or independent of the aircraft structure co ordinates $\{x\}$.

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$$\{ q \} = \left\{ \begin{array}{c} q_d \\ q_i \end{array} \right\} \quad \ldots (3)$$

The relationship between the terms of interaction aircraft-landing gear from (1) and (2) is:

$$\{ F_{t/a} \} = - \{ F_{a/t} \} + \left[\bar{\mathbf{V}}_{a1} \right] \{ F_a \} \quad \ldots (4)$$

where $[\bar{\mathbf{V}}_{a1}]$ is a matrix which depends on the L/G type and the shock absorber orientation with respect to the structure. In the EADS-CASA tool there is a topological database with a set of different types of L/G that covers most of landing gears in use in current aircrafts.

Next step is to introduce the individual contributions of each landing gear component. The description of all the tyre forces and shock absorber forces details, with its two components (liquid and gas forces) etc, are beyond the scope of this paper and will not fit in this reduced number of pages. Let's only say that the non-linear differential equations resulting system are first approximated by finite differences and then transformed in an algebraic system that is solved using the Levenberg-Marquardt algorithm (a variation of the Newton method).

As a result of the system integration, in addition to the loads in the L/G elements and the parameters defining its behaviour (tyre deformation, shock absorber displacement…) the interaction forces between the A/C and the L/G can be obtained. These loads could be applied in turn to the aircraft structure to obtain the aircraft response on the considered runway.

The analytical method needs to be validated. The validation is achieved by numerical simulation comparison with test results.

2.1.3 Analytical method validation by test

An extensive tests campaign of the CASA C-295 aircraft taxiing/running over standard obstacles and a typical uneven/unpaved runway was performed in the year 2000[12]. The tests were performed in two phases. The first one was the jumping over standard obstacles required by the most common military regulations and were carried out on the paved Manises runway (Valencia). The second one consisted of trials with taxi, landing and take off configurations on a representative uneven/unpaved runway, Agoncillo airfield (La Rioja). This runway profile PSD would locate it in the upper band (the most severe) of the MIL-A-87221 normative semi-prepared runways.

An exhaustive instrumentation pick-ups set covered the entire aircraft structure (wing & HTP tips; nose & rear fuselage; engine & aircraft c.g.; …) and the L/G (leg forces; shock absorber force & deflection; shock absorber oil & gas pressure; …).

The obstacles type selection is a critical choice in these tests. As in any other dynamic test oriented to match a numerical model, test conditions (in this case, test obstacles) should reflect as close as possible the real operational environment. Short obstacles can be the most critical for L/G components, but in a real unpaved or uneven runway, the obstacles typical wavelength is of tens of meters. These considerations lead to the selected obstacles:

- Taxi over standard obstacles built specifically for these tests in the middle of a regular paved runway. The reason of using a paved runway before the obstacle is that the aircraft conditions and attitude just before the obstacle can be more easily controlled and known for subsequent comparison with the numerical simulations.
  - Standard short obstacles:
    - single rectangular step (1m length, 60mm height) to analyse the tyres maximum deformation.
    - single repair-plate MAT-2 (1·5m up ramp, 1m flat, 1·5m down ramp with a max. height of 60mm) to analyse the system response to a single impact
    - double repair-plate MAT-2. It consist in two single MAT-2 separated by 20m. The aim is to analyse the effect of a second impact tuned with the first one.

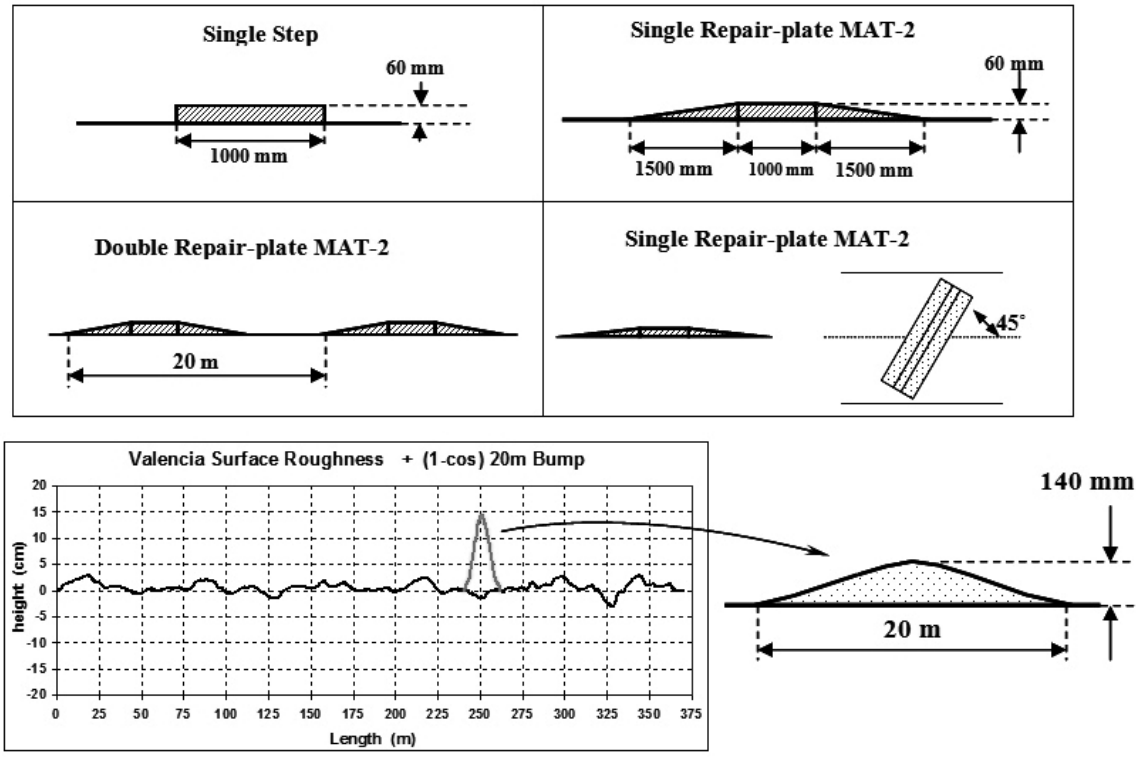


Figure 2. Top: the four short obstacles used in the CASA C-295 taxi tests campaign.
Bottom: (1-Cos) 20m long obstacle used in the CASA C-295 taxi tests campaign.

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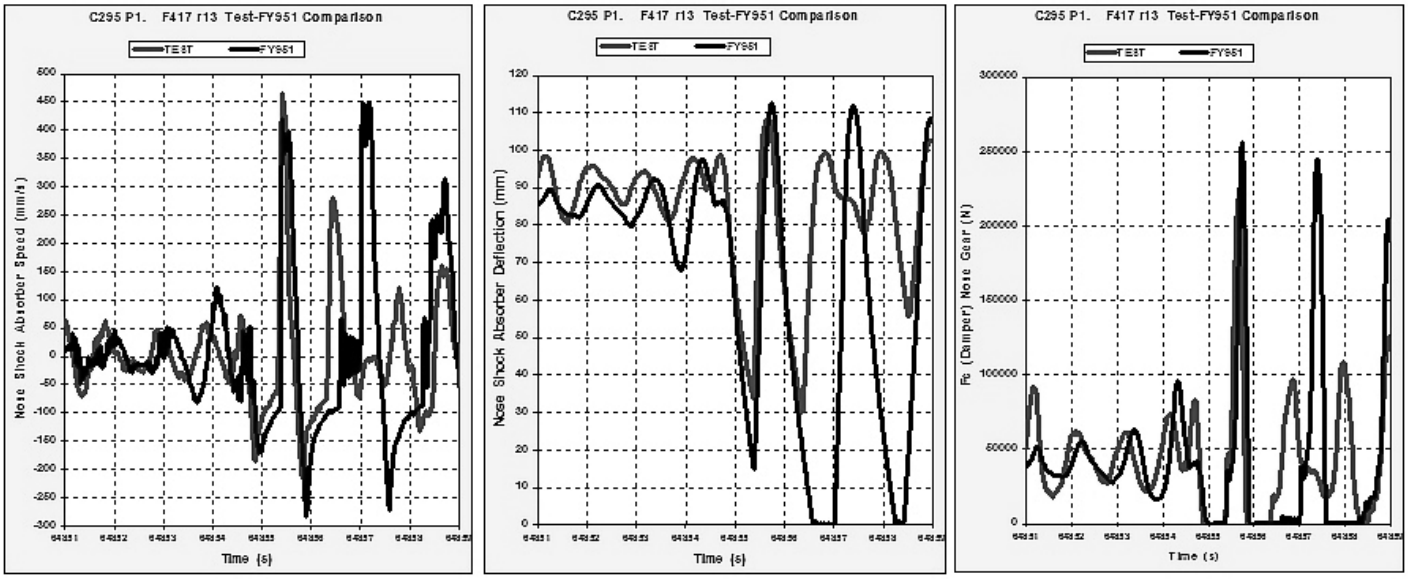


Figure 3. C295 taxi tests comparison with pre-test simulation. NLG S/A speed (left), stroke (centre), force (right).

– single repair-plate MAT-2 traversed at 45°, to analyse lateral loads and A/C roll.

– Standard long (1-Cos) obstacle (20m) to study the system response to an obstacle representative of real unpaved runways but under controlled circumstances.

- Unpaved real runway (Agoncillo) to analyse the system behaviour in a real scenario.

Successive runs over each obstacle were carried out by increasing the speed from 20kt up to 100kt and with use of brakes and c.g. position, flap setting, engine thrust variations.

Pre-test simulations were performed with the numerical model obtained in the CASA CN-235 aircraft taxi tests[1] (early 90s) corrected with C-295 L/G manufacturer nominal data. Figure 3 shows some comparison of C295 taxi test results (blue curves) with pre-test simulations (black curves). Right-hand plot shows the NLG Shock Absorber (S/A) force versus time. When this force is zero this means that the nose tyre has separated from the ground. There is a significant difference between the two curves, not only in peak values but also in the evolution versus time and specifically in the time ranges in which nose tyre is not in contact with ground. Because this parameter is very important to reflect that the aircraft global attitude has been adequately represented, the model should be updated to close the gap between these curves. Curves in the left-hand plot (NLG S/A speed) and centre plot (NLG S/A stroke) show also differences.

The key factor in the matching process is to tune, as close as possible, the shock absorber (S/A) speed. Three parameters needed to be updated in the shock absorber model:

- The S/A gas polytrophic constant (γ): The same value ($\gamma = 1{\cdot}2$) was used for all legs and conditions in pre-test simulations. Nevertheless, test results showed that:

  – high piston speed in the S/A movements has higher γ values than low piston speed.

  – for high piston speeds, the Main LG has higher γ values than Nose LG.

  – low piston speeds correspond to the stage before the obstacle jumping, and high piston speeds to the obstacle jumping and subsequent time instants.

- The friction between the shock absorber cylinder and piston: It was fixed to the value suggested by the manufacturer ($\mu = 0{\cdot}1$). The friction is opposed to the piston movement, decreasing its velocity. The friction force value is similar in extension and in compression phases. Nevertheless, the friction effect is larger in the extension phase because the rest of forces are lower. Therefore, the friction main effect is to decrease the piston speed during the expansion phase.

- The oil damping constant in the extension phase (KE) has to be obtained from the numerical simulation results to the test results matching. This is done once γ and μ have been updated. Oil constants in the extension phase have been increased to tune test results piston velocities and shock absorber deflections.

Figure 4 shows the test-analysis comparison after model updating for several NLG S/A magnitudes. Plots show a piston speeds very good tuning (left) and in turn a good correlation in stroke (centre) and forces (right). After all the runs comparison, a conclusion is that the correlation has been good, being the numerical simulation – in general – slightly conservative. The matching has been performed for the so-called magnitudes 'large values' (speeds, strokes and forces), paying less attention to the tuning process in the case of magnitudes 'low numerical values'.

Table 1
Polytrophic adjustment versus piston speed

	Before obstacle jumping Low piston speed	Obstacle jumping and subsequent phase High piston speed
Nose landing gear	$\gamma = 1{\cdot}0$	$\gamma = 1{\cdot}2$
Main landing gear	$\gamma = 1{\cdot}0$	$\gamma = 1{\cdot}4$

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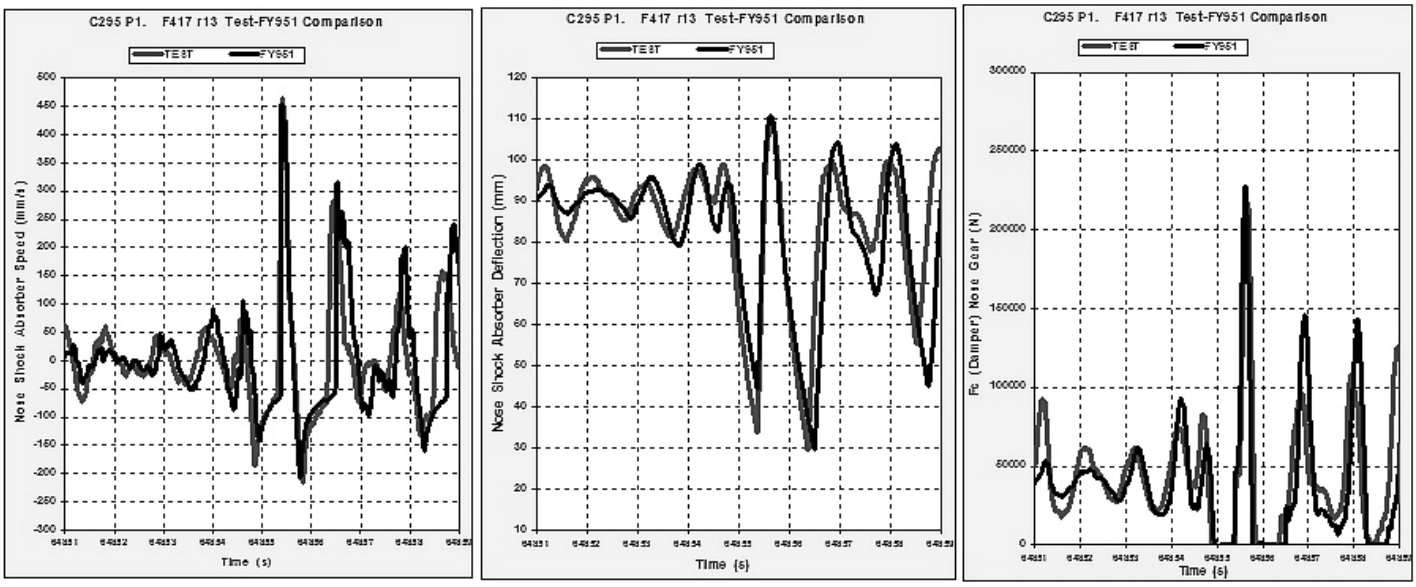


Figure 4. C295 taxi tests comparison with post-test simulation. NLG S/A speed (left), stroke (centre), force (right).

2.2 Dynamic landing analysis

2.2.1 Introduction

During landing, the aircraft vertical velocity is quickly reduced to zero when wheels strike the ground. This process transfers the sinking aircraft kinetic energy to internal energy in the shock absorption system. The rapid change in velocity and equally rapid forces application causes dynamic phenomena in the aircraft structure. Dynamic landing loads may be the sizing cases for some aircraft components like forward and rearward fuselage or wing down bending.

First attempts to address the dynamic landing problem made the assumption that the 'landing impact force is independent of structural response'[13,14]. The 'uncoupled assumption' allows the problem treatment as two separate systems: landing gear and aircraft. The L/G is a complex and very non-linear system which representation should include the L/G kinematics, components like tyres, shock absorbers, spinning wheels to account for spin-up and spring-back effects, etc. When analysing the L/G under this uncoupled assumption, the aircraft is considered rigid. The landing gear numerical model is used to obtain transient loads at the pintle points time-histories. Then, these pintles loads are applied to an aircraft flexible model to obtain the internal loads at the aircraft structure. This typically conducts to slightly conservative results in relatively rigid aircrafts where in turn these cases may be non-dimensioning cases.

For larger and more flexible aircraft, the 'uncoupled' assumption may produce too conservative loads. In addition, for these aircraft, dynamic landing cases may be the critical ones for some components. Therefore, continuing with the 'uncoupled' assumption may produce an undue penalisation of aircraft structural weight. To avoid this, a coupled landing gear and flexible aircraft approach should be followed. Non-linear models of all landing gear components (tires, shock absorber, large displacements, legs flexibility, adequate local pintle representation, etc.) should be coupled with the classical aircraft linear model. Then a mathematical procedure to couple both models should be established (similar to what is already used in taxi loads analysis [2]).

In order to validate the numerical simulation approach a series of experimental tests are required:

- Landing gear drop test. Performed, previous to the aircraft first flight, with the aim to validate the L/G models.
- Full aircraft landing flight tests[15], in order to validate the coupled approach.

2.2.2 Problem statement

EADS-CASA is using the modern coupled approach for some years in the A400M design, an aircraft in which dynamic landing cases are sizing large parts of its structure. The approach uses the Finite Element Method (FEM) technique to model completely the L/G, the A/C and the coupling:

- L/G modelled using MSC.ADAMS
- A/C modelled using MSC.NASTRAN
- coupling using MSC.ADAMS

In order to obtain the L/G-A/C attachment loads taking into account the A/C flexibility, the appropriate way to introduce the A/C FE model is to use the Craig-Bampton Method, a component mode synthesis technique for tailoring the modal basis to capture both the desired attachment effects and the desired level of A/C dynamic content. The coupled system of equations that defines the system aircraft-landing gear movement is a non-linear system that should be solved numerically in an iterative process in the time domain.

Figure 5 shows (left) an A400M aircraft landing idealisation. On the right-hand, the vertical forces on pintles summation comparing coupled-uncoupled assumption can be seen. In this large and very flexible aircraft, a difference in the order of 10% can be observed what in turn will result in internal loads significant differences and the corresponding structural weight.

Figure 6. shows (left) the C295, a medium and less flexible aircraft. On the right-hand, a comparison of internal forces (bending, shear, torque) calculated at the wing root comparing coupled-uncoupled assumption. Although differences are lower than those obtained in the A400M, the coupled approach could either save structural weight or improve the aircraft.

2.2.3 Analytical method validation by a hard dynamic landing test

Real aircraft landing flight tests are needed to validate the mathematical coupled approach. But before them, the two main actors are tested separately: aircraft in the Ground Vibration Test (GVT) and landing gear in the drop test.

EADS-CASA has validated the coupled assumption making use of C295 Full aircraft landing flight tests[15]. These tests were landings at several sink speeds including a severe hard landing close to 12ft/s. An exhaustive set of instrumentation pick-ups covered the entire aircraft structure and the landing gear.

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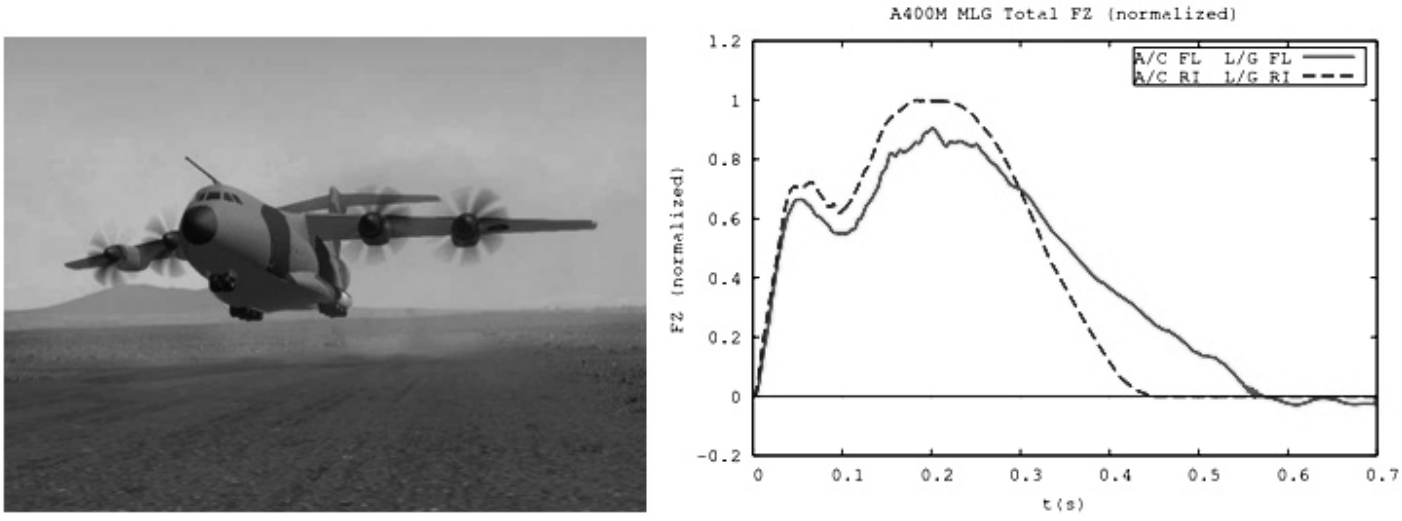


Figure 5. A400M heavy transport military aircraft (left). Summation of vertical forces at pintle points. Coupled (continuous red line) / Uncoupled (dotted blue line).

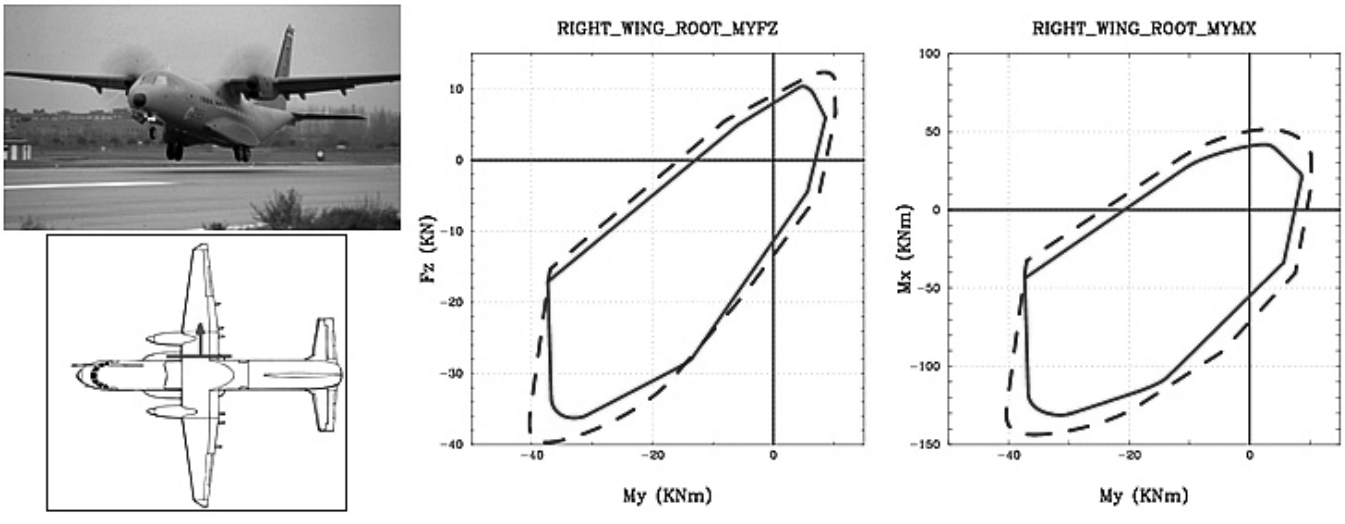


Figure 6. C295 Medium transport military aircraft (left). Wing root internal loads comparison: Coupled (continuous red line) / Uncoupled (dotted blue line).

Numerical simulations were performed using MSC.ADAMS tool with the C295 A/C and L/G fully coupled. Figure 7 shows a comparison test-simulation of three acceleration time-histories corresponding to wing tip, HTP tip and rear fuselage. Continuous red line represents the numerical simulation while the black line is the measured test result. A green line on top of each plot indicates the relevant control surface deflection (aileron for the wing, elevator for the HTP). All of them correspond to the hard dynamic landing case close to 12. The time-histories show a good comparison in both, shape and evolution with time.

3.0 IMPACTS TECHNOLOGY: EXPLICIT FINITE ELEMENT METHODOLOGY APPLICATION

3.1 Introduction

Aeronautical airworthiness regulations (CS-25) explicitly require to aircraft structures to resist specific impact conditions that may occur during aircraft in-service life:

- bird impact against lifting surfaces and low curvature panels.
- metallic and composite fuselages crashworthiness.
- emergency landing due to wheels extension failure (wheels up landing).
- emergency landing on water (ditching).
- impacts originated by propeller malfunctions like blade loss.
- impacts due to ice released by the blade.
- vulnerability applications for composite fluid-filled structures protection against fragment impacts in military applications.

The means of showing compliance with these conditions are typically analysis, tests or combination of both.

During last decades numerical simulations have gained maturity for impacts analysis. As a consequence, explicit FE methodology is used to complement tests in these impact conditions certification process.

High velocity impacts are dynamic problems highly non-linear in nature. Sources of structural non-linearity arise from contact boundary conditions to complex material constitutive laws plasticity in metals, damage in composite materials, hydrodynamic models, etc– and from inherent large strain and displacement conditions to material failure. These specific characteristics plus impacts phenomena reduced time scales make explicit FE numerical methods

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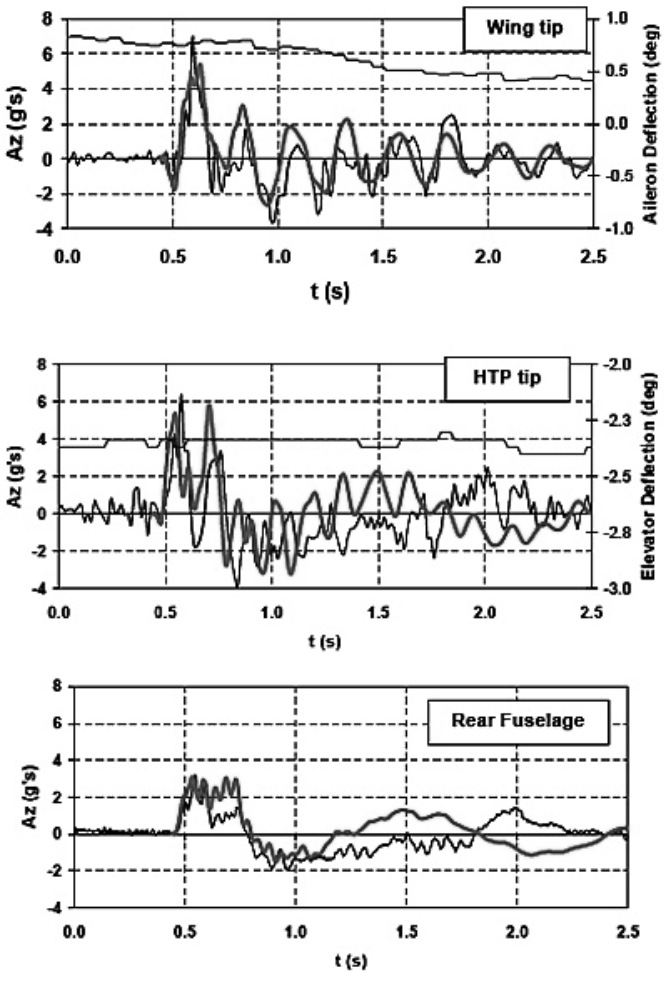


Figure 7. C295 test-simulation comparison. Acceleration time-histories due to a 12ft/s dynamic landing.

a good option to address this type of problems. This formulation main advantage is that equations of motion are solved locally, node by node, without the need of assembling global matrices. Since all equations are uncoupled, the procedure is very simple and extremely robust, even with difficult contact conditions or sophisticated non-linear material models. The limitation imposed by stability on the integration time step size is obviously of little consequence in a short-duration problem.

3.2 Bird strike

EADS-CASA accumulates an extensive background in bird strike numerical simulations gathered during the past 20 years.

One of the major challenges in bird strike simulation is how to properly model the impactor (bird) in terms on non-linear material equations and element formulation[16]. Initially, bird models were prepared using classical Lagrangian formulation. However, a step further was to include SPH (Smooth Particle Hydrodynamics) elements and tune their properties by means of tests. This formulation is much suitable to deal with large deformation patterns typical of this kind of problem. Figure 8 presents a comparison of both modelling types in the Airbus A340 Horizontal Tail Plane (HTP) leading edge bird strike simulation.

One of the inherent characteristics of non-linear problems is that two apparently similar initial conditions may end with very different final result. From the engineering standpoint, solving non-linear problems means also solving the way of handling uncertainties. These uncertainties are inherently present in any physical problem: in materials, in the specimen manufacturing tolerances, in impactor characteristics… An appropriate way of handling uncertainties is by using the stochastic approach. Within the CRAHVI project framework (2001-2003), EADS-CASA developed, implemented and validated a stochastic methodology applied to the problem of high velocity impact/crashes on aeronautical structures[17,18]. In particular and for the bird-strike numerical simulation, this methodology has been applied to:

- A340 HTP metallic leading edge design improvement[17].
- EF-2000 metallic slat certification, only by means of numerical analyses[19].

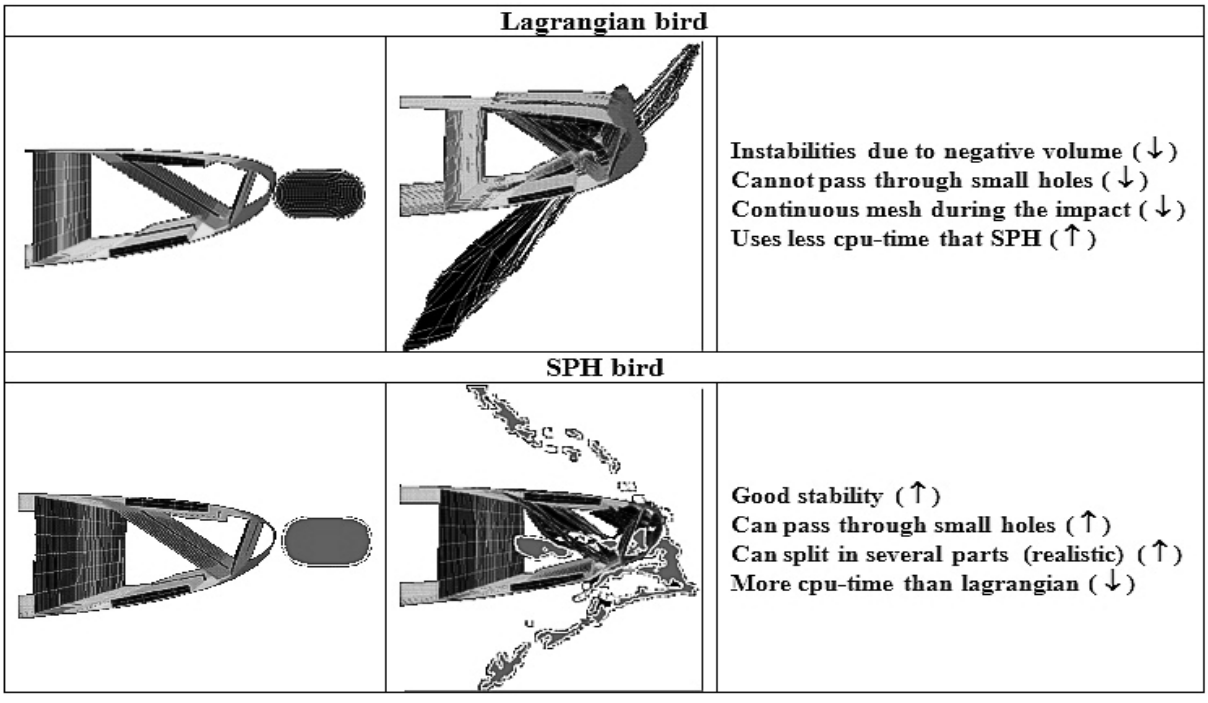
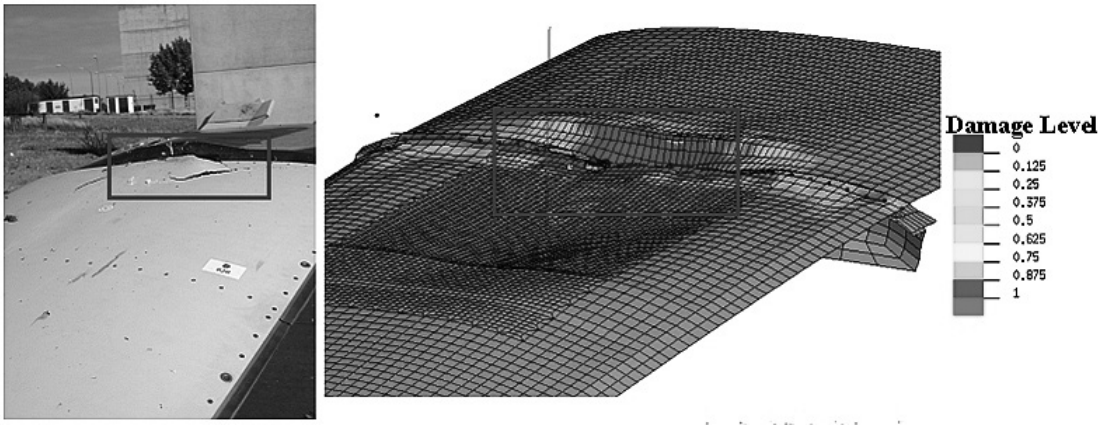
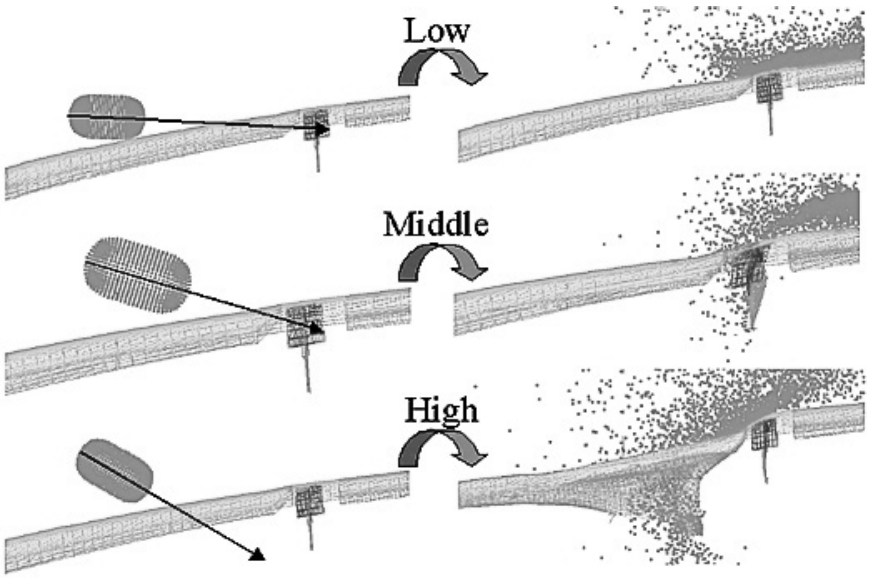


Figure 8. Comparison of two bird modeling approaches: lagrangian (top) and SPH (bottom).

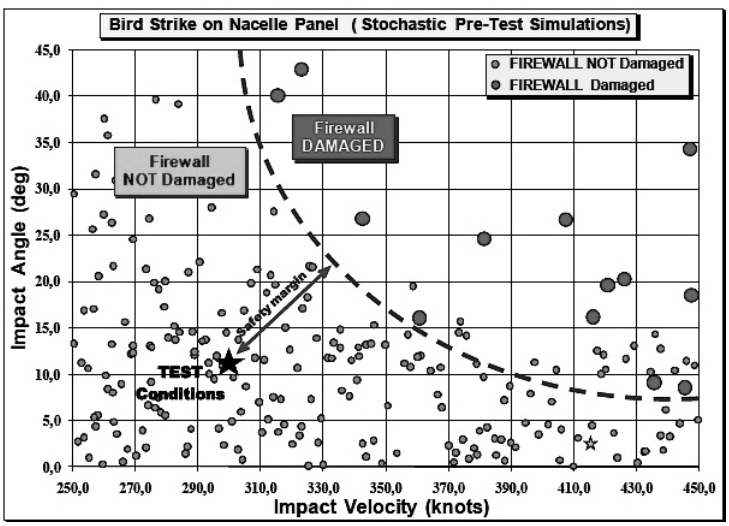
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(a)



(b)



(c)

Figure 9. (a) A400M nacelle upper cowl explicit FE model matched to bird strike test.
(b) A400M nacelle upper cowl damage extension as function of bird impact angle
(c) A400M nacelle upper cowl design failsafe curves for bird strike. Sensitivity to impact velocity and angle.

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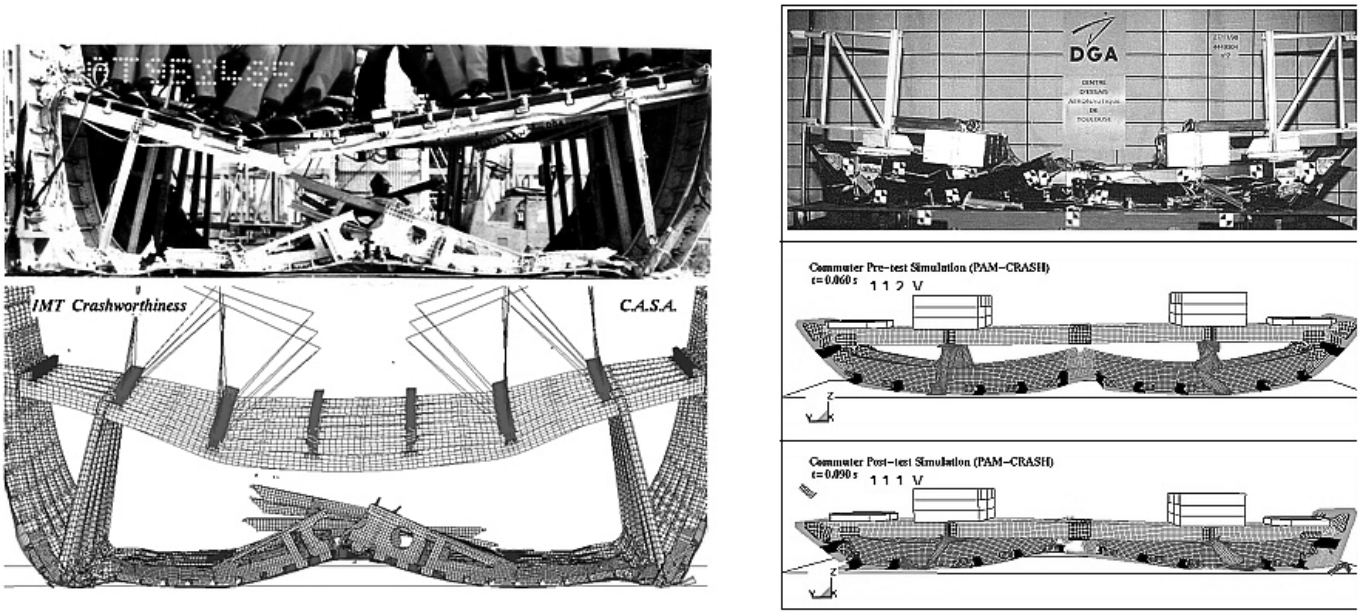


Figure 10. Airbus A320 fuselage slice drop test sequence, left[5]. Commuter composite drop tests, right[6]. Comparison of tests and numerical simulations.

- reduction in the number of Falcon F7X HTP leading-edge qualification tests.
- A400M HTP monolithic composite leading edge design[20].
- A400M nacelle upper low curvature honeycomb panels certification[21].

As an example of recent application, a model of the A400M nacelle upper cowl low-curvature honeycomb panel was prepared and matched to bird strike tests[21]. This numerical model has been very useful to analyse additional configurations that were not experimentally tested. The stochastic approach helped to deal with many design uncertainties and it has been crucial for this component certification purposes (Fig. 9). This model included uncertainties due to material properties and also deterministic variables that could vary within certain ranges, like bird velocity and angle of impact.

3.3 Crashworthiness

From 1993 to 1996 CASA participated in the EU founded CRASHWORTHINESS research project. The main milestone of CASA in this project was the numerical simulation of the Airbus A320 complete metallic fuselage slice (five frames) drop test made by CEAT at its facilities in Toulouse[5]. The final numerical simulation correlation with tests was excellent (Fig. 10, above left).

From 1997 to 2000 CASA crashworthiness activities were performed in the CRASURV project framework[6]. The objective of this program was to develop the technology for the composite airframes design with maximum safety with respect to potentially survivable crash scenarios. It was the CRASHWORTHINESS project natural continuation because it extended the features developed for metallic fuselages to composite fuselages, including damage propagation and material failure.

The last European initiative in which CASA participated was the CRAHVI project[22] (2001-2004) that was devoted to high velocity impacts on aeronautical structures. The main activities were numerical simulation and correlation with impact tests of: bird strike on HTP, HTP crash against an ILS tower obstacle and flying debris impact on HTP. CRAHVI included non-linear numerical simulations using explicit FE models and stochastic methods to deal with uncertainties probabilistic approach and design optimisation.

Two direct applications of these three research projects about different aspects of crashworthiness were:

- impact load calculations for the A400M aircraft wheels up landing certification.
- CN-235 US Coast Guard version ditching certification.

These works are described in the subsequent sections.

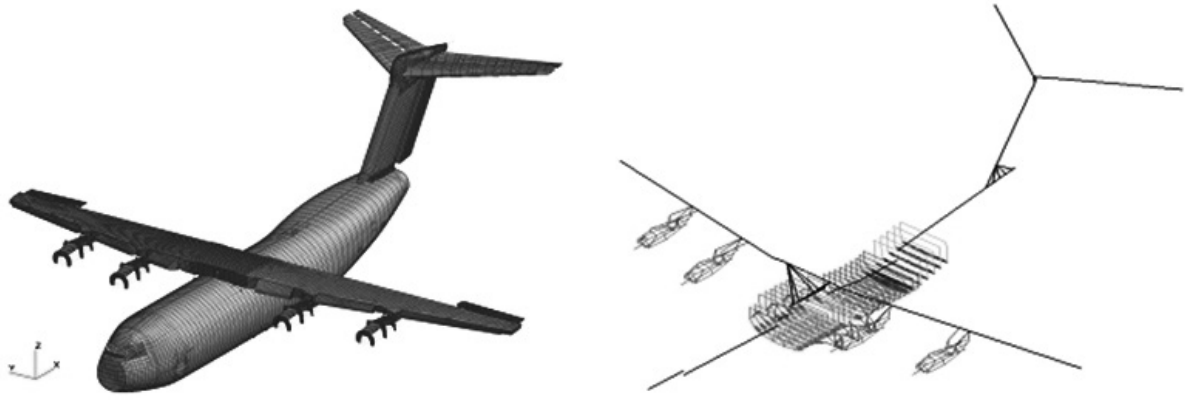


Figure 11. A400M FE models: linear FE model (left) and non-linear WUL model (right).

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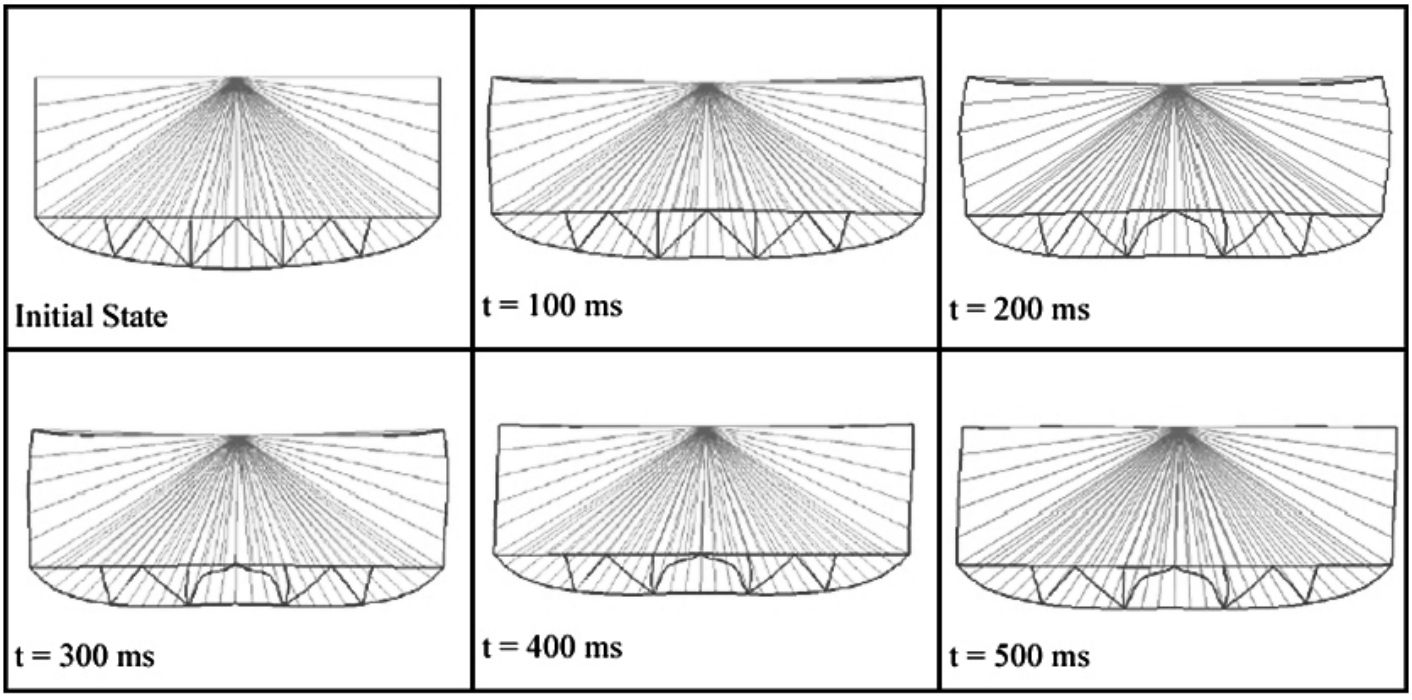


Figure 12. Deformed crushable structure, scale factor 1·8 – Pitch 6·9º.

3.4 Wheels-up-landing

Wheels Up Landing (WUL) is an emergency event in which the aircraft makes a controlled landing on a paved runway without one or more landing gear legs extended. According to current regulations, the aircraft must be designed to withstand the loads derived from a landing event with all gears retracted or any combination of gear legs extended or retracted without sustaining a structural component failure that is likely to spill enough fuel to constitute a fire hazard. EADS-CASA has been in charge of WUL loads calculations[23,24,25] in the large transportation A400M programme.

In the all-landing-gear-legs-retracted configuration, impact is studied on the basis of an explicit FE model. The selected approach for the WUL impact consisted of generating a simple global model representing the aircraft overall mass and stiffness distribution and implementing at every impacting fuselage frame a crushable structure to provide the required contact interface with the runway. This approach combines the ability of calculating impact loads in a non-linear approach and obtaining results at monitor station level. That allows an immediate comparison with the rest of A/C design loads.

Non-linear FE model overall view is presented in Fig. 11 (right), where the global stick model is shown in black lines, while the crushable structure, the main landing gear (MLG) structure and engine mounting system (EMS) are in colours.

The structural behaviour of low-fuselage impacted frames involved in a 6·9º pitch angle case is shown in Fig. 12. The large displacements obtained in the under floor bars are evident. In these high pitch angle scenarios, the lower and upper caps transmit the load exerted by the impact at the mid-span (XZ A/C symmetry plane) to the points of connection with the stick model corresponding node.

The internal forces monitored at the stick model nodes along the fuselage longitudinal axis are plotted in Fig. 13 which represents the maximum and minimum bending moment along the fuselage (loads envelope). This type of envelope allows a direct and clear comparison between the structure WUL loads and ultimate design loads, which turned out to be particularly useful for screening purposes.

The impact problem is solved by using an explicit numerical approach. Loads results (in form of envelopes along fuselage, wing and principal structural elements) do not exceed aircraft ultimate design loads and may be directly compared with the rest of aircraft design cases (manoeuvre, gust, landing, taxi, continuous turbulence, etc.).

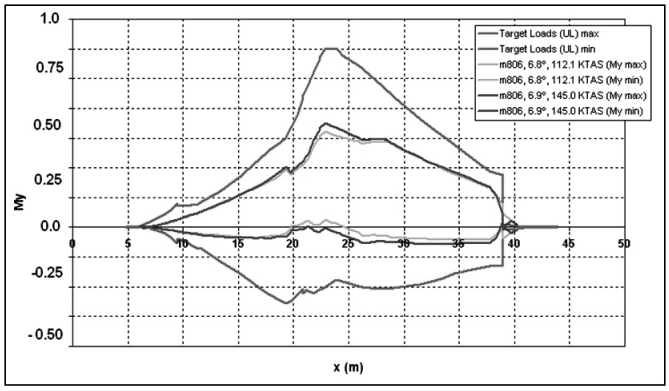


Figure 13. WUL fuselage envelope. Pitch 6·8 º and 6·9º -MLW, 145 KTAS, flap 47º-

3.5 Ditching

Ditching is an aircraft emergency condition that ends with the aircraft planned impact with water. This kind of impact develops high pressures which may cause the structure rupture, jeopardising the required safe evacuation of crew and passengers[26].

The classical approach to ditching has been to test a ditching mock-up under several ditching scenarios. By these means, the mock-up global behaviour is assessed and extrapolated to the real aircraft size in order to define the optimum ditching conditions. In addition, the mock-up is instrumented with pressure transducers that in turn may be used to compute loads on the structure.

For the CN-235 US Coast Guard version ditching certification, the approach followed by EADS-CASA was twofold (Fig. 14):

- Perform a ditching test campaign[27] with a 1:8 subscale model covering 112 ditching conditions (varying A/C mass state,

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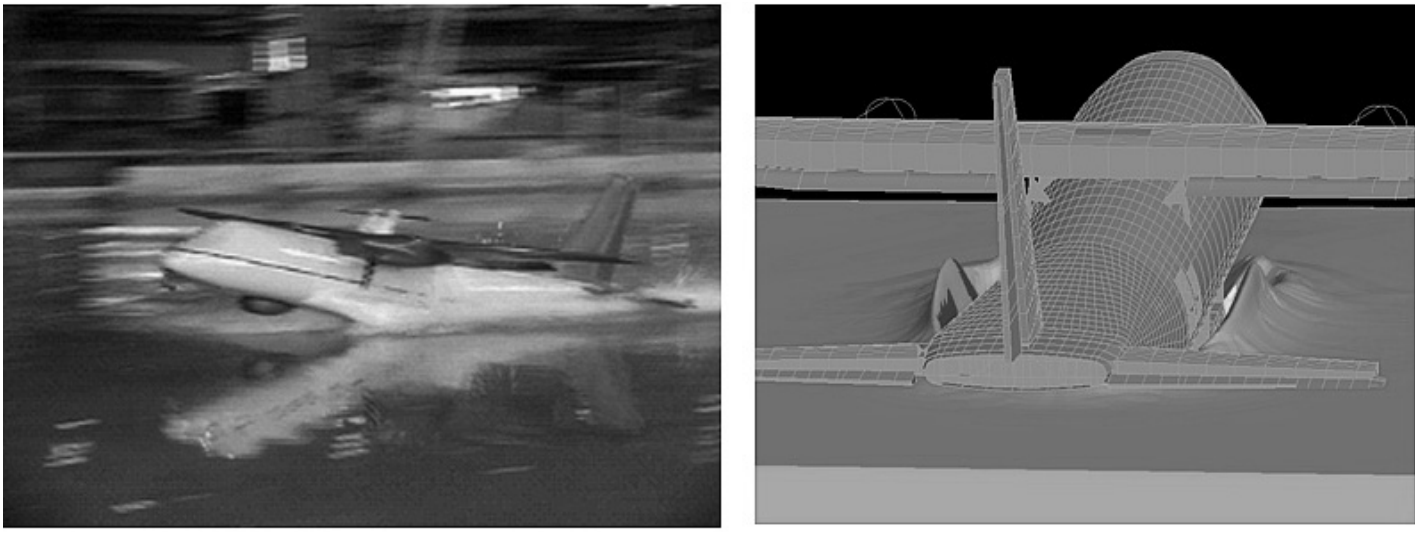


Figure 14. CN-235 subscale ditching tests (left). CN-235 vertical drop numerical simulations (right).

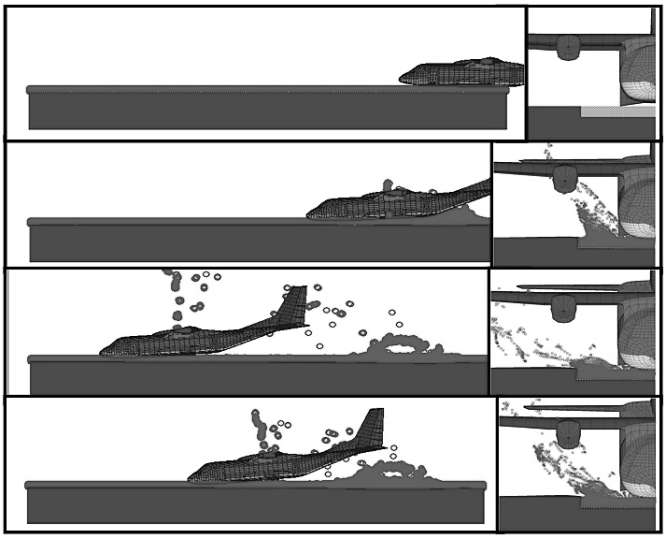


Figure 15. CN-235 Numerical simulation considering the horizontal component of velocity and water modeled with smooth particle hydrodynamics (SPH).

ditching velocities and attitudes, sea state, etc.). Pressure transducers at the lower fuselage allowed to measure the pressure field due to water contact.

- Hybrid approach that combined tests with impact numerical simulation to justify fuselage structure resistance. In particular complete numerical simulations considering the water – structure interaction for cases with vertical-velocity only (i.e. helicopters) were very promising. The use of techniques like Smooth Particle Hydrodynamics (SPH) has proven to be very effective in vertical impacts[28] in which good correlations have been demonstrated with tests including full-scale tests.

However, cases with combined vertical speed and horizontal speed (i.e. aircraft) are significantly more difficult. Pressures on the aircraft structure produced by water may be either positive (over pressures) or negative (suction) and the SPH technique with the available constitutive laws is not able to properly represent suction forces (Fig. 15)

Since pressures on the fuselage were measured directly in the scale-model, next step of numerical simulations was the use of measured pressures to justify the structure under ditching loads. The success of numerical simulation for vertical ditching impacts may be used to determine factors that account for the flexibility effect that in turn may be used to reduce pressure loads.

The non-linear structural analyses performed (Fig. 16) showed that the aircraft is able to withstand the first impact derived loads, and that the effects of first touchdown analysis covered the subsequent ones. The aircraft checkstress verification was performed with a detailed explicit FE model loads with scaled pressures from tests.

3.6 Ice impacts

During turboprops operations, and under adverse atmospheric conditions, some ice aggregates on the propeller blades. This ice may be released from the blade tip at high speed and it may impact on the neighbour structure causing damages. In the A400M project EADS-CASA launched an internal research programe[29] devoted to gather test information to adequately simulate this event. The project had several steps:

- First, a gun was designed and manufactured, suitable to launch ice-slabs at the adequate speed (i.e. long distance of acceleration inside the gun in order not to break the ice).
- A test facility was designed to reproduce as close as possible the propeller-released-ice-impacts physics. A dedicated room at the Carlos III University of Madrid was selected to install the specific slow acceleration gun needed to shot the ice sheds without destroying them in the acceleration phase.
- Tens of composite structures specimens were manufactured and tested against ice impact, first without protection and then with different types of protection. The test campaign was split in several increasingly complex phases:
  - slow-speed impacts on rigid surface.
  - high-speed impacts on rigid surface.
  - impacts on composite unprotected specimens.
  - tests on protected specimens.

The composite specimens were manufactured from same material as A400M nacelle. Figure 17 shows an example of a high-speed ice-shed impact on an unprotected specimen where damage is clearly visible. On the other hand, the protection performance glued to the composite panels improves significantly its impact behavior.

The non-linear explicit FE simulations were focused on a proper ice shed modelling using Smooth Particle Hydrodynamics (SPH) particles with hydrodynamic constitutive equations. Figure 18 shows comparison between tests and numerical simulation after the model

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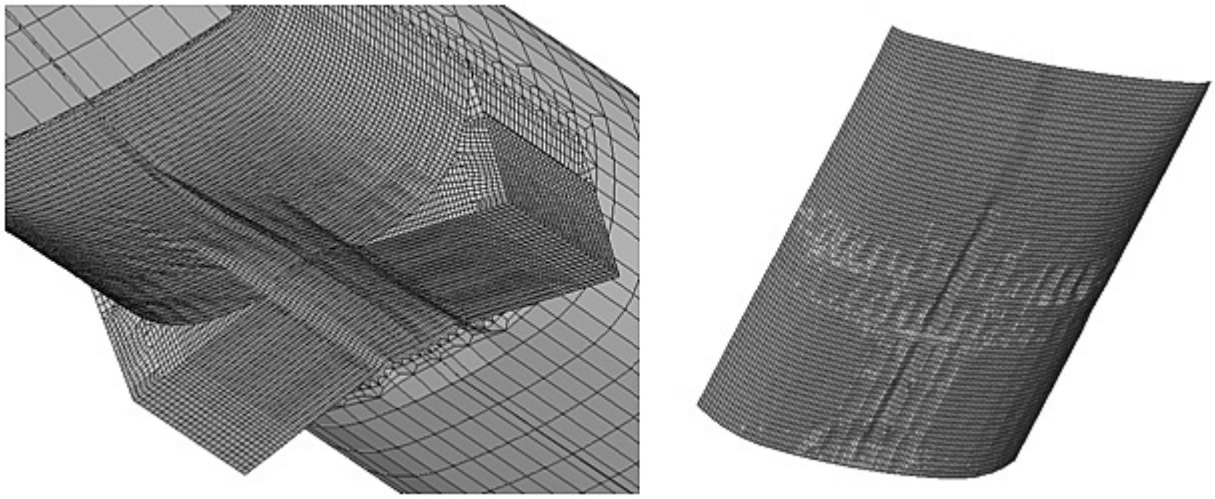


Figure 16. CN-235 Ditching structural analysis.

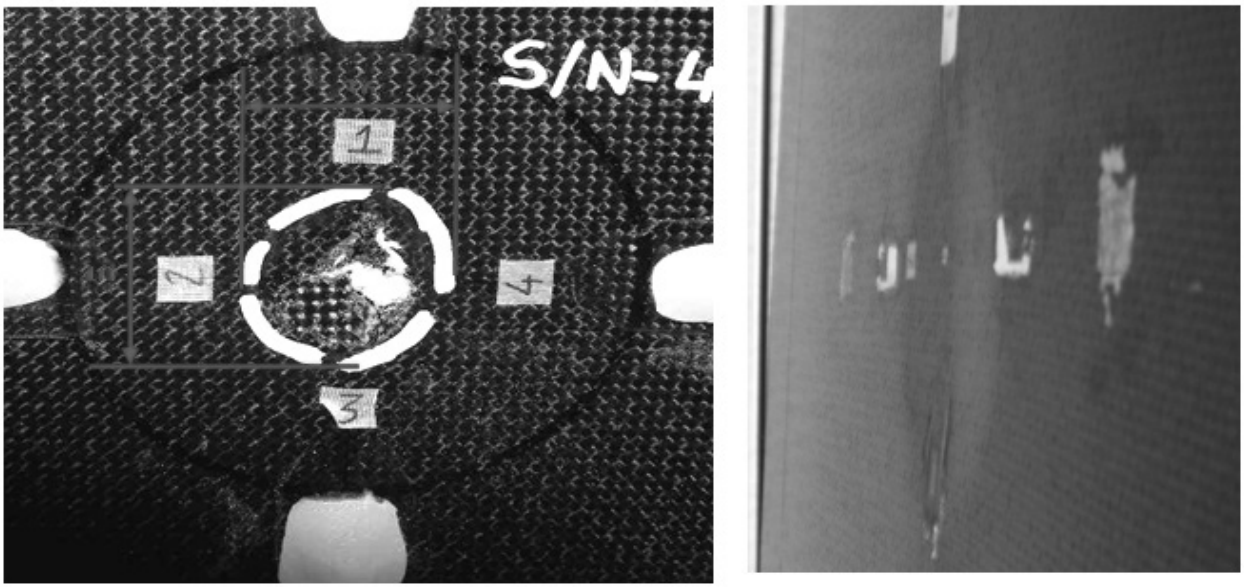


Figure 17. Ice-shed impact on unprotected (left) and protected (right) composite panel.

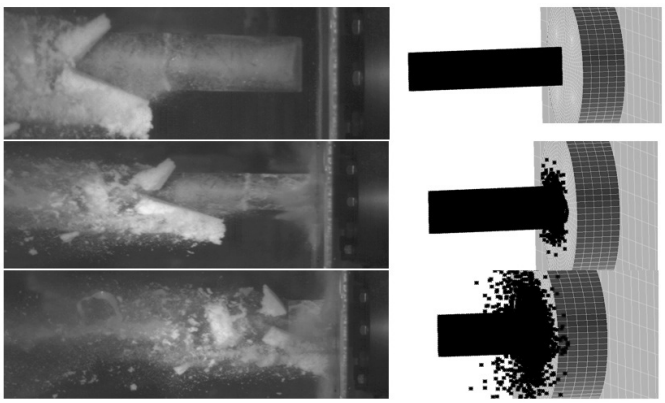


Figure 18. Comparison of ice impact collapse sequence on a rigid surface (368J / 90º).

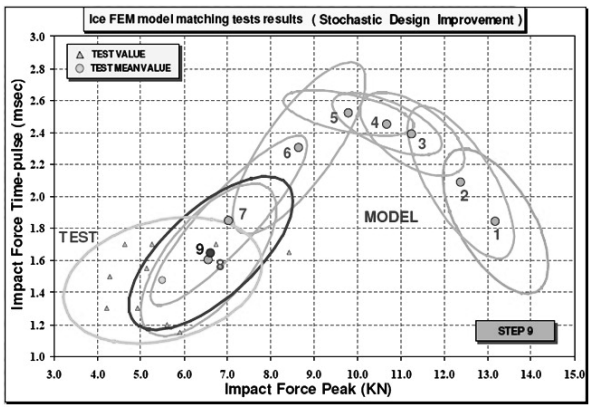
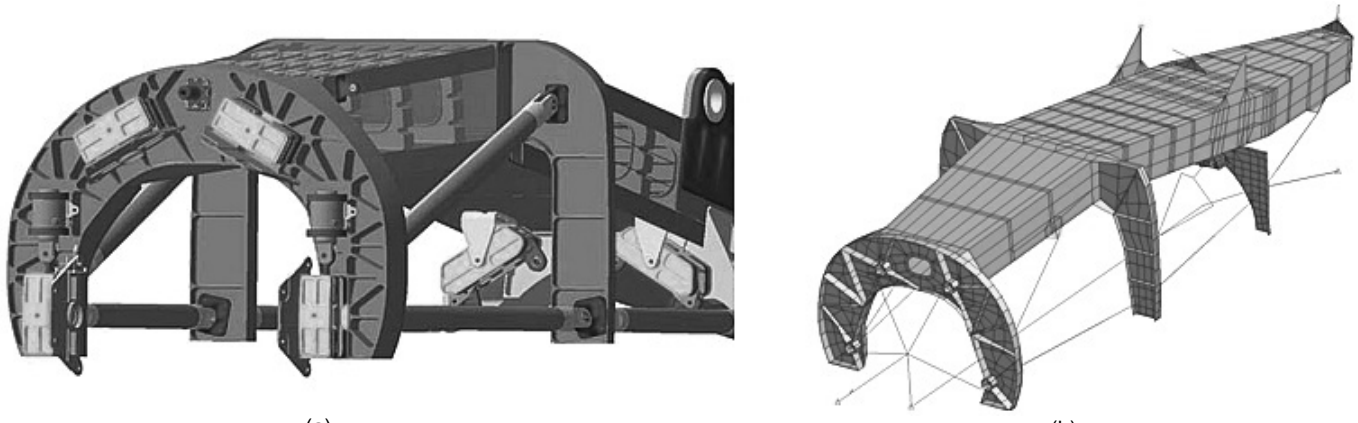


Figure 19. Correlation simulation progress – tests made with stochastic analysis.

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(a) (b)

Figure 20. (a) A400M engine mounting system (b) EMS FE model – shells and bars – and engine – beams.

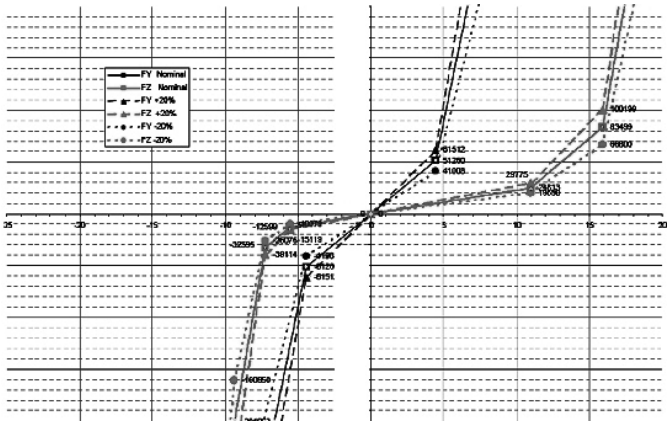


Figure 21. Typical non-linear material curve of an elastomeric device.

matching using stochastic methods for the ice model parameters (Fig. 19).

As a result of the research a deep insight on the composite structures behavior under ice impacts has been gained. Enhanced ice-protection designs have been defined and the area to be protected will be reduced to the minimum needed, thus optimising the added weight due to protections.

3.7 Blade loss

Current regulations concerning turboprop aircrafts require minimising the risk in case of a blade loss. The release of one of the propeller blades produces a strong unbalance at the propeller centre due to rotating centrifugal force. This force is proportional to the propeller mass and to the square of rotating velocity. Dynamic effects may cause high load levels at engine, engine supports –usually elastomeric devices–, engine mounting system (EMS) (Fig. 20), wing and the rest of the A/C.

In most cases, unbalance due to blade release has not been catastrophic because it only causes severe damage at the engine and its supports. Precisely, these devices failure, typically elastomeric, interrupted the load path to the rest of A/C structure and dynamic transient loads are significantly damped. Therefore this is a dynamic problem where structural fuses are expected to fail in order to minimise risk for the rest of the structure.

This non-linear problem needs the elastomeric devices rupture characteristics consideration in addition to its non linear stiffness, (Fig. 21). In the frame of A400M programme, EADS-CASA is responsible of blade loss load calculations and a non-linear explicit FE simulation is currently on course. This simulation models the structural elements that connect the engine to the EMS collapse sequence.

3.8 Vulnerability

The main 'Low vulnerability structures for military aircraft' project objective, taking into account a structural box performance against impacts, was to obtain the more complete comprehension of damage on a carbon-fibre-reinforced-panel (CFRP) wing fuel tank primary structure when a missile fragments impact on it. That would consolidate design improvements, protection materials and repair concept developments. This project was developed within the framework of EADS Research and Technology Project RTP 3.32[30].

Fluid filled structures have a special damage mode with respect to ballistic impact: the HRAM effect, resulting in non-localised damage from a much localised event. Structures susceptible to HRAM are all integral tanks, where a direct coupling of pressure waves in the fluid and the tank structure is possible. In a modern fighter such integral tanks can be embodied in the fuselage, mainly in its upper part, and in the wing tanks. Former threat analyses have revealed that the most probable shot lines come mainly from the target A/C lower hemisphere. Therefore, wing tanks are more vulnerable due to larger area being exposed to the threat and hence resulting in a high probability of being impacted.

A set of experimental tests was performed considering a simplified CFRP structure of integral fuel tank, where fluid pressures measurements were taken using two gauges placed in threaded holes inside the lateral window. Numerical studies performed using Smooth Particle Hydrodynamics (SPH), after a necessary fluid medium equation of state calibration, provide good agreement with tests in terms of projectile evolution in the fluid. Figure 22 shows the pressure field in the cavity which is extremely dependent on the minimum number of particles and the proper impactor deformation representation. In addition, numerical simulations to study protection materials benefits, design parameters and the effect of pre-load due to evasive manoeuvre have also been done in the EADS RTG 3.32 program.

4.0 CONCLUDING REMARKS, LESSONS LEARNED AND FUTURE CHALLENGES

This paper has revisited 25 years of research and development in structural dynamics non-linear problems at EADS-CASA (Airbus Military). References of the work carried out on non-linear aeroelastic activities have been omitted because of space limitation.

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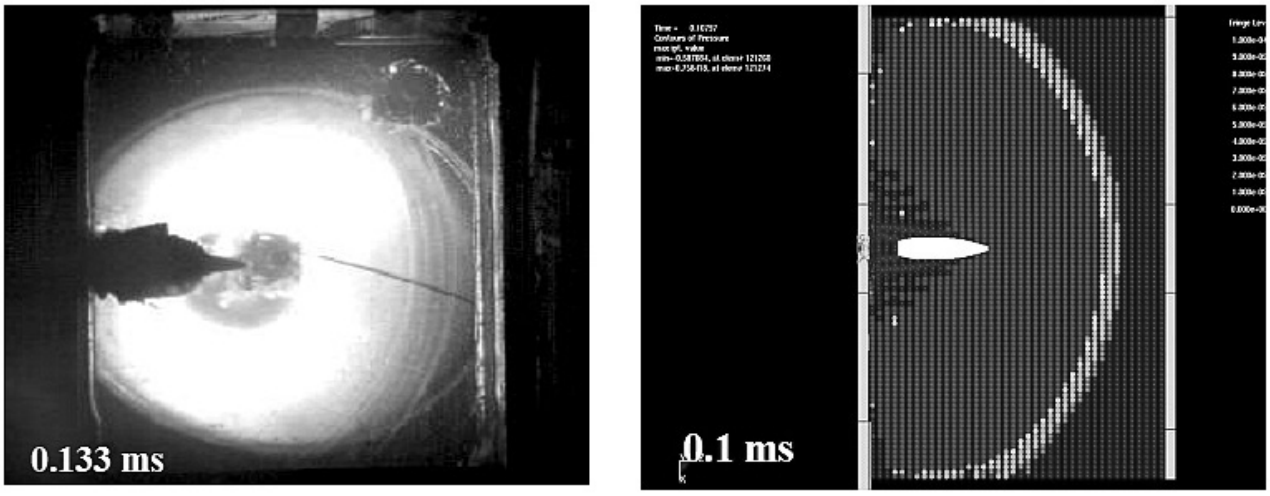


Figure 22. High velocity impact tests vs SPH numerical simulations – pressure field in the cavity.

The main lessons learned can be summarised below:

- The research in non-linear structural dynamics has paid tremendous dividends in terms of progress and techniques and tools development. It has had direct and immediate application in solving actual engineering problems, thus producing more robust aeronautical structures with an optimum weight. This seems to be in clear contrast with the huge amount of money invested in non-linear aerodynamics research (orders of magnitude larger than the research in non-linear structural problems) with more limited outcome so far.
- Numerical simulation tools in non-linear structural dynamics have reached a significant degree of maturity that makes them suitable for the aircraft certification process. Qualification by analysis –at least partial qualification– is closer to become the standard at industry in chapters like bird strike, ditching, blade loss and wheels up landing.
- Savings due to non-linear structural dynamics simulation are relevant in:
  - A/C Development time from conception to service
  - weight reduction
  - safer structures
  - safer emergency procedures
  - test reduction
  - faster certification
  - design improvement...

Future challenges include further refinement of all the techniques showed in the paper.

- For ground loads: unsteady aerodynamics with ground effect inclusion; 1-p effects with ground proximity inclusion; fuel sloshing in tanks analysis...
- For impacts technology: better fluid-structure coupling strategies; better composites rupture criteria for suitable simulations of its collapse sequence, structural fuses design for controlled energy absorption, simulation of shields and protection devices...

CASA has been designing, certifying and delivering aircraft for more than 86 years. Today, CASA continues its activities integrated in the European company EADS as Airbus Military. The challenges mentioned in this paper last section are a constant stimulus for the continuation of research and development in non-linear structural dynamics inside our company.

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