Numerical simulation of impact on solid rocket motors

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Abstract

Weapons safety and vulnerability have become a major field of activities for DGA EM in the past decades. It is now a major actor, along with its state and industrial partners, for the safety evaluation and the qualification of all missiles to be fielded in the French armed forces.

While test activities were presented in a previous paper [1], the present paper focuses on the simulation activities and the numerical tools developed to assess the vulnerability of solid rocket motors (SRMs) under impact loading. Finite element models for low or high velocity impact are both developed using LS-DYNA but the methods and constitutive models differ.

Introduction

DGA EM is a test and expertise centre dedicated to SRMs and related pyrotechnic components of strategic and tactical missiles. It operates for DGA, the French MoD procurement agency, but also for a number of companies such as MBDA, ROXEL, SME, PROTAC, SAFRAN and EADS. Its major facilities consist of open-air test benches for motors up to 250 tons of thrust and a unique altitude simulation test facility able to replicate conditions of pressure and flow at altitudes up to 70 km.

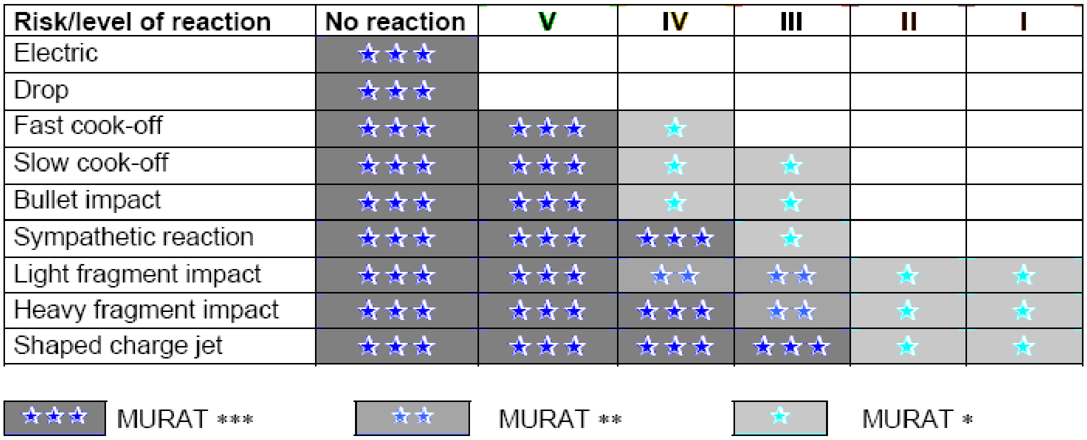
This paper is focused on the safety and vulnerability assessment of munitions. This activity has experienced a significant growth at DGA EM since the early nineties following the hardening of the regulations related to transport, production and use. The development of increasingly energetic materials as propellants, their integration into complex weapon systems and the combination with nuclear powered submarines or aircraft carriers finished to set the trend.

DGA EM is now a major actor, along with its state and industrial partners, for the safety evaluation and the qualification of all missiles to be used in the French armed forces. It also participates in the definition of standards and policies for the design, testing, qualification and classification of munitions. These discussions are conducted at national, European or NATO level on behalf of IPE, the French authority on pyrotechnics and munitions.

Test of insensitive munitions

Insensitive munitions are defined as munitions that reliably fulfill their performance, readiness, and operational requirements on demand, but will minimize the violence of a reaction and subsequent collateral damage to weapon platforms and personnel when subjected to unplanned stimuli [2].

There are several potential threats to munitions ranging from magazine fires to inadvertent impact into energetic materials. According to the MURAT French doctrine (Figure 1), the possible hazards are described through 9 generic types of threats (thermal, electric or mechanical), either accidental or hostile. The assessment is conducted independently of any specific application, thus giving an evaluation of the intrinsic safety level of the munitions. This logic enables a direct comparison of the degree of insensitivity of munitions and eases interoperability within national and international Forces. Alternatively, a specific demonstration can be required to qualify munitions for use on board an aircraft carrier or a warship. This analysis not only involves the ammunition response to specific events, but also the consequence of a possible propellant reaction on the whole weapon system, including the possibility of initiation of other munitions.



Risk/level of reaction	No reaction	V	IV	III	II	I
Electric	★★★					
Drop	★★★					
Fast cook-off	★★★	★★★	★			
Slow cook-off	★★★	★★★	★	★		
Bullet impact	★★★	★★★	★	★		
Sympathetic reaction	★★★	★★★	★★★	★		
Light fragment impact	★★★	★★★	★★	★★	★	★
Heavy fragment impact	★★★	★★★	★★★	★★	★	★
Shaped charge jet	★★★	★★★	★★★	★★★	★	★

★★★ MURAT ***

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Fig. 1 Requirements for MURAT qualification

The primary feature of these requirements is compliance with full-scale testing procedures and results. These tests are performed at DGA EM on pyrotechnic systems (missiles, bombs…) containing up to 500 kg of explosives or 30 tons of propellant. The different safety zones are free from any obstacles for 200 metres around and are equipped with underground instrumentation and measurement facilities [1]. The results are examined in order to determine the level of reaction for each test, from non-reaction to detonation (type I). After completion of all tests, an analysis of the results is conducted in order to propose a rating to the munitions. Additional tests incorporating new materials or innovative concepts can be performed to provide capability to mitigate ammunition response.

Fig. 2 Large areas dedicated to security tests

Impact simulations

Safety demonstrations can be greatly enhanced by the appropriate use of the current generation of simulation codes. Once validated in a given test configuration, these tools enable investigators and designers to better understand driving phenomena, as they can provide significant details of stress, strain and displacement level even throughout the structure. It is also cost and time effective to analyse the influence of parameters such as changes in the design or materials, location and speed of impact…

To achieve these goals, it is necessary to model the entire chain of events starting from the impact of the rocket motor to its rupture. Successive phenomena include elastic response of the casing, progressive damage and perforation of the different layers, propellant initiation, reaction and eventually the explosion and ejection of fragments.

Finite element models for low or high velocity impact are developed using LS-DYNA. This explicit analysis tool, including a comprehensive library of constitutive models, is well-suited for modelling non-linear dynamics. Since no equilibrium condition is sought during an analysis time step, phenomena that exhibit sudden changes in stiffness such as failure by plastic deformation or by brittle failure can be easily included compared to an implicit solution. The fully automated contact algorithm also proves easy to use and robust.

Predicting the response of inert materials

A wide range of material models is usually required to describe the different parts of a SRM, often including metallic alloys, elastomers and composites. For the same material, different constitutive equations may be used depending on the loading regime. Elastic behaviour may be sufficient to represent the slowest regimes for metallic alloys. In the opposite case, different effects such as plasticity, strain rate hardening, pressure dependent response and temperature have to be incorporated (Cowper-Symonds, Johnson-Cook, Mie-Gruneisen models…).

Projectiles used for high-velocity impact (bullet, shaped charge jet, fragment) are generated by means of a home-developed library called IHMDYNA. This library also stores material data, contact and solver parameters.

Materials fracture criteria are coupled with an element erosion algorithm available in LS-DYNA. Indeed, element distortions in Lagrangian calculations cause undesirable effects including small time step size and element inversion. The main drawback of the element erosion method is the physics approximation and loss of information due to the deletion of elements. In many cases, a non-physical element failure strain has to be determined [3]. The method used here consists in adjusting the element failure strain so that the calculated residual velocity is in agreement with the experimental value in a simplified configuration (Figure 3). Furthermore, it is well known that there is an increased element size dependency in models that include failure due to damage growth. This emphasizes the need for preliminary calculations to set and validate failure strain, mesh density and elements formulation.

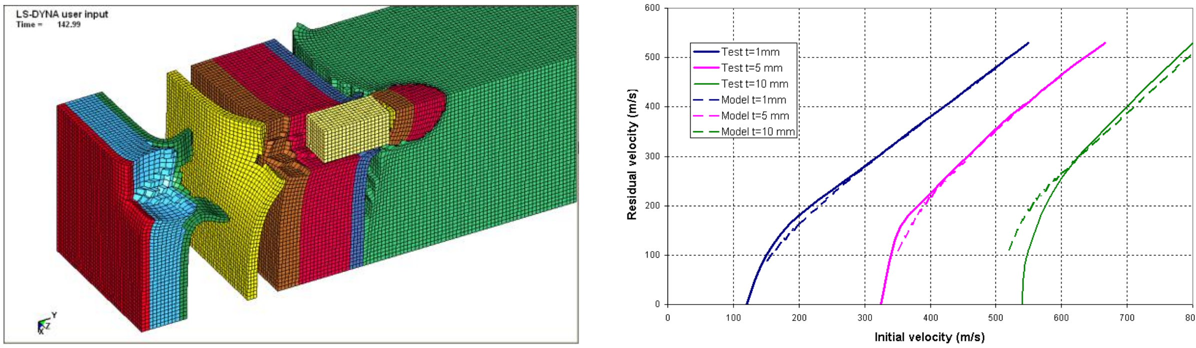

Fig. 3 Fragment impact calculation and comparison with test results

In the case of composite envelopes, not only the orthotropic behaviour of the individual ply has to be defined, but also the lay-up of the different layers. In the cylindrical area, the laminate lay-up is rather simple to describe with an assumed constant value of winding angle and direction of all plies. Conversely, the complex dome geometry involves a rapid change in angle and thickness along a meridian. Different netting theories [4] based on geometrical or mechanical approaches describe this distribution. The large amount of data required to model the composite casing is generated by a home-developed routine including the planar netting theory. This theory assumes that the fiber patterns lie in a plane which is tangent to the polar opening at one end and tangent to the opposite side of the polar opening at the other end (Figure 4).

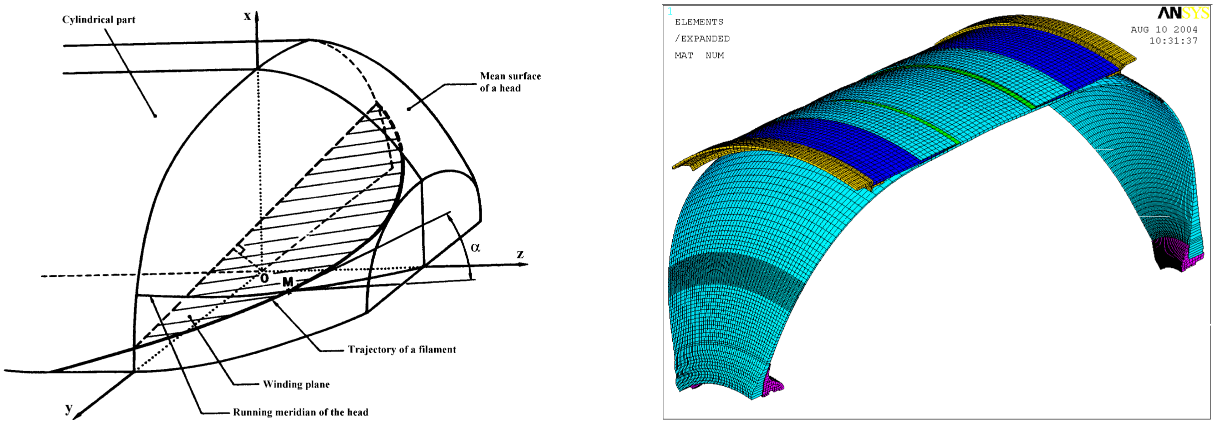

Fig. 4 Representing the laminate lay-up for filament-wound structures

The theoretical winding law and other uncertain parameters in the initial model (geometry, material properties, influence of manufacturing process…) can be optimized by means of a method known as experimental / numerical dialog or inverse identification [5]. This technique takes advantage of various complex tests performed on the full scale specimen in order to identify uncertain parameters: an initial reference model is built up using preliminary data and then a sensitivity analysis is carried out to assess the influence of a slight change in the input data. The best set of input data is obtained with a multivariate analysis.

The fracture process of high performance composite laminates is quite complex, involving both intra-laminar and inter-laminar damage mechanisms. Low velocity impact damage is insidious because it can create serious non-visible damage at very low impact velocities. In thick rocket motor cases the prevalent impact damage is fiber fracture and matrix cracking adjacent to the front face. In contrast, low velocity loading of thin-wall cylinders induces flexure, and consequently delamination and tensile cracking on the back face wall opposed to impact [6]. Higher velocities can cause even greater amounts of damage such as partial or complete material break-out, and at ballistic impact velocities a clean shear-out of material close to the size of the projectile can be found.

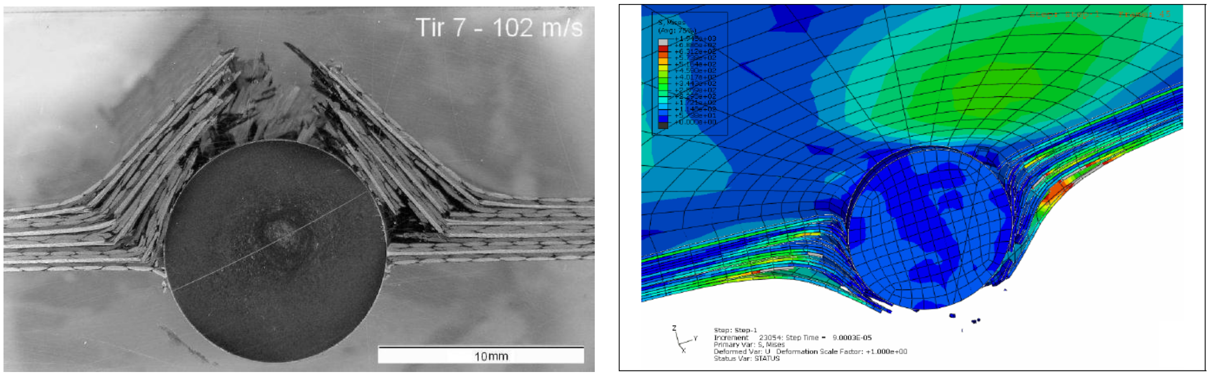

Fig. 5 Impact against a CFRP (tests and calculations by DGA/CEP [7])

Capability to model progressive failure for composite materials is offered by LS-DYNA under additional license from MSC. This failure model, formulated in terms of quadratic stress forms, can be used to simulate fiber failure, matrix damage and delamination. However this requires extensive materials characterization tests in tension, compression and shear to accurately model the damage initiation, propagation and post failure behaviour.

Predicting the response of energetic materials

The microstructure of a typical solid propellant material consists of polymeric binder, oxidizer, metal fuel, and some other additives for improved bonding and burning. From a mechanical behaviour perspective, each of these phases exhibits a complex constitutive response that varies with temperature and load. For engineering purposes, such behaviour is often approached by combining hyperelastic and viscoelastic behaviours: the stress is split into an equilibrium stress that corresponds to the stress response at an infinite slow rate of deformation and a viscosity-induced overstress. The overstress is expressed as an integral over the deformation history and a relaxation function is specified by means of Prony series. The temperature-dependence of the modulus is modelled using the Williams-Landel-Ferry shift function. Fracture initiation under three-dimensional stress states is controlled by simplistic criteria such as Von Mises, Stassi or a combination of these.

Under low velocity impact such as incidents during handling, the required level is an absence of reaction. Indication in this way is absence of plastic deformation in the propellant and integrity of the layer next to it. Otherwise, the possibility of initiation by friction or adiabatic heating has to be discussed. Indeed, it is well known that damage is not the single contributing factor to reaction violence. The energy content of the material is critical, with the most energetic materials producing the highest response. The combustion properties, such as ignitability and burning rate also play a role in the response of the material to its hazards threat [8]. It has been observed that energetic materials may ignite when subjected to a mechanical stimulus, even when the energy is insufficient to raise the bulk temperature of the material to its auto-ignition threshold. This observation has led to the assumption that local regions of high energy density, or hot spots, are formed due to a mechanism by which the energy of the stimulus is localized into small regions of the solid propellant. Numerous mechanisms for hot spot formation have been proposed by various researchers: void collapse with shock or plastic heating, shear banding or cracking, high strain energy concentration [9].

Due to a lack of confidence in analytical methods, pessimistic criteria were used to qualify recent SRMs for use in the French armed forces. A series of drop tests on full scale specimens (Figure 6) is planned in order to gain further understanding on initiation criteria.

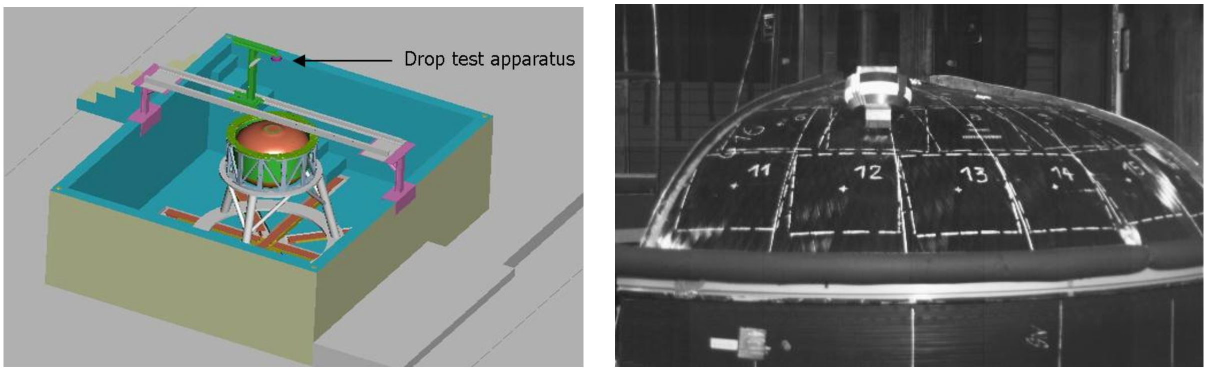

Fig. 6 Drop tests on full scale SRM with composite structure

For high velocity impact, maximum reaction criterion for passing MURAT protocol ranges from non-propulsive combustion to total detonation, depending on the different tests and the aimed level of certification. Among the different mechanisms leading to detonation (termed SDT, XDT or DDT), Shock-to-Detonation Transition (SDT) is the most documented and the most easily approached by simulation techniques. The thermal effects due to projectiles penetration are often neglected and the finite element model can be restrained to a local description (the reaction is initiated within a few μs after impact).

The approaches to predict SDT events using LS-DYNA are either reactive or non-reactive. In the latter approach, the simulation aims to quantify the shock experienced by the energetic material in terms of pressure and transmitted energy. These quantities are afterwards compared to threshold values from criteria such as Peugeot-Quidot. In the reactive approach, the Lee-Tarver [10] ignition and growth model is used to directly describe both the ignition and the subsequent expansion of the detonation process (Figure 7).

Modelling the onset of other violent but slower transitions such as delayed detonation (XDT) and deflagration-to-detonation (DDT) is an even more challenging task and currently remains beyond our reach. When the shock wave generated in a propellant by an impacting projectile is insufficient to cause SDT, the subsequent penetration of the case by the projectile is often followed by ignition. The projectile and case debris, heated by the impact, penetrate the propellant and continue to be heated by friction as they decelerate transfering heat into the propellant [2]. Due to the confinement, internal pressure following the generation of decomposition and combustion gases can increase without relief. This in turn enhances the damage mechanism of individual grains, and as reaction grows, a runaway to detonation can occur [11].

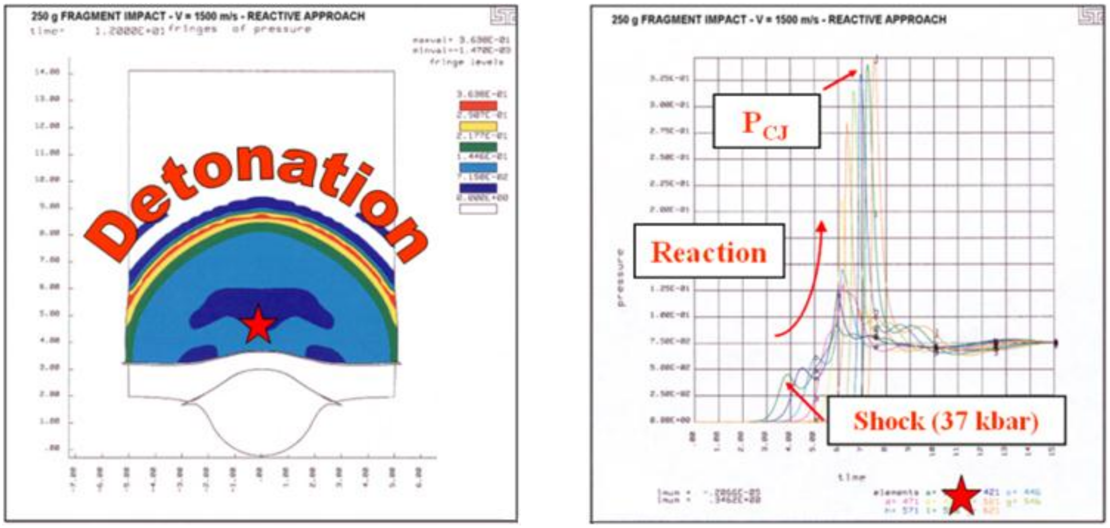

Fig. 7 Fragment impact calculation using the reactive approach

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