

Simulating Spacecraft Launch and Re-entry

Dutch Space uses Abaqus to virtually test a new metallic thermal protection system for hypersonic space vehicles

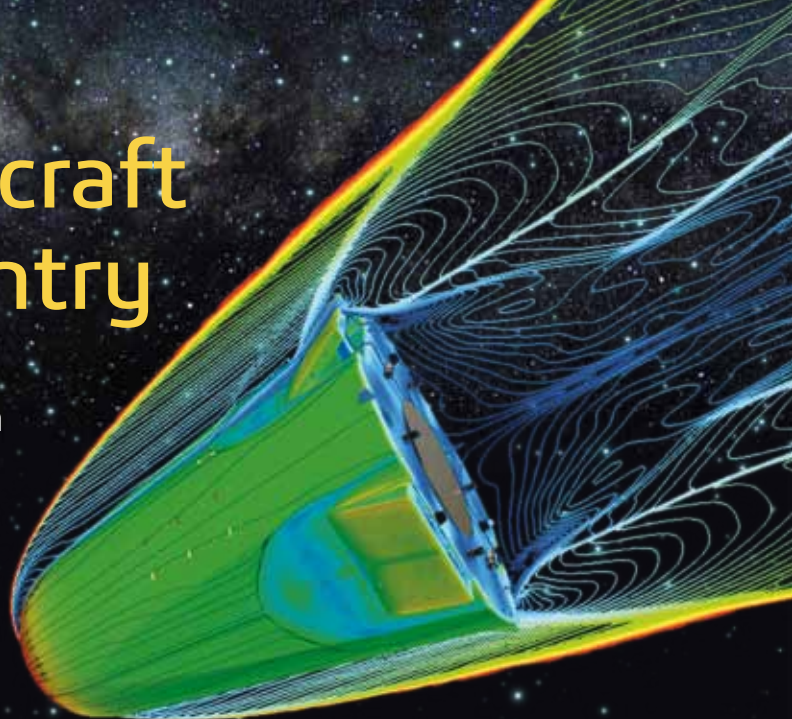


Figure 1. Simulation of the flow around EXPERT during atmospheric re-entry. Employing the CFD code, LORE, the heat flux over the vehicle's outer surface has been determined during the hypersonic phase (Courtesy L. Walpot, European Space Agency - AOES).

For a spacecraft to be reusable, it must first withstand a controlled explosion powerful enough to propel it through the earth's gravitational grip. Then to come home intact, it must survive the blast furnace of atmospheric re-entry with temperatures hot enough to melt steel. Acceleration, vibration, shock, skin friction, heat flux, and aerodynamic forces: These are not trivial design challenges. This *is* rocket science.

Thermal Protection Systems (TPS) have played a critical role in reusable vehicle designs since NASA engineers first began work on the Space Shuttle in 1972. Before that, with disposable space capsules (Mercury, Gemini, Apollo), ablative materials were used to absorb heat energy and then dissipate it through vaporization. To accommodate multiple missions, such as with the Shuttle, TPS designs took a different tack, utilizing a variety of materials (flexible insulation blankets, composites, ceramic tiles, and others) to protect the craft and its occupants from the extreme heat of re-entry. But since the Columbia accident in 2003, engineers have been particularly motivated to find more durable designs.

Since the mid-1990s, Dutch Space (Leiden, the Netherlands), a supplier of high-quality subsystems and products for the international space industry, has been a key player in the development of metallic TPS and hot structures for reusable craft. The metallic TPS of the European Experimental Re-entry Testbed (EXPERT), an unmanned capsule developed by the European Space Agency and the prime contractor, Thales Alenia Space of Italy, is one of Dutch Space's latest efforts (Figure 1). Its pending launch from a Russian submarine aboard a three-stage Volna rocket in the summer of 2011 promises validation, not only of new materials, but also of simulation as an integral tool in the development process.

New TPS technology: A tale of two materials

From the start, Dutch Space has focused on the use of metallic materials for TPS designs. According to Javad Fatemi, technical leader of the EXPERT's TPS project, metals have a lot of

advantages over ceramics. "Metals are easy to use and maintain," says Fatemi. "They can handle impacts much better, and inspection is easier." But on the negative side, metals are heavier than other materials and can't cope with high temperatures as well as ceramics. So to take maximum advantage of material properties, Fatemi is betting on a TPS that uses a combination of metallic and ceramic parts.

The thermal protection system of the approximately five-foot-high, four-foot-diameter EXPERT is comprised of two major components: a nose cap made of a ceramic matrix composite (CMC), which takes the brunt of the thermal load during re-entry; and a conical metallic after-body that is manufactured from an oxide dispersion strengthened alloy, PM1000. These two materials were chosen for their high-temperature stability and weight efficiency. Four flaps that protrude from the surface at the base of the vehicle are also made of the more heat-tolerant CMC (Figure 2). "We couldn't make the whole craft out of

metal," says Fatemi, "because the temperature is roughly 1900 degrees C at the nose and 2050 degrees C at the flaps, which are both higher than the 1200-1250 degrees C limit for the metal."

But while providing material advantages, a two-part, two-material design also introduced the project's greatest design challenge: The thermal expansion of the metal is eight times greater than that of the ceramic. "At the junction between the nose cap and the after-body, we had this huge thermal mismatch," says Fatemi. If the shape of the vehicle was to change during re-entry from the thermal mismatch—even just slightly—it could alter the flow from laminar to turbulent and, as a result, increase heat flux by a factor of two to three.

The solution was a structure that bridges the two components while allowing for differential heat expansion. "We needed to design the TPS so that we were sure it wouldn't trigger turbulence," says Fatemi. "Simulation was key to solving that problem."

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Javad Fatemi
Technical leader of the
EXPERT's TPS project

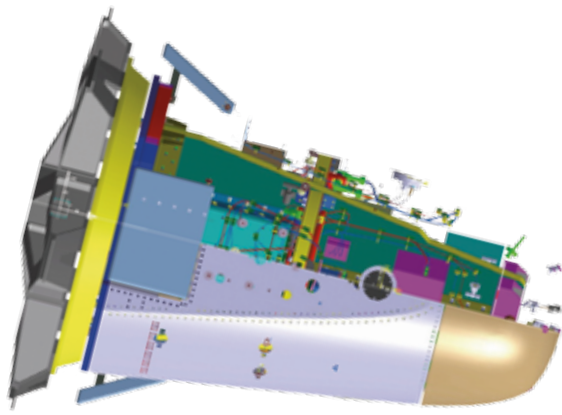


Figure 2. The European Experimental Re-entry Testbed (EXPERT), an unmanned capsule developed by the European Space Agency, utilizes a hybrid thermal protection system (TPS) comprised of a ceramic matrix composite (CMC) blunt nose (designed by DLR, Germany's national research center for aeronautics and space) and a metallic conical after-body (designed by Dutch Space). (Courtesy European Space Agency)

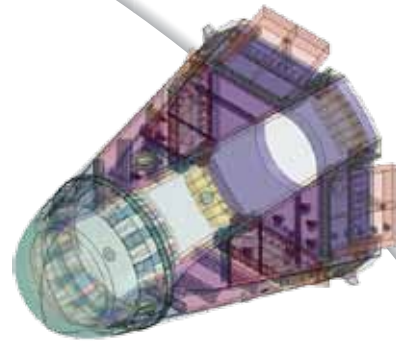


Figure 3. Thermal and structural models for the EXPERT TPS with integrated payloads.

Realistic simulation of launch and hypersonic re-entry

When Fatemi joined Dutch Space's EXPERT team in 2004, one of his first tasks was to compare commercially available finite element analysis (FEA) software that is used for simulating structural and thermal behavior. After conducting a tradeoff study, his reasons for selecting Abaqus were clear.

For one, says Fatemi, "With Abaqus, you have a unified finite element (FE) model. That means if you want to create both a thermal and a structural model, you can use the same mesh and easily change the element type and the boundary conditions."

Another reason was that the software could be easily coupled with CATIA. "We imported the CATIA model directly into Abaqus/CAE to make the FE model," says Fatemi. "Every time we made a revision based on our analysis, the CATIA model would automatically update."

Abaqus could also handle the complexity of the highly nonlinear TPS simulation with its robust interface between the pre- and post-processors and the solver. "The contact and specialized mechanisms, like special joints on the flaps, were all easy to model," says Fatemi. "With Abaqus, we are able to closely simulate reality."

The extreme in-flight forces that EXPERT encounters are a variety of thermal and mechanical loads: during the launch, it will experience acceleration, random vibration, and acoustic and shock loads; during re-entry, it will be subject to severe aerodynamic heating and aerodynamic forces; and there is, of course, the shock of impact when it comes back to earth, landing on the Kamchatka peninsula.

To accommodate the multiple physics that the vehicle is subjected to, Fatemi developed both 3D structural and 3D thermal models (Figure 3). He used the structural model to analyze the stiffness, strength, and thermo-mechanical behavior of the TPS when subjected to launch, aerodynamic heating, and pressure loads. In this model, all nonlinearities (geometrical, materials, and boundary conditions) were taken into account and the mechanical properties of all materials were treated as temperature dependent. The model used four-node linear quadrilateral shell elements (S4R), with each element having six degrees-of-freedom (DOF) per node (three translations and three rotations).

The thermal model was used to estimate the temperature histories for all TPS parts as well as payloads. This model was

constructed from four-node, heat transfer quadrilateral shell elements (DS4) with DOF represented as temperature; it had a total of 112,994 elements and 128,358 nodes.

In the most recent analyses, Fatemi used CATIA V5 and Abaqus V6.10. Because of analysis complexity, he ran them on a high-performance Linux-based compute cluster for parallel computing.

Analyzing lift-off loads

The loads being analyzed during lift-off included quasi-static accelerations from the rocket, acoustic loads from the rocket engine, rapid depressurization at second-third stage separation, and random vibrations and shock each time a stage separates.

To ensure that the vibrations of launch do not occur at the vehicle's resonant frequencies, which can accentuate stresses, Fatemi carried out a normal mode analysis using the structural model. The requirement for minimum eigen frequency for the EXPERT was set at 80 Hz. The minimum value reached during analysis was 86 Hz, falling within specification.

A nonlinear static strength analysis was also performed to verify the structural performance of the TPS during launch. This analysis indicated that maximum loads occur during the separation of the second and third stages of the rocket and that during this event all EXPERT components had positive Margins of Safety (MS).

Re-entry challenges

While launch will generate harsh loads on the EXPERT, it is during re-entry that the vehicle is really tested by extreme thermal and mechanical loads. As the approximately half-ton vehicle slams into a wall of air at fourteen times the speed of sound, it generates tremendous kinetic energy. According to basic physical principles, this energy is translated into heat: when friction from the air slows the craft, its surface heats up, as governed by the relationship between air flow and heat flux. The 150-second re-entry window officially begins when the 436 kg (961 lbs) craft is at an altitude of 104 km (64.6 mi) and first encounters the atmosphere. Velocity at that time will be 5 km per second (11,184 mph), with an entry path angle of -5.5 degrees.

To simulate the aerodynamic heating of the EXPERT, a computational fluid dynamics (CFD) code, called Lore (developed by a student at Delft University of Technology), was used to calculate spatial distributions of heat flux over the vehicle's outer surface at five discrete speeds (between Mach 18 and Mach 10)

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Cover Story

Mach 18

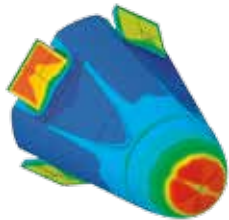


Figure 4. A series of simulation results for heat flux distributions at discrete Mach numbers.

Mach 16



Mach 13.47



Mach 12



Mach 10

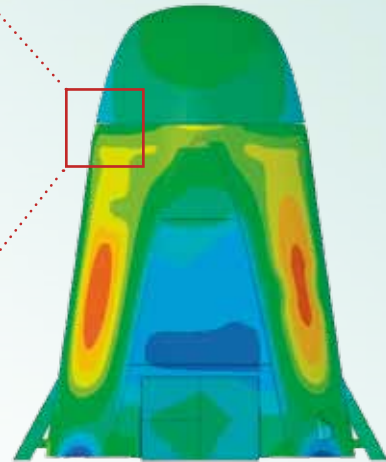


Figure 5. A side-view of EXPERT illustrates the temperature differences at the junction between the ceramic nose and the metallic after-body. The detail view (right) shows where step (radial displacement) and gap (axial displacement) measurements are made. The analysis verified that step and gap changes during re-entry fall within specifications.

on the re-entry trajectory. The heat flux distributions were then directly mapped from the CFD mesh to the thermal FE mesh in Abaqus using a dedicated sub-routine developed at Dutch Space (Figure 4). The stagnation heat flux profile was used to interpolate the spatial distribution of heat flux between different Mach numbers. Spatial distributions of dynamic pressure (at the same five trajectory points) were also calculated using CFD and mapped in the same way.

During re-entry, aerodynamic heating and dynamic pressure create severe loads on the TPS dependent on vehicle shape, atmospheric density, and speed. In addition, as the temperature increases, the mechanical properties of TPS materials degrade. To measure these effects, Fatemi used a sequential thermo-mechanical analysis, which predicted the temperature history in the EXPERT's TPS and payload, and generated maximum temperatures for each of the three critical EXPERT structures at specific times during re-entry: CMC nose (2165 K at 102 sec), CMC flaps (2328 K at 95 sec), and metallic after-body (1464 K at 112 sec).

The thermo-mechanical analysis also calculated the effects of the thermal mismatch between the composite nose and the metallic conical structure, generating gap (axial displacement) and step (radial displacement) measurements (Figure 5). Gap evolution is important in determining the design of the seals between the nose and the TPS, while the step values guarantee that changes in surface geometry will not trigger turbulent flow during re-entry. In both cases, analysis results fell within specified requirements. In addition, plastic stress/strain and MS (which vary as a function of loads and material temperature for specific parts) were calculated and determined to be within specification.

Confidence high in simulation results

As the EXPERT project neared completion, the Dutch Space team took the final step of conducting physical tests to validate the predictions of analysis with actual measurements. In one scenario, Fatemi modeled and tested a highly nonlinear bolt joint at very high temperatures. In another, engineers conducted a dynamic test of the vehicle and compared it with simulation results.

Comparing test and analysis results, accuracy for the bolt joint was within three percent and for the dynamic test within five percent. "These comparisons gave everyone—the customer, the prime contractor, and Dutch Space—high confidence in the Abaqus FEA results," says Fatemi. "This is important since budgets were limited, full-scale thermo-mechanical tests are

extremely expensive, and the EXPERT is going to fly without any full-scale thermo-mechanical tests."

The next project for Fatemi will be a complete vehicle analysis of EXPERT in which a CFD aerothermodynamic analysis is coupled with the Abaqus FE model (a first for non-military vehicles). He is also moving on to develop carbon fiber-reinforced polymer (CFRP) engine thrust frame technology for the European Space Agency's (ESA) next-generation launchers, with FEA slated to play a key role again.

"My objective is to build our capability for virtual testing and replace as much physical testing as possible," says Fatemi. "With EXPERT, we proved that simulation shortens the time-to-market and reduces costs. We have done all of our design verification using high-fidelity analysis and have confidence in the power of FEA to predict outcomes we can rely on."

About Javad Fatemi



Since arriving at Dutch Space seven years ago, Systems Engineer Javad Fatemi (Ph.D. mechanical engineering, University of Lyon 1, France) has lived and breathed every design

detail and decision for the EXPERT's TPS, relying heavily on Abaqus and realistic simulation. He was honored by SIMULIA in 2009 (the bi-annual Ruben van Schalkwijk Award) for his technical achievements and enthusiasm, and continues to champion the use of simulation technology at Dutch Space. "I always wanted to be part of the space business," Fatemi says. "Every day, I love coming to work."

For More Information
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