DEEP DIVE

ANSYS software helped in designing a deep-sea submersible to reach the lowest point on earth.

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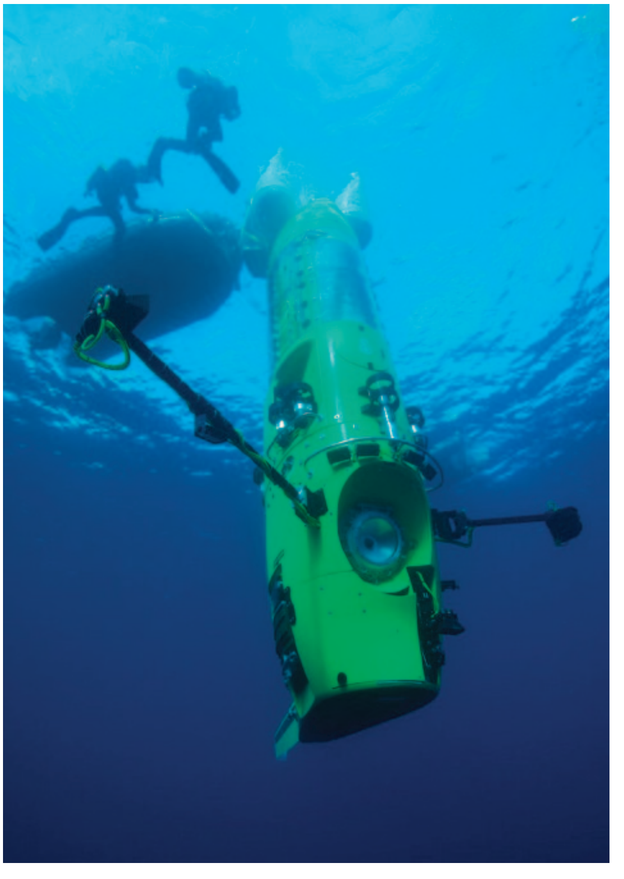
On March 26, 2012, Canadian film director and experienced submariner James Cameron solo piloted the *DEEPSEA CHALLENGER*, a 24 foot (7.3 meter)-long submarine, to the lowest-known point on Earth — Challenger Deep, 6.8 miles (11,000 meters) beneath the sea. The crucial structural elements of the vessel — such as the pilot capsule (which carried Cameron) and the syntactic foam body of the sub (which housed the pilot capsule) — were engineered and optimized by Finite Elements, an engineering design consulting company that specializes in custom-engineered solutions for heavy industry, power generation and deep-sea equipment.

The Finite Elements team used ANSYS Mechanical software to design a geometrically complex capsule that can withstand pressures of 16,500 pounds per square inch (114 megapascals, or MPa), 1,100 times the pressure at sea level. ANSYS software played a further substantial role in developing the craft's syntactic foam body and in resolving thermal issues in the manufacture of the pilot capsule and syntactic foam. For six years, Phil Durbin of Finite Elements has been the principal mechanical and structural engineering advisor to *DEEPSEA CHALLENGE*, a joint scientific expedition by James Cameron, *National Geographic* and Rolex to conduct deep-ocean research and exploration. Durbin's application of engineering simulation in the design process gave early confidence about the submarine designs, materials and construction methods — saving time, enabling rapid and innovative design modification, and substantially reducing ultimate failure risk.



The ***DEEPSEA CHALLENGER*** **submersible begins its first 2.5-mile (4-km) test dive off the coast of Papua New Guinea.**

PHOTO BY MARK THIESSEN/*NATIONAL GEOGRAPHIC.*

DEEP SEA EXPLORATION CHALLENGES

The Challenger Deep undersea valley lies in the Mariana Trench, about 300 miles (500 kilometers) southwest of Guam in the Pacific Ocean. A piloted vessel reached these depths only once before, in the 1960s. That craft, known as the *Trieste*, was very heavy (150 tons), over 58 feet long and over 11 feet wide. It housed two pilots but was unable to take film footage, retrieve samples or conduct scientific experiments. It took nearly five hours to descend and more than three hours to ascend, affording only 20 minutes of bottom time.

Cameron and his Australian partner, Ron Allum, started working on the concept design for the *DEEPSEA CHALLENGER* about seven years ago. Their goal was to convey one man to the deepest point on earth to bring back never-before-attained scientific data and high-definition film footage. Ideally, the vessel would benefit from much faster descent and ascent times, thus affording more time to explore the bottom. It would be able to traverse significant distances across the sea floor and would be lighter and, therefore, easier to manage on the deck of a ship.

The *DEEPSEA CHALLENGER* is a vertical torpedo for rapid descent and ascent. It contains a spherical pilot capsule (internal diameter of 43 inches), only large enough to house Cameron

Finite Elements engineers used ANSYS Mechanical software to design a geometrically complex capsule that can withstand pressures 1,100 times those at sea level.

and his equipment. Further, the buoyancy required to return the pilot to the surface is provided by the structural beam of the submarine, thus further reducing weight.

At depth, weight is the enemy, a crucial factor in designing this type of vessel. The foam used to provide buoyancy for the return trip is about seven-tenths as dense as water. This means that for every kilogram of "in-water" weight that goes down, another 2.3 kilograms of foam is needed to bring it back up.

SIMULATION NEEDED TO DESIGN COMPLEX GEOMETRY

Ideally, the *DEEPSEA CHALLENGER* pilot capsule would be a perfect sphere, if not for the requirement of an entrance hatch for the occupant and a separate penetrator plate opening to admit electrical cables. These wires control a wide array of equipment, including a sediment sampler, a robotic claw, lights, thrusters, a descent-weight trigger, 3-D video cameras, and, for the return to surface, an ascent-mass drop trigger and a trim ballast system. Unlike the *Trieste*, the *DEEPSEA CHALLENGER* pilot capsule is so small that the size and shape of the entrance hatch and penetrator plate represent a significant structural discontinuity to its roughly spherical shape. This greatly increased the difficulty of designing the capsule shell when compared with a large spherical shape.

Many ANSYS Mechanical simulations, including the use of contact formulations with friction, were essential in developing the final complex shape: one that would properly distribute the bending stresses in the shell caused by the shape of the hatch and hatch interface. The metal-to-metal contact surfaces of the hatch and the penetrator plate were carefully angled to remove relative deformation of the hatch to the shell as pressure is applied throughout the dive. Friction coefficients were determined experimentally under stress conditions similar to those experienced in the pilot capsule.

Analysis further showed complexities with the set of holes in the penetrator plate that accepts the electrical cables: This configuration represented a stress concentration sufficient to cause the hole to become out of round and plastically deform onto the penetrator body. The Finite Elements team eliminated the plastic deformation through careful geometric design combined with the introduction of ultra-high-strength 300 M alloy steel in the hatch and penetrator plate.

Allum's experience with Russian Mir submersibles (and similar plastic deformation issues) confirmed the Finite Element team's findings, that the penetrators would jam in their sockets if not given sufficient clearance.

The Finite Elements engineering team performed further full nonlinear plastic analysis to determine the

A stunning use of design at the highest order... This is incredible, inspirational, a total game-changer.

– Judges at the 2012 Australian International Design Awards at which the DEEPSEA CHALLENGER *took the top spot*

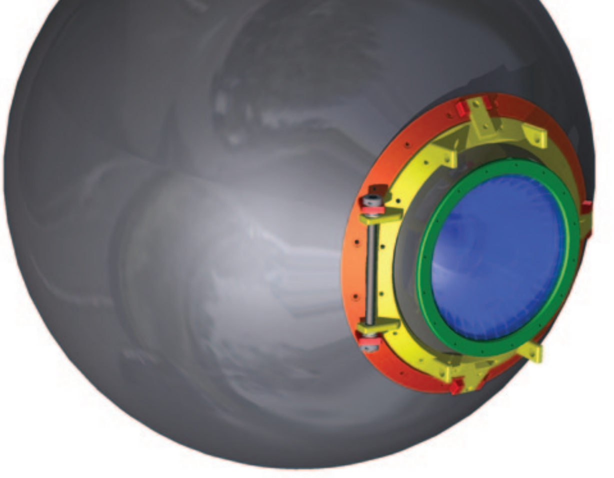
Filmmaker and *National Geographic* Explorer-in-Residence James Cameron emerges from the *DEEPSEA CHALLENGER* submersible after his successful solo dive to the Mariana Trench, the deepest part of the ocean.

PHOTO BY MARK THIESSEN/*NATIONAL GEOGRAPHIC.*

ultimate collapse pressure for the pilot capsule. It is hard to predict buckling of a perfect sphere because the structure is equally likely to collapse at any point of the geometry. The discontinuities in the *DEEPSEA CHALLENGER* pilot capsule provided a reliable and predictable mode of collapse that improved engineers' confidence in the outcome. To minimize the weight of the structure, the team targeted a safety factor on yield of 1.5. Iterative modifications to the shape and selective application of high-grade, heat-treated alloy steels allowed the team to achieve this in simulation. Finite Elements engineers were not satisfied with material properties data provided by the steel suppliers, so they worked with Allum and performed their own compressive failure tests. Physical testing of the weld-zone prequalification material demonstrated that it was not as strong as stated in published data, lowering the safety factor at the weld zone to 1.36.

Housed within the entry hatch is the viewport, made of a cast acrylic material. Finite Elements engineers developed the final design for the shape, starting from a rough design concept based on the work of a leading industry expert. The viewport was manufactured and later tested in a pressure chamber at Pennsylvania State University in a test jig designed using ANSYS Mechanical. The team simulated the test jig to ensure that the jig would not bias the results of the test. The acrylic fractured at the edges in early testing. Engineers compared the data generated in the test rig to an ANSYS Mechanical model of the acrylic port and rig at test pressure. This led to fine tuning material properties in ANSYS software until the behavior of the viewport matched the strains and deflections that were seen in physical testing. After correcting material properties, engineers used parametric analysis in ANSYS Mechanical to optimize the viewport geometry and shape of the supporting seat and to eliminate fracturing. In the final design, the viewport deflects by almost 5 mm toward the pilot at full depth, a safe but unnerving experience for the pilot.

The complete pilot capsule (including the viewport entrance hatch and the penetrator plate) was successfully tested twice to the maximum pressure rating at the Pennsylvania State University



Model of pilot capsule and hatch

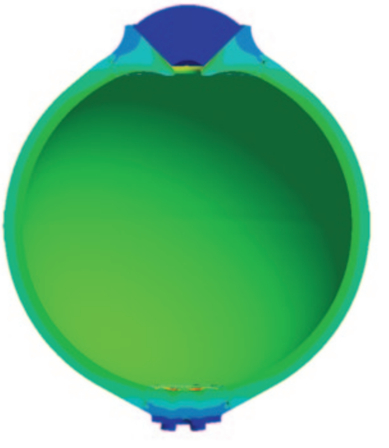
pressure test facility, a few percent shy of full ocean depth.

DESIGNING AND MANUFACTURING A NEW FOAM

The design team expended a considerable amount of effort to find the right syntactic foam for the backbone, which constitutes the bulk of the sub's structure. Deep-sea exploration submarines of this type have traditionally been built with a metal frame and attached foam. To save weight and make the volume of the craft as small as possible, Cameron wanted to explore using the foam as the sub's structural backbone. There are commercial foams that claim to be capable of operating at full ocean depth, but they are not rated for manned-submersible use — they do not meet strict toughness and consistency properties required for the task.

Durbin and Allum set about designing foam made from epoxy resin and hollow glass micro-balloons with the required mechanical properties. It was important both to improve the packing density of the balloons and to identify an appropriate resin and material additive to produce toughness in what was a brittle material. Durbin used ANSYS structural mechanics at a micro level to research how the hollow glass spheres interact with each other within the foam matrix. The studies led to successful development of the new foam.

Durbin and Allum developed the new foam manufacturing process. When the epoxy cures, it releases heat, which damages the foam. The Finite Elements design team employed ANSYS transient thermal modeling to understand this process and implement changes to the manufacturing method.



Stress analysis of the pilot capsule

Finite Elements engineers also designed three pressure vessels using ANSYS Mechanical. The first, a 14 MPa vessel with yoke closure mechanism, was used for the new syntactic foam manufacturing process. The second, a large 140 MPa fully forged pressure vessel with a screw-thread enclosure, was used to test the production foam blocks and all other equipment to full ocean depth, prior to assembly. The latter vessel is the largest high-pressure test chamber in the southern hemisphere. A third small 140 MPa pressure vessel was used for testing electronic components to full ocean depth.

ENGINEERING THE BEAM

Large foam blocks were glued together and CNC-machined to form the entire structure of the submersible. Finite

Elements developed a specially designed surface laminate to sheath the beam to mitigate the risk of brittle failure of the foam during launch and recovery operations. The Finite Elements team used ANSYS Mechanical to prototype the laminate/foam combination to understand its performance under the high isostatic pressure conditions at full ocean depth. Final confirmation of the laminated foam was achieved by physical testing.

Finite Elements engineers worked with Allum and the Acheron manufacturing team and performed tests on foam samples with strain gauges. They then compared results to simulation predictions to establish material properties, which then were used in the analysis to design the backbone. The sub's fully constructed foam beam was too large to test; the Mariana Trench dive served as the ultimate test.

COPING WITH SHRINKAGE UNDER PRESSURE

The craft's length shrinks by 70 mm due to the pressure exerted by the ocean at Challenger Deep levels. With all components deforming at different rates as the craft descends, it's critical that size changes of mating parts be consistent to avoid generating unnecessary stresses. The Finite Elements team employed ANSYS Mechanical to determine appropriate clearances and then design necessary compliance into the fastener systems that retained the major components, such as pilot capsule, battery modules and thruster blocks.

Engineers used ANSYS CFX to analyze "through-water" performance of the submarine to predict stability for ascent and descent, and to predict horizontal "in-flight" drag. The results correlated favorably with the results of one-fifth scale model physical tests conducted in the United States, all of which directed important design alterations.

ANSYS Mechanical and CFX proved to be very powerful tools. The contact formulations provided robustness needed to converge to a solution with the complex geometries and high stresses involved in this project. ANSYS Workbench made ANSYS Mechanical much easier to use by streamlining the interchange of computer-aided design (CAD) geometry and simplifying the process of defining loads and contacts.

After a descent of just over two and a half hours, the 12 tonne *DEEPSEA CHALLENGER* sub spent three hours hovering the desert-like seafloor, collecting samples and 3-D videos. Crammed with equipment, the interior of the capsule is so small that Cameron had to keep his knees bent and could barely move during the entire trip. The ascent to the surface took just over one hour, after which a helicopter spotted the craft and a research ship's crane picked it up. "When you are actually on the dive, you have to trust the engineering was done right," Cameron said. Scientists are now busy analyzing the enormous hoard of data and samples collected by the voyage. Footage from the dive will be used in a feature-length 3-D documentary, and an article about the expedition will be featured in *National Geographic* magazine.

References

www.finiteelements.com.au
www.deepseachallenge.com

Authors' Note

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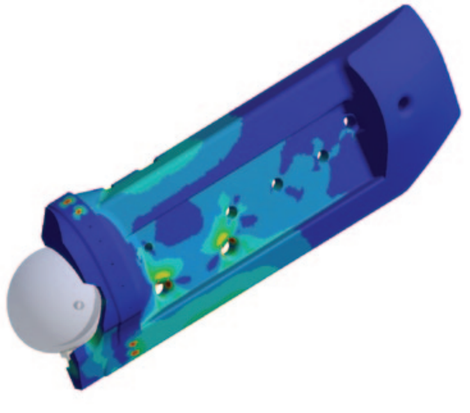
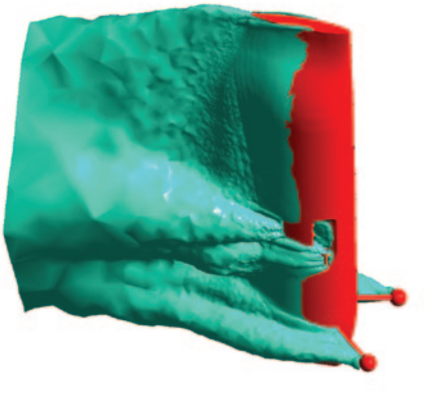
– James Cameron



Syntactic beam stresses during recovery lift



Flow separation in forward flight based on early design iteration