Earth mover with hydraulic cylinders on boom, arm, and bucket.

Tenaris Digs Deep into Hydraulic Cylinder Performance with Abaqus FEA Crack Simulation

In the hands of a skilled operator, an earth mover makes construction-site work look easy. The smooth flow of the shovel as it digs into the soil and lifts its heavy load seems effortless. But much like a human arm with interconnected bones, muscles, and tendons, this labor-saving machine must harness a complex array of parts to perform in perfect synchrony.

Key to the earth mover's fluid movements is an array of hydraulic cylinders, located along the boom, arm, and bucket, that act as actuators to convert hydraulic energy into mechanical energy (similar technology is also used for cranes, presses, and industrial machinery). Filled with pressurized oil that transmits force to move a piston, each cylinder barrel (housing) is a seamless steel tube designed to resist fatigue from the very high number of operating cycles that it endures.

Hazards on the job site

However, operator error, accidental shovel overloads, and accidental impacts from falling debris are regular occurrences on a job site. So Tenaris, a leading supplier of seamless tubes for earth-moving machinery manufacturers worldwide (customers include Caterpillar, Volvo, LT Komatsu and Dong Yang), devotes considerable R&D resources to anticipating such events. By studying the effects of a wide range of operational and environmental stresses on a cylinder's service life, Tenaris can fine-tune material design to best tolerate such extremes and improve safety for thousands of machine operators worldwide each year.

"The failure mode and the limit load beyond which a tube rupture can occur are extremely important to identify," says Mihaela Cristea, a researcher in the structural integrity department at the Tenaris R&D center in Dalmine, Italy, one of four such centers around the globe. "Our OEM customers are looking for high-yield strength above all, so fracture toughness is the key parameter for ensuring integrity and safety."

"Leak" is preferable to "break"

Fracture toughness plays a critical role in the 'leak before break' behavior that is desirable in order to avoid the hazards that can result from a sudden, brittle fracture, says Cristea. "In all situations ductile fracture, or cracking, is usually preferred for several reasons. Unlike brittle fracture, which occurs rapidly without warning, ductile materials plastically deform, slowing the process of fracture and providing a window of time to act."

> We aim to reduce the number of long and expensive full-scale tests.
>
> **Mihaela Cristea**, Researcher, Tenaris

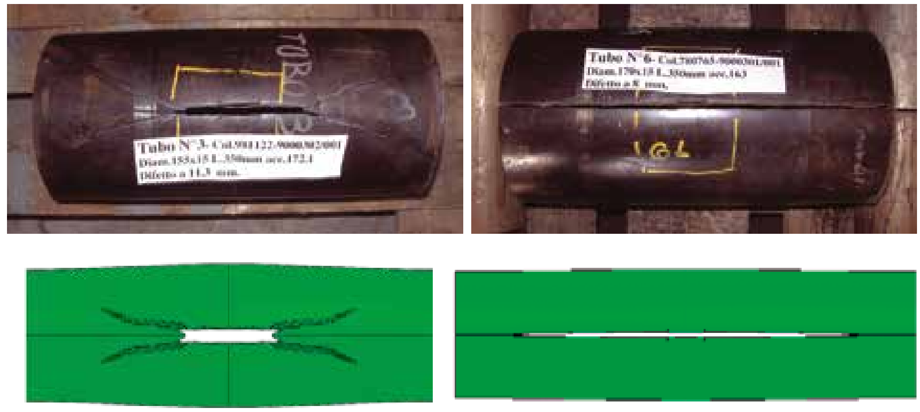
Particularly for hydraulic cylinder applications where the variable loads induce fatigue and the environment can be very severe (low temperatures decrease fracture toughness), the ideal housing combines high-tensile properties and fatigue resistance with good toughness. To reach these materials goals, Tenaris has been developing new high-toughness (HT) grades of steel from which they can manufacture cold-drawn precision tubes with improved combinations of toughness and strength.

New materials must withstand both internal and external forces

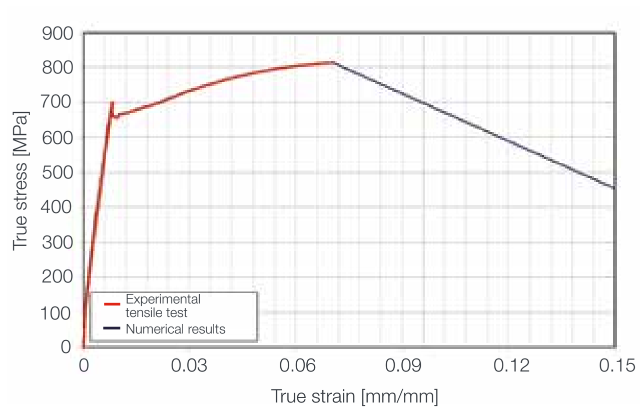
The primary stress on a hydraulic cylinder during normal operation comes from the internal pressure generated by the oil. This is much greater around the circumference of the tube (hoop stress) than along its length (the longitudinal stress is only about half the hoop stress). So as Tenaris develops its new materials, they look to maximize this circumferential yield strength. But, in addition, they need to demonstrate that each material can also withstand a wide range of physical stresses that can happen unexpectedly on a job site. "Critical defects, from which fatigue cracks can initiate, occur on the external surface of the tube," says Cristea.

To prove out the performance and quality of their products, the Dalmine R&D center has been conducting extensive full-scale testing of its hydraulic cylinder products for many years. This process begins with detailed mechanical characterization and fracture tests on tube materials. Then artificial defects are manufactured on the external surfaces of full scale tubes by means of electro-discharge machining. The tubes are then pre-cracked to different depths, capped, and chilled to minus 20 degrees Centigrade. Finally, they are pressurized with an alcohol water mix (aluminum filler bars are inserted inside the tubes to take up space and thus avoid extreme volumes of high-pressure fluid being released during bursting) and subjected to burst tests.

"With this 'build and break' test program we have been able to demonstrate the performance of our products to our customers in a way that's close to the



High-toughness (HT) steel burst test and Abaqus/Explicit model (left upper and lower) and low-toughness steel and Abaqus/Explicit model (right upper and lower).



Strong agreement between experiment and Abaqus FEA (numerical) results under tensile tests.

real-service behavior of the components," says Dalmine researcher Marco Spinelli. "But the test regimen is complex and quite expensive. We wanted to find out if numerical models could effectively replicate our experimental results, reduce our costs, and save us time."

Going deeper than stress and structural analysis to 3D crack prediction with Abaqus FEA

So the team turned to Abaqus unified finite element analysis (FEA) for realistic simulation of their fracture toughness testing regime. They were already familiar with the power of FEA, notes Spinelli, using it for stress distribution analysis in welded-joint applications and structural analysis of complex components. "The suite of software applications available with Abaqus is widely used for product design in our R&D center, mainly due to its pre- and post-processing advantages," he says. "We felt we had the tools in hand for deepening our inquiries into the performance of our new materials."

Since they already had recorded a great deal of accurate real-world test data, the group was able to create very precise FEA models of their cylinders using the materials definitions, geometries, crack dimensions, boundary conditions and burst pressures that were identified during their previous experiments. While the focus was on HT materials, low toughness material models were also examined to evaluate the overall performance of the software for predicting failure. The Tenaris team decided to try two methods in Abaqus for 3D crack modeling: ductile/fracture in Abaqus/Explicit and the new eXtended Finite Element Method (XFEM) capability in Abaqus/Standard.

Within Abaqus/Explicit, the team found they could take advantage of tube symmetry to create 1/8 models and reduce simulation time. Pressure was applied to the inner surface of the model, ramping up from zero to burst (1600 bar). Crack occurrence was simulated by employing 'element deletion' to signal when the plastic strain in a particular part of the model reached the critical value previously identified through the real-world burst tests: When the failure criterion is met for a particular element, that element drops out of the model, leaving a space behind. The series of connected, deleted-element spaces creates the appearance of the crack.

The Abaqus/Explicit simulation phenomenon is essentially static until the opening of the initial crack, after which the analysis becomes dramatically dynamic. Just as in the case with the real-world tests, the models demonstrated the more desirable ductile-failure mode when the material was HT steel and a brittle-failure mode with low-toughness steel. "When we compared our simulations with the real-world tests, we had excellent results predicting the failure modes for the cases we were investigating," says Cristea.

XFEM provides advanced crack modeling capabilities

After a series of Abaqus/Explicit modeling exercises, the team ran a final test case using XFEM. A relatively new addition to the Abaqus Unified FEA suite, XFEM, currently available in Abaqus/Standard, allows the simulation of crack propagation along an arbitrary path, even cutting across element boundaries in an FEA model. Based on a solution-independent crack initiation and propagation path, XFEM does not require the mesh to conform to geometric discontinuities, thus requiring less mesh refinement in the neighborhood of the crack tip.

"We obtained similar results to the ductile damage module with XFEM," says Cristea. "Going forward, implementing the XFEM capability in the Abaqus/Explicit code will further develop the methodology."

Their research into the use of FEA for crack prediction is already having a positive impact on the R&D workflow at Tenaris. "We aim to reduce the number of long and expensive full-scale tests," says Cristea. "Simulation has enabled us to establish the relative weight of the different factors that affect the in-service behavior of a component and arrive faster at an interpretation of our laboratory results. And where we deal with repetitive cases that were already experimentally validated, FEA offers us a powerful alternative tool for results prediction."

For More Information
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