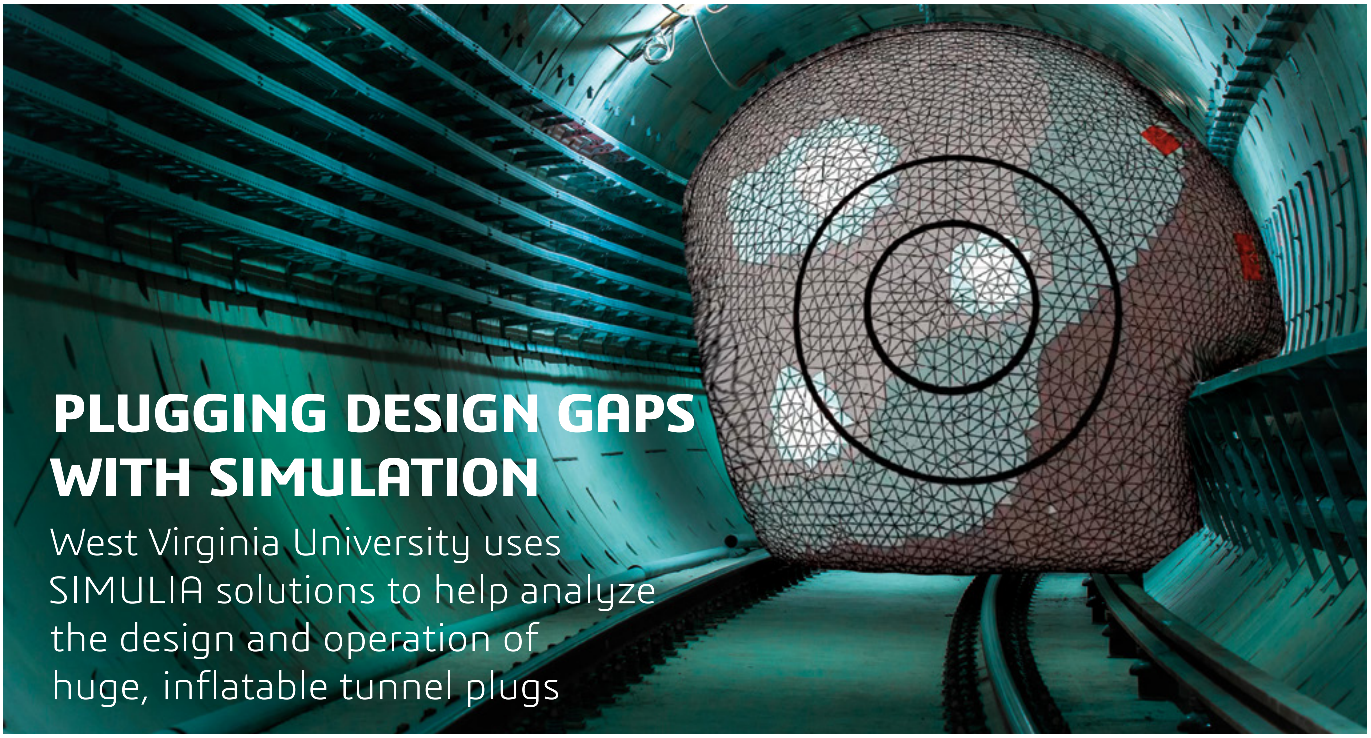

PLUGGING DESIGN GAPS WITH SIMULATION

West Virginia University uses SIMULIA solutions to help analyze the design and operation of huge, inflatable tunnel plugs

Imagine an airbag inflating in a vehicle. Now imagine it big—really big—big enough to close off a tunnel. Such a structure, expanded in an underground mine, subway, or road tunnel, would surely stop traffic. It would also stop the advance of water, excessively heated air, or toxic, chemical, and biological agents in the case of a flood, fire, crash, or other emergency.

The need for such a plug exits. Consider these incidents: In the fall of 2012, Hurricane Sandy flooded seven of New York City's subways and several of its major road tunnels, closing them for days. In 1999, a truck carrying margarine and flour in the Mont Blanc Tunnel between Italy and France caught fire, filling the tunnel with noxious smoke and burning for 50 hours. In March 1995, sarin gas was released in the Tokyo subway system.

Events such as these have concerned safety officials worldwide for decades and they have considered a number of ways of closing off subways, tunnels, or pipelines in order to control hazardous conditions quickly.

THE IMPETUS FOR INFLATABLES

In 2007, the U.S. Department of Homeland Security began looking for "out-of-the-box" ideas for protecting subway systems from extreme events, whether natural or man-made. One idea was to retrofit tunnels with rigid, metal floodgates or other types of solid structures. Another idea, which had surfaced earlier in Europe during the development of the Chunnel between England and France, was to install an inflatable plug at strategic locations inside the structure.

This inflatable concept, though never implemented in the Chunnel, was intriguing for several reasons. A plug that could inflate quickly like a giant airbag only in an emergency would not interfere with normal tunnel operations. An inflatable would be better than floodgates at fitting to the shape of a tunnel, and especially to the obstructions within, such as tracks, pipes, and walkways. This kind of "softer" fit—i.e., conformance—could be very effective at creating an air- or water-tight seal. An inflatable would also be less bulky than floodgates, and therefore easier and less expensive to install.

The idea was to set up inflatable structures, either permanently or temporarily, in multiple locations where an emergency was anticipated. The inflatables would be folded and packed in a container, readied for activation similar to that car airbag. The plug could be inflated by air from fans installed nearby or through pipes. Sensors embedded in the tunnel walls could trigger inflation, or inflation could be activated remotely. When the inflatable was no longer needed, it could be deflated and removed. A replacement could be swapped in or installed nearby in preparation for the next emergency.

> "We've concluded that our simulations demonstrate significant benefits from the use of FEA to predict the behavior of large-scale confined inflatables, as well as estimate quantities that can't be directly obtained from physical experiments"
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> —Eduardo M. Sosa, Research Professor, West Virginia University

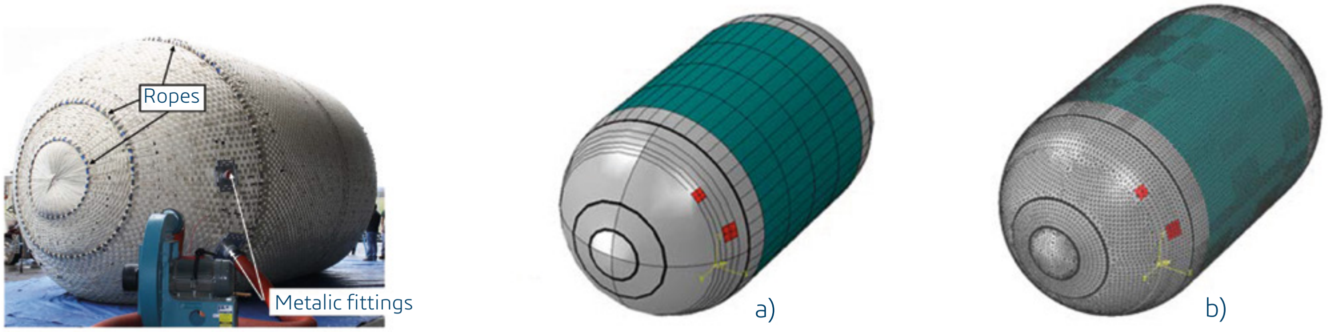

Figure 1. Inflatable plug prototype (left), and Abaqus model of the initial geometry: a) geometry b) meshed.

HOW TO VIRTUALLY PLUG UP A TUNNEL

Intrigued by the inflatable concept, Homeland Security reached out to the mechanical and civil engineering departments at West Virginia University (WVU). A full-scale test facility was constructed and an initial concept was tried out inside a structure that mimicked a segment of an actual rail-transportation tunnel.

Of course, scaling up an airbag to tunnel size required entirely new approaches in storage, deployment, and manufacture. And real-world testing proved to be complex, time-consuming and not as predictive as desired.

So WVU turned to realistic simulation, developing a series of finite element models of a confined inflatable plug in a tunnel. "By comparing the behavior of our computer models to experimental data from the full-scale tests, we could better refine our deployment designs and improve the ability to predict the complete sequence of real-world deployment more accurately," said Research Professor Eduardo M. Sosa. He presented his results, from his work at the University with colleagues Choo-Siang Wong and Ever J. Barbero, at the 2015 SIMULIA Community Conference in Berlin.

The primary analysis tool WVU used was Abaqus Unified Finite Element Analysis (FEA) from Dassault Systèmes' SIMULIA. FEA simulations included folding, positioning, settling (from gravity), deploying, and inflating the plug, as well as the plug's conformance to a tunnel and its adjustment against other objects typically found within a tunnel.

The team's Abaqus models covered a variety of components, the main ones being the inflatable plug and a tunnel segment. The inflatable plug consisted of a cylinder with two hemispherical end-caps (Figure 1), and two metal fittings on the same end-cap to inflate and deflate the plug. The perimeter of the plug is larger than the tunnel's perimeter for two reasons. First, the over-sizing compensates for any wrinkles and sags in the fully inflated plug after deployment. Second, it ensures better conformance, resulting in a better seal in the tunnel.

Model setup of the tunnel section was fairly straightforward. Unlike the plug, the tunnel is considered a non-deformable object, so while the structural membrane of the plug was modeled using membrane elements, the tunnel and plug fittings could be modeled using rigid elements.

THE COMPLEXITIES OF FOLDING AND INSTALLATION

Simulations of folding and positioning the plug consisted of both rigid body rotations and translations applied as boundary conditions to selected nodes and elements on the surface of the plug model. Folding was mostly a set of geometric transformations divided into three general steps: unconstrained, unstressed inflation; flattening and grounding (Figure 2); and folding by rolling.

The second step, flattening, incorporated both horizontal displacements and vertical gravity force. The final step of rolling the flattened inflatable was simulated using rotational rigid plates to represent the successive lifting and partial rotations of simulated folds. This last step consisted of three sets of lifting and rotation, all under the influence of gravity.

Modeling the positioning of the folded inflatable also fed into the simulations for plug deployment and inflation by accounting for the effects of gravity on the deflated, folded plug (i.e., how the plug settles when stored). The settling sequence essentially restored elements distorted through

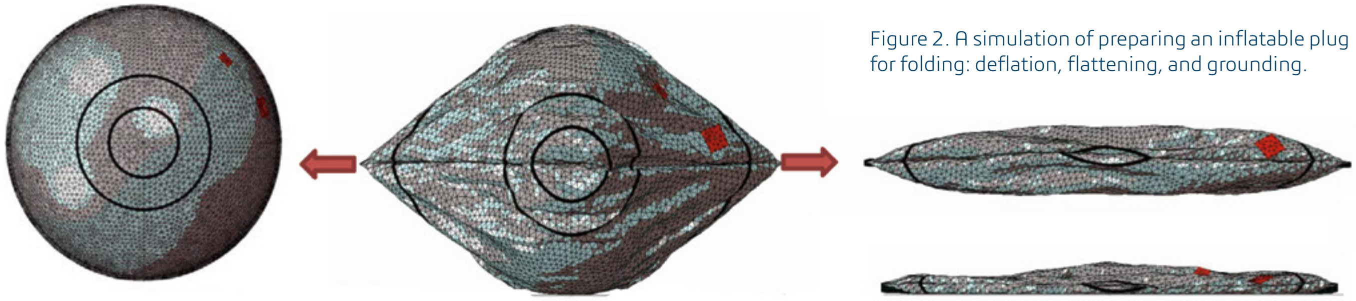

Figure 2. A simulation of preparing an inflatable plug for folding: deflation, flattening, and grounding.

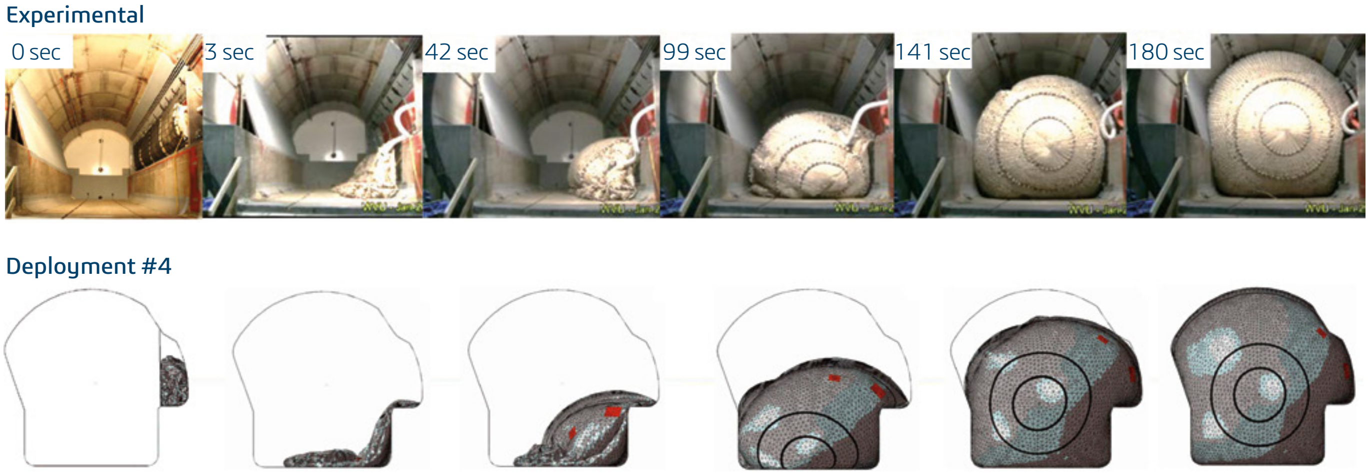

Figure 3. The simulated deployment of the inflatable plug closely matches the deployment of a plug in a full-scale test.

the folding and positioning back to their initial state before rerunning a deployment simulation. This reset also avoided distortions on the membrane surface and minimized the kinetic energy in deployment, thereby helping stabilize the entire deployment simulation.

DEPLOYING THE PLUG MODEL

The WVU engineers based their simulations on the Uniform Pressure Method (UPM) because it is simple, computationally efficient, and adequate for modeling relatively slow inflation. The UPM implemented in Abaqus/Explicit defines surface-based cavities to model the fluid-structure interaction during deployment and inflation. These surface-based cavities were complemented by the addition to the model of multiple internal chambers for a more precise control of the airflow during the inflation sequence.

Modeling the entire deployment of the inflatable plug (Figure 3) starts with the folded plug stored against the tunnel. When the virtual vertical gate to the plug container drops away, gravity causes the plug to fall out and unroll.

For refining the accuracy of their simulations, WVU had four deployment options to explore. In the first option, the folded plug did not have passive restraints in the form of tie-downs to control the unfolding membrane, and airflow was not directed within the plug. Instead, air filled the plug evenly, spontaneously, and immediately once it entered the plug. The second option included the tie-downs. In the third option, additional stiffness was added to the tie-downs as compensation for the dynamic response associated to a mass scaling factor. The fourth option was similar to the third except that, unlike in the other options, the sequence of airflow within the plug was defined (i.e., directed).

The team's analyses showed that the first and fourth deployments were extreme cases compared to experimental results in terms of conformance. The airflow as defined in the fourth deployment caused the simulation to most closely replicate the actual behavior seen in the full-scale tests.

THE PRESSURE TO CONFORM

Conformance is key in inflatable structures that need to tightly fill uneven spaces. Lack of conformity shows up as gaps between the inflated plug and the tunnel perimeter, usually at corners and around obstructions such as pipes. "Obviously, such gaps, and the leaks that result, need to be minimized, and this is where simulation came to be particularly useful for fine-tuning our deployment designs," said Sosa.

The position and extension of wrinkles in the plug fabric turned out to be critical too. Accumulation of membrane material in the form of wrinkles in one location leads to gaps in other locations around the contact perimeter. The presence of gaps is a clear signal of suboptimal deployment. Both wrinkles and gaps can be greatly reduced by optimizing several aspects of plug behavior including the folding pattern and deployment sequence, the location and number of passive restraints, as well as the friction characteristics of the interacting surfaces.

While previously obtained real-world data contributed to the accuracy of the team's models, conformance during full-scale inflatable tests had not been easy to measure in the test facility. But FEA could of course simulate expected conformance. Here, the ability of Abaqus to calculate contact between two objects highly accurately was of particular value: WVU found that their simulations were an extremely close visual match to real-world deployments conducted to study the contact area between the inflated plug and the tunnel walls in a variety of scenarios.

"We've concluded that our simulations demonstrate significant benefits from the use of FEA to predict the behavior of large-scale confined inflatables, as well as estimate quantities that can't be directly obtained from physical experiments," said Sosa. Going forward, the researchers plan to continue using such tools to further study other aspects of the tunnel-plug solution, including looking for additional applications that would benefit from the methodologies they have developed.

For More Information

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