Porting SI's ANACAP Concrete Model into LS-DYNA

Advanced Structural Analysis

LIVIA MELLO
lmello@structint.com

SHARI DAY
sday@structint.com

One of Structural Integrity Associates' (SI) strengths is combining state-of-the-art software with material science expertise to solve difficult structural and mechanical problems. A notable example in recent years is the Aircraft Impact Analysis (AIA) performed by SI for NuScale Power, using the ANACAP concrete material model. With SI's support, NuScale's Small Modular Reactor (SMR) building design passed NRC's comprehensive inspection, bringing NuScale's SMR technology one step closer to market [N&V Vol. 47 p. 5].

SI's success in AIA is due not only to our team's capabilities but also due to the capabilities of our proprietary concrete constitutive model, ANACAP, developed by Joe Rashid, Robert Dunham, and Randy James of ANATECH, now part of SI. Modeling reinforced concrete, which is both nonhomogeneous and anisotropic, is often a challenge in advanced structural analysis. However, ANACAP has a long track record of accurately capturing nonlinear concrete response in structural systems subjected to static, impact, and seismic loads. Its application goes beyond AIA; it has also been utilized in several of SI's commercial building, bridge infrastructure, nuclear plant, and hydroelectric facility projects.

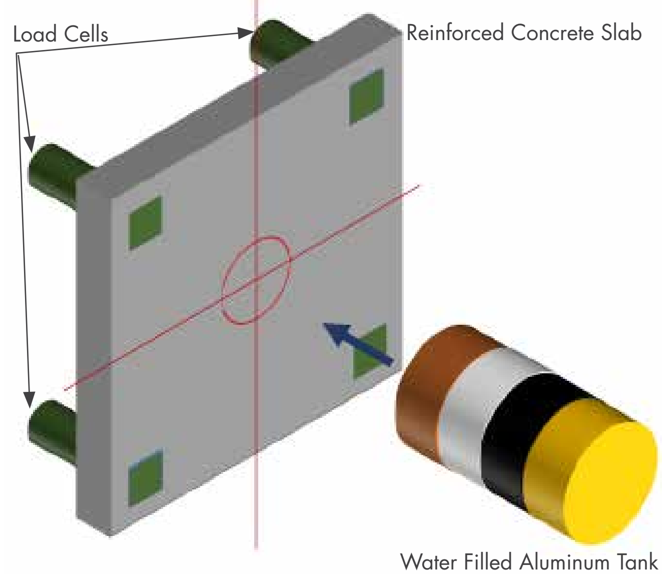
ANACAP has the ability to account for cyclic degradation, multi-axial cracking, load-rate effects, aging, creep, shrinkage, crushing, confinement, concrete-reinforcement interaction, and high-temperature softening behavior. The combination of these features results in an exceptional representation of concrete intricate behavior. It also leads to more accurate results when compared to standard finite element "built-in" concrete material libraries, all the while being implemented within the same standard finite element formulation.

With the purpose of expanding ANACAP's reach and better attend to our clients' safety-related needs, SI is integrating the concrete model into the specialized structural analysis software LS-DYNA, an explicit transient dynamic finite element code. Explicit finite element solvers are typically required to evaluate shock, blast, impact, drop, and other complex loading scenarios.

Following the Nuclear Energy Institute (NEI) 07-13 guidance, this software coupling must be extensively tested and verified for a wide range of problems representative of missile impacts on reinforced concrete slabs. One of these problems is presented here--a water slug impact test (WS test), in which a water-filled cylindrical aluminum tank impacts a reinforced concrete slab at a high velocity, as depicted in Figure 1.

Continued on next page

FIGURE 1. Depiction of water slug impact test



In LS-DYNA, the WS test is simulated using a half symmetric model that includes the load cell connection, as illustrated in Figure 2. The pipes connected to the bearing plates are modeled, and the bolts running through pipes that tie the slab to the load cell are also modeled. Contact surfaces are set up between the concrete and load cells as well as between the bearing plates and nuts securing the tie rod bolts. The model includes a symmetry boundary condition on the vertical cut along the center of the slab. The ends of the load cells are fixed in the lateral direction to represent support from the reaction test frame. The loading is simulated with an applied pressure over a semi-circular area.

Analysis results are shown in Figures 3 through 6, in comparison with the test data. Figures 3 and 4 provide comparisons of the displacement histories at two points along the horizontal centerline of the impact location. Point D8 is at the center of the impact and point D6 is off-center, as shown in Figure 2. These plots show that the analytical results are in good agreement with the measured experimental data, which indicates that the concrete model for the slab is performing well in simulating the actual concrete response.

Figure 5 compares the total reaction force in the direction of the impact calculated from the analysis to that measured in the test. The higher initial peak in the data is due to the hardness of the tank's front-end cap, which is not modeled in the analysis and produces a higher initial impact force in the experiment. Figure 6 compares the impulse of the total reaction force between the test data and analytical results. Also included in this plot is a dashed line representing the final value of the impulse calculated as the mass times the initial impact velocity of the water tank. The plot not only shows a close relationship between experimental and analytical results, but it also shows that the analysis captures the total impulse converging to the initial momentum of the impactor.

Snapshots of maximum principal strain in the concrete slab are shown in Figure 7,

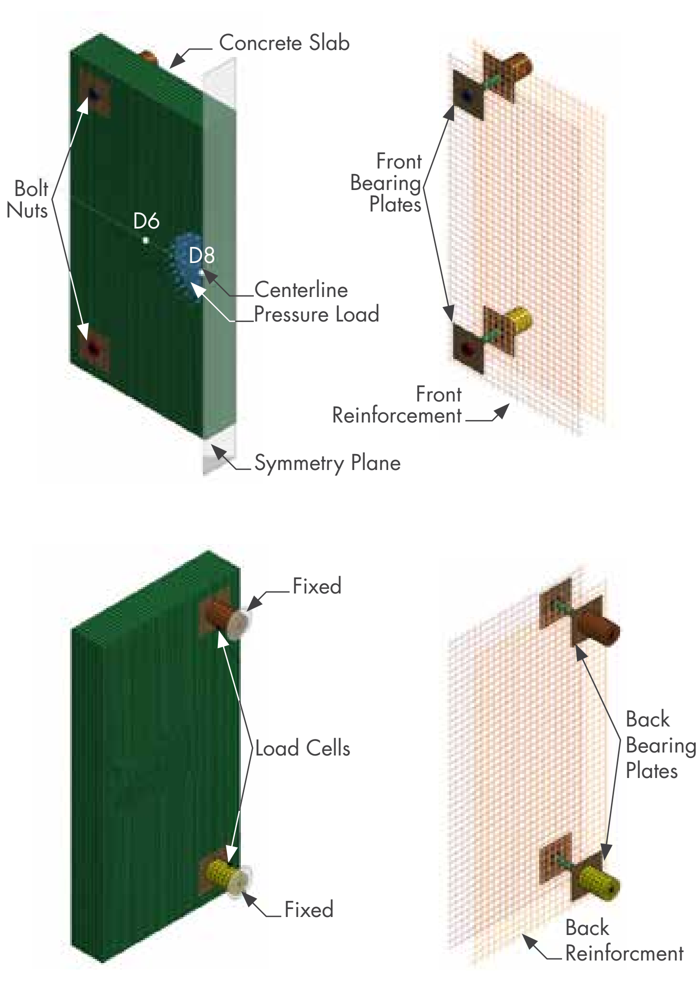


FIGURE 2. Schematic of LS-DYNA model

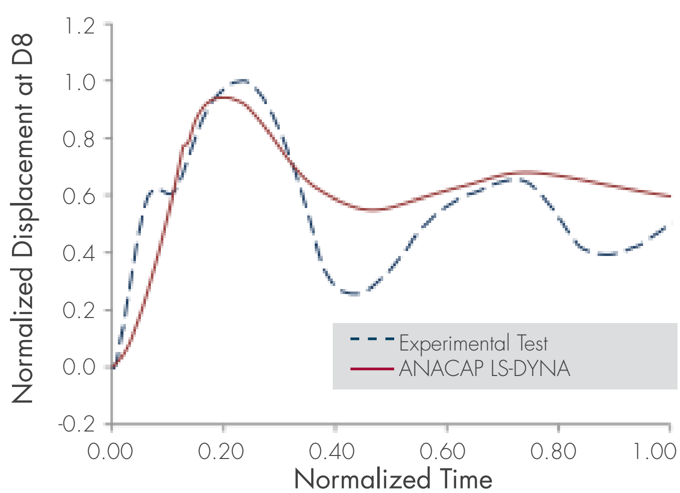


FIGURE 3. Displacement evolution at point D8

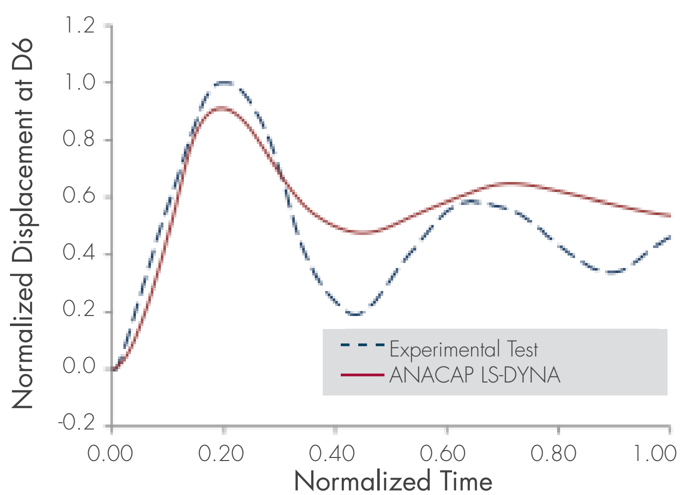


FIGURE 4. Displacement evolution at point D6

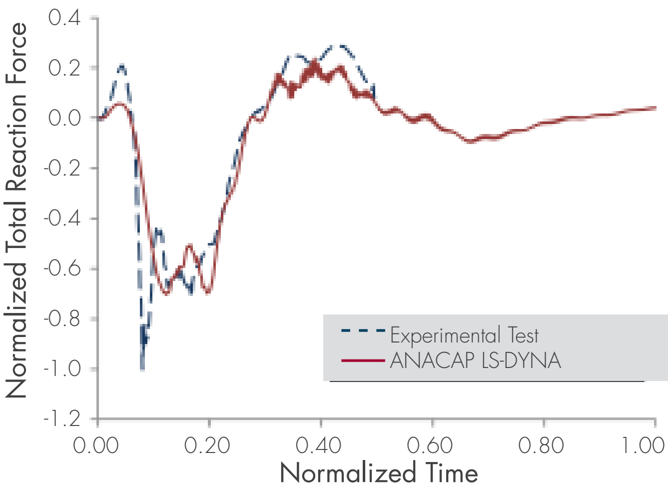


FIGURE 5. Total reaction force evolution in direction of impact

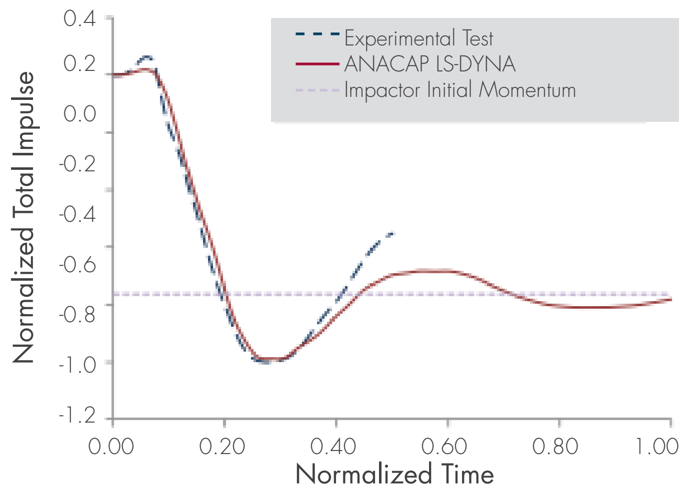


FIGURE 6. Impulse of total reaction force

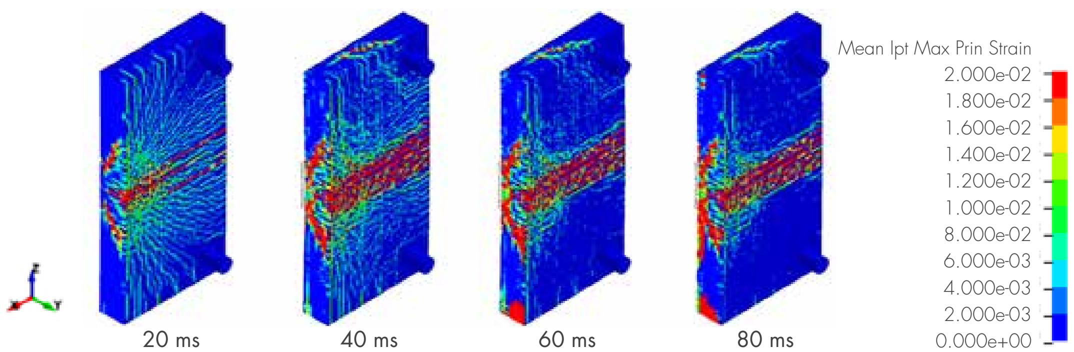


FIGURE 7. Snapshots of maximum principal strain on the concrete

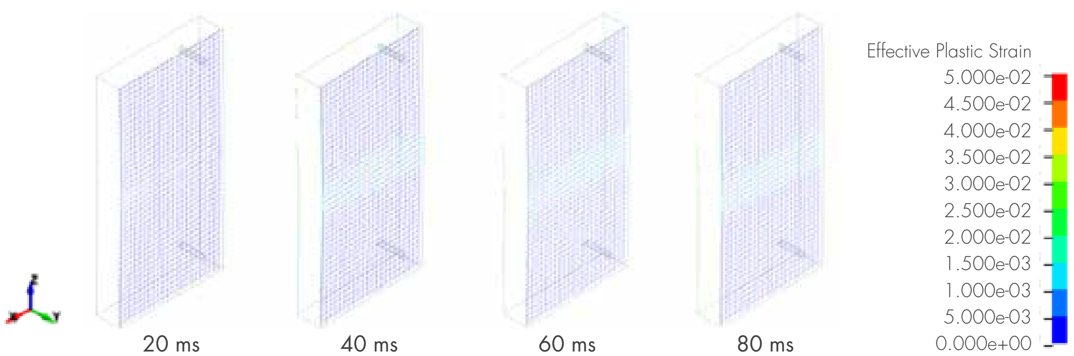


FIGURE 8. Snapshots of accumulated plastic strain in reinforcement on back face of slab

with a view from the back of the slab at solution time states of 20, 40, 60, and 80 milliseconds. This figure shows that heavy cracking damage develops in the slab without perforation, which is consistent with observations of the experimental results. This figure also shows that the concrete model can capture the closure of some of the initial cracking as the slab oscillates. Although ANACAP does not allow for any of the formed cracks to fully heal, it does allow for crack closure and consequent load-carrying capacity under compression and shear.

Snapshots of accumulated plastic strain in the bending reinforcement on the back face of the slab are shown in Figure 8. We see moderate yielding of the bars, but the plastic strain remains below 5%, which is the assumed strain rupture criteria. This indicates that the damage is sufficient to yield a few reinforcing bars but that slab failure due to bending does not occur, which is again consistent with what was observed during the test.

Based on these results, the ANACAP/LS-DYNA simulation reproduces the correct structural response and correlates well with the damage sustained by the slab documented in the WS test. This validation, combined with additional verification and validation problems in the suite of software testing SI performs, provides confidence that SI's ANACAP model has been successfully integrated into LS-DYNA, and that the material routine can capture the complexities of reinforced concrete behavior for advanced analysis applications such as AIA.