



ALE Modeling of Explosive Detonation on or near Reinforced-Concrete Columns

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Abstract

*The detonation of explosive threats in contact with or near reinforced concrete columns was modeled using the Arbitrary Lagrangian-Eulerian (ALE) capability of LS-DYNA, in support of the development of a software tool for assessing the vulnerability of structures subjected to terrorist attack. The explosive, air, and concrete were modeled as fluids, and the reinforcement was modeled using beam elements. *MAT_72R3 was used for the concrete, and column damage was characterized using the scaled damage measure, an output from the constitutive model that quantifies damage to the material. The model was initially validated against a large database relating spall and breach thresholds of reinforced concrete slabs to charge weight and standoff. It was further validated against a small database for explosive loading against reinforced concrete columns. A parameter study was then performed to populate a results space comprising four column shapes over a representative range of dimensions. This results space was used to develop a fast-running algorithm that will be implemented in the structural vulnerability assessment software.*

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1 Introduction

Protection Engineering Consultants (PEC) and the University of Texas at Austin (UTA) have been collaborating to develop an anti-terrorism planning tool (ATP) as part of a broad effort by the Department of Homeland Security (DHS). The ATP tool is a fast-running software for determining damage and failure of structural components due to terrorist attack. Engineers may use the ATP tool to estimate the damage or failure state of a component and, from that, determine the remaining capacity of the component itself.

In support of the ATP tool, PEC has developed an algorithm for predicting spall and breach of a reinforced-concrete column. Spall is partial rubbleization of the cross section; breach is total rubbleization of the section. These conditions are illustrated in Figure 1(a) and Figure 1(b), respectively. The basis of the algorithm is limited test data and extensive synthetic data generated using LS-DYNA[®] Arbitrary Lagrangian-Eulerian (ALE). This paper discusses the parametric ALE model, and focuses on how the concrete was modeled as a fluid and how damage to the column was estimated.

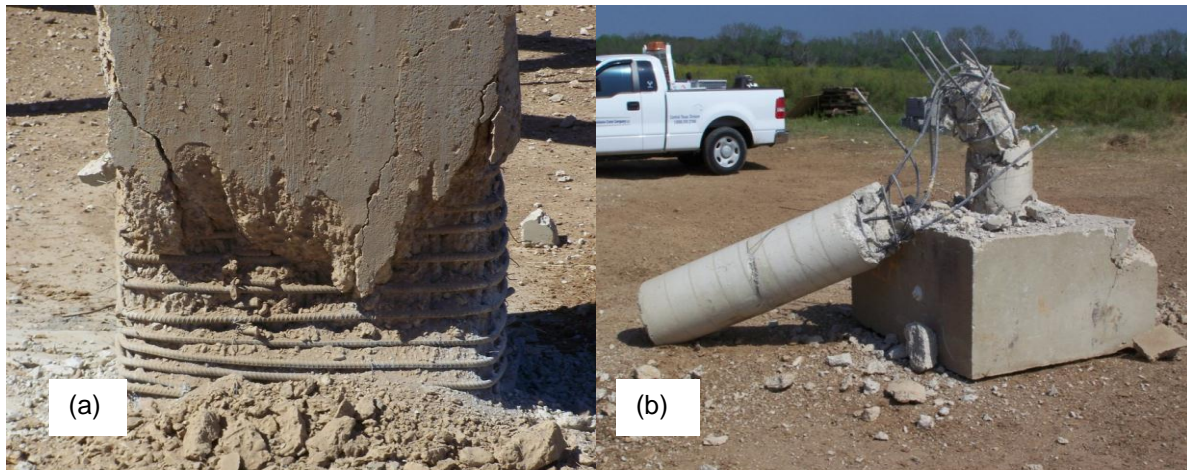


Figure 1(a) Column Spall (b) Column Breach

2 Methodology

The strategy for development of the algorithm was to extend existing 1D spall-breach methodology (for slabs) to include 2D effects (column). Edge effects in the 2D case influence both the applied load and material response. The existing 1D methodology is highly empirical, comprising a set of best-fit curves to spall-breach test data. This slab data was generated from a large set of tests where explosives were detonated on or near different slab geometries. The damage state (breach, spall, or no damage) and damage extent (breach or spall diameter) were recorded.

Such an extensive data set does not exist for the 2D column case. The limited data on spall-breach of columns came from a series of blast tests supporting National Cooperative Highway Research Program (NCHRP) Report 645 *Blast-Resistant Bridges: Design and Detailing Guidelines*(1). Therefore, a parametric ALE model was developed, and parameters such as charge weight, standoff, and column geometry were varied to populate a results space with

synthetic data. This results space served as the basis for calibrating best-fit curves for the 2D column case, shown in Figure 2. τ is an inverse measure of impulse attenuation through the target thickness; i is applied impulse.

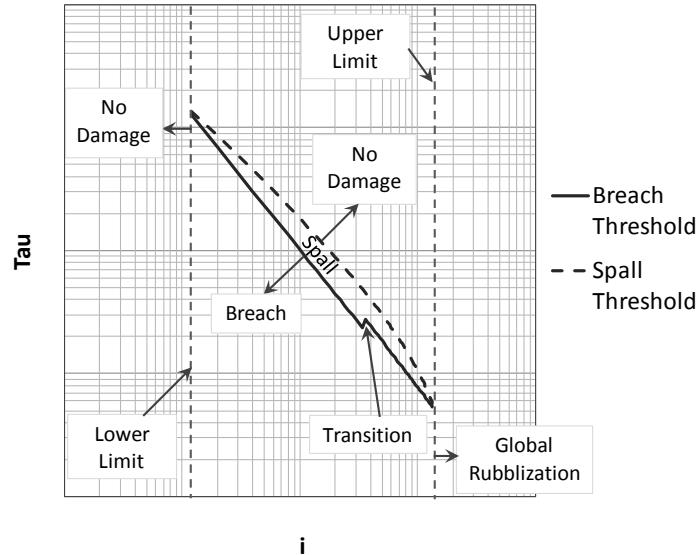


Figure 2. Threshold Curves

3 Independent Parameters

To generate the synthetic data, a parametric ALE model was developed and validated against the NCHRP 645 data. Then, 325 ALE simulations were run of RC columns subjected to close-in and contact detonations. For those simulations, charge weight, standoff, charge L/D ratio, column shape (circular, square, or rectangular section), and column dimensions were varied. For most simulations:

- Compressive strength was 4,000 psi, per the test series supporting NCHRP 645 (1);
- Steel reinforcement was 60 grade;
- Longitudinal steel ratio (percent cross section) was 1%;
- Volumetric steel ratio (per ACI 318-08 (2) definition of ρ_s) varied from 0.05% to 0.27%.

Four column sections were included in the simulations:

- Circular, typically 36-in, 48-in, or 60-in diameter
- Square, typically 32-in, 42-in, or 52-in edge
- Rectangular with $D/W = 2$, typically $D = 45$ in, 60 in, or 75 in
- Rectangular with $D/W = 0.5$, typically $D = 22.5$ in, 30 in, or 37.5 in

For most simulations, the longitudinal bar diameter was calculated from the column cross-sectional area and longitudinal steel ratio (generally 1%). The transverse bar diameter was typically 50% of the longitudinal bar diameter. The cover on all columns was 2 in.

The shape of the charge was cylindrical for all simulations, and the most common L/D ratio was 1.0, with the range being from 1.0 to 2.5.

4 Multi-Material Group and Fluid Structure Interaction Coupling

The LS-DYNA ALE models included air, explosive, and concrete as Eulerian fluids composing a multi-material group. As shown in Figure 3, a quarter-symmetry, cubic Eulerian domain was used for the multi-material group filling. The column is shown on its side to emphasize symmetry planes. *INITIAL_VOLUME_FRACTION_GEOMETRY was used for filling. First, the entire Eulerian domain was filled with air; then the concrete and charge volumes were filled using parameterized coordinate definitions. The concrete was unsupported (inertial resistance to charge only), and gravity was not included in the simulation.

The reinforcement was included as beam elements coupled to the concrete as discussed below; ELFORM 1 (Hughes-Liu with cross section integration) was used. *BOUNDARY_NON_REFLECTING was applied to the exterior faces of the domain to simulate free-field (outdoor) explosion; these are all non-symmetry planes in Figure 3 (a). A detail of the filled concrete, steel reinforcement, and explosive is shown in Figure 4; air is not displayed for clarity.

A cubic domain rather than spherical was used, because a spherical domain caused initial distortions in the rectangular concrete target, and these exaggerated the damage predictions. A mesh biased with respect to the charge center was generated using the block mesher in LS-PrePost (LSP). Beyond the joint shown in Figure 4, the mesh was biased at a 5% increase per element. At the charge center, the element size was 1.2 in. (3 cm), as shown in Figure 5; this dimension was selected on the basis of a mesh convergence study performed during initial modeling. Overall dimensions for the Eulerian mesh were selected to accommodate the maximum column size and permit minimal reflection from exterior *BOUNDARY_NON_REFLECTING, which is known to amplify applied pressure and impulse if the boundary is too close to the target or charge. Method 2 was used for the advection method.

Figure 6 through Figure 8 illustrate detonation of a 100-lb TNT charge at a 40.8-in standoff from a 42-in square column. The animation of the quarter-symmetry models is reflected about symmetry planes, and air is excluded for clarity.

The steel beam elements were coupled to the concrete using *CONSTRAINED_LAGRANGE_IN_SOLID. For the coupling, CTYPE was set to 2 and MCUP to 1.

No contact was defined between the longitudinal and transverse beam elements; both sets of beam elements interacted through coupling to the concrete. This approach permitted consistent, robust modeling of the reinforcement for all simulations. A penalty-based contact between the steel beam elements likely would have introduced instabilities and would have required intermittent adjustment for different geometries. Therefore, no beam-to-beam contact was considered sufficient for the fidelity of the models.

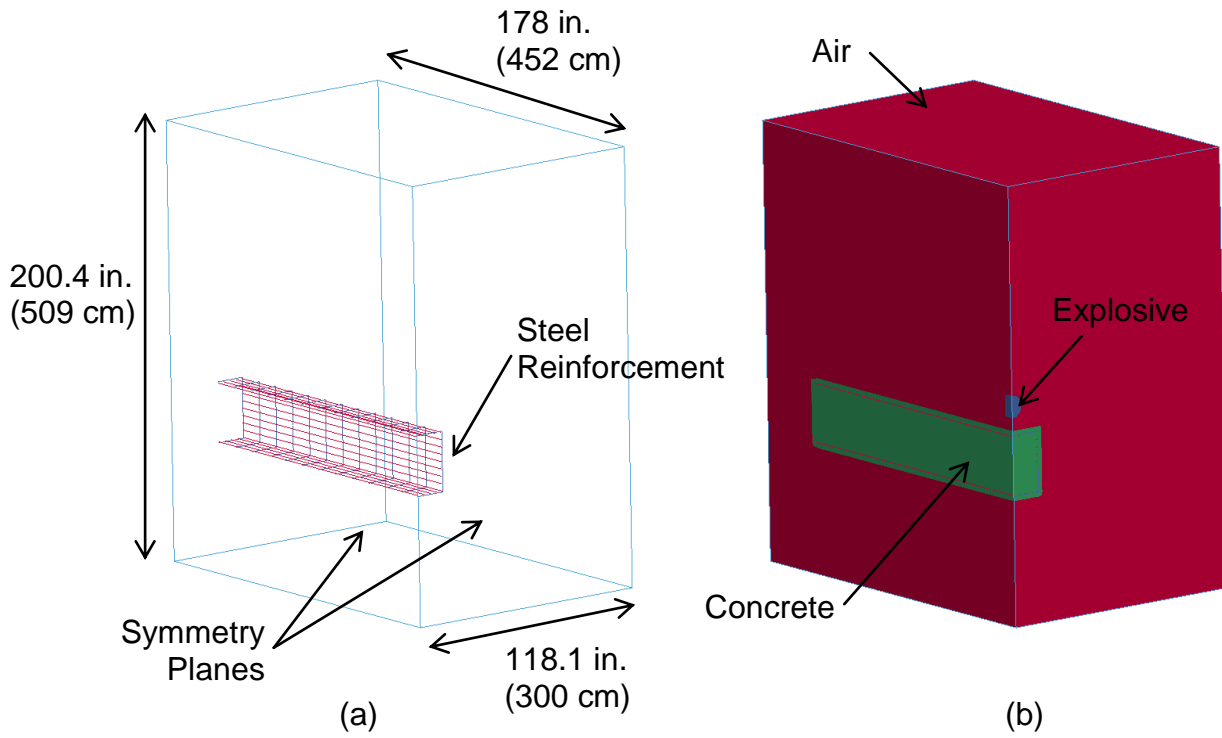


Figure 3. (a) Eulerian Domain Prior to Filling; (b) After Filling

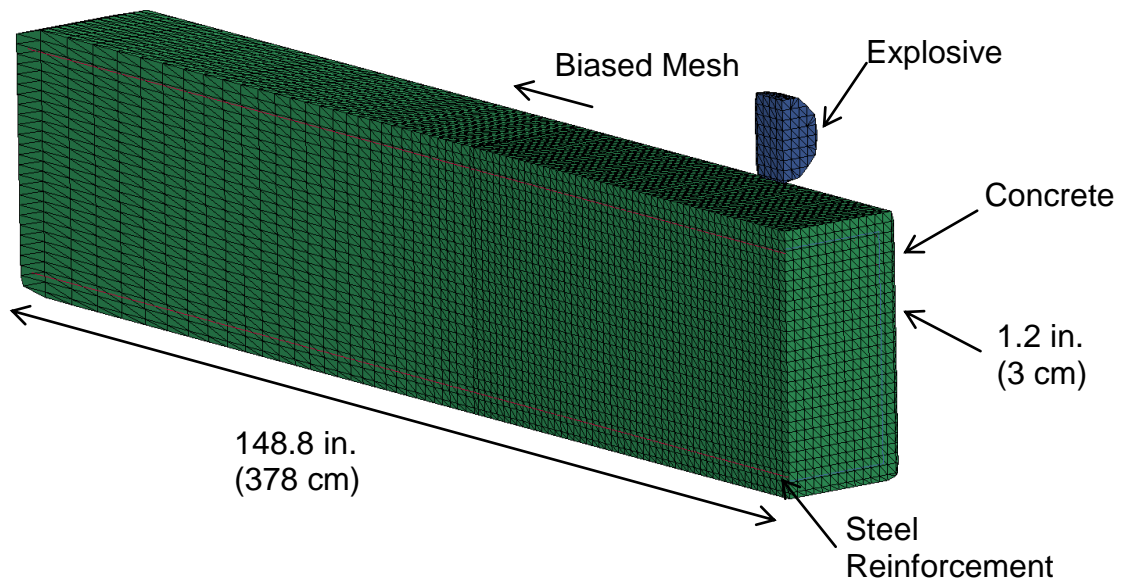


Figure 4. Detail of Filled Concrete, Steel Reinforcement, and Explosive



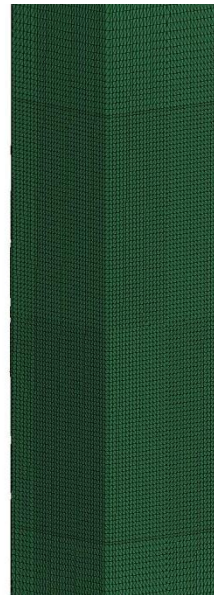
Figure 5. Characteristic Element for Parametric Simulations
(3.05 cm X 3.06 cm x 3.06 cm)

LS-DYNA keyword deck by LS-PrePost
Time = 0



(a)

.S-DYNA keyword deck by LS-PrePost
Time = 59.812



(b)

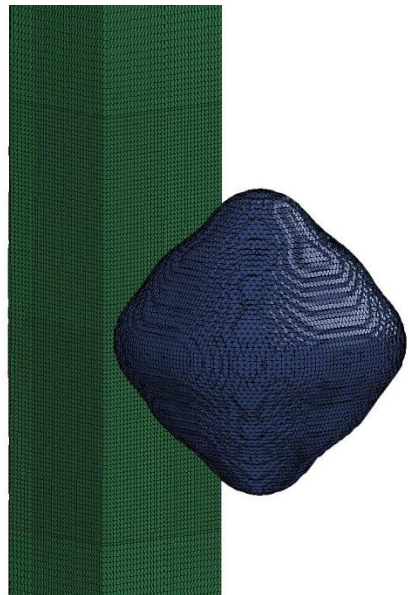
Figure 6. 42-in Square Column, 100-lb TNT, 40.8-in Standoff:
(a) 0 usec; (b) 60 usec [315]

LS-DYNA keyword deck by LS-PrePost
Time = 113.81



(a)

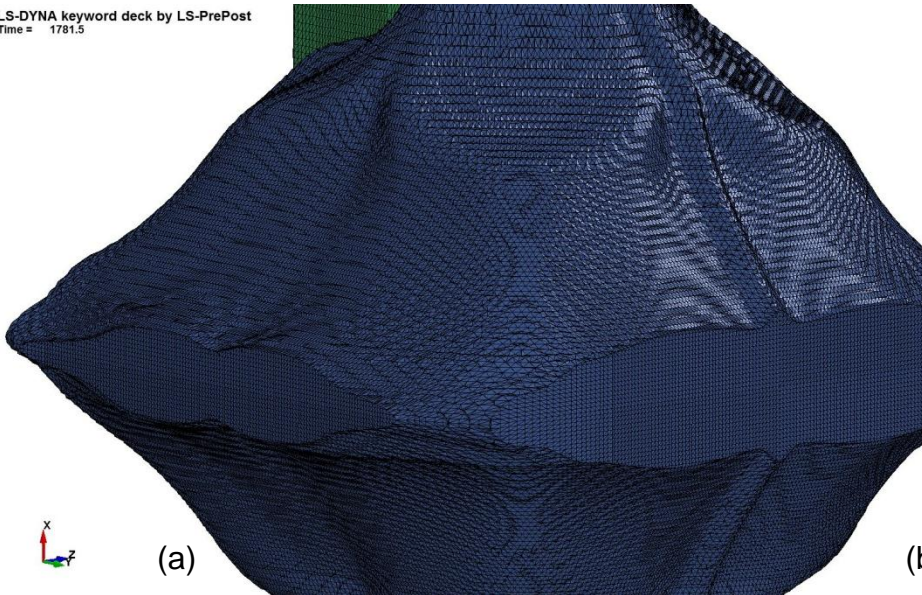
S-DYNA keyword deck by LS-PrePost
Time = 257.81



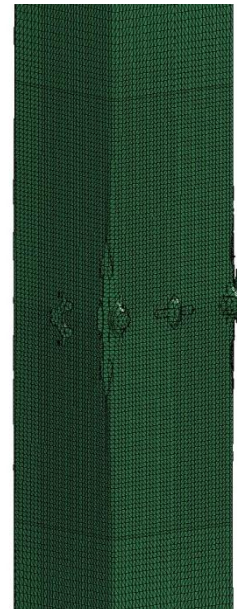
(b)

Figure 7. 42-in. Square Column, 100-lb TNT, 40.8-in. Standoff:
(a) 114 usec; (b) 258 usec [315]

LS-DYNA keyword deck by LS-PrePost
Time = 1781.5



(a)



(b)

Figure 8. 42-in. Square Column, 100-lb TNT, 40.8-in. Standoff:
(a) 1782 usec; (b) 4000 usec (column only) [315]

5 Constitutive Models

Constitutive models and equations of state for these materials are detailed below. All simulations used units of g, cm, usec (10^{-6} seconds). Parameters used for the constitutive model are reported in units of lb, in., sec for familiarity and report consistency.

5.1 Air

The constitutive model for the air was *MAT_NULL. Its only input was density, and this equaled $1.22\text{E-}07$ lb-sec²/in⁴.

5.2 TNT Explosive

TNT (Trinitrotoluene) was selected for the explosive. The constitutive model used was *MAT_HIGH_EXPLOSIVE_BURN, and the equation of state was *EOS_JWL. Standard input parameters for the constitutive model and equation of state were used. The cylindrical charge was detonated at its centroid.

5.3 Concrete

*MAT_72R3 was used as the constitutive model for the concrete. The parameter generation option was used where the strength and mechanical properties (unconfined tensile strength, cap model parameter, etc.) are inferred from nominal unconfined compressive strength.

Rate effects were included using the strain rate curve in the LS-DYNA Keyword manual. Including rate effects can overestimate compressive strength, because that strength increase is added to a contribution from inertial confinement. However, the spall threshold is largely determined by tensile strength, and past work suggested that including rate effects was necessary to capture rate-dependent increase. This is consistent with the fact that rate effects in tension are significantly greater than rate effects in compression. Assuming *MAT_72R3 was calibrated primarily for compression, including rate effects, is appropriate. The appropriateness was confirmed against the NCHRP 645 test data.

5.4 Steel

*MAT_PIECEWISE_LINEAR_PLASTICITY was used for the steel constitutive model. The input parameters are shown in Table 1. Rate effects were not included.

Table 1. Steel Constitutive Parameters
(*MAT_PIECEWISE_LINEAR_PLASTICITY)

Parameter	LS-DYNA Symbol	Value	Units
Density	RO	7.40E-04	lb-s ² /in. ⁴
Modulus of Elasticity	E	29.0E+06	psi
Poisson's Ratio	PR	0.33	
Yield Stress	SIGY	60.0E+03	psi
Hardening Modulus	ETAN	29.0E+03	psi
Failure Strain	FAIL	0.30	in./in.

6 Damage Characterization

Because the concrete was modeled as a fluid, erosion was not added to the constitutive model. Rather, damage was characterized using the scaled damage measure, an output from the *MAT_72R3 constitutive model. This measure is recorded for each concrete Eulerian cell, at each time step. The parameter ranges from 0 to 2. If it is between 0 and 1, the concrete is in the elastic range; if it is between 1 and 2, it is yielding. If it reaches 2, it is fully damaged and has a residual compressive strength of pulverized concrete. Therefore, any concrete Eulerian cell that reached 2 was used to define the extent of the damaged region and to identify the occurrence of breach, spall, or no damage.

Inspection and measurement of the damaged region was performed using LSPP. The scaled damage measure was displayed as a contour plot, the damage state (breach, spall, or no damage) was identified, and the extent of damage measured. Examples of this transition are shown in Figure 9(a) (spall of square section) and Figure 9(b) (breach of square section). In all cases, the scaled damage measure was displayed from 1.9 to 2.0 for clear distinction between failed and intact elements.

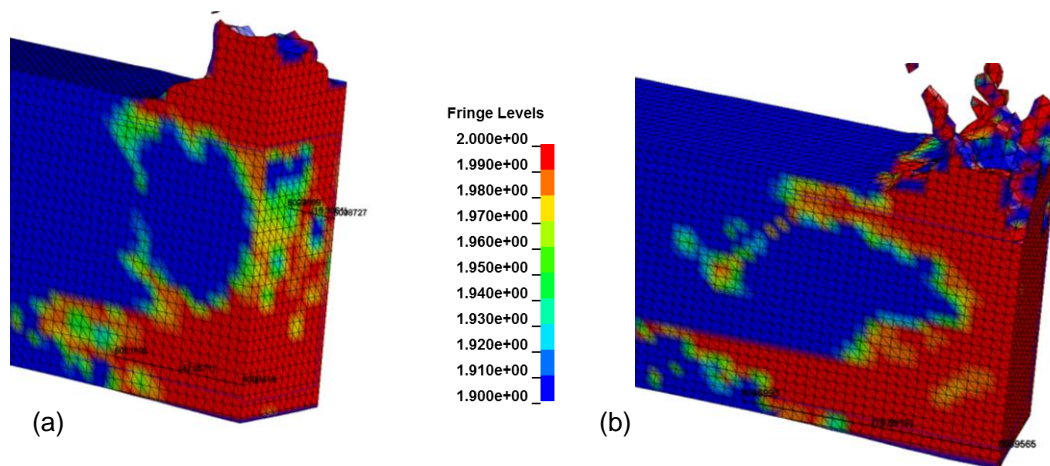


Figure 9(a) Spall of Square Section [302] (b) Breach of Square Section [283] (Scaled Damage Measure from 1.9 to 2.0)

7 Mass Scaling

For all simulations, mass scaling was used. In an ALE simulation, a small body of Eulerian fluid can separate from its species and cause the time step to plummet, increasing computation time significantly. When mass scaling is turned on, the mass of the Eulerian element containing the small body is scaled to increase the time step. The change in mass is tracked and reported so that the analyst can ensure that the effect on the model's performance is small. Large batches of simulations were performed, and mass scaling was necessary to prevent any one run from stopping the batch with a plummeting time step. Simulations with non-trivial increases (greater than 1%) in mass were excluded from the database to ensure mass scaling had little effect on results.

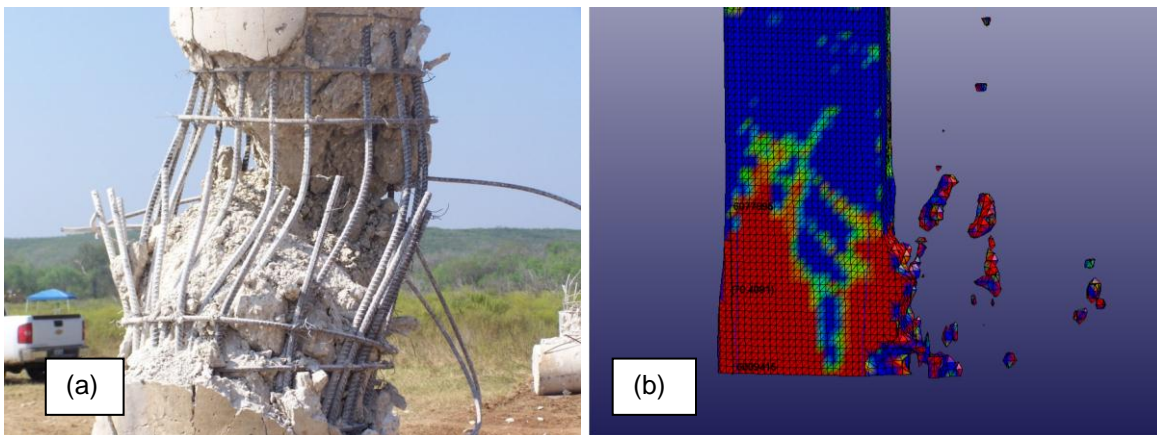
8 Validation against NCHRP 645 Data

The parametric model was initially validated against a large database relating spall and breach thresholds of reinforced-concrete slabs to charge weight and standoff. After that initial validation, it was further validated against the eleven NCHRP 645 tests. As shown in Table 2, the models agreed with test data for damaged state in all cases but one. In the case of the exception, BR5-1, the column had just barely breached in the simulation. Agreement on extent of damage was acceptable. The post-test condition of BR2 and results from the numerical model are shown below in Figure 10(a) and Figure 10(b).

Table 2. Comparison of Column ALE Models versus NCHRP 645 Tests

Test ID1	NCHRP Damage State	NCHRP Side Damage [in]	NCHRP Rear Damage [in]	ALE Damage State	ALE Side Damage [in]	ALE Rear Damage [in]
BR1	Breach	na ¹	na ¹	Breach	77	84
BR3	Breach	na ¹	na ¹	Breach	55	55
BR2	Spall	60	48	Spall	53	55
BR4	Spall	60	48	Spall	53	55
BR5-1	Spall	24	20	Breach	43	43
BR 5-2	Spall	30	0	Spall	46	43
3-Blast	Spall	30	20	Spall	36	37

¹In breach cases, the column disintegrated and no damage length could be measured



*Figure 10(a) Post-Test Damage to BR2 (Avg. 54 in)
(b) Parametric Model Damage (Avg. 54 in)*

9 Conclusions

Modeling concrete as an Eulerian fluid using ALE methodology yields good results where the explosive is explicitly modeled. Concrete as fluid permitted the column to respond with large deformations at very high rates. In addition, the approach was stable over a wide range of charge weights, standoffs, and column geometries.

Furthermore, when rate effects are added to the *MAT_72R3, its scaled damage measure accurately reports spall and breach damage to a reinforced-concrete column from a close-in or contact detonation. It is necessary to add rate effects, because spall and breach of concrete are tension-dominated responses, and concrete is more rate-sensitive in tension than compression. Accurate damage reporting was achieved using unmodified strength properties from *MAT_72R3 parameter generation based on unconfined compressive strength.

10References

1. **Williamson, Eric B., et al.** *Blast-Resistant Highway Bridges: Design and Detailing Guidelines*. Washington, D.C. : Transportation Research Board, National Cooperative Highway Research Program, 2010. Report 645.
2. **ACI Committee 318.** *Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary*. Farmington Hills, MI : American Concrete Institute, 2008.

11 Acknowledgements

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