Naval Facilities Engineering Command

EXWC Engineering & Expeditionary Warfare Center

Modeling Reinforced Concrete Protective Construction for Impact Scenarios

International Explosives Safety Symposium and Exhibition

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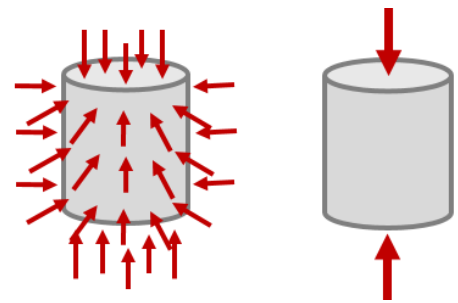
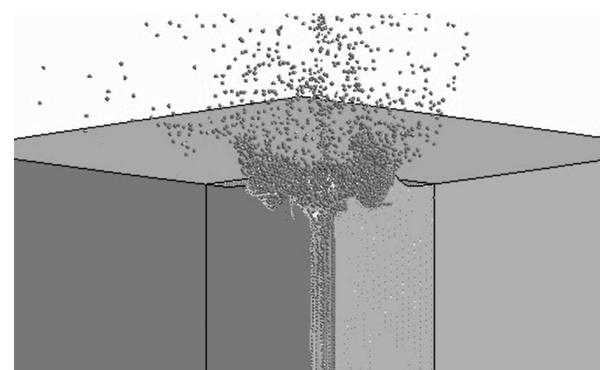
Introduction

- Protective construction for explosives safety compliance
- Challenges associated with modeling concrete structures subjected to large debris impact
- Use of a high-fidelity physics-based code (LS-DYNA) to simulate impact into high-strength concrete
- Performance comparison of several concrete models against laboratory test data (quasi-static and impact)
- Correlations between material model fits to quasi-static test data and ability to simulate response to impact loading





Protective Construction for Explosives Safety Compliance

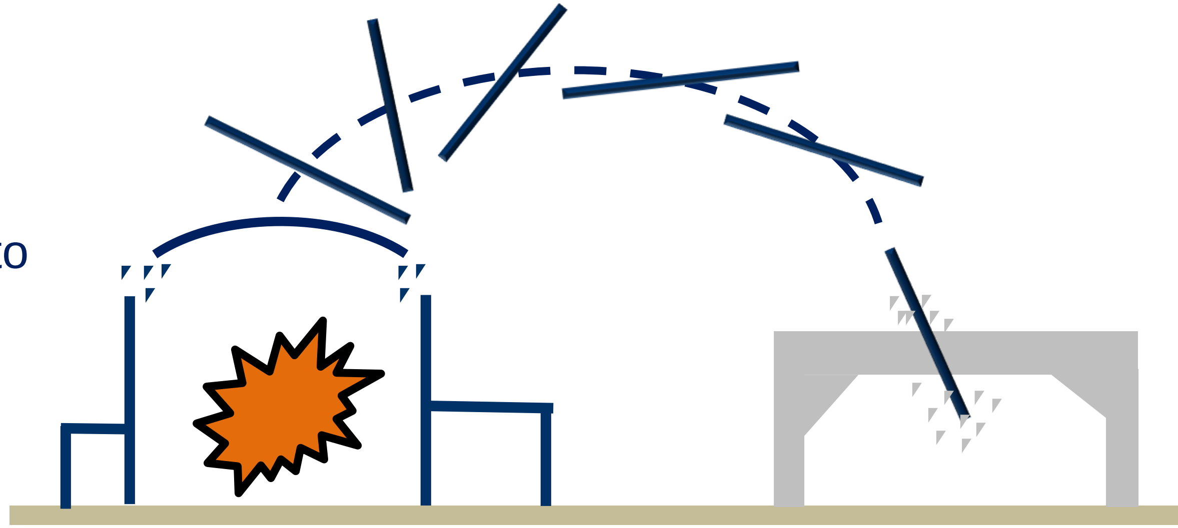
- **Separation distance vs. protective construction**
- **DoD Manual 6055.09-M references UFC 3-340-02 for protective construction analysis procedures**
  - **Documented methods for blast and primary fragments**
  - **Gap in criteria for large debris impact hazards**

UNIFIED FACILITIES CRITERIA (UFC)

STRUCTURES TO RESIST THE EFFECTS OF ACCIDENTAL EXPLOSIONS

Protective Construction for Explosives Safety Compliance

- **Case Study – Roof Beam Impact on Occupied Building**
  - **Hazard:**
    - Accidental blast in building with structural steel framing
    - Failure of connections at roof beam-column joints
    - Trajectory analysis of roof beam shows impact at nearby occupied building
  - **Analysis Results:**
    - Global roof slab deflection is acceptable based on flexural response
    - Conservative local impact analysis shows slab perforation
  - **Challenges:**
    - Estimating duration of impact load
    - Energy absorption due to beam deformation, etc.



Concrete Modeling for Impact Loading

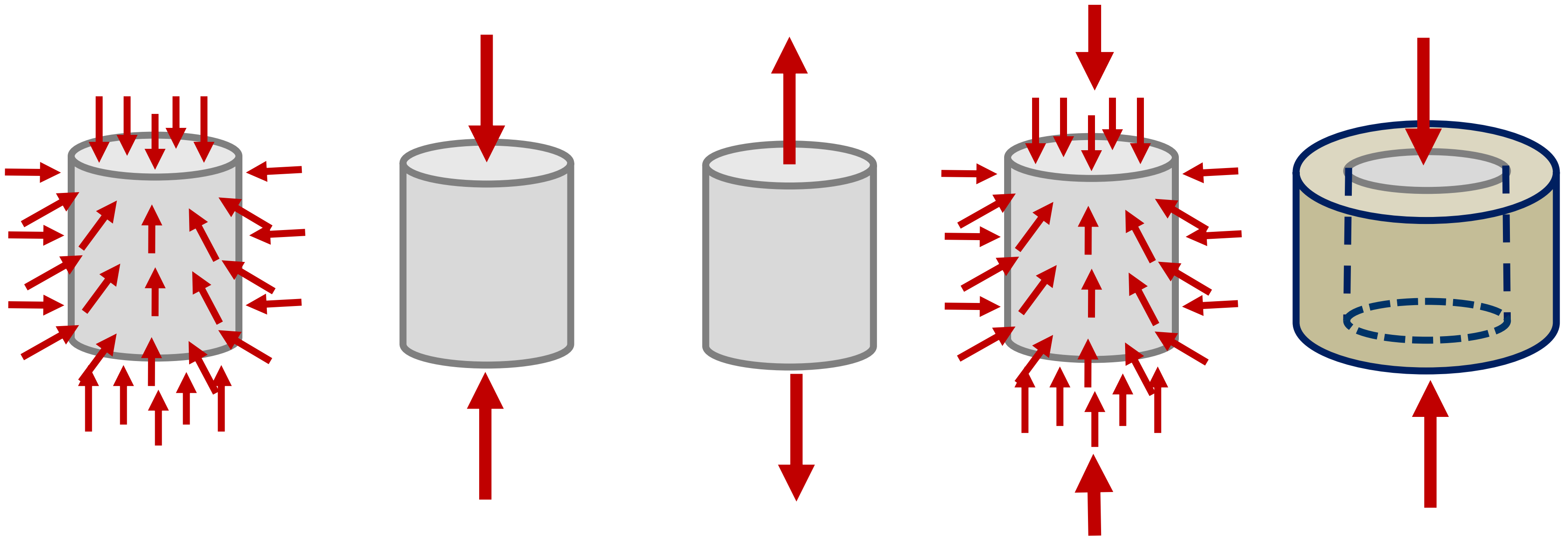
- **The material model should be capable of handling...**
  - Complex states of stress
  - Large deformations
  - Material discontinuities (cracking)
  - High strain rates
- **The model strength envelope should be a function of...**
  - Pressure
  - Volumetric compaction
  - Dilatancy due to shearing
  - Brittle and ductile material responses
  - Strain rate effects

Concrete Modeling for Impact Loading

- **Material models evaluated in this study**
  - **Using automatic parameter generation:**
    - K&C Concrete Model, Rel. 3 (*MAT_CONCRETE_DAMAGE_REL3)
    - Continuous Surface Cap Model (*MAT_CSCM)
    - Riedel-Hiermaier-Thoma Model (*MAT_RHT)
    - Winfrith Concrete Model (*MAT_WINFRITH_CONCRETE) [quasi-static only]
  - **Using parameters fit to material test data:**
    - Johnson-Holmquist Model (*MAT_JOHNSON_HOLMQUIST_CONCRETE)
    - K&C Concrete Model, Rel. 4

Experimental Test Data

- **Material test data (quasi-static)**

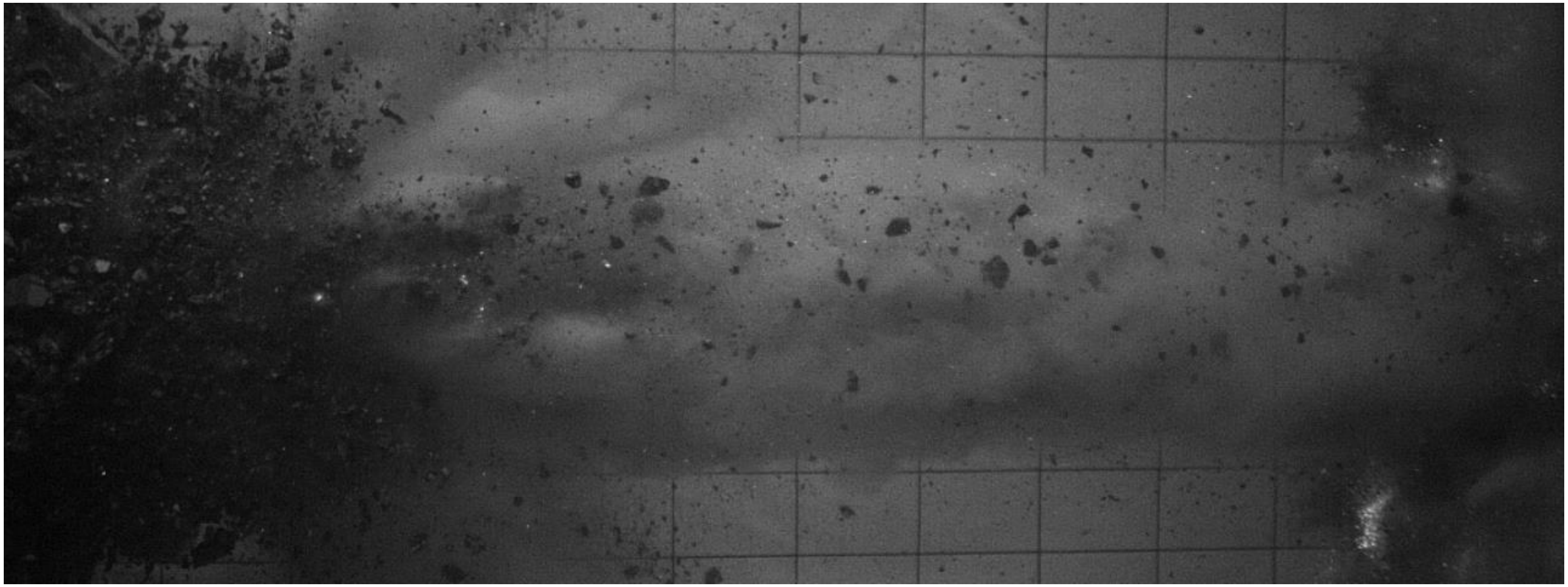


Hydrostatic Compression	Unconfined Compression	Uniaxial Tension	Triaxial Compression	Uniaxial Strain

Experimental Test Data

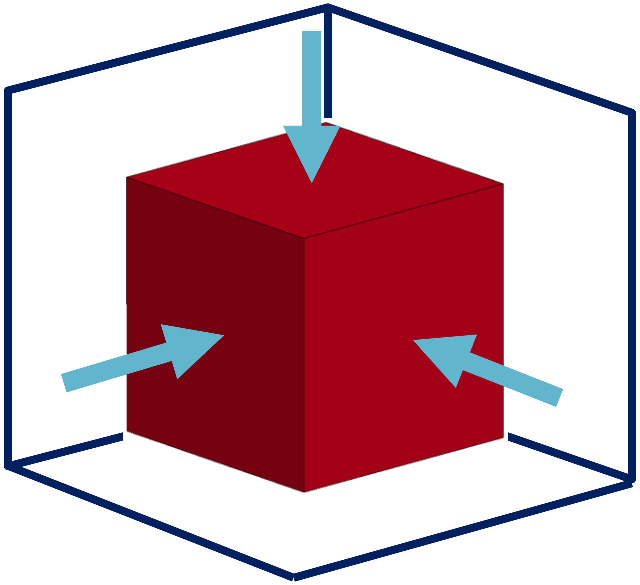
- **Projectile impact test data**

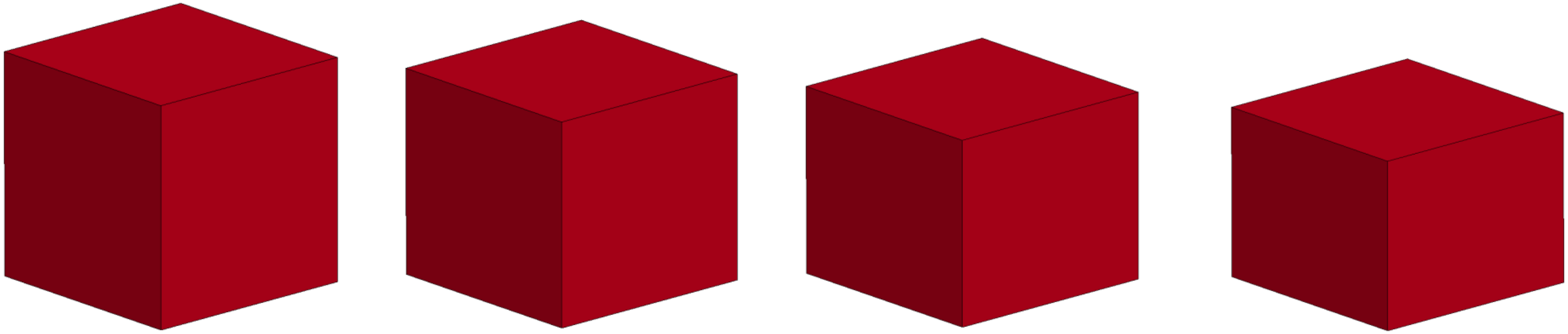
Test	Result
1	Projectile Perforation with Exit Velocity = 6% of Impact Velocity
2	Depth of Penetration = 97% of Slab Depth (No Perforation)



LS-DYNA Single Element Simulations

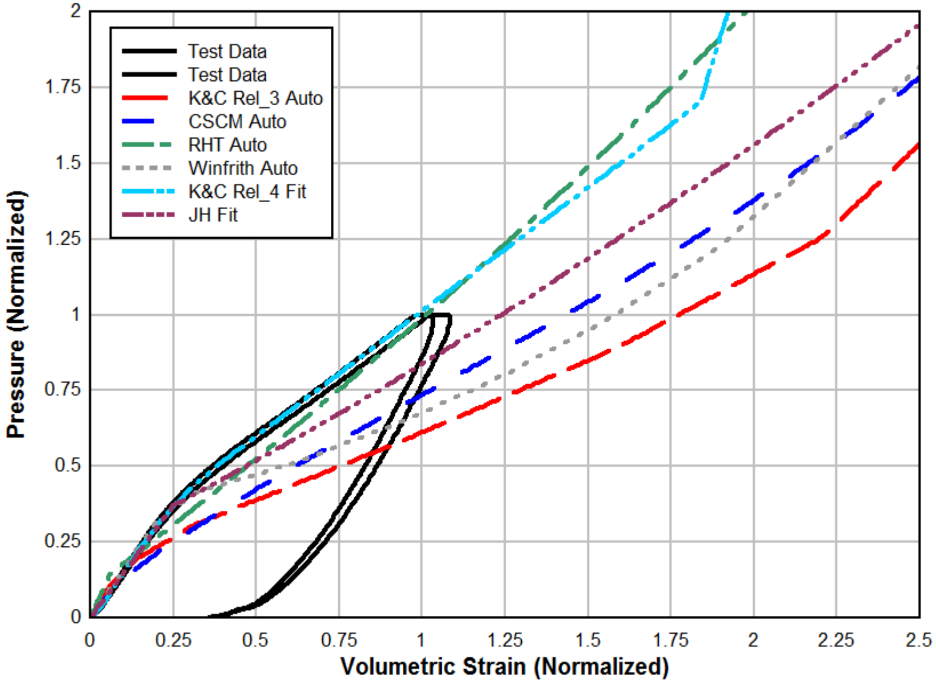
- Single cube elements subjected to:
  - Hydrostatic compression
  - Unconfined compression
  - Uniaxial tension
  - Triaxial compression
- Symmetry condition at 3 faces
- Single integration point
- Quasi-static loading (no rate effects)



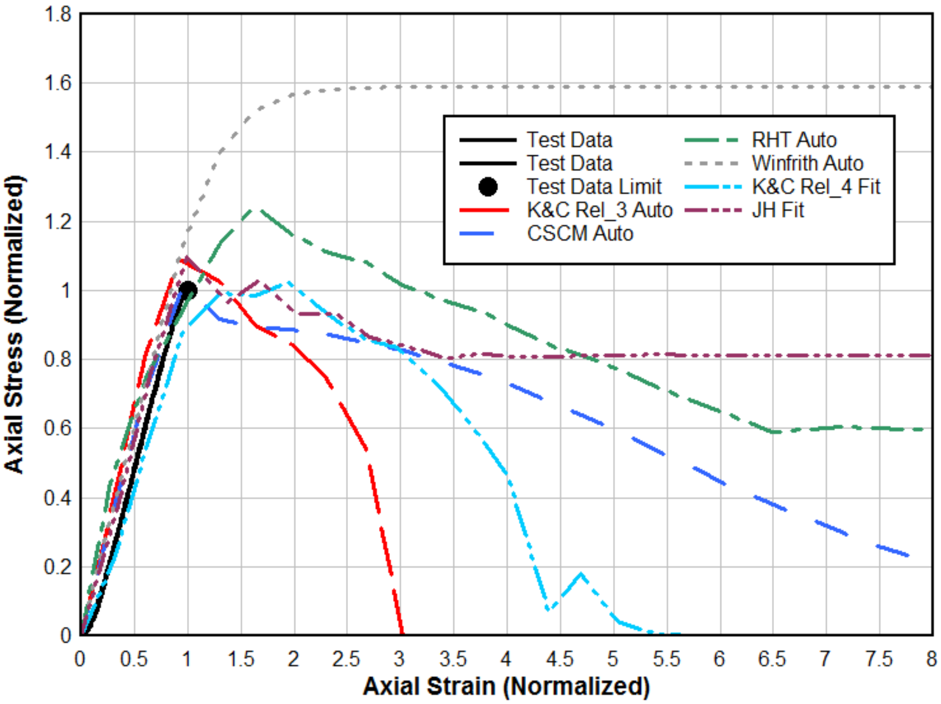


LS-DYNA Single Element Simulations

Hydrostatic Compression

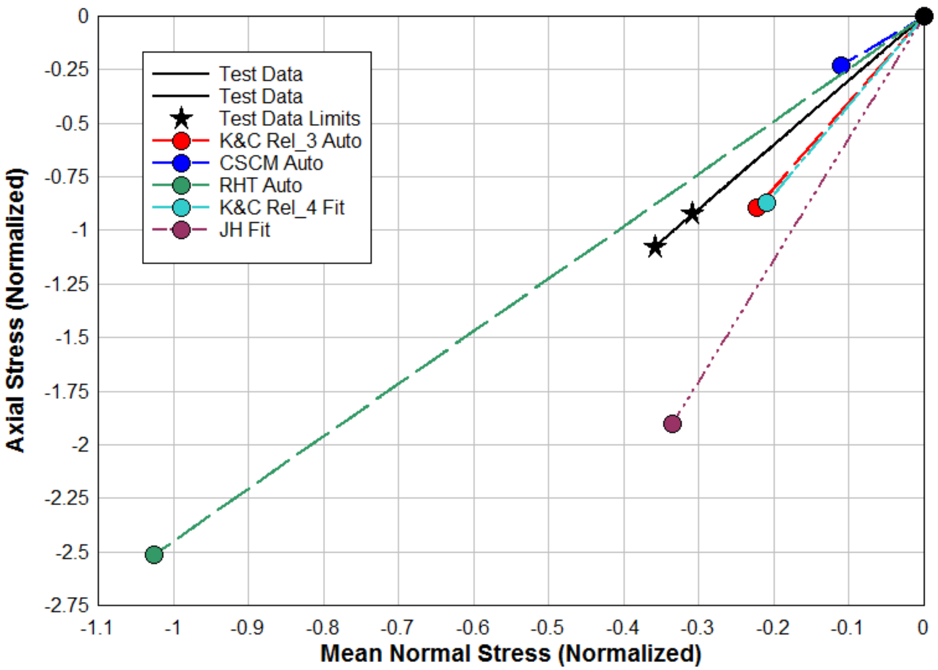


Unconfined Compression

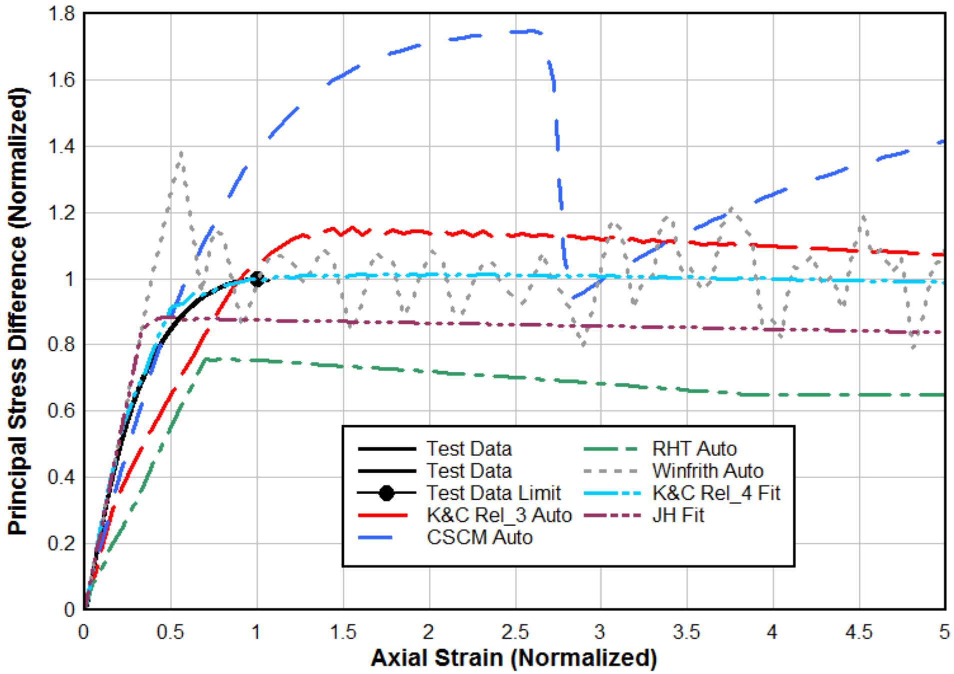


LS-DYNA Single Element Simulations

Uniaxial Tension

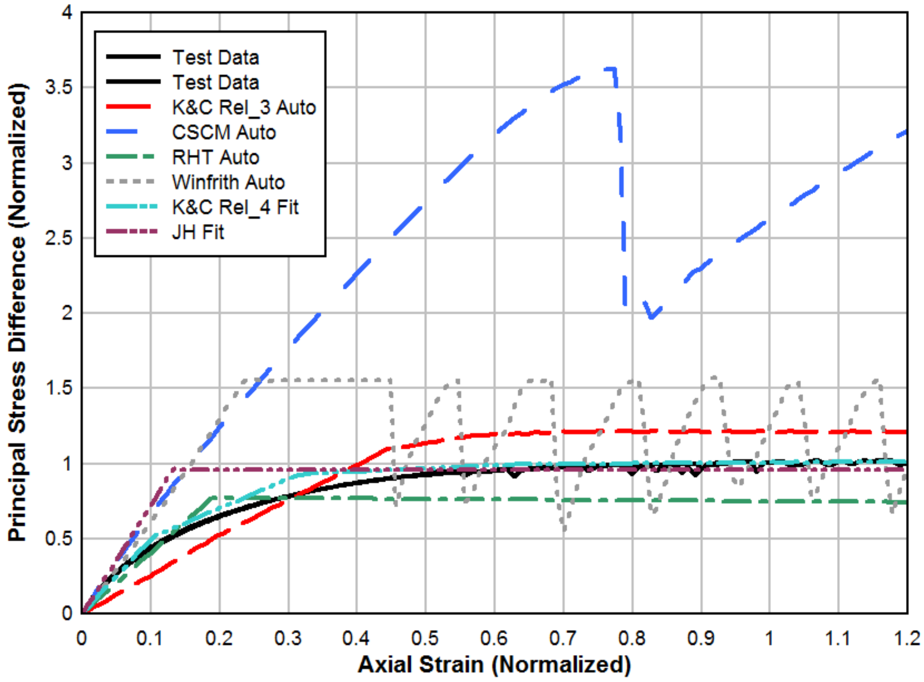


Triaxial Compression with1x Confining Pressure

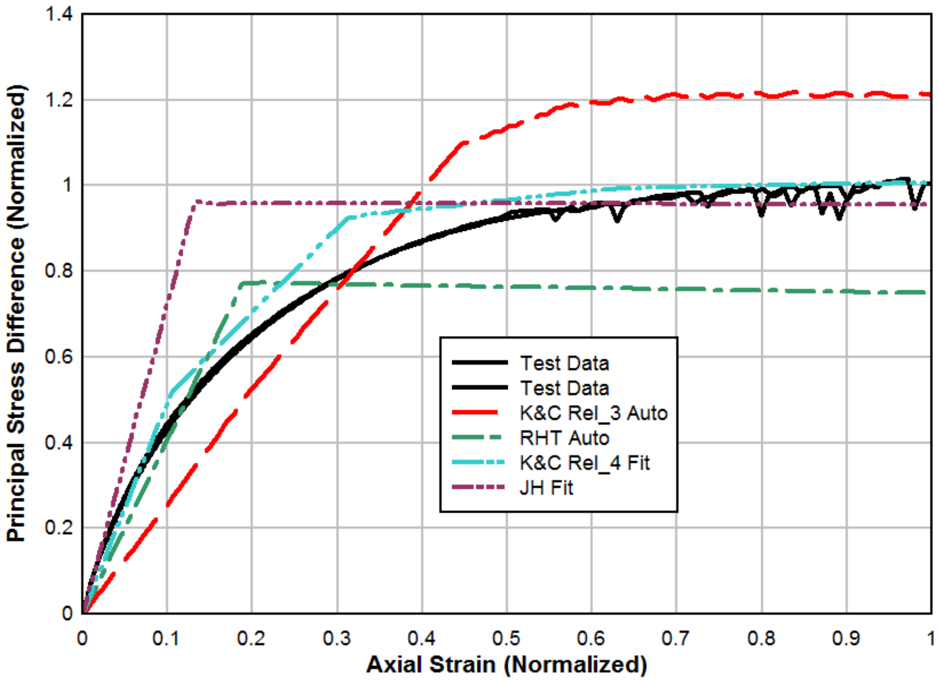


LS-DYNA Single Element Simulations

Triaxial Compression with 4x Confining Pressure

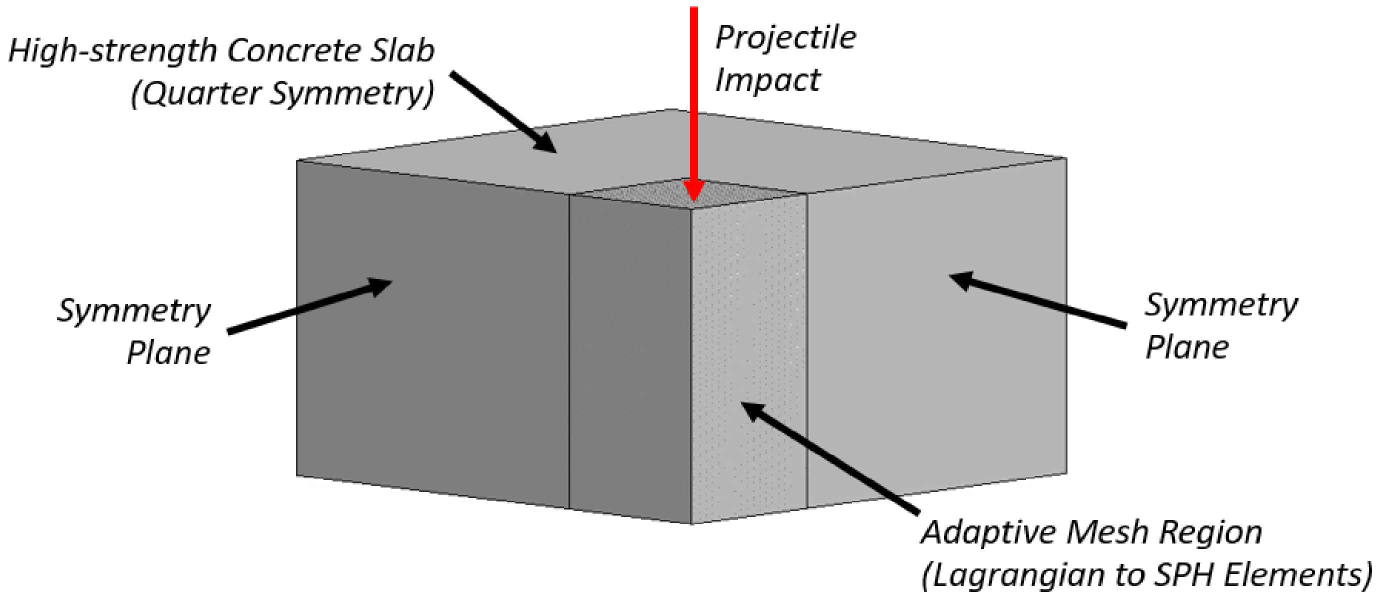


Triaxial Compression with 4x Confining Pressure



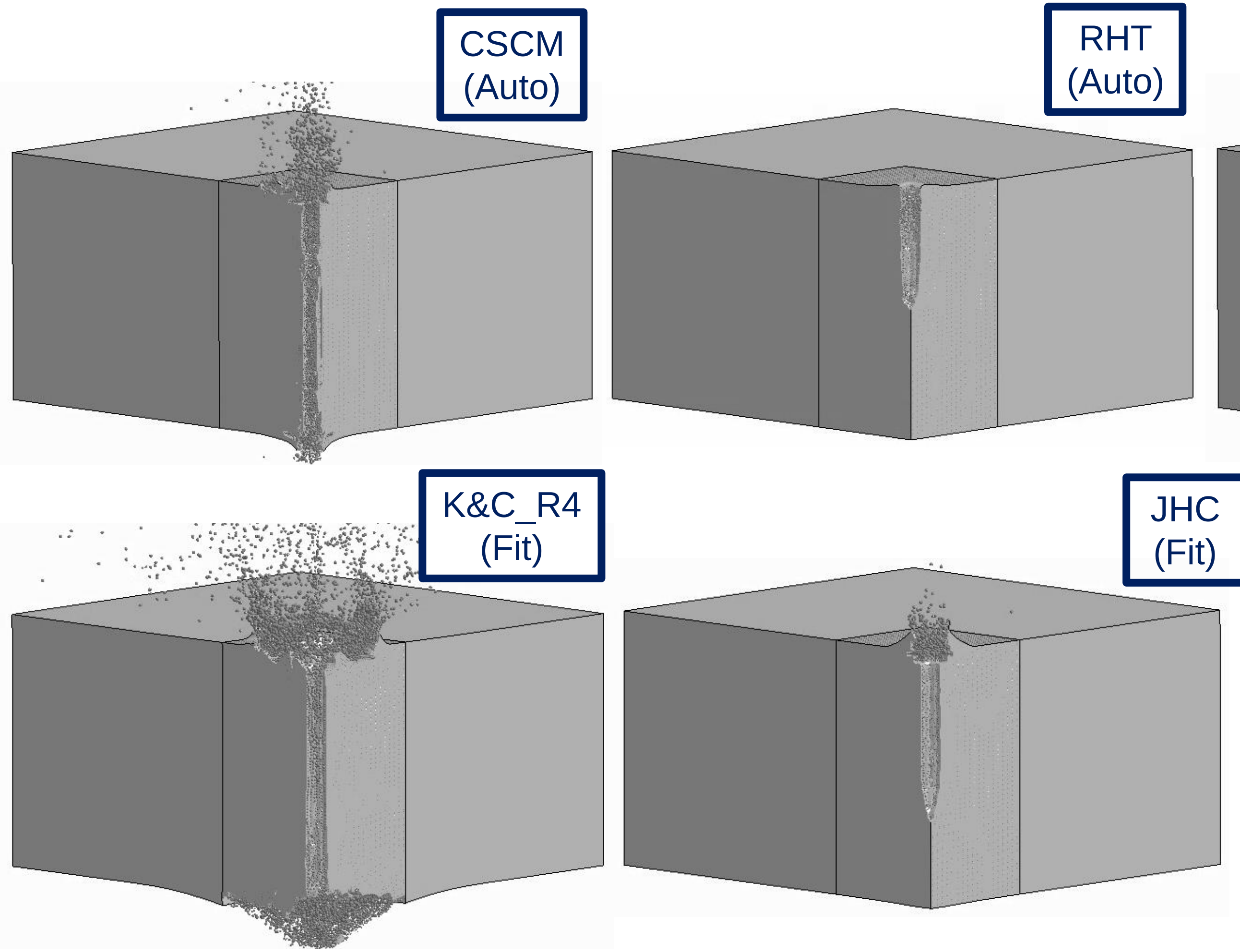
LS-DYNA Projectile Impact Simulations

- Impact normal to slab
- Quarter-symmetry
- Slab model is solid (Lagrangian) elements
- Adaptive mesh around line of impact (Lagrangian to SPH)



LS-DYNA Projectile Impact Simulations

- **Test 1 Simulations: Final State**



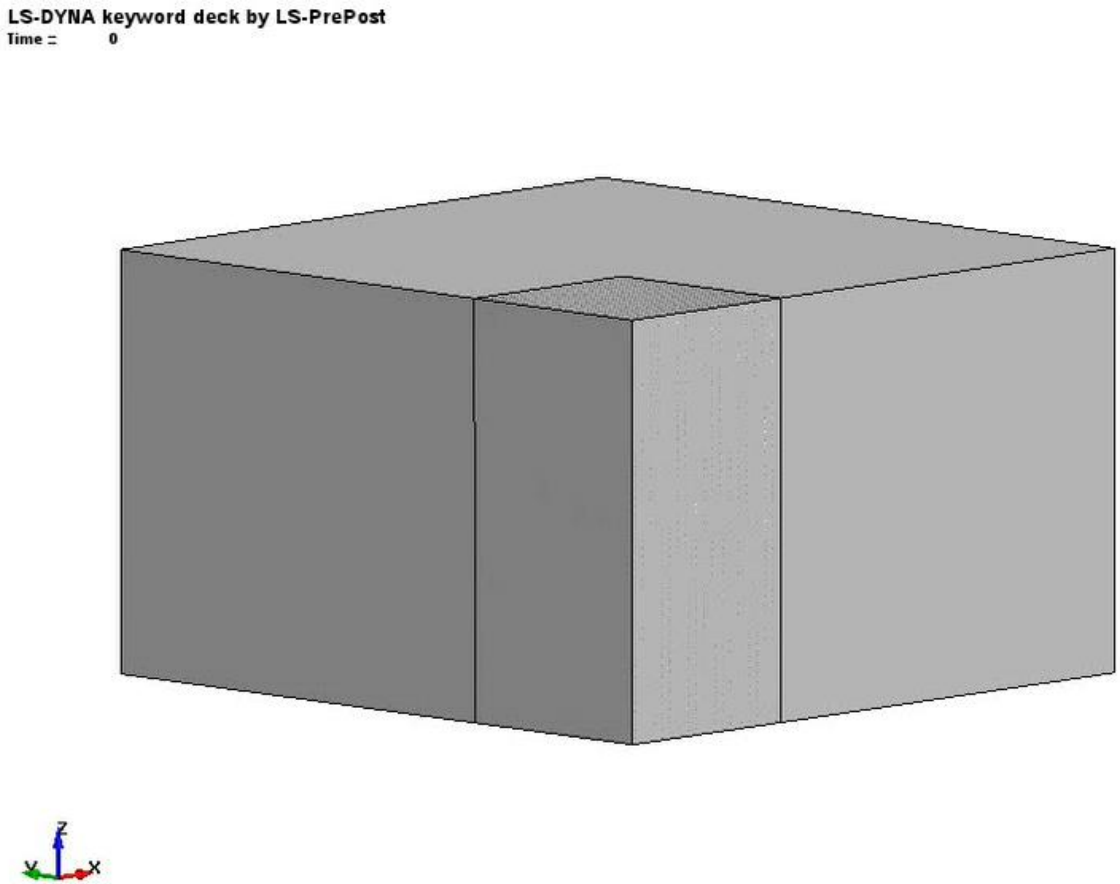
Test Result:

$$\frac{Exit\ Velocity}{Impact\ Velocity} = 0.06$$

(Perforation)

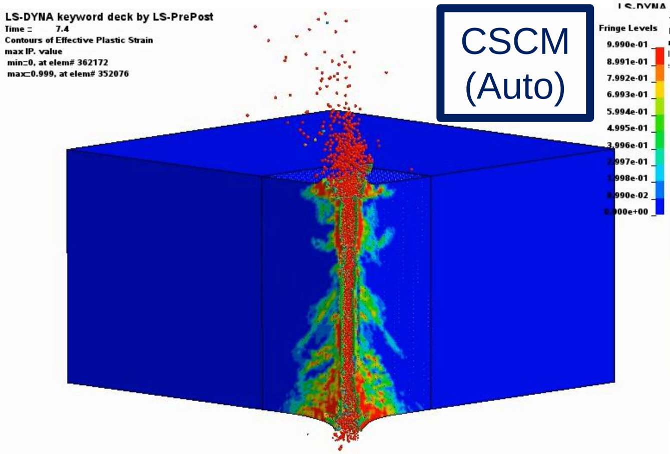
LS-DYNA Projectile Impact Simulations

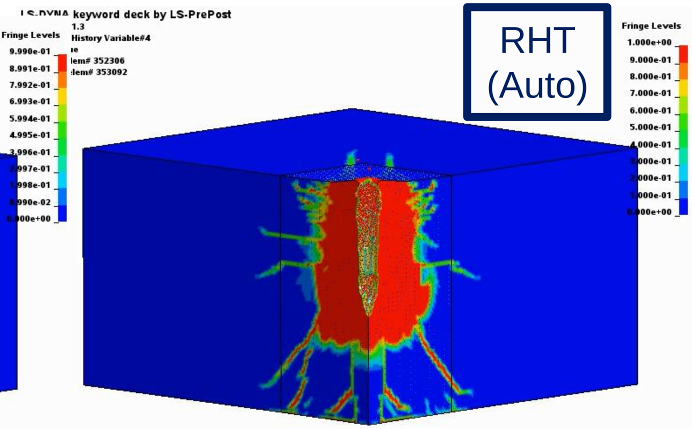
- **Test 1 Simulation: K&C Release 4**

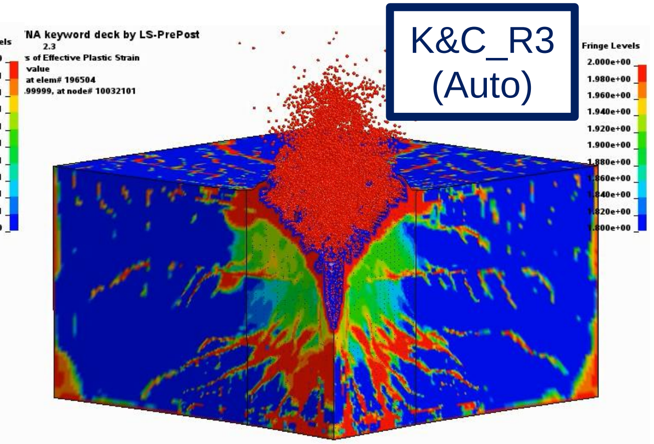


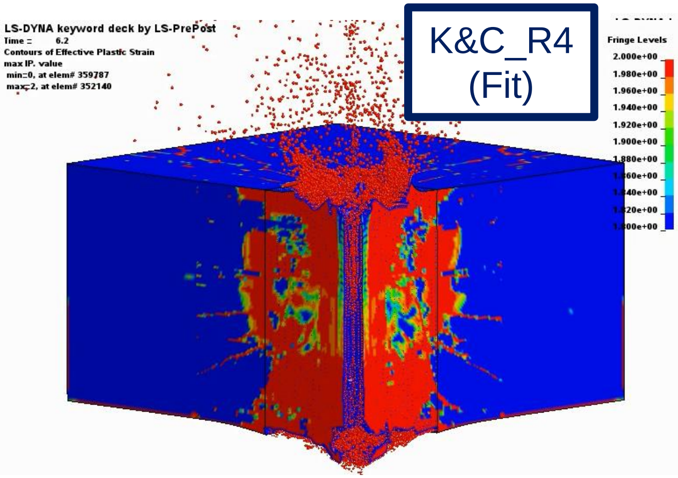
LS-DYNA Projectile Impact Simulations

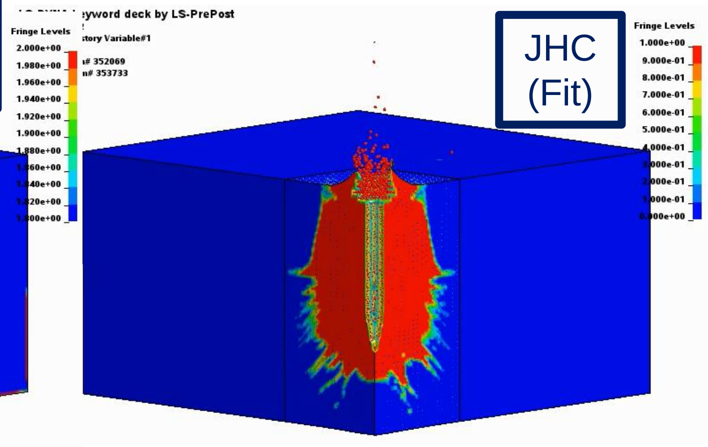
- **Test 1 Simulations: Final Damage Contours**











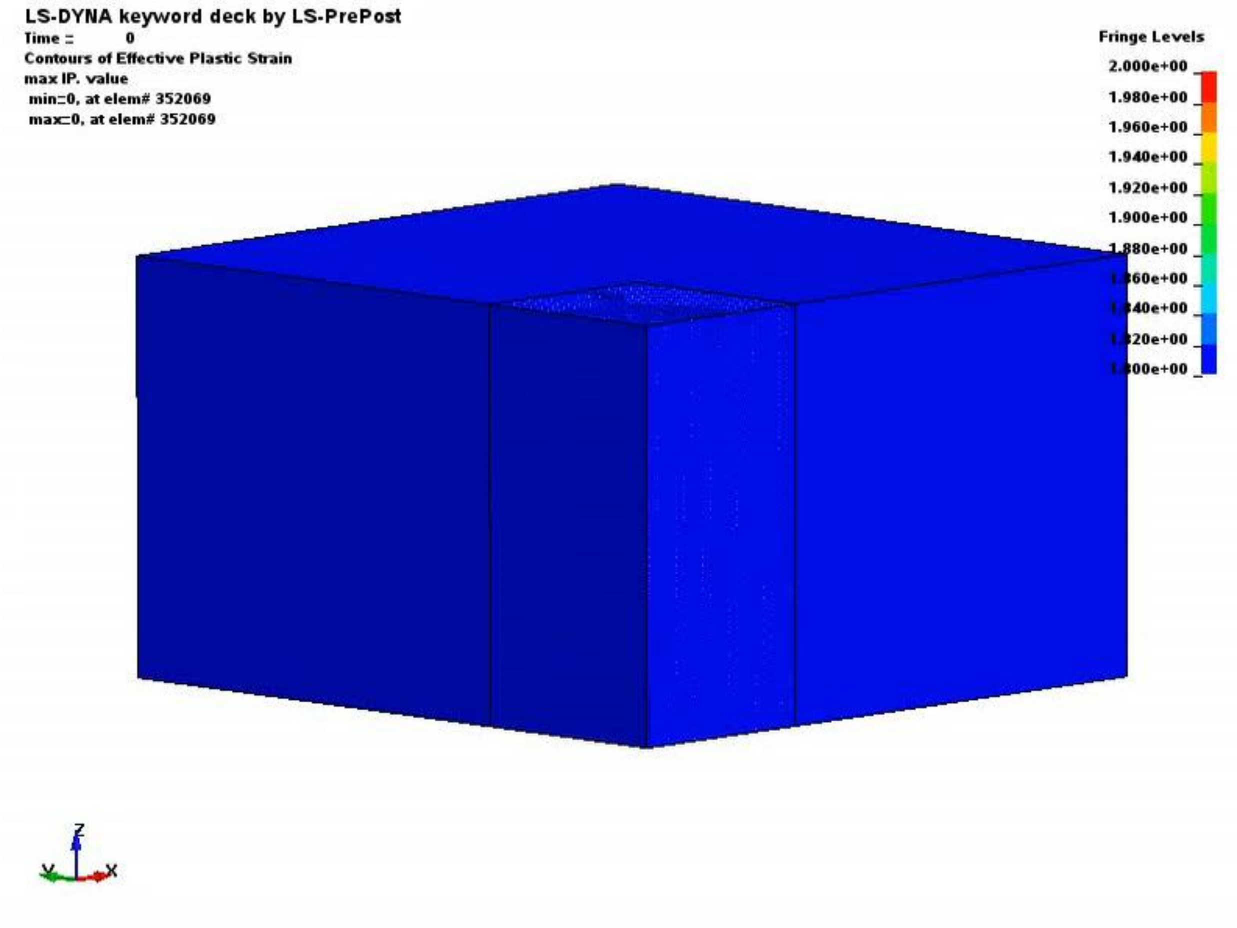
Test Result:

$$\frac{Exit\ Velocity}{Impact\ Velocity} = 0.06$$

(Perforation)

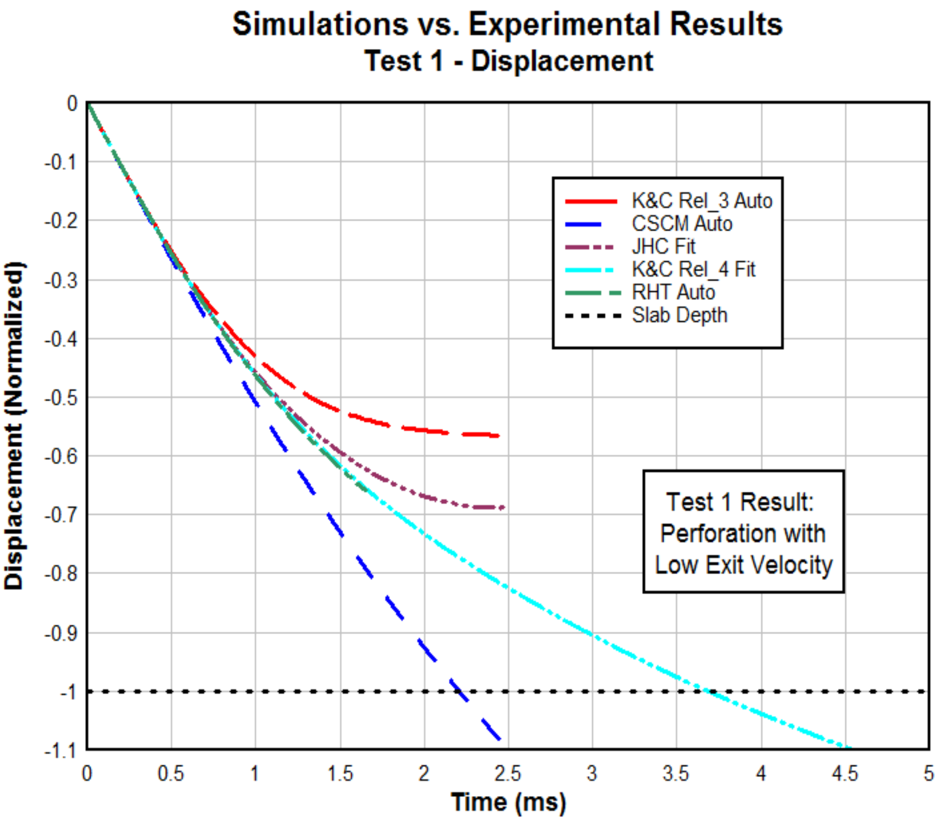
LS-DYNA Projectile Impact Simulations

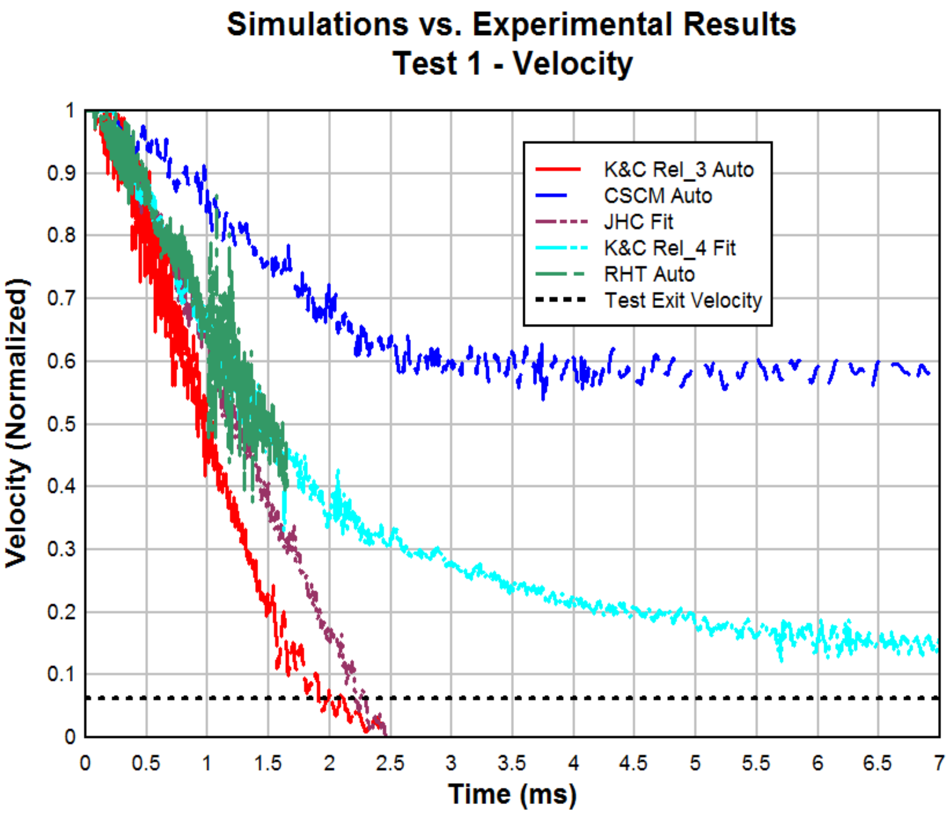
- **Test 1 Simulation: K&C Release 4 Damage**



LS-DYNA Projectile Impact Simulations

- **Test 1 displacement and velocity plots**

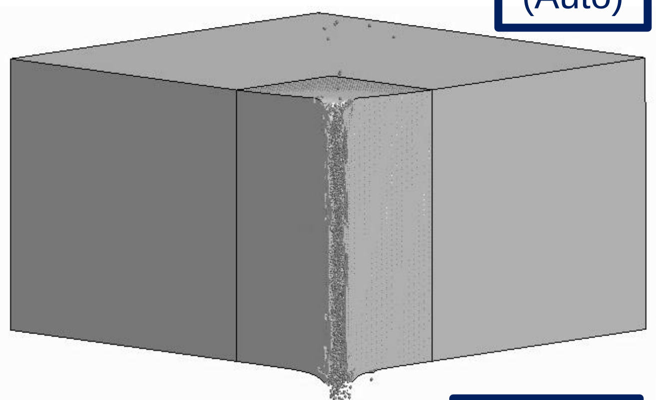




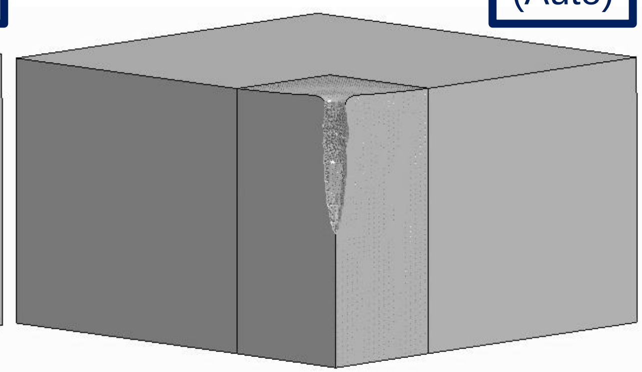
LS-DYNA Projectile Impact Simulations

- **Test 2 Simulations: Final State**

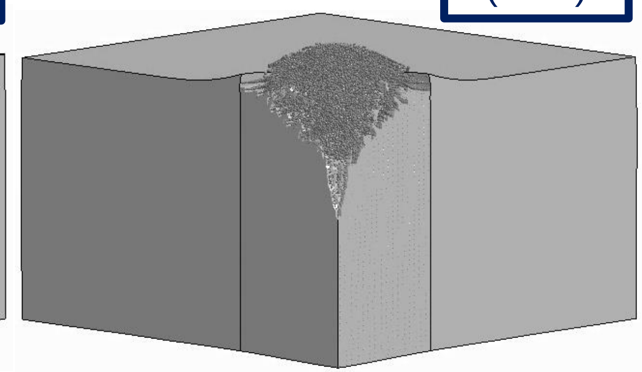
CSCM
(Auto)



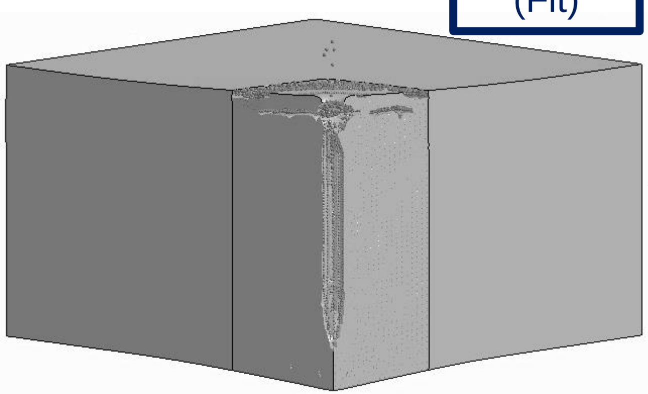
RHT
(Auto)



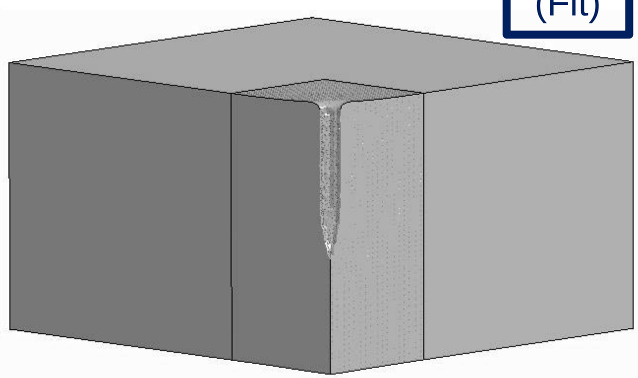
K&C_R3
(Auto)



K&C_R4
(Fit)



JHC
(Fit)



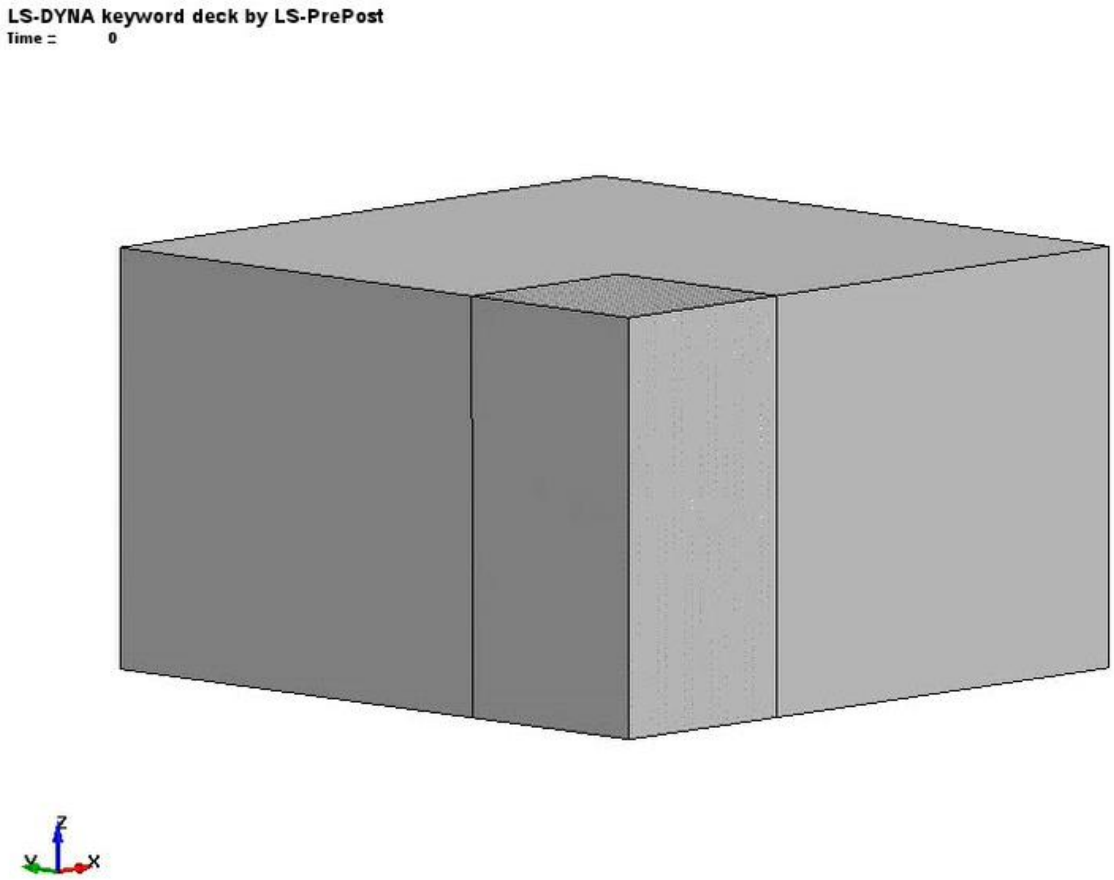
Test Result:

$$\frac{Depth\ of\ Penetration}{Slab\ Depth} = 0.97$$

(No Perforation)

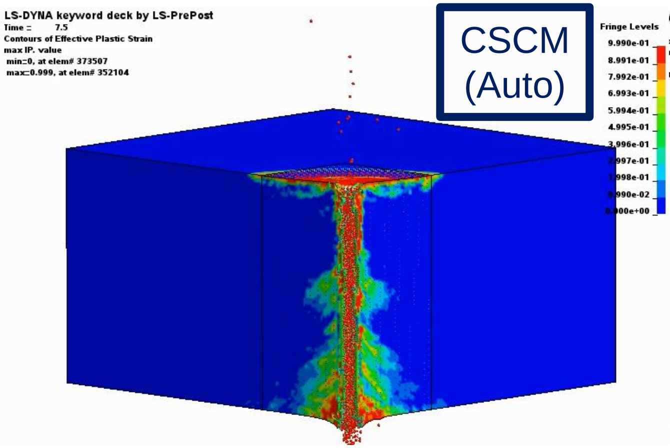
LS-DYNA Projectile Impact Simulations

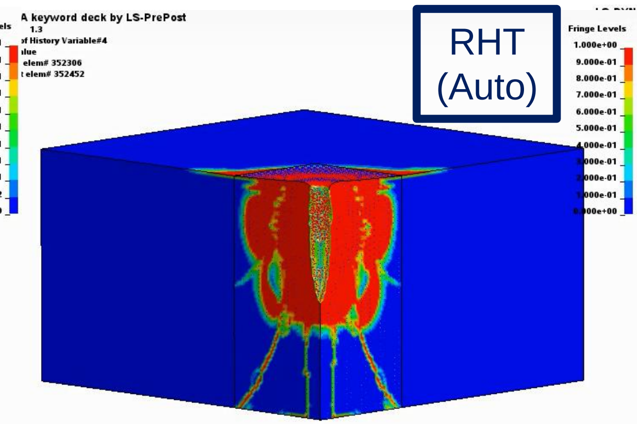
- **Test 2 Simulation: K&C Release 4**

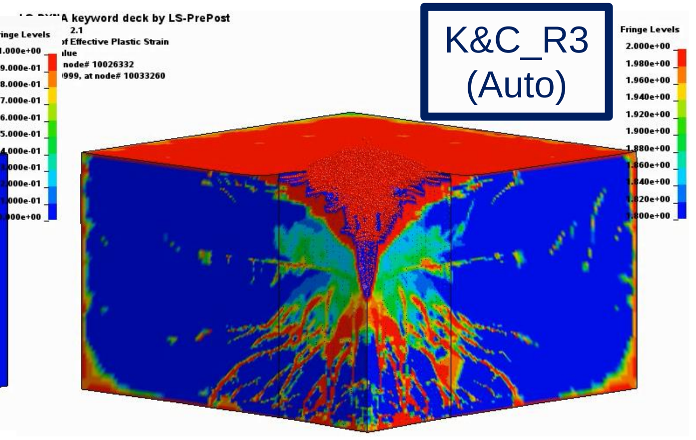


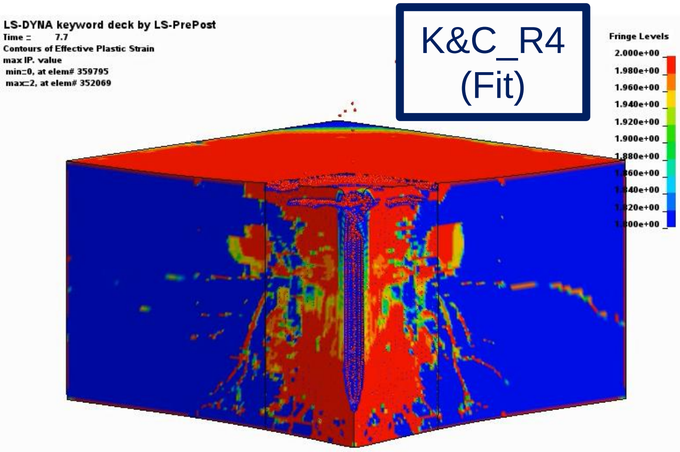
LS-DYNA Projectile Impact Simulations

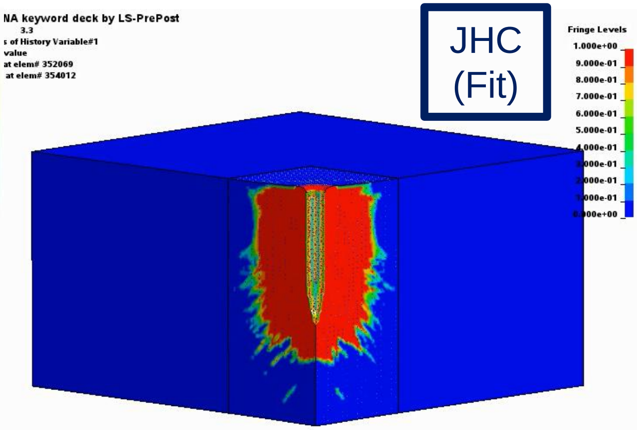
- **Test 2 Simulations: Final Damage Contours**











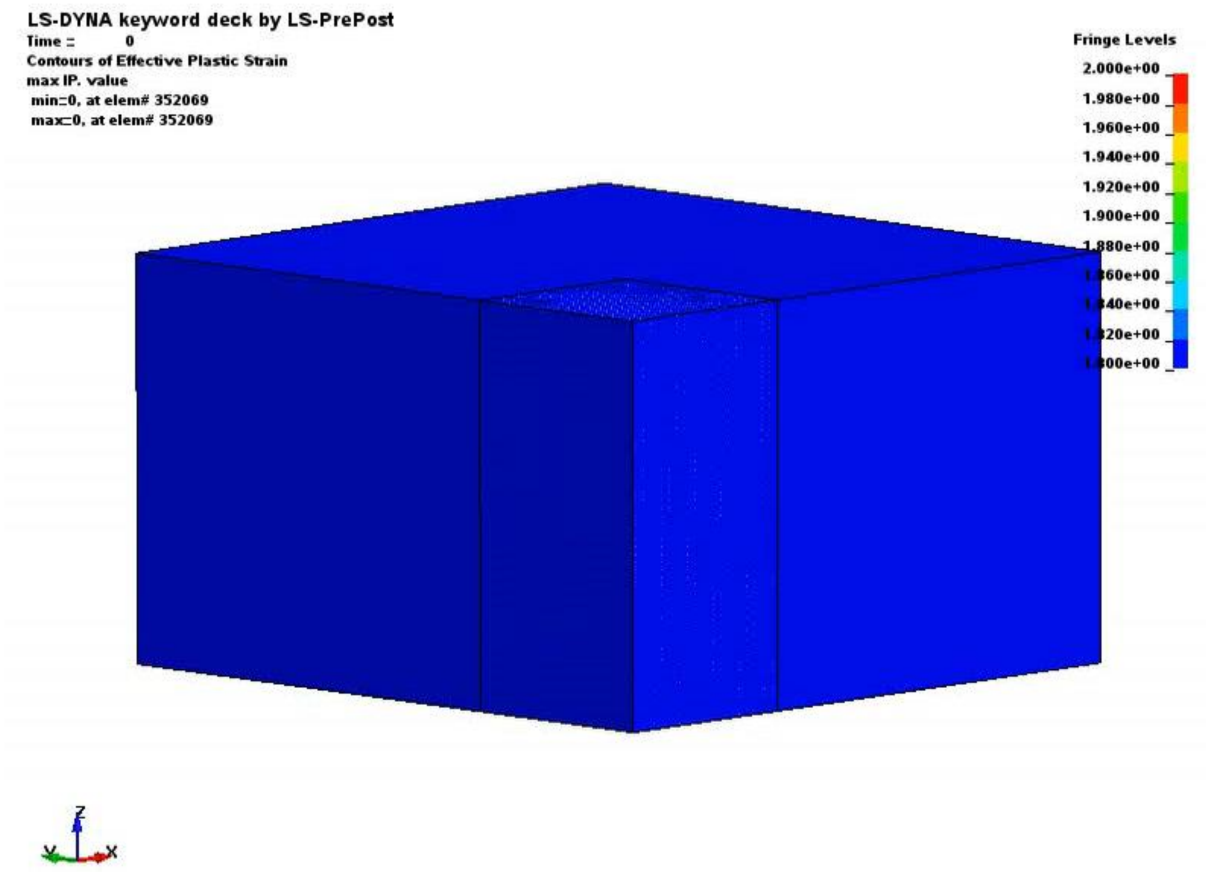
Test Result:

$$\frac{Depth\ of\ Penetration}{Slab\ Depth} = 0.97$$

(No Perforation)

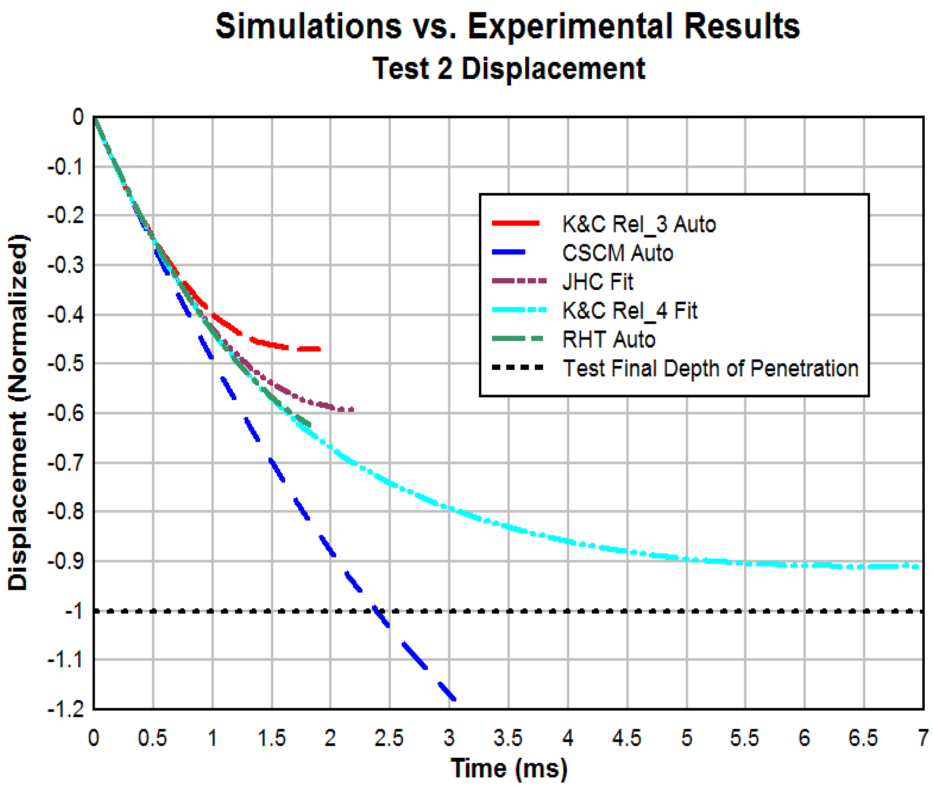
LS-DYNA Projectile Impact Simulations

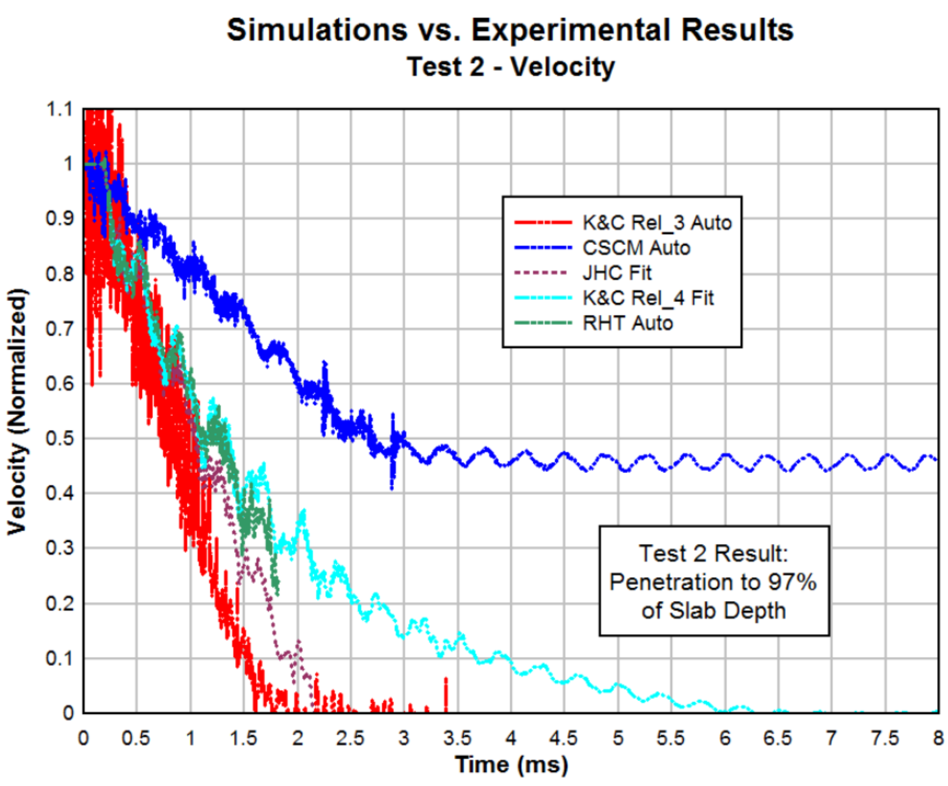
- **Test 2 Simulation: K&C Release 4 Damage**



LS-DYNA Projectile Impact Simulations

- **Test 2 displacement and velocity plots**





LS-DYNA Projectile Impact Simulations

- **Summary of Test 1 and Test 2 Results**

Test	Material Model	Simulation Result*	Experimental Result
1	K&C Rel. 3 Auto	DOP / DS = 0.56	VE / VI = 0.06
	CSCM Auto	VE / VI = 0.58	
	RHT Auto	VE / VI ≈ 0 – 0.2 **	
	JHC Fit	DOP / DS = 0.46	
	K&C Rel. 4 Fit	VE / VI = 0.14	
2	K&C Rel. 3 Auto	DOP / DS = 0.46	DOP / DS = 0.97
	CSCM Auto	VE / VI = 0.45	
	RHT Auto	DOP / DS ≈ 0.7 – 0.8 **	
	JHC Fit	DOP / DS = 0.57	
	K&C Rel. 4 Fit	DOP / DS = 0.85	

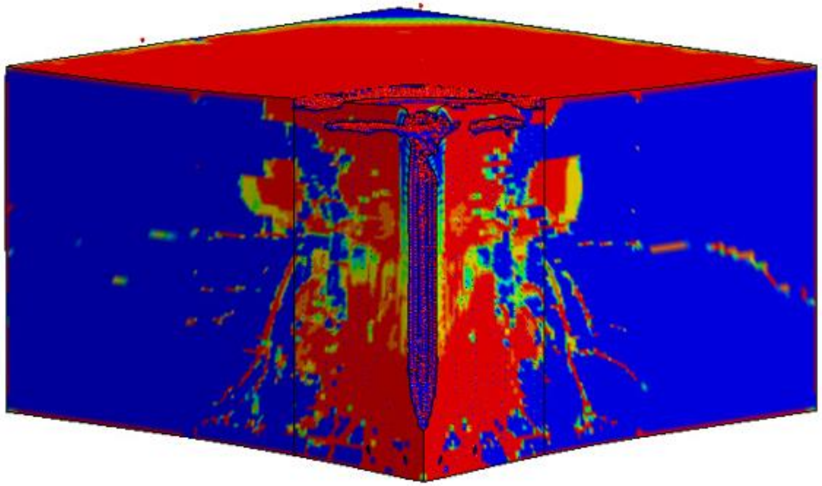
* VE = Exit Velocity; VI = Impact Velocity; DOP = Depth of Penetration; DS = Slab Depth
** Range estimated based on observed trends in simulation results up to point of memory error

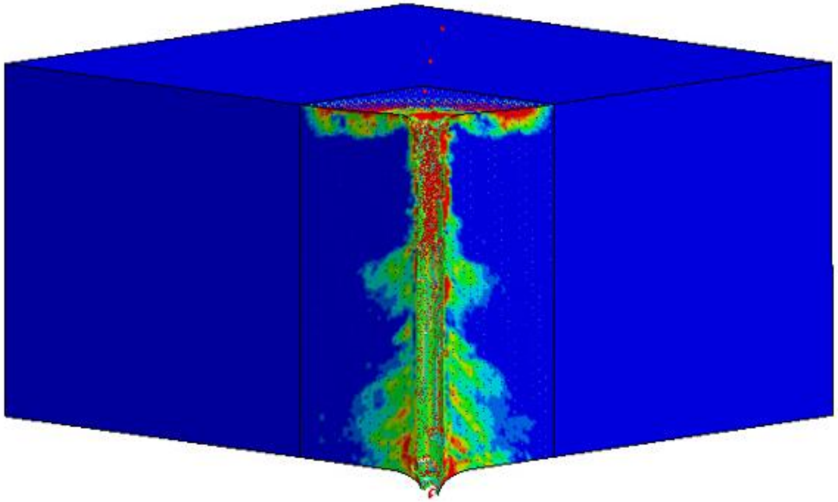
Observations

- The observed correlation between better fits to quasi-static material test data and better ability to simulate impact is not unexpected
- K&C Release 4
  - Best fit to quasi-static material test data of all models
  - Best results in impact simulations
- RHT
  - Best fit to quasi-static material test data of all automatic parameter generation models
  - Projectile displacement and velocity trends show that RHT would likely have produced the best impact simulation results of all automatic parameter generation models in absence of memory error
- CSCM
  - Concrete strength was likely too high for use with the automatic parameter generation feature (supported by results and literature)

Conclusions

- **High-fidelity physics-based software tools are capable of accurately simulating impact and penetration into reinforced concrete protective construction when care is taken by the analyst to properly model the material.**
- **Software users should exercise extreme caution when considering the use of automatically generated material parameters for problems involving impact into high-strength concrete. It is recommended that models be fit to material test data as much as possible.**
- **Once a model is fit to test data, users should take the necessary steps to be aware of the limitations of the model and the fit for their specific application.**





Thank You