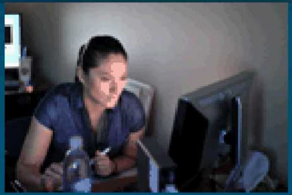
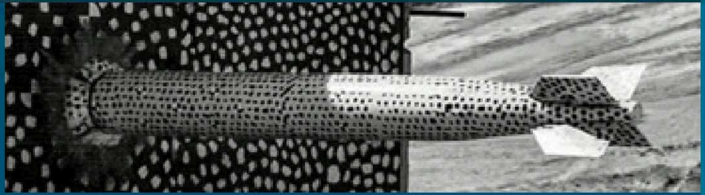
SAND2019-9094C

Predictive Maturity of Non-Linear Concrete Constitutive Models for Impact Simulation





PRESENTED BY

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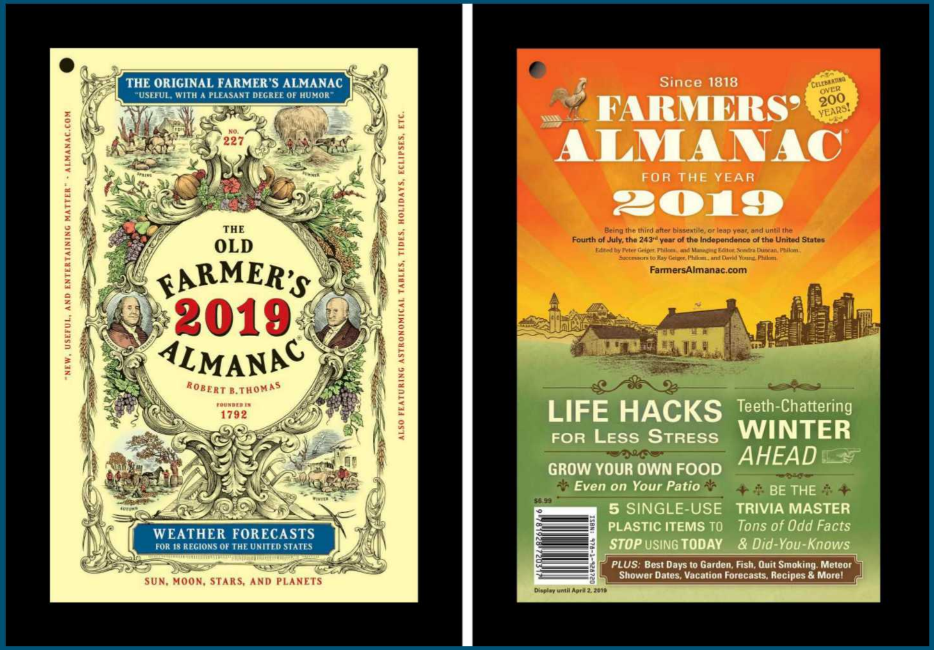
Prediction

Many scientific fields are interested in predicting future or hypothetical events

- Meteorology
- Structural / Mechanical Design
- Electric Power Generation
- Nuclear Power Safety

Computational simulation has enabled prediction with high spatial/temporal resolution



Prediction in Nuclear Safety

NUREG/CR-6906: *Containment Integrity Research at Sandia National Laboratories*

IRIS: Improving Robustness for Impact Simulations

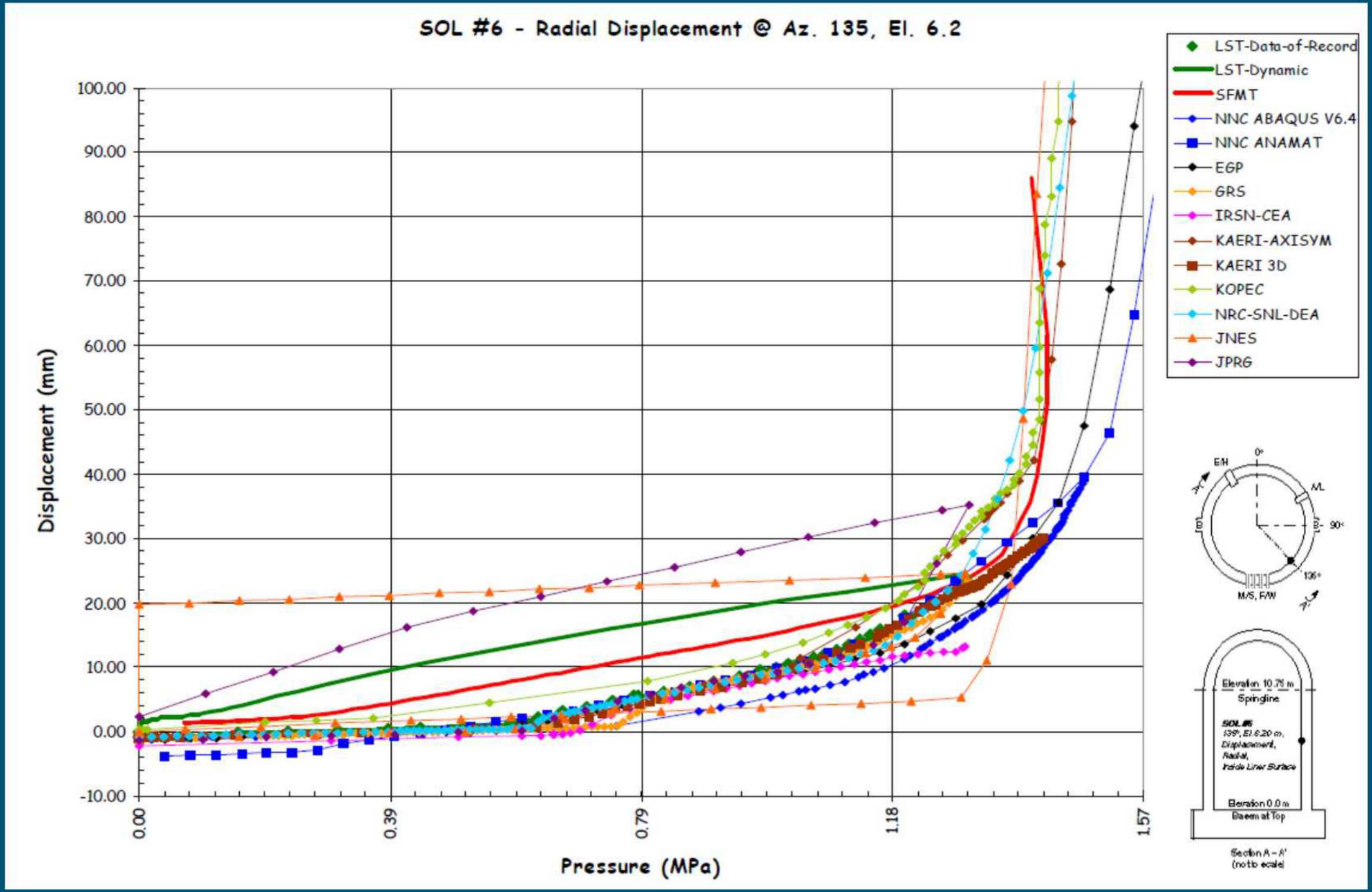
VeRCoRs: Verification of Reinforced Concrete Response

CASH: Seismic Capacity of RC Shear Walls

Regardless of country or regulatory body, the nuclear power safety case is based on a prediction of performance for safety systems

Predictive Capability

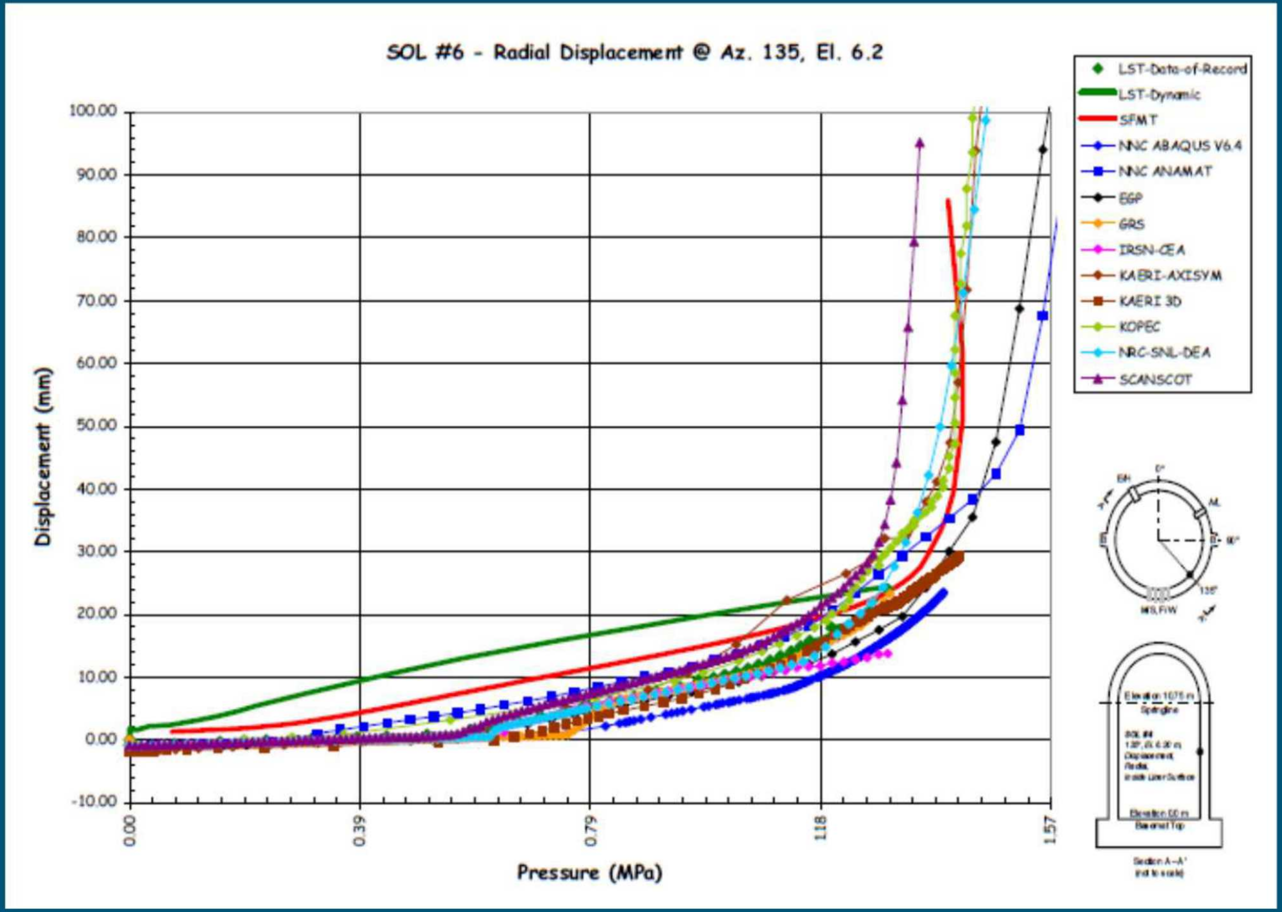
Mid-Height radial displacement predictions from ISP-48



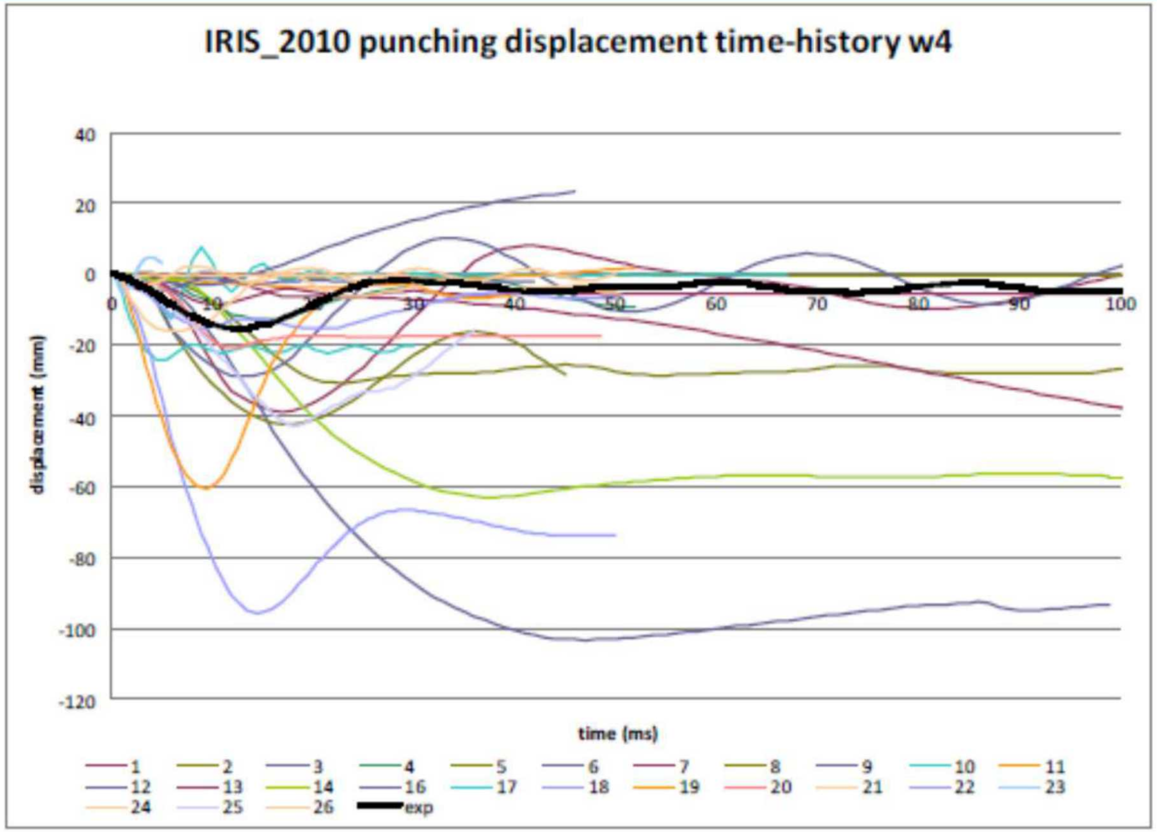
Post Test Predictions

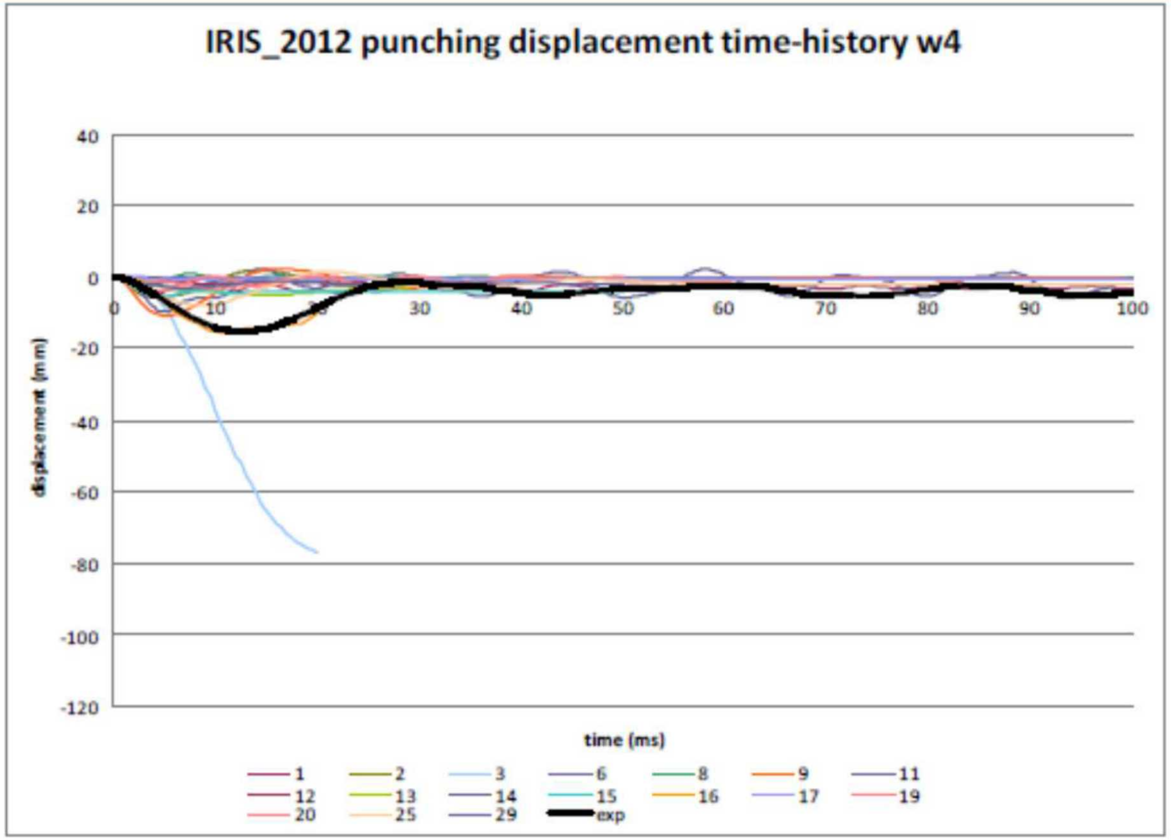
Predictions made after the experiment has been performed are generally improved significantly

Sozen's Rule: Show me the data and I can make a model to fit it



IRIS 2010 vs 2012

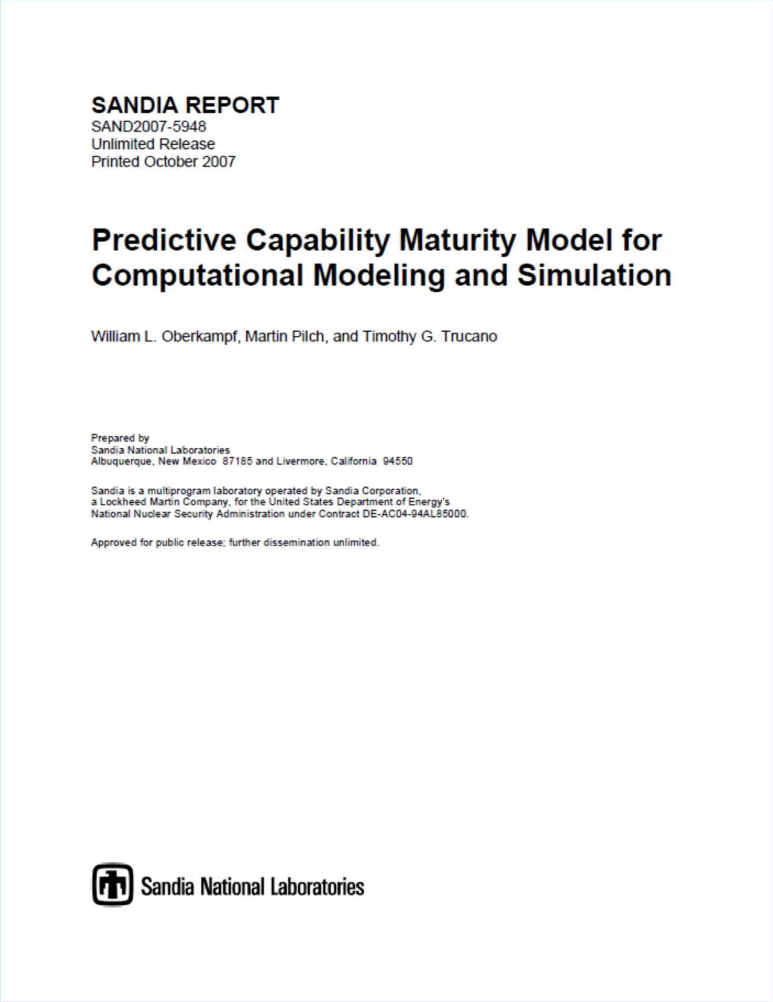




Predictive Capability Maturity Model

PCMM provides a framework for assessing a set of mutually exclusive and collectively exhaustive factors that influence predictive capability

VVUQ roots



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Predictive Capability Maturity Model for Computational Modeling and Simulation

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Sandia National Laboratories

MATURITY / ELEMENT	Maturity Level 0 Low Consequence, Minimal M&S Impact, e.g. Scoping Studies	Maturity Level 1 Moderate Consequence, Some M&S Impact, e.g. Design Support	Maturity Level 2 High-Consequence, High M&S Impact, e.g. Qualification Support	Maturity Level 3 High-Consequence, Decision-Making Based on M&S, e.g. Qualification or Certification
Representation and Geometric Fidelity What features are neglected because of simplifications or stylizations?	• Judgment only • Little or no representational or geometric fidelity for the system and BCs	• Significant simplification or stylization of the system and BCs • Geometry or representation of major components is defined	• Limited simplification or stylization of major components and BCs • Geometry or representation is well defined for major components and some minor components • Some peer review conducted	• Essentially no simplification or stylization of components in the system and BCs • Geometry or representation of all components is at the detail of "as built", e.g., gaps, material interfaces, fasteners • Independent peer review conducted
Physics and Material Model Fidelity How fundamental are the physics and material models and what is the level of model calibration?	• Judgment only • Model forms are either unknown or fully empirical • Few, if any, physics-informed models • No coupling of models	• Some models are physics based and are calibrated using data from related systems • Minimal or ad hoc coupling of models	• Physics-based models for all important processes • Significant calibration needed using separate effects tests (SETs) and integral effects tests (IETs) • One-way coupling of models • Some peer review conducted	• All models are physics based • Minimal need for calibration using SETs and IETs • Sound physical basis for extrapolation and coupling of models • Full, two-way coupling of models • Independent peer review conducted
Code Verification Are algorithm deficiencies, software errors, and poor SQE practices corrupting the simulation results?	• Judgment only • Minimal testing of any software elements • Little or no SQE procedures specified or followed	• Code is managed by SQE procedures • Unit and regression testing conducted • Some comparisons made with benchmarks	• Some algorithms are tested to determine the observed order of numerical convergence • Some features & capabilities (F&C) are tested with benchmark solutions • Some peer review conducted	• All important algorithms are tested to determine the observed order of numerical convergence • All important F&Cs are tested with rigorous benchmark solutions • Independent peer review conducted
Solution Verification Are numerical solution errors and human procedural errors corrupting the simulation results?	• Judgment only • Numerical errors have an unknown or large effect on simulation results	• Numerical effects on relevant SRQs are qualitatively estimated • Input/output (I/O) verified only by the analysts	• Numerical effects are quantitatively estimated to be small on some SRQs • I/O independently verified • Some peer review conducted	• Numerical effects are determined to be small on all important SRQs • Important simulations are independently reproduced • Independent peer review conducted
Model Validation How carefully is the accuracy of the simulation and experimental results assessed at various tiers in a validation hierarchy?	• Judgment only • Few, if any, comparisons with measurements from similar systems or applications	• Quantitative assessment of accuracy of SRQs not directly relevant to the application of interest • Large or unknown experimental uncertainties	• Quantitative assessment of predictive accuracy for some key SRQs from IETs and SETs • Experimental uncertainties are well characterized for most SETs, but poorly known for IETs • Some peer review conducted	• Quantitative assessment of predictive accuracy for all important SRQs from IETs and SETs at conditions/geometries directly relevant to the application • Experimental uncertainties are well characterized for all IETs and SETs • Independent peer review conducted
Uncertainty Quantification and Sensitivity Analysis How thoroughly are uncertainties and sensitivities characterized and propagated?	• Judgment only • Only deterministic analyses are conducted • Uncertainties and sensitivities are not addressed	• Aleatory and epistemic (A&E) uncertainties propagated, but without distinction • Informal sensitivity studies conducted • Many strong UQ/SA assumptions made	• A&E uncertainties segregated, propagated and identified in SRQs • Quantitative sensitivity analyses conducted for most parameters • Numerical propagation errors are estimated and their effect known • Some strong assumptions made • Some peer review conducted	• A&E uncertainties comprehensively treated and properly interpreted • Comprehensive sensitivity analyses conducted for parameters and models • Numerical propagation errors are demonstrated to be small • No significant UQ/SA assumptions made • Independent peer review conducted

Concrete Constitutive Models

Nonlinear constitutive models are critically important for safety simulation

For impact

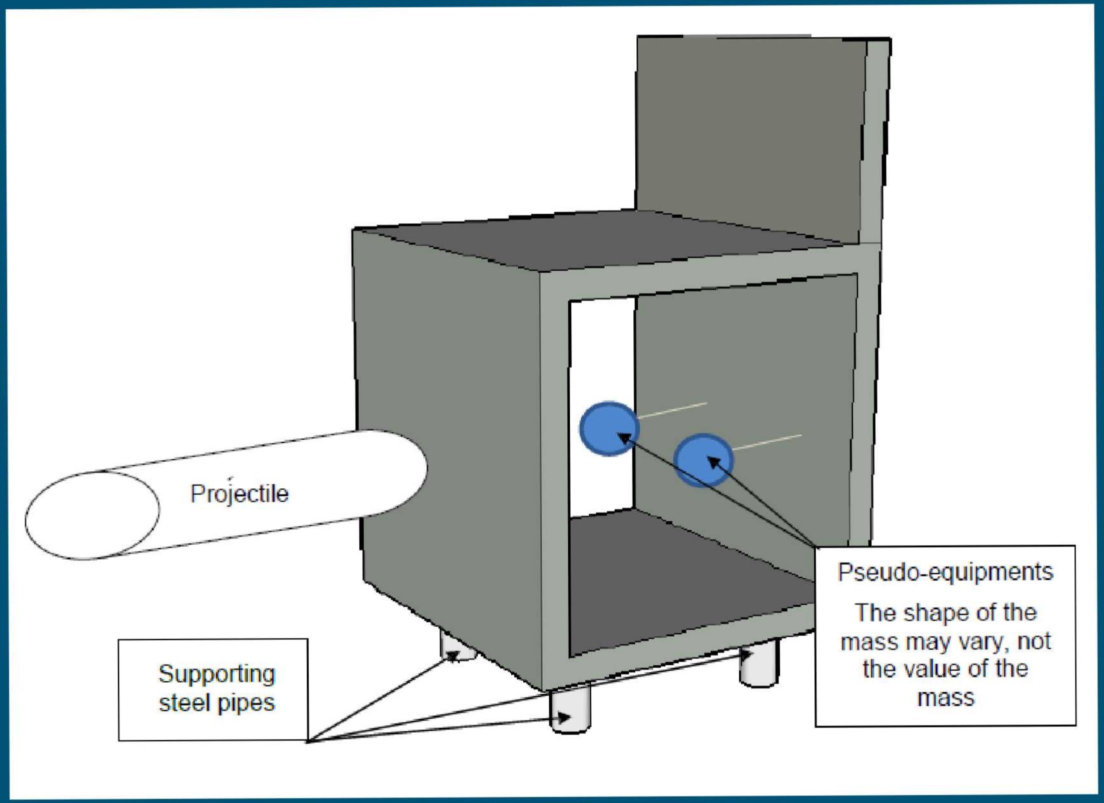
- Pressure dependent plasticity
- Damage
- Rate dependence

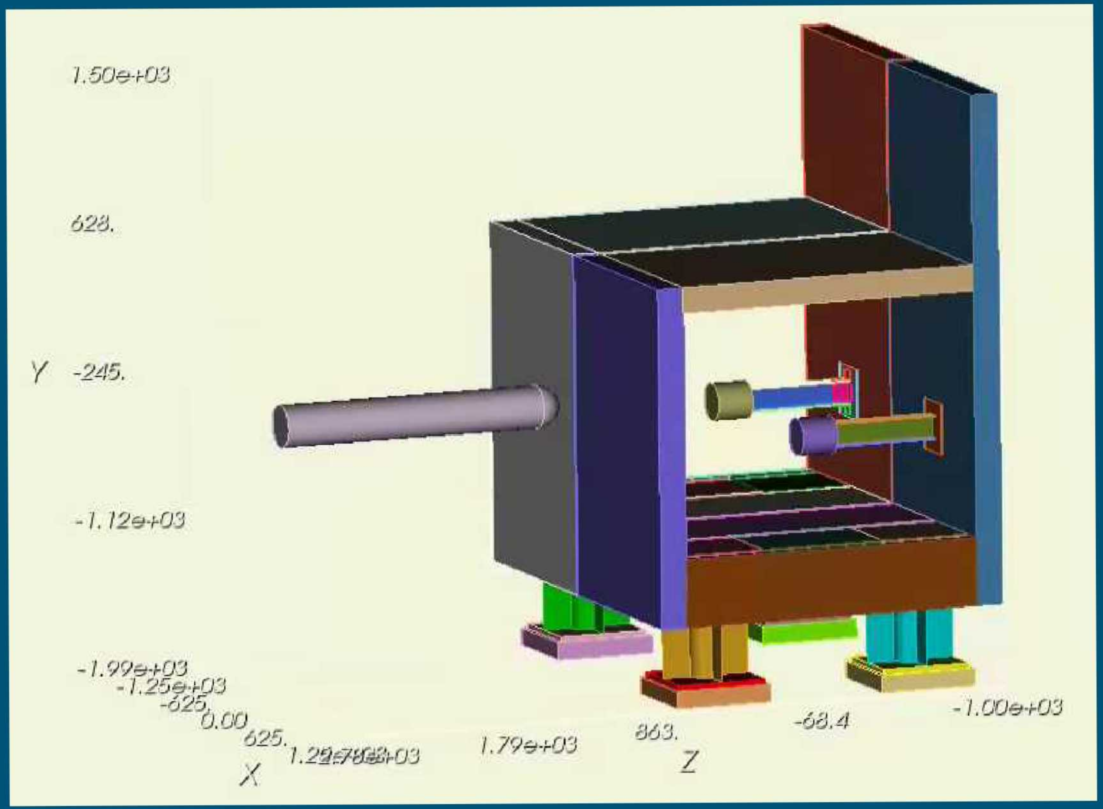
Winfrith, Karagozian & Case, ANACAP-U, Holmquist Johnson Cook, Elastic Fracture

Constitutive Model Maturity

Maturity Level	0	1	2	3
Physics and Material Model Fidelity: How fundamental are the physics and material models and what is the level of model calibration?	• Judgment only • Model forms are either unknown or fully empirical • Few, if any, physics-informed models • No coupling of models	• Some models are physics based and are calibrated using data from related systems • Minimal or ad hoc coupling of models	• Physics-based models for all important processes • Significant calibration needed using separate effects tests (SETs) and integral effects tests (IETs) • One-way coupling of models • Some peer review conducted	• All models are physics based • Minimal need for calibration using SETs and IETs • Sound physical basis for extrapolation and coupling of models • Full, two-way coupling of models • Independent peer review conducted

IRIS-III Simulation





Numerical Simulation and Concept

Sierra Solid Mechanics

3 Constitutive Models

- Holmquist Johnson Cook Concrete
- Karagozian and Case
- Elastic Fracture

Explicitly Modeled Rebar Elements

Element Type	No. of Elements
8-node hexahedral	217,616
4-node shell	3,464
2-node beam	80,218
Total	301,298

The IRIS-III Model was executed with each constitutive model

Each constitutive model was calibrated only with available material test data

Simulations were done after the release of experimental results, but no effort was made to “tune” the model

Model Calibration

Maturity levels 0-2 require model calibration, level 3 does not require as much (if any)

Some model parameters are experiment-based, some are phenomenological

Is experimental data available?

Experiment based:

- Compressive strength
- Tensile strength
- Elastic modulus
- Poisson’s ratio

Phenomenological:

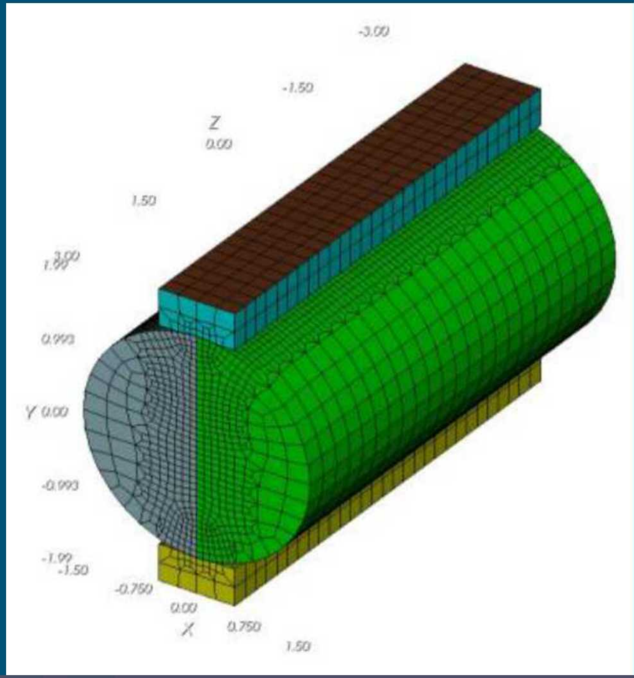
- Damage parameter(s)
- Post-peak behavior
- Other model constants

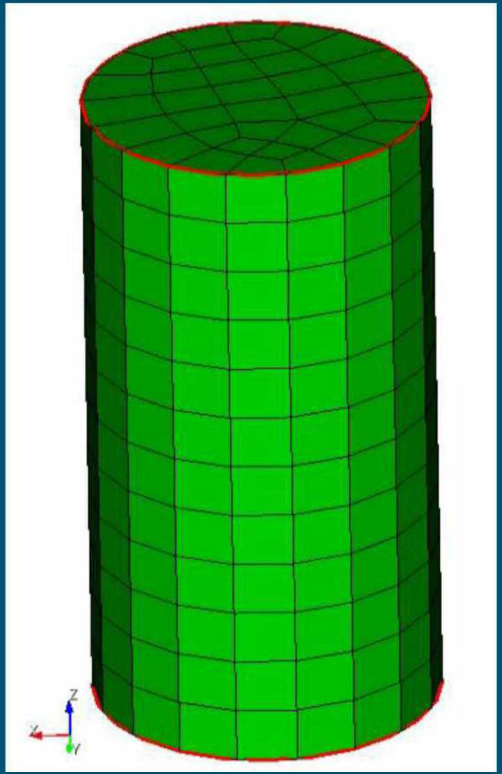
Model Calibration Simulations

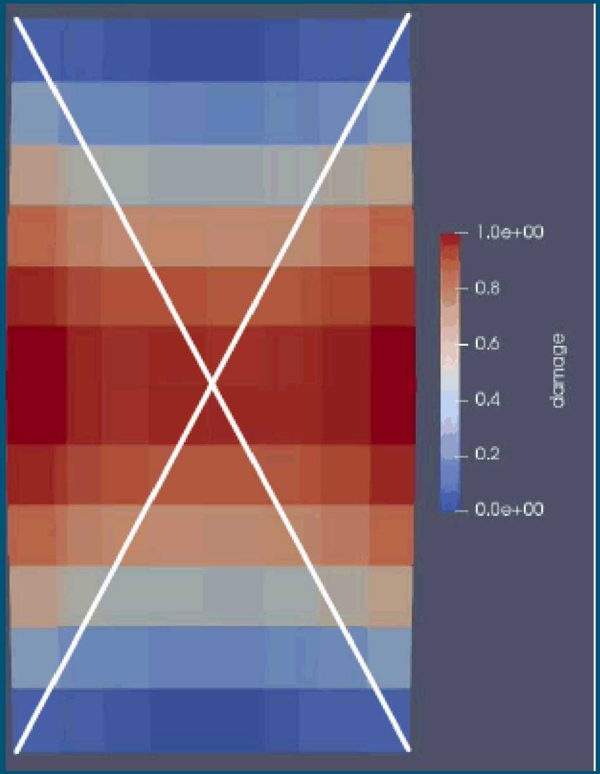
Single element compression/tension

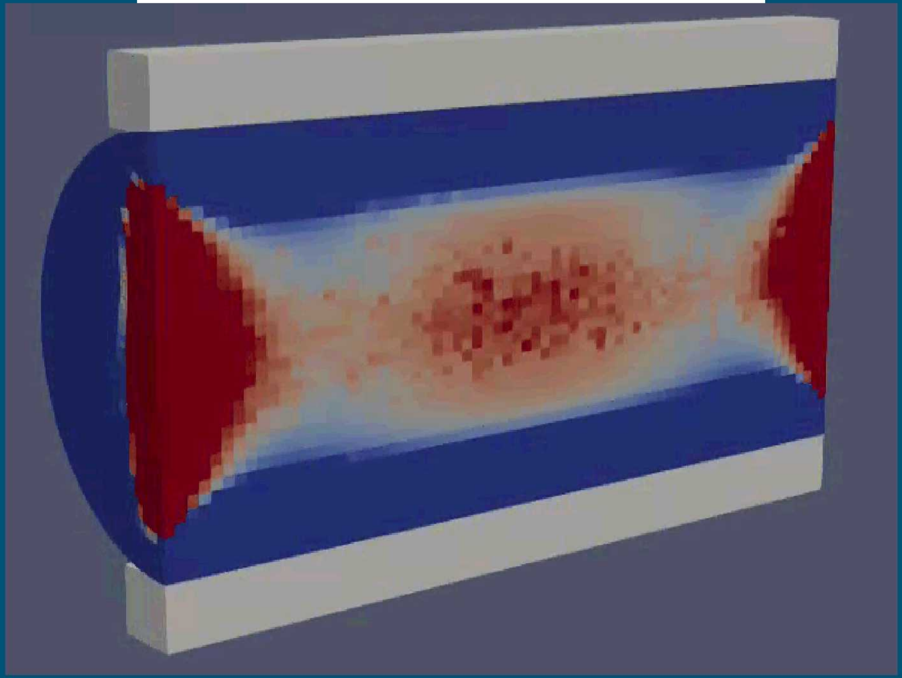
Concrete cylinder uniaxial/triaxial compression

Concrete split-cylinder

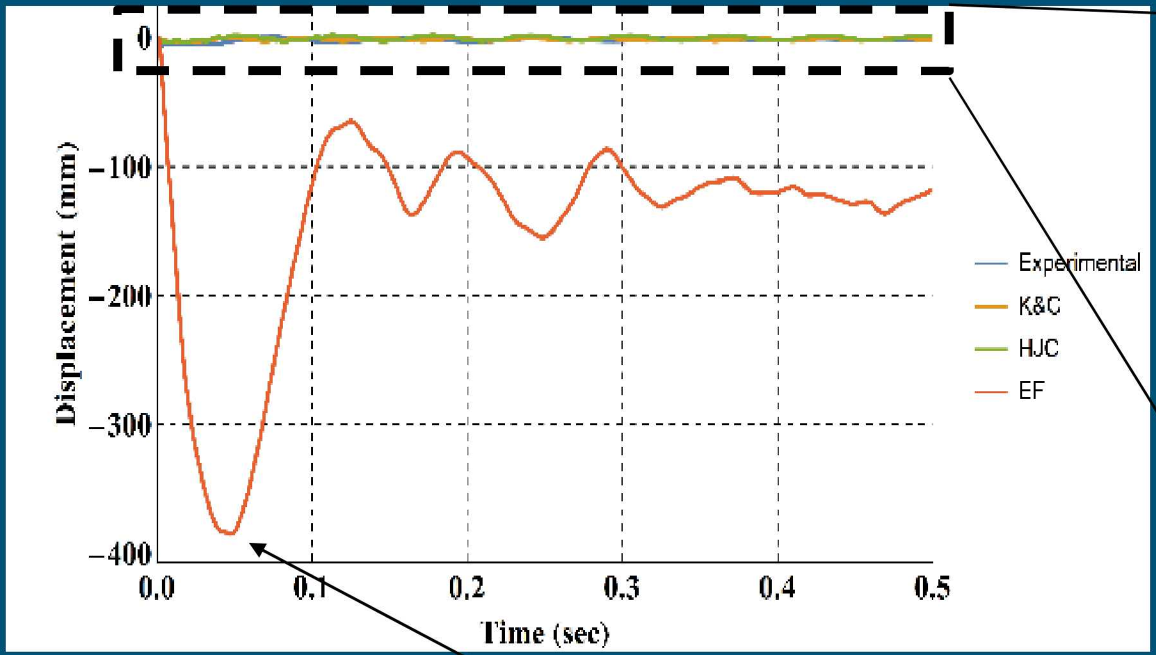


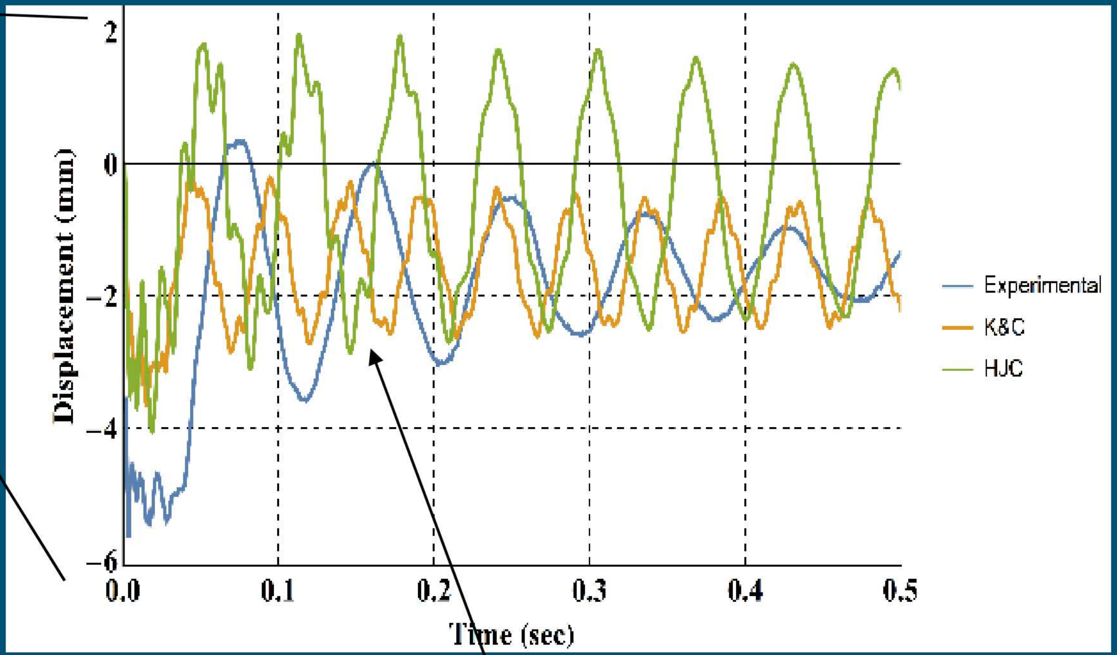






Results: Displacement @ Impact Face

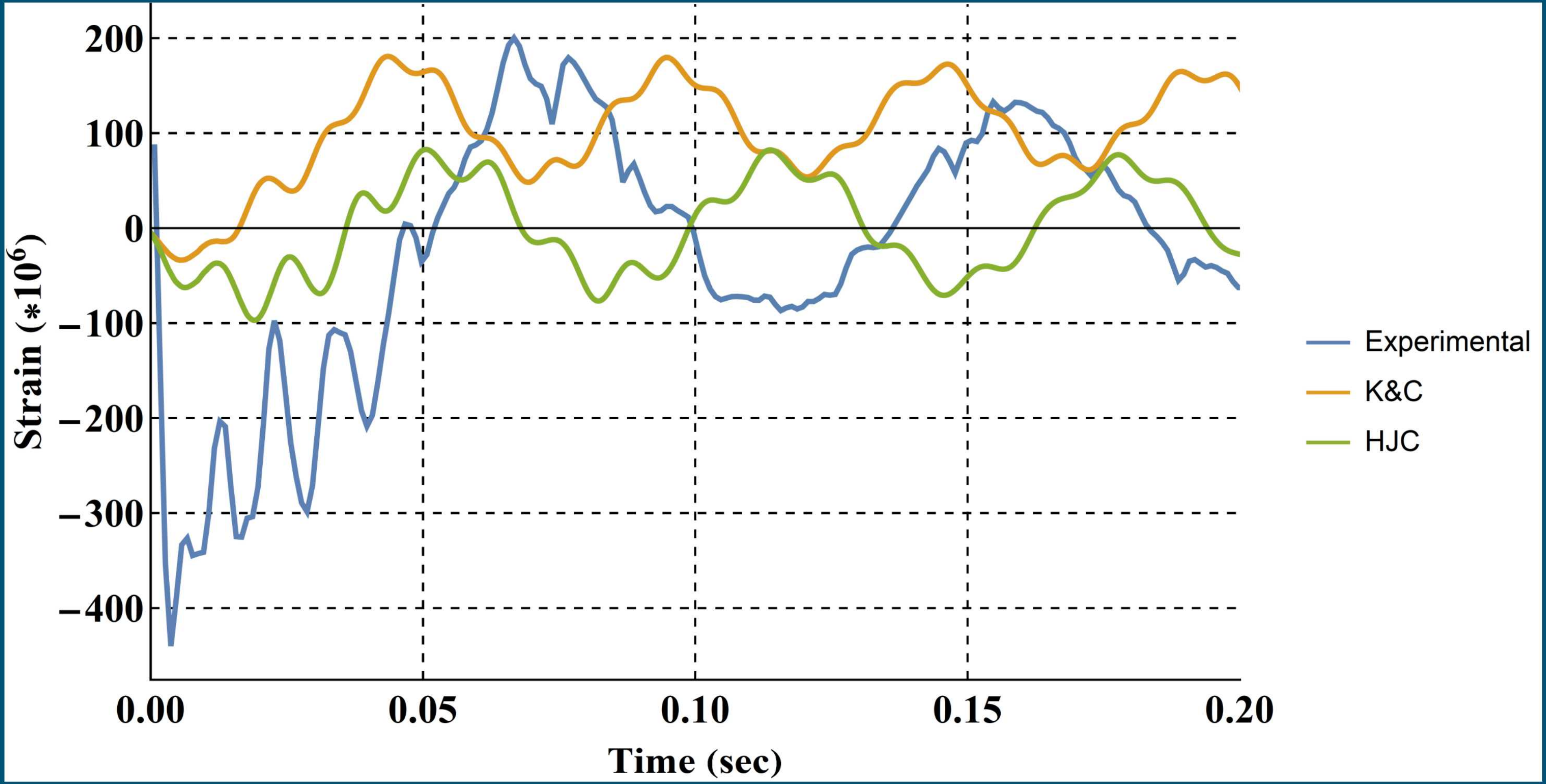




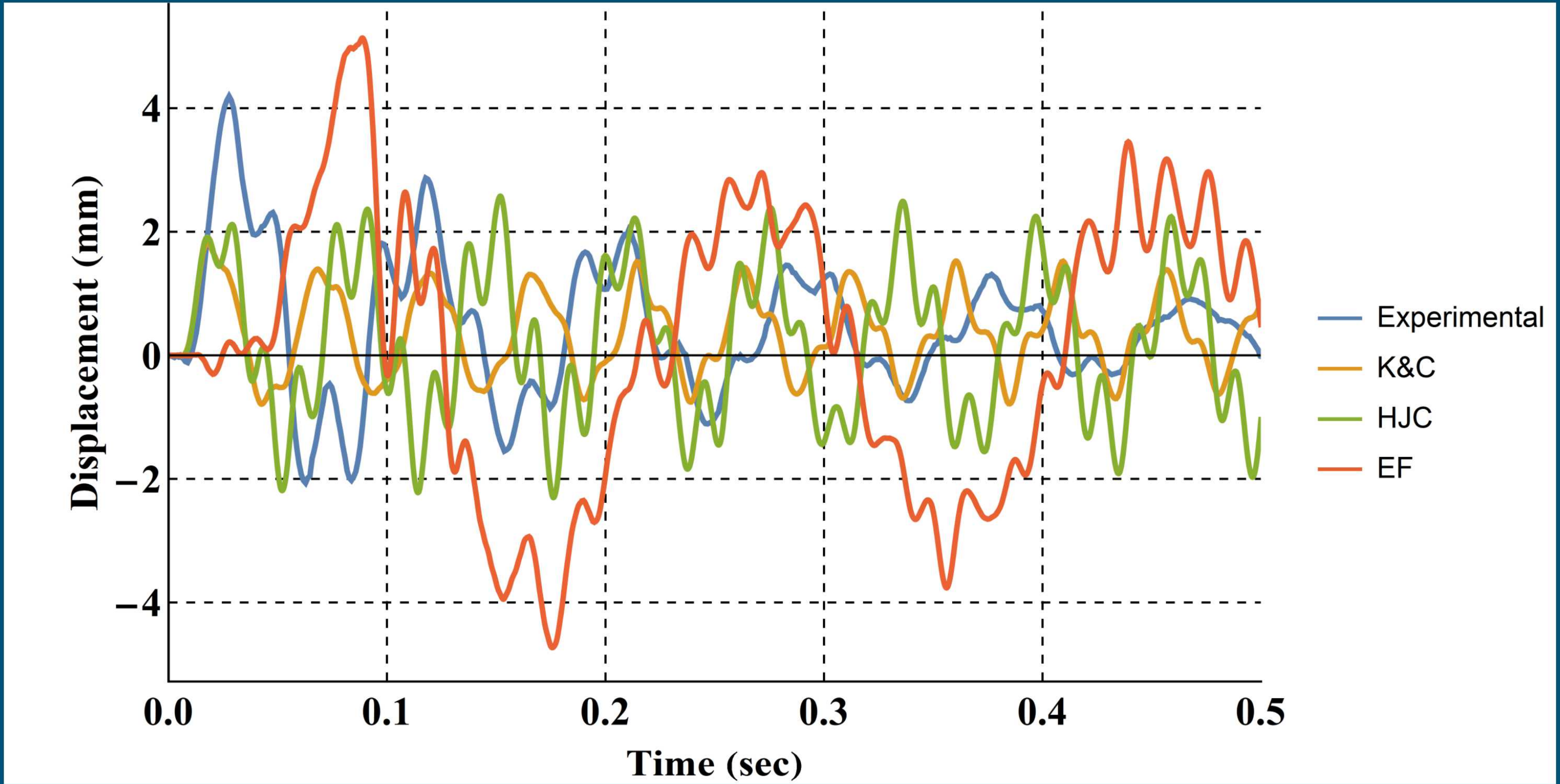
Unsuitable prediction from the Elastic-Fracture for this model response

Reasonable prediction for HJC and K&C models

Results: Concrete Strain, Back of Impact Face



Results: Pseudo-Equipment Displacement



Conclusions and Discussion

The HJC model **has too many variables** to be used in a concrete that is *not* specifically described in the original document. The experiments required to get the inputs are difficult and the authors do not provide a means to estimate unknown inputs. That being said, the model is **designed to be completely numerically stable** in high-damage scenarios, a huge benefit in impact simulations.

The **K&C model gives reasonable results** and the original document describes exactly how to obtain the inputs from standard concrete testing inputs (e.g. compressive strength and Young's modulus). Others can be estimated using the original document's guidelines.

The EF model is extremely simple to implement but is **likely not useful in high-damage or impact simulations**. It could be useful in low-damage or whole structure reaction simulations.