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

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ABSTRACT

This paper explores the concept of predictive maturity for non-linear concrete constitutive models employed in the computational prediction of the structural response of reinforced concrete structures to impact from free-flying missiles. Concrete constitutive models are widely varied in complexity. Three constitutive models were utilized within the same finite element structural model to simulate the response of the IRIS III experiment. Each of the models were individually calibrated with available material testing data and also re-calibrated assuming limited availability of test data. When full calibration is possible, more sophisticated constitutive models appear to provide more predicative maturity; however, when this data is not available (e.g. for an existing structure where representative test specimens may not be available), the expected maturity is reduced. Indeed, this hypothesis is supported by the simulations that indicate good agreement with measured experimental response quantities from the IRIS III tests with complex constitutive models and full calibration, and accordingly poor predictions when less complex models are used or when the more sophisticated models are poorly calibrated. Thus, predictions of structural response where incomplete material testing data is not obtainable should be understood as less predictive.

INTRODUCTION

Computationally predicting the material and structural effects of free-flying missile impacts into reinforced concrete has garnered much attention in recent years. A series of round-robin predictive and experimental campaigns, “Improving the Robustness Assessment Methodologies for Structures Impacted by Missiles” (IRIS), has recently concluded. IRIS assessed hard and soft missile impacts as well as the structural vibration response associated with soft missile impacts [1]. A key finding of the IRIS program is the unique role concrete constitutive models (within the larger structural model) play in simulating quantities of interest. In general, the better performing models were those that captured more physical phenomena; however, developing constitutive model input parameters to describe these phenomena require additional and sometimes difficult testing. This paper evaluates the predictive maturity of three concrete constitutive models in the context of the Predictive Capability Maturity Model (PCMM) [2] or the problem of reinforced concrete damage and structural response resulting from free flying missile impact.

COMPUTATIONAL PREDICITON

Computational simulation of physical phenomena has received significant attention for academic research, engineering design, and safety assessment [3]. The benefits of simulation are numerous and involve the ability to explore events and phenomena that may be difficult or impossible to physically test. Computational simulation is also generally less expensive than experimental campaigns, especially when the physical phenomena being simulated are hazardous. A key challenge facing physics simulation

SNL statement: This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

approaches involves predicting the outcomes of future events or experiments where the outcome is unknown. Indeed, many codes are able to post-dict the outcomes of known experiments. However, accurately simulating quantities of interest (QOIs) without knowledge of the real outcome is much more challenging. This observation is strongly supported by qualitatively comparing prediction accuracy of pre-test and post-test round-robin simulation campaigns commonly conducted in the nuclear safety field [1,4-6]. With the cessation of nuclear weapons testing, US stockpile assurance has turned increasingly to computational simulation to ensure operational readiness. The reliance on simulation has been enabled by the field of verification, validation, and uncertainty quantification (VVUQ). VVUQ can be considered as a collection of mathematical and procedural techniques used to build evidence that in aggregate supports confidence in simulated QOIs. The various types of evidence used for VVUQ can be challenging to organize and consider together, but the predictive capability maturity model (PCMM) developed at Sandia National Laboratories (SNL) is helpful for this purpose. The PCMM identifies 6 different VVUQ attributes that in combination are each mutually exclusive and collectively exhaustive for evidentiary support of computational simulation [2]. The PCMM has been used to conduct code assessments for several US Department of Energy simulation code development programs.

The PCMM works by defining attributes that contribute to simulation confidence and maturity level for each attribute is determined by comparing available evidence to standardized definitions for each maturity level. A key concept for PCMM assessment of computational simulation, that is often misunderstood, is the intended purpose of the simulation. Understandably, the expected maturity for initial project scoping studies may be much less than for nuclear power industry licensing. Furthermore, the PCMM can be used to clarify expectations between stakeholders involved in physics simulation campaigns.

Table 1: Predictive Maturity Descriptors for Physics and Material Model Fidelity. [2]

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

EXPERIMENTAL

Many countries have performed missile impact analyses, but due to their sensitivity, the results are not easily shared. Therefore, it was considered important and worthwhile to perform a study that can be publicly vetted as a means of validating the evaluation techniques used in these analyses. The Committee on the Safety of Nuclear Installations (CSNI) approved in December 2008 a proposal of the Working Group on Integrity and Ageing of Components and Structures (WGIAGE) to conduct the round robin study IRIS. The different computer codes, modelling approach methods, and results were to be compared to experimental data and other participants' codes used to determine effective means of analysing the structural and vibrational effects of a postulated missile impact on a nuclear power plant.

The full project was comprised of three phases: Phase I, impact of walls; Phase II, impact of larger structures; and Phase III, transmission of shock and vibration to internal components. Phase I consisted of numerical simulations and comparisons to existing experimental data of three impact scenarios involving a steel missile striking a concrete target heavily reinforced with steel bars; participants were not given the results of the test prior to submission of their simulations. Results from participants varied widely; therefore, Phase II was implemented to allow participants of Phase I to update and improve their simulations with the knowledge of the test results. Phase III consisted of two parts, both involving analyses and numerical results obtained from simulations of a hollow steel missile impacting a concrete target reinforced with steel bars. The goal of Phase IIIA was to give participants an opportunity to calibrate calculations on an impact test from a previous experimental program. Test displacements, accelerations, and strains were given to the participants for them to calibrate their models prior to simulation submission. Some important QOIs of Phase IIIB were strains, displacements, reaction forces, and accelerations of a box-shaped reinforced concrete structure with a cantilevered arm subject to impact from a soft steel missile. A schematic is shown in Figure 1.

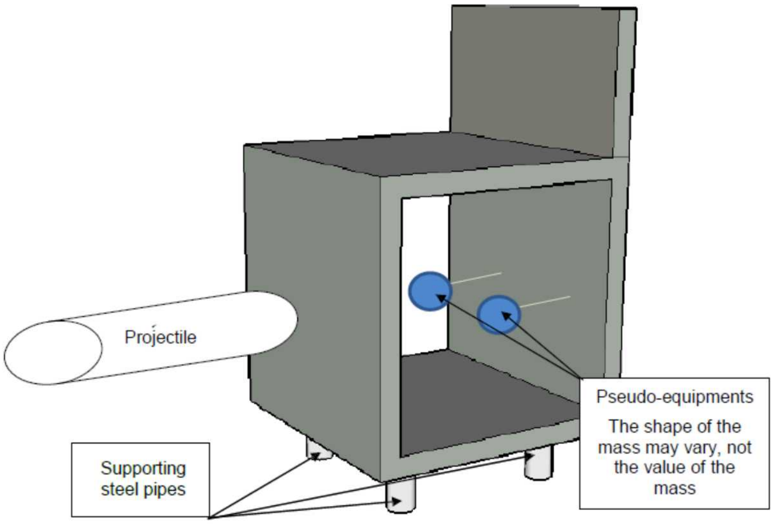


Figure 1: IRIS Phase IIIB mockup schematic [7].

61 kg cylinders were used for the pseudo-equipments shown in Figure 1. The pseudo-equipments were attached to the concrete via base plates and IPE 140 I-beams. One I-beam was welded to its base plate while the other was bolted. Participants were not guided in any way on how to model any of the simulation, which encouraged a wide variety of techniques to be shared between participants.

The assessment in this document will utilize the IRIS IIIB mockup, simulation techniques, and results and will not include prior IRIS phases.

STRUCTURAL MODEL

The simulations performed by SNL in support of IRIS IIIB were executed using Sierra, SNL's internal code. Sierra's solid mechanics module is massively parallel capable and contains a full suite of features that span explicit and implicit transient dynamics, and implicit quasi-statics [8]. Geometry and meshing was performed using the software CUBIT. Cubit is a full-featured solid-modeller based pre-processor that meshes volumes and surfaces for finite element analysis [9].

As shown in Figure 2, the mock-up is a 2.5 m wide structure made of reinforced concrete. It composed the following structural elements: impact wall 2.5 m x 2 m x 15 cm; rear wall 2.5m x 2 m x 15 cm; lower floor 2.5m x 2 m x 40 cm; upper floor 2.5m x 2 m x 15 cm; cantilevered wall 2.5 m x 1 m x 15 cm.

The concrete was constructed entirely with 8-noded hexahedral elements. Rebar was constructed entirely with 2-noded beam elements embedded into the concrete and given the properties of the specified rebar diameter. Each piece of rebar was constructed as specified in the drawings and embedded in the concrete. The I-beams, the metal plates connecting the I-beams to the concrete, the angle steel on the “bolted” I-beam, and the metal plates connecting the supports to the concrete and the ground were constructed with 8-noded hexahedral elements. The supports and the missile were constructed with 4-noded shell elements extruded to the thickness specified in the drawings. 3D hexahedral elements were analyzed with a single integration point at the midpoint. 2D shell elements were integrated as a 5 point trapezoidal rule through the thickness. 1D beam elements extruded as a rod were analyzed with 9 integration points. The mockup geometry is shown in Figure 2 and Figure 3. Element information is listed in Table 2. The mesh (both concrete and steel) was refined in areas of high deformation, e.g. corners, the impact face, or the nose of the missile. The minimum mesh edge length was ~6.9 mm and the maximum was ~61.7 mm.

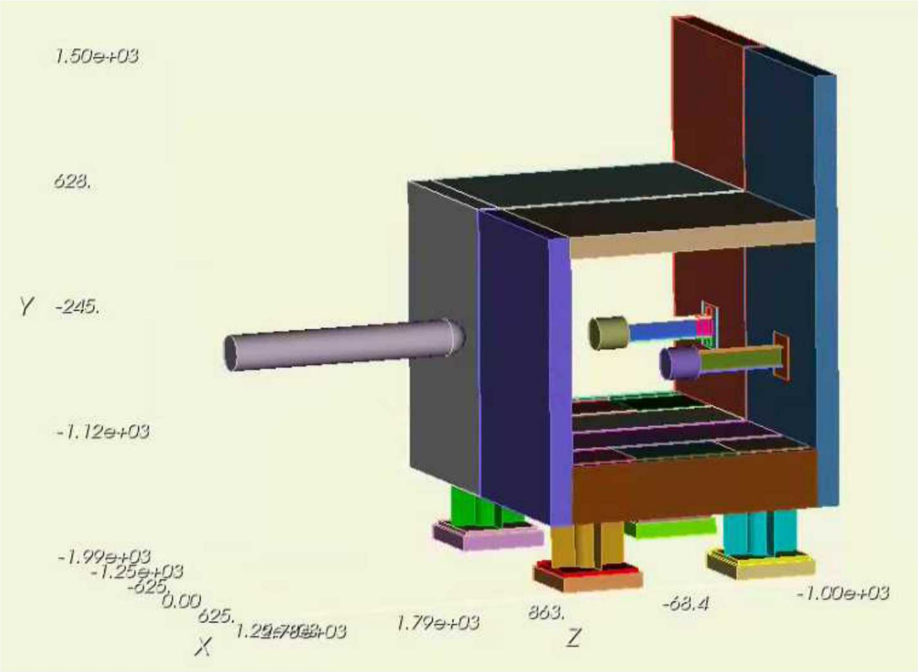


Figure 2: Overall mockup without mesh. Units are in mm.

Table 2: Elements in the mockup.

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

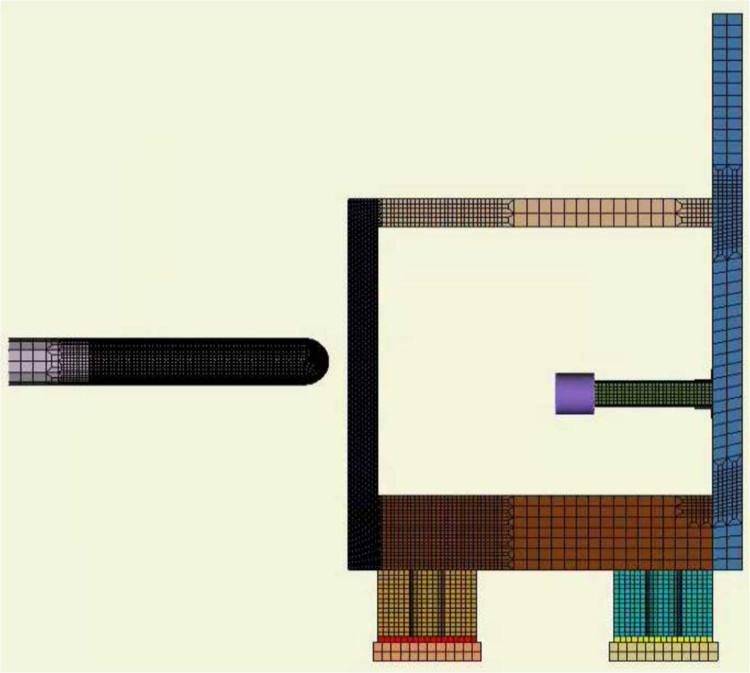


Figure 3: Side profile of the mockup and missile mesh.

Rebar is not shown in this document, but the mockup rebar was modelled explicitly. The 2-noded beam element rebars were perfectly embedded into the concrete; no slip was allowed. Standard rebar dimensions throughout the structure were HA6 bars @ 50 mm, both longitudinal and transverse, with either U-bars or L-bars in the corners. Shear stirrups are interspersed throughout, notably in the entire impact face, over the supports, and near the cantilever junction.

The missile was modelled using 4-noded shell elements extruded to 1.89 mm thick. A cast iron rear plate was modelled on the missile to ensure that the total mass was 50.1 kg.

All rebar was modelled as elastic-plastic with a yield stress of 500 MPa, Young's modulus of 200 GPa, and post-yield modulus of 1.2 GPa. The cast iron missile end plate was modelled as perfectly elastic as it never impacts the concrete. The missile was modelled as multi-linear elastic-plastic to ensure that the steel behaved correctly in extremely high strains and strain rates. The nodes on the bottom of the foundations were considered fixed in all directions. The missile was given an initial velocity of 90 m/s.

CONCRETE CONSTITUTIVE MODELING

Constitutive modelling involves the defining a mathematical relationship between strains and resulting stresses in the finite element modelling framework. For concrete these constitutive models typically involve initial linear elastic response followed by inelastic response for higher strains. Concrete demonstrates a notably different mechanical response in compression, tension, and shear. Furthermore, concrete inelasticity is known to be rate and confining pressure dependent.

Three different constitutive models were used in this study.

- Holmquist-Johnson-Cook Concrete Model [10]
- Karagozian & Case Concrete Model [11]
- Elastic-Fracture Material Model [8]

The concrete model proposed by Holmquist, Johnson, and Cook (HJC) has many promising features for use in the IRIS program. The HJC model increases the compressive strength of the material with increasing confining pressure, and damage decreases the overall strength of the material. In addition, the damage parameter is stabilized such that damage requires a minimum strain to begin accruing, preventing unstable damage propagation through the material due to numerical artifacts or artificial material shock. Artificial material shock potentially occurs in finite element simulations when an element becomes damaged. The damaged element instantly transfers from the undamaged strength/strain to the damaged strength/strain, and the sudden change in strain can cause a shockwave through the simulation instantly damaging surrounding elements that would otherwise be undamaged.

The HJC incorporates damage into the model based on hydrostatic pressure and excessive strains as shown in Equation 1.

$$Damage = \sum \frac{\Delta\varepsilon_p + \Delta\mu_p}{D_1(P^* + T^*)^{D2}} \tag{1}$$

In Equation 1, $\Delta\varepsilon_p$ and $\Delta\mu_p$ are the equivalent plastic strain and plastic volumetric strain, respectively; *D1* and *D2* are constants; and P^* and T^* are the pressure and hydrostatic tensile pressure normalized by f'_c. Hence, larger hydrostatic compressive pressures P^* can negate damage from hydrostatic tensile pressures T^*, and no damage accrues without plastic strain. The HJC also accounts for concrete crushing under large hydrostatic compressive pressures since concrete is porous as shown in Figure 4. Plastic volumetric strain increases linearly with pressure until reaching P_{crush} and μ_{crush}. Then the concrete crushes resulting in more volumetric strain per unit increase in pressure until reaching P_{lock}, after which all pores have been crushed and the concrete behaves as a solid without pores.

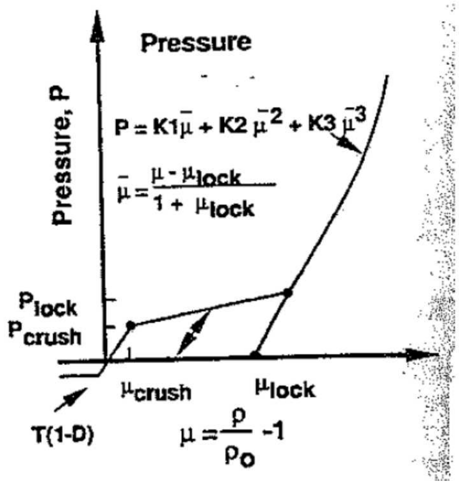


Figure 4: HJC pressure vs plastic volumetric strain crushing behavior [12].

The biggest drawback in using the HJC concrete model is its large list of variables, 21 in all: Young's modulus, Poisson's ratio, initial concrete density, compressive strength f'_c, two damage coefficients, initial shear modulus, a variable titled "maximum stress", maximum tensile pressure, minimum failure strain, P_{crush}, P_{lock}, μ_{crush}, μ_{lock}, three post-crushing behavior coefficients K_1, K_2, and K_3, a pressure hardening coefficient, a strain rate coefficient, and another maximum yield stress variable. Experiments can determine each variable, but many of the required experiments are rarely performed except in extremely specific scenarios (such as determining the pressure at which pore crushing begins and ends). Either the engineers must use/modify the inputs given in the original documentation, or trial and error is required to hone the model to existing data. Several variables have significant impact on the material behavior that should be governed by other variables, making trial and error efforts difficult and time consuming. Attempts at fitting the HJC model to the existing triaxial data suggested multiple sets of variables that can match triaxial data.

The Karagozian & Case (K&C) concrete model is an inelasticity model appropriate for approximating the constitutive behavior of concrete and has been widely utilized in finite element impact simulations for reinforced concrete. Coupled with appropriate elements for capturing the embedded deformation of reinforcing steel, the K&C concrete model can be used effectively for simulating the mechanical response of reinforced concrete structures. The K&C model has several useful characteristics for estimating concrete response, including strain-softening capabilities, some degree of tensile response, and a nonlinear stress-strain characterization that robustly simulates the behavior of plain concrete.

The K&C model requires 14 inputs, and four of those inputs are functions requiring x/y data. That being said, the original authors understood that performing the exact experiments to obtain said inputs can be tedious and expensive. Therefore, the authors included detailed instructions on how to approximate the required inputs from more standard concrete material information such as compressive strength, Poisson's ratio, tensile strength, and elastic modulus.

The Elastic-Fracture (EF) material model provided in Sierra is a relatively simple material model. The model requires two elastic constants (e.g. Young's modulus and Poisson's ratio), maximum tensile stress, and the strain over which the tensile stress returns to zero after fracture. The model is perfectly elastic in compression but fractures in tension after reaching the maximum tensile stress.

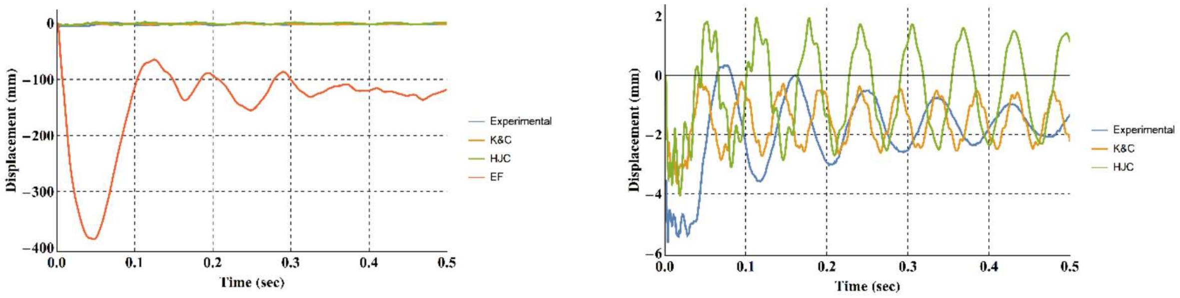
As described in the introduction, the PCCM provides a framework for assessing the predictive maturity of various aspects of computational simulation. The EF model most closely matches the descriptors of maturity level 1. The EF model does not capture significant physical phenomena such as concrete crushing and rate dependence. Both the K&C and HJC models match closely with the descriptors for maturity level 2. Both K&C and HJC capture relevant physical phenomena for impact problems and both require significant calibration. The K&C model has received significantly more peer review and has been more widely utilized in both practice and research settings. This has led to widespread experience with calibrating the K&C model parameters, which is a significant advantage over the HJC model Based on this scoring, and assuming adequate test data to calibrate the models, the K&C and HJC models would be expected to provide more predictive capability than the EF constitutive model.

SIMULATION RESULTS

To assess the predictive capability of the three concrete constitutive models described in the previous section, the finite element model created for the IRIS IIIB Round Robin was evaluated with each constitutive model. Each constitutive model was calibrated using available material test data and, importantly, was not specifically tuned to match overall mockup response. Thus, these simulations are representative of a prediction, even though the experimental results were in-hand.

An important aspect to consider when modelling reinforced concrete structures with high damage is that modelling results will vary widely with subtle changes in input parameters. For example, an over-strict boundary condition can fully damage elements in the supports that would otherwise acquire only minor damage, causing major structural response changes. Rebar modelling (e.g. fully embedded, allow slip, "smeared" vs explicitly defined…) can also have significant impact on the results.

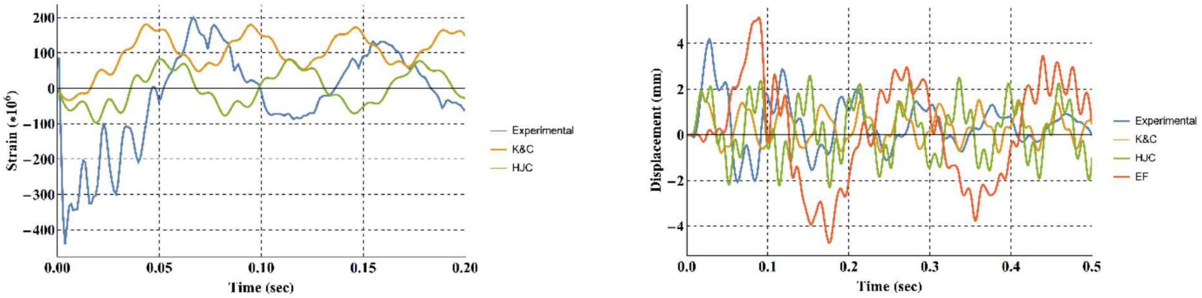
Figure 5 shows the displacement response for the simulation on the impacted face of the mockup. The displacement response in Figure 5(a) indicates the primary deficiency in the EF constitutive model, which is excessive damage. The missile in the experiment did not penetrate the concrete, and only minor spalling occurred on the back of the impact face. The EF model allowed the missile to fully penetrate the concrete and severely deform the rebar. The difference between the EF model and the other two models is an example of how vast the results can vary between constitutive models. Figure 5(b) shows the same response without the EF model data. Both the HJC and K&C models predicted the behaviour reasonably well: displacements were in the same order of magnitude, and the oscillation periods were relatively similar. The K&C model more closely agreed with displacements.



a b

Figure 5: (a) Horizontal displacement of the back side of the impact face immediately behind missile the missile impact, (b) without EF model

Figure 6 shows the strain in the impact face of the mockup and the vertical displacement of the pseudo-equipment. While the K&C and HJC models both predicted the measured displacement of the impacted face relatively accurately (Figure 5), neither closely predicted the initial peak strain shown in Figure 6(a). However, both models predicted the impact-face oscillation strains. The EF model is not shown due to its excessively large strains in the impact face. Figure 6(b) highlights the ability of all constitutive models to capture structural response away from damaged regions and for this QOI, all models performed reasonably well.



a b

Figure 6: (a) Strain gage on the impact face halfway between the missile impact and the top of the impact face excluding the elastic-fracture model results, (b) Vertical displacement of the pseudo-equipment attached to the welded I-beam.

A key finding from comparing results in Figure 5 and Figure 6 is that all three models performed comparably well in portions of the structure away from damage. Even though the HJC and K&C models had 21 and 14 inputs, respectively, the EF model predicted similar responses (away from damage) with only 4 inputs. This observation raises an important and often misunderstood aspect of the PCMM scoring framework. Depending on the QOI, a low maturity simulation approach may be suitable for the intended purpose, and thus a higher PCMM score does not equate to a "better" model. Another key finding is that the HJC and K&C models performed comparably well with each other despite the fact that the HJC model required 50% more inputs, and the HJC model did not provide a means to estimate unknown inputs. In this document, the HJC inputs were taken unaltered from the original publication. The K&C and EF models were made to fit the HJC concrete, showing that models with simpler inputs can be more useful than a model based on more physics but with difficult inputs.

CONCLUSIONS

Three concrete constitutive modeling approaches with varying complexity have been employed to model the structural response of a reinforced concrete structure to free-flying missile impact. The HJC and K&C models are representative of maturity level 2 while the EF model is representative of maturity level 1 in the PCMM scoring framework. The predictive maturity of the overall modeling approach is strongly influenced by the constitutive response for this class of impact problems. The challenge with many concrete constitutive models is the large number of model parameters that must each be defined to achieve an accurate prediction. For existing concrete structures or for pre-construction analysis, the material test data to populate these parameters may not be available thus significantly limiting the ability to make accurate predictions. From the simulations described in this document, several conclusions on the constitutive models can be obtained.

- 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.

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