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Qualification of Reinforced Concrete Slabs Subjected to Tornado Induced Impact

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ABSTRACT

In recent years, safety of nuclear power plants against external missile impacts such as those due to tornadoes has gained significant attention. In many cases, advanced simulation tools based on finite element method (FEM) or smooth particle hydrodynamics (SPH) are being employed to simulate missile impact behavior and to evaluate vulnerability of nuclear facilities. Due to the complex nature of impact behavior, it requires appropriate calibration of parameters in the advanced simulation models that are used to represent them. In this manuscript, we propose a novel approach for modeling the behavior of reinforced concrete slabs subjected to missile impact. First, we use data from one experimental study to develop and calibrate various models needed to conduct the finite element analysis. Then, the calibrated models are used to conduct a predictive analysis for a different experimental setup. A comparison of the experiment and the analytical results for the new test provides confidence in the predictive capability of the simulation approach with calibrated parameters. The calibrated models are then used to conduct the analysis of a postulated falling steel beam on the reinforced concrete slab in Auxiliary Building of a nuclear power plant.

INTRODUCTION

In response to the accidents at the Fukushima Daiichi nuclear power plant (NPP) following the 2011 Great Tohoku Earthquake and subsequent tsunami, the US Nuclear Regulatory Commission (NRC) released a regulatory issue summary (RIS) “2015-06 Tornado Missile Protection” (US NRC, 2015). Acting on the recommendations in RIS, USNRC requested the licensees and holders of construction permit to reevaluate plant’s current, site-specific licensing basis for tornado-generated missile protection. The safety of structures, systems, and components (SSCs) should be ensured against major damage following external events including tornadoes among others.

Many experimental studies (Fang and Wu, 2017; Hakola et al., 2013; Kojima, 1991; Li et al., 2005; NEA/CSNI/R(2011)8, 2011; NEA/CSNI/R(2014)5, 2014; Orbovic and Blahoianu, 2013; Orbovic et al., 2015; Saarenheimo et al., 2009; Vepsä et al., 2012) have been conducted in the past to study the local damage behaviour of missile impact on reinforced concrete (RC) slabs. These experimental studies have been used to develop empirical formulas for evaluating the penetration depths and the minimum thickness required to prevent perforation (Fullard et al., 1991; Kojima, 1991; Kosteski et al., 2015; Li et al., 2005). The empirical formulae provide simple and reasonable approach to impact assessment. However, the empirical formulae are derived based on the experimental test data rather than the underlying mechanics/physics based phenomenon. Moreover, actual conditions in the assessment of an impact behavior in a real structure often varies significantly from those used in the experimental studies. Some of these conditions relate to the type of concrete, reinforcement ratio, boundary conditions, presence of additional structural members such as supporting beams, type of missile/impacting object, velocity of impact, etc. Some experimental studies (NEA/CSNI/R(2011)8, 2011; NEA/CSNI/R(2014)5, 2014; Othman and Marzouk, 2018; Sangho et al., 2021) have also been used to develop and calibrate finite element (FE) models. Modeling the impact behavior in RC slabs using sophisticated FE studies has gained wider attention only in the past decade or so, as the advanced models for material characterization and conducting large deformation nonlinear analysis have become readily available.

In 2010 and 2012, a series of bending and punching tests on impact of a rigid missile on a RC slab were conducted by VTT Technical Research Center of Finland (NEA/CSNI/R(2011)8, 2011; NEA/CSNI/R(2014)5, 2014). In a round-robin study named "Improving Robustness Assessment Methodologies for Structures Impacted by Missiles" (IRIS) organized by IRSN France and CNSC Canada, 28 teams around the world participated in simulating the bending and punching tests using various FE software (NEA/CSNI/R(2011)8, 2011; NEA/CSNI/R(2014)5, 2014). The objective of IRIS study was to investigate the effectiveness of current analytical and computational methods for modeling RC structures being impacted by missiles. Out of 28 teams only 8 teams have results within the range of $\pm 40\%$ error. However, none of these teams have proposed a methodology to calibrate the sensitive parameters that is applicable to a wide range of test setups nor assessed the applicability of calibrated FE model for a different experimental setup.

In this study, a novel approach is proposed for modeling the behavior of RC slabs subjected to missile impact. First, the data from IRIS study is used to develop and calibrate various models needed to conduct the FE analysis in ABAQUS (ABAQUS, 2021). Then, the calibrated models are used to conduct a predictive analysis of the experimental setup used by Kojima (1991). The purpose of this approach is to establish and provide additional evidence so that models calibrated using IRIS test are able to produce acceptable results for another independent experimental test which in this case is taken as the tests conducted by Kojima (1991). After establishing this additional confidence, the calibrated models are used to conduct the analysis of a postulated falling steel beam on the reinforced concrete slab in Auxiliary Building of a nuclear power plant.

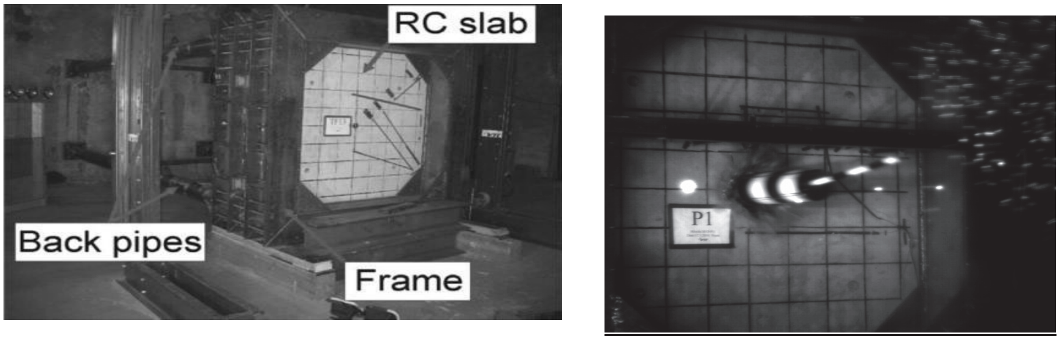
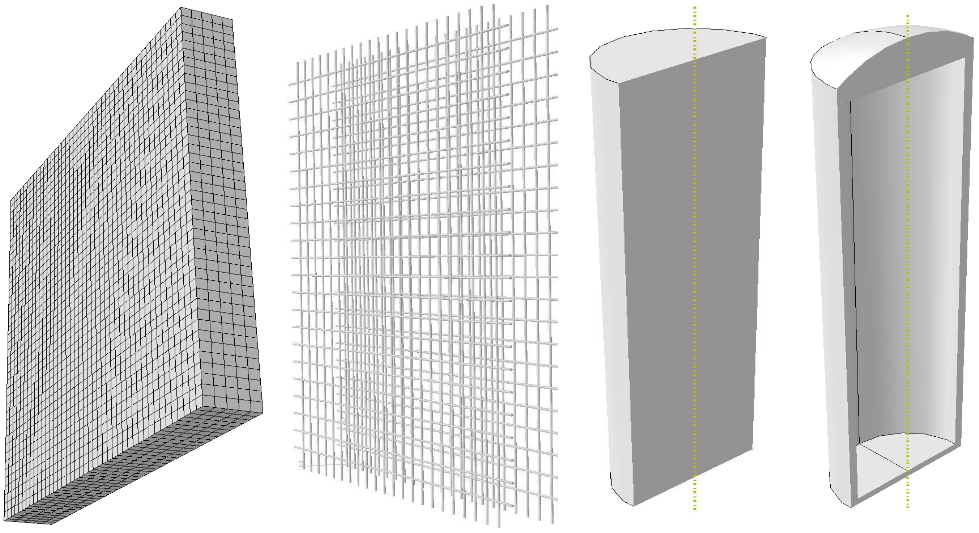


Figure 1. Test setup and missile at the moment of impact from IRIS study (Hirosaka et al., 2017)

FINITE ELEMENT ANALYSIS OF IRIS EXPERIMENTS

In this study, FE software ABAQUS (ABAQUS, 2021) is used for simulating the IRIS experiment because it has material models that can represent cracks, damage, and element erosion. The concrete slab, reinforcement bars, and missile (which contains steel and concrete) are all modeled independently as shown in Figure 2.



(a) Concrete Slab (b) Reinforcement (c) Missile-Concrete (d) Missile-Steel

Figure 2. FE model of IRIS experiment

The concrete slab and reinforcement bar are meshed using 8-noded linear 3D brick elements (C3D8R) with an element size of 15 mm and 10 mm, respectively. The steel and concrete part of the missile are meshed using 10-noded modified quadratic tetrahedron elements (C3D10M) with an element size of 25 mm. Steel and concrete parts of the missile are later assembled to work as a single component during the impact. The reinforcement bars are constrained to concrete slabs in translation degrees of freedom using embedded region. The experimental test setup is replicated using the FE model by applying a fixed boundary condition at all four sides of the slab and the missile is imparted an initial striking velocity of 135 m/s. The FE analysis is carried out using dynamic explicit method which considers an explicit central-difference time integration rule.

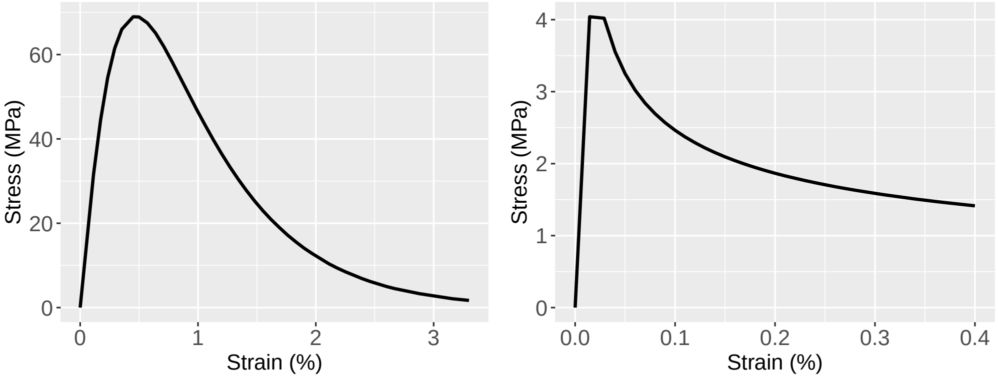
Modeling the material behavior

ABAQUS provides several material models to represent the plastic behavior of concrete and steel, such as cap plasticity, Drucker-Prager, Concrete Damage Plasticity, concrete smeared cracking, Moher-Coulomb plasticity, and simple elastoplastic model. The concrete damage plasticity (CDP) model is the most commonly used material model because of its capability to represent both modes of failure in concrete, i.e., tensile cracking and compressive crushing (ABAQUS, 2021; Lee and Fenves, 1998). For the reinforcement bar, a simple elastoplastic material model is used.

The CDP model can exhibit element erosion which is essential to model perforation or penetration. To define CDP model in FE analysis, stress-strain curves are required in tension and compression. The stress-strain curves for the tensile and compressive side are generated using closed-form equations (Syed and Gupta, 2015a,b). Stress–strain curves were generated based on the maximum tensile and compressive strength, as illustrated in Figure 3. If there is any damage, the strain is categorized as plastic strain, which is defined with the damage parameter. The value of the damage parameter at each data point on the stress strain curve is generated using Equation 1 (Hafezolghorani et al., 2017).

$$\begin{aligned} d_c &= 1 - \frac{\sigma_c}{\sigma_{c,max}} \\ d_t &= 1 - \frac{\sigma_t}{\sigma_{t,max}} \end{aligned} \tag{1}$$

where, d_c, d_t are damage parameters in compression and tension, $\sigma_{c,max}, \sigma_{t,max}$ are maximum or ultimate stress of concrete in compression and tension.



(a) Compressive behavior (b) Tensile behavior

Figure 3. Compressive and tensile stress-strain plots from closed form equations

In addition to the stress–strain curves, there are two other essential CDP parameters which affects the simulation results significantly:

- *Dilation angle* ψ: controls an amount of plastic volumetric strain developed during plastic shearing, and it is assumed constant during plastic yielding.
- K_c: ratio of the second stress invariant on the tensile meridian to that on a compressive meridian. K_c varies between 0.5 and 1.

The value for parameter K_c is calibrated based on tri-axial test validations, and the dilation angle ψ is calibrated using a parametric study.

Calibration of CDP parameter K_c

In the second phase of IRIS study, tri-axial tests were conducted on concrete cylindrical specimens with material properties same as the concrete slab (NEA/CSNI/R(2014)5, 2014). The stress-strain curves from the tri-axial tests are provided for confining pressures of 15.5, 26, 47, 100 MPa. To understand the behavior of concrete, a FE model is created to replicate the tri-axial tests. The concrete is characterized using the CDP model and the stress-strain curves are generated for different confinement pressures. A parametric study is conducted by varying the values of K_c and it is found out that the stress-strain curve shifts upwards or downwards based on different values of K_c. To establish satisfactory reconciliation between the experimental and stress-strain curves from the FE analysis, different values of K_c must be chosen for different confinement pressure.

In order to generalize the relationship between K_c and confinement pressure for other strengths of concrete, tri-axial test data available in the published literature is studied (Imran and Pantazopoulou, 1996). These test cases are simulated in this study by developing various FE models. To establish a good match, a parametric study is undertaken by varying the values of K_c. Based on that, a curve is generated to choose value of K_c based on confinement pressure and maximum concrete strength in compression ($f_c^{'}$) as shown in Figure 4.

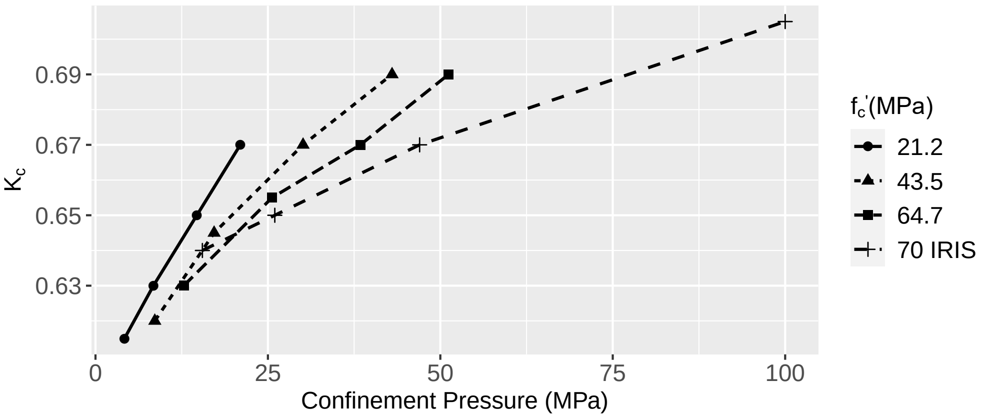


Figure 4. Plot used to estimate the value of K_c for different confinement pressures and $f_c^{'}$ (Patel et al., 2021)

Calibration of CDP parameter dilation angle ψ

Vermeer and De Borst (1984) proposed a relationship (Equation 2) for dilation angle (ψ) in terms of volumetric plastic strain rate ($\dot{\varepsilon}_v^p$) and axial plastic strain rate ($\dot{\varepsilon}_1^p$) based on experimental data.

$$\sin\psi = \frac{\dot{\varepsilon}_v^p}{-2\dot{\varepsilon}_1^p + \dot{\varepsilon}_v^p} \tag{2}$$

Using Equation 2, dilation angle is calculated in this study using the following approach:

- Select the default value of $\psi = 36°$ in the CDP model.
- Conduct the impact analysis for the FE model with $\psi = 36°$ and estimate the volumetric and axial plastic strain rates at the center of the impact zone. Calculate final ψ using Equation 2.

Failure criteria

The element failure criteria is essential for removing the concrete elements so that the missile can perforate through the concrete slab. Based on parametric studies performed by comparing the residual velocity of missile in this study, it is determined that a good estimation of inelastic failure strain in compression (ε_c^{in}) can be characterized by selecting the inelastic strain value corresponding to a stress of $0.01 f_c^{'}$ after the occurrence of peak on the stress vs inelastic strain plot, where $f_c^{'}$ is the maximum stress. It is also observed that the results are not sensitive to inelastic failure strain in tension (ε_t^{in}), therefore it can be taken as a constant value of 0.01.

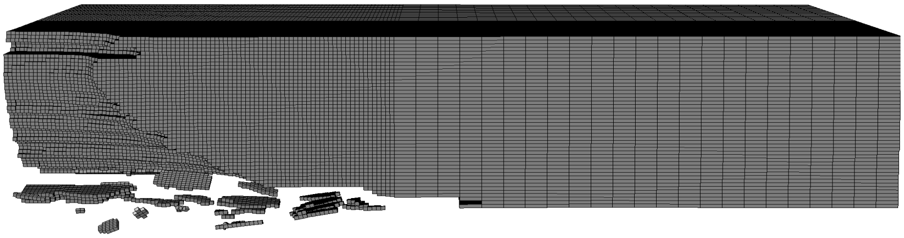
Results

A comparison of results between the three experiments and FE analysis is shown in Table 1. The primary results such as residual velocity of missile after perforation, number of broken rebars, and mass of ejected concrete from the calibrated FE model are close to the corresponding values from the experiments. Additionally, the FE model is able to replicate the damage pattern as shown in Figure 5.

Table 1: Comparison of experimental and finite element results

Test No.	Residual velocity after perforation	Broken rebars in horizontal and vertical directions	Mass of ejected concrete
IRIS P1	33.8 m/s	Front: 2H 2V, Back: 1H 1V	30–60 kg
IRIS P2	45.8 m/s	Front: 2H 2V, Back: 1H 2V	116 kg
IRIS P3	35.8 m/s	Front: 2H 2V, Back: 2H 1V	121 kg
Finite Element	38.86 m/s	Front: 2H 2V, Back: 2H 2V	92.68 kg

(a) Damaged slab from experiment

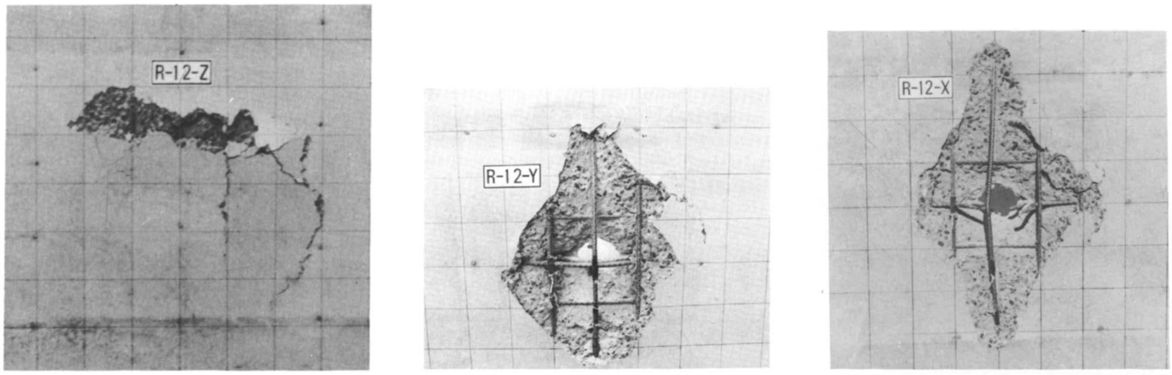


(b) Damaged slab from FE analysis

Figure 5. Comparison of damage pattern for quarter part of concrete slab after impact

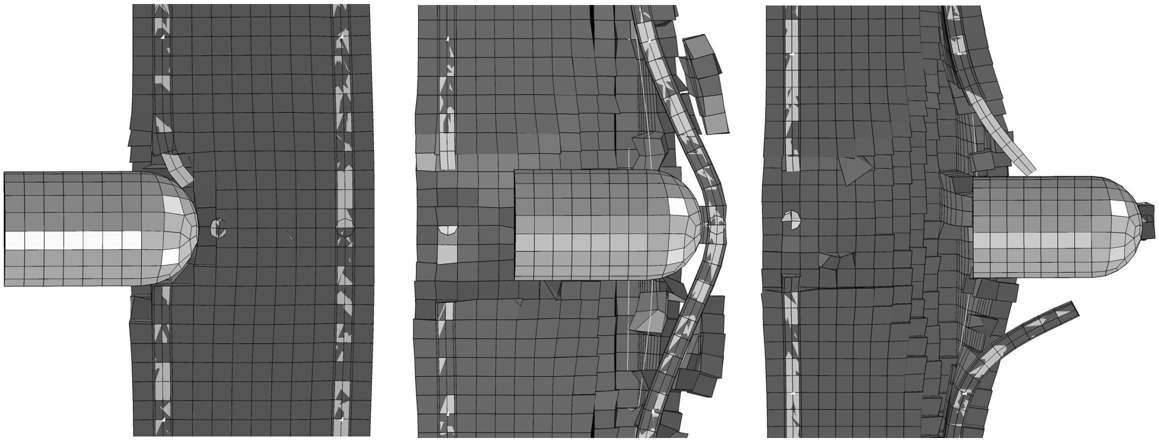
PREDICTIVE ANALYSIS

Kojima (1991) conducted a series of tests on impact behavior of RC slabs in 1987 and 1988. The dimension of the RC slab is 1200 mm × 1200 mm with a thickness of 120 mm. The bending reinforcement consists of 10 mm diameter steel bars in both the vertical and horizontal directions on the front and the back face with a cover of 15 mm. The concrete has a compressive strength of 27 MPa and tensile strength of 2.2 MPa. The rigid steel missile has a length of 100 mm and a diameter of 60 mm with a hemispherical tip. Kojima (1991) studied the impact behavior for varying missile impact velocities of 95 m/s, 164 m/s, and 215 m/s. For the three impact velocities, the RC slabs showed varying degrees of damage (Figure 6). Depending on the impact velocity, the results are given in terms of penetration depth and perforation. In this study, the above three tests are simulated using FE analysis (Figure 7), and the parameters for modeling are chosen using the proposed method.



(a) 95 m/s (b) 164 m/s (c) 215 m/s

Figure 6. Back face of Damaged slab after impact with different impact velocities (Kojima, 1991)



(a) 95 m/s (b) 164 m/s (c) 215 m/s

Figure 7. Cross-section of damaged slabs from FE simulations

The concrete slab and the reinforcement bars are meshed using 8-noded linear 3D brick elements (C3D8R) with an element size of 10 mm. The missile is modeled using a rigid shell element with an equivalent mass. The stress–strain curves for the compression and tension side are generated using closed form equations. The dilation angle ψ is taken as 54° based on the calibration from IRIS study. Based on a confinement pressure of 13 MPa and concrete compressive strength of 27 MPa, K_c is taken as 0.64 according to Figure 4. The element erosion is simulated using a failure criteria of $\varepsilon_t^{in} = 0.01, \varepsilon_c^{in} = 0.052$ (at 0.01% of $f_c^{'}$). The dynamic explicit analysis is performed for three different impact velocities, and the results of penetration depth and number of broken rebars are compared with the experiments.

Figure 7 shows the cross-section of the damaged slab during the impact. The penetration depth is evaluated by calculating the distance between the maximum depth of damaged concrete from the front face of the deformed concrete slab. For the impact velocity of 95 m/s, the analysis gives a penetration depth of 44.38 mm compared to 45 mm from experiments. For an impact velocity of 164 m/s, penetration of 100 mm inside concrete compares well with 100 mm recorded in the experimental results. For an impact velocity of 215 m/s, the simulation shows complete perforation of RC slab which is same as observed in the experiment. The comparison of penetration depth from the experiments and the FE model is given in Table 2, along with the number of broken rebars due to impact. The results from the calibrated FE model matches very well with the experiments.

Table 2: Comparison of experiment and FE model results

Missile Velocity	***Penetration depth***		***Number of broken rebars***	
	Experiment	FE Analysis	Experiment	FE Analysis
95 m/s	45 mm	44.38 mm	0	0
164 m/s	100 mm	100 mm	1	2
215 m/s	Full perforation	Full perforation	3	4

APPLICATION TO NUCLEAR POWER PLANT BUILDING

After establishing the additional validation, the calibrated models are used to conduct the analysis of a postulated falling steel beam on the reinforced concrete slab in Auxiliary Building of a nuclear power plant.

It is assumed that the heaviest steel beam from the building roof uplifts and falls vertically on the concrete floor from roof elevation due to a tornado. The worst-case scenario is considered here in order to simulate the worst possible outcome due to a tornado. FE analysis is carried out for various velocities of falling beam, including the free fall velocity, two and four times the free fall velocity.

The 216 mm thick reinforced concrete floor, the supporting steel beams, and the falling steel beam are modeled using 8-noded linear 3D brick elements (C3D8R). Falling and supporting steel beams along with the reinforcement are defined using bi-linear stress-strain curves. The stress-strain behavior in CDP model for tensile and compressive part of concrete is generated using closed-form equations. Other CDP parameters, such as dilation angle, K_c, and failure criteria are defined using the proposed methodology based on experimental validation. The dynamic explicit analysis is performed for various impact velocities of falling steel beam.

Damage in concrete at the impact zone is observed in terms of penetration depth, deformation of concrete slab, exit velocity of steel beam (if applicable), stresses in concrete, stresses in supporting beams and column. It is observed that the falling beam at the free fall velocity is not able to cause permanent damage to the concrete floor. However, at higher velocities the falling beam is able to generate major damage and even full perforation of concrete floor as shown in Table 3. Although, the observations at the supporting steel beams and columns show that the stresses at these support locations do not exceed the ultimate stresses. This shows that even with the full perforation of concrete floor due to falling steel beam, the building should remain intact.

Table 3: Damage prediction for nuclear power plant building

Impact Velocity	Concrete penetration depth	Condition of supporting beams	Condition of supporting columns
11.176 m/s (free fall)	No damage	No damage	No damage
22.352 m/s	123.19 mm	No damage	No damage
44.704 m/s	Full perforation	No damage	No damage

SUMMARY AND CONCLUSIONS

In this paper a new methodology to calibrate the FE model of RC slabs subjected to missile impact is proposed. The experimental observations made in IRIS study are used for calibrating the parameters in the CDP model and element failure criteria. The concrete properties are calibrated using tri-aixal test data from various studies available in published literature. Then, the calibrated parameters based on IRIS study are used to perform a prediction analysis for the impact tests conducted by Kojima. The key conclusions of this study are summarized as follows:

- Based on the sensitivity analysis and parametric study, the analysis results are found to be sensitive to mesh size, dilation angle ψ, CDP parameter K_c , and failure criteria.
- The comparison of tri-axial test results with FE analysis show that the CDP parameter K_c is dependent on the confinement pressure and the maximum strength of concrete.
- The dilation angle ψ calculated by using strain rates is found to be quite stable and can be used effectively in such an analysis.
- The calibrated FE models captured the impact behavior by not only predicting the residual exit velocities but also the penetration depth when there is no perforation.
- The proposed methodology is applied to Auxiliary Building of a nuclear power plant building to predict damage when impacted by a postulated event of a falling steel beam.

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