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PROBABILISTIC MODELS FOR REINFORCED CONCRETE SLABS SUBJECT TO MISSILE IMPACT BASED ON EXPERIMENTAL AND NUMERICAL OUTCOMES

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Abstract
Due to series of military invasions among countries, development of probabilistic models for predicting the effect of various local hard missile impact on reinforced concrete (RC) protective panels gained momentum. Parameters of the study include penetration depth, perforation limit, ballistic limit of missile, and residual velocity of missile. These probabilistic models are developed using the union of experimental tests (Berriaud's test in 1978) and finite element numerical results. The components are residential slabs, bunkers, containments, aircraft shelters, and storage tanks. Numerical modelling is sculpted in Hypermesh and post-processed in LS-DYNA. These models are grounded on Gardoni's probabilistic technique in association with the Bayesian approach. The established formulae account for all aleatoric and epistemic uncertainties involved in missile impact interaction with the target, geometrical configurations, material properties, and measurement errors. Also, these models account for strain rate & inertia effect, the multi-modal response of structure, and multiple transitions of failure modes, etc. The prediction from the developed equations has been validated with the experimental results, in order to verify the reliability and credibility of the estimated equations. Not alone missile impact but present study can accommodate wind-borne missiles,pressure pipes, iron rods, etc.
Keywords: reliability, Impact load, Concrete , response structure

1. Introduction

The majority of the prevailing structures are made of concrete due to their ease in construction, availability and cost-effectivity. Currently, research on structural safety due to high strain loadings like impact, blast, impact-induced blast and shock are well focused. It seems the possibility of missile impact occurrence on structures has increased during the past century. This can be in the form of natural or manmade hazards such as ballistic missiles plane crashes; fragments due to premeditated detonations and rock falls; etc.,The external wall of NCS is made up of reinforced concrete (RC), and the interior wall is made up of reinforced post-tensioned prestress concrete (PC) with a steel liner at the rear side. So far, three large scale nuclear accidents have occurred in history, which are: Three Mile Island (TMI) accident (March 28, 1979), the Chernobyl accident (April 25-26, 1986) and the Fukushima accident (March 11, 2011). reviewed these three disasters, which sheds light on the distinct reasons behind each. Due to the advancements in technology, it becomes easy for anti-social activities in operating high strain loadings such as Boeing aircraft's collision, conventional/nuclear missileimpact, near/far-field detonation, debris hit due to hurricanes, etc. Military and nuclear agencies are constantly working from the 17th century in the field of impact loadings because of tornadoes, rock falls, pipe break generated missiles like turbine blades, steel pipes and so on. However, most surviving engineering structures like residential buildings, bunkers, silos, nuclear containments are constructed with concrete material because of its robustness, cost- effectivity and availability (Li et al.,2005). Impact loading is categorized based on the rigidity of the impactor, i.e. hard and soft missile impact. If the impactor is deformable compared to the target structure is classified as soft or semi-hard missile impact. The classic example is the impact of aircraft fuselage (Sugano et al.,1993). The vice-versa scenario is classified as hard missile impact. For example, the engine of the plane, ejections of steel rods due to pressure leakage, heavy wooden logs as a result of hurricanes, cruise missiles, etc., (Distler et al.,2021). Next to blast loading, impact loading generates a higher strain rate which ranges from 10^{-4} to 10^{2} per second (Bischoff & Perry, 1991).

2. Literature Review

Experimental and numerical investigations on the impact resistance of SHCC- strengthened RC slabs subjected to drop weight loading, Elnagar et al., (2019). In this paper, a thin layer of Strain-Hardening Cementitious Composites (SHCC) is provided in either tension or compression side of RC slabs aiming to improve their impact resistance under the effect of drop weight loading. The main parameter of the current study is the condition of the contact surface between the substrate slab and the SHCC overlay that was prepared by grinding, grinding plus steel dowels or grinding plus epoxy adhesive. Experimental investigation and numerical analyses of reinforced concrete structures subjected to external missile impact

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Heckotter&Vepsa (2015), The test setup can also be used for testing of water filled missiles. In these cases, liquid spray front velocities as well as the droplet size distributions of flying droplets can be measured. Further, the range of liquid spray, spatial deposition of fluid and droplet size distributions of droplets fallen to the ground can be determined. The Technical Research Centre of Finland VTT has setup a test facility which is designed to study RC structures under impact loading. Global bending failure of RC slabs as well as local failure modes such as punching and perforation are considered.A reviewof producersfor theanalysis and designof concrete structuresto resistmissile impact effect Kennedy (1976), 'Hard' missile impact results in both local wall damage and in overall dynamic response of the target wall. Local damage consists of spalling of concrete from the front, (impacted) face and scabbing of concrete from the rear face of the target together with missile penetration into the target.

3. Finite Element Validation

In the current chapter, a detailed analysis of Reinforced Concrete (RC) member subject to missile impact is presented. The material model, structural configuration, the element type is presented. Two sets of independent validation are carried out to establish the accuracy of the Finite element method in order to simulate the complex phenomenon. Experimental capturing of the essential parameters such as penetration depth, displacement, ballistic limit, residual velocity, impact force, etc., desires an arrangement of sophisticated setup and equipment. However, FE simulations are flexible in capturing the anticipated parameter which is cost effective and lesser time duration. In this study, post processing of numerical analysis is carried out using commercial FE program LS-DYNA (Livermore, 2006 (a)). The realistic models of RC slabs subject to missile impact are generated using HyperMesh (Altair, 2003). Quantity of interests chosen for the validation in current study are penetration depth of hard missile, impact force of missile and damage pattern of the panel. Grounded on this FE technique numerous probabilistic studies associated with missile impact have generated adequate outcomes.

In this analysis two experiments are chosen based on the literature available for FE validation i.e. subjected to hard missile impact (Kojima 1991). With the technique of similar keywords as cited in are used for FE validation. Two hemispherical hard missile experimented with velocity of 164 m/s & 95 m/s, certain missile mass of 2 kg is impacted on RC panel of 1.2m X 1.2m X 0.12m. The strength of concrete is 27MPa with a reinforcement ratio of 0.6%. The

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acquired outcomes were compared with investigations shows the trustworthiness of FE validation as detailed in (Gangolu et al.,2022). The penetration of missile for the velocity of 164 m/s is 108 mm experimentally which is similar as validation i.e. 100 mm Likewise, the obtained penetration for 95 m/s is 44 mm experimentally which is identical to validation of 45 mm. The mesh size is converged to 7.5 mm after series of trails. An alike analysis was evaluated by (Ranjan et al.,2014), and determined FE models recommend sensible end result. The mean line data from Figure suggests that FE fallouts are more accurate than empirical for two experiments. In excess to this, the damage pattern of RC slab at 164 m/s missile velocity is compared with experimental damage which shows the identical pattern.However, a significant match with impact force for either cases i.e. 144.47kN (test) & 145kN (FE) for 95m/s and 117.57kN (test) & 112kN (FE) for 164m/s. Based on these matches with experiments, the reliability of FE models can be trusted. As discussed previously, the current analysis is based on FE simulations developed in (Gangolu et al.,2022) and experimental studies conducted by (Berriaud et al.,1978). The experimental design of both numerical and experimental studies is discussed in following section.

3.1 Winfrith Concrete

Winfrith Concrete constitutive model with material ID 84 is best suited in solving impact loads towards RC structures. This model was implemented into LS-DYNA in 1991 but has developed in the 1980s (Wu et al., 2012), (CEB-FIP MODEL CODE 1990, 1993). Smeared reinforcement can directly be included in this model, which is not offered by other concrete models. The number of inputs is more than CSCM concrete, but this model is a basic plasticity model with Mohr coulomb behavior with third stress invariant to treat triaxial extension in compression and tension and strain-softening behavior in tension to make material regular via fracture energy, crack width, and aggregate size. Strain rate has ensured by the advantage of Mat_Add_Erosion (000). ('Ceb-Fip Model Code 1990', 1993) The code is used to give inputs for this model. Damage of both compression and tension has considered in two different variables. The study of Wu et al., 2012 concluded that this model is best suitable for high strain impact loadings. Auto-generation capability is limited. Next section focuses on existing nuclear containment structures and predicts threats on those structures which are mainly made-up of concrete material.

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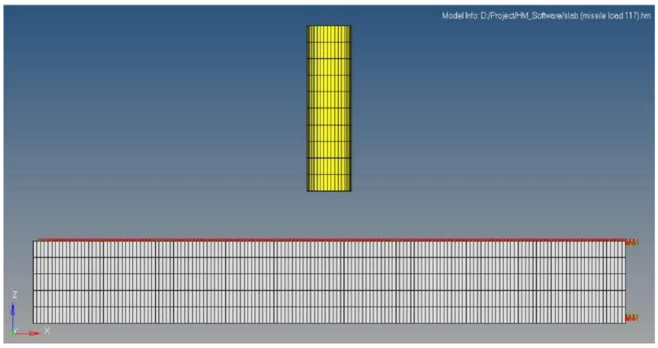

Figure 1 : Slab subjected to missile load (Hypermesh)

Solid model with three-dimensional squared panel is configured subjected to missile impact. Constant stress solid element which is default element form is used to model concrete panel and missile. A one-dimensional steel reinforcement with a formulation of default element form i.e. Hughes-Liu with cross section integration is used to model. This model exhibits both bending and axial stiffness while impacting. A well-used lagrangian coupling method is used to fix the contact between concrete and rebars which is challenging task especially in complex configurations like containments and composite structures. Hourglass energy is ensured with Flanagan-Belytschko stiffness form and the mesh refinement is ensured. A keyword ‘Velocity Generation’ is used to instigate missile with initial velocity. The contact between missile & concrete is assured by eroding surface to surface and eroding nodes to surface for missile &rebars. Missile is always considered as master in either contacts. All the squared slabs are constrained in all degrees of freedom. The Keywords used for FE analysis is abstracted in and similar technique is used for rest of the FE simulations. In advance of developing probabilistic models, a FE model assurance with test results is essential and addressed below.

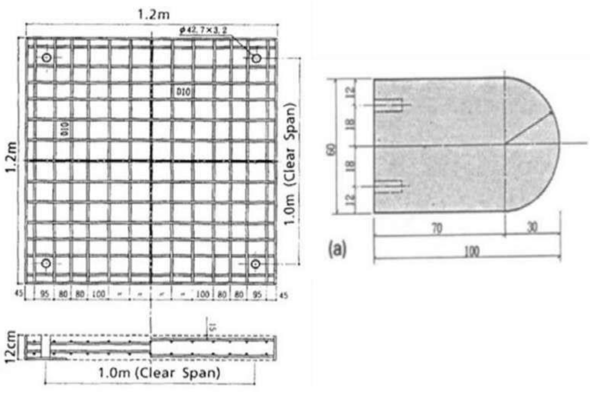

Figure 2 : Layout of RC slab and missile

In this analysis two experiments are chosen based on the literature available for FE validation i.e. subjected to hard missile impact (Kojima 1991). With the technique of similar keywords as cited in are used for FE validation. Two hemispherical hard missile experimented with velocity of 164 m/s & 95 m/s, certain missile mass of 2 kg is impacted on RC panel of 1.2m X 1.2m X 0.12m. The strength of concrete is 27MPa with a reinforcement ratio of 0.6%.

3.2 Hyper Mesh:

Hyper Mesh is a CAE software which comes in after a model has been developed in any CAD software. One should know it is an integral part of PLM (Product life cycle management) where the focus is to prepare the model to see how should it behave in a real-life environment or simulation in other words. Now CAE software's are three types mainly pre-processing, solving, postprocessing. Hyper mesh is a pre-processing software where you divide the model into no. Of elements and nodes for a solver to apply the mathematical functions on it. If you read FEM OR FEA you would know the underlying theory behind the practice. Pre-processing is generally used to 'mesh' the model. See the image below an example of a gear being meshed. The green coloured elements are the region where contact has been defined which means it is in contact with other components for a solver to know about the simulation. HyperMesh is a solver neutral environment with the broadest set of direct interfaces to commercial CAD and CAE systems and a rich suite of easy-to-use tools to build and edit CAE models. The advanced geometry and meshing capabilities provide an environment for rapid model generation. The ability to generate high quality mesh quickly is one of HyperMesh's core competencies. With automatic and semi-automatic shell, tetra, and hexa meshing capabilities, HyperMesh simplifies the modeling process of complex geometries. HyperMesh has advanced model assembly tools capable of supporting complex sub-system generation and assembly, in addition, modelling of laminate composites is supported by advanced creation, editing and visualization tools. Design change is made possible via mesh morphing and geometry dimensioning. A flexible set of morphing tools allows users to modify mesh without re-meshing to automate the investigation new design proposals.

4. Experimental Design:

To achieve reliable models good representative data that covers entire range of variables is needed. Minimization of statistical uncertainty is possible with adequate data (Gardoni et al.,2002). So, a substantial number of actual experiments are required to create the probabilistic information. Due to limited experimental data available in the literature, the current study combines the results obtained from experiments (Berriaud et al.,1978) and FE analysis (Gangolu et al.,2022). Thus in this regard the uncertainty can be reduced in framing the flawless formulations. A series of field tests were conducted by (Berriaud et al.,1978) in 1976 with various ranges of compressive strength, panel thickness and configuration; missile dia, mass and velocity. The obtained parameters after seventy-nine examinations are penetration depth, ballistic limit and residual velocity of missile, of which fifty-five are chosen for current analysis. In addition to this investigations, seventy-three FE models are added from (Gangolu et al.,2022), to attain efficient design guidelines.

4.1Selection of Range of Variables

Based on the existing literature and real case scenarios, current study considered the depth and compressive strength of RC slab from normal building to hefty structures such as bunkers, aircraft shelters, nuclear containments, etc. The range of variables chosen in this research are stated in respectively. Selected ranges of geometrical and material properties of RC panels are chosen from (Balamenos and Pandey 2017), grade of reinforcement and ratio (Choi et al.,2017), mass and velocity of missile (Wen and Xian, 2015). This adopted values are not only considering the prevailing one’s but also forthcoming panels. The impact of concern categories like wind borne missiles, cruise missiles, pressure released pipes are covered in this study. Grounded on the realistic variables as shown in the range of derived variables like reinforcement spacing, diameter of rebars are developed This analysis is chosen a total of 128 various combinations of experiments and FE simulations subject to diverse missile loading. And, missile is impacted in the centre of the panel. For FE analysis, the cases are selected based on the scheme as discussed below. D-optimal point selection scheme is used to choice the best set of combinations as per design guidelines (Myers and Montgomery, 1995). Any number of design cases can be chosen using this scheme with irregular boundary condition. This scheme is also suggested for polynomial response surfaces (Livermore, 2006 (b)). In generating database, lower boundary value and upper boundary value is essential for each parameter. These inputs are placed in scheme generated software i.e. LS-OPT (Livermore, 2006(b)). In the same way, seventy-three set of cases are chosen of thosecombinations and analysed the parameters for FE analysis alone. Finally, the aim of current study i.e. development of probabilistic models which can be established subsequently from this process.

5. Probabilistic Models of Local Damage Effects of Hard MissileImpact

The existing formulae of local damage effects of hard missile are deterministic models based on experimental data and simplified rules of mechanics. Subsequently the inherent uncertainties are not accounted in the deterministic model and produces biased estimation. Even though current practice of structural engineering is establishing safe design, for the sake of immaculate provisions the design must be unbiased and account explicitly for the prevailing uncertainties. The current study is presented on Bayesian basis for the evaluation of multivariate probabilistic models for structural members that appropriately account for all the predominant uncertainties (Gardoni et al.,2002). Such as measurement errors, statistical uncertainty and also modelling inaccuracies from an incorrect model. Instead of modifying existing models, this research developed novel probabilistic models due to significant mismatch of test results with empirical studies for penetration depth, perforation limit, ballistic and residual velocity of missile. The present study considers the general approach as reported in (Gardoni et al.,2002) in developing fresh formulations. This methodology is capable of capturing and understanding all the underlying phenomena of physics which results in enhanced model.

As suggested in (Gardoni et al.,2002), the probabilistic models were constructed by adding essential correction terms to deterministic models. Precise probabilistic models were delivered by numerous studies using same approach. However, due to the novelistic approachof current analysis is not evaluated based on deterministic models. The FE simulations are conferred with no error and uncertainty, but experimental studies might. To reduce theintrinsic error, the input data is increased with the combination of FE study (Gangolu et al.,2022) as well as experimental approach (Berriaud et al.,1978). A significant amount of data plays very crucial role to accurately implement the risk-based design concept (Haldar and Mahadevan, 2000). The general approach proposed by (Gardoni et al.,2002) for probabilistic models is formulated as,

where P_i = Probabilistic performance level of a panel for various parameters such as penetration depth, perforation limit of the concrete, ballistic limit and residual velocity of missile and; p_i = Determistic performance level of a panel for same parameters but it turns to nil due to development of novel formulations; $\gamma P(x, \theta P_i)$ = correction term for bias inherent in the model defined as,A non-informative prior has been selected (Box and Tiao, 1992). For a parsimonious model, current analysis adopted stepwise deletion process. In making easily comprehensible probabilistic models limited explanatory terms with higher accuracy is chosen. With one-by- one omission of functions the standard deviation (σ) and precision of plots are plaid fairly. Similarly, largest coefficient of variation (COV) is identified and deleted, again the reduced model COV is monitored persistently until the development of authentic model. The strongest correlated explanatory terms are selected for the ultimate probabilistic model. The obtained standard deviationfor each explanatory function takes care of complete inherent uncertainties in the model, which benefits a designer to evaluate exactly.

5.1 Parameter Estimation

By means of the acquired results from FE simulations (Gangolu et al.,2022) following the experimental design and experimental test results (Berriaud et al.,1978), current section predicts probabilistic models for penetration depth (x), perforation limit (h_p), ballistic limit of missile (V_{bl}) and residual velocity of missile (V_r). These parameters are developed for RC panels subjected to hard missile impact targeted at centre. Probabilistic Model for Penetration Depth

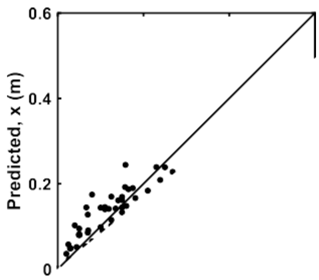

Figure 14 : Penetration depth

The proposed formulation to evaluate the probabilistic model of penetration depth (x) for an RC panel subjected to hard missile impact is, The influential functions are J_4, J_6, J_7 and the points are near to mean line Figure 13. Theattained COV of the probabilistic model is 0.35.

5.1.1Probabilistic Model for Perforation Limit:

The evaluated probabilistic equation for estimating perforation limit of concrete target i.e., minimum required thickness of panel to avoid complete penetration after missile impact upon RC panel is, Where, The COV of probabilistic model is 0.26 and the points are near to mean line

A factor of safety is considered with an excess thickness of 75 mm for estimating this formulation. In case of double wall containment structures and protective structures this model is helpful in arresting missile on the surface. However, designer could frame guidelines based on penetration depth or place a steel liner to avoid complete passage. This solution could be useful for economical codal provisions for construction purposes.

5.1.2Probabilistic Model for Ballistic Limit of Missile

In designing containment or protective structures subject to missile impact, it is mandatory to ensure minimal velocity required to avoid complete penetration of missile to rear side of target. Contemporary research is very less focused on formulation for a ballistic limit of missile. Current analysis developed a reliable and economic probabilistic equation to estimate ballistic limit of missile with an RC panel is,

The influential functions for this model are J_2, J_4, J_6, J_7 and the obtained COV of the probabilistic model is 0.29. The obtained points are nearby as shown in Figure

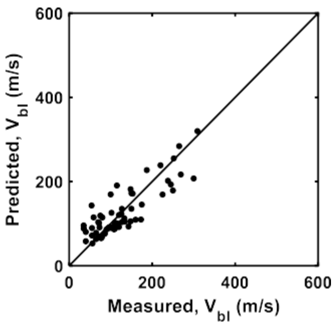

Figure 16 : Ballistic Limit of Missile

The influential functions for this model are J_2, J_4, J_6, J_7 and the obtained COV of the probabilistic model is 0.26. The obtained points are near to mean line as seen in Figure 16. Since the influence of panels depth is significant the current study modified J_2 function with depth parameter.

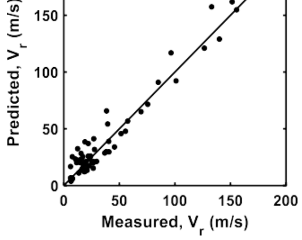

Figure 17 : Residual Velocity of Missile

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where, x – penetration depth of missile into concrete target, d – diameter of the missile (m), M – Mass of the missile (kg), V_0 – Velocity of the missile (m/s), f'_c – Compressive strength of concrete (N/m^2), A_s – Area of Steel, b – width of the panel, H – depth of the panel, M_c – Moment carrying capacity of the target, h_p – perforation limit of the concrete target (m), V_{bl}– Ballistic limit of the missile (m/s), V_r= Residual Velocity of Missile.

6. Comparative Study of Proposed Formulae

The current study has compared the proposed formulae with existing experimental results. The chosen material and geometrical properties of RC slab are shown. From this study it is very evident that the obtained probabilistic models are similar to test results.

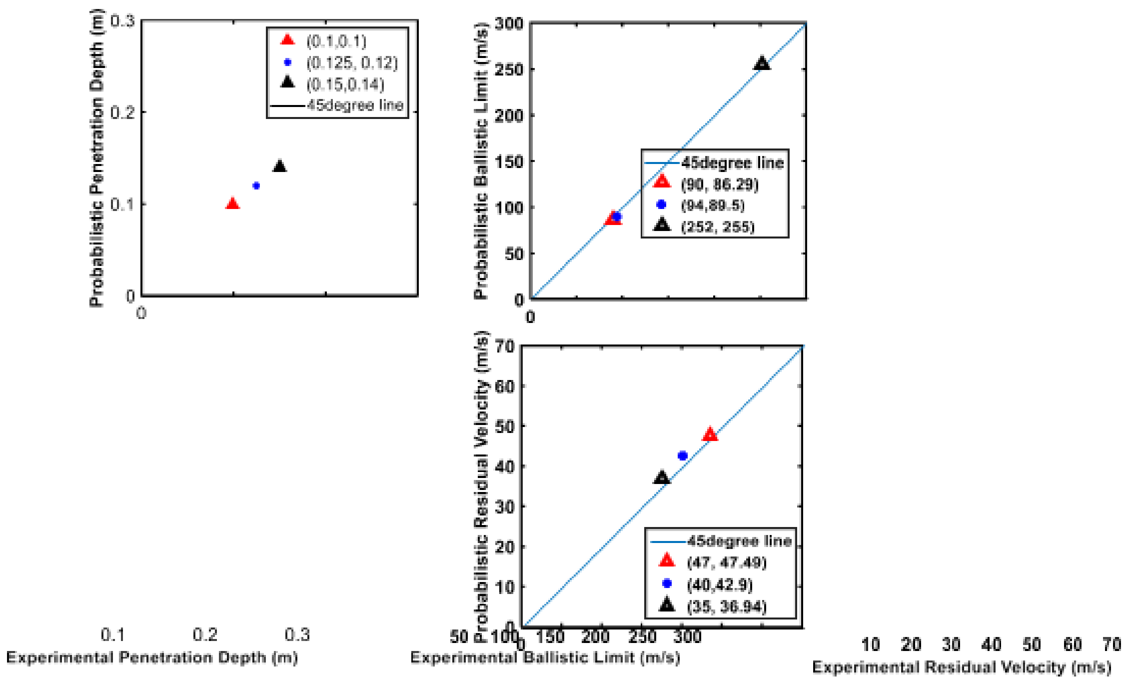

Figure 18 : Comparative Study with Test results (a) Penetration Depth (b) BallisticLimit of Missile (c) Residual Velocity of Missile

7. Conclusion:

The current study deals with four novel probabilistic models developed for local hard missile impact effects. The parameters of the study include penetration depth of missile, perforation limit of the target, ballistic limit of the missile and residual velocity of the missile. These formulations are developed with 128 models by the union of experimental results and finite element (FE) analysis results. Before estimating formulations, a proper numerical validation is obtained, and similar keywords are used for post-processing (LS-DYNA). The obtained probabilistic equations are based on Gardoni's probabilistic technique along with Bayesian inference. From the formulations the influence of missile kinetic energy, internal energy of panel, reinforcement ratio, slenderness ratio of panel and moment carrying capacity has been realised. A comparative study has been performed with test results, which shows a great match. These probabilistic models consider various relevant uncertainties like material modelling, dimensional errors, statistical uncertainty, strain rate effect, boundary condition, and other aleatoric and epistemic uncertainties. COV for these models are in the acceptable range, showing the trustworthiness of developed models. This process can be extended to blast loadings, various nose shapes impact and so on.The present work can be extended to estimate the capacity and demand of other structural members like steel decks, columns and beams. Some impact scenarios like ship collisions, vehicle falling on slabs due to tornadoes and also like missile impact with ogive, point, hemispherical nose shapes. This achieved work can be utilized for wind-borne missileshitting to containment structures.

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