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Local impact effects on concrete target due to missile: An empirical and numerical approach

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A B S T R A C T

Concrete containment walls and internal concrete barrier walls of a Nuclear Power Plant safety related structures are often required to be designed for externally and internally generated missiles. Potential missiles include external extreme wind generated missiles, aircraft crash and internal accident generated missiles such as impact due to turbine blade failure and steel pipe missiles resulting from pipe break. The objective of the present paper is to compare local missile impact effects on reinforced concrete target using available empirical formulations with those obtained using LS-DYNA numerical simulation. The use of numerical simulations for capturing the transient structural response has become increasingly used for structural design against impact loads. They overcome the limits of applicability of the empirical formulae and also provide information on stress and deformation fields, which may be used to improve the resistance of the concrete. Finite element (FE) analyses of an experimental impact problem reported by Kojima (1991) are carried out that are able to capture the missile impact effects; in terms of local and global damage. The continuous surface cap model has been used for modelling concrete behaviour. A range of missile velocity has been considered to simulate local missile impact phenomenon and modes of failure and to capture the concrete response from elastic to plastic fracture. A comparison is then made between the empirical formulations, numerical simulation results, and available experimental results of slab impact tests. While the numerical simulation is able to capture the experimental trend and results, a comparison of penetration depth and scabbing and perforation limits as per different empirical formulation shows substantial divergence.

1. Introduction

Concrete has been widely used over many years by structural engineers in the design and construction of protective structures to resist impact loads. Impact loads are of sub-second duration and of magnitude many times higher than any other loads that act during the design life of the structure. Concrete containment walls and internal concrete barrier walls of a Nuclear Power Plant safety related structures must be analyzed to ensure requisite margin for missile impact. Potential missiles include external extreme wind generated missiles, aircraft crash, and internal accident generated missiles (turbine blade, and steel pipe missiles resulting from pipe break). Impacting missiles can be classified as either 'hard' or 'soft' depending upon whether the missile deformability is small or large relative to the target deformability.

The three important methods of studying local effects on a concrete target arising from missile impact are experimental, analytical and numerical simulation. Empirical formulae based on experimental data are especially important in this field due to the complexity of the phenomena. These empirical formulations are defined in terms of impact parameters such as mass, velocity and shape of missile, its rigidity, relative stiffness, and mass ratio of missile and target, mechanical properties of the target, reinforcement amount, size and area of impact. Simple analytical models are available which offers more efficient and economic way of predicting the local missile impact effects and help to continue the experimentally based empirical formulae and often extend the range of parameters for which it could be valid. However, with the developments of computational tools, computational mechanics and material constitutive models, the numerical simulation of missile impact effects have become more exact and reliable. In addition, with exhaustive

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numerical data generated through computation, carefully controlled limited number of experiments can be performed.

Islam et al. (2011) conducted numerical simulation of high velocity ogive-shaped projectile penetration of concrete target and emphasized the importance of element erosion in the lagrangian based FE method. Jose et al. (2010) has indicated the importance of effect of reinforcement and erosion criteria for better representation of local missile impact effect on concrete slab. Sangi and May (2009) has reported numerical simulation of an experimental drop tower test using two different mesh sizes and two different concrete model and was able to capture the kinematic response under low velocity impact. Tahmasebina (2008) carried out numerical simulation of slab impact test and has found divergence in terms of mesh convergence and failure modes. Murray et al. (2007) carried out drop tower impact test on plain, under-reinforced and over-reinforced concrete beams and has shown good agreement in terms of deflection time histories and damage mode under low strain-rate loading. Cotovos et al. (2008) studied the localized impact loading on reinforced beams under high strain-rate loading such as blast and ballistic loads. Liu et al. (2011) have studied the oblique penetration of missile into RCC slab using a dynamic constitutive model based on composite damage formulations for tension and compression failure and showed good agreement with experimental data. Suanno et al. (2003) carried out impact analysis of reactor containment for impact load and has discussed the importance of constitutive modelling of impact related parameters to avoid error in numerical simulation.

This paper presents an overview on the empirical formulation of studying the local missile impact effect and computation of penetration depth, scabbing and perforation limits for a typical Reinforced Cement Concrete (RCC) slab panel to assess the local impact resistance. The paper attempts to quantify the factor of safety that is in-built in these formulations as most of them are conservative in nature. Seldom structural adequacy check requires exact determination of local missile impact effects as the margins available are less and it becomes pertinent to quantify the exact structural response for qualification against such loads.

A benchmark problem has been used to determine the applicability of these empirical formulations in predicting local missile impact effects. A numerical simulation using finite element (FE) code LS-DYNA has been carried out to capture the different modes of failure and capture and concrete response from elastic to plastic failure that will occur for low velocity impact to high velocity impact. The continuous surface cap model has been used for modelling concrete behaviour. This model includes isotropic constitutive equations for three stress-invariant shear surfaces with translation for prepeak hardening, a hardening cap that expands and contracts, damage-based softening with erosion and rate effects for high strain rate applications. The reinforcement bars have been modelled as truss element using plastic kinematic material model using strain rate effect of Symonds–Cowper model.

Numerical simulation for studying impact problem on concrete suffers from mesh sensitivity. The present paper addresses this issue while simulating impact problem within the framework of continuum damage modelling and highlights its effect on the structural response. Mesh sensitivity study has been carried out using three different mesh sizes to arrive at a FE model that is able to predict the concrete response using the concrete material model. Segment based penalty formulation has been used to model the contact interface between missile and concrete. Nodes to surface contact algorithm has been used to model contact between missile and rebar, if any, which will occur for high velocity impact. A range of missile velocity has been considered to simulate local missile impact phenomenon and modes of failure and to capture the concrete response from elastic to plastic fracture. A comparison is then made between the empirical formulations, numerical simulation results and available experimental results of slab impact tests reported by Kojima (1991).

2. Local missile impact effects

The impact load effects can be broadly classified into two categories: *local* and *global*. The local effects relate to the local structural response in terms of spalling, scabbing, perforation, and penetration. The global effect includes the structural response in terms of global displacement, concrete cracking, yielding of steel and stresses in concrete and steel members for identifying critical zones.

Displacement of missile into the target with possible formation of inlet funnel (facing spalling) without passing through it is called penetration. Spalling is the ejection of target material from the proximal/front face of the target by reflection of tensile waves from structure behind surface. Scabbing is the ejection of structural material from the distal or back face of the target due to impact on the proximal side. Perforation is defined as the complete passage of the missile through the target with or without a residual velocity.

The impacting missile can be classified as 'hard' or 'soft' depending upon the relative deformability of the missile and the target. If the deformability of the missile is negligible compared to the target, the missile can be considered as hard. However, if the missile deformability is moderate or high compared to the target, the missile can be considered to be soft. This paper basically concerns with the hard missile.

3. Empirical formulations

The problem of missile impacting a concrete target is an extremely complicated phenomenon and hence empirical formulas are especially important in this field. The empirical formulations for predicting local missile impact effects for hard missiles are based on the regression analysis of experimental test results conducted by striking projectiles/missiles on reinforced concrete target slabs. Large numbers of impact experiments involving reinforced concrete slabs are reported in literature (Kennedy, 1976; Sliter, 1980; Li et al., 2005). Various methods such as free fall, air guns, cannons and actuators have been used to obtain high velocity impact. Some of the empirical formulations also possess a partial theoretical basis.

Each of the empirical formulations have their range of application in terms of mass, velocity and shape and size of the missile owing limitations due to experimental setup and are based on the assumption of rigid mass impacting a flexible target. Most of these formulations are unit-dependent which poses difficulty while comparing different experimental results. The missile nose shape factors used in many of the formulae are ambiguous (Li et al., 2003) and thus introduce uncertainty in the determination of the local missile impact effects.

The empirical formulae mentioned in this paper have been collected on the basis of publications and review works of Kennedy (1976), Bangash (1993) and Li et al. (2005). The penetration depth (x), perforation limit (e) and scabbing limit (h_s) for some of the formulations in FPS (mass in lb, strength and elasticity in psi, length in inch, velocity in ft/s) and SI (mass in kg, strength and elasticity in Pa, length in meter, velocity in m/s) units are re-produced.

3.1. Petry formula (1910)

The Petry penetration formula (Bangash, 1993; Li et al., 2005; Amirikian, 1950) is the oldest penetration formula and was one of the most common formulas in the United States (US) for predicting the penetration depth for infinitely thick concrete target. The formula was derived from the solution of equation of motion in which the instantaneous resisting force is expressed by a constant