

Prediction of impact induced failure modes in reinforced concrete slabs through nonlinear transient dynamic finite element simulation



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ARTICLE INFO

Article history:

Received 7 November 2012

Received in revised form 11 January 2013

Accepted 16 January 2013

Available online 16 February 2013

Keywords:

Impact

Flexural and punching shear

Fracture energy

Concrete damaged plasticity

ABSTRACT

A systematic numerical and analytical approach, to predict the various global failure modes such as flexural, punching shear and mixed flexure-shear failures along with the local failure modes such as crushing, cracking, spalling and scabbing, under impact load is investigated in this study. Numerical simulation on reinforced concrete (RC) slab impacted with cylindrical drop hammer has been carried out using ABAQUS finite element code to obtain the failure modes. Also a comparison has been made to validate the results of numerical simulation with the Zineddin and Krauthammer experimental results. The simulation results are in excellent agreement with the experimental failure modes reported by Zineddin and Krauthammer.

The behavior of RC slab under impact load is simulated with the conventional limiting strain criteria as well as fracture energy softening models within the framework of damage plasticity model. It is found that the limiting strain criterion suffers from the limitation of mesh sensitivity and results from the fracture energy approach are close to the actual experimental results. Therefore the fracture energy softening models have been recommended as robust method for these types of studies.

Besides the complexities due to concrete heterogeneity, the inelastic concrete and rebar behavior, strain rate effect and mesh sensitivity issues are addressed in the present paper to evolve a robust nonlinear transient dynamic finite element simulation. It is illustrated that the global and local failure modes can be numerically predicted through identifiable and measurable parameters such as the point of inflection, bi-axial failure criteria, strain based failure criteria, shear failure criteria, rebar strain and tensile damage profiles.

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1. Introduction

The safety of critical structures such as Nuclear Power Plant (NPP), fuel storage facilities and important facilities under impact load is of prime concern. Impact loading is an extremely severe loading condition characterized by the application of a force of great intensity within a short duration. Impact on a reinforced concrete (RC) structure like aircraft crash, missile hit and free fall of a heavy machine part leads to different types of global and local damage such as flexure, penetration, scabbing, spalling, crushing, cracking, mixed mode and punching shear failure (Zineddin and Krauthammer, 2007). The evaluation of each of the above phenomena is highly complex from the point of view of experiments as well as numerical simulations. The impact load application due to internal/external accident condition on nuclear structures is one of the main safety concerns for NPP. It is, therefore, an important issue to invoke the computational systematic approach for

identification of the impact induced failure modes since experimental approach is not cost-effective practicable solution.

Hanchak et al. (1992) conducted experiments on 140 MPa and 48 MPa RC slabs impacted normally by ogive nosed steel projectiles. The impact velocity of projectile was varied and the residual velocity of projectile for 140 MPa plate was found to be 20% lower than that for 48 MPa plate. Teng et al. (2004) and Polanco-Loria et al. (2008) simulated experiment (Hanchak et al., 1992) using DYNA-2D code and LS-DYNA finite element code respectively and ballistic limit predicted was found to be closer to the measured value obtained in experiment (Hanchak et al., 1992). Zhang et al. (2005) studied experimentally the ballistic resistance of 45–235 MPa concrete targets subjected to impact by ogive nosed projectile by varying the impact velocities. It was found that on increasing the compressive strength of concrete, the crater diameter and penetration depth reduces. Beppu et al. (2008) carried experimental study on concrete plates impacted normally by rigid mushroom shaped projectile to visualize the failure process of crater and spalling by a high speed video camera and reproduced the experimental results using AUTODYN code for numerical simulation. The similar types of studies were carried by Agardh and Laine (1999), Zhoua et al. (2008), etc.

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These experimental and numerical studies carried out in the past reveal the considerable attention received for impact problems on RC structure and focused mainly on the influence of grade of concrete, impact velocity and residual velocity of projectile. However the analytical procedure to predict the different type of failure modes is not readily available in the literature which is being investigated in the present study. The impact behavior of concrete is quite complex due to heterogeneity of material which results in various global failure modes such as flexural, punching shear and mixed flexure-shear failures along with the local failure modes such as crushing, cracking, spalling and scabbing. To accurately analyze the structural failure modes due to transient dynamic loads, it thus becomes necessary to develop a three-dimensional finite element model, which takes into account different types of material and geometrical nonlinearities.

Among the various inelastic models for RC structure, the conventional limiting strain criteria and the fracture energy softening models are used in the present numerical simulation. The mesh dependent results are obtained from the conventional limiting strain criteria whereas the fracture energy softening model gives the mesh independent results which is in-line with the study produced by Bazant and Planas (1998) and Singh et al. (2009). The present simulation focuses to identify the failure modes of RC slab subjected to impact load using ABAQUS (2008). A systematic three dimensional finite element inelastic analysis procedure for transient dynamic behavior of RC slab is presented and a definite criterion is evolved for identifying the global and local failure modes as observed in the reported experiments of Zineddin and Krauthammer (2007). The comparison of numerical results of limiting strain based approach and fracture energy is carried out with the experimental results and the adequacy of fracture energy approach is validated by comparison with the reported experimental results.

2. Impact simulation of RC slabs

In Zineddin and Krauthammer (2007) experiment on the RC slabs of $3.496 \text{ m} \times 1.672 \text{ m}$ span and 90 mm thickness were impacted by a cylindrical drop hammer of 2608 kg weight and 250 mm diameter. The hammer was dropped with three predetermined heights of 152 mm (case A), 305 (case B) mm and 610 mm (case C) respectively at the center of the slab. The reinforcing bars of 10 mm diameter were placed along both the spans at a spacing of 152 mm. The location of the reinforcement mesh in the slab was varied. Three slabs have reinforcement arrangement with two steel-meshes placed at a cover distance of 25 mm from both the faces and the rest three have single steel-mesh at the slab center with cover of 45 mm from both the faces and they are designated as A-2mesh, B-2mesh, C-2mesh, A-1mesh, B-1mesh, and C-1mesh respectively in the present numerical study for convenience. The experimental peak loads in cases A, B and C in the slab at the center are shown in Table 1. The displacement values and the failure modes such as punching shear failure, flexure failure and the mixed failure modes were reported in the experimental result by Zineddin and Krauthammer (2007) for the above cases.

Impact loading in present simulation is modeled as a time dependent pressure loading over the diameter of 250 mm at the center of slab for the peak loads of two steel-meshes and single steel-mesh in the slab. Since the present study does not aim in early contact development between the cylindrical drop hammer and RC slab during impact hence the contact modeling is not carried out. The failure modes in RC slab will be observed when the contact between the cylindrical drop hammer and RC slab is fully developed which is incorporated by applying the pressure loading over impact area. The pressure loadings for the above mentioned cases are given in Table 1 which is obtained by distributing the

Table 1

Impact induced peak pressure loads for different slab tests.

Cases	A- 1mesh	B- 1mesh	C- 1mesh	A- 2mesh	B- 2mesh	C- 2mesh
Experimental peak load, kN (Zineddin and Krauthammer, 2007)	228	212.6	553	304	374	539
Calculated pressure load, N/m^2	5.66e6	7.63e6	11.06e6	6.2e6	7.63e6	10.78e6

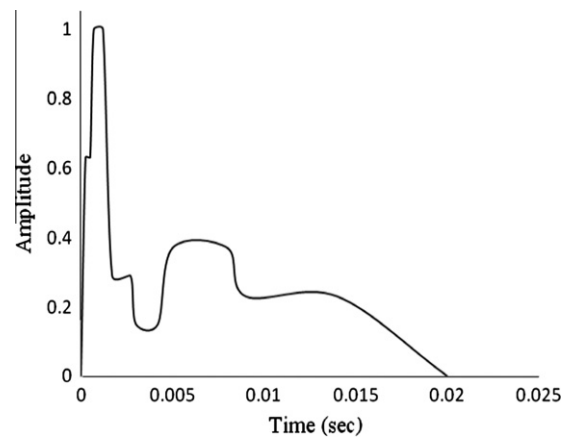


Fig. 1. Time-amplitude response for C-2mesh.

peak load over the area of the impacted diameter. The load time history available in the study of Zineddin and Krauthammer (2007) is simplified by enveloping the experimental time-amplitude curve in the present numerical study. The typical amplitude-time curve for one of the case C-2mesh is shown in Fig. 1, where the Y axis presents the amplitude which is the ratio of load acting at particular instant of time to the peak load and X axis represents the time.

3. Constitutive model

3.1. Introduction to concrete damage plasticity

Continuum damage-plasticity model (ABAQUS, 2008; Tao and Phillips, 2004) as shown in Fig. 2 for concrete is based on the mechanism of tensile cracking and compressive crushing. The evolution of the yield/failure surface is governed by the tensile and compressive equivalent plastic strains respectively. The constitutive behavior of concrete is described by introducing a scalar variable d which is designated as d_t and d_c for concrete in tension and compression respectively. In continuum damage-plasticity model, the degradation of the elastic modulus induced by plastic straining both in tension and compression of concrete is given in terms of a scalar degradation variable d as:

$$E = (1 - d) \times E_0$$

The uniaxial compression response is linear up-to the value of initial yield σ_{c0} . In the plastic regime the response is characterized by stress hardening followed by strain softening beyond the ultimate stress σ_{cu} as shown in Fig. 3a. The stress-strain response under the uniaxial tension follows a linear elastic relationship until the value of the failure stress σ_{t0} . Beyond the failure stress the

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