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Impact Analysis of Concrete Structure using Rate Dependent Damage Model

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Abstract

The concrete subjected to dynamic loading shows increased strength compared to the static strength. The common way of using the dynamic increase factors depending on the assumed value of the strain rate is not an appropriate method of numerical analysis. Thus, there is a need to understand the dynamic increase in strength of the concrete using the physical mechanisms. The material effects like viscosity and the reduced micro-cracking evolution are observed in the concrete caused by an increased rate of loading. The increased strength is mainly caused by the greater resistance of water in the capillary system of concrete. The increase in strength should be limited by giving the maximum value of strength for the material under dynamic loading. It is not possible for the material to increase in strength indefinably. The yield surface is defined considering the effect of lode angle. The yield surface increases its size with the increase in the strain rate of the material. Thus, the improved plasticity-based damage material model considering the pressure and the rate dependency is proposed. The validation of the model is done with the experimental impact results available in the literature. It is observed that the proposed model is capable of predicting the material and mechanical behavior of the material accurately. The parametric study is carried out to understand the behavior of the structure under impact loading.

Keywords: Impact, Rate dependent, Damage, Evolution of failure surface and Strain rate

1. Introduction

It is well known that the higher strain rate causes the increase in strength of the concrete both under compression and tension loading. There are experiments to study the material characteristics under a dynamic loading. The Split Hopkinson Pressure Bar (SHPB) is used for this purpose. It helps in finding the dynamic strength of the material.

The strength of the material under dynamic load increases because of various physical mechanics. One is the strain rate sensitivity of the material and the other is the inertial effect. The dynamic to static strength of the material is related to using the dynamic increase factor (DIF). The concrete shows reduced tensile strength under static loading. But the DIF in tension shows a greater influence on concrete strength under dynamic loading.

Nomenclature

$\bar{\sigma}_{ij}$	Effective stress
D	Damage parameter
H	Heaviside function
K	Bulk Modulus
ε_{kk}^{e}	Elastic volumetric strain tensor
G	Shear Modulus
ε_{ij}^{e}	Elastic shear strain tensor
η	Viscosity coefficient
$\dot{\varepsilon}_{ij}^{p}$	Plastic strain rate tensor
F	Yield function
Y	Yield surface
σ_m	Maximum failure surface
σ_r	Residual failure surface
C	Fitting coefficient
$\dot{\varepsilon}^*$	Dimensionless strain rate
P	Hydrostatic pressure
D_c	Compression damage
D_t	Tension damage
$\bar{\varepsilon}_p^t$	Effective plastic strain in tension
$\bar{\varepsilon}_p^c$	Effective plastic strain in compression
ε_{frac}	Fracture strain

1.1. Physical mechanism of increase in dynamic strength of concrete

There is an increase in the strength of concrete strength under dynamic loading because of the strain rate dependency of concrete and the inertial effect. The classification of strain rate is made in three regions. They are low, intermediate and high range if the value is less than to and greater than respectively. The strain rate-dependent behavior is caused by the thermal vibration of the atom and the viscosity of the material. The thermal vibration of the atom breaks the atomic bonds and the micro-cracks are formed. As the strain rate increases the atomic vibration and more cracks are produced. In region I less number of cracks are produced. The crack propagates through the weakest path. The strength of concrete is lower in the region I and there is only slight increase in strength with increasing strain rate. More number of cracks are produced when the strain rate experienced by the material is in region II. There is no time for the energy in the concrete to release. Thus, the strength of the material increases to a greater extent. The cracks propagate through the aggregate. In region III, the concrete crushes failed by forming rubbles.

The moisture present in the concrete causes additional strength to the material with respect to the strain rate. The film of moisture present in the concrete exerts the return force promotional to the velocity of separation of the material. This induces an additional increase in the material strength due to the effect of strain rate produced in thw material.

The strength of the material increases indefinitely with the higher value of rate of strain the material is under-going [1]. This is caused due to the acceleration of particles even after the concrete crushes and rubble. The inertial effect is related to the size and shape of the concrete specimen. This is not true and has to be avoided while defining the DIF definition. This inertial effect can be avoided in the DIF definition by providing the limiting value of DIF or by giving a better definition of strain rate enhancement.

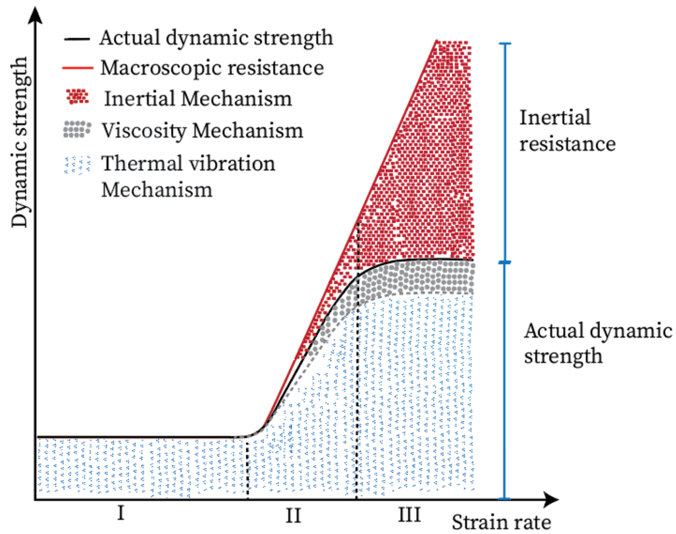


Fig. 1. Mechanism of dynamic increase in strength of material

2. Material model

2.1. Constitutive equation

The constitutive equation is defined in terms of effective stress.

$$\bar{\sigma}_{ij} = \left[(1-D) + DH\left(\text{sign}(\sigma_{kk})\right)\right]K\varepsilon^{e}_{kk}\delta_{ij} - \frac{2}{3}(1-D)G\varepsilon^{e}_{kk}\delta_{ij} + 2(1-D)G\varepsilon^{e}_{ij} \qquad (1)$$

In the above expressions $K, G, \varepsilon^{e}_{kk}$ and ε^{e}_{ij} are the bulk modulus, shear modulus, elastic volumetric strain tensor and elastic shear strain tensor. H denotes the Heaviside function of hydrostatic pressure, with $H = 1$ under compressive loading ($\sigma_{kk} > 0$). Thus, the reversal of stress state is taken into account. The damage parameter has a bound, $0 \leq D \leq 1$, where 0 and 1 represent an undamaged and fully damaged material state, respectively. If we consider the elasto-plastic spring along with viscous damper in the system. The elasto-plastic spring will consider the elasto-plastic behavior of the material under dynamic loading. The viscous damper will account the incremental strength of the concrete. Thus, the total stress in the system will be given as

$$\sigma_{ij} = C^{epd}_{ijkl}\varepsilon^{e}_{kl} + \eta\dot{\varepsilon}^{p}_{ij} \qquad (2)$$

Where $C^{epd}_{ijkl} = \left[\{(1-D) + DH(-\sigma_{kk})\}K - \frac{2}{3}(1-D)G\right]\delta_{ij}\delta_{kl} + (1-D)G\left[\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}\right]$. Thus, the following form of stress rate tensor is obtained to finding the time derivative of the stress function by considering the viscous formulation and is given as

$$\dot{\sigma}_{ij} = \left(C^{epd}_{ijkl}\dot{\varepsilon}_{kl} - C^{epd}_{ijkl}\dot{\varepsilon}^{p}_{kl}\right) - \dot{D}C_{ijkl}\left(\varepsilon_{kl} - \varepsilon^{p}_{kl}\right) + \frac{\eta}{dt}\dot{\varepsilon}^{p}_{ij} \qquad (3)$$

2.2. Failure surface

In the framework of the developed material model, based on the the Drucker-Prager strength criterion, the yield surface can be expressed as a function of hydrostatic pressure, strain rate and damage [2]. The specific yield surface expression is of the form

$$Y = [\sigma_m(1-D) + \sigma_r D][1 + C\ln(\dot{\varepsilon}^*)] \tag{4}$$

Where $\dot{\varepsilon}^*$is the dimensionless strain rate defined as $\dot{\varepsilon}^* = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)$, σ_m and σ_r are the maximum and residual strength surfaces. D is the damage parameter. $C = 0.007$ is the fitting coefficient.

$$\sigma_m = \begin{cases} (3T + 3P)r(\theta, e) & \mathrm{P} \le 0 \\ [3T + 3(f_c' - 3T)P^*]r(\theta, e) & 0 < P < f_c'/3 \\ \left[f_c' + Bf_c'\left(P^* - \frac{1}{3}\right)^N\right] r(\theta, e) & \mathrm{P} \ge f_c'/3 \end{cases}$$

$$\sigma_r = \begin{cases} 0 & P \le 0 \\ B_1 f_c (P^*)^{N_1} r(\theta, e) & \mathrm{P} > 0 \end{cases}$$

$$\cos(3\theta) = \frac{3\sqrt{3}}{2} \frac{J_3}{{J_2}^{3/2}}$$

Where J_2 and J_3 are the second and third derviatoric stress invariants of concrete. The ratio of the current meridian to the compression meridian (r) is defined as

$$r(\theta, e) = \frac{2(1-e^2)\cos\theta + (2e-1)\sqrt{4(1-e^2)\cos^2\theta + 5e^2 - 4e}}{4(1-e^2)\cos^2\theta + (1-2e)^2}$$

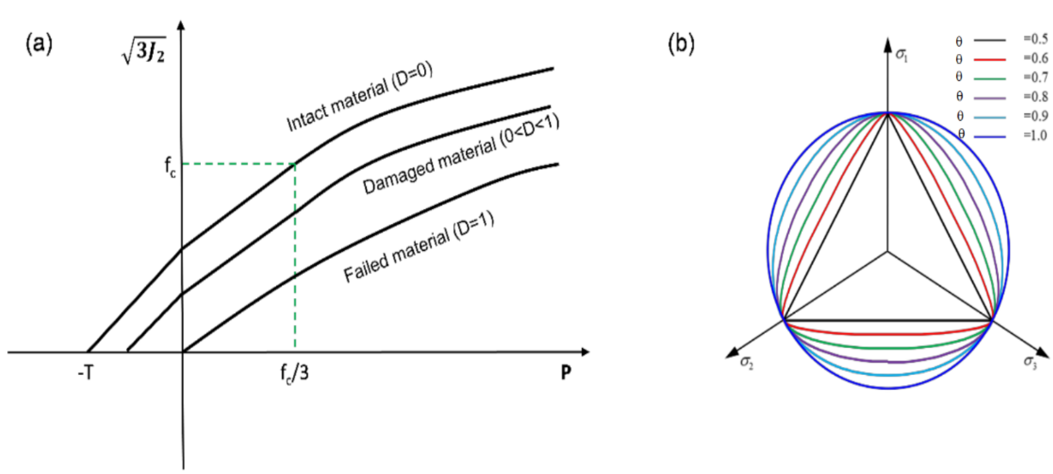
Where e is the the ratio of tensile to compressive meridian which depends on the pressure.

The yielding surface of concrete is expressed as

$$F = \sigma_{eq} - [\sigma_m(1-D) + \sigma_r D][1 + \mathrm{Cln}(\dot{\varepsilon}^*)]$$

Where $\sigma_{\mathrm{eq}} = \sqrt{3J_2}$, J_2 is the 2nd invariants of the deviatoric stress tensor.

Fig. 2. Failure surface in hydrostatic and deviatoric plane



2.3. *Damage modelling*

The compressive damage is defined as

$$D_c = \frac{\alpha \bar{\varepsilon}_p^c}{1 + \bar{\varepsilon}_p^c}$$

The damage in tension is defined in terms of fracture strain and effective plastic strain [3]. The fracture strain defines the complete damage of the concrete. The exponential form of tensile damage definition is given.

$$D_t = 1 - \left(1 + \left(c_1 \frac{\bar{\varepsilon}_p^t}{\varepsilon_{frac}}\right)^3\right) \exp\left(-c_2 \frac{\bar{\varepsilon}_p^t}{\varepsilon_{frac}}\right) + \frac{\bar{\varepsilon}_p^t}{\varepsilon_{frac}} (1 + c_1^3) \exp(-c_2)$$

Where c_1 and c_2 are constants taken from the quasi-static test under tensile state of loading. The values are 3 and 6.93 respectively. Under triaxial state of loading the value of stress is measured to be zero. The additional tensile damage ΔD_t is considered while defining the damage.

$$\Delta D_t = d_3 \times f_d \times \Delta\varepsilon_v$$

$$f_d = \begin{cases} 1 - \left|\sqrt{3J_2}/P\right|/0.1 & 0 \le \left|\sqrt{3J_2}/P\right| < 0.1 \\ 0 & 0.1 \le \left|\sqrt{3J_2}/P\right| \end{cases}$$

f_d gives the damage nearer to triaxial tension. $\Delta\varepsilon_v$ is the incremental value of volumetric strain. The total damage is defined as.

$$D = 1 - (1 - D_c)(1 - D_t)$$

3. Impact analysis

The impact analysis is done on the RCC slab of $1000 \times 1000 \times 75mm$ with $8\ mm$ reinforcement bar. The steel of $105\ kg$ mass is dropped from the height of $2.5\ m$. Fixed boundary condition is provided along all the boundary. Table 1 gives the property of the material used in the RCC slab.

Table 1. Material property under impact loading

Material	Property	Value
Reinforcement	Modulus of elasticity	198 GPa
	Ultimate strength	501 MPa
	Yield strength	422 MPa
	Failure strain	0.15
Drop weight	Denisty	7850 kg/m^3
	Poisson's ratio	0.3
	Modulus of Elasticity	198 GPa
	Velocity	6.86 m/s

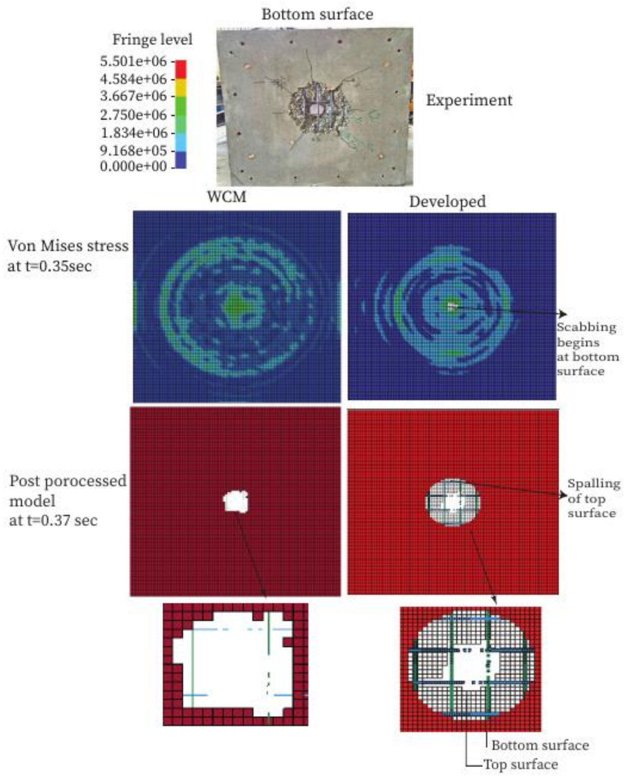


Fig. 3. Failure of concrete slab under impact loading

4. Parametric study

The parametric study is carried out by increasing the impact velocity. It is observed that the depth of localized damage is proportional to the velocity of impact load.

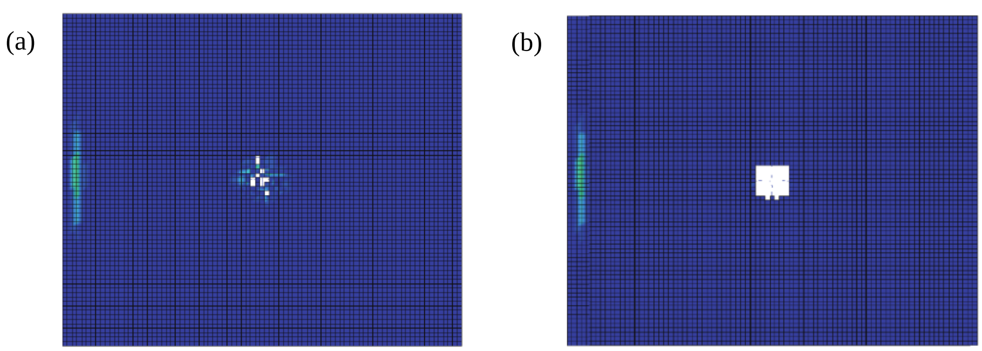


Fig. 3. Slab subjected to (a) 6.86 m/s impact velocity (b) 13.72 m/s impact velocity

The study is carried out by changing the impact duration acting on the slab. It is seen that as the impact duration acting in the slab increases, the slab localized damage increases.

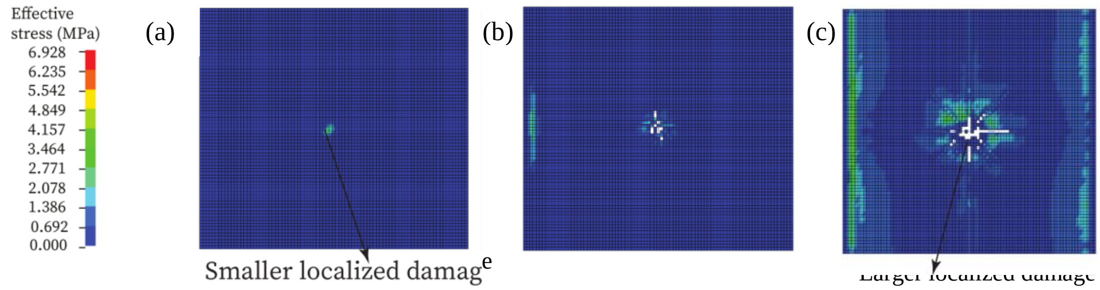


Fig. 3. Slab subjected to increased impact duration (a) 3 ms (b) 6 ms (c) 20 ms

5. Conclusion

The plasticity based damage model is able to predict the exact results to that of experimental predication. The yield surface expands with the increase in strain rate acting on the material. The maximum value is limited by giving the maximum value. This helps in avoiding the infinite increase in strength of concrete. The damage definition is helps in predicting the scabbing and spallation effect of the concrete when subjected to the impact loading.

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