STUDYING THE EFFECT OF PROJECTILE VELOCITY ON PENETRATION DEPTH IN CONCRETE WITH THE SIMPLIFIED CONCRETE DAMAGE PLASTICITY MODEL BY ABAQUS SOFTWARE

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Abstract
This paper calculates the penetration depth of 85 mm projectile in concrete block B20 by Abaqus software, with the concrete in simplified concrete damage plasticity (SCDP) model. Comparing the results calculated by Abaqus software with the Berezan formula and the improved Petry formula to check the reliability of the computational model and material model. From there, studying the effect of projectile velocity on penetration depth in concrete B20.

Keywords: *Simplified concrete damage plasticity (SCDP); impact; penetration depth; velocity.*

1. Introduction

Concrete has been widely used for military and civil engineering in the design and construction of protective structures to resist impact and explosive loads. There are several material models to represent concrete, which have been implemented in commercial software used for simulation of concrete structures subjected to impact loads. For example, the Drucker-Prager/Cap model, Johnson and Holmquist concrete model (JH model), concrete damage plasticity model, The Winfrith Concrete model...

This paper calculates the structure of the building subjected to bomb penetration, with the concrete in concrete damage plasticity (CDP) model. Due to the complexity of the CDP theory, the procedure was simplified and a simplified concrete damage plasticity (SCDP) model was used [1, 2]. In this model, studying the effect of projectile velocity on penetration depth in concrete structures.

Using Abaqus to calculate B20 concrete structures subjected to bombs according to the SCDP material model to compare, verify, and evaluate the effects of the bomb parameters on penetration depth is scientific and realistic.

2. Simplified Concrete Damage Plasticity [1, 2, 8]

The values of the hardening and softening variables were used for the determination of the cracking and crushing trends, respectively. They were responsible for the loss of the elastic stiffness and the development of the yield surface. The damage

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states in compression and tension were characterized independently by two hardening variables. These were indicated by $\varepsilon_c^{pl,h}$ and $\varepsilon_t^{pl,h}$, which referred to equivalent plastic strains in tension and compression, respectively.

Uniaxial Compressive Behavior

In concrete damage plasticity models, the plastic hardening strain in compression $\varepsilon_c^{pl,h}$ played a key role in finding the relation between the damage parameters and the compressive strength of concrete (see Fig. 1a) as follows:

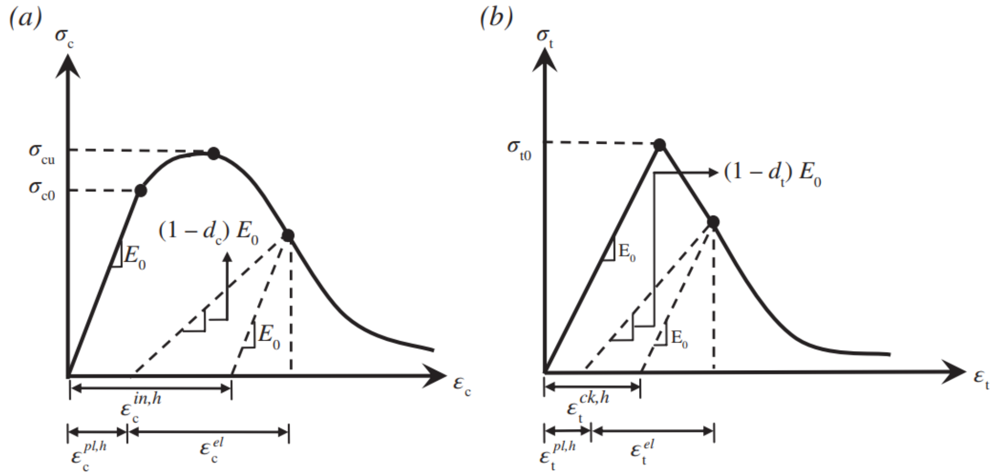

Fig. 1. Response of concrete to a uniaxial loading condition:
(a) Compression; (b) Tension.

$$\sigma_c = (1-d_c)E_0(\varepsilon_c - \varepsilon_c^{pl,h}) \tag{1}$$

$$\begin{cases} \varepsilon_c^{\mathrm{in},h} = \varepsilon_c - \dfrac{\sigma_c}{E_0} \\ \varepsilon_c^{pl,h} = \varepsilon_c - \dfrac{\sigma_c}{E_0}\left(\dfrac{1}{1-d_c}\right) \end{cases} \tag{2}$$

$$\varepsilon_c^{pl,h} = \varepsilon_c^{\mathrm{in},h} - \left(\frac{d_c}{1-d_c}\right)\frac{\sigma_c}{E_0} \tag{3}$$

where $\varepsilon_c^{\mathrm{in},h}$ is inelastic compression strain, σ_c is nominal compressive stress, ε_c is nominal compressive strain, d_c is damage parameter, E_0 is initial modulus of elasticity, $\varepsilon_c^{pl,h}$ is the plastic hardening strains in compression.

Generally, uniaxial compressive behavior could be characterized by either experimental tests or existing constitutive models [5, 6]. However, the present study employed the Kent and Park [6] parabolic constitutive model for unconfined concrete, which was expressed by the following equation:

$$\sigma_c = \sigma_{cu}[2(\frac{\varepsilon_c}{\varepsilon_c^{'}}) - (\frac{\varepsilon_c}{\varepsilon_c^{'}})^2] \tag{4}$$

where σ_{cu} is ultimate compressive strength, $\varepsilon_c^{'}$ is ultimate compressive strain, $\varepsilon_c^{'} = 0.002$.

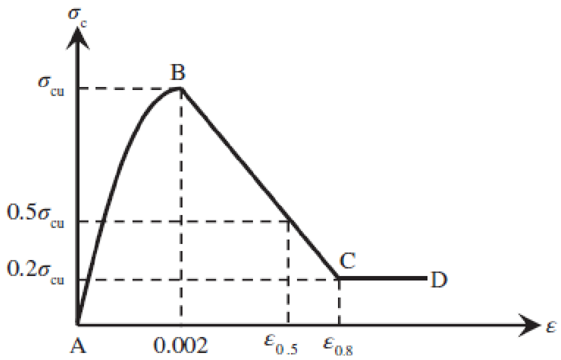

Fig. 2. Kent and Park model for confined and unconfined concrete.

According to Figs. 1a and 2, $\varepsilon_c^{in,h}$ was derived as follows:

$$\varepsilon_c^{\mathrm{in},h} = \varepsilon_c - \frac{\sigma_c}{E_0} \tag{5}$$

d_c could be expressed as follows:

$$d_c = 1 - \frac{\sigma_c}{\sigma_{cu}} \tag{6}$$

Uniaxial Tensile Behavior

In concrete damage plasticity models, the plastic hardening strain in tension $\varepsilon_t^{pl,h}$ was derived (see Fig. 1b) as follows:

$$\sigma_t = (1 - d_t)E_0(\varepsilon_t - \varepsilon_t^{pl,h}) \tag{7}$$

$$\begin{cases} \varepsilon_t^{\mathrm{ck},h} = \varepsilon_t - \dfrac{\sigma_t}{E_0} \\ \varepsilon_t^{pl,h} = \varepsilon_t^{\mathrm{ck},h} - \dfrac{\sigma_t}{E_0}(\dfrac{1}{1-d_t}) \end{cases} \tag{8}$$

$$\varepsilon_t^{pl,h} = \varepsilon_t^{\mathrm{ck},h} - (\frac{d_t}{1-d_t})\frac{\sigma_t}{E_0} \tag{9}$$

where σ_c is nominal tensile stress, d_t is damage parameter, $\varepsilon_t^{pl,h}$ is the plastic hardening strains in tension.

Figure 1b showed that with a further increase in the hardening cracking strain, $\varepsilon_t^{\mathrm{ck},h}$ is the tension damage continued to increase, and this could be expressed as follows:

$$d_t = 1 - \frac{\sigma_t}{\sigma_{t0}} \tag{10}$$

where $\sigma_{t0} = 0.1\sigma_{cu}$.

Application of SCDP Parameters in Finite element programs

Poisson's ratio range for concrete was between 0.1 and 0.2. Poisson's ratio, elasticity modulus, and stress - strain curve of concrete in compression and tension were related to loading history, which resulted in strain differences. The dilation angle was equal to volume strain over shear strain. The dilation angle for concrete was usually 20° to 40°, which affected material ductility. Consequently, the dilation angle had considerable effects on the entire model. An increase in the dilation angle increased the system flexibility. From a practical viewpoint, the internal dilation angle depended on certain parameters, including plastic strain and confined pressure. An increase in plastic strain and confined pressure decreased the internal dilation angle. The material has a congrades (B20) implemented within the framework in tabular format, that is (Table 1), respectively. Accordingly, the hardening and softening rule as well as the evolution of the scalar damage variable for compression and tension were presented for concrete grades B20. The general framework of the damage plasticity formulation was clearly stated.

Table 1. Material properties for concrete with SCDP model in class B20 [1, 8]

Material's parameters B20		**Plasticity parameters**	
Modulus of elasticity (GPa)	21.2	Dilation angle	31
		Eccentricity	0.1
Poisson's ratio	0.2	$\sigma_{b0} / \sigma_{c0}$	1.16
		K	0.67
		Viscosity parameter	0
Concrete compressive behavior		Concrete compression damage	
Yield stress (MPa)	Inelastic strain	Damage parameter C	Inelastic strain
10.2	0	0	0
12.8	$7.74.10^{-5}$	0	$7.74.10^{-5}$
15	0.000174	0	0.000174
16.8	0.000289	0	0.000289

Yield stress (MPa)	Inelastic strain	Damage parameter C	Inelastic strain
18.2	0.000423	0	0.000423
19.2	0.000575	0	0.000575
19.8	0.000747	0	0.000747
20	0.000938	0	0.000938
19.8	0.001147	0.01	0.001147
19.2	0.001375	0.04	0.001375
18.2	0.001623	0.09	0.001623
16.8	0.001889	0.16	0.001889
15	0.002174	0.25	0.002174
12.8	0.002477	0.36	0.002477
10.2	0.002800	0.49	0.002800
7.2	0.003142	0.64	0.003142
3.8	0.003502	0.81	0.003502
Concrete tensile behavior		Concrete tension damage	
Yield stress (MPa)	Cracking strain	Damage parameter T	Cracking strain
2	0	0	0
0.02	0.000943	0.99	0.0009433

where σ_{b0}/σ_{c0} is equibiaxial to uniaxial initial yield ratio; K is tensile to compressive meridians slope ratio.

3. Numerical Computation

Using Abaqus software to calculate the penetration depth of 85 mm projectile with parameters given in Table 2 into concrete block B20 with the size of 1.5x1.5x1.5 m, the concrete block is simulated and fixed around the boundary. Projectile begins to penetrate at the center position of one side.

Table 2. Properties of 85 mm projectile

P (kG)	d (m)	l (m)	l_t (m)	v_0 (m/s)	E (GPa)	μ
9.54	0.085	0.397	0.1996	650	200	0.3

where l is length of projectile; l_t is long part understand projectile; P is mass of projectile; d is diameter of projectile; v_0 is velocity of projectile; E is modulus of elasticity; μ is Poisson's ratio.

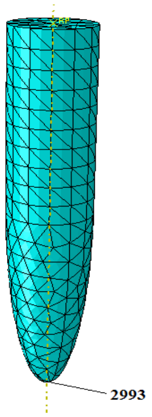

Fig. 3. Meshed and node numbers of projectile

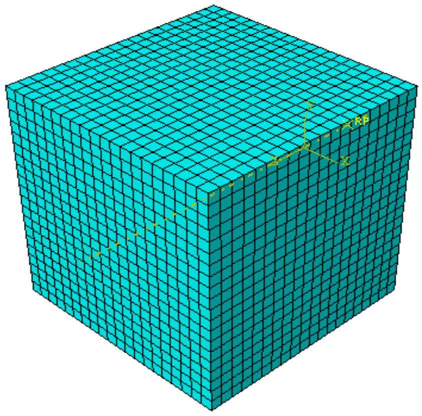

Fig. 4. Meshed and node numbers of projectile concrete

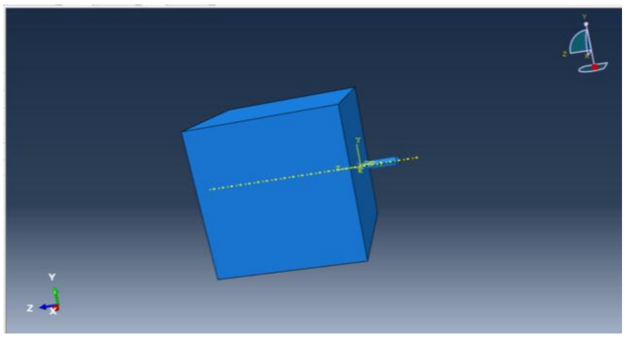

Fig. 5. The model of numerical computation

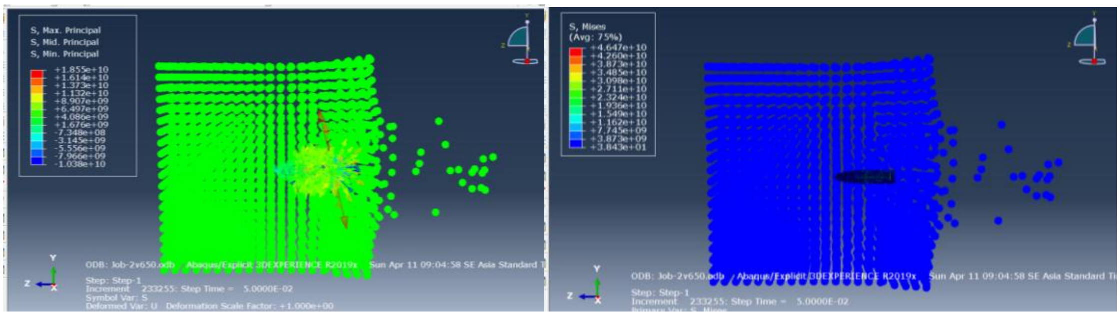

Fig. 6. The result of numerical computation

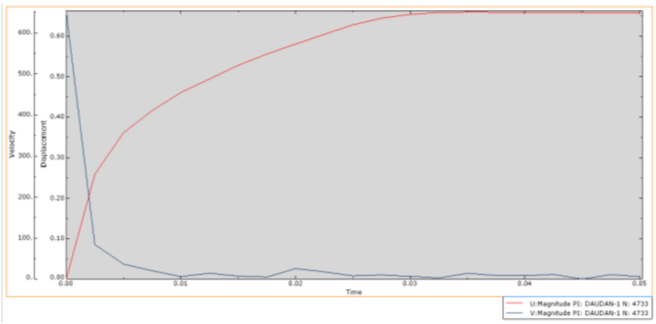

Fig 7. Graph of velocity and displacement of head of the projectile (node 2993)

From Fig 7, at time t = 0.045 s, the velocity of the projectile v = 0.3073 m/s, is the time when the projectile stops penetrating, penetration depth of projectile in concrete structures is 0.675 m.

Calculated with Berezan method [7]

Penetration depth is given by a group of Russian engineers:

$$h_x = \lambda_1 \lambda_2 . \mathrm{K}_x . \frac{P}{d^2} v_0 \cos\left(\frac{n+1}{2}\right)\alpha \tag{11}$$

where K_x is the number of anti penetration, depending on the concrete; λ_1, λ_2 is the coefficient depends on the size of the projectiles, $\lambda_1 = \sqrt{\frac{l_t}{1.5d}}$, $\lambda_2 = 2.8\sqrt[3]{d} - 1.3\sqrt{d}$; α is minds of projectiles hit, degrees, $\alpha = 0$; n is the number of projectiles changed direction in the concrete; l_t is long part understand warheads, m; P is mass of projectile, kG; d is diameter of projectile, m; v_0 is velocity of projectile, m/s;

with $K_x = 12.10^{-7}$ - granite stone concrete B20 [7], $h_x = 0.531$ m (12)

with $K_x = 16.10^{-7}$ - hard stone concrete [7], $h_x = 0.709$ m (13)

Calculated with Modified Petry Formula [4]

$$h_x = k\frac{P}{d^2}\log_{10}\left(1 + \frac{v_0^2}{19974}\right) = 0.607\,\mathrm{m} \tag{14}$$

where $k = 0.0795.K_p$ = 0.000342 [4], K_p is concrete penetrability coefficient, it depends upon the strength of concrete.

The assumptions attached to (11), (14) are: the trajectory of the projectiles movement in the environment is a straight line; projectiles is absolute hard. Abaqus calculates as a mechanical system, taking into the deformation of the projectiles.

The results of Abaqus with SCDP are in the Berezan method range [7], approximately calculated according to Modified Petry Formula, so it can be confirmed that the calculation model is reliable.

Studying the effect of projectile velocity on penetration depth in concrete

Using Abaqus software, studying the effect of 85 mm projectile velocity on penetration depth in concrete block B20 (with SCDP model). The result of penetration depth in concrete given in Table 3 and Fig. 8.

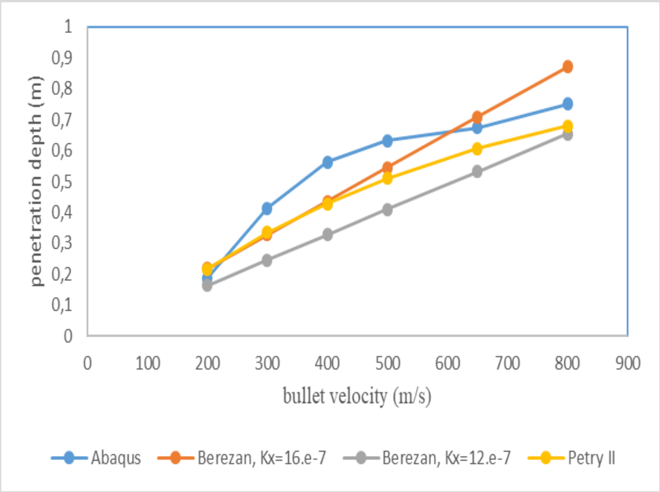

Fig. 8. The result of penetration depth in concrete

Table 3. The result of penetration depth in concrete

v_0 (m/s)	200	300	400	500	650	800
h_x (m)	0.188	0.413	0.563	0.633	0.675	0.75

From the results in Fig. 8 it can be seen that the penetration depth is proportional to the projectile velocity but not linearly. Therefore, in calculation, penetration depth is not a linear function of the projectile velocity, on a function of higher order or transcendental.

4. Conclusions

- The results of Abaqus with SCDP are in range of the Berezan method [7], and Modified Petry Formula, so it can be confirmed that the calculation model is reliable. This model can be used in research and calculation of the penetration of projectile, especially with which class concrete have full parameters, for example B20, B30, B40, B50.

- The penetration depth is not a linear function of the projectile velocity.

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NGHIÊN CỨU ẢNH HƯỞNG CỦA VẬN TỐC ĐẠN ĐẾN CHIỀU SÂU XUYÊN TRONG BÊ TÔNG THEO MÔ HÌNH PHÁ HỦY DẺO ĐƠN GIẢN BẰNG PHẦN MỀM ABAQUS

Tóm tắt: *Bài báo tính toán chiều sâu xuyên của đạn 85 mm trong bê tông B20 bằng phần mềm Abaqus, trong đó bê tông được mô phỏng theo mô hình phá hủy dẻo đơn giản (SCDP). So sánh kết quả tính toán bằng phần mềm Abaqus với chiều sâu xuyên tính toán theo công thức Berezan và công thức Petry cải tiến để kiểm tra độ tin cậy của mô hình tính toán, mô hình vật liệu sử dụng. Từ đó nghiên cứu ảnh hưởng của vận tốc đạn đến chiều sâu xuyên trong bê tông B20.*

Từ khóa: Phá hủy dẻo đơn giản bê tông (SCDP); va chạm; chiều sâu xuyên; vận tốc.

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