Finite Element Model of RC Columns Subjected to Projectile Impact with Different Velocities

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***Abstract*—Today, buildings are exposed to the effects such as explosion and impact loads. Usually explosion and impact loads that act on the buildings such as nuclear power plants, airports, defense industry and military facilities, can occur occasionally on the normal buildings because of some reasons like drop weight impacts, natural gas system explosions and terrorist attacks. Therefore, it has gained importance that to research the effects of the impact loads in reinforced concrete buildings. Experimental studies realized for these structures and their structural members are very expensive and difficult. Therefore, development of computational mechanics has facilitated the modeling of such loading conditions. In this study, it was tried to numerically validate experimental results of the local damage of the reinforced concrete columns by the impacts of the high velocity projectiles. For the numerical studies, ABAQUS finite element software was used. The five standard series of reinforced concrete columns (100x100x280 mm) were numerically subjected to the projectile with a diameter of 9.54 mm to validate local damages. As a result of the analyses, depth profiles of the crater and appearance of the damages were obtained and compared with numerical results.**

***Index Terms*—impact load, reinforced concrete columns, finite element analysis**

I. Introduction

Reinforced concrete is one of the most popular materials used in many engineering applications like nuclear plants, airports, military stations. Sometimes, reinforced concrete structures are subjected to extreme dynamic loading such as blast and direct impact depend on accidental explosion and terrorist attacks. However, this loading conditions cause especially irreparable loss of lives and property. In recent years, many countries have been attacked by terrorists and threats have increasingly continued. For this purpose, reinforced concrete structures which consisted of reinforced concrete members (columns, beams and slabs etc.) should be made secure against to blast and impact weight loading and also analysis of these structures under blast and impact loading and identification of damage mechanism or modes are of grade importance for structural engineering.

Many experimentally and theoretically studies related with impact resistance and perforation of reinforced concrete elements subjected to blast and impact loading have been demonstrated by researchers. But full scaled experimental studies of structures and structural elements are very expensive and difficult and so numerical modeling techniques (finite element method, discrete element models) have gained importance gradually. Experimental studies have been supported by numerical studies. Martin (1994) gave a review of model of localized concrete behavior when impacted by undeformable missiles at wide range of incident velocities [1]. According to this study, four important aspects of the prediction of local impact effects on concrete were evaluated such as investigation of strain rate dependence of material parameters, empirical equations for predicting the effects of local impact, a review of analytical models and computational approaches to impact. Saito et al. (1995), aimed to clarify experimentally and analytically the loading capacities, deformations and failure modes of various types of reinforced-concrete structure subjected to loads applied at various rates [2]. Sawamoto et al. (1998) proposed a new analytical approach for assessing local damage to reinforced concrete structures subjected to impact load by applying the discrete element method (DEM) developed by Cundall (1971) [3]. The DEM can easily treat fracture mechanics of concrete such as cracking, splitting and crushing [4]. Thabet and Haldane (2000) aimed to develop an approach that took account of the continuity in the response of concrete structures when subjected to impact loads [5]. The study investigated the development of an analytical procedure that can be used to predict the behavior of structural concrete members subjected to impact loads. The results obtained using the proposed approach show that the failure modes of a number of reinforced concrete beams subjected to impact loading can be predicted to reasonable degree of accuracy. Zhang et al. (2005) presented results from an experimental study on the impact resistance of concrete with compressive strengths of 45-235 MPa impacted by 12.6 mm ogive-nosed projectile at velocities ranging from ~620 to 700 m/s [6]. The effects of the compressive and flexural tensile strength of the concrete, the presence of coarse aggregate or steel fibers, and the curing temperature of the concrete are discussed. Tai and Tang (2006) conducted numerical simulation of the dynamic behavior of reinforced concrete plates under normal impact [7]. They used finite element method on the reinforced

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concrete structural dynamic response and failure behavior when subjected to the projectile impacts to different velocities, using the test conducted by Reference [8]. Reference [9] aimed to examine behaviors of reinforced concrete slabs under impact loads and increasing impact strengths. They researched the effects of different types of slab reinforcements and the applied impact loads on the dynamic response and behavior of reinforced concrete slabs. Reference [10] conducted a research about the effects of objects by creating impact loads with higher weights and impact in low velocities on reinforced concrete elements such as beams and plates, etc. Reference [11] searched with numerical modeling for structural behaviors of structural elements under impact loading. Finite element models were developed for different structural behaviors under different material models. Effects of soft and hard impact loads were modeled both by deformable and rigid bullets. Reference [12] conducted a study consist of numerical models to predict the various global failure modes such as flexural, punching shear and mixed-shear failures along with the local failure modes such as crushing, cracking, spalling and scabbing, under impact loads. Numerical simulation on reinforced concrete slab impacted with cylindrical drop hammer has been carried out using finite element analysis to obtain the failure modes. A comparison has been made to validate the results of numerical simulation with the experimental results of Reference [9]. Reference [13] performed impact experiments using a gun method to evaluate local damages of reinforced columns by the impact of a high velocity projectile. Effects of an amount of main bar and spacing between hoops were examined and scaling effects were evaluated to ensure the effectiveness of the computer simulations. Reference [14] examined numerically reinforced concrete plates with different span sizes for both free and fixed support conditions. Reference [15] created the finite element models in ABAQUS/Explicit software to examine perforation of steel and aluminum plate specimens. Impact load was applied on composite plate with eight layers reinforced by carbon fibers. In simulations, The Johnson-Cook model for strain rate effects in the material and in compressibility and Hashin failure criterion for damage of composite plate were used. In this study, it was tried to numerically validate experimental results of the local damage of the reinforced concrete columns by the impacts of the high velocity projectiles In this line, the five standard series of reinforced concrete columns which are investigated experimentally by Reference [13] were modeled with ABAQUS finite element software. A comparison was been made to validate the results of numerical simulation with experimental results of Reference [13]. The concrete and reinforced concrete and steel members were modeled with Concrete Damage Plasticity (CDP) and Classical Metal Plasticity (CMP), respectively. As a result of the analyses, depth profiles of the crater and appearance of the damages were obtained and compared with numerical results.

II. Material Models

A. *Concrete Damage Plasticity (CDP) Model*

1) *Constitutive model of concrete*

Mechanical properties of concrete were defined by CDP material model in Abaqus FE software. The model is a continuum, plasticity-based, damage model for concrete. It assumes that the main two failure mechanisms are tensile cracking and compressive crushing of the concrete material. The evolution of the failure surface is controlled by two hardening variables, ε_c^{pla} and ε_t^{pla} , linked to failure mechanisms under tension and compression loading, respectively [16]. These strains are calculated as in (1)-(2). Also the damage variables (d_c, d_t) were defined together with hardening variables for stiffening degradation behavior. The damage variables can take values from zero, representing the undamaged material, to one, which represents total loss of strength. If E_o is the initial (undamaged) elastic stiffness of the material, the stress-strain relations under uniaxial tension and compression loading are, respectively:

$$\varepsilon_c^{pl} = \varepsilon_c^{in} - \frac{d_c}{1-d_c}\frac{\sigma_c}{E_o} \tag{1}$$

$$\varepsilon_t^{pl} = \varepsilon_c^{ck} - \frac{d_t}{1-d_t}\frac{\sigma_t}{E_o} \tag{2}$$

$$\sigma_c = (1-d_c)E_o(\varepsilon_c - \varepsilon_c^{pl}) \tag{3}$$

$$\sigma_t = (1-d_t)E_o(\varepsilon_t - \varepsilon_t^{pl}) \tag{4}$$

Stress-strain relations of concrete were given (Fig. 1).

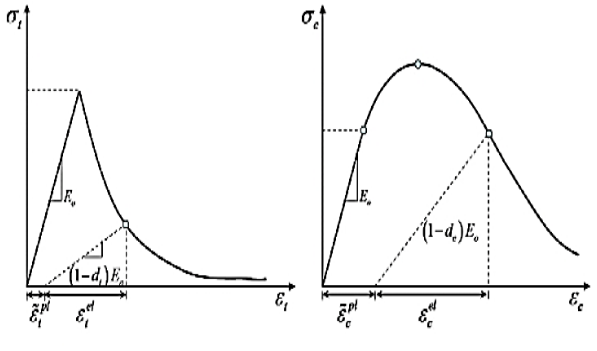


Figure 1. Stress-strain curves of concrete in CDP model.

Yield function was developed by Reference [17], with the modifications which were proposed by Lee and Fenves (1998). The yield surface in CDP model is modified Drucker-Prager material model. The CDP model is developed by adding two independent variables. The first variable is the ratio of biaxial compressive strength f_{bo} to uniaxial compressive strength f_{co} . The second variable is K_c that controls the shape of yield surface in deviator plane (Fig. 2).

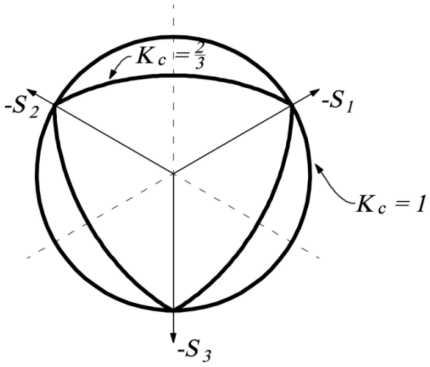


Figure 2. Yield surface in deviatoric plane for different values (Abaqus 2008).

CDP model assumes non-associated potential plastic flow. The flow potential G used for this model is the Drucker-Prager hyperbolic function [16]:

$$G = \sqrt{(e.\sigma_{to}.\tan\psi)^2 + \overline{q}^2} - \overline{p}\tan\psi \tag{5}$$

This function is influenced by the three main variables. The first is the eccentricity e, is defined as eccentricity in function at asymptotes. The second σ_{to} is the uniaxial tensile stress at failure, taken from the user-specified tension stiffening data. The last variable is dilatation angle ψ which defines amount of plastic volumetric strain developed plastic yielding Reference [18]. The dilation angle measured in the p–q plane at high confining pressure (Abaqus, 2008.)

2) Concrete modelling

The behavior of concrete was defined with constitutive properties, yield surface and plastic flow parameters. Stress-strain relationship, modulus of elasticity, E=32000 MPa, and poisson ratio, $\upsilon = 0.2$, for all elements were defined according to experimental results. Compressive and tensile strength of concrete were obtained respectively 40 MPa and 2.2 MPa. The stress-strain curves were implemented in Abaqus CDP model (Fig. 3).

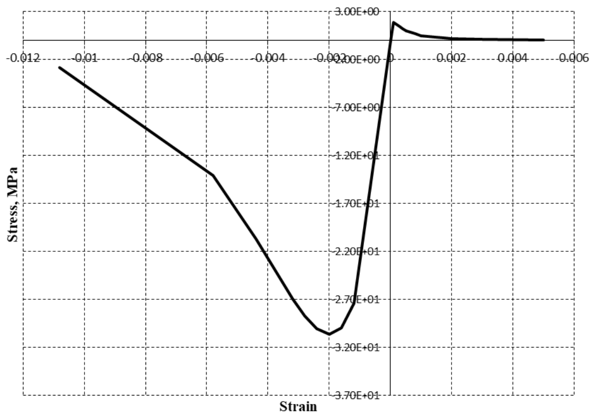


Figure 3. Tension and compression curve of concrete in CDP model.

Additionally, the other parameters were defined about yield surface and plastic flow, the following data was taken:

-Dilatation angle, ψ defines amount of plastic volumetric strain developed plastic yielding. The dilatation angle varies between 35 and 40 [18]. It was taken 35.

- K_c is coefficient about shape of yield surface in deviator plane. It was taken 0.667.

- $\left(\frac{f_{bo}}{f_{co}}\right)$ is the ratio of initial biaxial compressive yield stress to initial uniaxial compressive yield stress [16]. The default value of this parameter is 1.16 for normal strength of concrete in Abaqus.

B. Classical Metal Plasticity (CMP) Model

Classical Metal Plasticity (CMP) is a material model for behavior under uniaxial tensile loading of reinforcing steel. In this model elastic and plastic behavior of the material is thought to be separated. The elastic behavior is defined with elastic modulus E and poisson ratio υ. Plastic behavior of reinforcing steel is defined true stress σ_{tru} and plastic strain σ_{pl}. The nominal stress-strain curve can be converted to plastic strain-true stress curve as in Eqs. (6)-(8) [19].

$$\sigma_{tru} = \sigma_{nom}(1+\varepsilon_{nom}) \tag{6}$$

$$\varepsilon_{tru} = \ln(1+\varepsilon_{nom}) \tag{7}$$

$$\varepsilon_{pl} = \varepsilon_{tru} - \frac{\sigma_{tru}}{E} \tag{8}$$

In this study, yield strength of reinforcement was 420 MPa. True stress-plastic strain curve of reinforcement steel were given (Fig. 4).

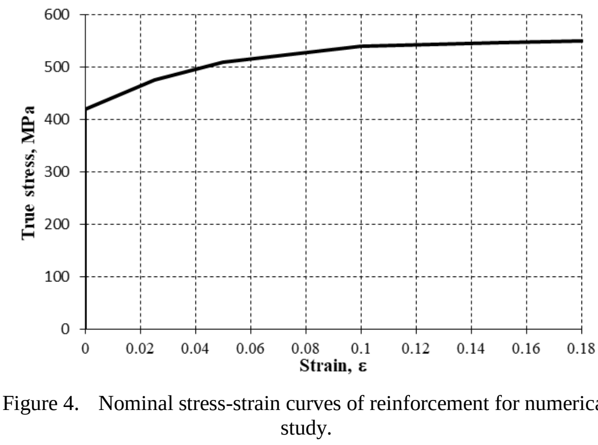


Figure 4. Nominal stress-strain curves of reinforcement for numerical study.

III. Numerical Study

In this study, damage mechanisms of reinforced concrete columns under the impacts of different high velocity projectiles numerically investigated. Finite element analysis was ensured with ABAQUS finite element software. Although the finite element software ABAQUS has been validated extensively against test data on reinforced concrete elements under static and impact loads, additional validations had to be considered for other parameters (velocity of projectiles, modeling effects etc.). Unfortunately, any study were not been undertaken for reinforced concrete members under different velocity projectiles and then reinforced concrete elements have not been showed stable behavior and so accuracy of finite element analysis for reinforced concrete elements had to be validated. In this line, the study presented by Reference [13] was chosen as a validation study to ensure the effectiveness of the computer analysis.

Reference [13] tried to evaluate the local damage of the reinforced concrete columns by the impacts of the high velocity projectiles. As the test specimens, 1/10 scale 5 standard series of RC columns (100x100x280 mm) were mainly used. Projectile was sphere made of 304 steel, 9.54 mm in diameter. The projectile was accelerated by a single-stage propellant gun and a two-stage light gun to 0.53-1.76 km/s). Table 1 shows specifications of the reinforced concrete column specimens and projectiles used in the impact experiments.

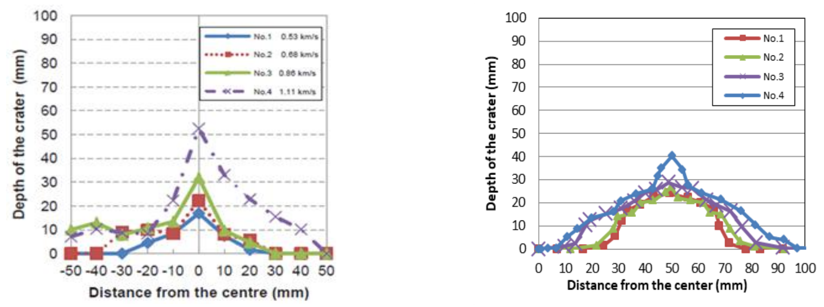
Depth profiles of crater were given (Fig. 5). For an appearance of the damage, Figs. 6-8 shows the experimental and numerical view of the impacted specimens at various velocities (No 2: 682 m/s; No 3: 855 m/s; No 5: 1765 m/s). Similar to experimental study [13], apparent cratering damage has been observed in numerical study for No.2 and No.4 specimens. Cover concrete spalled from the front side and radial cracks developed from center of the crater to back surface. Amount of spalled concrete increased depend on velocity of projectiles. When No. 5 specimen is viewed, experimental results were verified. Cover and core concrete completely crushed and spalled. Stirrups on center of the crater were fractured. Although the main bars on the front side damaged more than the back side, all main bars remained. Fractured stirrups and remained main bars given in Fig. 9.

TABLE I. SPECIFICATIONS OF THE REINFORCED CONCRETE COLUMN SPECIMENS AND PROJECTILES

No	Scale	b(mm)	D(mm)	L(mm)	Strength of concrete
1					
2					
3	1/10	100	100	280	40
4					
5					

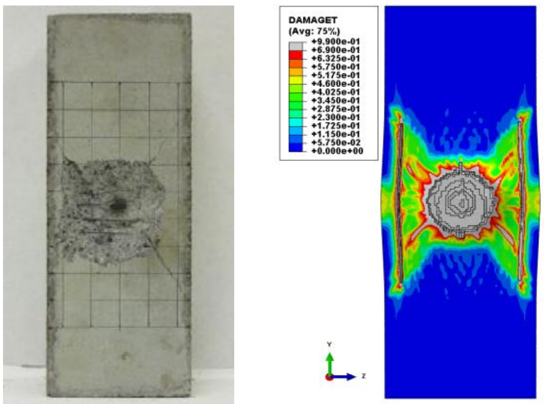
	Main bar			Hoop	
Steel bar (in)	Cov. ratio	Yield Strength (MPa)	Arrg.	Cov. ratio	Yield Strength (MPa)
4-D4	0.56	295	D1@10	0.15	295

		Projectile	
	Flyer		Impact
Weight (g)	Dia.	Mat.	V(m/s)
3.516	9.64	304 steel	533
			682
			855
			1105
			1765



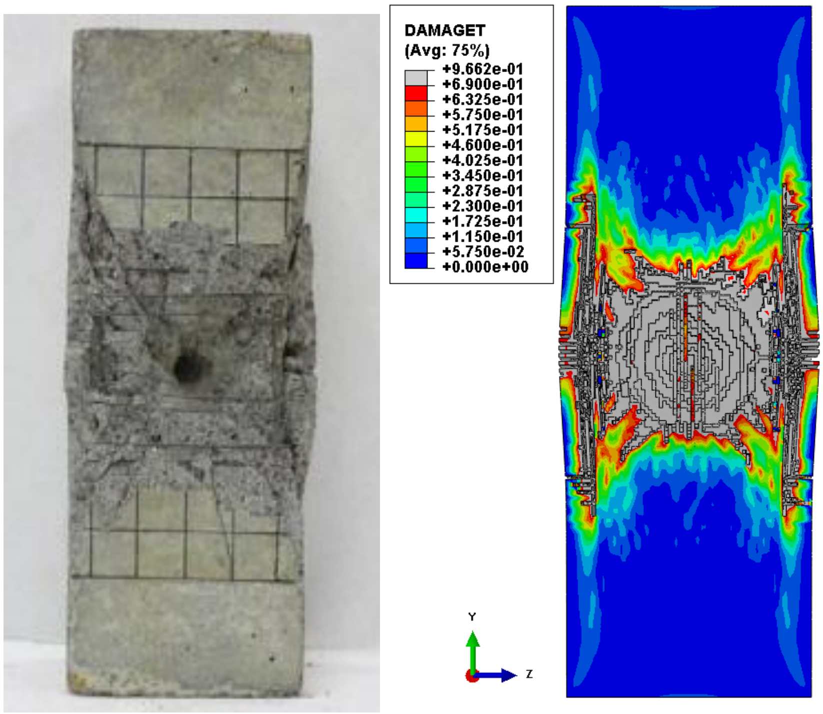
a) b)

Figure 5. Depth profiles of the crater: a)For experimental study, b) For numerical study.



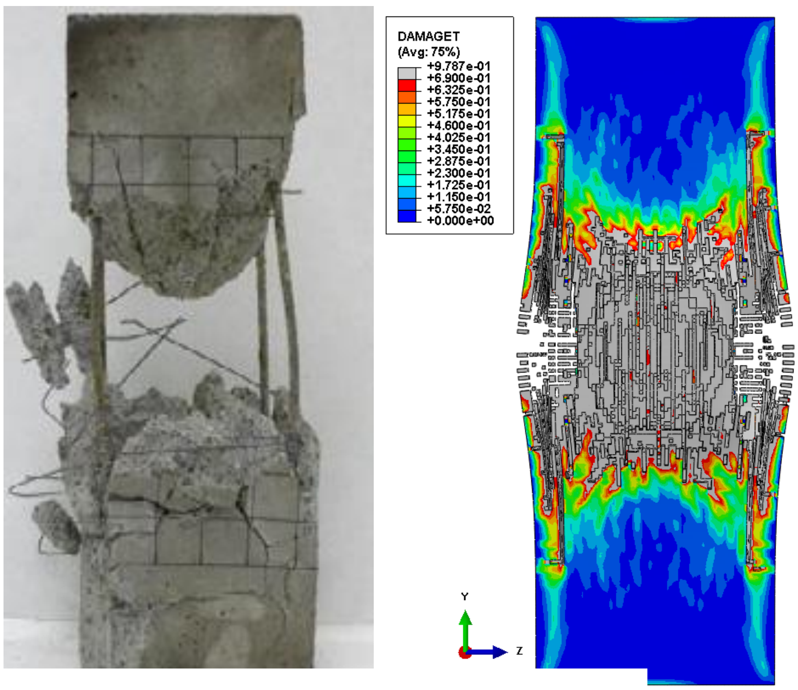
a) b)

Figure 6. Experimental (a) and numerically (b) impacted No:2 specimen (Velocity=682 m/s).



a) b)

Figure 7. Experimental (a) and numerically (b) impacted No:4 specimen (Velocity=1105 m/s).



a) b)

Figure 8. Experimental (a) and numerically (b) impacted No:5 specimen (Velocity=1765 m/s).

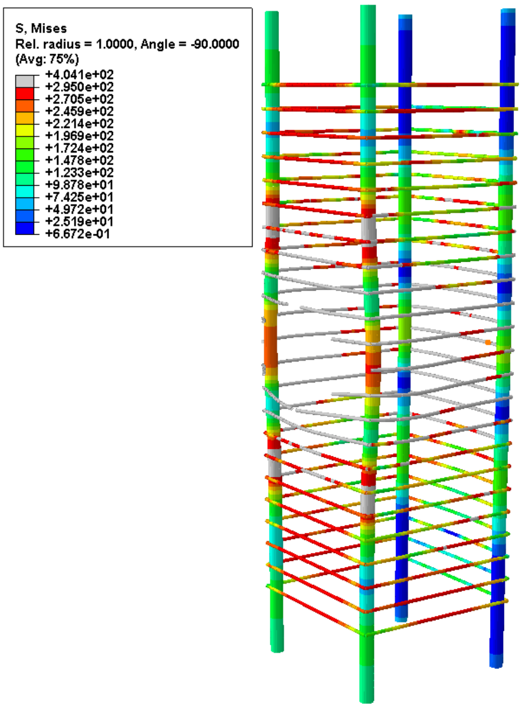


Figure 9. Fractured stirrups and remained main bars in numerical model for No.5 specimen.

This verification results indicated that ABAQUS finite element software can be used to simulate the response of the reinforced concrete members under impact loads and that the results would be acceptable.

IV. Conclusion

In this study, five standard reinforced concrete columns which are investigated experimentally by Atou et al. (2013) were modeled with ABAQUS finite element software. In this line, the study presented by Atou et al. (2013) was chosen as a validation study to ensure the effectiveness of the computer analysis. The five columns were subjected to impact of high velocity projectiles. The concrete and reinforced concrete steel members were modeled with Concrete Damage Plasticity (CDP) and Classical Metal Plasticity (CMP), respectively. The conclusion drawn from the results obtained in this study are as follows:

- The crater depth results obtained from numerical study agree with experimental results. Changing of crater depths obtained for column models was approximately same as experimental results.
- Amount of spalled cover concrete, radial cracks developed from center of the crater to back surface depend on velocity of projectiles and fractured stirrups and remained main bars obtained from numerical models showed similarity with experimental results.
- Concrete Damaged Plasticity (CDP) and Classical Metal Plasticity (CMP) material models and modeling process represented concrete behavior under projectile impact loading properly.

This verification results indicated that ABAQUS finite element software can be used to simulate the response of the reinforced concrete members under impact loads and that the results would be acceptable. Especially, this study enable usage of ABAQUS finite element software for different reinforced concrete members under projectile impact with different velocities.

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