

A criterion to minimize FE mesh-dependency in reinforced concrete structure subjected to impact loading

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ABSTRACT

In the process of high strain rate condition modeling, mesh dependency is the key problem because simulation results under high strain rate condition are quite sensitive to applied finite element (FE) mesh size. This paper introduces a criterion to minimize the mesh dependency in simulation results on the basis of the fracture energy concept, and penetration simulation with a reinforce concrete plate under a projectile (bullet) is performed using HJC (Holmquist Johnson Cook), CSC (Continuous Surface Cap) and K&C (Karagozian & Case) models. Simulation results shows that the variation of residual velocity with the used FE mesh size is quite reduced by applying a unique failure strain value determined according to the proposed criterion.

1. INTRODUCTION

Under hard impact, blast and impulsive loading condition, concrete shows quite different behavior compared to that in static state. Many material properties of concrete such as strength, tangent modulus and critical strain are changed with strain rate (Biscoff 1991). several material models are proposed and used to describe the high strain rate behavior under high strain rate condition. In this process of modeling, mesh dependency in the used finite element (FE) is the key problem because simulation results under high strain-rate conditions are quite sensitive to applied FE mesh size. This paper suggests a criterion that minimizes mesh-dependency in applied FE mesh size on the basis of fracture energy concept. The typical high strain rate models (HJC (Holmquist 1993), CSC (Malvar 1997), K&C (Schwer 1994)) are examined with penetration simulation to check improvement in accuracy of simulation results by applying a unique failure strain value determined according to the proposed criterion.

2. Size effect on fracture behavior of concrete

Since concrete is a brittle material which fails due to creation and propagation of internal microcracks in fracture process zone (Taylor 1986), concrete shows different failure behavior according to pattern of internal microcracking. As can be seen in Fig. 1,

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internal crack pattern changes according to size of specimens. This difference in crack pattern causes different behavior of concrete shown in Fig. 2 (Vonk 1993). The reason of this difference in crack pattern is that shear force cannot reach to bottom and spread out to lateral direction for long specimens. Therefore, size of the concrete specimen should be considered in estimation of fracture energy.

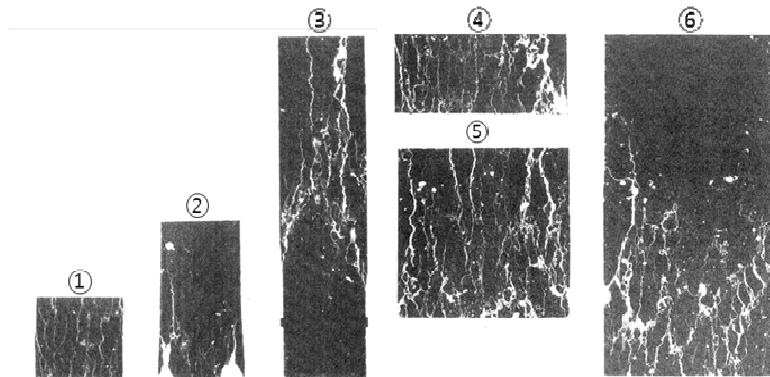


Fig. 1 Crack patterns for different size of specimens

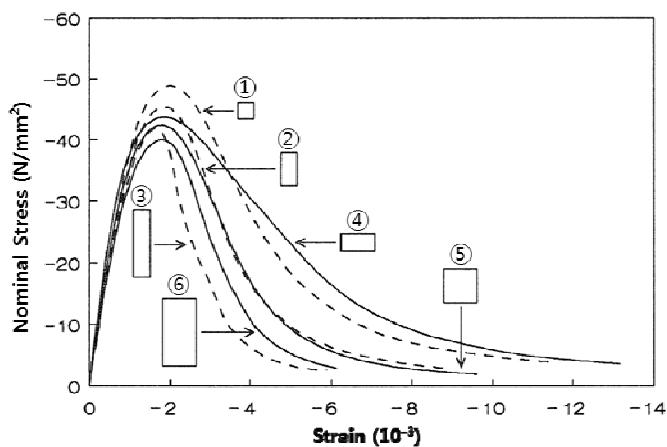


Fig. 2 Stress-Strain curve for different size of specimens

This size effect is also observed in element mesh size of FE analysis. When large finite elements are used, each element has a large effect on the structural stiffness. When a single element cracks, the stiffness of the entire structure is largely reduced to fails easily (Kwak 1990). By focusing on this size effect on failure behavior of concrete in FE mesh and specimen, criterion is proposed based on the fracture energy concept and analytical approach for the size effect is conducted with penetration simulation at the next chapters.

2. INTRODUCTION OF A FRACTURE ENERGY BASED CRITERION

As can be seen in Fig. 3(a) (Vonk 1993), fracture energy is divided into continuum damage energy part and local fracture energy part. Continuum damage energy represents strain hardening portion which varies with size of specimen and local fracture energy represents strain softening portion which has constant value regardless of specimen size (Kwak 1990). Local fracture energy which has large influence on failure behavior of concrete is used to propose a criterion because difference in size can be converted to difference in failure strain with local fracture energy. Local fracture energy part can be approximated by the area of a triangle in Fig. 3(b) and be formulated by adding $F(x)$ the size effect function which has length scale. As a result, eqn (1) is the formulated equation for local fracture energy where ε_0 is the failure strain and ε_c is the critical strain.

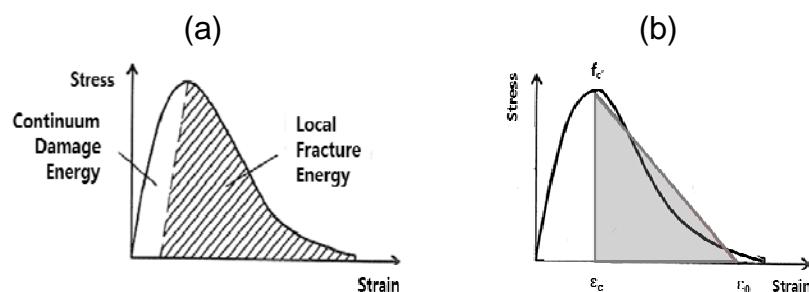


Fig. 3 Fracture energy (a) Configuration, (b) Estimation

The size effect function $F(x)$ divided into $F(b)$ and $F(h)$. $F(b)$ is the function of specimen width and $F(h)$ is the function of specimen length. $F(b)$ is calculated with assuming crack pattern as an exponential function $f(x)=ae^{\beta x}$ [7]. Boundary conditions $f(0)=1$ and $f(b/2)=(b_0/b)^\gamma$ are gained by setting b is width of specimen and center of the specimen is $x=0$ [9]. Using two boundary conditions, $a=1$ and $\beta=(2/b)^\gamma \ln(b_0/b)$ are gained. $F(b)$ is calculated as eqn (2) by integrating $f(x)$ with b and inserting maximum length $b_0=6\text{mm}$ that uniform crack pattern occurs. Fracture energy is given by eqn (3) by substituting $F(b)$ into eqn (1).

$$G_f = \frac{1}{2}(\varepsilon_0 - \varepsilon_c)f'_c F(x) \quad (1)$$

$$F(b) = \frac{2}{b_0} \int_0^{b/2} e^{-\left(\frac{2}{b}\right)\gamma \ln\left(\frac{b}{b_0}\right)x} dx = \frac{\left(\frac{b}{b_0}\right)^\gamma - 1}{\gamma \ln\left(\frac{b}{b_0}\right)} \quad (2)$$

$$G_f = \frac{1}{2}(\varepsilon_0 - \varepsilon_c)f'_c \frac{\left(\frac{b}{b_0}\right)^\gamma - 1}{\gamma \ln\left(\frac{b}{b_0}\right)} F(h) \quad (3)$$

Regression analysis has been carried out to formulate $F(h)$ with experiment data of

failure strain value according to specimen size. In this procedure, $\gamma = 1$ is assumed (Kwak 1990). As can be seen in Table 1 (Van Mier 1986), failure strain is rarely affected by the width of specimen b . Subsequently, $F(b)$ is set to the constant value $F(50)$ during calculation process. $F(h)$ is governed by eqn (4), where critical strain $\varepsilon_c = 0.0135$ that is normal value for 48(Mpa) concrete and fracture energy $G=8.5(\text{Nmm/mm}^2)$ given by experiment by Vonk(1993).

$$F(h) = \frac{2G_f}{(\varepsilon_0 - \varepsilon_c)f'_c F(50)} \quad (4)$$

Table 1: Measured failure strains according to size of specimens

Height of specimen (mm)	Width of specimen (mm)	Failure strain (ε_0)
50	50	0.0103
50	100	0.01
100	100	0.0069
100	50	0.0071
200	50	0.0052
200	100	0.005

Fig. 4 shows result of regression analysis with the data from Table 1. The trend line follows $F(h)$ function. Finally $F(h)$ is governed by eqn (5) and criterion is proposed by eqn (6).

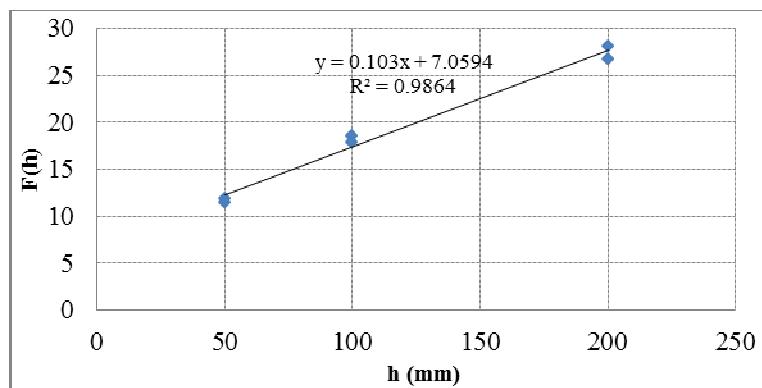


Fig. 4 Regression analysis for $F(h)$

Unique failure strain for each mesh size is proposed by this criterion eqn (6) and applied to FE analysis under high strain rate condition. b is defined as mesh width size and h is defined as mesh height. The optimized value of $\gamma = 4.9$, which shows good

agreement with being applied to mesh, is assumed.

$$F(h) = 0.0103h + 7.06 \quad (5)$$

$$\varepsilon_0 = \frac{2G_f \gamma \ln(\frac{b}{b_0})}{f_c' \left(\left(\frac{b}{b_0} \right)^\gamma - 1 \right) (0.103h + 7.06)} + \varepsilon_c \quad (6)$$

3. PENETRATION SIMULATION

In this chapter, penetration simulation is performed for HJC, CSC, K&C models using LS-DYNA commercial FE analysis program. Configuration of simulation can be seen as Fig. 5. Initial velocity of projectile is 400(m/s) (Hanchak 1992) and original failure strain is 0.01 (Holmquist 1993). Residual velocity of projectile after penetration is checked with changing mesh size of plate to find out mesh-dependency. Furthermore, after applying failure strain of criterion on concrete plate, residual velocity of projectile is rechecked to confirm improvement in mesh-dependency.

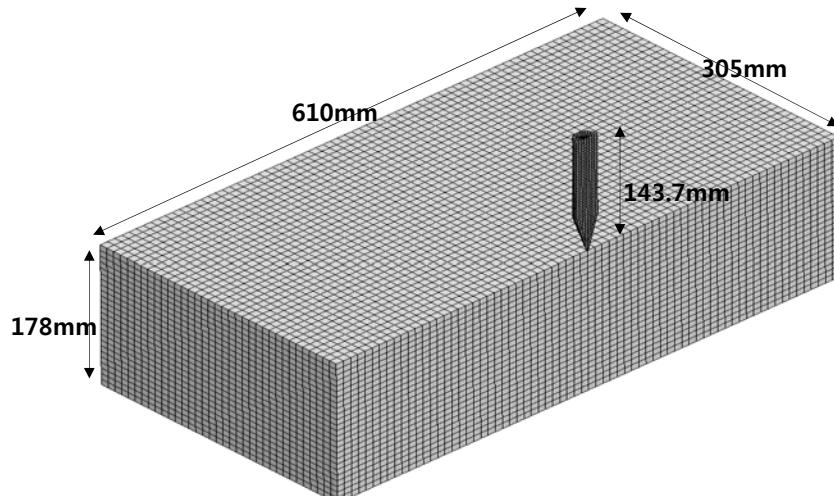


Fig. 5 Configuration of penetration simulation

Each model has 3 sets of cases which has different height of mesh. For case1, plate is divided into 5 pieces along the height direction, for case 2, 10 pieces, and for case 3, 25 pieces. All cases have 6 different width size of mesh. Simulation results are shown as Fig. 6, 7 and 8. Black lines are case 1, grey lines are case 2, light grey lines are case3 and dashed lines represent the results of simulation that failure strain of criterion is applied to.

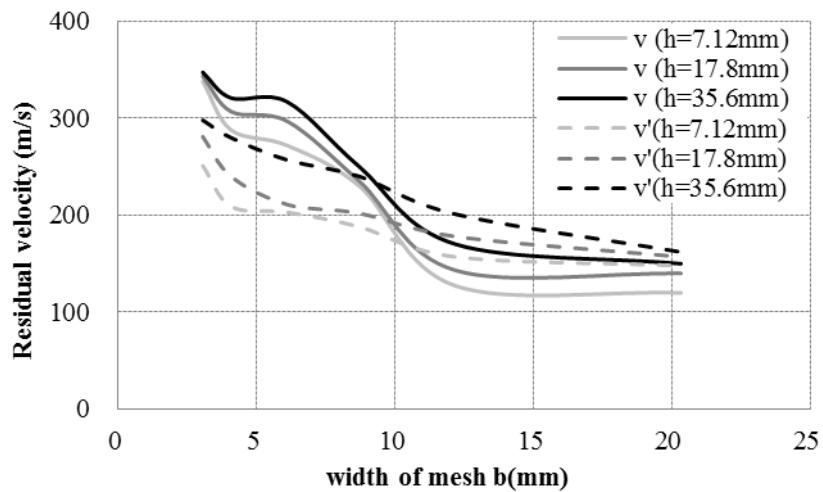


Fig. 6 Residual velocity versus width of mesh (HJC model)

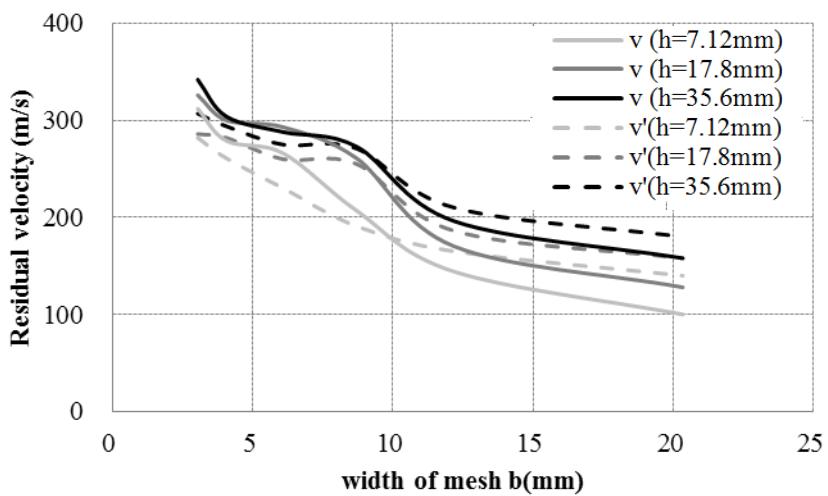


Fig. 7 Residual velocity versus width of mesh (CSC model)

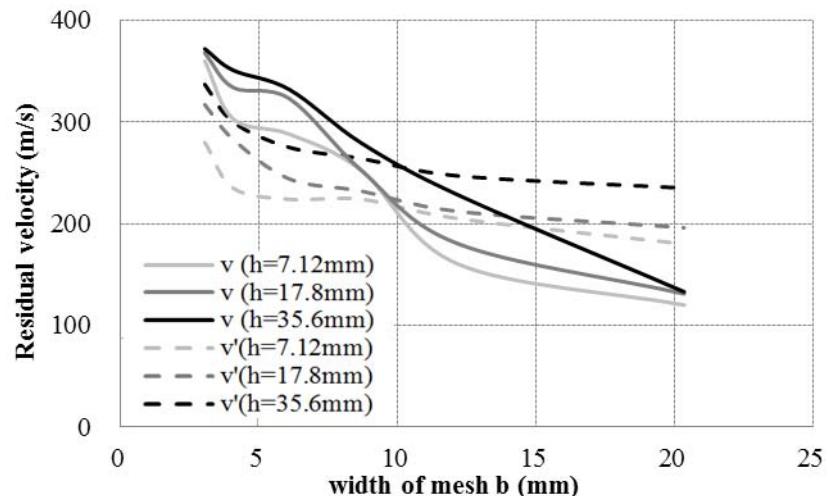


Fig. 8 Residual velocity versus width of mesh (K&C model)

Failure strain caculated by criterion is described in Table 2, where h is height of mesh and b is width of mesh. As can be seen in these figures, simulation results before applying criterion shows a significant mesh-dependency. HJC model has 201(m/s) difference in residual velocity, CSC model has 198(m/s) and K&C model has 239(m/s) difference in residual velocity according to mesh size. Accuracy of simulation results cannot be assured with these values. When failure strain determined by the criterion is applied to concrete plate in FE analysis, variation of simulation results are greatly decreases. As can be seen dashed lines in Fig. 6, 7, 8, difference in residual velocity is reduced. HJC model has 121(m/s) difference in residual velocity, CSC model has 131(m/s) and K&C model has 100(m/s) difference in residual velocity according to mesh size. In conclusion, mesh dependency in penetration simulation accompanied with high strain rate is improved by using the criterion proposed in this paper.

Table 2: Failure strain calculated by criterion according to size of mesh

b (mm)	Case 1 (h=35.6mm)	Case 2 (h=17.8mm)	Case 3 (h=7.12mm)
3.05	0.0354	0.0414	0.0460
4.07	0.0354	0.0414	0.0460
6.1	0.034	0.0397	0.0445
8.71	0.0133	0.0154	0.0171
12.2	0.00512	0.00578	0.00634
20.3	0.00187	0.00196	0.00203

4. CONCLUSION

In this study, the mesh-dependency of high strain models (HJC model, CSC model and K&C model) is investigated with the penetration simulations. Criterion based on the concept of fracture energy is introduced to minimize the mesh-dependency. Simulation results show that the variation of simulation results(residual velocity) with the used FE mesh size is greatly reduced by applying a unique failure strain value determined according to the proposed criterion. In conclusion, the mesh-dependency in FE analysis of concrete structure subjected to blast and impact loading can be improved with the criterion proposed in this paper.

Acknowledgments

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