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# Nonlinear analysis of RC slab subjected to blast loading

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## ABSTRACT

This study proposes an improved numerical model for nonlinear analysis of reinforced concrete (RC) slab subjected to blast loading. The proposed model deals with the orthotropic constitutive model of concrete considering the strain rate effect. The mesh size sensitivity of numerical results is solved by introducing failure criteria into the stress-strain relation of concrete on the basis of the fracture energy concept. Moreover, the bond-slip effect, which has a significant influence on the nonlinear behavior of RC structures, is considered by introducing the modified bending stiffness. The correlation studies between the numerical results and the experimental data are conducted in terms of time history relation.

## 1. INTRODUCTION

In RC structures, structural behavior under dynamic loading condition is remarkably different from that under quasi-static loading (Qu et al. 2016). Under high strain rate condition, material properties of concrete and reinforcing steel are changed Carta and Stochino 2013; Jacques et al. 2013; Zhao and Chen 2013). Since RC slabs represent two-dimensional out-of-plane behavior, orthotropic concrete model to describe biaxial behavior of concrete is adopted. The model determines stresses in each principal coordinate by using uniaxial stress-strain relations with equivalent dynamic strengths determined from strain rate dependent biaxial strength envelope. To solve size dependency in a finite element, the improved failure strain describing the softening behavior of concrete is introduced on the basis of fracture energy concept. In this equation, the increase in fracture energy due to strain rate as well as the increase in strength due to strain rate is reflected. The bond-slip between concrete and reinforcing bar significantly affects the nonlinear response of RC members. The previous bond-slip model proposed by Lee and Kwak (2018) had a limitation that the length of the element should be fixed to the plastic hinge length in order to consider the bond-slip effect. Since the application of this model increases the number of elements in the slab members, this reduces the efficiency of the analysis. To improve this, this

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study proposes a model considering the bond-slip effect on arbitrary element length. Correlation studies between the numerical results and experimental test data have been conducted in terms of the mid-span deflection and time histories.

## 2. CONSTITUTIVE MATERIAL MODELS

### *2.1 Concrete*

Strengths of concrete depend on combination of stresses under biaxial stress state. This paper adopts the biaxial strength envelope proposed by Gang and Kwak (2017a) in Fig. 1, which consists of biaxial compression region, compression-tensile region, and biaxial tensile region. Strain rate effects are considered in each region. HJC model (Holmquist et al. 1993) is adopted for dynamic increase factor (DIF) equation of uniaxial compressive strength, and the equation is multiplied by static biaxial compressive strength envelope of concrete which modified Yan and Lin (2007) model. Modified CEB-FIP (Malvar and Crawford 1998) is considered as DIF of uniaxial tensile strength. In the compression-tension region, compressive strength decreases almost linearly with increasing principal tensile strength.

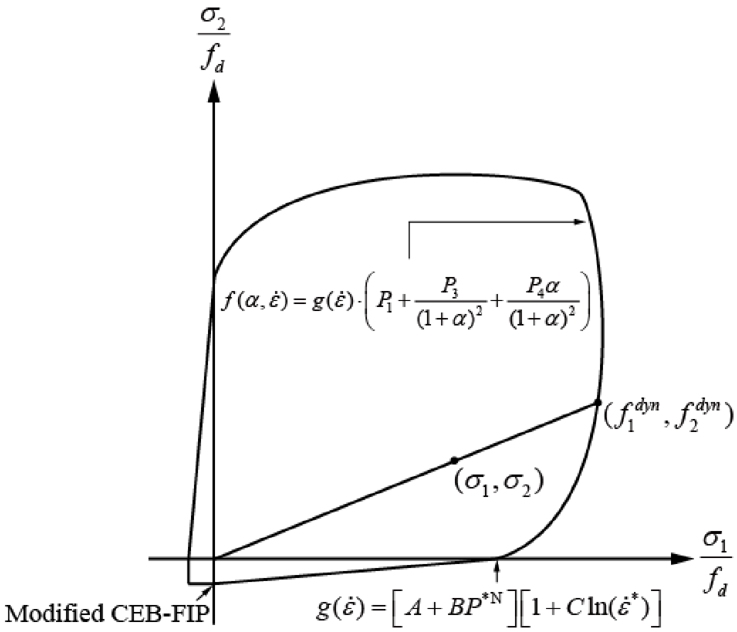



Fig. 1 Biaxial dynamic strength envelope of concrete

By using biaxial strength envelope, equivalent uniaxial strengths to reflect biaxial stress state can be determined (Fig. 1). Uniaxial stress-strain relations of concrete with these strengths are defined. Kent and Park (1971) model is adopted for the compressive region and the tension region consists of bilinear curves. The ultimate strains to determine softening behavior of concrete have a significantly important role in minimizing size sensitivity of numerical results. This study proposes the criteria of ultimate strains based on the fracture energy concept. The criterion proposed by by Gang and Kwak (2017b) has been modified to reflect the increase in material properties such as strength and fracture energy under dynamic stress conditions, and the equation is expressed as follows;

$$\varepsilon_{tu} = \frac{4.2G_f(1+0.883(\dot{\varepsilon}_t)^{0.331})\ln(b/b_0)}{3f_t(\dot{\varepsilon}_t/\dot{\varepsilon}_{t0})^{\delta}((b/b_0)^{2.1}-1)} + \varepsilon_{t0}, \quad \dot{\varepsilon}_t \le 1s^{-1}$$
$$\varepsilon_{tu} = \frac{4.2G_f(1+0.745(\dot{\varepsilon}_t)^{0.785})\ln(b/b_0)}{3f_t\beta(\dot{\varepsilon}_t/\dot{\varepsilon}_{t0})^{1/3}((b/b_0)^{2.1}-1)} + \varepsilon_{t0}, \quad \dot{\varepsilon}_t > 1s^{-1} \tag{1}$$

where $G_f$ and $f_t$ represent the static tensile fracture energy and the static tensile strength, respectively; *b* is the width of an element; $b_0 = 6mm$, $\dot{\varepsilon}_{t0} = 10^{-6}s^{-1}$, $\delta = (1+8f_c/10)^{-1}$, $\log\beta = 6\delta - 2$.

The difference of analytical results according to consideration of tension stiffening effect was confirmed in numerical application of chapter 4. From the stress-strain relations, modulus of elasticity and principal stress in each principal direction are determined and the constitutive relation can be constructed. Finally, stresses in global coordinates can be calculated by applying transformation matrix of orthotropic model.

### *2.2 Steel*

Reinforcing steel consists of linear elastic curve and strain hardening curve after yielding. The strain rate effect of reinforcement is also taken into consideration. Dynamic increase factor as used by Malvar (1998) is adopted.

## 3. BOND-SLIP EFFECT

Consideration of the bond-slip effect is important for accurate prediction of nonlinear analysis of RC members because the bond-slip between concrete and reinforcement is enlarged to accompany the rigid body rotation as additional rotation. The bond-slip effect can be considered in the previous paper (Lee & Kwak, 2018) by using equivalent bending stiffness, and the equation can be expressed as follows:

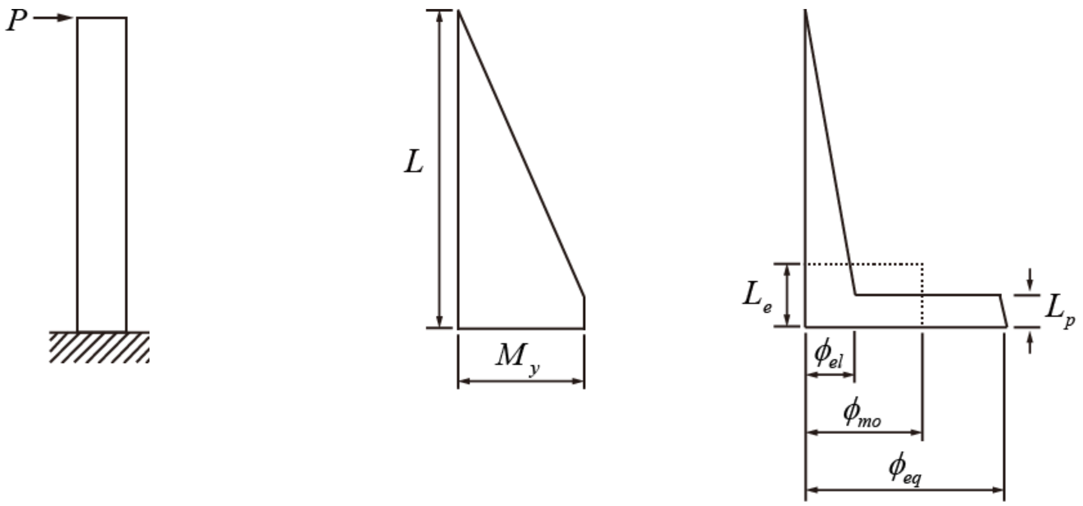
$$\frac{1}{EI_{eq}} = \frac{1}{\beta \times K_\theta \times L} + \frac{1}{EI} \tag{2}$$

where $\beta = \alpha(1-\alpha+1/3\alpha^2)$ and $\alpha = L_p/L$. β is the proportional constant depending on boundary condition and loading type. In the case of simply supported beam under uniformly distributed loading, the expression of $\beta = \alpha(1-1/2\alpha-1/3\alpha^2+1/4\alpha^3)$ can be obtained. The plastic hinge length $L_p$ proposed by Paulay and Priestley (1992)is used.

However, this model has a limitation that the length of the element should be equal to the plastic hinge length. In order to consider the bond-slip effect regardless of the element size, this paper proposes the modified bending stiffness on the basis of the energy equilibrium equation. Fig. 2 shows assumed distributions of moment and curvature in a RC member. Strain energy $U$ can be defined by the relation between moment and curvature of $U = \int M \cdot \emptyset dx$. The strain energy $U_1$ within element length $L_e$ can be evaluated from the sum of elastic region of $L_e - L_p$ and plastic region of $L_p$, and the average strain energy $U_2$ within the same region of $L_e$ can be obtained by the average curvature $\emptyset_{mo}$. From the equality between $U_1$ and $U_2$, the modified bending stiffness can be determined as following relation.

$$\frac{1}{EI_{mo}} = \frac{R_1}{EI} + \frac{R_2}{EI_{eq}} \tag{3}$$

where $R_1$ and $R_2$ depend on the loading types. $R_1 = \left(L - (L_e + L_p)/2\right)^2 (L_e - L_p)/\{(L - L_e/2)^2 L_e\}$, $R_2 = \left(L - L_p/2\right)^2 L_p/\{(L - L_e/2)^2 L_e\}$.




(a) a cantilever RC member (b) moment distribution (c) curvature distribution

Fig. 2 Moment and curvature distributions in a cantilevered RC member

## 4. NUMERICAL APPLICATIONS

The nonlinear analysis model is based on 8-node element with 3x3 Gaussian integration for bending and the reduced integration for shear stiffness by using Fortran code. In order to verify the accuracy of the proposed model, in this study the correlation studies between numerical simulations and experimental data have been conducted. The slab of RSCR1, which was experimented by Thiagarajan and Johnson (2014), was used for numerical simulation. The blast loading used in numerical analysis was obtained from linear idealization of the experimental data. The blast load was assumed to be uniformly distributed load. As shown in Fig. 3, two different element sizes modeled 12 elements and 16 elements are considered to check the efficiency of the proposed bond-slip model. Fig. 4 shows the time-displacement relations according to consideration of bond-slip effect. The numerical results considering bond-slip effect show good correlations with experimental data regardless of element sizes. However, the remarkable difference occurs by consideration of the bond-slip effect or not. Thus, the consideration of bond-slip effect is important to improve the accuracy of the simulation results, and the proposed bond-slip model can be effectively used to reduce the number of element in numerical analysis. In addition, Figure 5 shows analytical results without considering the tension stiffening effect. Unlike the results shown in Fig. 4, it can be seen that the results of Fig. 5 depend on the size of the element.

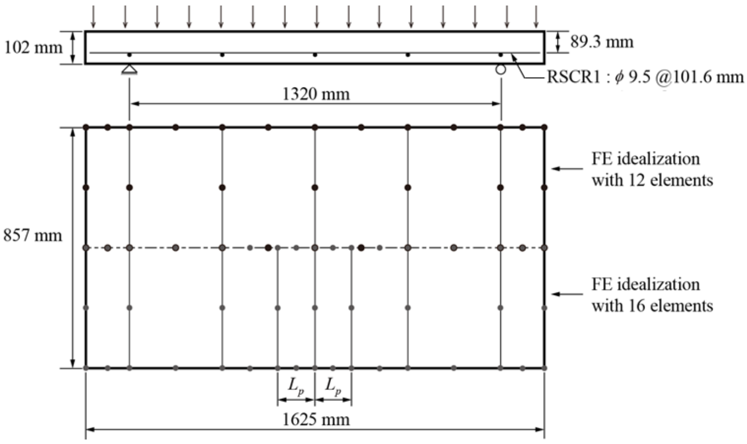



Fig. 3 FE idealization of RSCR1 slab

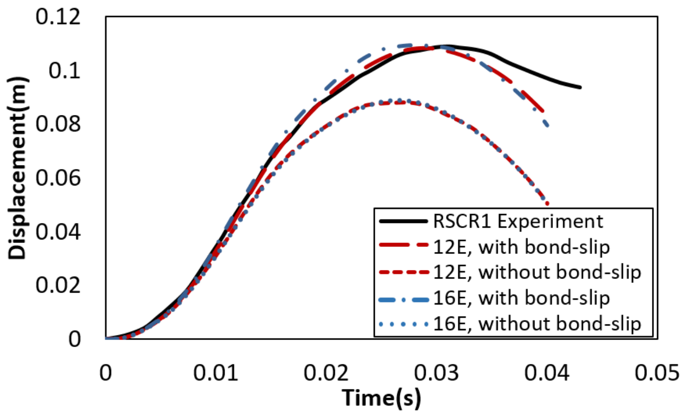



Fig. 4 Time-displacement relations of RSCR1

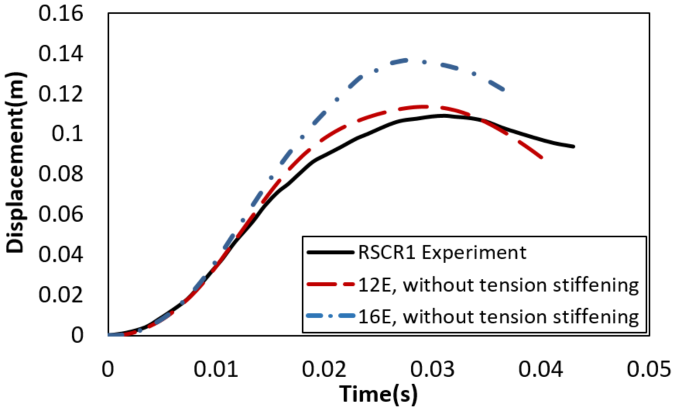



Fig. 5 Time-displacement relations without considering tension stiffening effect

## 5. CONCLUSIONS

This paper introduces the numerical model for reinforced concrete (RC) slab subjected to blast loading. The proposed model considers the orthotropic model with biaxial strength envelope for concrete, and strain rate effects for concrete and steel are also taken into account. Furthermore, bond-slip effect by changing the bending stiffness of elements. The numerical results have been compared with experimental results to testify the accuracy of the numerical model. As a result, the proposed model can be used to describe the nonlinear behavior of RC slabs under blast loading condition.

## ACKNOWLEDGEMENTS

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