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Nonlinear dynamic analyses of RC beams under blast loading

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ABSTRACT

This paper presents the numerical model using the improved layered section method that reflects the bond-slip effect to estimate the structural responses of reinforced concrete beams under blast loading. The material strength increment at high strain rates is considered by using the dynamic increase factor (DIF). To consider bond-slip effect, the equivalent bending stiffness within plastic hinge length is introduced. Through the comparisons of the numerical results and experimental test data in terms of the mid-span deflection and time histories, the results demonstrate that the proposed model can be effectively used in estimations of time-displacement response.

1. INTRODUCTION

The studies of the dynamic responses of RC members like beams, slabs, and columns under extreme loads have been conducted with considerable attention. In RC structures, structural behavior under blast and impact loads is remarkably different from that under quasi-static loading (Qu et al. 2016). The material strength increment at high strain rates is considered by using the dynamic increase factor (DIF), defined as the ratio of dynamic to static strength. The bond-slip between concrete and steel bar is important for accurate prediction of nonlinear response of RC structures. At the plastic hinge region such as the mid-span of the beam or the beam-column joint, bond-slip occurs and accompanies the additional rotation. To consider bond-slip effect, the equivalent bending stiffness within plastic hinge length is introduced. Verification of the numerical model is made through the comparisons of the numerical results and experimental test data in terms of the mid-span deflection and time histories.

2. NUMERICAL MODEL

2.1 Material models

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In this study, Kent and Park (1971) model is adopted to define monotonic envelope curve for concrete, and Taucer et al. (1991) is used for the cyclic stress-strain relation. Concrete is strain rate sensitive material. To consider the strain rate effect for compressive and tension region of concrete, dynamic increase factor (DIF) is used and can be expressed as follows (Saatcioglu et al. 2011).

$$\mathrm{DIF} = 0.03 \ln \dot{\varepsilon} + 1.30 \geq 1.0 \quad \text{for } \dot{\varepsilon} < 30s^{-1} \tag{1}$$
$$\mathrm{DIF} = 0.55 \ln \dot{\varepsilon} - 0.47 \quad \text{for } \dot{\varepsilon} > 30s^{-1} \tag{2}$$

For reinforcing steel, Menegotto and pinto (1973) model is used. The strain rate effect of reinforcement is also taken into consideration. Dynamic increase factor as used by Saatcioglu et al. (2011) is adopted and is presented as Eq. (3).

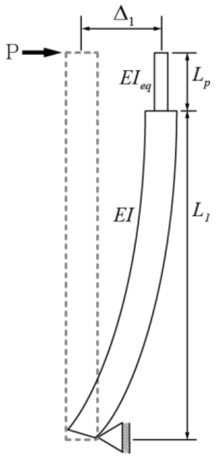
$$\mathrm{DIF} = 0.034 \ln \dot{\varepsilon} + 1.30 \geq 1.0 \tag{3}$$

2.2 bond-slip effect

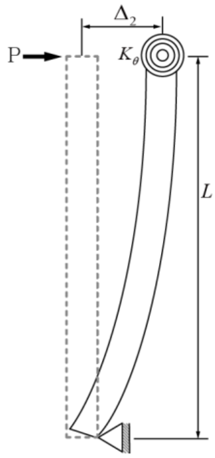
The bond-slip between concrete and steel bar is important for accurate prediction of nonlinear response of RC structures. The bond-slip effect becomes more significant after reinforcing steel yields. As bond-slip occurs, the rigid body rotation as additional rotation is accompanied in RC beam. In this study, it is assumed that the bond-slip is concentrated in plastic hinge region. The plastic hinge length L_p proposed by Bayrak and Sheikkh (1997) is used. To take into account the bond-slip effect, this study introduces equivalent bending stiffness EI_{eq} within plastic hinge length. A half of a simply support RC beam considering equivalent bending stiffness is represented as free body diagram in Fig. 1(a). If load P is applied on the beam, the maximum deflection Δ_1 can be obtained by the moment area method. As shown in Fig. 1(b), the beam can also be idealized by using rotational stiffness K_θ, and the maximum deflection Δ_2 is evaluated from the sum of the elastic deformation and the deformation due to the rigid body rotation. From the equality between Δ_1 and Δ_2, the equivalent bending stiffness can be determined as following relation.

$$\frac{1}{EI_{eq}} = \frac{1}{\beta \times K_\theta \times L} + \frac{1}{EI} \tag{4}$$

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.



(a) RC beam with EI_{eq}

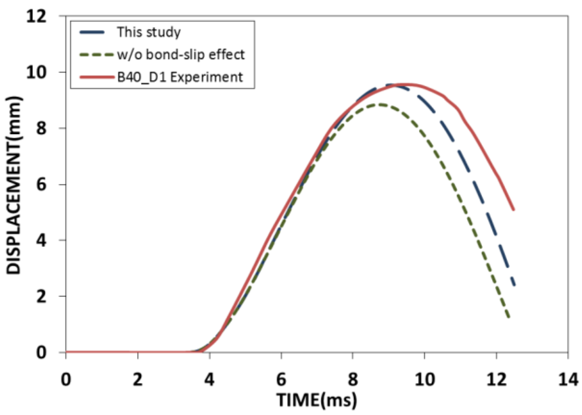


(b) RC beam with K_θ

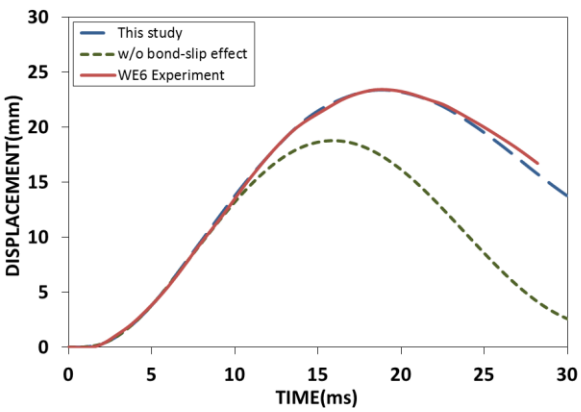
Fig. 1 Half-span of RC beam

3. MODEL VERIFICATION

In order to verify the proposed model, simply supported RC beams of B40_D1 and WE6 under blast loading are investigated and discussed (Magnusson and Hallgren 2000; Seabold 1967). More details related to the experimental setup can also be found elsewhere (Magnusson and Hallgren 2000; Seabold 1967). Figure 2 presents a comparison of the experimental results with the predicted results for the mid-span deflections with time for specimens B40_D1 and WE6. The results of the proposed model show a good correlation with experimental data. In the case of B40_D1, because the blast loading is not large enough to develop yielding of tensile reinforcement, the difference in numerical results according to consideration of bond-slip effect is small. After yielding, the bond-slip effect becomes significant. An exact prediction of the post-peak displacement history may depend on the exactness in defining the unloading and reloading behavior of reinforcing steel.



(a) B40_D1



(b) WE6

Fig. 2 Mid-span deflection with time

4. CONCLUSIONS

In this paper, the numerical model using the improved layered section method is presented and this model can reflect the bond-slip effect to estimate the structural responses of RC beams under blast loading. The numerical results demonstrate that the proposed model can be effectively used in estimations of time-displacement response.

ACKNOWLEDGEMENTS

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REFERENCES

Bayrak, O., & Sheikkh, S. (1997), “High-strength concrete columns under simulated earthquake loading”, *ACI Structural Journal*, 94(6), 708–722.
Kent, D. C., & Park, R. (1971), “Flexural members with confined concrete”, *In Journal of the Structural Division.,* 97, 1969–1990.
Magnusson, J., & Hallgren, M. (2000), “High performance concrete beams subjected to shock waves from air blast”, Tumba, Sweden.
Qu, Y., Li, X., Kong, X., Zhang, W., & Wang, X. (2016), “Numerical simulation on dynamic behavior of reinforced concrete beam with initial cracks subjected to air blast loading”, *Engineering Structures*, 128, 96–110.
Saatcioglu, M., Lloyd, A., Jacques, E., Braimah, A., & Doudak, G. (2011), “Focused research for development of a CSA standard on design and assessment of buildings subjected to blast loads”, *University of Ottawa*.
Seabold, R. H. (1967), “Dynamic shear strength of reinforced concrete beams, part 2”, Port Hueneme, CA: US Naval Civil Engineering Laboratory.
Taucer, F. F., Spacone, E., & Filippou, F. C. (1991), “A fiber beam-column element for seismic response analysis of reinforced concrete structures”, *Report No. UCB/EERC-91/17*.