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Analysis of dynamic behavior of RC structures subjected to blast loading

*Hyo-Gyoung Kwak[1],Gang-Kyu Park[2] and MinJoo Lee[3]

[1), 2),3)] *Department of Civil Engineering, KAIST, Daejeon, Korea*
[1)] *kwakhg@kaist.ac.kr*

ABSTRACT

This study proposes a nonlinear numerical method to predict dynamic behavior of RC structures subjected to uniformly distributed blast loadings. Based on the Timoshenko's beam theory, a nonlinear analysis is carried out on the basis of the moment-curvature relationship of RC section and a dynamic increase factor (DIF) depending on the curvature rate, instead of strain rate, is newly designed. The plastic hinge length is considered to simulate the plastic deformation mainly occurred at the critical regions such as beam-column joint and mid-span. Within the regions, the modification of the moment-curvature relationship is performed in order to simulate the bond-slip after yielding of main reinforcement. Then, the validity of the proposed method is performed by comparing the numerical results with the experimental results.

1. INTRODUCTION

When subjected to blast or impact loading, the structural behavior is different from the behavior under static loading. This difference arises from the change in material properties with the effect of high strain rate(Bischoff and Perry 1991). Therefore, to exactly simulate the structural behavior subjected to blast or impact loading, the increase in material properties according to strain rate must be considered in numerical analysis. The change in the material properties according to strain rate can be expressed by DIF (Dynamic Increase Factor) equations and these equations are usually defined on the basis of stress-strain curves. Many researchers has proposed various DIF formulations including CEB-FIP model and can be found elsewhere (CEB-FIP 1993; Malvar and Crawford 1998; Saatcioglu et al. 2011).

In this paper, a numerical nonlinear method based on the moment-curvature relationship of a RC (reinforced concrete) section is proposed. Since the moment-curvature relationship of a RC section is basis of the proposed numerical method, a DIF equation in terms of the curvature rate, instead of strain rate, should be newly designed.

[1)] Professor
[2)] Graduate Student

In addition, the moment-curvature relationship of a RC section should be modified in order to consider the bond-slip between steel and surrounding concrete, which is caused by the onset of the crack and will be increasingly accelerated with the increase of the crack width. Then, the proposed method is verified by comparing the numerical results with the experimental results.

2. MATERIAL PROPERTIES

2.1 Concrete

Among the numerous concrete numerical models to simulate the nonlinear behavior of RC structures, this paper adopted the stress-strain curve proposed by Kent and Park and modified by Scott et al. (Scott et al. 1982). Based on the used numerical model, the DIF equation should be taken into account in order to reflect the increase in the material properties with the strain rate under blast or impact loading condition. In this paper, the DIF equation proposed by Saatcioglu et al. (Saatcioglu et al. 2011) is applied among many proposed relations, and can be expressed as follows: $\mathrm{DIF} = 0.03\ln\dot{\varepsilon} + 1.3 \geq 1.0$ for $\dot{\varepsilon} < 30s^{-1}$, and $\mathrm{DIF} = 0.55\ln\dot{\varepsilon} - 0.47$ for $\dot{\varepsilon} \geq 30s^{-1}$.

2.2 Steel

The stress-strain relation of reinforcing steel is modeled as a linear elastic and linear hardening material. As in the case of concrete, the DIF equation proposed by Saatcioglu et al. (Saatcioglu et al. 2011) is adopted to take into account the effect of strain rate and is presented as follows: $\mathrm{DIF} = 0.034\ln\dot{\varepsilon} + 1.30 \geq 1.0$

2.3 Moment-curvature relationship

The moment-curvature relationship of a RC section can be determined through the strain compatibility and force equilibrium in a section on the basis of the given condition of the section such as the position and amount of steel, material properties of concrete and steel, and the size of the section (Al-Zaid et al. 2012). From the obtained moment-curvature relationship, tri-linear relationship including the crack point and the yield point is used and presented in Fig. 1.

Basically, the moment-curvature relationship is constructed on the basis of the perfect bond assumption between concrete and steel (Kwak and Kim 2004). However, the occurrence of crack leads to the bond-slip between concrete and steel, which causes inelastic deformation. After yield of reinforcing steel, especially, the inelastic deformation will increase with the enlarged bond-slip. In that case, therefore, the moment-curvature relationship based on the perfect bond assumption is no longer applicable, and the moment-curvature relationship should be modified to exactly simulate the inelastic behavior caused by the bond-slip effect, which is presented in Fig. 2. The modification of the moment-curvature relationship is applicable to the plastic hinge region such as the mid-span or beam-column joint. Then, DIF equation in terms of curvature rate is applied to the moment-curvature relationship.

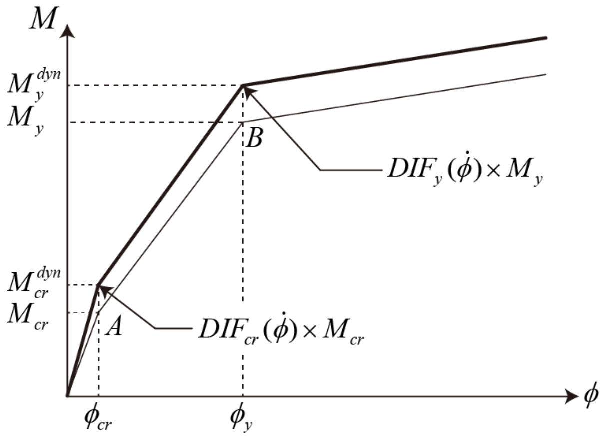

Fig. 1 Moment-curvature relationship of a RC section

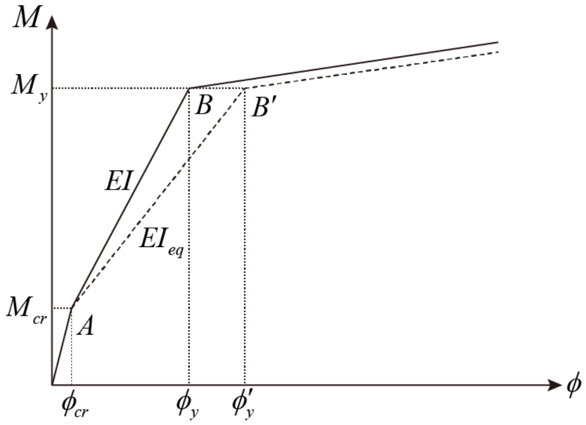

Fig. 2 Modification of the moment-curvature relationship

3. APPLICATION

Two RC structures are investigated to verify the applicability of the proposed method. First, a simply supported beam B40-D3 tested by Magnusson and Hallgren (Magnusson and Hallgren 2000) is employed, and the experimental and the numerical results are presented in Fig. 3. This beam is modeled with 10 elements along the entire span, and 2 elements are assigned to the plastic hinge region (the mid-span) in order to the effect of the bond-slip. Two different numerical results are classified as follows: the first case takes into account the effect of the bond-slip (Case A), and the second case does not consider bond-slip effect (Case B).

As can be seen in Fig. 3, the numerical results by Case A and Case B provide good agreement with the experimental result for the maximum displacement as well as the corresponding time. In this case, the applied blast loading is too small to reach the yield point, which means the effect of the bond-slip has little influence on the numerical results.

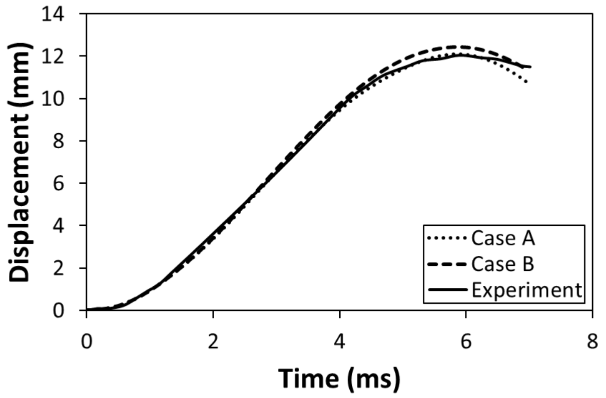

Fig. 3 Displacement time history of B40 beam

Second specimen is SCC column which was examined by Burrell et al. (Burrell et al. 2014). The classification of the numerical results is the same as for beam B40. A total of 18 elements are used, and 4 elements are assigned to the plastic hinge regions (the mid-span and both clamped boundary). The numerical result with consideration of the effect of the bond-slip show relatively good agreement with the experimental data for the maximum displacement as well as the corresponding time. On the other hand, the numerical result without consideration of the effect of the bond-slip shows considerable difference from the experimental result. This means that the effect of the bond-slip should be considered if blast loading is large enough to cause the yielding.

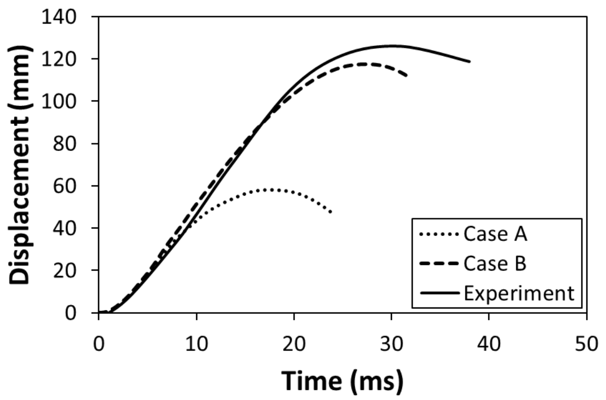

Fig. 4 Displacement time history of SCC column

4. CONCLUSIONS

The nonlinear numerical method is introduced to simulate the dynamic behavior of RC structures subjected to blast loading. The proposed method can effectively predict the structural response.

ACKNOWLDEGEMENT

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