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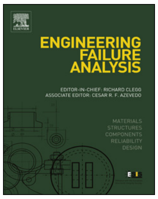

Evaluation of nonlinear behavior and resisting capacity of reinforced concrete columns subjected to blast loads

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ABSTRACT

A numerical method to estimate the dynamic response of reinforced concrete (RC) columns subjected to axial and blast loads is introduced in this paper. Upon adopting Timoshenko's beam theory, both the flexural and direct shear behaviors are incorporated into the numerical formulation. The moment-curvature relationship of a reinforced concrete (RC) section is based on the construction of the bending stiffness and, in advance, a dynamic increase factor (DIF), usually defined in the stress-strain relations of concrete and steel, is newly designed to be defined in the moment-curvature relation. In addition to the description of the dynamic characteristics in the RC section, additional modification of the moment-curvature relation is also performed to exactly simulate the large plastic deformation concentrated at the mid-span or beam-column joint due to the bond-slip or anchorage slip after yielding of the main reinforcement. Finally, the validity of the proposed method is verified by comparing the analytical results with the experimental data, and then the pressure-impulse (P–I) diagrams are constructed and compared to review the change in the resisting capacity of a RC column according to the variation of the axial force and slenderness ratio.

1. Introduction

As concerns about explosions including bombing attacks rise, blast-resistant design has become one of the most important factors for structural safety. When a reinforced concrete (RC) structure is subjected to impact or blast loading, the strength and stiffness of the concrete and reinforcing steel increase with the strain rate, unlike a quasi-static loading condition, which does not accompany strain rate dependent behavior [1]. Therefore, in order to accurately describe the nonlinear behavior of RC structures subjected to impact or blast loading, the strain rate effect on the constituent materials must be taken into consideration.

Beyond previous studies ranging from experiments including SHPB (Split Hopkinson Pressure Bar) tests [2, 3] to identify material properties under a high strain rate condition to numerical analyses of structures under impact loading [4, 5], Remennikov et al. [6] conducted static and dynamic experiments with conventional RC columns by applying static loading and impact with a drop hammer, respectively. The numerical results for the load-deflection and cracking responses of the specimens were also compared with experimental data. With regard to numerical analyses of RC columns, Bao and Li [7] conducted numerical analyses of RC columns subjected to blast loads by using the commercial program LS-DYNA in order to simulate the dynamic response and to evaluate the residual axial strength after the blast loadings. In addition, various numerical algorithms or models, from a simple approach using a

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SDOF(Single Degree Of Freedom) model [8] to a rigorous finite element analysis using numerous solid elements [9], have been proposed, and the obtained results have been implemented into commercial programs such as LS-DYNA [10] and ABAQUS [11] used to describe the nonlinear behavior of RC structures under impact or blast loading conditions.

While various numerical methods have been proposed, each method still presents some problems or difficulties in numerical modeling of RC columns. In the case of using a solid element, since the numerical results vary depending on the mesh-size [12] and the adopted 3D(three dimensional) failure criterion for concrete such as the HJC (Holmquist Johnson Cook), CSC (Continuous Surface Cap) or K&C (Karagozian & Case) model, the user must be skilled and have a great deal of experience. The classical layer model, which is popularly used in the nonlinear analysis of RC structures [13, 14], is not an exception. Since an RC section must be divided into multiple layers in order to simulate nonlinear behavior, a large number of solution steps are required, and thus this model has a restriction for the nonlinear analysis of an entire structure. In addition, the bond-slip effect is not considered in this model since a perfect bond is assumed between the main reinforcement and surrounding concrete [15]. Therefore, the layer model has inherently difficulty in simulating the behavior after yielding of the main reinforcement accompanying fixed-end rotation. Besides, the use of a SDOF model is also limited in the design practice because this model may lead to unreliable results because a large number of simplified assumptions are adopted. [16, 17].

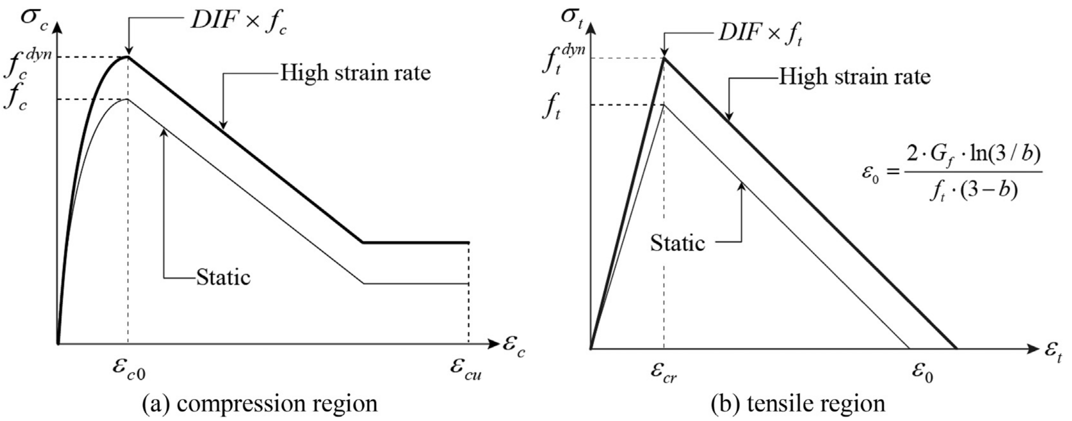
To address these restrictions in the nonlinear numerical analyses of RC columns, an improved nonlinear method including the flexural and direct shear behaviors is introduced in this paper. Upon constructing the moment-curvature relationship for flexural behavior, a DIF (Dynamic Increase Factor) equation defined in terms of the curvature rate has been newly proposed to reflect the strain rate effect, and the proposed DIF makes it possible to trace the dynamic behavior of RC columns subjected to blast loadings on the basis of the moment-curvature relation. The moment-curvature relationship is modified in order to describe the effect of bond-slip caused by the yielding of reinforcement at the critical regions. In particular, the use of the moment-curvature relation of a RC section makes it possible to trace the global behavior of RC structures subjected to blast loadings. This is because, unlike the rigorous 3D analyses of RC structures based on advanced modeling techniques that employ 3D failure criterion, the proposed analytical approach does not need to discretize the entire structure with numerous elements. On the other hand, very high amplitude blast loading with high pressure and short duration leads to a shear dominant structural response that is remarkably different from the usual bending behavior [18, 19]. Accordingly, to exactly evaluate the resisting capacity regardless of the blast loading characteristic, the direct shear behavior has been taken into account as well through implementation of the shear stress-slip relation empirically proposed by many researchers [20–22]. Finally, the efficiency of the proposed method is verified through a comparison of the experimental data with the numerical results of RC columns subjected to blast loading, and additional parametric studies are carried out to examine the influence of the parameters on the resisting capacity of RC columns which can be expressed by the pressure-impulse (P–I) diagram.

2. Material properties

2.1. Concrete

To trace the nonlinear behavior of RC structures under static or dynamic loadings, the stress-strain relations of concrete must be defined. Numerous mathematical models have been proposed to describe the nonlinear behavior of concrete, and this paper adopts the monotonic stress-strain relation proposed by Kent and Park and later modified by Scott et al. [23] because of its simplicity and computational efficiency. Fig. 1(a) represents the stress-strain relation consisting of three regions in compression regime and more details related to the corresponding equations can be found elsewhere [24, 25].

On the other hand, it is assumed that concrete in tension is linearly elastic up to reaching the tensile strength and then the tensile stress linearly decreases with an increase of the tensile strain, as shown in Fig. 1(b). When the strain exceeds the value of ε_0, concrete in tensile fiber does not have any more resistant capacity because of cracking. The equation of the stress-strain relation in the tension region is expressed in Fig. 1(b), where b is the length of elements and G_f is the fracture toughness of concrete [24].



(a) compression region (b) tensile region

Fig. 1. Stress-strain relation of concrete.