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An improved criterion to minimize FE mesh-dependency in concrete structures under high strain rate conditions

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ABSTRACT

In the context of rising demand for reliability and safety in concrete structures subjected to blast or impact loading, the behavior of concrete under high strain rate conditions is an important issue. Since concrete subjected to impact loading associated with high strain rates shows quite different material behavior from that under monotonically increasing quasi-static loads, several material models have been proposed and used to describe the high strain rate behavior of concrete under blast and impact loadings. In the process of modeling the high strain rate condition with these material models, mesh dependency in the used finite element (FE) is the key problem because simulation results under high strain-rate conditions are quite sensitive to the applied FE mesh size. This means that the accuracy of simulation results for concrete structures may be strongly dependent on the FE mesh size. This paper introduces an improved criterion that can minimize the mesh-dependency of simulation results on the basis of the fracture energy concept, and the HJC (Holmquist Johnson Cook), CSC (Continuous Surface Cap), and K&C (Karagozian & Case) models are examined to trace their relative sensitivity to the employed FE mesh size. Consistent with the purpose of a perforation test for a concrete plate under a projectile (bullet) impact, the residual velocities of a projectile after perforation are compared. Correlation studies between analytical results and associated parametric studies show that the variation of residual velocity with the used FE mesh size is substantially reduced and the accuracy of simulation results is improved by applying a unique failure strain value determined according to the proposed criterion.

1. Introduction

With increasing need to ensure safety of concrete structures from explosions, which recently have occurred frequently, as well as against the risk of bombing terror, various studies ranging from identification of dynamic material properties to analysis of the structural responses under blast and impact loadings have been conducted, with priority given to military facilities [1–4]. These studies have also been extended to civil structures following the 1999 Murrah building bombing [5] and 2001 World Trade Center terrorist bombing [6]. Moreover, a recent increase in the size and height of civil structures necessitates additional attention to secure the safety of structures against blast and impact loadings.

Concrete structures subjected to blast or impact loading present significantly different structural behavior from that observed under quasi-static loading conditions. This difference is basically caused by the change in the material properties of concrete and reinforcing steel under dynamic loading accompanying high strain rate deformation and it is enlarged with an increase of strain rate [7]. Furthermore, compared to reinforcing steel, whose material properties are relatively well defined and governed by yielding, concrete develops larger deformation because of the broad distribution of micro-cracks preceding cracking and crushing in the cases of both tensile and compressive failure [8] and presents more sensitive material behavior to the strain rate dependent deformation. Hence, nonlinearity of concrete with respect to the effect of high strain rate deformation that occurs during a short period of time must be taken into account to exactly describe the behavior of concrete structures subjected to blast or impact loading.

In this context, numerous studies, from the Marais experiment [9], which identified material properties of various materials with the SHPB (Split Hopkinson Pressure Bar) test, to research by Georgin and Reynouard [10], who carried out a numerical analysis

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for structures under impact loading, have been conducted [9–12]. The obtained research results have been used in developing design codes such as the CEB-FIP model code [13] and ACI-381-08 [14] and also have been implemented into many commercialized programs including LS-DYNA [15] and ABAQUS [16] to be used in tracing the nonlinear response of structures subjected to blast and impact loadings. Unfortunately, most research to date has been conducted in relation to metallic materials, partly because of the difficulties involved in dynamic experiments for concrete, and only a few studies of the dynamic tensile behavior of concrete have been reported [7,17,18]. Fortunately, in the context of recent increasing need for research on brittle materials, the body of experiments and numerical analyses for concrete structures under high strain rate condition has gradually increased.

Generally, in order to predict the structural response of concrete structures under high strain rate conditions, a material model constructed on the basis of high strain rate experiment data [19] must be defined first. The selection of a damage model from among conventional damage plasticity models for concrete is then followed for the mathematical formulation of damage in concrete together with the determination of material constants to define the selected damage model. A numerical analysis is then conducted up to the point where the final damage state in the concrete structure is reached through an explicit solution algorithm [19]. For numerical analyses, the smeared crack model is usually used to describe the failure process of concrete structures caused by internal microcracks [20].

The smeared crack model, representing cracked concrete as an elastic orthotropic material with a reduced elastic modulus in the direction normal to the crack plane, has been widely adopted to describe the nonlinear behavior of concrete structures. However, it has a major drawback of dependency of the numerical results on the size of the finite element (FE) mesh used in the analysis [20]. This drawback is not limited to the quasi-static loading case but manifests identically in the dynamic loading case accompanying high strain rate deformation [10]. The nonlinear analyses of concrete structures consequently may give different results with a change in the FE mesh size only, and, in advance, the accuracy of the simulation results may not be guaranteed. Nevertheless, no criterion or guideline for the numerical analyses of concrete structures subjected to dynamic loading accompanying high strain rate deformation has been introduced to minimize the relative difference in the numerical results according to the applied FE mesh size. No criterion is also introduced for the compressive failure of concrete structures even in the case of the quasi-static loading. It means that selection of the FE mesh size entirely depends on the researchers' empirical decision.

To address this mesh-dependency problem in the numerical analysis of concrete structures subjected to blast and impact loadings, this paper introduces an improved criterion on the basis of the fracture energy concept. Since the criterion simply requires changing the ultimate strain value in the stress–strain relation of concrete whenever the FE mesh size is changed, its application to one of the conventional damage plasticity models for concrete such as the HJC (Holmquist Johnson Cook), CSC (Continuous Surface Cap), or K&C (Karagozian & Case) model [21–23], which are generally used for the blast or impact analysis of concrete structures, would not lead to any difficulties in compatibility with the adopted damage model. The validity of the introduced criterion is established by comparing the analytical predictions with experimental data [24] obtained from the perforation test of a concrete plate under a projectile. Moreover, numerical analyses for the same concrete panel are conducted to verify the applicability of the introduced criterion to the conventional damage plasticity models.

2. Material properties

Since most structural materials used in practice exhibit strain-rate sensitivity to strength, stiffness, and ductility, strain-rate effects induced from high-amplitude short-duration impulse loadings must be taken into account when defining the material properties for an exact evaluation of the resisting capacity of structures subjected to explosions or impact loadings. The strain-rate dependency of materials can be traced by dynamic load tests [25], although they are more markedly affected than static tests by parameters such as specimen geometry, uniformity of stress and strain along the specimen length, stress-wave propagation effect, inertia effect, and the limitation of the one-dimensional wave theory [7]. Meanwhile, the split-Hopkinson pressure bar (SHPB), which covers a strain-rate range of 10/s to 10^3/s [18], usually requires definition of the material properties for the blast or impact analyses of structures. Researchers have used the SHPB to verify dynamic properties of various materials including concrete and steel, and a few relations are also described in design codes [13,14] for use in the design and construction of reinforced concrete structures.

2.1. Concrete

When concrete is gradually loaded to failure, the concrete becomes a discontinuous structure and undergoes severe internal cracking, resulting in dilation. However, a concrete specimen loaded rapidly does not have time to develop sufficient internal cracking in the lateral direction, thus producing an effective confining stress on the central core of the specimen [7]. This causes the concrete to be initially in a state of uniaxial strain with corresponding lateral stresses that act as a form of confinement. This lateral inertia confinement not only can lead to a significant increase in the dynamic strength but it may also lead to an increase in the critical strain [7,26]. This phenomenon is called the inertia resistance effect. In addition to this effect, the change of the crack pattern also should be considered. A specimen subjected to rapid loading will experience to diffuse micro-cracking on the crack tip through aggregate particles instead of propagating macro-cracks around the aggregate particles. This effect can be explained as follows: if energy is introduced into the system in a very short time, then cracks are forced to develop along shorter paths of higher resistance, and this leads to an increase of the compressive strength of concrete [27].

The increase of the tensile strength of concrete subjected to rapid loading is higher than that of compression under a given strain rate and can similarly be explained. More details on the behavior of concrete at high strain rates can be found in previous experimental studies [12,28]. Moreover, numerous mathematical models to describe the increase of strength and critical strain according to the strain-rate have also been introduced [18,26,29].

The response of reinforced concrete structures under impact or blast loading depends to a large extent on the stress–strain relation of the constituent materials and the magnitude of stress. Since the target structures considered in this paper are reinforced concrete panels accompanying perforation failure by a projectile, the stress–strain relation under compression is of primary interest. Among many empirical formulas to describe the strain-rate dependent uniaxial stress–strain behavior of concrete [12,28], this paper adopts the relation in Fig. 1, which takes into account nonlinear strain hardening and linear strain softening behavior, because this model is capable of representing the material behavior quite well in a wide range of loading history. The same material model is also adopted to define the tensile region in concrete. In Fig. 1, the ascending part is defined according to the Holmquist