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Monte Carlo simulations of meso-scale dynamic compressive behavior of concrete based on X-ray computed tomography images

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ABSTRACT

The dynamic damage and fracture behavior of concrete under compression with strain rate up to 100 s^{-1} is investigated by Monte Carlo simulations (MCSs) of realistic meso-scale models based on high-resolution micro-scale X-ray computed tomography (XCT) images, using the concrete damaged plasticity (CDP) model. For a given strain rate, 93 2D XCT images of a 37.2 mm concrete cube are simulated to obtain statistical results of macroscopic stress–strain curves. The predicted compressive dynamic increase factor (CDIF)–strain rate curve is in good agreement with existing experimental data and empirical curves. The effects of aggregate/void area fraction on dynamic compressive strength are also analyzed, and an augmented compressive strength-strain rate relation considering the void area fraction is proposed. A full 3D model is also simulated under various strain rates. It is found that the realistic XCT-image based meso-models with the CDP model are very promising in effectively elucidating the complicated and fundamental dynamic failure mechanisms of concrete.

1. Introduction

Numerous civil and military concrete structures may be exposed to dynamic loadings at a wide spectrum of strain rates from 10^{-8} to 10^{3} s^{-1} [1,2]. Understanding the dynamic properties of concrete material is paramount for better designs and safety assessment of concrete structures under dynamic loadings such as impact and blast. The dynamic compressive properties of concrete and concrete-like materials have been investigated extensively by uniaxial compressive tests using drop hammers and split-Hopkinson pressure bars (SHPB) [1,3]. Many studies [1–8] reveal that the concrete compressive strength increases with the strain rate, and the strength improvement can be described by the compressive dynamic increase factor (CDIF) defined as the ratio of dynamic-to-static strength. For the purpose of engineering practices, the CDIF is normally introduced as a macroscopic material property based on test data [1,6,9].

However, whether the CDIF measured from macro-scale dynamic experiments is a material property or a structural effect remains questionable. Apart from strain-rate properties at nano/micro/meso-meter length scales (i.e., the commonly called ‘material effects’ in the literature), several structural factors associated with stress wave propagation contribute to the CDIF, including the lateral inertia confinement and the end friction confinement. Among these factors, how the lateral inertia confinement affects the CDIF is mostly debated. Le Nard and Bailly [10] argue that the dynamic strength enhancement is only caused by the inertia force. Cotsovos and Pavlović [11] also believe that the CDIF is caused primarily by the lateral inertial confinement and it cannot be used to describe dynamic material properties of concrete. Cusatis [12] finds that the inertia force contributes significantly to the dynamic strength enhancement and cannot be neglected for strain rates higher than 0.1 s^{-1}. However, some researchers [7,13] find that significant lateral inertial confinement occurs only when the strain rate exceeds 200 s^{-1}. The end friction confinement effect is caused by boundary constrains from friction. According to Li and Meng [7], the end friction effect on the CDIF is insignificant when the friction coefficient is lower than 0.1, but becomes considerable when it is higher than 0.2. Thus it may be inappropriate to directly use the CDIF obtained from macroscopic dynamic tests as a material property of concrete, because it includes both the material effects and the structural effects.

It should be noted that dynamic experiments, especially at high strain-rates, are usually time-consuming and costly in need of sophisticated testing equipments, and it is still difficult to precisely control the boundary conditions. This makes numerical simulations, mostly using the general-purposed finite element method, a strong alternative for dynamic studies because of the ease in the precise control of boundary conditions and fast parametric studies for elucidating the effects of key factors. In particular, meso-scale numerical modeling can provide more insights to the mechanical responses of concrete, because the meso-features, such as the shapes, volume fractions and distributions of multiple phases (aggregates,

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mortar, interfacial transition zones (ITZs) and voids), can be explicitly modeled in detail. These meso-scale features, which are obscurely considered as material effects by macroscopic dynamic tests or numerical simulations assuming homogeneous material behavior, now become structural in meso-modeling, and their effects on the dynamic strength enhancement can be thoroughly investigated. Many concrete meso-scale models have been built by random aggregate generation and packing algorithms, e.g., in the publications [14–21]. Most of these meso-scale simulations are 2D under static loadings. Meso-modeling of concrete damage and fracture under dynamic loadings is still very limited although increasingly attracting attention. For example, using meso-models, Park et al. [22] and Hao et al. [23] find that the compressive strength increases as the aggregate volume fraction at strain rates higher than 50 s^{-1}; Cusatis [12] and Song and Lu [24] conclude that the dynamic strength enhancement is attributable mainly to the inertial confinement effect; and Du et al. [25] find that more branching cracks occur as the strain rate increases.

However, the above random aggregate models use assumed meso-scale morphologies that are not necessarily the same as in real concrete samples. Therefore, the simulated results could be neither representative nor fully verifiable. In addition, the effects of random distribution of multiple phases, especially the aggregates and voids, on the statistical information of dynamic properties of concrete, have been hardly investigated, although limited Monte Carlo simulation (MCS) studies have been carried out for static 2D cases by the authors [21,26,27]. 3D meso-scale modeling of concrete under dynamic loadings is rarely reported either.

More recently, digital images, acquired by optical devices such as cameras, microscopes and X-ray computed tomography (XCT) scanners, have been used to generate micro/meso-scale numerical models [28–36]. These image-based models take into account realistic sizes, shapes, volume fractions and distributions of multiple phases and thus result in more accurate mechanical responses. The simulated damage and fracture processes can even be directly validated by in-situ XCT tests of concrete samples [33,35,36]. However, no image-based micro/meso-scale models have been used to simulate damage and fracture of concrete under dynamic loadings, to the best knowledge of the authors.

This paper aims at a better understanding of the dynamic mechanical behavior of concrete under compression by extensive Monte Carlo simulations (MCSs) of 2D and 3D meso-scale concrete models based on micro-scale XCT images. These high-resolution, physically-based models are more accurate and realistic than assumed meso-models and are promising to yield more insights into the dynamic damage and fracture processes as well as more accurate CDIF values for practical design. The concrete damaged plasticity (CDP) model in ABAQUS is used in this paper to simulate complicated damage initiation and evolution. The paper is organized as follows. Section 2 presents the methodology in detail, including the algorithms to generate 2D and 3D finite element models based on XCT images of a concrete cube, the constitutive laws and the material parameters. In Section 3, eight Monte Carlo simulations are conducted for 93 2D XCT image slices comprising the 3D image under uniaxial compression with different strain rates, and the dynamic load-carrying capacity, the crack pattern and the void effect are statistically investigated based on the MCSs results. A full 3D model of the concrete cube is also simulated under various strain rates. The main conclusions are drawn in Section 4.

2. Methodology

2.1. XCT-image based model

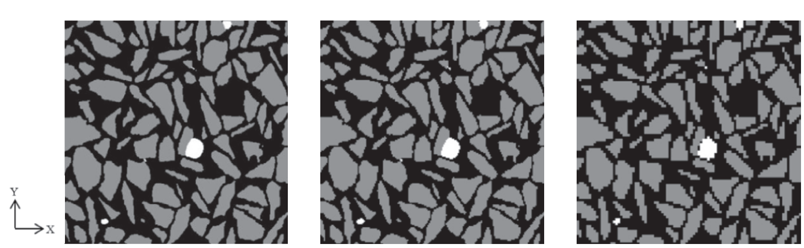
The detailed image-based modeling method can be referred to [36], and only the essential information is briefly presented here. The 2D images are obtained from the in-situ X-ray Computed Tomography test [34], and have 372 pixels of 0.1 mm in both directions. An image slice is first processed with grey-value based segmentation to label pixels with material identity of aggregates, mortar or initial cracks/voids, resulting in a ternary image. Then an image compression process is carried out to reach a balance between morphology accuracy and computational efficiency. Fig. 1a–c shows three examples of an image slice with pixels of 0.1 mm, 0.2 mm and 0.4 mm, respectively.

To construct the 3D model, the 2D image slices (on the *xy*-plane) are stacked along the out-of-plane direction (namely, the *z*-axis) to generate voxels [36]. Each generated voxel is assigned with the corresponding material label. The aggregates, mortar, and initial cracks/voids of the full 3D model (37.2 mm-sized), are shown in Fig. 2a, 2b and 2c, respectively.

Next, the mortar pixels/voxels connected with aggregate pixels/voxels are identified to model the weaker aggregate-mortar interfaces, namely the interfacial transition zone (ITZ) as illustrated in Fig. 3. In the meso-scale analysis, the ITZ generally serves as the weakest link in concrete and have a significant influence on the failure pattern and the macro-mechanical properties of concrete [37,38]. According to experimental results [39,40], the thickness of ITZ is typically 10–50 μm. However, modeling such microscale thickness in a mesoscale continuum FE mesh may lead to too fine meshes along the ITZ and thus numerical difficulties. Therefore, the ITZ thickness in most numerical studies is set as 0.2–0.8 mm [13], for example, 0.5 mm in Ref. [24] for simplicity. Kim and Abu Al-Rub [41] set ITZ thickness as 0.1–0.8 mm and find that it has only slight influence on the post-peak behavior of concrete. In the present model, the ITZ thickness is set as 0.4 mm. After the material labels are assigned, the pixels/voxels of aggregate, mortar and ITZ are converted into square and cubic FE elements for 2D and 3D models, respectively (see Fig. 3).

2.2. Concrete damaged plasticity model

The concrete damaged plasticity (CDP) model was first proposed by Lubliner et al. [42] for monotonic loading, and it was



(a) 372×372 pixels (0.1mm) (b) 186×186 pixels (0.2mm) (c) 93×93 pixels (0.4mm)

Fig. 1. Image processing and compression.