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Effect of strain rate on post-peak cyclic behavior of concrete in direct tension

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HIGHLIGHTS

- Post-peak cyclic behavior of concrete in direct tension is studied.
- Various loading regimes are performed on concrete in tension.
- Strain rate effect on the post-peak stress-strain response is considered.
- Stress releases and damage accumulations are independent of strain rate.
- Damage constitutive model is proposed to describe the stress-strain relation.

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ABSTRACT

A test method has been developed to obtain reliable post-peak cyclic behavior of concrete in this study. Considering three various loading regimes, strain rate effect on post-peak stress-strain response of concrete is investigated. The envelope curve is found coincides with the monotonic loading curve, which is shown to govern the cyclic response. Concrete presents slightly rate sensitive when it is subjected to static loading. The tensile strength increases with the increasing of strain rate. The stress releases with cyclic even if the maximum strain is constant. It demonstrated that the stress release process is independent of strain rate and it can be expressed by a power function. Analytical expressions introducing damage index are proposed to describe the entire monotonic behavior, as well the response to cyclic loadings. The analytical model uses the concept of uniqueness of envelope curve. The calculated results predicted by the analytical expressions have good agreement with test data.

1. Introduction

It is well known that concrete exhibits post-peak softening behavior, in which large strains are involved. To investigate the softening behavior of concrete the complete stress strain curve need to measure. The development of testing machine and computer technique in recent years has promoted the investigation on cyclic behavior of concrete. The first work considering the cyclic behavior of concrete was published by Sinha et al. [1], in which a significant concept of uniqueness of envelope curve was put forward. Subsequently, numerous constitutive models have been proposed in the last few decades. Sima et al. [2] proposed a constitutive model for concrete subjected to cyclic loadings in compression and tension, in which two independent damage variables in compression and in tension have been introduced. To improve the damage accumulation evolution, Breccolotti et al. [3] modified the model proposed by Sima et al. This model took into account the damage increment in concrete under constant and variable amplitude loadings.

Except the damage constitutive models, thermodynamic models have also been developed. Lee and Fenves [4] proposed a plastic damage model based on continuum damage mechanics. This model used two damage variables for concrete in tension and compression. To better and truly describe the plasticity and damage of plain concrete, Cicekli et al. [5] introduced an anisotropic damage with new plasticity yield and damage criteria in the plastic-damage constitutive mode. Tensile and compressive damage criteria are separately used in the model, which took also into account the stiffness recovery caused by crack opening and closing.

These above models have been evaluated by simulating experimental stress strain curves of plain concrete and reinforced concrete subjected to cyclic compression. However, only a few

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models consider the tension response because direct tension test on concrete is difficult to conduct. In recent years, Chen et al. [6–8] have performed experimental researches on dynamic tensile behavior of concrete. Ranaivomanana et al. [9] and Alhussainy et al. [10] have studied the creep behavior of normal concrete in tension and stress-strain relation of self-compacting concrete by improving the direct tensile test method, respectively. However, the cyclic tensile behavior has ever been concerned little [11–14]. Xiao et al. [11] studied the fatigue strain variation and the fatigue modulus degradation of recycled aggregate concrete. Yankelevsky and Reinhardt [12] proposed analytical expressions describing both the entire monotonic and cyclic response of concrete. Rather simple expressions have been proposed to reproduce any unloading or reloading curve as function of the starting point coordinates. Reinhardt and Cornelissen [13] established complete stress-deformation curves for concrete in tension and alternating tension-compression. Crack growth and strain distribution around the crack tip of concrete in cyclic tension was studied. Gopalaratnam and Shah [14] developed an available testing method to obtain reliable complete load-deformation curve in direct tension. They performed both monotonic and cyclic tests and developed an analytical expression to describe the entire tensile response of concrete. However, the analytical expression is not applicable to cyclic stress strain response. Some simple constitutive models have been proposed and evaluated by using experimental results from the above literatures [2,15–17]. Constitutive formulations are presented for concrete subjected to reverse cyclic loading consistent with a compression field approach by Palermo and Vecchio [15]. Features of the modeling include: nonlinear unloading using a ramberg-osgood formulation; linear reloading that incorporates degradation in the reloading stiffness based on the amount of strain recovered during the unloading phase; and improved plastic offset formulations. Formulations for partial unloading and partial reloading are also presented. Additionally, the authors used a straight line to model the unloading and reloading branches in tension under cyclic loading when there is no incursion in compression during a cycle. This concept is used by Forster and Mati [16], Mansor and Hsu [17], and Sima et al. [2].

Non-elastic materials like concrete have strain rate sensitive characteristic which have been verified by numerous researches [6,7,18]. It was demonstrated that the strength increases with increasing of strain rate by performing dynamic mechanical tests on concrete. However, the effect of strain rate on the post-peak cyclic behavior is not concerned.

Experimental results about stress strain response of concrete subjected to cyclic tension are still limited. The existing models are always based on their own experimental results, which need further verification by other test results. So the existing constitutive models are not verified capable to arbitrary loading conditions. In this paper, an experimental study on the constitutive behavior of concrete subjected to cyclic tension is carried out. To obtain a complete understanding of cyclic post-peak behavior of concrete in tension, tests are performed on concrete specimens at various loading regimes. The effects of strain rate on the cyclic post-peak behavior are also performed in this study. Analytical expressions introducing damage index is proposed to describe the entire monotonic behavior, as well the response to cyclic loadings. Finally, comparisons with typical test data are shown in this paper.

2. Experimental program

2.1. Test specimens

During the present study tests have been performed on specimens made of the same concrete mix proportions (shown in Table 1) and having a same geometry: cylinder specimens with diameter of 73 mm and height of 146 mm. The concrete is a mixture of ordinary Portland cement and secondary fly ash, river sand with particle size distribution fitting ASTM C33 [19], aggregates of 20 mm maximum size, portable water and polycarboxylate superplasticizer to obtain a well flow-ability. The concrete was cast into cylinder PVC pipes in diameter of 73 mm and kept in curing room for one day. After demolding the specimens were cured under water for 7 days, and then cured in nature till 28 days. Before testing the concrete cylinders were cut in height of 146 mm. The two ends of cylinder specimen were paste into the steel platen by structural adhesive to get enough adhesive strength before testing. The instrumented cylinder concrete is shown in Fig. 1.

Table 1
Concrete mix proportions by weight.

Mass of concrete ingredients (kg/m^3)					
Water	Cement	Fly ash	Sand	Aggregate	Water Reducer
205	328	82	668	1089	2.05

2.2. Loading and measurement

The tests were carried out on a servo controlled electro-hydraulic material testing system (MTS 322) equipped with two manufactured spherical joints to reduce eccentricity in testing. The load transferred to the specimen by the spherical joints and screws. Across the lateral three LVDTs (linear variable differential transducer) were attached to the concrete with a measuring length of 140 mm under 120° between each other. The three strain values were recorded. And the strain values were averaged and fed into a variable-gain amplifier, so a specific strain rate was achieved. Three different strain rates of 1 με/s, 5 με/s and 10 με/s were performed on specimens in this study.

Fig. 1. Instrumented concrete cylinder.