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Hysteretic model for concrete under cyclic tension and tension-compression reversals

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ABSTRACT

A hysteretic model for concrete structure subjected to cyclic tension and tension–compression reversals is presented. The proposed model was intended to predict the complex hysteretic behavior of concrete under cyclic loading in a simple and practical way. Based on the analysis of the characteristic hysteretic behavior of concrete, the residual deformation in tension was considered principally due to the incomplete closure of the opening cracks. The mechanism for the hysteretic behavior of concrete under tension–compression reversals was suggested as the crack closing and opening. Considering the application within different numerical approaches, dimensionless stress-deformation coordinates was adopted to perform the hysteretic model. The unloading and reloading paths have been derived from the crack closing and opening mechanism and were represented as straight lines in the model. Partial unloading and reloading were considered in both cyclic tension and tension–compression reversals. The proposed model has been validated by comparison with available experimental results and the seismic response of a SDOF system with the hysteretic model has been analysed.

1. Introduction

The safety assessment of concrete structures subjected to cyclic loading such as seismic excitation requires realistic constitutive models to reproduce the real behavior of the materials. Because of the low tensile strength, the concrete subjected to seismic load usually presents softening behavior in tension and hysteretic behavior in tension-compression reversals. As a result, the hysteretic model for concrete plays a significant role in determining the seismic responses of concrete structures including the deformation and energy evolution. However, for lack of experimental data, there are few specialized researches on the modeling of hysteretic behavior for concrete under cyclic tension and tension-compression reversals.

Most existing models for concrete considering the cyclic loading in tension assumed linear unloading-reloading paths without hysteretic energy dissipation [1–4]. Some authors (Vecchio and Palermo [5], Reinhardt et al. [6], Yankelevsky and Reinhardt [7], Chang and Mander [8]) have proposed more advanced models considering the complete and partial unloading-reloading hysteretic behaviors with different modeling approaches.

Vecchio and Palermo [5] presented constitutive formulations for concrete subjected to reversed cyclic loading consistent with a compression field approach. The model was built upon the preliminary work presented by Vecchio [9] and intended to apply in the context of smeared rotating cracks. The hysteretic rules used in cyclic tension followed the philosophy for concrete in compression. The unloading path was modeled with a Ramberg–Osgood formulation and the reloading path was modeled as a straight line with degrading reloading stiffness. A plastic offset during complete unloading in tension has been defined in the model and formulated based on the test data from Yankelevsky and Reinhardt [7] and Gopalaratnam [10]. Although the crack-closing process in compression loading has been described with a linear formulation in the literature, the hysteretic behavior in tension-compression reversals has been neglected.

Reinhardt et al. [6] proposed a relationship between the stress and crack opening displacement for concrete in the tension and compression region. The total deformation during cyclic load was split up into a crack opening displacement part and a strain part consisting of an elastic strain and an irreversible strain, and the irreversible strain part was neglected in the model. As a result, the uncracked material behaved in a liner manner and all nonlinearities were comprised in the crack. The model can be applied in numerical simulation through a discrete crack approach or smeared crack approach. Straight lines were used as the unloading and reloading paths. Because the crack opening displacement was assumed constant during the unloading process in tension, the hysteretic behavior in cyclic tension cannot be simulated by this model.

Yankelevsky and Reinhardt [7] developed a stress versus total

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Nomenclature

c	viscous damping coefficient
f_0	maximum of the earthquake induced resisting force in a linear system
f_t	tensile strength of concrete
F_s	resisting force
k	elastic stiffness of SDOF system
k_0	normalized elastic stiffness in compression
k_{crcl}	normalized crack-closing stiffness
k_{crop}	normalized crack-opening stiffness
k_{tpre}	normalized partial reloading stiffness
m	quality
R_s	strength reduction factor
u	deformation relative to the ground
$\ddot{u}_g$	ground acceleration
u_0	maximum of the earthquake induced deformation in a linear system
x	normalized strain
x^0_{close}	normalized strain corresponding to crack-closing compressive stress
x_{res}	normalized residual tensile strain
x_{tpre}	normalized partial reloading strain
x_{tun}	normalized unloading strain on tension envelope curve
y	normalized stress
y_{tun}	normalized crack-closing compressive stress
y_{tpre}	normalized partial reloading stress
y_{tun}	normalized unloading stress on tension envelope curve
δ_t	tensile displacement corresponding to the tensile strength
ε_t	tensile strain corresponding to the tensile strength
ζ	damping ratio
ω	undamped elastic circular frequency

deformation relationship for concrete behavior in cyclic tension and compression. The model was based on a given experimental cyclic stress-deformation envelope, and has defined focal points which were used to reproduce the complete unloading-reloading cycles. The focal points governed the unloading and reloading curves either by rays transmitted from a certain focal point towards known points in the stress-deformation plane, or by their stress level. When all the focal points were located, the complete unloading-reloading curves can be produced through a simple graphical process. Although the model represented well the test results, the definition of focal point purely derived from the graphic feature needs more physical significance and the procedure determining the unloading and reloading curves is too complex.

Chang and Mander [8] proposed a rule-based hysteretic model to simulate the hysteretic behavior of confined and unconfined concrete in both cyclic compression and tension for both ordinary as well as high strength concrete. Fifteen unloading and reloading paths determined by fifteen different rules were distinguished in the model. The fifteen paths were divided into three types: envelope curve, connecting curve and transition curve. The equation used by the authors for the unloading and reloading curves was a polynomial adjusted by a series of parameters: the slope at the origin and the slope at the end of each curve. To determine the parameters of cyclic curves for concrete in compression, statistical regression analysis was performed on the experimental data from Sinha et al. [11], Karsan and Jirsa [12], Spooner and Dougill [13], Okamoto et al. [14] and Tanigawa et al. [15]. The expressions proposed for compression have been modified by the authors for the condition of tension cyclic behavior.

In the documented literatures, the most refereed experimental studies on the uniaxial tensile cyclic behavior of concrete are from Reinhardt [16], Cornelissen et al. [17] and Mazars et al. [18]. More recently, Nouailletas et al. [19] have performed direct cyclic tension tests on the concrete specimens, and the effect of crack reclosing on properties of concrete has been studied at the macroscale using the digital image correlation (DIC) technique.

At present, the hysteretic model considering the hysteretic behavior during cyclic tension and tension-compression reversals is still rarely used in the seismic response analysis of concrete structure. The principal shortcoming of the available hysteretic models for concrete in the literatures is the complicated hysteretic rules applied to reproduce the unloading and reloading curves. These rules are usually derived from the geometrical properties of the cyclic stress-strain curves, which results in the lack of a clear physical meaning of the proposed model. A set of parameters is required to perform the complex rules and it reduces the applicability of the hysteretic model.

In this paper, an efficient model capable of predicting the hysteretic behavior of concrete under cyclic tension and tension-compression reversals is presented. Compared to previous ones, the model presents several advantages. It affords to consider the essential features of the complex hysteretic behavior of concrete in a simple and practical way. It can be used to simulate the complete or partial unloading and reloading behaviors for concrete under cyclic tension and tension-compression reversals. Straight lines are adopted to describe the unloading and reloading paths and several necessary hysteretic rules are proposed based on the mechanism of crack closing and opening. Furthermore, all the required input parameters can be obtained through conventional laboratory monotonic tension tests. The model has been validated by comparison with available experimental results in different cases and the analysis of seismic response based on the hysteretic model has been performed.

2. Characteristic behaviors of concrete in tension-compression reversals

Before the introduction of the hysteretic model, it is necessary to describe the characteristic behaviors of concrete in tension-compression reversals. Direct tension cyclic tests with different stress ranges on a double-notched specimen have been performed by Reinhardt [16] in 1984 and the corresponding stress-deformation relationships were obtained. The deformation was defined as relative displacement and measured by four extensometers with 35 mm gauge length. One of the test results with complete hysteretic loops has been selected to study the feature of concrete behaviors in tension-compression reversals.

Fig. 1 shows the reproduced three successive unloading-reloading cycles. The positive stress means the tension and the unloading is

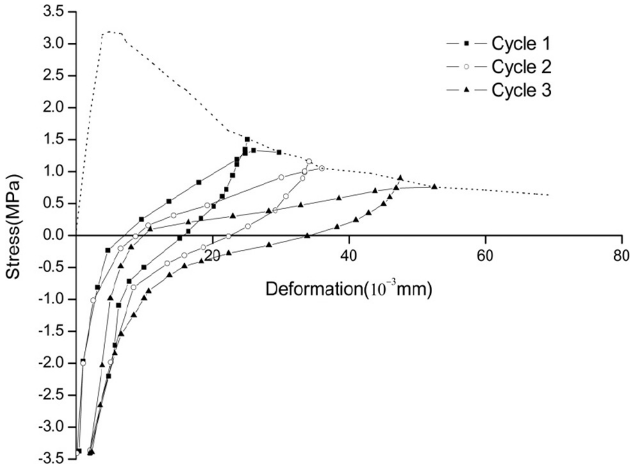

Fig. 1. Three successive unloading-reloading cycles under tension-compression reversals.