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A fracture mechanics-based method for prediction of cracking of circular and elliptical concrete rings under restrained shrinkage

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ABSTRACT

A new experimental method, utilizing elliptical ring specimens, is developed for assessing the likelihood of cracking and cracking age of concrete subject to restrained shrinkage. To investigate the mechanism of this new ring test, a fracture mechanics-based numerical approach is proposed to predict crack initiation in restrained concrete rings by using the *R*-curve method. It has been found that numerical results accord well with experimental results in terms of cracking ages for both circular and elliptical concrete rings, indicating that the proposed fracture mechanics-based numerical approach is reliable for analyzing cracking in concrete ring specimens subject to restrained shrinkage.

1. Introduction

When volume change of concrete from autogenous, drying or thermal shrinkage is restrained, residual stress will be developed and crack may occur once the residual tensile stress exceeds the tensile strength of concrete. This shrinkage cracking is a major problem for flat concrete elements/structures with a large exposed surface area-to volume (A/V) ratio, such as industrial floors, concrete pavements and bridge decks, in particular when concrete is at early ages. Cracking in concrete can reduce load carrying capacity and accelerate deterioration, which shortens the service life of concrete structures and increases maintenance costs. Therefore, researchers are seeking to develop simple tests to assess how susceptible a concrete mixture may be to cracking in decades. So far, such as the bar [1,2], the plate/slab [3,4] and the ring tests [5,6] have been developed to evaluate the cracking tendency of concrete under restrained conditions. However, it has been found difficulties in providing sufficient restraint in the bar and plate/slab tests [7]. On the other hand, the circular ring test has been widely used for assessing cracking tendency of concrete and other cement-based materials [8,9] due to its simplicity and versatility. It has subsequently become a standard test method for assessing cracking potential of concrete and other cement-based materials recommended by American Association of State Highway and Transport Officials (AASHTO) (i.e., AASHTO PP34-99: *Standard Practice for Cracking Tendency using a Ring Specimen*) and by American Society for Testing and Materials (ASTM)

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Nomenclature

R	critical energy release rate (fracture resistance)
G	crack driving energy rate
R_0	internal radius of a circular concrete ring
R_i	external radius of a circular concrete ring
R_1	inner major radius of an elliptical concrete ring
R_2	inner minor radius of an elliptical concrete ring
d	wall thickness of a restraining steel ring
E	elastic modulus
f_t	splitting tensile strength
f_c	uniaxial compressive strength
t	age of concrete
K_{IC}	critical stress intensity factor
$CTOD_C$	critical crack tip opening displacement
a	crack length
a_c^f	critical crack length
w	concrete ring wall thickness
σ	nominal stress
T	fictitious temperature drop
α_c	linear expansion coefficient of concrete
a_c	critical crack length
a_0	initial crack length
α, β	coefficients of R-curve
$\varepsilon_{c\sigma}(t,t_0)$	stress–dependent strain at time t
$\sigma_c(t_0)$	stress in concrete at the time of loading t_0
$E_{ci}(t_0)$	elastic modulus of concrete at the time of loading t_0
$J(t,t_0)$	creep function
$\varphi(t,t_0)$	creep coefficient
$\Delta\sigma_\theta$	increment of the circumferential tensile stress

(i.e., ASTM C1581/C1581M-09a: *Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage*).

As a test method for assessing cracking potential of concrete, the ability of generating a visible crack within a short period is desirable for large amount of assessment of cracking tendency of concretes or other cement-based materials. However, it has been found that it may result in a fairly long period before the first cracking occurs in a restrained circular concrete ring due to either the restraining steel core is not stiff enough or the concrete is characterized with high crack resistance [10,11]. Besides, initial cracking may appear anywhere along the circumference of a circular ring specimen, making it difficult to be detected or traced in experiment. Therefore, although standard dimensions of circular ring specimens are recommended by AASHTO and ASTM, respectively, many researchers have used circular ring specimens with other geometries [8,9,11–15]. Meanwhile, a novel elliptical ring geometry was adopted for assessing cracking tendency of mortar under restrained condition. In this initiative, the first cracking was expected to occur earlier than in a circular geometry to shorten experiment duration. It was believed that there is higher stress intensity in an elliptical ring due to geometrical effect [16,17]. This initiative has been recognized as an effort to increase the stress concentration provided by the ring by Moon and Weiss [14]. It should be noted that, although it is generally regarded that higher degree of restraint can be provided by an elliptical geometry than a circular one in the restrained ring test, there is no evidence having been presented in scientific literature to validate this. So far, the researches related to elliptical concrete ring test [16–18] are focused on using elliptical ring test as a better tool than the circular ring test for estimating the cracking tendency of concrete or other cement-based materials. No much effort has been made on exploring the mechanism of the elliptical ring test or validating the advantages of elliptical geometry overwhelming circular geometry in shortening ring test which is still not clear to concrete science and engineering community.

A few theoretical/numerical models have been proposed to predict residual stress development and cracking age of concrete in restrained circular ring specimens. In a circular ring specimen, restraining effect from the central steel ring to the surrounding concrete ring is uniform along its circumference. Consequently, uniform circumferential tensile stress is resulted in the concrete ring along its circumference. Therefore, the restraining effect from the central steel ring on surrounding concrete can be conveniently replaced by a fictitious uniform pressure applied on the internal surface of the concrete ring in analytical/numerical analyses [11,12,19,20]. But, things are different in case of an elliptical geometry. The elliptical geometry produces a complicated and non-uniform circumferential stress in the elliptical concrete ring. Consequently, a closed-form analytical solution is not available for predicting residual stress development in an elliptical concrete ring subject to restrained shrinkage. Recently, Zhou et al. [21] conducted comparison test of a series of circular and elliptical concrete