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A fracture mechanics-based approach to modeling the confinement effect in reinforced concrete columns

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HIGHLIGHTS

- The effective stress in the transverse reinforcement at peak stress is estimated.
- A relation between the crack formation, the fracture energy in compression, and the lateral deformation is established.
- The stress and strain behavior of the confined concrete core is mechanically determined.
- The comparison between test results and predictions is made.

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ABSTRACT

It is well-known that the failure of concrete in compression is characterized by the localization of deformations. As a consequence, the failure of a reinforced concrete column localizes, in its turn in the same localized fracture zone in which passive confinement provided by the transverse reinforcement can be locally activated due to the significant expansion of the concrete in the lateral direction. By this means, fracture mechanics-based approaches may be considered as applicable for the modeling of this effect. This paper presents a new approach to modeling of the effect of confinement in reinforced concrete columns through observations of the crack formation in the presence of a confining stress. The effective stress in the transverse reinforcement at peak stress is estimated by taking the compatibility of deformations between the confined concrete core and the transverse reinforcement into consideration. Furthermore the strain behavior of the confined concrete core is determined by establishing a relation between the crack formation, which is represented by the fracture energy in compression, and the lateral deformation. The comparison between test results and predictions, by the means of the confined compressive strength with corresponding strain and the total stress–strain curve, shows that the proposed approach yields a reasonable level of accuracy.

1. Introduction

Research on the behavior of concrete under an active confinement originated in the early 20th Century in the work of Richart et al. [1]. In this pioneering work a linear relation between the lateral stress (σ_l) and the triaxial compressive strength (f_{cc}) was introduced as

$$f_{cc} = f_c + k \cdot \sigma_l \tag{1}$$

where the constant k was determined from tests to be 4.1, f_c is the compressive strength of unconfined concrete.

Since that time enormous efforts have been made both to comprehend this phenomenon and also to achieve more accurate modeling of the triaxial compressive strength. Many complicated formulations for compressive meridian of the failure surface have been proposed in the modeling context during the course of the research history and recognized to more accurately predict the triaxial compressive strength. Nevertheless, the formulation proposed by Richart et al. [1] given above is still considered as suitable for representing the confining effect and has been adopted in some recent research works by modification of the constant k, e.g. [2–4]. It is also an attempt to explain the confining effect through observing the crack formation of cylinders in a triaxial test, e.g. [5]. Instead of unstable distributed cracking, crack formation is more stable with finer micro-cracking, when the lateral stress increases. This leads not only to an increase of the axial load-carrying capacity and the corresponding axial strain, but also to higher lateral strain at peak stress [6].

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Notations

A_c	area of specimen cross-section
A_{cc}	area of core of section enclosed by the center lines of the perimeter spiral or hoop
A_{pre}	pre-peak portion of compressive fracture energy per unit specimen area
A_{post}	post-peak portion of compressive fracture energy per unit specimen area
$A_{sx,y}$	areas of transverse reinforcement in x- and y-directions
$c_{x,y}$	widths of confined concrete core of a rectangular reinforced concrete column ($c_x > c_y$)
$C_{x,y}$	widths of a rectangular reinforced concrete column ($C_x > C_y$)
d_c	diameter of confined concrete core of a circular reinforced concrete column
D	diameter of a circular reinforced concrete column
E_c	modulus of elasticity of concrete
E_s	modulus of elasticity of reinforcing steel
f_c	compressive strength of concrete
f_{cc}	compressive strength of confined concrete
f_{co}	in-place compressive strength of unconfined concrete
f_{cu}	axial stress of confined concrete core at complete failure
f_{yh}	yield limit of transverse reinforcement
I_e	confinement index $I_e = \sigma_l/f_c$
K_e	geometric coefficient of confinement effectiveness
L_d	length of the localized fracture zone of a concrete specimen
$L_{d,i}$	length of the *initial fracture zone* of a concrete specimen
s	clear spacing of ties or spirals
w_i	clear spacing between longitudinal reinforcing bars
W_{pre}	pre-peak portion of compressive fracture energy per unit volume in the *initial fracture zone* of unconfined concrete
W'_{pre}	pre-peak portion of compressive fracture energy per unit volume in the fracture zone of confined concrete
W_{post}	post-peak portion of compressive fracture energy per unit volume in the *initial fracture zone* of unconfined concrete
W'_{post}	post-peak portion of compressive fracture energy per unit volume in the fracture zone of confined concrete
δ_{inel}	post-peak inelastic deformation
ε_c	longitudinal strain of concrete
ε_{cc}	longitudinal strain of confined concrete at peak stress (f_{cc})
ε_{ccl}	lateral strain of concrete of confined concrete at peak stress
ε_{cl}	lateral strain of concrete
ε_{co}	strain at peak stress of unconfined concrete
ε_{col}	lateral strains at the compressive strength of unconfined concrete
ε_{hcc}	strain in the transverse reinforcement at peak stress of confined concrete
$\varepsilon_{inel,i}$	post-peak inelastic strain of the *initial fracture zone* of unconfined concrete
ε'_{inel}	post-peak inelastic strain of the fracture zone of confined concrete core
ρ_s	geometric reinforcement ratio of longitudinal reinforcement
ρ_{sh}	geometric reinforcement ratio of transverse reinforcement
σ_c	concrete stress
σ_{hcc}	stress in the transverse reinforcement at peak stress of confined concrete
σ_l	confining (lateral) stress in an active confinement
σ_{le}	effective confining stress provide by transverse reinforcement in columns
θ	inclination angle of the shear failure plane

The effect of confinement can also be obtained in reinforced concrete columns through the lateral pressure provided by the transverse reinforcement arranged in the form of ties or spirals, as demonstrated in Fig. 1. In contrast to the behavior of a concrete specimen in the triaxial compression test, the confinement in reinforced concrete columns is a passive phenomenon. Apart from the influence of the column geometry and reinforcement arrangement, which can be well captured using a geometric coefficient of confinement effectiveness proposed by Mander et al. [7], the passive confining stress in reinforced concrete columns depends decisively on the interaction between the amount of the transverse reinforcement and deformation capacity of confined concrete in the lateral direction. It has been experimentally observed for normal-strength concrete columns confined with normal-strength steel ties that the stress in transverse reinforcement can generally reach its yield limit at the peak stress of confined concrete [8]. By contrast, the yielding limit of the transverse reinforcement can only be reached at peak stress of confined concrete for high-strength concrete columns employing a relatively large amount of transverse reinforcement [9–11]. It thus becomes clear that an assumption of the confining reinforcement yielding at the peak stress of confined concrete previously adopted in some previous research works [7,12–14] as well as in *fib* MC 2010 [15] can lead to an unsafe design, especially for high-strength concrete columns tied by high-strength steel. In order to avoid this, efforts have been made to determine the effective stress in the transverse reinforcement using complex iterative procedures [16,17] or formulations derived simply from regression analyses [18–21]. This inconvenience is caused by the fact that the concrete lateral strain in these models is formulated as a function of the axial strain, which is unknown at the beginning of the calculation.

The compressive strength of confined concrete can be well estimated in most existing models with the effective stress in the transverse reinforcement [16–20,22]. Some efforts have been made to describe the ductile behavior of confined concrete in reinforced concrete members on the basis of fracture mechanics in modeling

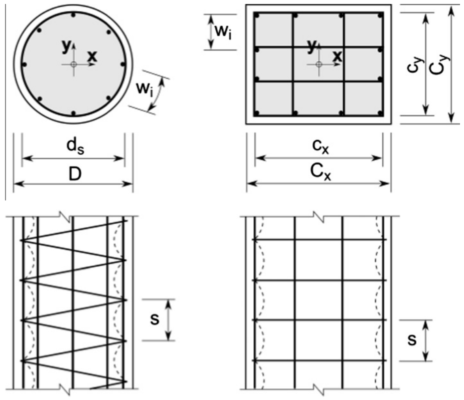

Fig. 1. Spirals and ties as confining reinforcement in reinforced concrete columns.