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A constitutive model for predicting the lateral strain of confined concrete

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ABSTRACT

Depending on the confining stress developed, the provision of confinement can substantially improve the strength and ductility of concrete members. However, the confining stress developed is related to the lateral strain (or lateral expansion) of the concrete and up to now it remains a difficult task to evaluate the lateral strain of confined concrete under inelastic condition. Herein, the lateral strain of confined concrete for the full stress–strain range from pre-crack and elastic state to post-crack and inelastic state is studied based on published experimental results, and a constitutive model for predicting the lateral strain of confined concrete is developed by back calculation from the experimental results. This model is a useful tool for analyzing the full range structural behaviour of various kinds of confined concrete columns and concrete-filled steel tube columns.

1. Introduction

Nowadays, high-strength concrete (HSC) with compressive strength up to 120 MPa or even higher can be produced readily [1,2]. It has various advantages but is generally more brittle [3–5] and thus requires particular care in the structural design and reinforcement detailing. One common method of improving the ductility of HSC members is to provide larger confinement by increasing the amount of transverse reinforcement [6–8]. However, there are limitations in the effectiveness of transverse reinforcement in providing confinement. Firstly, the confining stress would decrease with increasing distance from the bends of transverse reinforcement and the arching action, through which the confining stress is developed, is not fully effective unless the transverse reinforcing bars are closely spaced [9,10]. Secondly, the required close spacing of the transverse reinforcing bars often results in steel congestion thus posing difficulties during concreting.

For the sake of making better use of HSC and pushing the strength limit of concrete upwards without sacrificing ductility, more effective methods of providing confinement are needed. In recent years, several more advanced methods of providing confinement have been developed. These include: provision of external confinement in the form of fibre composites [11–17], filling of the concrete into steel tubes [18–24] and filling of the concrete into steel tubes with external confinement [25–28]. Such methods can provide substantially larger confinement than possible with the use of only internal transverse reinforcement and would not cause any difficulties in concreting due to steel congestion. In fact, the substantially larger confinement provided by these more advanced methods would increase not only the ductility but also the strength of the concrete member.

To analyze the complete axial stress–strain relation and simulate the concentric and eccentric load behaviours of concrete columns with various kinds of confinement provided, a constitutive model with the confining stress taken into account is needed. Since the external fibres and steel tubes can only provide passive confinement rather than active confinement, the confining stress is induced solely by the lateral strain (or lateral expansion) of the concrete with the magnitude and rate of change of the confining stress dependent on the mechanical properties and stress conditions of the confining materials. Hence, the confining stress induced by the lateral strain varies during loading and is highly indeterminate. On the other hand, the confining stress would delay the initiation of microcracks, restrict the development of splitting cracks and reduce the widths of splitting cracks formed in the concrete [29,30]. Hence, the confining stress would affect the lateral strain of the concrete whereas the lateral strain would affect the confining stress induced. As a result, the lateral strain and confining stress are inter-related and thus not easy to evaluate.

A number of constitutive models for confined concrete [9,11,31–50] have been developed. However, many models for confined concrete just focus on the effects of the confining stress on the axial stress–strain relation of the concrete or have not given any explicit formula for evaluation of the confining stress [9,11,36,41,45,47]. There are models for evaluating the lateral

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Nomenclature

E_x	Young's modulus in *x*-direction
E_y	Young's modulus in *y*-direction
E_z	Young's modulus in *z*-direction
E_c	Young's modulus of concrete
f'_c	unconfined concrete strength (cylinder compressive strength of concrete)
ε_x^e	elastic strain in *x*-direction
ε_y^e	elastic strain in *y*-direction
ε_z^e	elastic strain in *z*-direction
ε_x^p	inelastic strain in *x*-direction
ε_y^p	inelastic strain in *y*-direction
ε_x^T	total strain in *x*-direction
ε_y^T	total strain in *y*-direction
ε_z	axial strain in longitudinal direction (*z*-direction)
ε_{z0}	axial strain at formation of splitting cracks
ε_{co}	axial strain at peak stress of unconfined concrete
ν_{xy}	Poisson's ratio of strain in *y*-direction to strain in *x*-direction
ν_{xz}	Poisson's ratio of strain in *z*-direction to strain in *x*-direction
ν_{yx}	Poisson's ratio of strain in *x*-direction to strain in *y*-direction
ν_{yz}	Poisson's ratio of strain in *z*-direction to strain in *y*-direction
ν_{zx}	Poisson's ratio of strain in *x*-direction to strain in *z*-direction
ν_{zy}	Poisson's ratio of strain in *y*-direction to strain in *z*-direction
ν_c	Poisson's ratio of concrete
σ_x	normal stress in *x*-direction
σ_y	normal stress in *y*-direction
σ_z	normal stress in *z*-direction
σ_r	confining stress acting on the concrete

strain and confining stress in externally confined concrete columns under the condition that the confining stress to lateral strain ratio is constant, but these are applicable only when the confining materials would remain linearly elastic during loading, such as fibre-reinforced polymers [11,31,33,34,38,39,48,50]. Also, most models were derived from tests of normal-strength concrete specimens and thus are applicable only to normal-strength concrete. Moreover, nearly all models do not distinguish the pre-crack state and post-crack state when evaluating the lateral strain, but in reality, the lateral strains before and after formation of splitting cracks are very different and therefore should not be treated the same or evaluated using the same formula. However, even with the use of separate formulas for evaluating the lateral strains before and after formation of splitting cracks [32,36], there is no consensus of the criterion for formation of splitting cracks.

For passively confined concrete where the confining material has a nonlinear stress–strain curve or a Poisson's ratio larger than that of the concrete (for example, a steel tube), a more generally applicable constitutive model is needed. Herein, a constitutive model for predicting the lateral strain of confined concrete that is applicable to both normal-strength and high-strength concrete is developed. In the model, the effect of the confining stress on the axial strain at formation of splitting cracks is taken into account and separate formulas are used to evaluate the lateral strains before and after formation of splitting cracks. No assumption is made on the mechanical properties of the confining material and thus the model so developed should be generally applicable regardless of the type of confining material used.

2. Lateral behaviour of confined concrete

2.1. Passively confined concrete

Passive confinement is generally provided by restraining the lateral strain (i.e. the lateral expansion) of the confined concrete using internal transverse reinforcement and/or external confining materials such as fibre-reinforced polymers (FRP) or steel tubes. As compression load is applied to the confined concrete, the axial strain of the confined concrete increases (note that compressive strain is taken as positive) and due to the Poisson's ratio effect, the lateral strain of the confined concrete decreases (note that tensile strain is taken as negative). In other words, as the axial strain increases starting from zero, the magnitude of the lateral strain increases. For illustration, the lateral strain–axial strain curves of two real FRP-confined concrete specimens extracted from Ref. [45] are plotted in Fig. 1. At the beginning, before splitting cracks are formed, the magnitude of lateral strain increases steadily with the axial strain. Later, after splitting cracks are formed, the magnitude of lateral strain increases much more rapidly with the axial strain than before; this may be attributed to bonding failure, delamination and slip at the aggregate-paste interfaces.

On each lateral strain–axial strain curve, there is an obvious turning point, which to the authors' belief, corresponds to the point of splitting crack formation. Imran and Pantazopoulou [32] suggested that splitting cracks should be formed when the lateral strain reaches the cracking strain under direct tension. However, Candappa et al. [36] found that the turning point occurs when the axial stress to failure axial stress ratio is about 0.7 for 40 MPa concrete or 0.8 for 60–100 MPa concrete. Such discrepancy will be resolved later by checking against available experimental results. For passively confined concrete, the confining stress induced increases from zero with the magnitude of lateral strain. Since the magnitude of lateral strain at formation of splitting cracks is generally quite small, the confining stress induced at the time of splitting crack formation is also small and thus has little effectiveness in avoiding or delaying the formation of splitting cracks.

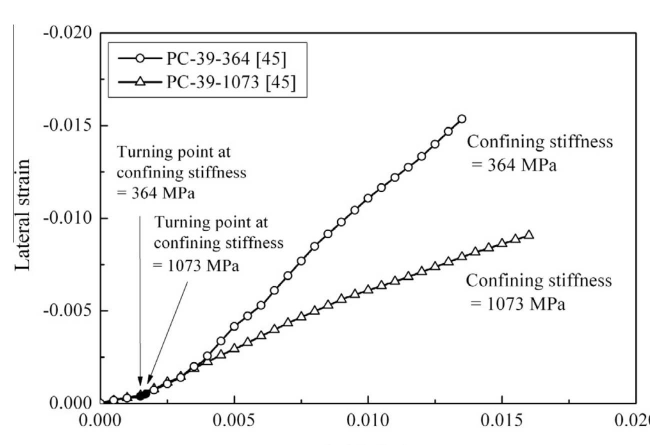

Fig. 1. Lateral strain versus axial strain for passively confined concrete specimens.