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Modified axial-shear-flexure interaction approaches for uncorroded and corroded reinforced concrete beams

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ABSTRACT

Two new axial-shear-flexure interaction approaches, the modified axial-shear-flexure interaction (MASFI) approach and its extension to consider the effects of reinforcement corrosion (MASFI-C), are proposed in this research to predict the lateral force-displacement behavior of uncorroded and corroded reinforced concrete (RC) beams, respectively. The MASFI considers the effects of shear on concrete confinement and buckling of longitudinal reinforcement, and the softening effect of tensile strains of transverse reinforcement on the flexural concrete compression zone. The MASFI-C considers the effect of reinforcement corrosion by using the corroded constitutive models for concrete, steel, and bond. The proposed models were used to predict the envelope response of uncorroded and corroded RC beams tested using cyclic loading. It was found that the MASFI captured well the behavior of uncorroded beams and the effects of shear on concrete confinement and buckling of longitudinal reinforcement are important for predicting the post-peak behavior. The MASFI-C with the average residual cross-sectional area and average strengths of corroded reinforcement captured well the initial stiffness and strength behavior of corroded RC beams before fracture of corroded reinforcement. However, with the average ultimate strain of corroded reinforcement, the MASFI-C did not captured well the drift at which longitudinal or transverse reinforcement fractured due to the variation in corrosion mass loss among corroded reinforcement and in ultimate strain for a given corrosion mass loss, and due to inelastic deformations caused by bending process for corroded transverse reinforcement.

1. Introduction

Seismic evaluation of existing reinforced concrete (RC) structures using pushover analysis [1–3] has been widely accepted by practicing engineers (e.g., [4,5]). To conduct pushover analysis, the lateral force-displacement envelope behavior of structural members is required. A prediction model of the lateral force-displacement behavior that would be appropriate for most applications needs to include the effects of axial, flexural and shear actions, and the bar-slip effect (member longitudinal reinforcement slipping out of adjoining anchorage regions). The axial and flexural effects can be considered by sectional analysis using uniaxial fibers combined with the use of plastic hinge length [6,7]. The bar-slip effect can be implicitly considered by plastic hinge length [6] or explicitly by bar-slip models (e.g., [8–10]). The shear effect (coupled with axial effect) is more complicated than the other effects because the shear effect is a two-dimensional problem while the other effects are one-dimensional problems. For members with flexural-dominated behavior, the shear effect may be ignored. However, for members with shear-dominated behavior or flexural-shear behavior, satisfactory prediction of the lateral force-displacement behavior requires the consideration of the shear effect and its interaction with axial and flexural effects.

One of the major thrusts in studying the shear effect is the development of smeared crack shear models that describe the shear behavior of cracked RC elements using average stress-strain relationships for cracked concrete derived over gauge lengths across several cracks. The smeared crack shear models developed over the past three decades include, but not limited to, the modified compression field theory (MCFT) [11], the rotating-angle softened truss model (RA-STM) [12,13], the fixed-angle softened truss model (FA-STM) [14], the disturbed stress field model (DSFM) [15], and the softened membrane model (SMM) [16]. These models were developed based on results of panel testing, which was designed to apply only axial and/or shear forces to RC specimens without the disturbance of the flexural effect, and have achieved various degrees of success in capturing

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the behavior of RC elements subjected to in-plane shear and axial loads. Some of these models have been implemented in finite element analysis programs and have shown to be capable of predicting well the behavior of RC members when the flexural effect is also present (e.g., [15] for MCFT, [17] for DSFM, and [18,19] for SMM). However, computational cost is high for finite element analyses. To reduce the computational cost, sectional fiber-based analysis approaches have been developed for the MCFT [20,21], SMM [22], and DSFM [23], and have shown be able to serve a viable alternative to the finite element method in predicting the lateral force-displacement behavior of RC beams and columns subjected to combined axial-shear-flexural actions [20–26]. In these fiber-based approaches, a section is discretized into several axial-shear fibers with their behavior described by a smeared crack model.

A further simplification was achieved in the axial-shear-flexure interaction (ASFI) approach [27], in which only one axial-shear fiber is used for the entire effective section for shear and is coupled with conventional sectional analysis that employs only uniaxial fibers. The ASFI approach was later simplified into the uniaxial shear-flexure model (USFM) [28], in which the methods to calculate the principal compressive strain and axial strain of an axial-shear element are simplified. The USFM was modified later to include a post-peak shear behavior to the axial-shear fiber [29]. Note that none of the models described above consider the shear effect on concrete confinement and to buckling behavior of longitudinal reinforcement in compression.

As shown and discussed in earlier studies [4,30–37] that corrosion of transverse reinforcement can reduce the shear capacity and hence increase the shear effect on the lateral force-displacement behavior of the beam. Most of the previous research on prediction of the lateral force-displacement behavior of corroded RC members adopt finite element methods [31,33,38–42], which, as stated previously, require high computational cost. Sectional analysis approaches based on that plane sections remain plane have been proposed [43,44]. However, the shear effect is not considered.

This paper presents new analytical models for uncorroded and corroded RC beams, referred to as modified axial-shear-flexure interaction (MASFI) approach and MASFI-C (C stands for corrosion), respectively. The MASFI approach is based on ASFI and includes modifications to consider the shear effect on concrete confinement and on the buckling behavior of longitudinal reinforcement, and modification to the method to soften the flexural compression zone due to shear. The MASFI-C approach is based on MASFI with extension to consider the effects of steel reinforcement corrosion. The MASFI and MASFI-C approaches are validated in this paper using experimental data presented elsewhere [35–37,45].

2. Axial-shear-flexure interaction (ASFI) approach

The ASFI approach [27] consists of two interactive models, the axial-flexure model and axial-shear model (Fig. 1). The axial-flexure model uses conventional sectional analysis with uniaxial fibers to capture the axial-flexure effect. The axial-shear model adopts the MCFT to capture the axial-shear behavior and employs only one biaxial fiber to represent the entire effective section for shear. A bar-slip model is linked to the axial-flexure model to capture the contribution to the lateral displacement of the member due to the slip of longitudinal reinforcement out of the adjoining anchorage regions (Fig. 1).

Equilibrium between the axial-flexure and axial-shear models is satisfied by imposing the same shear force (V) and axial force (P) to both models at any step during analysis. The shear stress in the axial-shear model (τ_s) is assumed to be constant over the depth of the section, i.e., $\tau_s = V/(b_w d_s)$, where b_w = width of the section; and d_s = depth of the section, which is equal to overall depth of the section (h) before concrete cracking in flexure, and equal to effective depth of the section (d) after cracking. The normal stress in the x direction (σ_x) of the axial-shear models is equal to the stress induced by the axial load, i.e., $\sigma_x = P/b_w h$. The normal stress in the y and z directions of the axial-shear model is assumed to be zero ($\sigma_y = \sigma_z = 0$). Compatibility between the axial-flexure and axial-shear models is satisfied by requiring the axial strain caused by the axial mechanism in both models equal to that caused only by the axial load.

Two further interactions are considered between the axial-flexure and axial-shear models. First, the compression softening coefficient (ξ, Eq. (1)) used in the axial-shear model to soften diagonal cracked concrete in compression is carried to the axial-flexure model to soften concrete in the compression zone. This is to consider the shear effect on degradation of concrete strength in the flexural analysis.

$$\xi = \frac{1}{0.8 + 0.34\frac{\varepsilon_1}{\varepsilon_c'}} \leqslant 1 \tag{1}$$

where ε_c' = strain at the peak stress of concrete in compression, taken as 0.002; and ε_1 = average concrete principal tensile strain determined from the axial-shear model. Second, the axial strain caused by the flexural mechanism (ε_{xf}, Eq. (2)) in the axial-flexure model is added to the axial strain in the axial-shear model ($\varepsilon_{xa} + \varepsilon_{xs}$). Therefore, the axial strain in the axial-shear model becomes $\varepsilon_x = \varepsilon_{xa} + \varepsilon_{xs} + \varepsilon_{xf}$ (Eq. (3)). Typically, the axial strain by the flexural mechanism is a tensile strain, which would result in an increase of principal tensile strain in the axial-shear model and hence decrease the shear strength of concrete.

$$\varepsilon_{xf} = 0.5(\varepsilon_o - \varepsilon_{xa}) \tag{2}$$

$$\varepsilon_x = \varepsilon_{xa} + \varepsilon_{xs} + \varepsilon_{xf} \tag{3}$$

where ε_o = centroidal strain at the fixed-end section; ε_{xa} = axial strain at the free-end section (due to axial load only); and ε_{xs} = axial strain due to shear mechanism.

3. Modified axial-shear-flexure interaction (MASFI)

It has been recognized that transverse reinforcement in a RC member has three functions: to resist shear, to confine concrete, and to resist buckling of longitudinal reinforcement. All these three effects can cause strain and stress in transverse reinforcement. The shear effect on transverse reinforcement starts to play a significant role after diagonal cracking of concrete. The confinement effect becomes significant after the confined concrete in compression reaches the critical stress [46], which is between 0.75 and 0.8 f_c', where f_c' is the unconfined concrete compressive strength. The buckling effect in most applications starts to affect transverse reinforcement after longitudinal reinforcement yields and starts to buckle [47]. The shear effect on transverse reinforcement in most applications precedes the confinement and buckling effects. Thus, the effectiveness of transverse reinforcement is reduced in resisting confinement and buckling if shear is present. This effect is not considered in the ASFI.

The first modification this research proposes for the ASFI is to consider the shear effect on the confinement. First of all, it is assumed that only the legs of transverse reinforcement that are in parallel to the applied shear are affected by shear. The legs that are perpendicular to the applied shear are not affected. Moreover, because the stiffness of transverse reinforcement is greatly reduced after yielding, it is assumed that when the stress in the parallel legs reaches the yield stress, the legs completely lose their capacities to provide confinement. When the shear effect is present but has not yielded transverse reinforcement, the confined con-