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# New opensees models for simulating nonlinear flexural and coupled shear-flexural behavior of RC walls and columns

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ABSTRACT

This paper describes new model elements and material constitutive relationships implemented by the authors into the widely-used open-source computational platform OpenSees (Open System for Earthquake Engineering Simulation), aimed to enhance current nonlinear analysis and response assessment capabilities for reinforced concrete (RC) walls and columns. Classes added to the existing OpenSees library include: (1) the Multiple-Vertical-Line-Element-Model (*MVLEM*) element with uncoupled axial/flexural and shear responses, (2) the Shear-Flexure-Interaction-Multiple-Vertical-Line-Element-Model (*SFI-MVLEM*) element with coupled axial/flexural and shear responses, (3) the Fixed-Strut-Angle-Model (*FSAM*), which is a two-dimensional constitutive model for RC panel elements, (4) an improved uniaxial constitutive model for concrete, and (5) an improved uniaxial constitutive model for reinforcing steel. Representative validation studies are also presented, where the analytical model predictions are compared with results of quasi-static lateral load tests on selected RC column and wall specimens. Response comparisons reveal that the implemented models capture, with reasonable accuracy, the experimentally-observed behavior of the test specimens investigated. Based on the comparisons presented, model capabilities are assessed and potential model improvements are identified.

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## 1. Introduction

### 1.1. Background and aim

With implementation of performance-based methodologies in modern seismic design codes and assessment guidelines, detailed modeling and simulation of the nonlinear seismic behavior of reinforced concrete (RC) structural systems has recently gained much importance. While modeling of the linear elastic response characteristics of systems with complex geometry is no longer a significant design challenge, reliable modeling approaches for robust simulation of the nonlinear hysteretic behavior of RC structural members are still needed.

RC structural walls and columns are often used as the primary vertical structural members for resisting lateral loads imposed by wind or earthquakes on buildings (e.g., core wall systems, wall-frame dual systems, special moment frames) and bridges (e.g., bridge columns). Their role is to provide sufficient lateral strength and stiffness to minimize nonlinear behavior and limit lateral displacements during service-level earthquakes, as well as to provide sufficient nonlinear deformation capacity (ductility) during a severe earthquake. Given the crucial role of walls and columns in the seismic performance of RC structural systems, it is essential that analytical models that are capable of capturing their important response characteristics are available, for either design of new structures or performance assessment of existing structures.

The most commonly-used modeling approach for nonlinear response analysis of RC structures involves adaptation of fiber-based models, with uncoupled axial/flexural and shear behavior, for simulating the hysteretic behavior of walls and columns. Using a plastic hinge model is typically deemed sufficient for beams, considering that axial loads in beams are negligible. In a fiber-based model, nonlinear axial/flexural response of a wall or column is simulated using a series of uniaxial elements (or fibers), the behavior of which is based on stress-strain relations for concrete and reinforcing steel (or simplified force-deformation relations), along with the plane-sections-remain-plane assumption. Shear behavior of the member is typically accounted for by using a horizontal spring

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in the model element, with a specified shear force versus deformation (backbone) relation. Fiber models have been implemented into various research-oriented (e.g., OpenSees, [21]) and commercially-available computer programs (e.g., PERFORM-3D, CSI; [35]), and have been widely used to simulate the nonlinear behavior of RC walls in particular. Studies that compare model and experimental results (e.g., [1,25]) show that conventional fiber models provide reasonably accurate predictions of the flexural response of walls. However, the inability of fiber models to account for the interaction (coupling) between axial/flexural and shear behavior is a significant drawback, as studies have shown that uncoupled models tend to underestimate compressive strains in concrete at the boundary regions of even relatively slender walls with flexure-controlled responses [25], and overestimate the lateral load capacity of walls with moderate aspect ratios [9]. Furthermore, using an uncoupled fiber model requires pre-definition of an ad-hoc shear force versus deformation relation, which may introduce bias in the analysis results. For example, Kolozvari and Wallace [10] showed that uncoupled wall models with linear-elastic shear force-deformation relationship with $0.5GA_g$ (commonly adopted approach) tend to overestimate wall shear force demand by approximately 30% and underestimate interestory drift by approximately 50% within the plastic hinge region compared to coupled models.

In terms of flexural and shear deformation contributions to overall response and failure mode, RC walls and columns are typically characterized by their shear-span-to-depth (*M*/*Vl*) ratio. Squat members – especially walls – with *M*/*Vl* ratios less than approximately 1.0–1.5, generally exhibit shear-dominant behavior, whereas well-designed slender members with aspect ratios greater than 2.5–3.0 demonstrate flexure-controlled responses. The lateral load behavior of walls and columns with intermediate *M*/*Vl* ratios of 1.0–3.0 is generally influenced by both nonlinear flexural and shear deformations. A number of experimental results obtained from tests on RC walls (e.g., [19,34,38,39]) as well as columns (e.g., [31–33]) have shown that nonlinear flexural and shear deformations occur simultaneously, and shear deformations can be influential on the response even when the overall response or failure mode of the member is not shear-governed. This indicates inherent coupling between nonlinear flexural and shear responses in RC members, which is commonly referred to as shear-flexure interaction (SFI). It has been observed experimentally that SFI can lead to increased compressive strain demands on walls and columns, especially with intermediate *M*/*Vl* ratios, resulting in reduced strength, stiffness, and deformation capacity compared to behavior under pure bending. Therefore, it is important that analytical models that can simulate this experimentally-observed SFI behavior in RC members are available to researchers and engineers.

A number of modeling approaches, with various levels of sophistication and capabilities that incorporate SFI behavior in RC walls (e.g., [6,7,11,18,20,28,30]) and columns (e.g., [4,44]), can be found in the literature. An effective approach to capture SFI in RC members using a fiber-based model formulation was first proposed by Petrangeli et al. [30]. Massone et al. [18] adopted this approach for analysis of RC walls under monotonic loading, whereas Kolozvari et al. [11] extended it to address reversed cyclic loading conditions, both using different constitutive modeling approaches to represent the behavior of concrete under combined normal and shear stresses. In the analytical model proposed by Kolozvari et al. [11], the uniaxial fibers in a fiber-based model formulation are replaced with RC panels, the biaxial behavior of which is described using a two-dimensional constitutive model with a fixed-crack-angle approach. Thereby, the effect of shear deformations on the strains in concrete is directly incorporated, and shear stresses developing in the model element evolve with the normal stresses developing in concrete (in parallel and perpendicular directions to cracks) and the shear stresses developing along the cracks, based on the constitutive stress-strain relationships adopted in the model (versus use of a pre-defined shear backbone relation). It has been shown that this model is capable of capturing successfully the overall load-deformation behavior, nonlinear shear behavior, coupling of nonlinear flexural and shear deformations, as well as local responses (e.g., strains and rotations) for RC walls that experience significant SFI behavior under reversed cyclic loading conditions [12].

Despite the significant number of analytical modeling approaches available in the literature, only a small number of model formulations are implemented in computational tools (commercial and open-source) available to the broader engineering and research community. One of the most widely-used computational platforms in structural/earthquake engineering is the Open System for Earthquake Engineering Simulation (OpenSees, [21]). OpenSees is an open-source software that includes a wide range of features (e.g., model elements, materials models, solution strategies, etc.) that can be used to conduct nonlinear analysis of structural components and systems under earthquake ground motions. Although OpenSees incorporates an extensive library of model elements, only a few options are available for modeling of RC walls and columns, where the displacement-based beam-column element that follows a fiber-based formulation with uncoupled axial/flexural and shear responses is being the most commonly-used. However, the computational stability (convergence), efficiency (rate of convergence), and accuracy of analytical results obtained using the displacement-based beam-column element have been shown to be sensitive to choice of number of integration points used along the element length [3,37]. Other models available in OpenSees for simulation of RC walls and columns are flexure-shear interaction displacement-based beam-column element proposed by Massone et al. [18], strut-and-tie-based model implemented by Panagiotou et al. [28], and shell element proposed by Lu et al. [14]. The modeling approach implemented by Massone et al. [18] is capable of simulating monotonic responses only. A strut-and-tie (truss) approach developed by Panagiotou et al. [28] is capable of capturing SFI, however, due to overlapping areas of vertical, horizontal, and diagonal concrete struts in the model, as well as the use of pre-define angles of concrete struts, achieving accurate displacement responses over a broad range of response amplitudes and wall configurations is a challenge. The shell element implemented by Lu et al. [14] is a relatively recent model based on a finite element formulation (not a macroscopic model), which has not been extensively validated and is intended to be used for RC walls only. In addition, material constitutive models available in OpenSees, which are used to represent the hysteretic stress versus strain behavior of concrete and reinforcing steel, incorporate certain simplifications and occasional inconsistencies in their formulation. In particular, existing uniaxial material models for concrete are characterized with simplified hysteretic rules, which represent material behavior in a crude manner and do not allow capturing of cyclic concrete behavior accurately (e.g., no gradual gap closure). Also, the most commonly-used uniaxial material model for reinforcing steel is subject to stress overshooting upon reloading after partial strain reversal, which can lead to unreasonable predictions of hysteretic loops of structural components subjected to cyclic or dynamic loading. Finally, a reliable and efficient two-dimensional constitutive model for representing the behavior of RC panel (membrane) elements under plane-stress conditions is not available. Therefore, there is still a considerable need for development and implementation of improved analytical models (model elements and material constitutive models) to enhance current OpenSees simulation capabilities associated with the nonlinear behavior of

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