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# Assessment of dynamic behavior and seismic performance of a high-rise rc coupled wall building

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ABSTRACT

This study evaluates the seismic behavior and performance of a code-based high-rise RC coupled wall building located at the site with high seismicity representative of the West cost of the United States. Modeling approach for dynamic analysis of a coupled wall system is developed based on novel model for RC walls that captures nonlinear axial-flexure-shear (P-M-V) interaction and is validated using detailed experimental data available in the literature, providing the opportunity to analyze the behavior of this system from the new perspective. Seismic performance assessment is conducted considering structural and nonstructural building components based on two performance metrics: repair cost and repair time. The loss metrics are evaluated using FEMA P-58 methodology in conjunction with a realistic repair time model considering frequent (50% in 50 years), rare (10% in 50 years), and very rare (2% in 50 years) earthquake events. Analysis results reveal that strong ground shaking causes significant variation of axial forces in piers of the coupled wall system resulting in P-M-V interaction and considerable shear-related damage (cracking) over most of the wall height, while coupling beam rotations and corresponding damage are relatively small due to their excessive capacity obtained from the code-based design. Although median repair cost is relatively low, less than 6% of construction cost for frequent and rare earthquakes and about 24% for very rare earthquakes, building functionality is impaired at all hazard levels ranging from few weeks for frequent earthquakes to several months for very rare earthquakes, predominantly driven by damage to wall piers and slab-column connections.

## 1. Introduction

Reinforced concrete (RC) wall piers connected with coupling beams form a so-called coupled wall system, which is commonly used as the main lateral force-resisting system (LFRS) for buildings in regions where moderate and strong earthquake ground shaking is anticipated. Planar walls are commonly used for high-rise buildings with heights less than 73 m (240 ft) and are typically designed using linear-elastic analysis and code-based approach (ASCE 7-16 [3], ACI 318-14 [2]). During an earthquake event, coupling beams are expected to act as fuses, undergoing significant nonlinear deformations and dissipating seismic energy, while only modest amount of nonlinearity is expected in wall piers. However, coupled walls might not behave as anticipated because their design is based on the design factors (i.e., R, $C_d$, Ω; ASCE 7-16) for cantilever shear walls due to the lack of such parameters for coupled wall systems in the current code provisions.

Although coupled wall systems are commonly used, their dynamic behavior is not well understood because of the lack of dynamic (shake table) experiments and sophisticated analytical investigations for this type of system. The experiments of planar coupled walls conducted so far considered small scale and relatively short specimens (i.e., less than seven stories) tested only under quasi-static loading (e.g., [39,41,33,23]). The analytical studies available in the literature were conducted using simplified analytical models such as lumped plasticity beam-column elements (e.g., [38,33]) or fiber-based models with uncoupled axial-flexural and shear behavior (e.g., [25]), so-called uncoupled models. However, due to coupling of walls with coupling beams, large axial forces are introduced to wall piers of the coupled wall system [38], which would significantly influence wall forces and deformations through axial-flexure-shear interaction that is not captured with uncoupled models. Therefore, performance assessment of wall piers conducted assuming only flexure-induced damage (e.g., [1]), which is a common practice, may result in significant bias when overall building seismic performance is assessed. Given recent development of nonlinear models for RC walls that capture axial-flexural-shear interaction and nonlinear shear deformations (e.g., [20,21,18], this study

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**Nomenclature**

*List of symbols*

| | |
|---|---|
| $AE_{col}$ | axial stiffness of all gravity columns |
| $A_g$ | gross cross sectional area of wall pier |
| $C_d$ | deflection amplification factor per ASCE 7 |
| E | modulus of elasticity |
| $EI_{col}$ | flexural stiffness of all gravity columns |
| $f'_c$ | concrete compressive strength |
| $F_{I,i+1}$ | pier inertial force at level $i + 1$ |
| $f_y$ | steel yield strength |
| $h_i$ | height of the *i-th* story |
| $I_{eff}$ | effective sectional moment of inertia |
| $I_g$ | gross sectional moment of inertia |
| $M_{L,i}$ | bending moment at level $i$ in left pier (other subscript variations similar) |
| $M_{node}$ | mass corresponding to wall pier |
| $N_{L,i}$ | axial force at level $i$ in left pier (other subscript variations similar) |
| $P_{1/2floor}$ | gravity load corresponding to one half of the floor |
| $P_g$ | pier gravity load at a floor |
| $P_{pier}$ | gravity load corresponding to wall pier |
| R | response modification coefficient per ASCE 7 |
| $S_{D1}$ | design, 5% damped, spectral response acceleration parameter at a period of 1 s per ASCE 7 |
| $S_{DS}$ | design, 5% damped, spectral response acceleration parameter at short periods per ASCE 7 |
| $T_u$ | building period upper limit per ASCE 7 |
| $V_{CB,i+1}$ | shear force in the coupling beam at level $i + 1$ |
| $V_{L,i}$ | shear force at level $i$ in left pier (other subscript variations similar) |
| $V_{y,exp}$ | expected coupling beam yield capacity |
| $\Omega_0$ | overstrength factor per ASCE 7 |
| $\varepsilon'_c$ | strain at peak compressive stress of concrete |
| $\varepsilon_x$ | axial horizontal strain in a RC panel (macro-fiber) |
| $\varepsilon_y$ | axial vertical strain in a RC panel (macro-fiber) |
| $\varepsilon_{yield}$ | reinforcement yield strain |
| $\gamma_{xy}$ | shear strain in a RC panel (macro-fiber) |
| $\rho_h$ | horizontal reinforcing ratio |
| $\rho_v$ | vertical reinforcing ratio |
| $\sigma_x$ | axial horizontal stress in a RC panel (macro-fiber) |
| $\sigma_y$ | axial vertical stress in a RC panel (macro-fiber) |
| $\tau_{xy}$ | shear stress in a RC panel (macro-fiber) |

analyzes the seismic behavior of coupled wall systems from a new perspective by considering shear-induced damage in wall piers, which allows more realistic estimation of the overall building seismic performance.

The main objective of this paper is to improve understanding of seismic behavior and performance of a code-based coupled wall buildings through comprehensive validation and application of novel model for RC walls that accounts for axial-flexural-shear interaction and nonlinear shear deformations [20,21,18]. To provide content to the study, a 15-story archetype building utilizing planar coupled RC walls as the LFRS is designed in line with current engineering practice (ACI 318 and ASCE 7). The seismic performance of the building is evaluated using two loss metrics, repair cost and repair time. Building repair cost is estimated using FEMA P-58 [6,7] methodology and building repair time is evaluated using realistic repair time model developed by Terzic et al. [43].

The study objective is achieved through sequential set of systematic studies that:

(1) Validate the proposed modeling approach for coupled wall systems using detailed experimental data;
(2) Analyze the dynamic behavior of the LFRS of the high-rise code-based coupled wall building in terms of the global and local responses, with a particular focus on the effects of axial-shear interaction in wall piers on the wall behavior;
(3) Evaluate seismic performance of the building through repair loss and repair time estimations for the three seismic hazard levels (i.e., frequent, rare, and very rare earthquakes);
(4) Compare the predicted seismic performance of the building considering two performance models that utilize either shear-controlled or flexure-controlled (commonly used) fragilities for wall piers;
(5) Identify major loss drivers; and
(6) Propose future research directions related to analysis and performance assessment of coupled wall systems.

It should be noted that this paper is focused on detailed evaluation of dynamic behavior and seismic performance of the selected archetype building to establish foundation for future studies that will consider a range of building heights and configurations.

## 2. Nonlinear modeling approach and validation

Earthquake engineering practice and recent research rely on applications of nonlinear wall models that consider uncoupled axial/flexural and shear responses, such as shear wall element in Perform 3D (CSI) [35] and beam-column element [42] in OpenSees. However, it is known that these models have limitations that arise from simplistic (e.g., linear-elastic) representation of shear behavior, which is also uncoupled from axial/flexural response, resulting in underestimation of interstory drift and overestimation of wall shear demand [19]. A number of analytical models that can capture axial-flexural-shear interaction are available in the literature. Models are characterized with various formulations and levels of sophistication, such as macroscopic models (e.g., [16,14,20]) and finite element models (e.g., [15,26,37]). In this study, a novel analytical model for RC walls proposed by [20], which simulates axial-flexural-shear interaction, is used to properly capture nonlinear behavior of coupled wall systems where this interaction is important due to significant variation of axial forces in wall piers. This analytical wall model is validated in the past against test results obtained from isolated wall tests, and showed to be a reliable, computationally stable, and efficient analytical tool for prediction of nonlinear wall behavior under lateral loading [21]. In this study, the axial-shear-flexural-interaction model is validated for the first time considering global and local system responses obtained from a test on a coupled wall system. In addition, mesh sensitivity study is performed to guide the choice of appropriate element size for assessment of global and local responses.

### 2.1. Modeling approach

Analytical model of the archetype building's LFRS is created in structural analysis software OpenSees [28] according to adopted geometry, cross-sections, and material properties of the structural walls and coupling beams. Symmetry is used such that a two-dimensional model consists of two coupled wall piers. Analysis is performed for each direction independently, and the damage assessment for each wall pier and coupling beam is based on their in-plane response. Note that all OpenSees modeling and analysis files are available in corresponding Data in Brief paper [22].

Structural wall piers are modeled using the Shear-Flexure-Interaction Multiple-Vertical-Line-Element-Model (SFI-MVLEM,