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Nonlinear seismic modeling of reinforced concrete cores including torsion

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ABSTRACT

Reinforced concrete (RC) cores are used in many residential multi-story buildings as the primary seismic force resisting system (SFRS). Due to architectural limitations, these buildings are often torsionally flexible. To assess the effect of torsion on the nonlinear seismic response of RC cores, a wide-column model (WCM) with fiber elements is used. The nonlinear warping and the nonlinear biaxial (P-M_x-M_y) cyclic behaviors of the WCM are validated against experimental results and exhibit excellent agreement. According to modal and linear time history analyses, the model can adequately capture the dynamic characteristics and seismic response of core structures, including torsion. The WCM is then extended to the nonlinear range to perform three-dimensional (3D) time history analyses of a typical RC building structure located in Eastern North America (ENA) that is subjected to high-frequency ground motions. Three different building configurations with increasing torsional flexibility (B = 1.7, B = 2.1 and B = 2.5, according to the current National Building Code of Canada) are studied to investigate the effect of torsion on the seismic behavior. The nonlinear envelopes of key response parameters are similar to the design envelopes obtained from the linear response spectrum analysis of a shell elements model (B = 1.7) with proper inelastic force modification factors. Aside from the story torque, the shear and moment demands remain relatively constant, regardless of the torsional flexibility value. The effective shear stiffness must be carefully selected in the WCM to avoid large questionable rotations.

1. Introduction

Reinforced concrete (RC) buildings are a very popular and cost-effective solution for residential multi-story constructions in Eastern North America (ENA). Planar and non-planar RC shear walls represent the typical seismic force resisting systems (SFRSs) associated with this type of structure. These walls should be located as close as possible to the perimeter of the building to reduce the torsional flexibility of the structure. To minimize the effect of the structural system on the architectural layout, shear walls often act as stairway and elevator shafts in many RC buildings. Commonly known as cores, non-planar shear walls can have many open tubular shapes and are commonly used in residential constructions (Fig. 1). RC cores are usually designed in each orthogonal direction using a linear response spectrum analysis combined with a static torque applied at each story of the building to account for torsional effects (NBCC 2010 [1], ASCE/SEI 7-10 [2]). Therefore, the nonlinear interaction (P-M_x-M_y and V_x-V_y-T) is not explicitly considered in design. The literature on the nonlinear three-dimensional (3D) behavior of reinforced concrete cores subjected to ground motions is very scarce, especially concerning the effect of torsion on the seismic response. To address this issue, 3D nonlinear time history analyses are performed using an efficient wide-column model (WCM) developed in OpenSees [3]. The model can be applied in commercial software using fiber elements. Thus, the two main objectives of this study are the following: (1) to assess the nonlinear torsional response of the WCM when employed to model reinforced concrete U-shaped shear walls (cores) and (2) to provide additional information on the seismic behavior of torsionally flexible buildings subjected to high-frequency ground motions. The content of this paper is organized as follows. First, a literature review on the consideration of torsion in the numerical analysis of RC cores is presented. Next, the WCM is described in detail and is validated against experimental data to assess its warping behavior. Finally, a typical RC multi-story building located in ENA is subjected to spectrally matched ground motions. Observations from the nonlinear dynamic response of cores are presented, and the principal conclusions are discussed.

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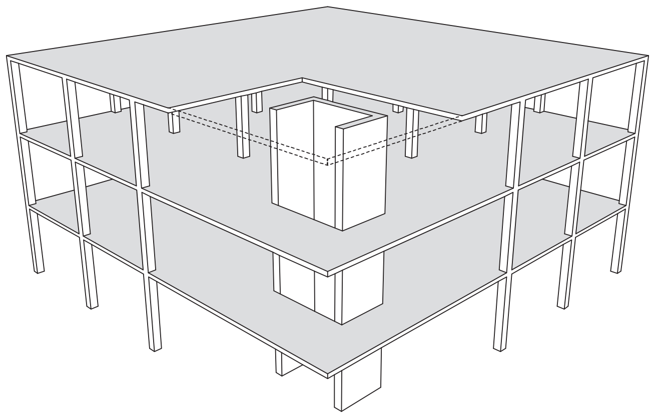

Fig. 1. Core wall in a reinforced concrete structure.

2. Consideration of torsion in the numerical analysis of reinforced concrete cores

2.1. NBCC 2010 and ASCE/SEI 7-10 provisions for torsion

When a building is subjected to earthquake loads, significant torsion can be induced based on the eccentricity e_x between the center of rigidity (CR) of the SFRS and the center of mass (CM) where the inertia forces are acting (Fig. 2). In NBCC 2010 and ASCE/SEI 7-10, this concept is defined as inherent torsion. The rotational component of ground motions and the uncertainties related to the position of the CM and the CR caused by an uneven mass distribution and the stiffness variation in the structural system, respectively, induce an additional seismic moment known as accidental torsion. In both Canadian and American design codes, this accidental torsional moment M_{ta} is considered based on an equivalent static force procedure and is computed as follows for each orthogonal direction at each level x:

$$M_{ta} = A_x F_x p_x D_{nx} \tag{1}$$

where A_x is a torsional amplification factor, F_x is the seismic force, p_x is a ratio, and D_{nx} is the dimension of the structure perpendicular to the direction of the applied forces. In NBCC 2010, p_x and A_x are equal to 0.1 and 1.0, respectively. In ASCE/SEI 7-10, p_x is equal to 0.05, and A_x is computed as follows if the structure is assigned to Seismic Design Category C, D, E or F with Type 1a or 1b torsional irregularity (flexible in torsion):

$$1.0 \leqslant A_x = \left(\frac{\delta_{max}}{1.2\delta_{avg}}\right)^2 \leqslant 3.0 \tag{2}$$

where δ_{max} is the maximum displacement and δ_{avg} is the average of the displacements at the extreme points of the structure for each orthogonal direction at each level x. These quantities are computed by applying F_x and M_{ta} to the structure, assuming A_x is equal to 1.0.

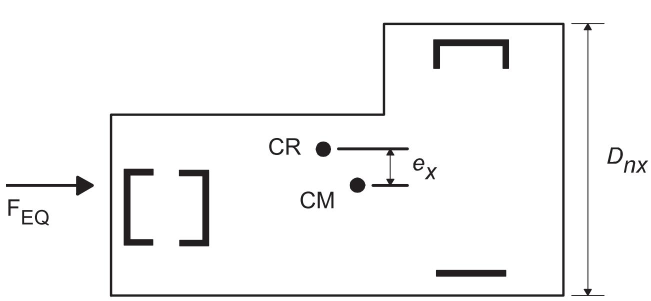

Fig. 2. Definition of e_x and D_{nx}.

In NBCC 2010, the same procedure is used to compute the parameter B_x:

$$B_x = \frac{\delta_{max}}{\delta_{avg}} \tag{3}$$

The parameter B defines the torsional sensitivity of a building and is computed as the maximum value of B_x for each level x in each orthogonal direction. This parameter, proposed by Humar et al. [4], is derived from the ratio between the uncoupled torsional and translational frequencies:

$$\Omega_R = \frac{\omega_\theta}{\omega_y} \tag{4}$$

Buildings can be considered torsionally flexible when this ratio is smaller than one [4]. According to the Canadian standard, a building is considered torsionally irregular when B is greater than 1.7, whereas this limit is equal to 1.2 in ASCE/SEI 7-10. In the American standard, there is an additional category for extreme torsional irregularities when B_x is greater than 1.4. In this paper, the NBCC 2010 limit is used to classify torsional irregularities because the building from the case study is designed in accordance with the Canadian standards.

2.2. Torsional behavior of reinforced concrete cores

Both planar shear walls and RC cores carry shear forces and bending moments when the structure is subjected to lateral loads. However, the torsional resisting mechanism is significantly different between planar shear walls and cores. For the former, torsion is resisted by developing shear forces inversely proportional to the lever of arm between the CR and the position of each planar shear wall. For the latter, the amount of torsion resisted by the cores is related not to their lever arm but rather to their torsional stiffness relative to the total torsional stiffness of the structural system. Thus, RC cores in buildings without planar shear walls can be submitted to large torsional loads because they provide the principal torsional stiffness of the structure. For such cases, the warping component of torsion can induce significant normal stresses at the base of cores, which can be of similar magnitude as the bending stresses [5]. These normal stresses are proportional to the applied torque at the shear center of the cross-section. Therefore, warping can affect the yielding of vertical reinforcement bars in the plastic hinge region of capacity-designed cores. The warping stiffness of cores is related to the amount of axial restraint, which can be influenced by boundary conditions, coupling beams and slab-column interaction. Foundations are often assumed as rigid and can restrain almost completely warping deformations at the base of cores. Similarly to coupling beams, the out-of-plane bending stiffness of the slab can also offer axial restraint, resulting in additional bending and shear forces. These forces induced in the slab have to be considered in design, especially near the openings of cores [6]. This stiffening effect is enhanced by the presence of peripheral columns supporting the slab. Coull and Chee [7] studied various slab support conditions, from free edges (no columns) to simply supported, to assess the effects of these columns on the warping stiffness of cores. They found that the slab-column interaction can significantly increase the stiffness of the system compared to the free edge configuration. Thus, the axial restraint may have an effect on the behavior of RC cores and therefore, it must be properly accounted for in numerical models.

2.3. Modeling strategies for reinforced concrete cores

If the cores were to be completely closed, it would be possible to model these structures with only beam elements located at the shear center of the cross-section because the warping behavior