Engineering Structures 138 (2017) 260–269

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Evaluation of code provisions for design of medium rise buildings supporting brick veneer wall systems under the effect of in-plane seismic loads

Niranjan Desai

Department of Mechanical and Civil Engineering, Purdue University Northwest, Westville, IN 46391, USA

ARTICLE INFO

Article history:
Received 6 June 2016
Revised 6 February 2017
Accepted 7 February 2017

Keywords:
Brick veneer
Medium-rise buildings
In-plane loading
Seismic response

ABSTRACT

The seismic performance of masonry veneer wall systems has come under increasing scrutiny in the past few years. As part of this scrutiny an investigation evaluating the interaction of masonry veneers and medium rise structural frames under seismic loads was conducted.

In this investigation, the in-plane interaction of structural frames and masonry veneer wall systems are evaluated. The responses of the medium rise building system to seismic loading are compared using a mass representation of the masonry veneer wall system (as is allowed by design codes) and by a more accurate strut and frame model. These building frame-wall system models were subjected to the design based earthquake (DBE) and maximum considered earthquake (MCE) levels of selected ground motion. A parametric study was conducted that encompassed the range of stiffness and strength of both the frames and the wall systems encountered in common construction practice in the United States.

The paper will present a summary of the effects of the veneer wall systems on the response of the building frames that support them, when loaded in their in-plane direction, during a seismic event. It will be shown that at the extremes of stiffness that bound the response of veneer wall systems, the prescriptive code requirements can significantly over estimate the effect of the wall systems when these are incorporated into highly flexible structural frames and can produce slightly unconservative results when addressing masonry veneer walls in very stiff reinforced concrete shear wall systems.

1. Introduction

Masonry veneer wall systems are commonly used in many parts of the United States. These wall systems are comprised of an exterior clay masonry layer connected to an interior backup wall system over an air cavity by ties. The air cavity functions primarily as a drainage system. The backup wall of wood or steel studs, reinforced concrete or concrete masonry units, supports the brick veneer and can support loads from the structure. The metal ties transfer lateral loads from the exterior veneer to the interior backup [1–4]. These wall systems provide an aesthetically pleasing, durable cladding. However, their performance under seismic loading has come under increasing scrutiny in the past few years.

Strong earthquake and wind events have caused damage to brick veneer wall systems [1–4]. This damage included cracking of the veneer wall, excessive differential movement, and even collapse. In most cases, the damage occurred under out-of-plane veneer loading. These loads induced high forces and displacement demands on the anchors (ties), eventually causing them to pull out of the backup wall. In many cases wall failures were caused by missing or corroded ties [1].

Research into the behavior of masonry veneer wall systems has been conducted in response to the variable performance of these systems under severe loading [3–10]. To date, the seismic performance of the masonry veneer wall systems have been examined in detail in isolation and in low rise structures. Additionally, an evaluation of the interaction between masonry veneer wall systems under out-of-plane seismic loads and medium-rise structural frames was conducted by Desai and McGinley [11].

The investigation described in this paper focuses on the interaction of masonry veneer wall systems under in-plane seismic loads, and medium size structural frames. The premise of this study is that even though veneer wall systems designed according to prescriptive code requirements are unlikely to collapse under in-plane seismic loading, they do interact with the building frame and affect the distribution of the lateral loads in the frame during a seismic event. The current design provisions do not address this transfer mechanism, and veneer wall systems are typically

E-mail address: desai39@pnw.edu

http://dx.doi.org/10.1016/j.engstruct.2017.02.022

modeled simply as masses [12,13]. As this modelling approach may overestimate the lateral seismic loads that act on structural frame, the study evaluated the effect of the veneer wall systems on a variety of medium rise structural frames under seismic loading to determine whether refinement of these provisions is warranted.

2. Methodology

2.1. Overview

In order to investigate the performance of the masonry veneer wall systems in structural frames, analytical wall system and medium rise structural frame models were developed, and the response of these combined models was studied under a variety of ground motions. This was accomplished by:

- Conducting a 3D equivalent static load design of the building frame using the procedures described in ASCE 7-05 [14]. A stiff reinforced concrete (RC) shear wall system, and a flexible steel moment resisting frame system were considered. These were used in order to represent the boundary values of the stiffness of building frame systems used in typical construction practice. It was assumed that the response of most medium rise building frame systems will lie between these bounds [15].
- Developing equivalent 2D frame and veneer wall system models, with the veneer systems represented only by lumped masses.
- Validating the 2D models by comparing their response during a nonlinear pushover analysis to that of similar frames investigated by other researchers.
- Developing and validating 2D tie and beam models of the in-plane veneer wall systems and incorporating these in-plane wall system models into the 2D building frame model, replacing the lumped masses.
- Selecting the critical ground motions to be used in a dynamic analysis of these models.
- Analyzing the response of the frames under the scaled levels of the ground motions, for both the mass and model representations of the wall, for a variety of wall and frame characteristics.

2.2. Building frame models

A prototype 10 story office building with a 22.86 m × 38.1 m (75 ft. × 175 ft.) plan dimension, a bay dimension of 7.62 m (25 ft.), and 3.66 m (12 ft.) story height was considered in this investigation. A 3-D steel moment resisting frame and reinforced concrete shear wall system were designed using common structural design software [16] in an attempt to ensure that frame member strengths and stiffness were consistent with those typically used for medium rise systems. The lateral seismic loads acting on the building systems were determined using the Equivalent Lateral Force Procedure defined in ASCE – 07-05 [14] for Seismic Category D regions in the United States. In the reinforced concrete system, the shear wall was located in the center bay of the peripheral frames, in both directions (see Fig. 1). The frame systems were intended to bound the range of mass and stiffness used for these types of structures, with the steel moment resisting frame being the most flexible, and the reinforced concrete shear wall system being the stiffest. It was assumed that the floor system in all the structures was a one-way concrete slab, supported by floor beams and girders.

The 3D building frame models were transformed into their equivalent 2D nonlinear finite element models using the OpenSees nonlinear element models and analysis platform developed by the Pacific Earthquake Engineering Research (PEER) Center at the University of California at Berkeley [17]. These 2-D frame models were designed to have the same initial strength and stiffness as the 3D model. This analysis approach is permitted in section 16.2 of the ASCE-07-05 provisions [14] for the nonlinear response history analysis of regular structures with independent orthogonal seismic force-resisting systems. Independent 2-D models are permitted to be constructed to represent each system. The building systems considered in this investigation satisfy these criteria.

The approach used to model the 3D systems and to subsequently convert them into their equivalent 2D systems is presented in Desai's work [11,15]. Additionally, a description of the element, material, connection, load and support models used in the 2D frames, and the calibration of the 2D frame models, is described in detail in Desai's work [11,15].

The goal of this research was to investigate the effects that different veneer wall system modelling approaches have on the response of a medium-rise building frame. This was accomplished by developing two separate representations of the combined veneer wall-building frame system. The first involved representing the veneer wall system by a lumped mass, with each story level sharing 1/2 the total mass. The second approach involved representing the wall system by a more accurate analytical model. In this case, the mass of the wall system was distributed through the wall model, which was attached to the frame nodes at each story.

For each frame and wall system, masses were assigned to the nodes based on the tributary area.

A dynamic time history analysis procedure was used to analyze the systems under seismic load. Rayleigh damping was used in a manner similar to work done by Biddah [18,19] and Hernandez [20], and the damping matrix was assumed to be proportional to the mass and stiffness matrices, as. A 2% damping ratio was used for the reinforced concrete frames [20], and a 5% damping ratio was used for the steel frames [21].

For each time step, the structural stiffness matrix was determined based on the conditions at the end of the previous time step and assumed to remain constant. The magnitude of the time steps varied for the different frame systems considered, and were selected to ensure convergence of the solution using a "Modified Newton" solution algorithm.

A dynamic analysis was performed on the combined veneer wall – building frame models under Design Based Earthquake (DBE) and the Maximum Considered Earthquake (MCE) scaled ground motions [8]. The ground motion records used for the analyses were selected to create the worst effect on the veneer wall systems. Additionally, select veneer wall system and building frame parameters were varied in order to understand their influence on the response of systems [15].

2.3. Nonlinear modelling of the veneer wall systems

The masonry veneer wall system configurations were selected to encompass the range encountered in construction practice. Three different types of wall systems were considered in this investigation [15]: A system having a high stiffness (a stiff concrete masonry unit (CMU) backed wall system and stiff "Tri-wire" ties) defined one extreme, one having a low stiffness (a flexible steel stud backed wall system and flexible "Double Eye and Pintle" ties) defined the other extreme, and finally, a system having an intermediate stiffness (a stiff CMU backed wall system and flexible "Double Eye and Pintle" ties).

2.3.1. Flexible steel stud Backed wall system

2.3.1.1. Modelling approach. A typical flexible steel stud backing wall has attached sheathing and acts somewhat like a shear wall.