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NONLINEAR ANALYSIS OF REINFORCED CONCRETE SHEARWALL BUILDINGS

NONLINEAR ANALYSIS OF REINFORCED CONCRETE

SHEAR WALL STRUCTURES

by

Dilip Khatri

VOLUME I

A Dissertation Presented to the

FACULTY OF THE GRADUATE SCHOOL

UNIVERSITY OF SOUTHERN CALIFORNIA

In Partial Fulfillment of the

Requirements for the Degree

DOCTOR OF PHILOSOPHY

(Civil Engineering)

May 1998

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THE GRADUATE SCHOOL
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LOS ANGELES, CALIFORNIA 90007

This dissertation, written by

Dilip Khairi

under the direction of his Dissertation Committee, and approved by all its members, has been presented to and accepted by The Graduate School, in partial fulfillment of requirements for the degree of

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TABLE OF CONTENTS

ABSTRACT

Reinforced concrete shear walls are an integral part of the lateral force resisting systems in multi-story buildings. The behavior of reinforced concrete shear walls is explored with nonlinear finite element software developed by Dr. K.J. Bathe of the Massachusetts Institute of Technology: Automatic Dynamic Incremental Nonlinear Analysis (ADINA). The purpose and scope of this thesis addresses practical considerations in the nonlinear analysis of reinforced concrete shear wall buildings.

Reinforced concrete behavior has various complexities that inhibit nonlinear analysis. Among these include: Concrete cracking in tension zones; Plastic behavior of steel reinforcing; Three dimensional behavior of concrete; Bond slip. These challenges prevent the engineer from realistically modeling the nonlinear behavior of reinforced concrete. Thus far, current design methodology relies on elastic finite element methods to design reinforced concrete structures. Elastic plate elements are used for shear walls, and beam-column elements are used for moment frame structures. The scope of this thesis addresses the shear wall buildings. Plate elements with a linear modules of elasticity accept tension and compression equally without distinguishing for cracked zones. Stress distributions in tension areas may be equal to those in compression zones.

For reinforced concrete structures, this is clearly not the case. There are limited finite element software packages available for addressing the concrete cracking problem on a large multistory building. Additionally, the contribution of steel is paramount in a reinforced concrete structure. No conventional provisions currently exist for including the reinforcing steel into a finite element model. Consequently, the structural design profession relies the linear finite element approach and compensates for these assumptions by introducing factors of safety to reduce the risk of failure. While this has demonstrated to be a successful tactic, further research to predict the ultimate failure capacity of a building is necessary.

The purpose of this dissertation is to introduce a useful practical methodology for addressing the nonlinear response of multistory reinforced concrete shear wall buildings. The prospect of applying these nonlinear analysis techniques on a broad scale to other reinforced concrete structures is possible, and encouraged. In light of this objective, the nonlinear finite element program is applied. The first portion of this thesis develops and examines a nonlinear methodology to predict behavior of individual shear wall specimens tested at the University of California, Berkeley. A reasonable correlation is observed for two test specimens. These tests consisted of increasing monotonic shear loads. Upon completing these verification tests, a fourteen story reinforced concrete building with seismic monitoring devices is analyzed for nonlinear capacity. The structure consists of six shear walls (four in the north-south direction, and two in the east-west direction). Each shear wall is modeled and analyzed for ultimate lateral capacity. Results are tabulated and compared with conventional design codes (i.e., Portland Cement Association, American Concrete Institute, and the Uniform Building Code).

A dynamic analysis is performed using time history input from the San Fernando (1971) and Northridge (1994) Earthquakes. Response Spectrum analyses are compared with recorded data with reasonable correlation. A second model using elastic finite elements is used to cross-check the results from nonlinear model. This program is the Extended Three Dimensional Building Analysis (ETABS) software, developed by University of California, Berkeley. Time history responses are compared between the elastic, inelastic, and recorded data. The inelastic model demonstrates itself a useful tool for practical nonlinear application on large building projects.

ACKNOWLEDGMENTS

Engineering research is an arduous task involving patience, dedication, perseverance, and more patience. I gratefully acknowledge the support of my father, mother, my sister and brother-in-law for encouraging me through this project, and my son for his sense of humor. This thesis would not have been possible without the guidance of my advisor, Dr. James Anderson, for his insight and expertise. Dr. Anderson allowed me to participate as a research scholar on several projects which enabled me to gain valuable experience in the analysis of multi-story buildings, and also provided precious financial support. Technical support from the ADINA Corporation assisted in solving complex problems through the course of the analysis work.. Throughout the course work and research effort, I wish to respectfully honor my employer; California State Polytechnic University, Pomona; which provided the financial base for me to finish the Ph.D. program. My highest regards to Dr. Ronald Carlyle, Chairman of the Civil Engineering Department at Cal Poly, Pomona, and Dr. Ed Hohmann, Vice President of Academic Affairs, California State Polytechnic University, Pomona, allowed me generous flexibility in scheduling my class load, office hours, and the academic freedom to pursue this degree to completion.

CHAPTER 1

INTRODUCTION

1.1 Shear Wall Buildings

Shear wall buildings comprise a large proportion of commercially constructed buildings. These structures serve as residential and office space occupancy, and range up to thirty stories and beyond. Shear wall buildings may be classified into two broad categories:

1. Shear/Flexural Wall Lateral Resisting Buildings.
2. Bearing Wall Buildings.

The major difference between the two is their lateral resisting design. A shear/flexural wall building (Category 1) relies on a primary vertical load carrying system, such as columns & beams while the shear walls function primarily for lateral resistance. The specific intent of the shear and flexural walls is to provide lateral stiffness. Vertical loads are carried by the beam-column system.

As an example, refer to Figure 1-1 which shows a combination concrete ductile moment frame with a shear walls. The shear walls brace the concrete moment frame against lateral deflections while the frame handles the vertical loads. This structural system is commonly utilized in multistory office structures.

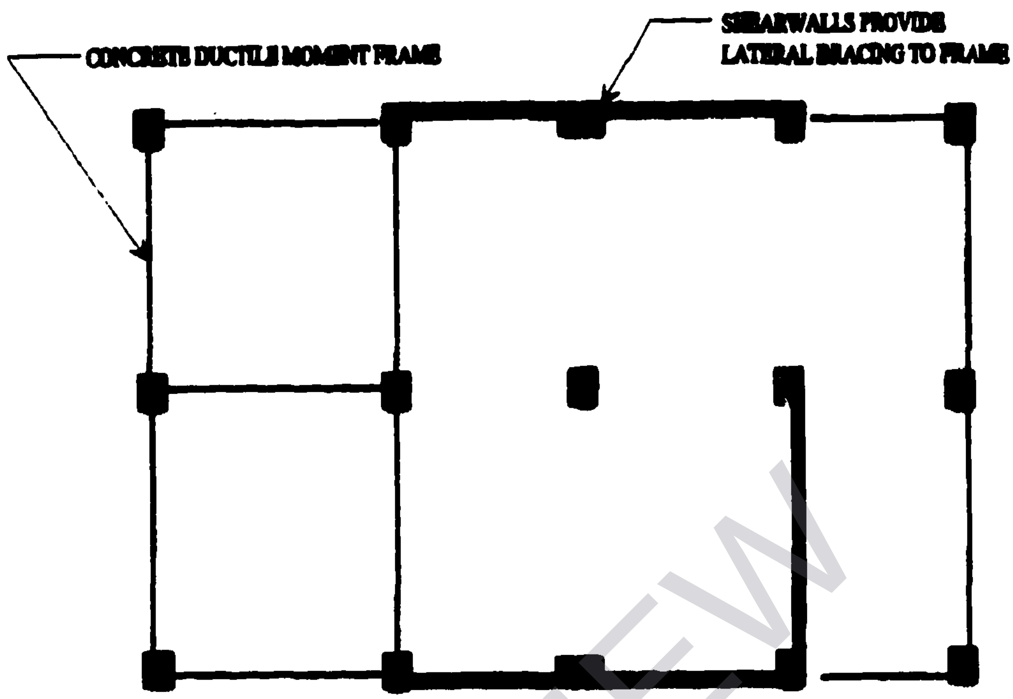

Figure 1-1. Category 1: Ductile Moment Frame, Shear Wall Floor Plan

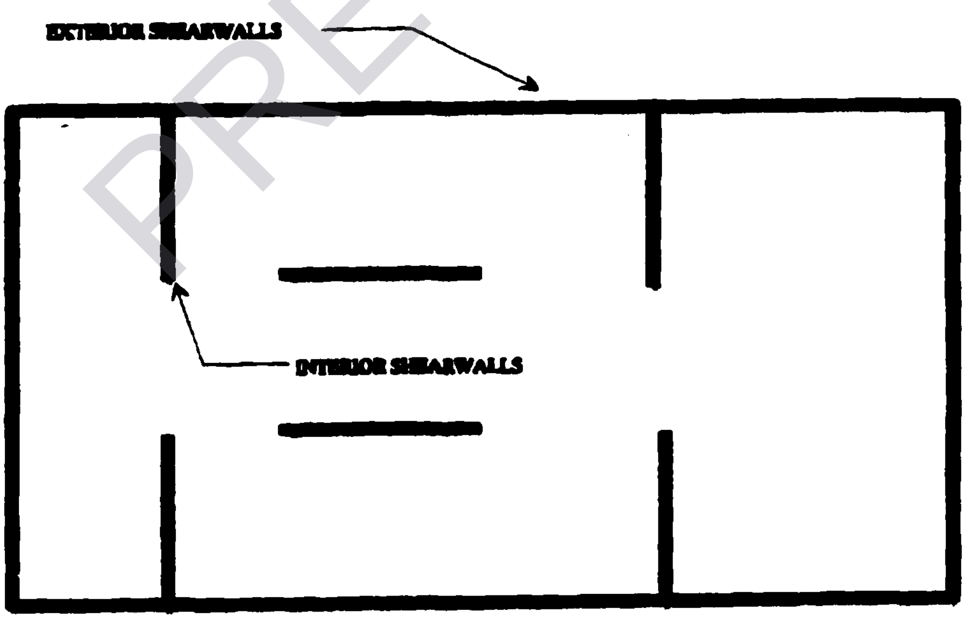

Figure 1-2. Bearing Wall Structure Floor Plan

Category 2 comprises a shear wall system that functions both as a vertical load carrying system and also a lateral resisting system. Vertical loads are transferred to walls and eventually to the foundation. Therefore, the axial force/stress increases on the wall toward the base of the building. In addition to this axial force, the wall is also expected to resist large dynamic loads (due to earthquake or wind) that strike "in-plane" and "out-of-plane" to the wall.

Refer to Figure 1-2, shows a bearing wall floor plan. Both the exterior and interior walls absorb vertical and lateral loads. The primary load carrying system are the walls, and there is no secondary load system.

By experience, shear wall buildings have demonstrated an excellent performance during earthquakes. They are stiff structures with high ductility. Generally, shear wall buildings survive earthquakes with minimal damage. This is due to a particular characteristic of shear wall structures which is their stiff in-plane resistance. The in-plane shear resistance provides bracing against dynamic loads and shortens the period of the structure.

To further clarify the difference between in-plane vs. out-of-plane resistance: Refer to Figure 1-3(a) which shows a shear wall loaded "in-plane". In-plane load

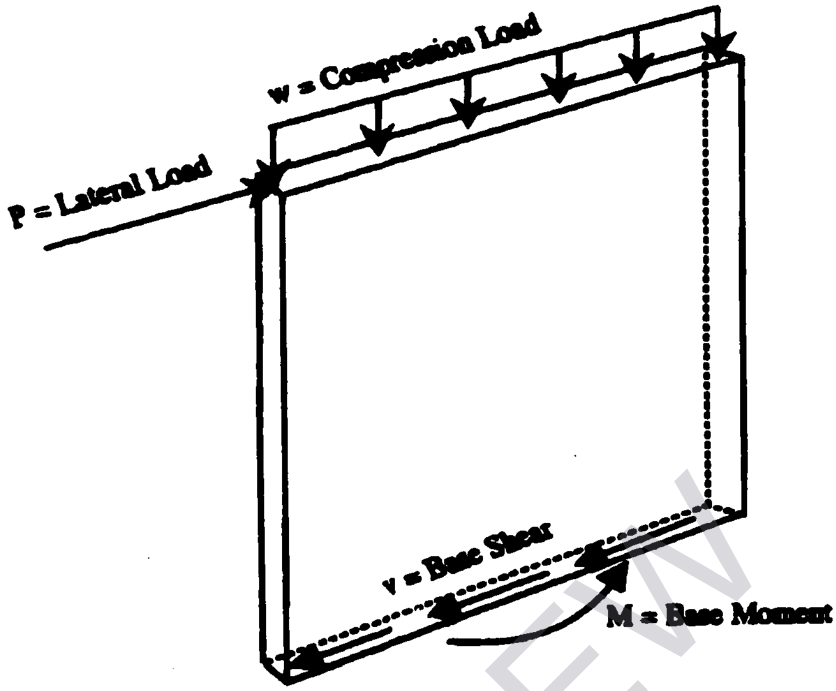

Figure 1-3(a). In-Plane Shear Capacity

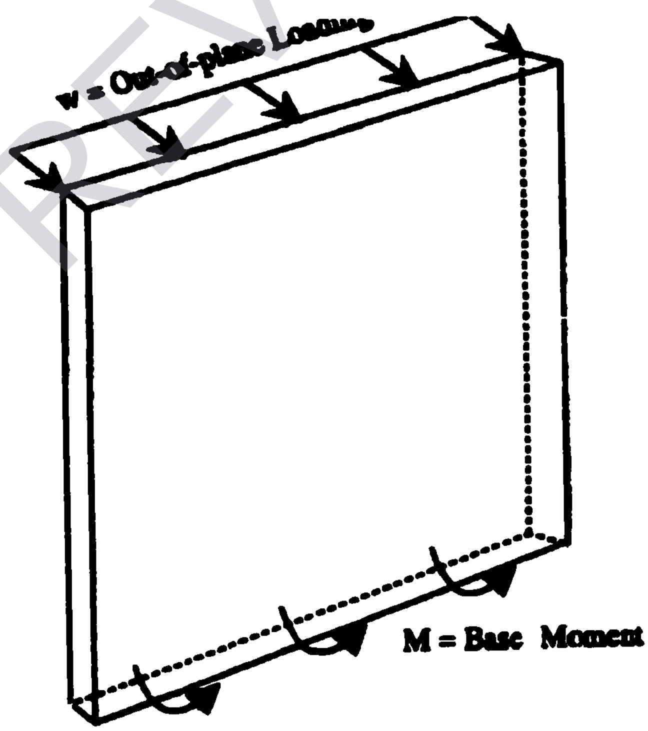

Figure 1-3(b). Out of Plane Flexural Capacity resistance is the principle strength of shear walls. Providing lateral bracing (against out-of-plane buckling) allows shear walls to accept very high in-plane loads. Out-of-plane forces are depicted in Figure 1-3 (b). Shear walls require bracing against out-of-plane loads by either additional shear walls or ductile moment frames. If the out-of-plane bracing is not provided, the shear wall will fail prematurely. From a practical standpoint, shear walls are usually braced in their perpendicular direction by additional walls to alleviate potential failure. With exception of retaining walls, in a building with a shear wall design, the out-of-plane forces are counteracted by either another wall or dual bracing system.

"Shear wall" is the industry accepted term. However, not all shear walls behave in a shear capacity, as shown in Figure 1-4. Tall slender walls are required to resist flexural stresses at the base. Flexural walls are referred to as "Structural Walls" by some researchers and practitioners, as opposed to "Shear Walls" that are shorter and longer. The difference is the in-plane capacity being linked to a flexural or shear deformation failure. For simplicity, in this thesis the term "shear walls" will be used throughout.

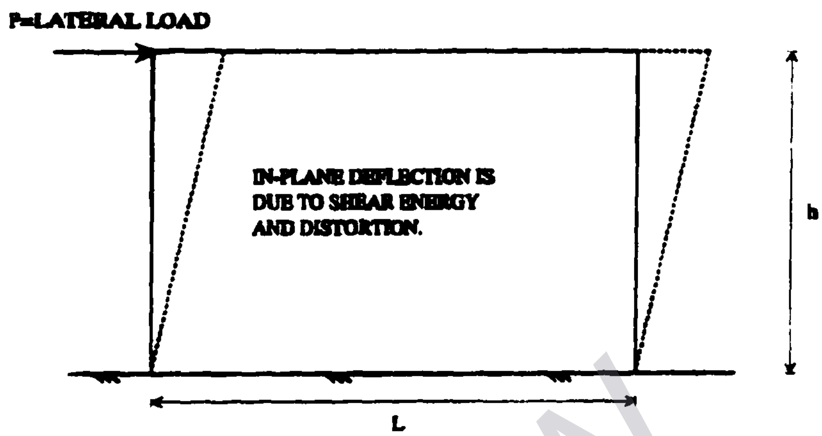

Figure 1-4(a). Shear Wall

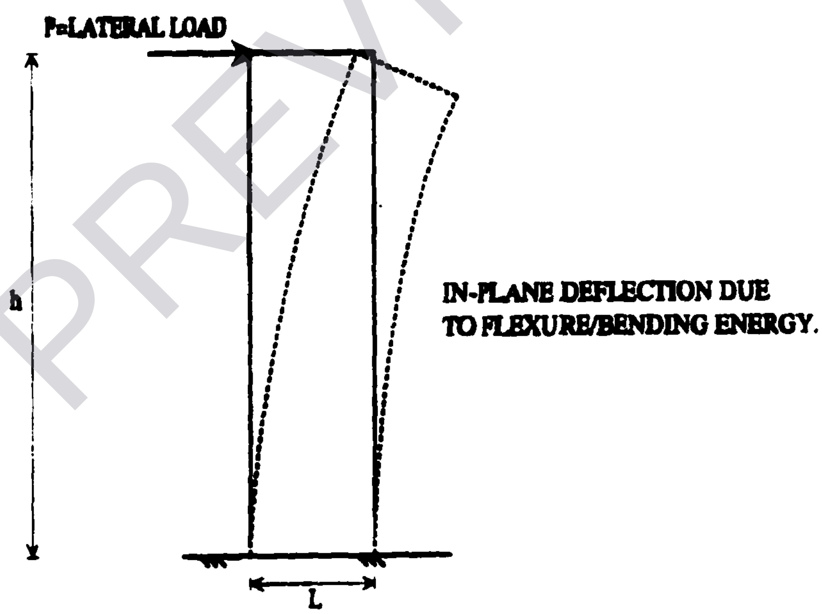

Figure 1-4(b). Structural Wall

In Figure 1-4(a) and (b), the deflected shape of a structural wall and a shear wall are shown. Since a structural wall absorbs significant bending stresses, its deflected shape may be calculated with flexural bending theory (in the elastic range) and ignoring shear deformation contributions. For a pure shear wall, it is necessary to account for shear deformation contributions. Therefore, the failure mode of these two types of walls are quite different. To analyze linear and nonlinear behavior requires a model that can allow for contribution of shear deformation displacement along with flexural displacement. Both are necessary to properly describe the wall behavior.

In order to develop flexural and shear strength, two significant components of a shear wall are necessary:

1. Web reinforcing: Web steel consists of horizontal and vertical reinforcing at uniform spacing.

2. Boundary reinforcing: Vertical steel with ties located at both ends of the shear wall.

Figure 1-5(a), (b), and (c) show three different types of shear walls.

Boundary reinforcing develops large axial tension/ compression forces that create an in-plane force-couple system to resist external moments. Boundary steel with horizontal ties (similar to column ties) contributes to

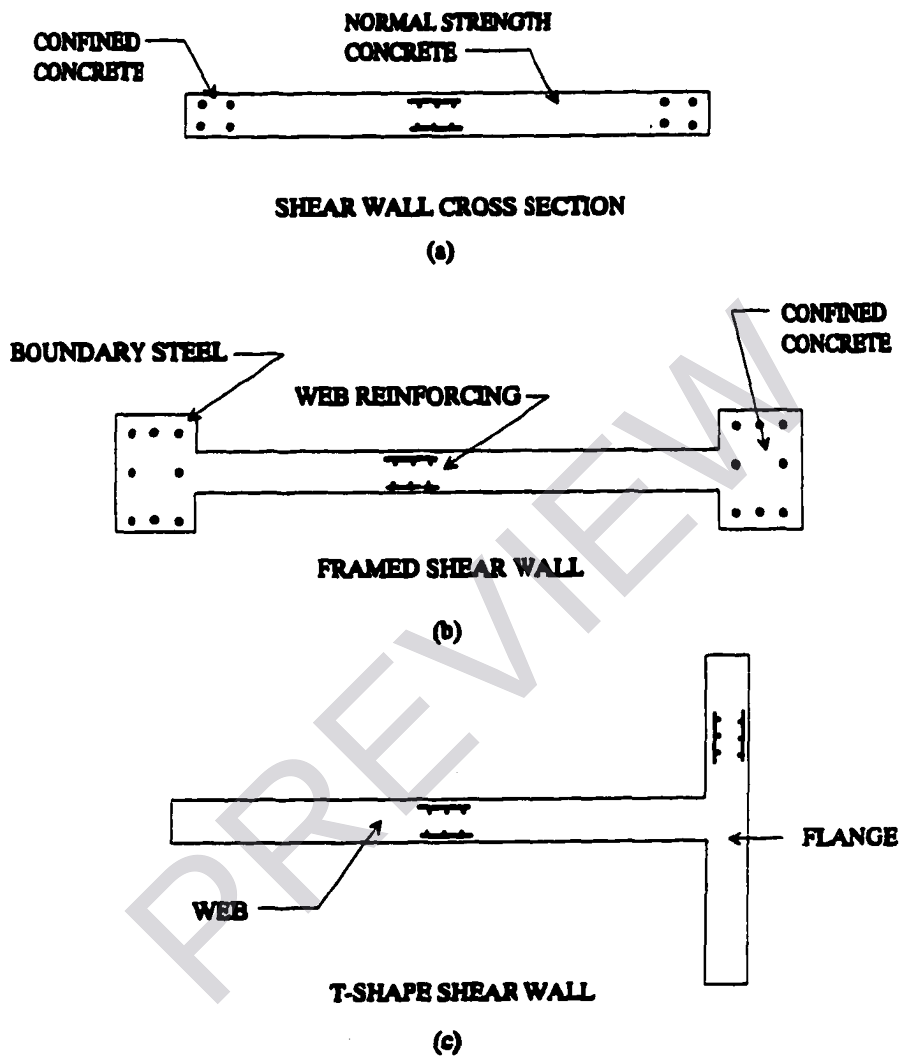

Figure 1-5(a), (b) & (c). Typical Shear Wall Configurations confinement of the concrete. Concrete confinement increases the material stress-strain curve to an enhanced capacity (i.e., the concrete is stronger and has greater ductility).

External moments also result in web shear that cause diagonal tension cracks. Web steel is responsible to resist in-plane shear stresses. Diagonal tension stress is a concept familiar from basic concrete courses. The "compression strut theory" identifies concrete as the principle vector to resist compression stresses, while steel provides tension resistance. Nevertheless, shear walls seldom fail due to high compression stress, but rather will crack in tension areas due to insufficient web steel.

Figure 1-5(a) is a typical uniform thickness shear wall. Confinement at the boundary elements are provided, and thus increases flexural capacity. Web steel provides in-plane shear resistance. Cross-sections of this type are commonly used in shear wall buildings of shorter height (i.e., less than five stories) because they provide good shear resistance and ductility, but do not have high flexural capacity under axial loads as the walls of Figure 1-5 (b) and (c). Additionally, web buckling is a consideration in slender sections.

Figure 1-5(b) is a typical "framed shear wall" because the boundary elements are column/pilaster thickness and "frame" the web area. Framed shear walls are particularly strong in developing moment-capacity because of the high axial forces in the boundary elements. These types of shear walls are used for tall multistory applications where vertical load capacity and lateral resistance are *both* necessary.

Figure 1-5(c) is a t-shaped shear wall. The perpendicular (flange) wall increases the web's in-plane moment of inertia. Although the flange is out-of-plane to the web, structural engineers have observed the performance of t-shaped shear walls to demonstrate strong bending resistance. Flanged shear walls do not enhance shear capacity as much as the moment, because the flange does not increase the gross area as it does the moment of inertia. Therefore, t-shaped shear walls have their best application in tall multistory buildings which require both vertical and lateral load capacity.

1.2 Shear Wall Building Design Considerations

There are many examples of shear wall buildings. From an engineering standpoint, there are many reasons for specifying shear wall resisting systems. From an architectural point of view, a problem arises with placing the shear walls in a strategic location to avoid impacting the view and/or floor plan arrangement of the design. Economical design of shear wall buildings so that the maximum structural efficiency is achieved is of tremendous value to all parties involved. Architectural considerations for the placement of shear walls revolve around efficient use of floor space to satisfy client requirements. A shear wall building requires permanent walls that cannot be moved for future tenant preferences. This is because the wall provides structural resistance and is tied to the floor and ceiling diaphragms. Consequently, for office buildings and retail space, ductile moment frame structures are selected because of the added flexibility provided to the architect designer. Floor plans may be readjusted to accommodate tenant requirements without compromising structural resistance.

1.3 Coupled Wall Buildings

The connecting beams are sized to be lower stiffness (i.e., weaker) than the shear walls. During wind/earthquake loads, the coupling beams will form plastic hinges at their joints with the shear walls. This allows for a ductile response to lateral loads by not allowing the shear walls to deform plastically. Rather, the inelastic damage is confined to the joints of the coupling beams. A