# CHAPTER I

# INTRODUCTION

Reinforced concrete (RC) structural walls are commonly used in buildings to resist lateral forces such as wind loads. or earthquake forces. In the past, structural walls were not widely used for buildings in seismic areas because engineers believed that they would not be ductile enough and would fail in brittle modes such as shear failure. However, observations of RC buildings after earthquakes indicate that the buildings with wall or frame-wall systems are effective in resisting earthquake forces and they sustain less damage than buildings that rely solely on frames for lateral resistance (Fintel 1973, 1991). Therefore, a wall or frame-wall system seems to be one of the best choices for protecting lives and properties during severe earthquakes. Because of their advantages, a number of researchers have studied the inelastic behavior of walls subjected to cyclic loading in order to obtain information for proper design and reinforcement detailing.

## 1.1 General Behavior of Structural Walls Subjected to Cyclic Loading

To study the ability of structural walls in resisting earthquake loading, test specimens are typically subjected to cyclic loads simulating earthquake loading. The primary response obtained from the tests is the relationship between the lateral force and the lateral displacement as shown in Fig. 1.1. This relationship reflects the behavior of structural walls including strength, stiffness, ductility, and energy dissipation. The characteristics of failure are also determined from the experiments.

### 1.1.1 Strength

The strength of a structural wall is the maximum lateral force that it can resist. For seismic design, the capacity design concept should be used in order that failure will be controlled by flexure, to avoid brittle modes of failure, and to ensure ductility with large dissipation energy capacity.

### 1.1.2 Ductility

In a seismic zone, it is not economical to design structures to remain elastic during a major earthquake, and it may even be impossible in the case of a very rare earthquake. Present seismic design practice allows the structures to respond beyond the elastic limit while retaining most of the peak lateral strength (usually taken as 80%). This ability of the structure to sustain inelastic response is described by the general term *ductility*. The displacement ductility is defined as the ratio of the maximum lateral displacement to the lateral displacement at the yield of reinforcing bars. For walls that are reinforced with several layers of reinforcement, the effective yield displacement should be based on an elastic- plastic idealization of the entire force-displacement diagram, the yield point being defined by the intersection of the elastic segment and the yield plateau representing the calculated flexural load (Paulay 1982). Similar ductility ratios may be described in terms of rotation and curvature. In order for a given structural element to develop higher ductility, special reinforcement details in critical regions are needed. For structural walls, special confinement of the boundary elements can help to increase the displacement ductility. However, shear modes of failure may limit the deformation of walls and must be controlled to ensure ductility (Oesterle et al. 1979).

### 1.1.3 Energy dissipation

Although energy dissipation is not directly considered in the present code, engineers have to design structures that can dissipate the energy induced by earthquake loading. The capacity design approach is often used to avoid brittle modes of failure so that sufficient energy can be dissipated by the structure.

To ensure good energy dissipation capacity of the structure, each structural element should dissipate energy reliably. The dissipated energy of a component in one cycle of loading is represented by the enclosed area of the lateral load-displacement curve for that cycle (Fig. 1.2). To enhance energy dissipation, the primary aim will be to minimize degradation in both stiffness and strength upon cyclic loadings, thereby maximizing the hysteretic loop shown in Fig. 1.2.

Structural walls with horizontal and vertical web reinforcement exhibit stiffness degradation called "pinching" because the shear resistance after inelastic shear displacements can be attained only when the subsequent imposed displacement is larger than the previously encountered displacements. Thus, it is desirable to minimize. (Paulay 1980).

### 1.1.4 Failure characteristics

From test results of structural walls subjected to cyclic loading, the failure characteristics can be classified into the following categories (Paulay 1980, Aktan and Bertero 1985):

*Flexural failure* (Fig. 1.3a): This mode of failure is characterized by the yielding of the longitudinal steel near one boundary of the wall and crushing of concrete near the other. It occurs when the shear strength of the wall is greater than the strength developed at the flexural capacity of the member. The wall failing in flexure is most ductile and dissipates more energy than other failure modes. Therefore, this is the most desired mode of failure.

If the spacing of transverse reinforcement is sufficiently large, the longitudinal bars in the boundary elements may buckle before crushing of the concrete. It must be ensured that buckling does not take place prematurely resulting in a brittle failure mode.

*Shear sliding failure* (Fig. 1.3b): This mode of failure is featured by excessive sliding displacement at the base or at the construction joint. The shear sliding resistance includes friction in the compression zone, dowel action from the vertical reinforcement, and the horizontal component from the inclined bars. This type of failure usually occurs in squat walls under high lateral forces.

*Diagonal tension failure* (Fig. 1.3c): Such failure occurs when horizontal shear reinforcement is insufficient to resist the shear stress developed in the web portion. Large diagonal tension cracks may develop in the web portion, leading to brittle type of failure.

*Web crushing failure* (Fig. 1.3d): This mode of failure is characterized by crushing of the concrete under diagonal compression in the web portion. This mode of failure often occurs in walls with boundary elements that have very large flexural capacities.

According to Paulay et al. (1980), diagonal compression failure may occur at a much lower shear load when the wall is subjected to reversed cyclic loading, resulting in significant loss of strength.

*Compression stability failure* (Fig. 1.3e): This mode of failure occurs after the longitudinal reinforcement in the boundary element has yielded in tension. Upon loading in the opposite direction, these bars must resist compression. However, after large inelastic excursions, the bars may not have the same ability to carry compression. This situation could lead to out-of-plane instability.

From the failure mechanisms described, it is evident that in the design of ductile structural walls, flexural yielding in clearly defined plastic hinge zones should control the strength, inelastic deformation and hence energy dissipation. Brittle failure mechanisms such as shear sliding failure, diagonal tension failure, and web crushing failure are highly undesirable and should be avoided.

## 1.2 Literature Review

The inelastic behavior of RC structural walls subjected to cyclic loads has received considerable attention in an attempt to improve the seismic performance of structural walls. The Portland Cement Association conducted an exclusive series of tests in 1970s (Oesterle et al. 1976, 1979). The experimental parameters included geometry of cross section, shear stress level, amount of transverse reinforcement, amount of horizontal and vertical web reinforcement, and axial load level. The aspect ratio of all specimens was 2.4. The experimental results reveal that walls with high shear stresses ($> 0.58\sqrt{f_c'}$ MPa) failed by web crushing while walls with low shear stresses ($< 0.26\sqrt{f_c'}$ MPa) failed in flexural modes. In addition, the amount of horizontal web reinforcement did not have a significant effect on the shear behavior, and the ductility capacity increased with amount of transverse reinforcement in the boundary elements. However, confinement of the boundary elements will not influence ductility capacity if the behavior of the wall is controlled by shear.

The behavior of properly designed walls with an aspect ratio more than 2.0 is generally dominated by flexure whereas that of walls with an aspect ratio less than 1.0 is dominated by shear. For walls with an aspect ratio around 1.5, a mixed mode of failure may result under seismic loading (Salonikios 1999, 2000).

The webs of structural walls are typically reinforced with horizontal and vertical reinforcement. However, engineers are not constrained to orient the web reinforcement in these directions.

Iliya and Bertero (1980) conducted early studies of walls with conventional and diagonal web reinforcement. The aspect ratio of the specimens tested was 1.3. The specimens were cyclically loaded up to the first yield of the longitudinal steel in the boundary elements. The cracks in the specimens were then repaired by epoxy grouting. The repaired specimens were subsequently loaded, with a few intermediate cycles, up to failure. Finally, the damaged walls were retrofitted and again subjected to cyclic loadings until failure. The diagonal reinforcement configuration was found to form a more effective shear resisting mechanism, resulting in higher energy dissipation capacity and less stiffness degradation with displacement reversals. Also the desirable flexure failure mode was attained in contrast to the predominantly web crushing and diagonal cracking failure mode in the conventionally reinforced wall.

The detrimental effects of sliding shear in squat shear walls under cyclic lateral loading have been demonstrated by Paulay et al. (1982) in their tests of four shear walls with an aspect ratio of 0.5. Two walls were reinforced with steel bars placed in the horizontal and vertical directions while the other two were provided with a reduced amount of conventional reinforcement plus two bands of diagonal steel bars extending from upper to lower corners of the walls. It was found that, although slip could not be prevented by the crossed diagonal reinforcement provided which contributed to only about 30% of the lateral load resistance, the walls exhibited significant improvement in energy dissipation capacity.

Salonikios et al. (1999, 2000) tested eleven walls, five of them with an aspect ratio of 1.0 and six with an aspect ratio of 1.5. All specimens were reinforced with conventional web reinforcement and four of them included groups of cross-inclined diagonal (bidiagonal) bars, which intersected near the center of the web. The contributions of flexure, shear and sliding to the total displacement of the walls were determined at different displacement ductility levels. Stiffness and energy dissipation capacity were also evaluated. The cross-inclined web reinforcement effectively controlled sliding at the base of the wall and subsequent pinching of the hysteresis curves, particularly when the groups of diagonal bars intersected near the critical section at the base of the wall. It should be noted that all walls failed at a shear stress significantly less than $0.66\sqrt{f'_c}$ MPa, and the influence of cross-inclined web reinforcement on web crushing was not investigated.

Recognizing the importance of preventing sliding failure in squat walls, Eurocode 8 (CEN 2004) recommends that cross-inclined web reinforcement be provided to enhance wall performance against sliding shear failure in shear walls with an aspect ratio less than 2.0. In such walls of the high ductility class, cross-inclined web reinforcement should be provided at the base of the wall at a quantity sufficient to directly resist at least 50% of the wall seismic shear force, whereas at higher levels at least 25% of the wall seismic shear force should be resisted by cross-inclined steel bars.

While distributed diagonal web reinforcement is more difficult to place than the concentrated bidiagonal bar arrangement recommended by Eurocode 8, this configuration has also been adopted by designers. Distributed diagonal web reinforcement was observed in several buildings in Viña del Mar following the 1985 Chile earthquake (Wood et al. 1987).

During the past ten years, Sittipunt et al. (2001), Mansour and Hsu (2005), Liao et al. (2004), and Chiou et al. (2004) have conducted experimental investigations on walls and panels with distributed diagonal reinforcement. Of particular interest is the work by Mansour and Hsu who carried out both experimental and analytical studies on cyclic shear behavior of RC membrane panels with the angle of inclination of the distributed steel reinforcement taken as an important parameter. Panels with reinforcement oriented in the direction of applied principal stresses were found to perform best. The panels exhibited ductile response and possessed large energy dissipation capacities. Tests of shear walls with 45° diagonal web reinforcement (Sittipunt et al. 2001, Liao et al. 2004, Chiou et al. 2004) under cyclic lateral loading led to the same conclusion with regard to improved performance in comparison with that of conventionally reinforced shear walls. Furthermore, it was postulated that the brittle mode of failure due to web crushing could be avoided by using diagonal web reinforcement provided that the boundary elements were adequately reinforced with confinement steel (Sittipunt et al. 2001).

Axial load has significant effects on the inelastic behavior of structural walls with regard to lateral stiffness, shear deformation, and failure modes. Oesterle et al. (1979) carried out studies on the influence of axial load. It was found that with an axial load of $0.07 f_c' A_g$, the moment capacity and stiffness increased, and the shear distortion at the hinging region decreased, leading to reduced pinching. Axial load also has a favorable effect with regard to sliding (Salonikios et al. 1999, 2000). On the other hand, the displacement ductility capacity is reduced with increasing in the axial load level (Oesterle et al. 1979, Salonikios et al. 2000, Kim et al. 2004). Moreover, with a high axial load of $0.35 f_c' A_g$, the walls could exhibit an undesirable out-of-plane buckling mode of failure in the post yielding state as reported by Zhang and Wang (2000).

## 1.3 Problem Statements and Objectives

Observations of RC buildings after earthquakes indicate that the buildings with wall or frame-wall systems are effective in resisting earthquake forces and they sustain less damage than buildings that rely solely on frames for lateral resistance. A number of researchers have studied inelastic behavior of RC structural walls subjected to cyclic loads in order to understand the response and develop more appropriate design provisions. One of the basic requirements in performance-based design is controlling damage in the structure during an earthquake. To achieve this, the structure should be able to dissipate energy reliably during an earthquake and brittle modes of failure should be avoided. The results of a recent study show that walls with diagonal web reinforcement can dissipate energy more than walls with conventional web reinforcement. In addition, by using diagonal web reinforcement, web crushing can be avoided. However, there is a limited amount of experimental data on the behavior of RC walls with distributed diagonal reinforcement. Furthermore, most related tests have not included the influence of axial loading on the walls, and the level of shear stress has been less than $0.66\sqrt{f_c'}$ MPa, the limit for possible web crushing failure specified by ACI318-05 (2005). This study was aimed at investigating the influence of 45° diagonal web arrangement on the characteristics of RC structural walls under a constant low axial load level and a cyclic lateral displacement history which produced a high shear stress level ($>0.85\sqrt{f_c'}$ MPa). Particular attention was paid to the web crushing failure mode. The objectives of the study are:

1. To study inelastic behavior of RC structural walls with diagonal web reinforcement subjected to cyclic loading.
2. To study the effect of axial load level on the inelastic shear behavior.
3. To develop a proper numerical model to simulate the experimental results and to extend the investigation of behavior of RC walls.
4. To identify the critical parameters and to propose simplied design procedure of using diagonal web reinforcement in RC structural walls for seismic design.

Six RC structural wall specimens were tested under a constant axial load and cyclic lateral loadings. The parameters varied in each specimen included the amount and orientation of web reinforcement and axial load level. The finite element procedure proposed by Sittipunt (1994) was extended to predict the envelope curve of the cyclic hysteresis loops obtained from experiments, taking into account the effects of buckling of longitudinal bars on the behavior of confined concrete and the difference in stress-strain characteristics of the cover and core concrete in the boundary columns.

## 1.4 Outlines

After the introduction in Chapter 1, the test specimens and test results are presented in Chapter 2. This chapter demonstrates the advantages of walls with diagonal web reinforcement compared with the conventionally reinforced wall. In Chapter 3, the results of finite element analyses are presented, which give insight into the mechanisms pertaining to the diagonally reinforced walls in resisting lateral loads. The influence of diagonal web reinforcement can thus be clearly understood. Subsequently, a simplified design procedure for walls considering web crushing is proposed in Chapter 4. Conclusions are finally given in Chapter 5.