16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 2279
Registration Code: S-D1463069594

ATC-92: COMPARISON OF U.S. AND CHILEAN BUILDING CODE REQUIREMENTS AND SEISMIC DESIGN PRACTICE 1985–2010

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Abstract

As a result of the February 27, 2010, magnitude 8.8 Maule earthquake that occurred off the coast of central Chile, the National Institute of Standards and Technology (NIST) funded a series of projects to investigate the performance of buildings and other structures affected by the earthquake. In the time leading up to the 2010 Maule earthquake, many U.S. design concepts were embodied in Chilean seismic design practice in NCh433.Of96, *Earthquake Resistant Design of Buildings*, and NCh430.Of2008, *Reinforced Concrete Design and Analysis Requirements*. As a result, the 2010 Maule earthquake represented a unique opportunity to study the behavior of modern engineered reinforced concrete construction, similar to that present in the United States, in response to strong ground shaking.

In order to draw linkages between observed performance in Chile and implications for U.S. practice, an understanding of the similarities and differences between U.S. and Chilean seismic design philosophies was needed. The ATC-92 Project was funded to: (1) document building code requirements and design and construction practices in effect in Chile during the period 1985–2010; and (2) compare and document observed differences between operative codes and seismic design practices in Chile and the United States. The resulting report presents a side-by-side comparison of design requirements in the United States and Chile, identifies similarities, and contrasts differences. It also provides an illustrative comparison of design practice through an evaluation of both Chilean and U.S. design provisions applied to a typical Chilean building configuration.

Keywords: Code; Comparison; Design

1. Introduction

On February 27, 2010, a magnitude 8.8 earthquake occurred off the coast near the Maule region of central Chile. The fault rupture generated wide-spread strong ground shaking and a damaging tsunami. The effects of shaking were observed in several major metropolitan areas, many of which also experienced damage in previous large-magnitude earthquakes that have occured in the region.

As a result of frequent historic seismic activity, building codes in Chile have included consideration of seismic effects, and building practice has included seismic-resistant construction. Because modern Chilean practice has been largely modeled after U.S. practice, investigations into the performance of engineered structures during the 2010 Maule earthquake was considered important to future seismic design and construction practice in both the United States and Chile. In order to draw linkages between observed performance in the 2010 Maule earthquake and implications for U.S. practice, an understanding of the similarities and differences between U.S. and Chilean seismic design philosophies was needed. The ATC-92 Project was funded by the National Institute of Standards and Technology (NIST) to: (1) document building code requirements and design and construction practices in effect in Chile during the period 1985–2010; and (2) compare and document observed differences between operative codes and seismic design practices in Chile and the United States. The resulting NIST GCR 12-917-18 report, *Comparison of U.S. and Chilean Building Code Requirements and Seismic Design Practice 1985–2010* [1], presents a side-by-side comparison of design requirements in the United States and Chile, identifies similarities, and contrasts differences. It also provides an illustrative comparison of design practice through an evaluation of both Chilean and U.S. design provisions applied to a typical Chilean building configuration.

Building construction in both Chile and the United States covers a wide range of building types and structural systems. This study focused on mid-rise and high-rise reinforced concrete bearing wall structures that are typically used in high-density, multi-family residential construction because:

- Structures of this type are common in both countries, and many are located in regions of high seismicity in the United States.
- Structures of this type are designed using sophisticated engineering techniques and typify the application of sophisticated building design and construction practices in both countries.
- Chilean practice in the design of these structures is based on U.S. building codes and standards (with some modifications), enabling lessons from observed performance to be applicable to design in both countries.
- Although the collective performance of these buildings was generally very good, a number of these building experienced heavy damage, and a few collapsed, as a result of the 2010 Maule earthquake.

2. Chilean Design and Construction Practice

In 1985, Chilean seismic design requirements governing the strength and stiffness of buildings were similar to the requirements contained in Section 2312 of the 1982 *Uniform Building Code* [2] then in use in the United States. Design and detailing provisions for concrete buildings were based on the German standard, DIN 1045, *Concrete and Reinforced Concrete* [3], and had not been substantially changed for more than 20 years. As such, they did not contain modern seismic detailing provisions intended to provide ductile behavior. Many Chilean engineers at the time were using ACI 318-83, *Building Code Requirements for Reinforced Concrete* [4] in lieu of requirements based on the German standard.

Although damage was extensive in the 1985 earthquake, taller concrete buildings in Valparaiso and Viña del Mar generally performed well. Floor plates in these buildings had dense shear wall patterns, with ratios of wall area to floor area that were in the range of 5% to 10% at a typical floor. These buildings generally lacked special seismic detailing, but had enough strength and redundancy to perform well without extensive damage. Following the 1985 earthquake, engineers updated Chilean seismic design provisions based on contemporary *Uniform Building Code* requirements, and formally adopted ACI 318 (with modifications) as the basis for detailing of concrete structures.

2.1 Operative Codes in Chile

Building codes in Chile are developed and published by the Instituto Nacional de Normalización (National Standards Institute), or INN, which is the Chilean member organization of the International Organization for Standardization (ISO). INN publishes design criteria in the form of individual Normas (Standards). In the time leading up to the 2010 Maule earthquake, many U.S. design concepts were embodied in Chilean seismic design practice in two primary standards governing seismic-resistant design of reinforced concrete structures in Chile:

- NCh433.Of96, *Earthquake Resistant Design of Buildings* [5]
- NCh430.Of2008, *Reinforced Concrete Design and Analysis Requirements* [6]

NCh433.Of96 encompasses requirements for calculating seismic loads for design of structures, and was based on seismic design requirements contained in various editions of the *Uniform Building Code*, which were used throughout the Western United States during the period 1988–2000. NCh430.Of2008 sets the criteria for design and detailing of reinforced concrete structures. After many years of unofficial use, the Chilean standard formally adopted ACI 318 for the design of reinforced concrete structures, and ACI 318-05, *Building Code Requirements for Structural Concrete* [7] became the basis of NCh430.Of2008, but adoption included some important exceptions for Chilean practice, including omission of requirements for confined boundary elements in reinforced concrete shear walls.

2.2 Design and Construction Practice in Chile

Low-rise construction has traditionally consisted of masonry or concrete bearing wall buildings with relatively short spans and many walls. The comparatively low cost of construction labor relative to materials in Chile favors the use of distributed structural systems in which many elements provide lateral resistance. As building practices evolved, and mid-rise and high-rise construction became more prevalent, engineers continued these same practices, employing relatively short spans in floor systems and providing many load-bearing walls for both gravity and seismic force resistance. As a rule of thumb, Chilean engineers generally knew that adequate earthquake performance could be achieved if they provided shear walls with sufficient density. Historically, a cross sectional area equal to approximately 2% to 4% of the gross area of the first floor was used. In the 25 years leading up to the 2010 Maule earthquake, a density of 0.1% of the total gross floor area above the first story was used [8]. Based on past experience, they believed that special ductile detailing of these walls was not necessary. Building performance in past earthquakes, including events in 1971 and 1985, generally confirmed that these practices provided good performance.

Typical Chilean mid-rise and high-rise construction favors reinforced concrete bearing wall construction that is mostly rectangular in plan, with extensive glazing and few exterior walls. Images depicting typical mid-rise and high-rise construction in Santiago and Viña del Mar are shown in Figure 1, Figure 2, and Figure 3.

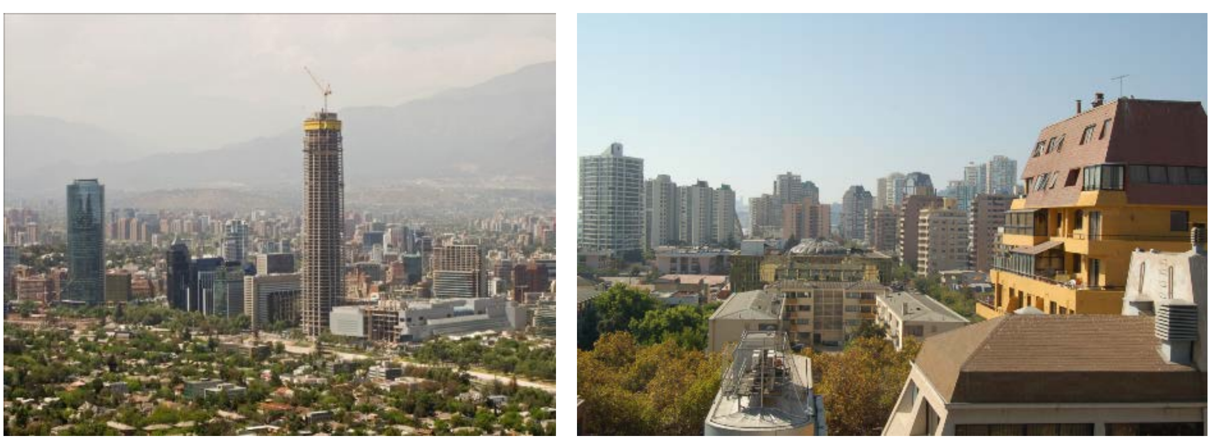

Fig. 1 – Typical mid-rise and high-rise construction in Santiago and Viña del Mar [1]

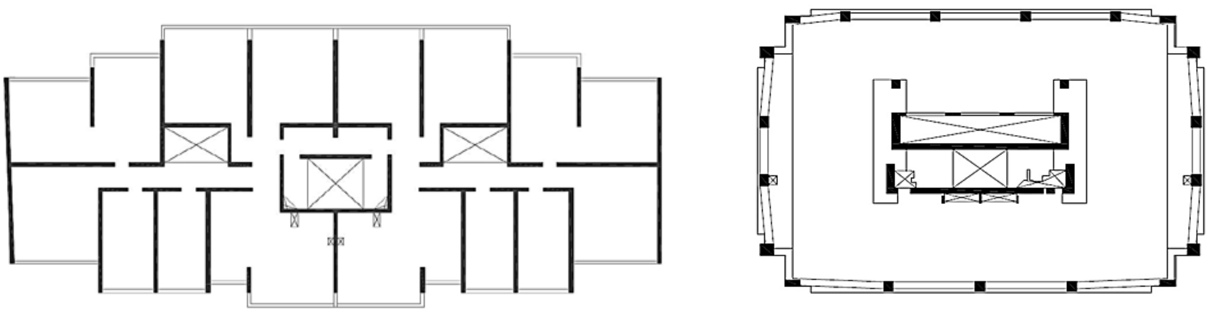

Fig. 2 – Typical floor plans of high-rise residential (left) and office (right) construction in Chile

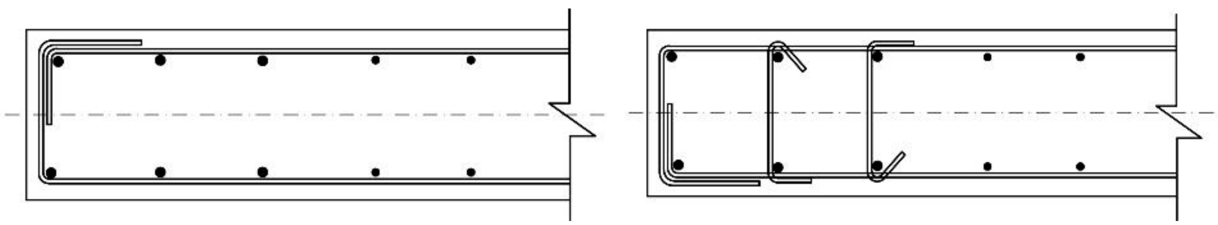

Fig. 3 – Typical unconfined shear wall boundary zone detail permitted in NCh430 (left) and partially confined shear wall boundary zone detail used by some Chilean engineers (right)

3. U.S. Design and Construction Practice

In the United States, building codes are locally developed and adopted at either the City, County, or State level. Almost all such agencies base their codes on one of several model building codes. For many years, most building regulation in the United States was based on one of three regional model codes: the *National Building Code* (NBC), developed by the Building Officials and Code Administrators International (BOCA), the *Standard Building Code* (SBC), developed by the Southern Building Code Congress International (SBCCI), and the *Uniform Building Code* (UBC), developed by the International Conference of Building Officials (ICBO). In the period between 1995 and 2000, the regional model code development agencies merged to form the International Code Council (ICC), and published the *International Building Code* (IBC) as a single national model code.

With funding from the Federal Emergency Management Agency (FEMA), the National Institute of Building Sciences (NIBS) Building Seismic Safety Council (BSSC) has been responsible for developing a series of recommended seismic design provisions to serve as the basis of modern seismic design practice in the United States. First published in 1985, the *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings* [9] have been regularly updated the BSSC Provisions Update Committee on a three-year cycle. Since 1997, the BSSC Provisions have formed the basis for the seismic provisions in the IBC.

3.1 Operative Codes in the United States

By 2010, most local governments in the United States had adopted a version of the *International Building Code*, with the 2006 IBC [10] being the most commonly adopted and enforced edition at the time. Unlike its predecessor model codes, however, the IBC is not a self-contained code. Instead, the IBC adopts structural design criteria through reference to a series of national consensus standards. In 2010, the two standards most relevant to the design and construction of reinforced concrete structures in the United States were:

- ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures* [11]
- ACI 318-08, *Building Code Requirements for Structural Concrete* [12]

ASCE/SEI 7-10 specifies loads, load combinations, and seismic design requirements for structural systems and nonstructural components. Seismic requirements in ASCE/SEI 7-10 are based on the 2009 edition of the *NEHRP Provisions* [13], which have diverged from the requirements contained in the legacy editions of the *Uniform Building Code* that served as the basis for recent Chilean standards. ACI 318-08 specifies requirements for design, detailing, and construction of reinforced concrete structures. Differences between the 2005 and 2008 editions of ACI 318 are subtle with regard to seismic design.

3.2 Design and Construction Practice in the United States

Although building codes in the United States and Chile are similar, the typical configuration of structural systems in buildings of similar size and occupancy tend to be quite different. In contrast with Chile, the cost of labor in the United States tends to be a more significant percentage of total construction cost, driving U.S. practice towards building configurations that minimize labor, even if this results in less than optimal use of materials. As a result, construction practice in the United States tends towards the use of longer spans, two-way flat slabs, and fewer structural walls. Typical floor plans depicting U.S. construction are shown in Figure 4.

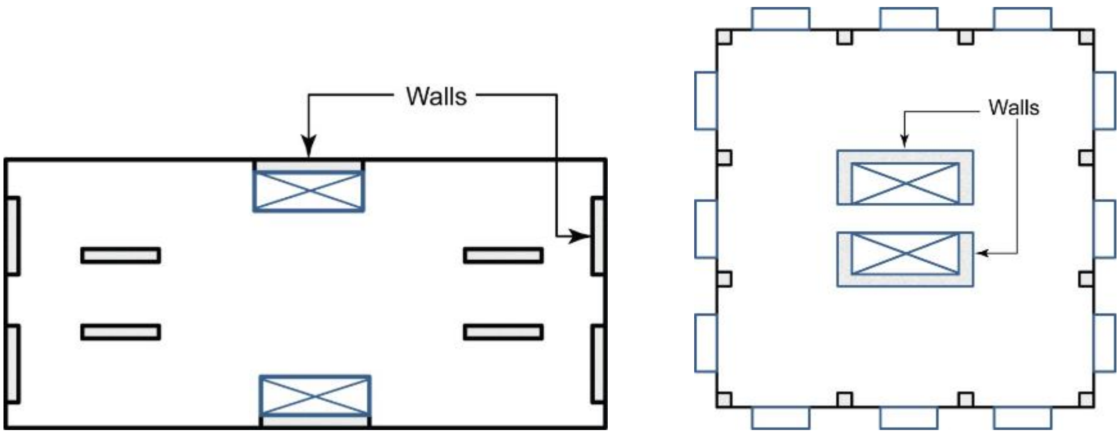

Fig. 4 – Typical floor plans associated with mid-rise (left) and high-rise (right) residential construction in the United States

U.S. design practice includes height restrictions on such systems, consideration of torsional resistance, provisions for back-up seismic force-resisting systems, and the use of ductile detailing in areas expected to experience significant inelastic behavior. In shear wall systems, ductile detailing is typically required at the base of slender walls, where flexural yielding is anticipated, and in coupling beams, where shear yielding, flexural yielding, or both are anticipated. Detailing of a confined shear wall boundary zone is shown in Figure 5.

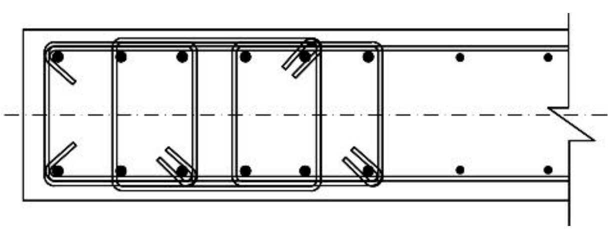

Fig. 5 – Typical confined shear wall boundary zone in the United States

4. Comparison Between U.S. and Chilean Seismic Design Requirements

U.S. and Chilean design requirements were compared in detail, on the basis of provisions related to performance categories, occupancy importance factors, seismic zonation, design ground motion, soil classification, load combinations, drift limits, base shear equations, period calculations, story force distributions, torsion, design spectra, analysis type, scaling of results, and consideration of orthogonal effects. The NIST GCR 12-917-18 report, *Comparison of U.S. and Chilean Building Code Requirements and Seismic Design Practice 1985–2010* [1], provides a side-by-side comparison of U.S. and Chilean seismic design requirements in tabular format, together with commentary on substantive differences, which has not been reproduced herein. Key differences are summarized in the sections that follow.

4.1 Comparison of Seismic Design Loading

Chilean seismic design codes evolved from U.S. practice in the mid-1990s. Important developments in U.S. codes that were not reflected in Chilean practice over this period include:

- Adoption of performance goals characterized by maximum acceptable probability of collapse conditioned on the occurrence of Maximum Considered Earthquake ground shaking.
- Definition of ground motion by reference to spectral response acceleration contour maps rather than broad seismic zones.
- Evolution of design ground motion from a pseudo-475 year earthquake basis, with a defined effective peak ground acceleration of 0.4g in the highest seismic zones, to specific calculation of design ground motion defined as a fraction (2/3) of a Maximum Considered Earthquake intensity with a probabilistic definition.
- Use of the maximum ground shaking component.
- Introduction of additional structural system variants, each with somewhat different detailing requirements, applicability, and design coefficients.
- Explicit consideration of potential system overstrength in the design of elements that, in the event of failure, could lead to collapse.
- Consideration of redundancy in determining seismic design forces.
- Evaluation of drifts and deflection at levels approximating actual response to earthquake shaking, rather than response to specified design loading.
- Adoption of strength-level, as opposed to allowable stress level, definition of seismic design forces.
- Refinement in the definition of system irregularities, and prohibition on some irregularities in regions of high seismic risk.
- Amplification of accidental torsion effects in torsionally irregular structures.

Conversely, enhancements incorporated in Chilean codes that have not been reflected in U.S. practice include:

- Period-dependent, response modification coefficients for use with modal response spectrum analysis techniques.
- Consideration of soil-foundation-structure interaction effects in modal response spectrum analysis.
- Adoption of spectral shapes appropriate to seismic hazards and site conditions prevalent in Chile.

4.2 Comparison of Reinforced Concrete Seismic Design Provisions

Chilean concrete design requirements in the period leading up to the 2010 Maule earthquake were based on requirements in ACI 318-05, but the following exceptions were identified to adapt ACI 318 requirements to Chilean practice:

- Omission of requirements for confined boundary elements in reinforced concrete shear walls.
- Permissive use of the detailing requirements for Intermediate Moment Frames when primary lateral resistance is provided by walls with the strength to resist 75% of the specified seismic design forces, even in regions of high seismic risk.
- Replacement of references to ASTM material standards with appropriate references to Chilean Normas.
- Adoption of reduced cover requirements for protection of reinforcement in various exposure conditions relative to U.S. requirements.

- Use of gross section properties, neglecting reinforcement, when calculating the distribution of internal forces within a structure, except in cases where P-delta stability effects are significant.
- Modification of load factors in load combinations, utilizing a factor of 1.4 on earthquake loads in lieu of 1.0, as specified in ACI 318.
- Permissive use of concrete cubes rather than cylinders for testing concrete strength in production.
- Modification of requirements for tension splices in reinforcement.

Developments in U.S. reinforced concrete design provisions in the period leading up to the 2010 Maule earthquake, which were not reflected in Chilean concrete design practice, include:

- Adoption of confinement rules for concrete shear walls based on estimated compressive strains in the zone of anticipated plastic hinging.
- Adoption of enhanced rules for detailing of coupling beams in walls to provide enhanced inelastic response capability.

5. Case Study Comparison of U.S. and Chilean Seismic Design Practice

To illustrate differences between U.S. and Chilean seismic design practices, and further investigate the effects of differences in seismic design requirements, a typical mid-rise, reinforced concrete shear wall building in Chile was selected as a case study building. The building was analyzed using both NCh433.Of96 and ASCE/SEI 7-05, and then redesigned as a hypothetical U.S. building, considering approximately the same seismic design environment and the same floor plate size and shape, utilizing shear wall configurations conforming to typical U.S. design practice. ACI 318-05 was referenced for reinforced concrete design requirements.

The Chilean case study building was a 10-story reinforced concrete shear wall building that was designed and constructed in 1996. The case study site was located in Viña del Mar, and considered by NCh433.Of96 to be Seismic Zone 3. The building was rectangular in plan, measuring approximately 37 m long by 16 m wide (121 feet by 52 feet). The basement story height was 3.6 m (11.5 feet), the first story height was 3.1 m (10 feet), and the typical story height was 2.6 m (8.5 feet).

The case study building sustained significant damage as a result of the 2010 Maule earthquake. Damage consisted of horizontal and diagonal cracking, spalling, crushing, and bar buckling in the reinforced concrete shear walls. Damage was concentrated primarily in the first story of the transverse shear walls, which led to differential vertical displacements on the order of 40 cm (16 in.) in the upper stories that damaged reinforced concrete beams and floor slabs. Cracking and spalling were attributed to the "flag-shaped" configuration of the shear walls, which resulted in reduced cross-sections and increased stresses where demands were expected to be the highest. Crushing and bar buckling were attributed to a lack of confinement reinforcing in the form of closed hoops and cross ties in the shear wall boundary zones. In spite of the observed damage, however, the case study building did not collapse.

5.1 Comparison of Design Parameters

Acceleration response spectra appropriate to the site were constructed in accordance with NCh433.Of96 and ASCE/SEI 7-05. The case study site in Viña del Mar is classified as Soil Type III. A similar site was assumed for the U.S. design, taken as a representative location in a region of high seismicity (San Francisco, California) with Site Class D. A comparison of the site response spectrum and design base shear parameters is provided in Table 1.

Table 1 – Design base shear and response spectrum parameters per NCh433.Of96 and ASCE/SEI 7-05

NCh433.Of96		**ASCE/SEI 7-05**	
Seismic Design Parameter	**Value**	**Seismic Design Parameter**	**Value**
Occupancy Category	C	Seismic Design Category	D
Effective Seismic Weight	7900 kips	Effective Seismic Weight	7900 kips
Seismic Zone	3	S_S	1.5 g
A_0	0.4 g	S_1	0.65 g
Soil Type	III	Site Class	D
n	1.8	F_a	1.0
p	1.0	F_v	1.5
T'	0.85	S_{DS}	1.0 g
S	1.2	S_{D1}	0.65 g
R	7	R (bearing wall)	5.0
Importance, I	1.0	Importance, I_e	1.0
T^* (longitudinal)	0.44 sec	Height, h_n	87 ft
T^* (transverse)	0.65 sec	$C_u T_a$	0.8 sec
C (longitudinal)	0.514 g		
C (transverse)	0.255 g	C_S	0.20 g
$C_{min} = A_0/6$	0.067 g	$C_{Smin} = 0.5\ S_1 / (R/I_e)$	0.065 g
$C_{max} = 0.35SA_0$ (for R=7)	0.168 g	$C_{Smax} = S_{D1}/T\ (R/I_e)$	0.163 g
LRFD conversion	1.4	Redundancy, ρ	1.3
$1.4 * C_{max}$	0.24 g	$\rho * C_{Smax}$	0.21 g
Base shear $1.4 * E$	1900 kips	Base shear $\rho * E_h$	1680 kips

5.2 Comparison of Case Study Design Configurations

In contrast with Chilean practice, U.S. practice is to configure buildings with longer spans and fewer structural walls. As a consequence, walls are thicker, allowing for easier placement of confinement reinforcing and lower compressive strains. A shear wall configuration for a hypothetical version of the case study building was developed consistent with U.S. practice. A comparison with the Chilean shear wall layout is shown in Figure 6.

This comparison was intended to illustrate differences in structural design practice and quantify the effects on detailing and potential behavior. No attempt was made to optimize the design of the U.S. configuration. It should also be noted that the U.S. configuration would not be suitable for Chilean architectural practice in which concrete walls also serve as partitions, acoustical barriers, and fire protection between units.

In the Chilean wall configuration, setbacks were provided at the base of the transverse walls. In the U.S. configuration, fewer walls provide fewer obstacles to circulation within the building. As a result, the setbacks have been eliminated and the base of the walls expanded to improve overturning resistance. A comparison between typical Chilean and U.S. transverse shear wall elevations is shown in Figure 7.

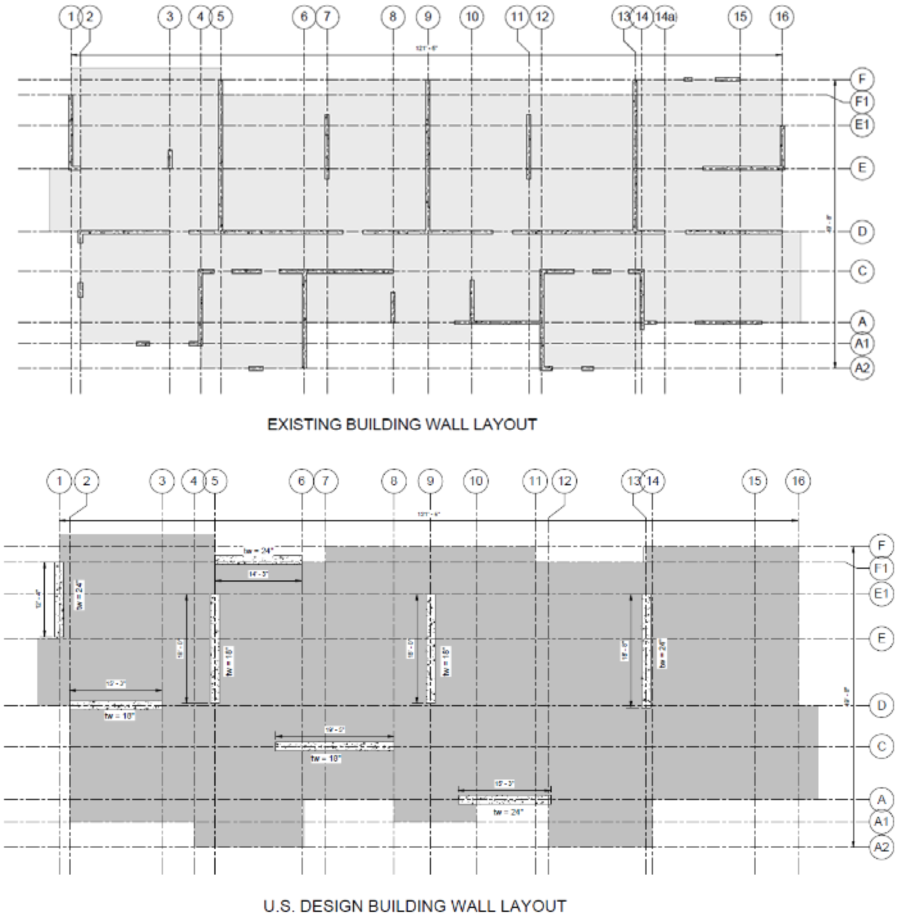

Fig. 6 – Comparison between Chilean (top) and U.S. (bottom) shear wall layouts

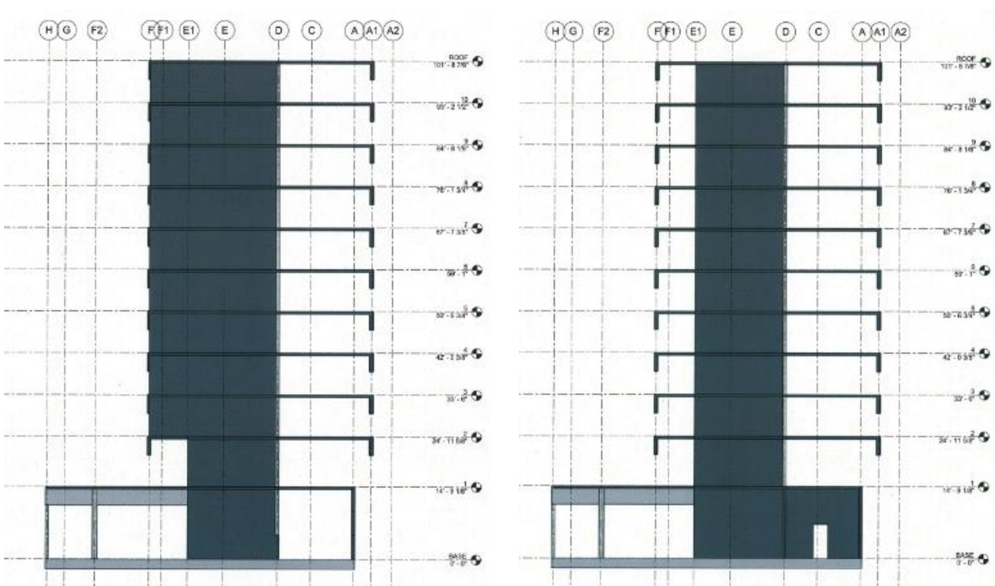

Fig. 7 – Comparison between Chilean (left) and U.S. (right) shear wall elevations

5.3 Case Study Results and Observations

Differences in U.S. and Chilean seismic design practice are the result of evolution in construction techniques, differences in labor costs as a portion of total construction costs, and differences in the roles that structural engineers play in the building design process. Evaluation of the Chilean configuration of the case study building for both NCh433.Of96 and ASCE/SEI 7-05 requirements, and comparison of the Chilean design with a hypothetical U.S. design, yielded the following observations:

- Chilean analysis of reinforced concrete structures considers gross section properties and all structural elements in the building, while U.S. practice considers effective section properties and only those elements designated as part of the seismic force-resisting system.
- Unreduced response spectra for NCh433.Of96 Soil Type III and ASCE/SEI 7 05 Site Class D, in regions of high seismicity, are similar in shape and magnitude, although the Chilean spectrum does not include a short period plateau. Chilean provisions do, however, include a maximum seismic design coefficient that varies with structural system.
- Permissible limits in NCh433.Of96 regarding drift at the diaphragm center of mass relative to the diaphragm edge would be classified as an extreme torsional irregularity in ASCE/SEI 7 05.
- NCh433.Of96 story forces (as a percentage of base shear) are higher than ASCE/SEI 7-05 story forces in the upper stories.
- When applied to the same structure, drift demands resulting from an application of NCh433.Of96 were more severe than drift demands per ASCE/SEI 7-05, even considering differences such as the use of effective section properties and a displacement amplification factor in ASCE/SEI 7-05. It appears that buildings meeting NCh433.Of96 drift requirements would also satisfy ASCE/SEI 7-05 drift requirements.
- Although attributed to somewhat different sources in NCh433.Of96 and ASCE/SEI 7-05, the estimated seismic weight is approximately the same in each code.
- Typical design base shear formulas, adjusted to a strength basis, produced nearly identical design base shear coefficients.
- ACI 318-05 provisions would have resulted in the need for confinement reinforcing in the shear wall boundary zones of the Chilean configuration, especially in the case of unsymmetric flanged walls (i.e., "T-shaped" walls).

6. Observations and Conclusions

Overall, seismic design requirements in Chile and the United States are similar. Standards in Chile are comparable to U.S. codes and standards in regions of high seismicity during the mid-1990s. Analytical procedures and design of reinforced concrete elements are nearly identical, with certain important exceptions.

Seismic design concepts embedded in the standards in each country are based on the same fundamental basis. Although the basis is the same, the details of present seismic design loading requirements in each country have diverged as a result of differences in the evolution and modification of requirements as they existed in the *Uniform Building Code* of the 1990s. Earthquake forces in NCh433.Of96 are allowable stress level forces, and earthquake forces in ASCE/SEI 7 05 are strength level forces. In spite of these and other differences, it can be shown that a typical Chilean mid-rise to high-rise residential building would be designed for an equivalent strength-level base shear coefficient that is nearly identical to the U.S. base shear coefficient.

Although many enhancements to U.S. seismic design requirements have occurred over the period 1985–2010, in general, it appears unlikely that these enhancements would have had a significant impact on the performance of buildings in the 2010 Maule earthquake. As an exception to this generalization, specific enhancements most likely to have had impact on performance of Chilean structures include:

- Requirements for confinement in shear wall boundary zones and plastic hinge regions.

- Requirements for ductile detailing of coupling beams.
- Limitations on the use of certain irregular structural configurations.

7. Acknowledgements

The work forming the basis of this paper was funded by the National Institute of Standards and Technology (NIST), under a contract with the NEHRP Consultants Joint Venture, a partnership between the Applied Technology Council (ATC) and the Consortium of Universities for Research in Earthquake Engineering (CUREE). The NEHRP Consultants Joint Venture is indebted to the leadership of Ron Hamburger, Project Director, and to the members of the Project Technical Committee, consisting of Loring Wyllie, Patricio Bonelli, and Rene Lagos, who identified and compared relevant code provisions and seismic design practices, and developed the resulting observations and conclusions. Working groups, consisting of Ady Aviram and Jose Flores Ruiz, provided translation services and performed comparative design studies. A special debt of gratitude is owed to our Chilean partners who collected and generously shared seismic design provisions, material design standards, ground motions, comparative studies, and other information that was instrumental in performing this work.

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