Detailed Recommendations from 2 June 2010 Meeting[1,2]

The 27 February 2010 Chile Earthquake: Implications for U.S. Building Codes and Standards

Code implications for ASCE 7 and ACI 318

Chilean buildings are engineered using standards and engineering methods that are similar to those used in the U.S.; in some cases, the Chilean standards are derived directly from U.S. standards. Consequently, there are many code implications to be derived from the Chile earthquake and its observed effects. In some cases there are data by which to test U.S. standards and engineering practices, suggesting future studies that can be aimed at conducting these tests. Other observations may directly suggest code changes that are needed in the short term. During the meeting, building code implications were enumerated under general categories of Ground motion/geotechnical; Architectural; Structural/new; and Structural/existing. Subsequent to the meeting, the listing was expanded by adding brief text to explain the item where necessary.

The list of code implications with expanded text follows. <u>The list is not in ranked order.</u>

1. Ground motion/geotech

a. *Co-seismic effects* – The earthquake was accompanied by a large permanent offset that occurred over a time of about 25 s. This co-seismic effect, which might have important implications for design, especially for tall buildings, is not considered directly by our current building codes or design practices.

b. *T_L for large subduction earthquakes* – Current codes use T_L as a transition period in the design seismic coefficient. The transition period for the Pacific Northwest should be compared with data from the Chile earthquake to determine if Code changes are required.

c. *Long duration* – The earthquake is characterized in part by long durations of ground shaking. Studies should be done to identify how duration might affect design of buildings in regions subject to similarly long shaking.

d. *Aftershocks* – In addition to long duration, the earthquake featured several large-magnitude aftershocks. Effects on structures, including re-occupancy considerations, could be studied.

e. *Directivity* – Anecdotal observations of effects of directivity on buildings and other structures were observed. More systematic study of these effects through data gathering and analytical study might suggest changes to Code design procedures.

[1] Meeting organized by ASCE, NIST and PEER Center, and hosted by SGH.
[2] Notes compiled by Professor Jack P Moehle, UC Berkeley

f. *Double earthquake* – Ground motion records indicate the earthquake was a result of multiple ruptures occurring in succession. What are the Code implications of this double/multiple rupture?

g. *Attenuation for subduction earthquakes* – Attenuation models are used to estimate shaking intensity as function of distance from the fault rupture. Models for very large magnitude subduction events should be studied when ground motion data become available to determine whether changes are needed.

2. Architectural

a. *Inelastic deformations and their effects* - Extensive damage occurred in coupling beams and floor slabs acting as coupling elements. This resulted in required repairs. It also resulted in jammed doors. Code writers should consider accommodation in the Code for the inelastic deformations implied by the design.

b. *Concrete and steel stairs* – Stairs sustained considerable damage in many buildings. This damage, plus debris from other architectural finishes, must have slowed egress. These aspects might be considered in future standards.

c. *Damage due to unrestrained contents* – Buildings of all types had significant damage to unrestrained or inadequately restrained contents. In some cases (*e.g.*, research laboratories), this resulted in significant losses.

d. *Nonstructural components* - Buildings of all types had significant damage to nonstructural components, including glazing, ceilings, fire sprinkler systems, piping systems, elevators, partitions, air handling units, and cable trays. The widespread nonstructural damage caused significant economic loss and major disruption to the normal functioning of Chilean society (all issues in considering resilience, beyond life safety). Code requirements and enforcement in Chile and the U.S. should be compared and contrasted to draw implications for possible Code changes in the U.S.

3. Structural

a. *Repair issues* – Many engineered buildings were severely damaged. On the one hand this provides a case study of the long-inferred performance objective for rare earthquake ground shaking in which buildings are safe from collapse but may not be economically repairable; *is this performance objective socially acceptable*? On the other hand, in some cases this will require extensive efforts to return buildings to plumb and to improve strength and ductility distributions; what are the requirements for accomplishing such repairs, and what are the future performance implications?

b. *Behavior of frame buildings* – There is a growing number of pure frame buildings in Chile. Those that followed the strong-column/weak-beam design approach are reported to have performed well. Further study of these buildings might reveal additional lessons and Code implications.

c. *Design requirements for anchors* – The earthquake provides a wealth of performance data on anchors (currently a subject of Appendix D of ACI 318). These data might be useful in suggesting simplifications of current procedures, which are considered by many to be overly complicated.

d. *Concrete wall design* – Observed damage in many concrete wall buildings led to lengthy discussion at this meeting regarding possible causes and fixes. Among the discussion items were:

   i. *Axial stress limits / neutral axis limit* – Current codes do not impose an axial stress limit similar to that imposed by past codes; should a limit be introduced? Furthermore, it may be more effective to impose a neutral axis limit rather than an axial stress limit.

   ii. *Wall boundary detailing and triggers* – To the knowledge of those attending the meeting, wall damage was limited to walls without confined boundary elements. In ACI 318, a deflection and neutral axis check is used to determine if special confined boundary elements are required. The Chile earthquake provides many examples of good and poor building performance that could serve as a check on the ACI 318 trigger for when confined boundary elements are required. Furthermore, there is some question as to whether failures were triggered by compression, or whether failures were triggered by yielding in tension followed by longitudinal reinforcement buckling and cover concrete spalling. The latter failure mode might suggest revisions to Code provisions for transverse reinforcement spacing.

   iii. *Wall cross sections / shapes* – Many (but not all) of the failed walls had T and L cross-sections. Enlarged boundary elements generally are not used. To what extent do these configuration aspects affect behavior, and are these aspects adequately included in our Codes?

   iv. *Lap splice failures* – Damage to wall boundaries along lap splices was observed in some buildings, and some outright lap splice failures occurred in a building that collapsed. Transverse reinforcement was light along the splices. Should U.S. codes have requirements for closely spaced transverse reinforcement along wall boundary lap splices? Also, some wall failures occurred just outside the lapped length. Perhaps confinement should extend beyond the lapped length to toughen the wall boundary in the regions just above and below the length of the splice.

   v. *Minimum longitudinal reinforcement requirements* – A wall with a low longitudinal reinforcement ratio is more prone to strain localization, which could contribute to concentrated failure modes of some walls. Should there be a lower limit on the longitudinal reinforcement ratio of walls?

   vi. *"Flag" walls* – This describes a vertical irregularity in which either façade walls are terminated in lower stories, or wall length is decreased in lower stories, or both, to accommodate activities in the first story or in subterranean levels (such as parking). Many such walls experienced distress at the irregularity. Is this irregularity adequately addressed in our Codes? Do engineering modeling procedures, which often are based on gross-level sectional models, adequately identify stress/deformation concentrations that can occur at these locations?

   vii. *Very thin walls / confinement / buckling* – Many buildings in Chile use very thin (as thin as 15 cm) wall boundaries. These boundaries are difficult to properly confine because the cover thickness is a considerable fraction of the total thickness and because adequate hoop configuration and spacing are difficult to provide in a thin section. Furthermore, initiation of compression failure can leave an even thinner section that is prone to lateral instability. What limits should be imposed in U.S. Codes?

viii. *Wall design in upper stories* – Some buildings show considerable structural damage in upper stories. Is this because of higher mode effects not adequately considered in current codes, or is this because of absence of a consistent capacity design procedure for walls? For slender walls, U.S. Codes are based on formation of a single yielding section near the base of a wall, but the Code procedure does not contain capacity design provisions that ensure that the yielding section is confined mainly to the base.

ix. *Fatigue* – The long duration of ground shaking resulted in many cycles of building response. Do current Code procedures adequately address low-cycle fatigue behavior of longitudinal reinforcement in regions of the U.S. where long-duration shaking is anticipated in the design loading?

e. *Precast structures* – Several precast structures performed poorly. Code implications, not discussed in detail in this meeting, should be investigated further.

f. *Effects of foundation rotation* – The ground around some buildings showed obvious effects of foundation rotation. Are Code changes for the design of foundations suggested? Furthermore, foundation rotation can result in significant increases in local demands on some parts of the building superstructure. Are Code requirements for foundation flexibility modeling adequate?

g. *Configuration / irregularities* – There were many cases of damaged buildings with vertical or horizontal irregularities. To what extent was the damage associated with the irregularity? Do U.S. Codes adequately address the performance of buildings with configuration / irregularity conditions observed in Chile?

h. *Participation of building parts not part of the seismic-force-resisting system, such as non-frame columns, slabs linking walls, etc.*

i. *Displacement estimation / C_d / damping* – Some provisions in U.S. Codes (notably the determination of when wall boundary element confinement is required) are based on the design displacement. The design displacement is based on DBE (rather than MCE) loading considering 5% of critical damping, and uses C_d less than R. Although not demonstrated by this earthquake (because the studies have yet to be undertaken), the observed damage in Chile suggests that the procedures used to estimate the displacement should be re-examined in the near term.

j. *Appropriateness of R factor for unconfined walls / single flexural hinge / walls versus frames* – Chilean practice uses the same R factor for walls and frames. Furthermore, the use of large R factors for walls without special boundary element detailing may be inappropriate. U.S. Codes might consider adjustments to R factors on the basis of the confinement reinforcement used in the wall boundaries.

k. *Repair of lightly damaged buildings / heavily damaged buildings* – Chile now has a large population of damaged buildings. Implications for Codes and for repair standards such as FEMA 306, 307, and 308 might be considered.

l. *Design of diaphragms* – Although diaphragms generally did not span long distances in Chilean buildings, some interesting cases of diaphragm damage were observed. The observed damage may have implications for U.S. Codes.

m. *Slider supports for structural elements* – Structural members spanning between independent portions of buildings fell off their supports due to insufficient slider support size. Further study might suggest changes in design practices for U.S. buildings.

n. F_T – Observations of structural damage in upper stories of some buildings suggests design forces may be higher in upper stories than reflected by the Codes. Past codes used a simple lateral force distribution with an extra force F_T at the roof. This has given way in recent codes to a more complicated force distribution without F_T. Further study might suggest modifications to the lateral force distribution.

o. *Collapse prediction* – Current Codes are based on an implied performance of non-collapse for MCE loading, yet current Code approaches use simplified analysis procedures that likely would not accurately assess either the collapse or lack of collapse in many of the observed buildings in Chile. Further study would lead to improved collapse prediction methods.

p. *Minimum base shear and drift limit requirements* – Chilean codes, though based in part on U.S. codes, use different drift and force criteria. Effectiveness of the Chilean approaches, and modifications to U.S. approaches, should be studied.

q. *Performance requirements for taller buildings / other high-risk category buildings* – The Chile earthquake presents many examples of heavily damaged tall buildings' condition affecting policy for surrounding buildings. Damage was also prevalent in several high-risk category buildings. Case studies could be useful in helping shape design approaches for tall and high-risk category buildings.

r. *Stairs acting as diagonal bracing* – Concrete stairs span from one story to adjacent stories, and consequently act as diagonal braces. This action affects both the stair and the primary structural system, both of which are not commonly considered in current practices.

s. *Requirements for modeling / sensitivity analysis / section cuts* – Buildings commonly are designed on the basis of simplified linear models with single-valued properties, often based on cross-sectional properties obtained by planar cuts through elements. Design might be improved by requiring bounding analyses in certain cases (for example, considering both rigid foundation and flexible foundation). Furthermore, models based on section cuts may be inadequate for irregular walls. Minimum requirements for modeling and analysis should be considered in light of observed performance of buildings in Chile.

4. **Existing buildings (it is understood that many of the topics included above are equally applicable to existing buildings, but those topics are not repeated here)**

a. *Impact of cumulative damage* – In addition to the long duration shaking of the 2010 earthquake, some buildings have been subjected to past earthquakes. Effects of cumulative damage on design properties are not generally considered in U.S. Codes.

b. *Effectiveness of previous repairs* – Significant repairs were implemented following past earthquakes (notably 1985), and significant repairs will be implemented following the 2010 earthquake. Aspects of repairability and performance of repaired buildings should be considered based on the experience gained in this earthquake.

Data needs and opportunities

Technical studies of the 2010 Chile earthquake will require collection and use of field reconnaissance and ground motion record data. Some data have already been collected and are available for use, while others are collected but not yet available. Additionally, some perishable data remain to be collected. Discussion at the meeting focused on ground motion records and documentation of building construction and damage.

The main shock of the earthquake was recorded by at least 15 strong motion instruments in the area bounded by the cities of Santiago, Viña del Mar, Angol, and Concepción. Several of these were maintained by researchers at the University of Chile; some other organizations also may have recorded the main shock and aftershocks. It was the understanding of the participants in the meeting that the release of the University of Chile records was contingent on receipt of government funding to support continued operations of the network, and that efforts were under way to put the funding in place. As of the time of this meeting, however, the recordings have not been officially released. Meeting participants also felt it was important to explore whether recordings might be available from other organizations such as USGS. Some thought that simulation procedures, calibrated to a limited number of records at discrete sites, may be useful to extend understanding of the variations of shaking throughout the affected region.

Reconnaissance teams collected damage data of varying quality from a range of buildings, and some structural drawings for buildings of interest already were available. It was noted that several buildings in Concepción and the surrounding region were scheduled for demolition and that important data (structural drawings, specifications, calculations, and detailed damage maps) might be obtained for several target buildings if a data gathering effort could be mounted in the near term.

A listing of specific buildings of interest was developed during the meeting. Particular details of this list, which was created from memory by meeting attendees, should be verified following the meeting. The buildings were:

- In Concepcion: O'Higgins, Alto Rio, Plaza del Rio (Towers A and B), Centro Mayor, Civic, Araucana, 152 Castellon, Salas, Bosquemar, Olas, Lincoyan 440 - Torre Libertad, Plaza Mayor II, Sodimac warehouse – Coronel.
- In Santiago: Emerald, 2150 Central Park, 1631 Hipodromo, Sol Oriente I and II, Patio Mayor I-4 (Enterprise City), Chilean Chamber of Construction, various tall buildings, 3 buildings instrumented for aftershocks, ACHS - Base isolated building.
- In Viña del Mar: Toledo, Festival, Coral, Torre del Mar, Bahia, Rio Petrohue, Malaga, Tenerife, Acapulco, Rio Imperial, ACHS - Base isolated building, Hanga Roa, Oasis.

- In Chillan: Torre Mayor.
- In Talca: Hall of Justice, Amalfi.

The above-listed buildings include mostly damaged buildings. For all of those, it is of interest to identify nearby buildings that were undamaged.

Highest priority topics for future study

The meeting concluded with discussion of the highest priority topics for future study. Several broad topical areas were developed on the basis of the suggested study topics submitted before the meeting plus additional items discussed at the meeting. From these, five topics emerged as being the highest, most time-sensitive priorities, with the first topic being the highest among those and the other four being listed without ranking. Some topics in addition to the top-five-ranked topics are included as well; these topics can be considered a second tier of highly ranked topics. Some of these were considered as critically important study topics, but they were down-ranked based on their perceived relevance to rapidly advancing U.S. building codes.

1. **Systematic collection of perishable data from buildings**

   In the next few months there is an opportunity to collect detailed information (structural drawings, specifications, calculations, and detailed damage data) from several buildings in and around Concepción that are scheduled for demolition. Possible buildings of interest include: in Concepción - Caupolicán 518 (FIUC), Los Carreras 1535 (Alto Arauco), Calle Obispo Hipólito Salas 1343 (Plaza del Rio, Towers A and B), Av. Bernardo O'Higgins 241 (Torre O'Higgins), Lincoyán 440 (Torre Libertad), Freire 1165 (Centro Mayor), Padre Hurtado 776 (Alto Rio); in San Pedro de la Paz – Camino Coronel Km 8 (Edficio Olas), Las Margaritas 1328 (Alto Huerto), Bayona 1900 (VISTAS B Condominio), and Av. Costanera 7488 (Bosquemar). There are other buildings , Plaza del Rio, Lincoyan 440, and other buildings in San Pedro such as Bosquemar, Olas, and Alto Huerto.

   This study involves selection of target buildings, determination whether data can be accessed, collection and study of structural drawings, detailed damage surveys, and uploading of data to a publicly accessible site. The work likely will require hiring of professionals, given the condemned condition of the properties.

2. **Study ground motions at key sites**

   Digital and digitized ground motion recordings will be valuable to detailed investigations of ground motion attenuation models, site amplification criteria, and building performance. Efforts should be made to facilitate release of the data either broadly or in conjunction with specific joint projects conducted by U.S. and Chilean researchers.

   A second step is to work with Chilean experts to study the records and their processing so that broad agreement on their validity is achieved.

   A third step is to use the recorded data along with simulation techniques to estimate ground shaking intensity and characteristics at selected building study sites, including, but not necessarily limited to, the sites for which systematic collection of perishable data has been accomplished (topic 1 above).

3. **Detailed analytical study of selected buildings**

   Using data gathered in topics 1 and 2, conduct in-depth studies of the performance of selected buildings, including both damaged buildings and nearby undamaged buildings. Investigate the degree to which conformance/nonconformance with U.S. codes, irregularities, axial stresses, and other parameters contributed to observed behavior. To the extent practicable, explore capabilities of current software and modeling approaches to simulate collapse/noncollapse.

4. **Study requirements for design and detailing of concrete wall boundaries**

   A majority of building failures was associated with failure of concrete wall boundaries. It is unclear whether this can be attributed to nonconformance with U.S. building codes or whether this was associated with parameters inadequately considered by current codes. Several studies should be considered, including:

   a. Collect structural drawings, computer models, and performance data on statistically significant sample of wall buildings, both damaged and undamaged. Study the degree to which buildings conformed with U.S. building codes and how this related to performance. Conduct statistical analyses of how performance related to other structural and ground motion parameters. Structural parameters should include axial stress level; neutral axis level; transverse reinforcement quantity, spacing, and detailing; boundary element longitudinal reinforcement ratio; wall thickness; and other parameters as deemed appropriate.

   b. Conduct fundamental studies of moment-curvature response, drift capacity, drift demands, and other parameters for a variety of configurations and ground motions to explore possible shortcomings in current U.S. building code provisions for wall boundary element design. Such studies could be conducted early to explore options for rapid building code change proposals, or could be conducted following more detailed building and ground motion studies noted above, or both.

5. **Post-earthquake clearinghouse**

   A clearinghouse is needed to store basic data collected in support of the technical studies as well as to collect derived data. The clearinghouse should be located with an organization having demonstrated capability to develop the clearinghouse in a timely and expert manner, as well as maintaining it over the long term so that it can continue to serve the community into the future. A layered approach may be required to protect confidentiality requirements of certain data.

6. **Advanced simulation capability for structural wall buildings**

   Current software for simulation of seismic performance of wall buildings emphasizes flexural response of wall cross sections. While these procedures may be suitable for nonlinear analysis of well configured and detailed buildings subjected to moderate levels of earthquake ground shaking, their suitability for buildings with irregular configurations and marginal transverse reinforcement, and for any wall building shaken to the collapse limit state, is questionable. Studies should be undertaken to benchmark current modeling and simulation software, and research should be undertaken to advance software where found lacking.

Laboratory testing should be pursued to supplement the available data on wall building performance.

7. **Comprehensive rehabilitation of damaged shear wall buildings**

Different techniques are being currently proposed to rehabilitate damaged wall buildings in Chile. Depending on the structure and its condition, these techniques involve special adjustable shoring, straightening of leaning structures, retrofitting and strengthening damaged shear walls, replacement other vertical elements, and introducing optimal energy dissipation devices. Some rehabilitation schemes, such as straightening leaning structures and introducing alternative energy dissipating devices, require detailed analytical study to explore their viability. Furthermore, documentation and analysis of the different rehabilitation solutions will provide valuable information for future emergency recovery of similar structures.

8. **Co-seismic effects**

In addition to transient ground shaking, the ground near the epicenter experienced a large co-seismic displacement during a time interval of approximate half minute. The effect of such movements on tall buildings is unknown and should be studied to determine whether modifications to seismic design and performance assessment methods are needed.

9. **Behavior of anchors**

Reconnaissance following the earthquake identified numerous buildings in which various types of anchors were employed. Examples both of good and poor performance have been documented. Systematic study should be made of anchor performance as function of anchor types, structural concrete details, installation technique, and loading demands. Results should serve as a basis for recommending changes to Appendix D of ACI 318.

10. **Site and basin effects**

Some sites, notably in Concepción and Santiago, experienced unusual ground motions because of site and basin effects. Apparent effects should be studied using available ground motion records. Where appropriate, instrumentation should be deployed to measure aftershock effects. Observations should be compared with procedures contained in current building codes. Numerical simulation techniques also should be explored to determine the degree to which these techniques are able to replicate the observed effects. Appropriately calibrated numerical simulation models also may be useful to estimate ground shaking at target sites where specific buildings are to be studied.