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Authors: Mark Sarkisian, Skidmore, Owings & Merrill LLP
Neville John Mathias, Skidmore, Owings & Merrill LLP
Eric Long, Skidmore, Owings & Merrill LLP

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Seismic Design and Detailing of Compound Shear Wall Plan Configurations Such as "I", "L", "C", and "T" Shapes for High-Rise Structures

Mark Sarkisian, S.E.
Neville Mathias, S.E.
Eric Long, P.E.
Skidmore, Owings and Merrill LLP
San Francisco, California

Introduction

The Uniform Building Code and ACI offer only limited guidance for the design and detailing of shear walls of compound configurations such as "I", "L", "C", and "T" shapes in plan. There is a dearth of examples for seismic design and detailing of such shear walls, particularly for high-rise buildings in zones of high seismicity in available references.

Using the recent design of the St. Regis Museum Tower, a 41-story cast-in-place reinforced concrete dual shear wall and special moment resisting frame structure in downtown San Francisco as an example, this paper examines the currently available and relevant recommendations and tools for modeling, analysis and design of compound shear walls.

Relevant Code Provisions

The Uniform Building Code (UBC) 1997 Edition, American Concrete Institute (ACI) 318-2002, and the Structural Engineers Association of California (SEAOC) Blue Book 1999 Seventh Edition all provide some guidance for the design and detailing of compound shear walls. The key topics that relate to the design and detailing of compound shear walls are the effective flange widths that may be considered for the overall design of the shear wall and the corresponding boundary zone lengths. The recommendations relevant to these topics are summarized as follows:

Effective Flange Width

The effective flange width is essential in maximizing the flexural and axial load capacity of a shear wall while minimizing the required reinforcement quantities. The reinforcement located in the webs of compound shear wall sections can be substantially reduced considering the effect of the flange that provides a larger effective depth for the section.

UBC 1997 Section 1921.6.6.2 states that "the effective flange widths to be used in the design of I-, L-, C-, or T-shaped sections shall not be assumed to extend further from the face of the web than (1) one-half the distance to an adjacent shear wall web, or (2) 15 percent of the total wall height for the flange in compression or 30 percent of the total wall height for the flange in tension, not to exceed the total projection of the flange."

ACI 318-2002 Section 21.6.5.2 states that "unless a more detailed analysis is performed, effective flange widths of flanged sections shall extend from the face of the web a distance equal to the smaller of one-half the distance to an adjacent web and 25 percent of the total wall height."

The SEAOC Blue Book Section 402.10 states that "connected or intersecting wall sections shall be considered as integral units with the strength of flanges, boundary members, and webs evaluated on the basis of compatible interaction between these elements. The effect of wall openings shall be considered. For the moment strength of I-, L-, C-, T-shaped or similar sections, the effective flange width on each side of the wall web shall be taken as the smaller of (1) one half the distance to an adjacent shear wall web, (2) the actual flange width, or (3) 15 percent of the total wall height for the flange in compression or 50 percent of the total wall height for the flange in tension."

While the UBC, ACI, and the SEAOC Blue Book all provide guidance to the flange widths that can be used in the design of compound shear walls, two clarifications should be made. First, the provisions for the effective flange width stipulate a maximum, not the required effective flange width. A less than maximum effective flange width can be used provided it can develop the required strength as determined by analysis. Second, the "total wall height" referenced in the provisions should be taken as the height above the level being considered, not the entire height of the building.

For the design of high-rise structures, utilizing the maximum flange width is often excessive and impractical, especially at the base of the building. If one were to take 15 percent of the total wall height above the location at which one was designing, the effective flange width of a 400-foot tall building would be 60 feet! This will often be much greater than one-half the distance to an adjacent shear wall web. After analysis in both orthogonal directions, the entire shear wall core would have to be designed and detailed as a confined boundary zone. Obviously, considering this would result in very heavily reinforced shear walls. Hence, the designer must carefully evaluate the implications when selecting appropriate effective flange widths.

Boundary Zone Length

Boundary zones are confined portions of longitudinal reinforcement located at the ends or corners of shear walls where compressive strains induced in the code design basis earthquake exceed 0.003. These zones of reinforcement increase the seismic strength and ductility of the shear walls.

UBC 1997 Section 1921.6.6.4 states that "shear walls and portions of shear walls not meeting the requirements of section 1921.6.6.4 Items 1 and 2, or 3 and having $P_u < 0.35\ P_o$ shall have boundary zones at each end a distance varying linearly from 0.25 l_w to 0.15 l_w for P_u varying from 0.35 P_o to 0.15 P_o. The boundary zone shall have minimum length of 0.15 l_w and shall be detailed in accordance with section 1921.6.6.6." This recommendation is well tailored to the design of planar shear walls but can result in excessive boundary zone lengths in compound shear walls.

Alternatively, boundary zones can also be computed "based on the determination of the compressive strain levels at the edges when the wall or portion of wall is subject to displacement levels" according to Section 1921.6.6.5. This approach ensures that boundary zones are designated and confinement is provided only where compressive strains exceed 0.003. This rational approach is equally suitable for the design of planar and compound shear walls.

In addition, Section 1921.6.6.6 item 1.3 states that boundary zones "shall have a minimum length of 18 inches at each end of the wall or portion of wall." Item 1.4 also states that "in I-, L-, C-, or T-shaped sections, the boundary zone at each end shall include the effective flange width and shall extend at least 12 inches into the web."

ACI 318-2002 Section 21.6.6.4 (a) states that the "boundary element shall extend horizontally from the extreme compression fiber a distance not less than the larger of c - 0.1 l_w and c/2" where c is the distance from the extreme compression fiber to the neutral axis. Item (b) states that "in flanged sections, the boundary element shall include the effective flange width in compression and shall extend at least 12 inches into the web."

Boundary zone lengths are strongly correlated to the effective flange widths as stated in both the UBC and ACI codes. The optimization of the boundary zone length and effective flange width is critical to the efficiency of a compound shear wall design. The full optimization process can be complex and tedious, especially in the design of high-rise structures. The designer often must use "engineering judgment" and make educated assumptions based on building type, plan dimensions, etc. in order to make the optimization process manageable.

A Practical Approach Respecting Code Requirements

For the recent design of the St. Regis Museum Tower, the key to optimizing the effective flange widths with the boundary zone lengths was designating all segments of compound shear walls as either primary or secondary shear wall elements. The primary and secondary shear wall element approach was established in order to designate which wall, or portion of a wall, acts as the flange and which wall, or portion of a wall, acts as the web.

Figure 1 shows a typical shear wall core plan for the St. Regis Museum Tower. To illustrate the primary and secondary shear wall element approach, a “C” shaped segment of the core has been selected for further discussion.

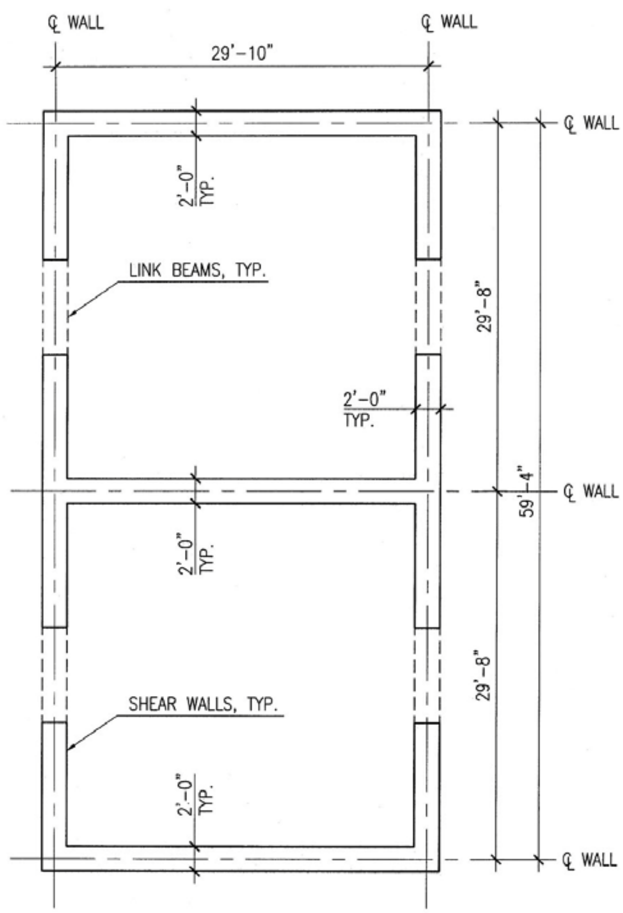

Figure 1 – Typical Shear Wall Core Plan

The primary shear wall element of a compound shear wall was designed considering an effective flange width of 12”, which becomes the minimum boundary zone length that extends into the web of the secondary shear wall element (Figure 2). This analysis ensured a primary shear wall boundary zone length based on the 0.25 l_w to 0.15 l_w for P_u varying from 0.35 P_o to 0.15 P_o as outlined in UBC Section 1921.6.6.4. Since the primary shear wall element was designed considering a minimum effective flange of 12”, the effective depth of the primary shear wall element was not greatly affected by the benefit of the provided effective flange width and was therefore designed using a method similar to a planar wall.

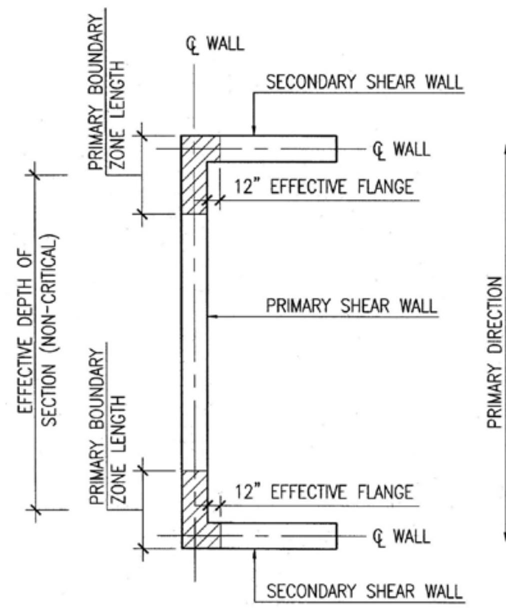

Figure 2 – Shear Wall “C” Section, Primary Shear Wall Element

The secondary shear wall element was designated and designed considering an effective flange width equal to the primary shear wall boundary zone length minus the shear wall thickness (Figure 3). This more substantial effective flange significantly increases the effective depth of the secondary direction.

At the end of the secondary shear wall element that is integrated with the primary shear wall element, the analysis provided a secondary shear wall element boundary zone length required, which was checked against the 12” minimum established in the primary shear wall element design. The 12" boundary zone was lengthened for additional longitudinal reinforcement as required by analysis. The 0.15 l_w minimum requirement was ignored for this analysis since it was proven that the compressive strains did not exceed 0.003. The end of the secondary wall which is not integrated with the primary shear wall was then designed considering the requirements of 0.25 l_w to 0.15 l_w for P_u varying from 0.35 P_o to 0.15 P_o as outlined in UBC Section 1921.6.6.4.

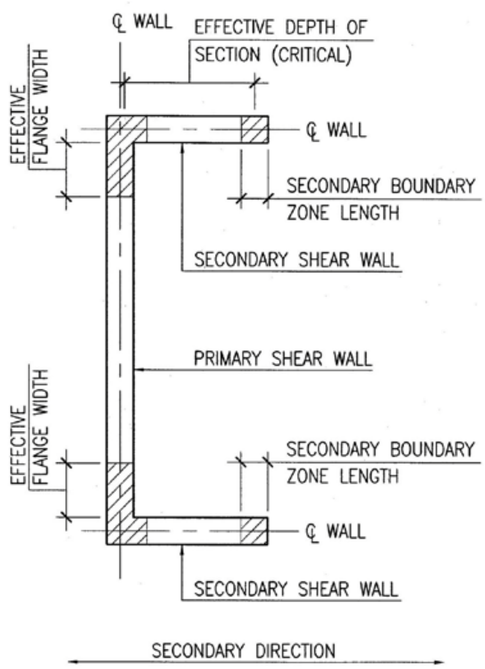

Figure 3 – Shear Wall "C" Plan Section, Secondary Shear Wall

In summary, the selection of the primary and secondary shear wall elements was made considering three items. First, to minimize the boundary zone longitudinal reinforcement, the primary and secondary wall elements were selected to give the largest effective depth to the critical direction. The critical direction was determined based on the relative moments and axial loads in each wall studied in relationship to the potential effective depth options.

Second, to minimize the amount of boundary zone confinement reinforcement required, the primary and secondary shear wall elements were also designated based on the geometry configuration to minimize the total boundary zone plan dimensions required per UBC Sections 1921.6.6.4 and 1921.6.6.6.

Finally, it was verified that a confined boundary zones are provided in portions of the web of a compound shear wall where the compressive strains exceed 0.003. The compressive strains were studied on a typical and worst case in order to ensure compliance with the requirements of UBC Section 1921.6.6.5.

Modeling and Analysis

Three-dimensional finite element modeling using common analysis programs such as ETABS, are important to the efficient design of compound shear walls. Appropriate modeling assures consistency with the planned design approaches, especially in the consideration of orthogonal effects in the design of corner boundary zone reinforcement.

For the St. Regis Museum Tower, orthogonal effects were accounted for by establishing a response spectrum function to be used in the load combinations, which utilized a directional combination per UBC Section 1633.1. This response spectrum directional combination was a scaled absolute method, which included a scale factor of 0.3. More specifically, the directional results are combined by taking the maximum, over all directions, of the sum of the absolute values of the response in one direction plus a scale factor times the response in the other directions.

Furthermore, the primary and secondary shear wall elements were modeled as shell elements and were given independent planar "pier" designations in order to extract the forces for each orthogonal shear wall separately. If openings occurred within the shear wall pier, the pier was divided into subpiers in order to extract the forces on each side of the opening (Figure 4). This allowed each pier to be designed considering the appropriate in-plane shear, moment, and axial loads.

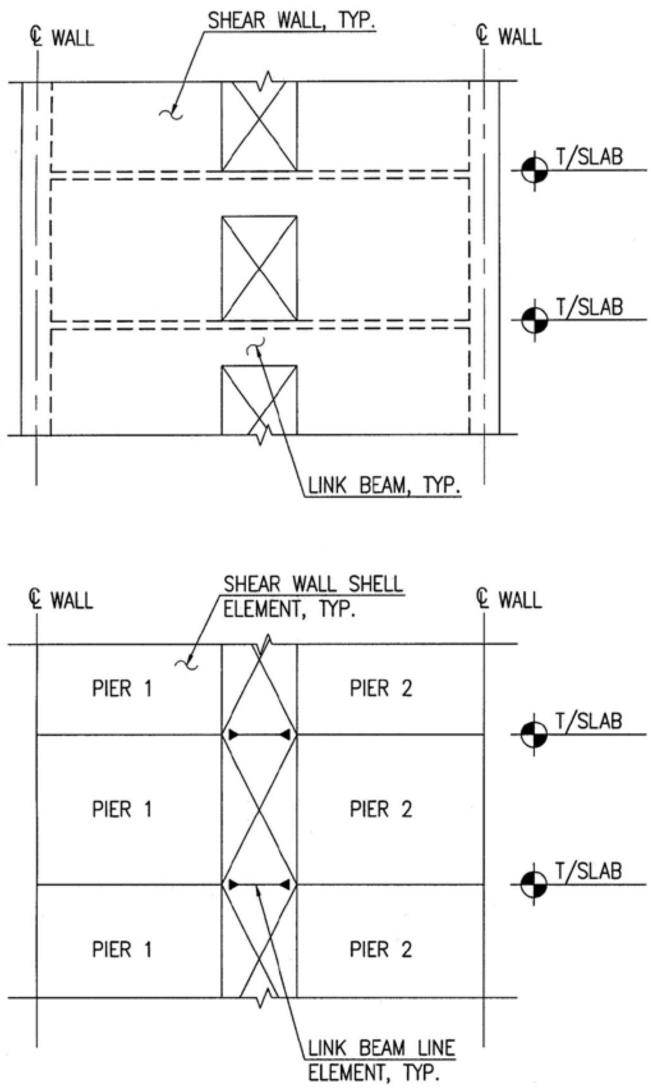

Figure 4 – Typical Shear Wall Elevation and Pier Assignments

Compound shear walls can also be modeled using common analysis programs as I-, L-, C-, or T-shaped pier elements versus individual planar pier elements. This can be beneficial by allowing the designer to extract integrated forces on the I-, L-, C-, or T-shaped pier as a whole and importing them to a post-processor able to design compound shear wall shapes. This however was not done for the St. Regis Museum Tower on account of limitations in the design programs available at the time as described in the following section.

Design Programs

A number of design programs and post-processors are currently available on the market which purport to be able to model, analyze, and post-process/design the lateral systems and their components. Careful consideration must be given to assuring that the program selected performs the analysis and design as expected given the building structural system, building geometry, plan and vertical irregularities, loading, special features such as compound shear walls, etc. Of particular importance in the case of compound shear walls is the assurance that the appropriate interaction is analyzed and designed paying particular attention to the minimum boundary zone length requirements and out-of-plane effects.

In the case of the St. Regis Museum Tower, the entire building lateral system was modeled and analyzed using the ETABS software package including the shear wall core, link beams, special moment resisting frames, and rigid diaphragms. At the time of the design, it was determined that the available design post-processor would not able to perform the most efficient and cost-effective design of compound shear walls. The design post-processor was geared primarily towards the efficient design of planar shear walls. Hence, EXCEL spreadsheets were developed in-house to perform the design of compound shear walls based on the primary/secondary shear wall element approach described.

Since the completion of the design of the St. Regis Museum Tower, design post-processors have evolved and can expedite the compound shear wall design process. For example, W-SECT, from the Softek Suite, is able to accept multiple sets of shear, moment, and axial loads for a given shear wall section, and plot them on the moment interaction graph. This allows the designer to input all of the results from the various load combinations directly from an analysis program without having to sort for the governing set of loads. In addition, W-SECT is able to design I-, L-, C-, or T-shaped sections. This allows the designer to input loads directly from I-, L-, C-, or T-shaped pier elements from an analysis program and consider various alternatives in order to select optimized effective flange widths and the corresponding boundary zone lengths.

Detailing Issues

Proper detailing of compound shear walls in high-rise structures, especially the boundary zones, can result in significant savings in reinforcement quantity as well as simplifying construction thereby saving time and money.

Per UBC Section 1921.6.6.6 item 2.1, "all vertical reinforcement within the boundary zone shall be confined by hoops or cross ties…" The confinement reinforcement often leads to congestion problems when considering all the legs and hooks from the hoops and cross ties, especially in lap splice regions (Figure 5). Moreover, the horizontal reinforcement and link beam diagonal reinforcement are required to be anchored within the boundary zone resulting in even further congestion.

For St. Regis Museum Tower, the ICBO approved "BauGrid" system was used to help alleviate congestion within the boundary zones. "BauGrids" consist of high-strength steel bars, which are resistance welded into grids, ladders, or cages to the specified dimensions. These prefabricated cages are used in lieu of the hoops and cross ties, eliminating the hooks and legs of the hoops and cross ties (Figure 6). "BauGrids" also reduce the multiple layers of hoops and crossties into two principal layers. This helps to minimize congestion and facilitate concrete placement.

Another benefit of the BauGrid system is that the longitudinal boundary zone reinforcement is easily placed in the corners of intersecting steel bars and can be laid out in a modular fashion. Based on the wall thickness and concrete strength used, a designer can easily choose a steel bar diameter as well as a horizontal and vertical spacing to be in accordance with the confinement requirements of UBC Section 1921.6.6.6 Item 2.1 – 2.5. The resulting modules can be used to efficiently plan the boundary zone dimensions and bring order to the longitudinal reinforcement layout. The boundary zones can then be easily prefabricated and "stacked" on top of one another in the field. This also ensures that the longitudinal reinforcement lap splices will align.

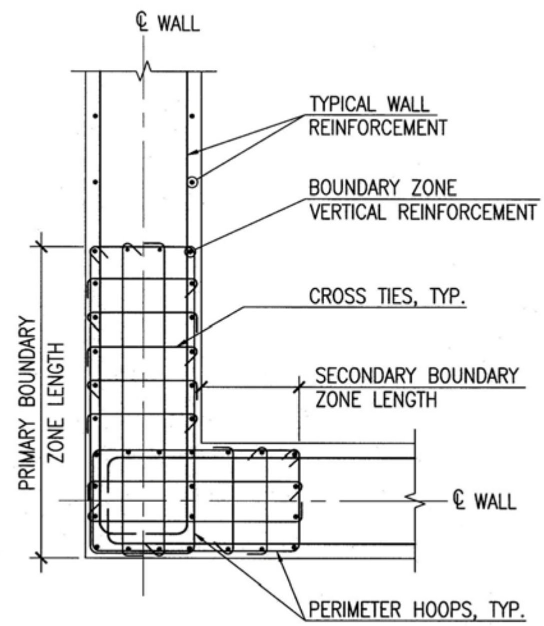

Figure 5 – Typical Boundary Zone Detail with Conventional Confinement Reinforcement

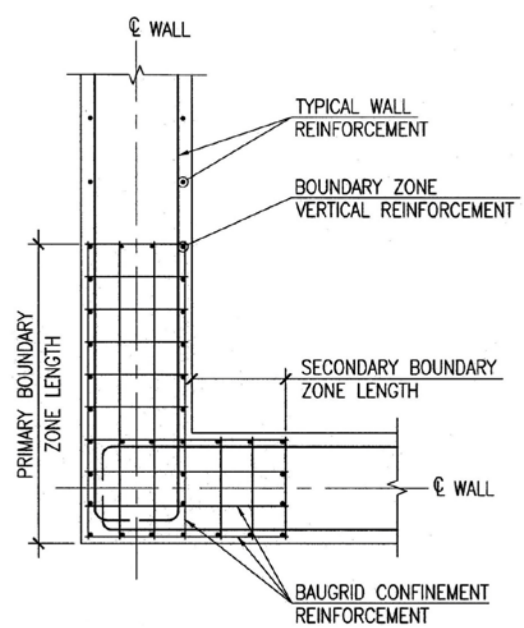

Figure 6 – Typical Boundary Zone Detail with "BauGrid" Confinement Reinforcement

Conclusion

Currently, provisions in the Codes, Standards, and References for shear wall design address the issues and requirements for planar shear walls very efficiently, but provide only very general direction the design of compound shear walls. Compound shear walls, by virtue of their three dimensional plan configurations, afford the possibility of enhancing structural performance and efficiency and reducing the cost if designed appropriately. A rational approach to selecting effective flange widths and boundary zone lengths, coupled with the judicious use of available design programs and reinforcement products are key to achieving this efficiency and economy.

References

ICBO, 1997, *Uniform Building Code, Structural Engineering Design Provisions*, Vol. 2, 1997 edition, pp. 2-161 to 2-162, International Conference of Building Officials, Whittier, California

ACI, 2002, *Building Code Requirements for Structural Concrete (318-02) and Commentary (318R-02)*, 2002 edition, pp. 320 to 322, American Concrete Institute, Farmington Hills, Michigan

SEAOC, 1999, *Recommended Lateral Force Requirements and Commentary*, 1999, Seventh Edition, pp. 66 to 67, Structural Engineers Association of California, Sacramento, California

ICBO, *Evaluation Report ER-5192* BauGrid Reinforcement*, 2000, pp. 1, ICBO Evaluation Service, Inc., Whittier, California