Structural Engineering Institute of ASCE
1801 Alexander Bell Dr., Reston, VA 20191
Tel 703 295 6195, Fax 703 295 6361
www.asce.org/SEI

White Paper on Connection Details
By SEI Design Practices Committee
September 8, 2011

C. Wilcox[1], S.E., B. Nuttall[2], S.E., and T. Barnett[3], S.E., B. Sanders[4], S.E.

The Design Practices Committee has completed evaluating two different Design Problems. One design problem was for the application of ACI 318-05 Appendix D cracked concrete anchor bolt design. The second problem was the analysis and detailing specification of Wall-to-Roof anchorage in masonry construction intended to be per ACI 530-08. The purpose of this white paper is to present the results of these trial problems and encourage further collaboration to advance the practice of structural engineering as it relates to code interpretation and design of elements and components. The objective is to improve clarity regarding current issues in the profession such as application of code sections, the complexity of codes and their detailed application.

Trial Design Problems – Two Trial Design Problems were completed that quantitatively evaluated the effectiveness of the ACI 318-05 Appendix D, ACI 530-08 and ASCE 7-05 codes in producing reliable, safe and consistent engineering design applications. The results of the Trial Design Problems presented in this paper quantitatively demonstrate that unnecessarily complex code provisions result in less reliable, less safe and less consistent design practices.

In general, Trial Design Problems are intended to:

1. Investigate how practicing engineers interpret and apply current code provisions.
2. Investigate the consistency of engineering judgment of practicing engineers.
3. Promote dialog and continuing education among practicing engineers.
4. Identify and promote needed improvements in the code requirements.

The Trial Design Problem process consists of:

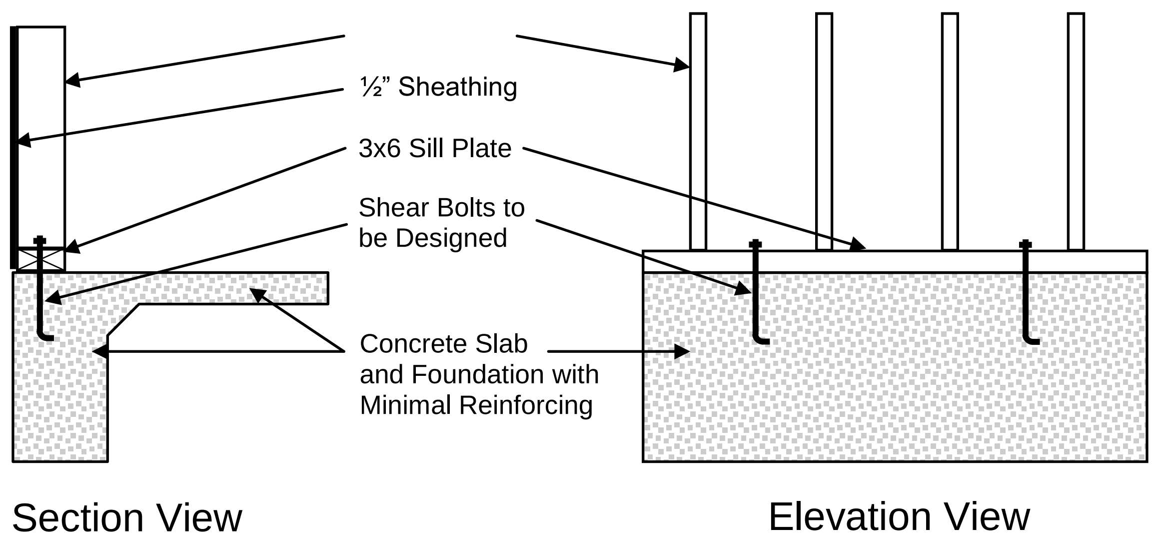
1. Developing a problem based on code provisions,
2. Enlisting practicing engineers to complete the engineering problem,
3. Evaluating the engineering solutions submitted by practicing engineers, and
4. Conveying the results of the problems to the engineering community and code development committees.

Trial Design Problem #1 - ACI 318 Appendix D

You are designing a new wood framed residence. You have already determined the lateral forces on the wood shear walls and that the house is classified as Seismic Design Category D. You have also determined that you will be using a 3x sill plate of pressure treated Hem Fir lumber and 2,500 psi normal weight concrete for the slab and foundation. The maximum in-plane shear force on the wood shear walls is as follows:

υ_{wind} = 600 plf ultimate / 420 plf allowable
$\upsilon_{earthquake}$ = 500 plf ultimate / 350 plf allowable

Design the shear anchor bolts connecting the 3x wood sill plate of the shear wall to the cast-in-place reinforced concrete foundation.



COMMITTEE SOLUTION - ANCHOR DESIGN PROBLEM 2009

Time to Complete: **Way, way too much time.**

Bolt Type: ***Cast-in-Place ‘J’ Bolt***
(e.g. cast-in-place ‘J’ bolt, post-installed expansion anchor, etc.)

Bolt Grade / Material: ***A307***
(e.g. A307, etc.)

Bolt Capacity Sources: ***ACI Appendix D, NDS***
(e.g. IBC Bolt Capacity Tables, ACI Appendix D, NDS, Bolt Vendor Information, etc.)

Bolt Diameter: ***5/8” diameter***

Bolt Embedment: ***7”***

Bolt Spacing: ***32"***

Anchor Selection

- Use 5/8" diameter A307 Hooked Anchor Bolts with 7" embedment

ACI Shear Anchor Design (ACI D.4.1)

- $\phi V_n \geq V_{ua}$ (Eq. D-1)
- ϕV_n equals lesser of ϕV_{sa} or ϕV_{cb} or ϕV_{cp}

Edge Distance (ACI D.8.2)

- Untorqued cast-in anchors
- Edge distance per cover requirements of ACI 7.7
- Concrete exposed to earth or weather = 1.5" < 2.5"

Steel Strength of Anchor in Shear (ACI D.6.1)

- $V_{sa} = n0.6A_{se,v} f_{uta}$ (ACI Eq. D-20)
    - $A_{se} = 0.226in^2$ (Threads considered)
    - $f_{uta} = 58{,}000\,psi$ (A307)
- $V_{sa} = (1)(0.6)(0.226in^2)(58{,}000\,psi) = 7{,}860lbs$
- $\phi V_{sa} = (0.65)(7{,}860lbs) = 5{,}110lbs$
    - $\phi = 0.65$ (ACI D.4.4)

Concrete Breakout Strength in Shear (ACI D6.2)

- $V_{cb} = 2\dfrac{A_{Vc}}{A_{Vco}}\psi_{ed,V}\psi_{c,V}\psi_{h,V}V_b$ (ACI Eq. D-21 & D.6.2.1.c)
    - $A_{Vc} = A_{Vco} = 4.5(c_{a1})^2 = 4.5(2.5")^2 = 28.1in^2$
        - $c_{a1} = 2.5"$
    - $\psi_{ed,V} = 1.0$ (ACI D.6.2.1.c)
    - $\psi_{c,V} = 1.0$ (ACI D.6.2.7)
    - $\psi_{h,V} = 1.0$ (ACI D.6.2.8)
    - $V_b = \left(7\left(\dfrac{l_e}{d_a}\right)^{0.2}\sqrt{d_a}\right)\lambda\sqrt{f_c^{'}}\left(c_{a1}\right)^{1.5}$ (ACI Eq. D-24)
        - $d_a = 0.625"$
        - $l_e = h_{ef} = 7"$ or $l_e = 8d_a = 5"$ (Gov.)
        - $\lambda = 1.0$
    - $V_b = \left(7\left(\dfrac{5"}{0.625"}\right)^{0.2}\sqrt{0.625"}\right)1.0\sqrt{2{,}500\,psi}\left(2.5"\right)^{1.5} = 1{,}658lbs$

- $V_{cb} = (2)\left(\frac{28.1in^2}{28.1in^2}\right)(1.0)(1.0)(1.0)(1{,}658lbs) = 3{,}316lbs$
- $\phi V_{cb} = (0.70)(3{,}316lbs) = 2{,}320lbs$
  - $\phi = 0.70$ (ACI D.4.4)

Concrete Pryout Strength (ACI D.6.3)

- $V_{cp} = k_{cp} N_{cb}$ (ACI Eq. D-30)
  - $k_{cp} = 2.0$
    - $h_{ef} = 6.38" > 2.5"$
  - $N_{cb} = \frac{A_{Nc}}{A_{Nco}} \psi_{ed,N} \psi_{c,N} \psi_{cp,N} N_b$ (ACI Eq. D-5)
    - $A_{Nc} = (c_{a1} + 1.5h_{ef})(2 \times 1.5h_{ef})$ (ACI Fig. Rd.5.2.1)
    - $A_{Nc} = (2.5" + 1.5(6.38"))((2)(1.5)(6.38")) = 231\text{in}^2$
    - $A_{Nco} = 9h_{ef}^2 = (9)(6.38")^2 = 366in^2$
    - $\psi_{ed,N} = 0.7 + 0.3\frac{c_{a,\min}}{1.5h_{ef}}$ (ACI Eq. D-11 for $c_{a,min} < 1.5h_{ef}$)
    - $\psi_{ed,N} = 0.7 + 0.3\frac{2.5"}{1.5(6.38")} = 0.778$
    - $\psi_{c,N} = 1.0$ (ACI D.5.2.6)
    - $\psi_{cp,N} = 1.0$ (ACI D.5.2.7)
    - $N_b = k_c \lambda \sqrt{f_c^{'}} h_{ef}^{1.5} = (24)(1.0)(\sqrt{2500psi})(6.38)^{1.5} = 19{,}338lbs$
  - $N_{cb} = \frac{231in^2}{366in^2}(0.778)(1.0)(1.0)(19{,}338lbs) = 9{,}495lbs$
- $V_{cp} = (2.0)(9{,}495lbs) = 18{,}990lbs$
- $\phi V_{cp} = (0.70)(18{,}990lbs) = 13{,}293lbs$
  - $\phi = 0.70$ (ACI D.4.4)

Wood Sill Plate (NDS)

- $Z^{'} = ZC_D C_M C_t C_g C_\Delta C_{eg} C_{di} C_{tn}$
  - $Z = 1{,}170lbs$ (NDS Table 11E)
  - $C_D = 1.6$, $C_M = 1.0$, $C_t = 1.0$, $C_g = 1.0$, $C_\Delta = 1.0$, $C_{eg} = 1.0$, $C_{di} = 1.0$, $C_{tn} = 1.0$
- $Z^{'} = (1{,}170lbs)(1.6) = 1{,}870lbs$

Wind Design

- Concrete

- $\phi V_n = \phi V_{cb} = 2{,}320 lbs$
- $V_u = 600\, plf$
- $Spacing = \dfrac{2{,}320 lbs}{600\, plf} = 3.8\, ft$

- Wood
  - $Z^{'} = 1{,}870 lbs$
  - $V = 420\, plf$
  - $Spacing = \dfrac{1{,}870 lbs}{420\, plf} = 4.5\, ft$

Earthquake Design

- Concrete
  - $0.75\phi V_n = 0.75(2{,}320 lbs) = 1{,}740 lbs$
  - $V_u = 500\, plf$
  - $Spacing = \dfrac{1{,}740 lbs}{500\, plf} = 3.5\, ft$ (Governs Design, Use 32" o.c.)
- Wood
  - $Z^{'} = 1{,}712 lbs$
  - $V = 350\, plf$
  - $Spacing = \dfrac{1{,}712 lbs}{350\, plf} = 4.9\, ft$

Final Selection

- Use 5/8" diameter cast-in-place hooked anchor bolts with 7" embedment spaced at 32" on center.

The demographics of the participants were as follows:

Highest Educational Degree	28% Bachelors	50% Masters	22% Unknown	
Years Experience	11% 0-4 Years	38% 5-10 Years	28% 11-20 Years	0% 21+ Years
Professional License	17% EIT Only	61% PE	17% SE	
States	33% Virginia	11% Minnesota	56% Other	

In order to properly evaluate the capacity of the anchor bolt connection, failure limit states must be checked in the steel bolt, the concrete foundation and the wood sill plate.

Calculating the bolt capacity in concrete using ACI Appendix D requires checking two concrete limit states, (a) concrete breakout in shear and (b) concrete pryout. Considering these two limit state, the committee's solution established a concrete capacity $\phi V_n = 2{,}320 lbs$ for wind and $\phi V_n = 1{,}740 lbs$ for earthquake design. The respondents solutions for the concrete bolt capacity ranged from a low of $\phi V_n = 521 lbs$ to a high of $\phi V_n = 41{,}800 lbs$. The committee's calculations to determine the concrete capacity were 40 lines long.

Calculating the bolt capacity in wood using the NDS entails the use of bolt capacity tables that incorporate multiple complex wood limit state calculations. The committee's solution established a wood capacity $Z' = 1{,}712 lbs$. The respondents solutions for the wood bolt capacity ranged from a low of $Z' = 400 lbs$ to a high of $Z' = 1{,}712 lbs$. The committee's calculations to determine the wood capacity were approximately 6 lines long.

The quantitative analysis of the Trial Design Problem solutions indicated serious concerns with the ability of practicing engineers to reliably and efficiently implement several provisions of the ACI 318 Appendix D procedures including:

- Significant variation in the application of Appendix D sections, different values, variation in the interpretation and misinterpretation of code sections and values. Specifically values for the seismic capacity of the anchor bolts in the concrete varied from a low of 521# to a high of 41,800#.

- Experience is essential as engineers with less than 5 years experience consisted of only 11% of respondents and one utilized only off the shelf software to complete the solution and did not check the wood capacity.

- Selection of Appendix D as the governing code for the concrete portion was made only 61% of the time even though ACI 318 Appendix D was referenced right on the problem statement.

- Short embedment depths for the 5/8" diameter anchors were selected many times that shows a lack understanding of the behavior of materials to keep connections ductile and not have brittle shear failures of the concrete. Over 60% of the embedments specified were 6 inches or less.

Experience is Essential - This is the first lesson learned (or reinforced) from the trial design solutions. Education alone is not adequate to ensure practicing engineers are able to safely and consistently design elements of structures. As an example, the concrete capacity from the published solution was 2.32 kips. The answer submitted by engineers with less than 5 years experience varied from 1.5 kips to 3.5 kips. While having experience certainly did not eliminate all errors, having at least 5 years of experience seemed to give engineers enough judgment to recognize unreasonable answers that were grossly incorrect. As a result of the large variation in results for those with less than 5 years of experience, findings for subsequent portions of the assessment were based on data gathered from those engineers with 5+ years of experience.

Use of ACI 318 Appendix D to solve for the concrete strength vs. Not solving for this at all or using IBC – Over 60% of the submitted solutions used the ACI 318 Appendix D Method to solve for the concretes wind and seismic capacity.

Degree of Difficulty on arriving at the solution - The average time to complete the analysis was approximately 2 hours, very long given the simplicity of the problem. The committee's solution included approximately 40 lines of calculation to determine the bolt capacity in concrete compared with only 6 lines for wood. Although bolt capacity equations for wood are complex, checking multiple limit states in wood, the calculations are greatly simplified by the addition of bolt capacity tables in the NDS code.

Recommendations – The results of this problem indicate that efforts should be made to:

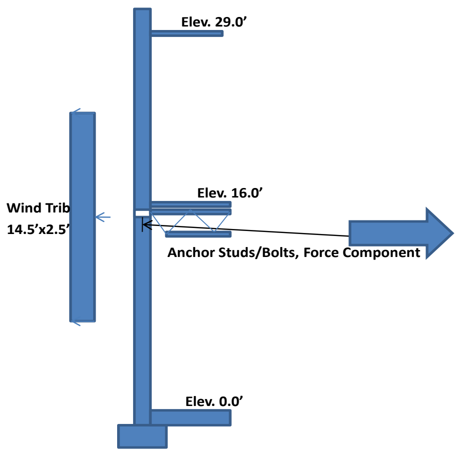
1. Include bolt capacity tables directly in ACI 318 Appendix D, similar to the bolt capacity tables included in the NDS for wood.

2. Increase engineer's awareness of the ACI 318 Appendix D Design Procedures. These efforts could include: (a) increased referencing to ACI 318 in the IBC and ASCE 7 code requirements, (b) increased exposure in ASCE 7 professional development seminars, (c) increased awareness of ductile behavior of anchorage in concrete construction.

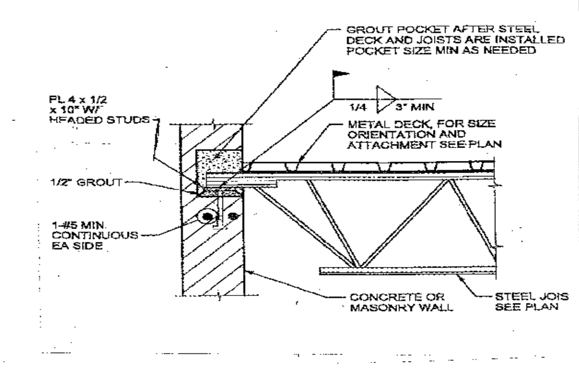
3. Increase training in and education in both younger engineers and among experienced senior engineers (10+ year's experience). The training should include ACI 318 Appendix D anchorage problem solutions for both concrete and steel elements and include applicable software solutions.

<u>Trial Design Problem #2</u> – Wall to 2nd Floor Anchorage in Masonry Construction per ACI 530-08

You are designing a new concrete block masonry wall Fire Station in New Orleans, Louisiana that is approximately 100’x100’ in plan and in a flat urban area. You need to determine the component wind lateral out-of-plane wall force based on the Code required 150 mph basic wind speed. The second floor open web joist framing will be anchored to the grouted 8-inch, f’m = 2000 psi reinforced concrete block masonry wall at joist pockets every 2.5’ feet on center. The tributary height contributing to the 2nd floor wind out of plane load is 14.5 feet so the out of plane wind load area is 2.5’ x 14.5’ to be attached to the floor framing. The Roof is at elevation 29 feet as shown in the wall section below.



WALL SECTION



<u>DETAIL AT SECOND FLOOR</u>

Determine the wind out-of-plane lateral force (leeward side) and the proposed number of 5/8-inch diameter anchors connecting the joist bearing plate to the masonry wall for the force. The governing Building Codes are IBC 2009, ASCE 7-05 and ACI 530-08.

Solution

Time to Complete: **Averaged about 2 hours**
Wind Resultant Force Component: ***2016#***

Anchor Type, Grade, Material: ***Cast-in-Place Headed Stud (Nelson Stud), ASTM A108***
(e.g. Headed Anchor Stud, cast-in-place ‘J’ bolt, post-installed expansion anchor, A307 Anchor Bolt, etc.)
Anchor Capacity Sources: ***ACI 530-08/ASCE 7-05***
(e.g. Code, Bolt Vendor Information, etc.)
Number of 5/8” diameter anchors per attachment: **2 @ *5/8” diameter***
Bolt Embedment and Spacing: ***7”embedment and 8 inch spacing***

Solution

Wind Resultant Force Component for lateral out-of plane load.
ASCE 7-05 Wind Components (ASCE 7-05 6.4.2.2)

- $p_{net} = \lambda K_{zt} I p_{net30}$ (EQ 6-2)
- In the City of New Orleans, Exposure B, Urban Area, $\lambda = 1.0$ for Urban Area
- Topographic Factor K_{zt} for the flat site is 1.0
- Fire station is an Occupancy Category IV structure per ASCE 7-05 Table 1-1
- Importance Factor per ASCE 7-05 Table 6-1 for Category IV in Hurricane Prone regions is 1.15
- End Wall Zone 5 used as 10% of the building length is = 100' (0.10) = 10'
- Tributary Wind Area on each joist anchor location component = 2.5'x14.5'= 36 ft^2
- p_{net30} from ASCE 7-05, Figure 6-3, Components and Cladding, Wall, End Zone 5, Greater than 20ft^2 but less than 50ft^2,
  Straight line Interpolate between the value for 20ft^2 of 50.5 psf and 50ft^2 of 45.7 psf for 36 ft^2.
- (50.5 psf – 45.7 psf) / 50ft^2 – 20ft^2 = 4.8 psf/ft^2
- (4.8 psf/ft^2) (36ft^2 -20ft^2 / 50ft^2 – 20ft^2) = 2.56 psf
- p_{net30} = 45.7 psf + 2.56 psf = 48.26 psf
- p_{net} =1.0 (1.0) (1.15) 48.26psf = 56 psf
- Wind Resultant Force Component = 56 psf (36ft^2) = 2016 #

ACI 530-08 Shear Design (ACI 2.1.4.3)

- Use 5/8" diameter A307 Headed Anchor Bolts
- L_{bc} = 7.625/2 = 3.81" which is governed by half the thickness of the 8" inch thick CMU wall
- $A_{pv} = \pi L_{bc}^2 / 2 = \pi 3.81^2 / 2$ = 22.8 sq. in.
- $A_{pt} = \pi L_{bc}^2 = \pi 3.81^2$ = 45.6 sq. in
- B_v is the lesser of $B_{vb} = 1.25\, A_{pv} \sqrt{f'm}$ (Eq. 2-6)
  -or-
  $B_{vc} = 350 \sqrt[4]{f'mA_b}$ (Eq. 2-7)
  -or-
  $B_{vpry} = 2.0\, B_{ab} = 2.5\, A_{pt} \sqrt{f'm}$ (Eq. 2-8)
  -or-
  $B_{vs} = 0.36\, A_b f_y$ (Eq. 2-9)
- $B_{vb} = 1.25\, A_{pv} \sqrt{f'm} = 1.25\,(22.8) \sqrt{2000}$ = 1275# <u>GOVERNS</u>
- $B_{vc} = 350 \sqrt[4]{(2000\,psi)(0.31in2)}$ = 1746#
- $B_{vpry} = 2.0\, B_{ab} = 2.5\, A_{pt} \sqrt{f'm} = 2.5\,(45.6) \sqrt{2000}$ = 5100#
- B_{vs} = 0.36 (0.31) 30,000 = 3350 #

- B_{vb} Masonry breakout controls
- Check overlap if bolts spaced at 8 inches on center.
  A_{pv} = 22.8 + 8"x3.81" = 53.2 sq. in.
  $B_{vb} = 1.25\ (53.2)\ \sqrt{2000} = 2974\#$ OK
- Number of 5/8" diameter Anchors Needed = 2016# / 1275# per anchor = 1.6 anchors

Final Selection
- Use (2) 5/8" diameter cast-in-place headed anchor bolts located in the center of the wall with 7" embedment spaced at 8" on center (one anchor each cell, 12 bolt diameters on center for the anchors.)

The demographics of the 27 participants were as follows:

Highest Educational Degree	63% Bachelors	37% Masters	0% Unknown	
Years Experience	18.5% 0-4 Years	37% 5-10 Years	18.5% 11-20 Years	26% 21+ Years
Professional License	26% EIT Only	74% PE	26% SE	
States	44% Virginia	11% Oregon	7.5% each NC, WI, GA	22.5% Others

Experience is Essential - This is the first lesson learned (or reinforced) from the trial design solutions. Education and number of years of experience alone are not adequate to ensure practicing engineers are able to safely and consistently design buildings. As examples, 4 participants arrived at only needing one 5/8" diameter anchor to secure this connection. Typically the answer of needing only one anchor bolt was arrived at due to a low wind force resultant and not checking for wind forces at the edge of the structure where the force can be higher. The answers submitted by engineers with less than 5 years experience varied from 1 kips to 2 kips for the wind force resultant on the detail. However even very experienced engineers arrived at wind force demands as low as 500 pounds. While having experience certainly did not eliminate all errors, having at least 5 years of experience seemed to give engineers more judgment to recognize unreasonable answers that were incorrect. Additionally the use of only one anchor is very impractical and can be irresponsible. The use of only one anchor will most likely result in an eccentric loading condition between the joist and the anchor that can result in unaccounted for torsion and failure of the anchor when loaded. Finally redundancy is an important topic fro all to learn in designing safe structures.

Central vs. End Wall Zone Wind Force – 55% of the submitted solutions did not calculate the end wall zone wind force component. Given the simplicity of the problem and the fact that many of the engineers that submitted solutions were from regions of the Atlantic or Gulf Coast, it is interesting to observe the omission of the End Wall Wind Zones from the calculations. This shows a lack of understanding of how wind acts.

Revision of ACI 530-05 to ACI 530-08 Section 2.1.4.3.2 - The determination of correct number of anchors changed from 4 to 2 by using the newer ACI 530-08 code section 2.1.4.3.2 as opposed to the previous version in ACI 530-05. The change in the code away from linear interpolation once 12 diameter edge distance was not achieved resulted in a significant change in the calculations and results. Most all respondents stated they used the ACI 530-08 code. However, one respondent stated they were using the ACI 530-08 code but upon examination of the submitted calculations they had actually used the ACI 530-05 section and arrived at the need for the 4 anchors instead of only 2. The practicality of 4 anchors in this type of detail would almost be prohibitive.

Bolt/Anchor Embedment – 52% of respondents have an anchor embedment of 4 inches or less. Further 22% of respondents had an embedment depth of only 2.5 inches. This shallow embedment does not allow for much if any ductility in the anchorages performance and can lead to a more brittle failure of the anchorage. This was not recognized by the respondents ion their solutions by upsizing the anchor embedment depths. With only a 2.5 inch embedment often times the bearing plates for such anchorage require the use of leveling grout that could truly jeopardize the true embedment in the masonry.

Headed Shear Stud Usage as opposed to Anchor Bolts – 22% of respondents utilized headed anchor studs that would need to be welded to the bearing plate above prior to either wet setting these bearing plates and anchors or carefully prepositioning and grouting around and underneath. The recognition that the placement of the prewelded headed shear studs to the underside of the bearing plates and then the difficulty of placing this in the grouted cell was assumed to take place by the other 78% of respondents and their use of cast in place anchor bolts. This observation by the majority of participants is encouraging. However having 22% of the respondents not recognize this also indicates more experience and judgment would be beneficial in the applications of the right materials for the right application.

Recommendations – The results of this problem indicate that efforts should be made to:

1. Increase engineers awareness of the ASCE 7 wind load requirements for end zones especially. These efforts can include increased exposure to ASCE 7 wind loading professional development seminars.

2. Increase engineer’s awareness of the ACI 530-08 procedures. These efforts could include: (a) increased referencing to ACI 530–08 Section 2.1.4.2.2.1 in ASCE 7 code requirements, (b) increased exposure in ACI 530-08 and ASCE 7 professional development seminars.

3. Increase training in practical detailing of connections for constructability and ductility. Often this training is best done in offices where experienced engineers can mentor junior engineers to avoid the lessons learned over the years. The training should include the various options and consequences for detailing critical connections in alternative ways. A good quality control program instituted by senior engineers reviewing junior engineers work can also yield these benefits from a training manner.

[1]Vice President, MWH Americas Inc., Walnut Creek, CA 94596; email: craig.j.wilcox@us.mwhglobal.com
[2]Associate Professor, Architectural Engineering Department, California Polytechnic State University, San Luis Obispo, CA 93407; email: bnuttall@calpoly.edu
[3]Partner, Hanson Professional Services Inc., Rockford, IL 61108; email: tbarnett@hanson-inc.com
[4]Project Manager, Graef, 125 S 84th St., Suite 401, Milwaukee, WI 53214; email: beau.sanders@graef-usa.com