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APPLICATION OF STRUT-TIE-METHOD (STM) TO RETROFIT AN EXISTING FOUNDATION ANCHORAGE

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A strut-and-tie model (STM) is an ultimate strength design method based on the formation of a hypothetical truss elements that transmit forces from loading points to supports. The STM utilizes concrete struts to resist compression and reinforcing ties to carry tension. Design using STM involves calculating the required amount of reinforcement to serve as the tension ties and then checking that the compressive struts and nodal zone (joints) are adequate to support the forces. A key advantage of design using STM is that the designer can visualize the flow of stresses in the member. This paper presents the basic concepts, assumptions and approaches using STM to perform the calculation and design for the existing foundation anchor retrofit based on a real application in high seismic zone. The analysis also includes up-to-date finite element modelling techniques for the machine base plate the anchor rods connection to the concrete foundation subjected to large forces (tension and shear).

Keywords: Base plate, Anchor rod, Hold down bolt, Rod stiffness, Finite element.

1 INTRODUCTION

Analysis and design of anchorage in concrete have evolved through various stages of improvements during last 50 years in the United States and Europe. In the early 1970s ACI 349 (2013) Appendix B recommendations on cast-in-place anchor capacity in concrete were based on concrete failure cone radiating from the base of anchor head embedded in concrete. The angle of the failure cone was assumed to be 45 degrees with the horizontal plane. The average principal tensile stress at the failure surface was limited to $4\sqrt{\text{fc}}$, where fc is the compressive strength of concrete. In the 1980s further research on cracked and un-cracked concrete generated Concrete Capacity Design (CCD) method for testing of anchors in concrete with various edge distance and spacing conditions. This research resulted in current recommendations listed in Chapter 17 of ACI 318 (2014). The angle of concrete failure cone initiating from the embedded anchor head per ACI 318 (2014) is changed from 45 to 35 degrees with the horizontal plane. In addition, the recommendations also include different possible failure mechanisms for steel and concrete along with group effect of anchors.

However, none of the recommendations for anchorage analysis takes into account the presence of reinforcing steel in the surrounding concrete. Since unreinforced concrete is uncommon, this paper attempts to take credit for the available capacity of reinforcing steel that are present in the concrete by means of code accepted Strut and Tie Method (STM) in calculating the anchorage capacity.

2 CASE DESCRIPTION

A pile supported reinforced concrete block type foundation was designed to support a compressor. The compressor was attached to a steel base frame comprised of wide flange beams and plate. The steel base frame was anchored to the block foundation by means of eight (8) – 1.0 inch diameter cast-in-place anchor bolts. The original design did not consider the effect of lateral loads from piping connections to the compressor nozzles. Thus, the anchorage was designed and installed for loads smaller than what could be anticipated during normal and upset loading conditions. Although the foundation block was found to be adequately designed for the additional loads from the piping connections, the anchorage design by standard engineering procedure was found inadequate to meet increased tension and shear demands. Therefore, a revisit of the anchorage design was warranted to develop the required modifications to the existing anchor bolt detailing. The existing foundation pedestal geometry and the anchor bolts configuration including location and sizes are shown below in Figure 1 and Figure 2:

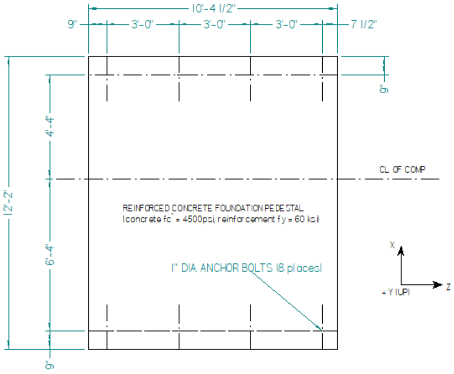

Figure 1. Foundation plan view.

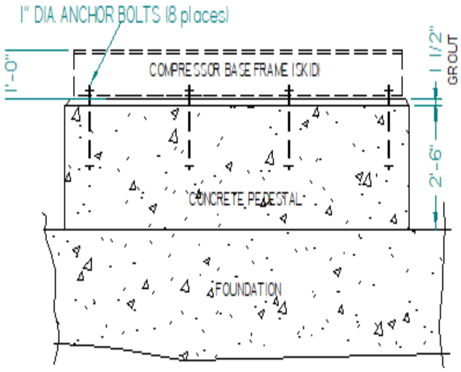

Figure 2. Foundation elevation view.

The detail of the existing anchor bolts and the reinforcement arrangement around the anchor bolts are shown in Figures 3 and 4. Note that the top of anchor bolts is embedded in sleeves in order to provide required stretch length in the bolts for ductility. The base of each anchor bolt is provided with double nuts to create a surface from which the concrete failure cone for tension can initiate. Eight (8) - #6 vertical rebars surrounding each anchor bolt are provided to facilitate tensile force transfer from anchor bolt to concrete. Similarly, adequate amount of #4 rebar ties are provided around each anchor bolt for proper transfer of shear force from anchor bolt to concrete.

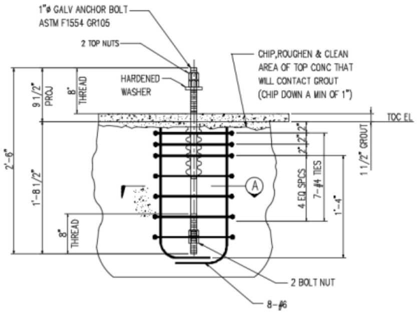

Figure 3. Anchor bolt.

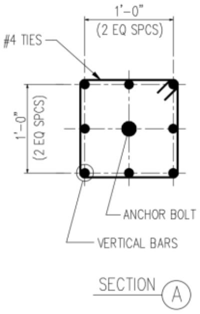

Figure 4. Rebar cage details.

3 COMPUTER MODEL

A Finite Element Analysis (FEA) model developed in STAAD Pro (2020) was utilized to simulate the machine / base skid and the anchor bolts for the load transfer from the machine base to the anchor bolt locations (see Figure 5 below). 4-noded shell/ plate finite elements with steel material properties were utilized to represent the stiffness and geometry of the machine casing and the base frames. The rigid links comprised of massless beam elements were used to transfer the machine loads from machine center of gravity (CG) location or piping connection locations to the steel base frame. Elastic modulus of these rigid elements was taken 100 times that of steel to simulate adequate rigidity for the links.

Design loads include the machine and base skid frame dead weight, operating weight, piping loads and the seismic loads from the machine and attached piping. The machine dead and seismic loads are applied at the machine center of gravity (CG) location. The piping loads were applied at the compressor nozzles locations.

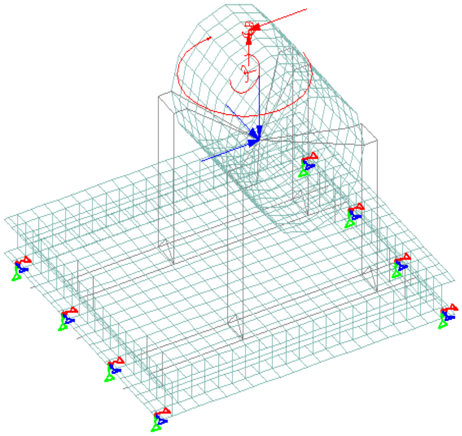

Figure 5. FEA model with anchor bolts.

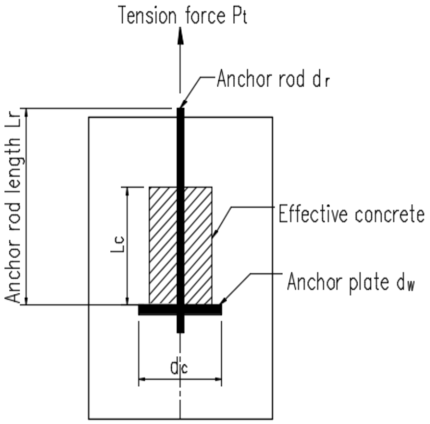

Figure 6. Anchor bolt tension stiffness.

Anchor bolt stiffness was considered in the FEA model for the load transfer from the machine base frame to anchor bolts. Eight (8) spring supports with the spring constants at the anchor bolt locations were used to simulate the anchor bolt axial and flexural stiffness as the boundary conditions for the analysis model. The Anchor Bolt tensile stiffness (K_t) was calculated based on the methodology suggested by Tsavdaridis *et al*. (2016) as indicated in Eq. (1).

$$K_t = \frac{E_s A_r}{0.8\, n\, d_r + L_r} \tag{1}$$

where,

E_s = Anchor bolt steel elastic modulus
E_c = Concrete elastic modulus which is a function of concrete compressive strength
$n = E_s / E_c$
A_r = Anchor bolt cross section area
d_r = Anchor bolt diameter
L_r = Anchor bolt length (see Figure 6)

Lateral (shear) stiffness of the anchor bolt is provided by bending of the partial embedded length of the anchor bolt. As suggested by several researches, the effective length of embedded anchor bolt in bending is a function of diameter of the anchor bolt. It is also dependent on the stretch length in the concrete embedment provided in anchor bolt detailing. The stretch length is provided by the anchor bolt sleeve near the concrete surface. The anchor bolts bending stiffness was calculated with Eq. (2):

$$K_v = \frac{3E_s I}{L_d^3} \tag{2}$$

where,

I = Moment of inertia of anchor bolt cross section
L_d = Effective length of anchor bolt in bending = Min ($8d_r$, Sleeve Length)

4 ANCHOR REINFORCEMENT DESIGN BY STM

For the anchor bolt reinforcement design, the tension in anchor bolt was not considered in this paper since the tension overload was dealt with in a different manner. Only the reinforcement design for the shear force generated on the anchor bolts from applied loads on the compressor was examined.

The anchor bolts were designed using STM procedure. Figure 7 below shows the location of the existing anchor bolts with respect to concrete reinforcements and free edges.

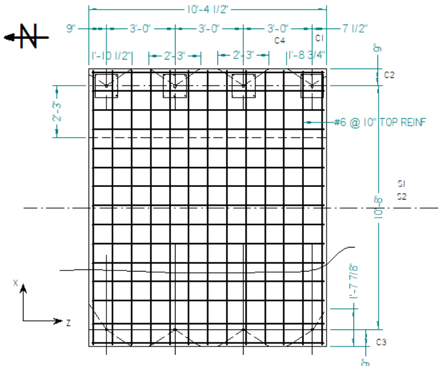

Figure 7. Concrete pedestal reinforcement plan view.

Based on the configuration of reinforcements around the anchor bolt, it was possible to generate STM comprised of concrete compression struts and rebar tension ties. Figure 8 and 9 below show a possible formation of a Strut and Tie system that can effectively resist the applied shear force from the anchor bolt.

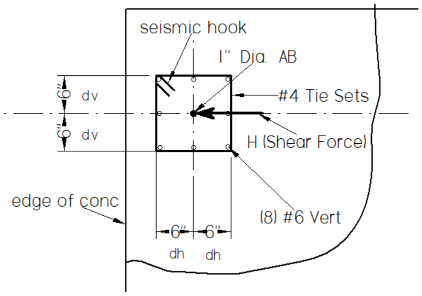

Figure 8. STM for anchor bolt.

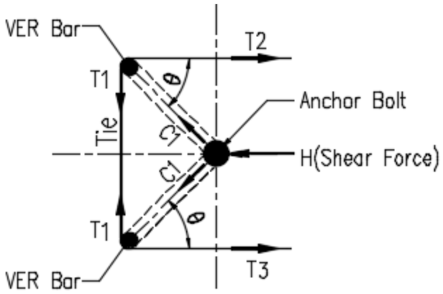

Figure 9. STM for anchor reinforcement (plan view).

The forces in the Struts and Ties as shown on Figure 9 are calculated as follows:

$$C_1=\frac{H}{2\cos(\theta)} \qquad T_1=C_1 \sin(\theta) \qquad T_2=C_1 \cos(\theta) \qquad T_3=T_2$$

Per ACI 318 (2014), the angle θ between strut and tie for an effective STM needs to be greater than 25 degree. Figure 10 below depicts the side view of the STM.

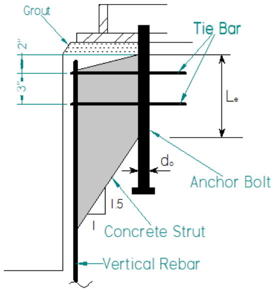

Figure 10. STM for anchor reinforcement (elevation view).

Strut compressive strength is limited to the following Eq. (3):

$$f_{ce}=0.85\beta_s f'_c \tag{3}$$

Bearing resistance of anchor bolt (C_{r_ab}) and vertical rebar (C_{r_rebar}) at the nodal zones are calculated with Eqs. (4) and (5):

$$C_{r\_ab} = n_s \emptyset_{stm}(0.85\beta_n f'_c)A_{brg\_ab} \tag{4}$$

$$C_{r\_rebar} = \emptyset_{stm}(0.85\beta_n f'_c)\,A_{brg\_rebar} \tag{5}$$

Where

L_e = Anchor bolt bearing length = Min ($8d_r$, h_{ef})
h_{ef} = Anchor bolt embedment length
n_s = the number of the anchor bolt
φ_{stm} = STM strength reduction factor
d_b = the vertical bar diameter
β_s = Factor to account for effect of cracking in concrete Strut
f'_c = Concrete compressive strength
β_n = Factor to account for effect of anchorage of ties at nodal zone
$A_{brg\_ab} = L_e \text{ x } d_r$
$A_{brg} = (L_e + 1.5\, d_{bd})\, d_b$
$d_{bd} = \sqrt{{d_v}^2 + {d_h}^2} - \frac{d_r}{2} - \frac{d_b}{2}$
d_v, d_h = Rebar location with respect to anchor bolt centerline (see Figure 8)

The bearing strength of the anchor bolt at the nodal zone need to be larger than the applied shear force H on the bolt. Since the compressive strength of strut is approximately similar to the nodal bearing strength ($f_{cu} = 0.85\ \beta_n\ f_c'$) and the available area for the strut is typically larger than the available area for bearing, the bearing strength of anchor bolt or vertical rebar governs over the strength of strut. Therefore, following conditions as seen in Eq. (6) should be met to ensure that the bearing strengths are adequate:

$$H > Cr\_ab \quad and \quad C1 > Cr\_rebar \tag{6}$$

As shown on Figure 10, only the top two layers of rebar ties are assumed to be effective in providing tension resistance in STM. For closed ties, the tie cannot develop full yield strength f_y at the hook location. Therefore, the pullout resistance in tension of a single hooked bolt is determined by the maximum force that can be developed at hook. Considering that one hoop tie and one hooked tie to contribute to the tension resistance for the STM suggested by Widianto and Jerry (2010), the total required resistance (R_{total}) developed by two ties are conservatively taken as seen in Eq. (7):

$$R_{total}=\psi_{cp}\,T_n=\psi_{cp}\,(T_{tie}+T_h) \tag{7}$$

Where

ψ_{cp} = Factor to modify pullout strength in presence or absence of cracking
$T_{tie} = A_{tie}\, f_y$
$T_h = 0.9\, f_c` e_h\, d_{tie}$
A_{tie} = Reinforcing tie cross section area
d_{tie} = Reinforcing tie diameter
f_y = Yield strength of reinforcing steel
e_h = Inner surface to outer tip of hook dimension

Finally, the design needs to meet the condition given in Eq. (8) to ensure that the total tie resistance (R_{total}) for tension from STM model is greater than T_1, T_2 or T_3 to complete the reinforcement design.

$$R_{total} > T_1 \;\; or \;\; T_2 \;\; or \;\; T_3 \tag{8}$$

5 CONCLUSION

A design procedure for calculating the required shear reinforcement around the anchor bolt in concrete pedestal by STM is presented in the paper. The shear force in anchor bolt is resisted by the anchor reinforcement comprised of horizontal ties and vertical reinforcing bars via formation of a Strut and Tie model. It is evident that if an effective Strut and Tie model can be generated around the anchor bolt, evaluating anchorage in concrete by STM method is simpler than that in unreinforced concrete using complex design equations from Chapter 17 in ACI 318.

Disclaimer

The views and opinions expressed by authors are entirely their own and do not represent either an endorsement by Worley or reflect the policies or official position of Worley on the matters raised herein.

References

ACI 318-14, *Building Code Requirements for Structural Concrete,* American Concrete Institute, 2014.
ACI 349-13, *Code Requirements for Nuclear Safety-Related Concrete Structures,* American Concrete Institute, 2013.
STAAD Pro, *3D Structural Analysis and Design Software*, CONNECT Edition, Bentley System, 2020.
Tsavdaridis, K. D. , Shaheen, M., Baniotopoulos, C., and Salem, E., *Analytical Approach of Anchor Rod Stiffness and Steel Base-Plate Calculation under Tension,* Structures, 5, 207-218, February, 2016.
Widianto, C. P., and Jerry O., *Design of Anchor Reinforcement in Concrete Pedestals,* CSA Today, 3(12), 2500-2511, 2010.