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DEVELOPMENT OF CONCRETE SHEAR STRENGTH FOR SHEAR LUGS IN UNCONFINED GROUT POCKETS

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The base plate anchorage system for major equipment supports is often designed with a combination of shear lugs and anchor bolts to resist equipment support reactions. Shear lugs are designed to transmit the design shear forces from the support base plates to the foundation concrete. The shear lugs are commonly placed inside a pre-formed grout pocket that is eventually filled with non-shrink high strength grout. The pre-formed grout pockets are sometimes left open to a free edge of concrete on one or more sides for ease of equipment installation and alignment before they are filled with grout. Where the equipment loads are applied in the direction of the free edge, the absence of adequate confinement makes it difficult to develop sufficient breakout strength in shear. This paper addresses a few practical issues that an engineer may face while designing non-confined grout pockets encasing equipment anchorage. It will also demonstrate different ways of improving the concrete breakout strength due to shear by means of providing reinforcements across the anticipated failure planes following the recommendations from different US codes and standards.

Keywords: Anchorage, Breakout strength, Confinement, Failure plane, Shear reinforcements, Machine foundations.

1 INTRODUCTION

Major equipment in industrial application is particularly sensitive to proper alignment during installation and functional performance of the foundation and anchorage system during its operational life. There are numerous design guides and procedures for analysis of equipment foundations subjected to static and/or dynamic loads. These design guides are often not prescriptive for anchoring techniques, varying widely between types of machines and machine vendors. This leaves much of the design up to engineering judgments on which design method or code requirement is appropriate for each situation. It is important to note that the design of proper anchorage of equipment support to the foundation concrete is crucial, since it is the primary conductor of the load transfer mechanism between the equipment and the foundation. Even a small amount of unexpected displacement or rotation of such anchor points can result in a severely detrimental effect to the safe operation and life of the equipment.

Currently Appendix D of ACI 318 and ACI 349 provide guidelines and requirements for anchor bolts and shear lug design. They do not necessarily cover all the conditions that machine foundation engineers encounter during design and construction. This paper discusses applicable code requirements for such anchorage design and suggests a method for developing required strength of an anchorage system that is not specifically addressed in either code.

2 PROBLEM STATEMENT

The base of major equipment such as a Gas Turbine Generator (GTG) or a Steam Turbine Generator (STG) may have a number of supports along its shaft. The support arrangement varies from machine to machine depending on the type of service and the manufacturer of the machine. Based on the functional requirement, the machine may be supported on a table top constructed of reinforced concrete beams and columns, or on a concrete-block type foundation. When the size of the machine requires them, the supports are raised above the surrounding floor to improve accessibility of piping and conduits. A typical machine support anchorage is shown on Figure 1 below.

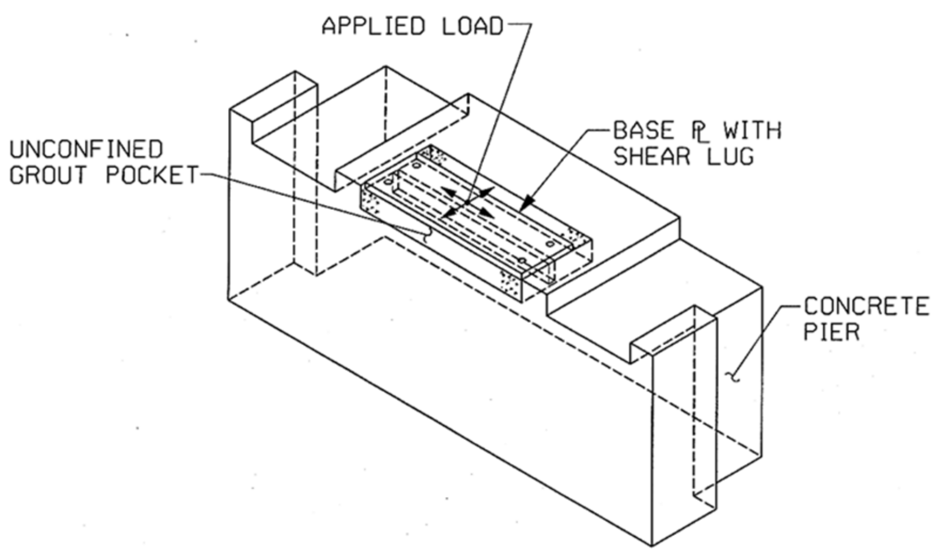

Figure 1. Typical machine support anchorage (anchor bolts not shown for clarity).

The support legs for the equipment are usually furnished with base plates including anchor bolt holes and welded shear lugs. The shear lug shown above is contained in a pre-formed grout pocket. The grout pocket is subsequently filled with non-shrink high-strength grout once the machine is aligned to its final axis and elevation. This will achieve ease of installation and provide adequate flexibility in machine alignment. With the operational loads from the machine, the shear lugs in the base plates can be subjected to large shear forces due to thermal, wind, seismic, abnormal, accidental load or their combinations. That shear force must be transferred to the foundation concrete via the non-shrink grout that is not totally confined. Although the anchor bolts in the base plate are pre-tensioned to keep the grout under permanent compression, the shear force on the shear lug is sometimes much larger than frictional resistance developed between the concrete and grout surfaces. Therefore, a different load transfer mechanism must be developed between the grout and the foundation concrete.

3 METHOD OF ANALYSIS

Typical anchorage design is addressed in Appendix D of both ACI 318 and ACI 349. ACI 318 primarily addresses the design of anchor bolts, not the requirements for design of shear lugs. ACI 349 presents a method for the design of shear lugs embedded in monolithically poured concrete and grout pockets fully confined by concrete. Since the machine anchorage in question is unconfined, the Shear-Friction provisions found in Section 11.6.4 of ACI 318 are incorporated into a hybrid design. This paper combines the requirements from ACI 349 Appendix D and ACI 318 Section 11.6.4 to arrive at a solution to the problem described above. The calculation of nominal shear strength of shear lug per ACI 349 involves the evaluation of the following failure modes:

(1) Shear strength of lug and weld material at the base-plate connection

(2) Flexural steel strength of lug material

(3) Bearing strength of lug material and grout

(4) Shear strength of the concrete breakout plane in front of the shear lug

Since item (4) assumes confined concrete, two additional failure modes are checked for unconfined condition based on the Shear-Friction method:

(5) Shear friction strength at the grout-concrete interface

(6) Shear friction strength of concrete-breakout plane in front of the shear lug

The nominal strengths obtained from above failure modes are then multiplied by appropriate strength reduction factors to establish the corresponding design strengths of each failure mode. For an acceptable design, the following equation must be true:

$$\phi V_n \geq V_u \tag{1}$$

Where:

ϕV_n = Minimum design shear strength of all failure modes above
V_u = Factored shear force

Failure modes 1 to 3 above are beyond the scope of this paper, since there are well-established procedures for addressing these items. This paper attempts to address the substitution of failure mode in item 4 with those in items 5 and 6 for unconfined concrete edges. Figure 2 illustrates the possible failure paths through the grout concrete interface (Plane “a-a”) and the concrete surface (Plane “b-b”) in front of the shear lug.

The failure paths shown above are for the factored shear force (V_u) in the direction perpendicular to the free edge, based on the recommendation from Appendix D of ACI 349 for concrete breakout. Note that the failure planes are assumed to initiate at the base of the shear lug instead of at the top, as it is generally recommended for anchor bolts. This is a valid assumption, considering the combined rigidity of the base plate-shear lug system and presence of non-shrink grout on both faces of the shear lug

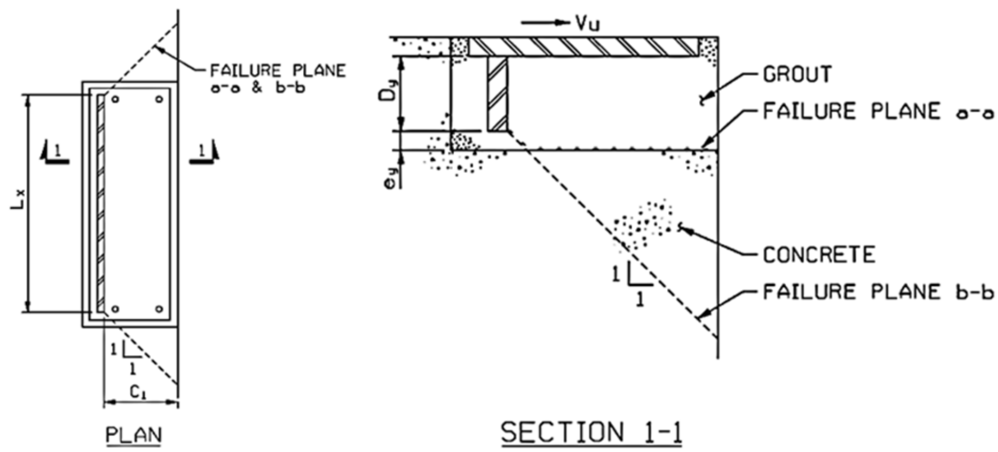

Figure 2. Postulated concrete breakout failure paths.

Design concrete breakout strength ($\phi V_{c\,a-a}$) in shear at Failure Plane "a-a" is calculated as follows:

$$\phi V_{c\,a-a} = \phi_v\, 4\sqrt{f_c} * [(C_1 + L_x + C_1)(D_y + e_y) - L_x D_y] \quad (2)$$

Where:

ϕ_v = Strength reduction factor for shear = 0.75
f_c = Specified compressive strength of concrete
C_1 = Free edge distance in the direction of shear force
L_x = Length of shear lug in the direction perpendicular to the shear force
D_y = Depth of shear lug below base plate
e_y = Distance from bottom of shear lug to bottom of grout pocket

Similarly, design concrete breakout strength ($\phi V_{c\,b-b}$) in shear at Failure Plane "b-b" is calculated as follows:

$$\phi V_{c\,b-b} = \phi_v\, 4\sqrt{f_c} * [(C_1 + L_x + C_1)(D_y + C_1) - L_x D_y] \quad (3)$$

The final design concrete breakout strength (ϕV_n) in shear is shown below:

$$\phi V_n = \phi V_c = \min(\phi\, V_{c\,a-a}, \phi\, V_{c\,b-b}) \quad (4)$$

If $\phi V_c \geq V_u$, the design is acceptable and no further calculation is necessary. In many cases, however, the factored design shear is well in excess of available concrete breakout strength. Therefore, reinforcement needs to be provided to increase the concrete breakout strength at the postulated failure planes. Note that if the reinforcements are provided to increase the concrete breakout strength, the contribution from concrete capacity (ϕV_c) towards breakout strength calculation should be ignored. It should be noted that due to the cyclic loading applied to the bolts, some relaxation in pre-tension is possible. Thus any increase in shear capacity due to confinement from the anchor bolts is conservatively omitted.

Since the failure planes are at the location of potential crack in the shear failure mode, shear friction can be considered to take place along the failure paths. An efficient way to mitigate cracks due to shear friction is to provide reinforcement across the failure plane. To determine the design strength of the shear friction reinforcement, let us examine two failure planes separately. Figure 3 below depicts the arrangement of reinforcement across the Failure Planes “a-a” and “b-b”:

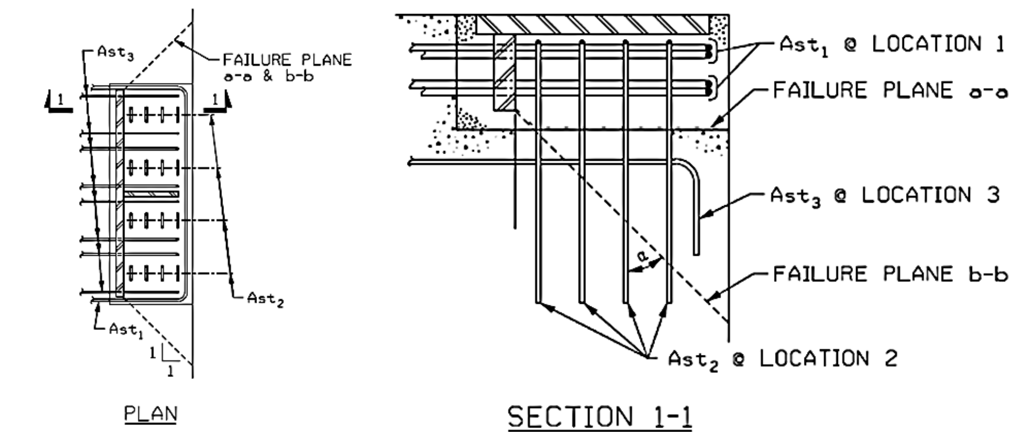

Figure 3. Reinforcement Arrangement Across Failure Planes “a-a” and “b-b”.

Design shear strength ($\phi V_{n\,a-a}$) developed by the reinforcement in shear friction along Failure Plane “a-a” can be calculated as follows:

$$\phi V_{n\,a-a} = \phi_v\, f_y * [n_1 A_{st1}(\mu\,\mathrm{Sin}\alpha + \mathrm{Cos}\alpha) + \mu n_2 A_{st2}] \qquad (5)$$

Where:

A_{st1}, A_{st2} = Area of reinforcing bars crossing shear friction plane at locations 1 and 2 respectively

n_1, n_2 = Number of reinforcing bars crossing shear friction plane at locations 1 and 2 respectively

f_y = Specified yield strength of reinforcement

μ = Coefficient of friction between surfaces across shear friction plane

α = Angle between the reinforcement and the shear friction plane

As per ACI 318 requirements, shear friction reinforcement should be developed on both sides of the failure plane for them to be effective. In case any reinforcement is partially developed, only a strength proportional to the required developed length should be considered in the capacity calculation. This condition exists for reinforcing bars (A_{st2}) at location 2 across Failure Plane “b-b” on Figure 3. Thus the design shear strength ($\phi V_{n\,b-b}$) developed by the reinforcement in shear friction along Failure Plane “b-b” can be written as follows:

$$\phi V_{n\,b-b} = \phi_v\, f_y * (n_1 A_{st1} + n_3 A_{st3} + \textstyle\sum_{i=1}^{n} n_{2i}\, A_{st2} \pounds_i) * (\mu\,\mathrm{Sin}\alpha + \mathrm{Cos}\alpha) \qquad (6)$$

Where:

A_{st3} = Area of reinforcing bars crossing shear friction plane at location 3

n_{2i} = Number of reinforcing bars in each row crossing shear friction plane at location 2

n_3 = Number of reinforcing bars crossing shear friction plane at location 3

$£_i$ = Ratio of available to full development lengths at location 2, where $£_i \geq 0.5$

Note that Equation 6 above assumes $\alpha_1 = \alpha_2 = \alpha_3$, indicating the angle between reinforcement and shear friction planes at locations 1, 2, and 3 are equal.

The final design concrete breakout strength (ϕV_n) in shear is shown below:

$$\phi V_n = \min\,(\phi\, V_{n\,a-a}\,, \phi\, V_{n\,b-b}) \tag{7}$$

Note: ϕV_n in Eq. (7) may not exceed the limits set forth in Section 11.6.5 of ACI 318.

The base plate and shear lug size and arrangement for the equipment supports are usually supplied by the equipment vendor, hence the length and depth of the shear lug is preset. Therefore, the way to satisfy the condition in Equation 1 i.e. $\phi V_n \geq V_u$, is to vary the reinforcing bar area, or number, or both. Significant increase in design strength is observed utilizing this method compared to that of Equations 2 and 3.

4 DISCUSSION

The objective of presenting the practical design problem and providing subsequent solutions is to offer guidance on how to improve concrete shear breakout strength to resist large amounts of shear force on a shear lug located in a grout pocket with an unconfined edge. The reinforcement arrangement suggested in this paper for strength improvement is one of the many different ways that the problem can possibly be solved. There could be other acceptable and more efficient ways to arrange the reinforcements, which may better suit the site or project specific requirements and accomplish the same objective. Other methods of analysis, including the strut-and-tie method, could be utilized to arrive at a similar reinforcing detail.

5 CONCLUSION

The methodology described in the paper is based on the standard engineering practice following the recommendations from ACI 318 and ACI 349. It is recommended that additional research and testing be performed to confirm that the actual design concrete breakout strength for shear lug meets or exceeds those calculated per the methodology utilized in this paper. The methodology can then be customized further to meet the design challenges that engineers face on a regular basis.

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References

ACI 318-11, Appendix D: Building Code Requirements for Structural Concrete.

ACI 349-06, Appendix D: Code Requirements for Nuclear Safety Related Concrete Structures.