The PCI headed stud anchorage research program: Scope and highlights of findings

Neal S. Anderson
Concrete Reinforcing Steel Institute, Schaumburg, Illinois, USA

Donald F. Meinheit
Wiss, Janney, Elstner Associates, Inc., Chicago, Illinois, USA

ABSTRACT: The construction industry has relied on the headed stud anchor to provide connection between concrete and multiple other structural elements for many years. In the past, the design engineer followed numerous accepted rational methods of designing for allowable strength and serviceability in accordance with accepted standard procedures.

Recent changes in the requirements in ACI 318, as well as new developments from testing completed by PCI, have started to impact the design engineer’s practice in designing anchorages to concrete. Failure to stay current with new design procedures can result in liberal design solutions.

The historical overview discusses the chronology of design methods based on various boundary conditions and load applications. The standard for designing headed stud anchor connections has been impacted by new testing results compiled by PCI. This article is an overview of the current state-of-the-art approach used by precast structural designers for headed stud anchor design.

1 BACKGROUND

For decades, the precast concrete industry has relied heavily on welded headed studs on anchorage plates to connect precast concrete elements to other structural elements. Formal headed-stud design concepts have existed in the Precast/Prestressed Concrete Institute’s (PCI) PCI Design Handbook since the early 1970s (PCI 1971). These early design concepts accounted for multiple anchors with variable spacings or those found close to free edges. New design concepts in the American Concrete Institute’s (ACI) Building Code Requirements for Structural Concrete Appendix D (ACI 318 2002) raised questions about the PCI design approach because the new design model produced designs more conservative than PCI’s design approach, even though the PCI approach worked successfully since 1971.

In 2002, ACI Committee 318, in Appendix D Anchoring to Concrete, included new provisions for designing all types of anchors, including headed studs, embedded bolts, and various mechanical expansion anchors. These new design provisions presented a simple physical model, which easily accommodates anchor spacing in two directions and the effects of free edges. The origins of the ACI design model date to the mid-1960s. However, the design model was more fully developed in the European Kappa method of the late 1980s and put into a comprehensive/transparent form with the development of the Concrete Capacity Design (CCD) model (Fuchs, Eligenhausen & Breen 1995). The motivation to create a chapter in the ACI Code was to rationally design both cast-in-place anchorages and post-installed mechanical anchorages.

The formal codification of the design requirements finally provided a design engineer with the methodologies to consider many of the geometry and member influences that can affect the capacity and the overall design of an anchorage group. Prior to the ACI codification of design provisions, post-installed anchors generally had to be designed using manufacturer’s catalogs/procedures and a standard factor of safety, usually 4. Hence, the codification of procedures greatly facilitates the general design of concrete anchors.

However, when thoroughly examining the research literature on headed studs and embedded bolts, the authors found that the database for tests on headed studs and embedded bolts loaded in shear was dominated by post-installed anchors. The database on tension is more substantially populated by headed studs and embedded bolts. Although there are no known systemic design problems with headed anchors designed using the pre-ACI 2002 procedures, it is fair to question the earlier design procedures when the new and old procedures give different solutions.
2 PCI'S RESEARCH INITIATIVE

The ACI Appendix D design method was calibrated using an extensive database, dominated mostly by post-installed anchor tests. This may have skewed the design equations toward post-installed anchors. Consequently, some current design provisions for headed-stud connections and other cast-in anchorages may not be totally appropriate.

In the mid 1990s, the Prestressed/Precast Concrete Institute (PCI) initiated a headed stud research program to create a database for headed-stud group connections. Originally, the PCI research program was conceived in response to the proposed ACI Appendix D provisions where certain provisions for the cast-in-place anchorage were found more liberal than the CCD approach. Because of the limited amount of research data on shear, PCI initiated an industry-sponsored research project to satisfy these objectives:

- Provide justification for the design procedures used in the past, which through Code implementation and adoption are now considered unconservative.
- Create a database of tests to (a) justify accepting and conforming to the provisions of ACI 318-02 Appendix D, (b) modify the ACI procedures, (c) refine the design procedures as currently published in the PCI Design Handbook (PCI 1999), or (d) create a database of tests to write a new design procedure independent of ACI 318, which is permitted in the Code.

3 THE PCI RESEARCH PROGRAM

PCI conducted this research work in two phases. Phase 1 of this study concentrated on examining headed-stud anchorages loaded only in shear because of the lack of headed stud test data in the anchor database. Phase 2 of this study reviewed the tension-only information from an existing, moderately-sized database. However, the more important part of Phase 2 included experimental studies evaluating the affects of combined tension and shear on multi-stud connections. Working for the consulting firm of Wiss, Janney, Elstner Associates, Inc. (WJE), the authors conducted both of these projects in the Northbrook, Illinois structural laboratory. In total, 412 headed stud tests were conducted by WJE.

The shear research program, and ensuing revisions to the PCI Handbook (the precast designers reference manual) considered the geometric effects of the front-edge distance, corners, side-edge distance, back-edge distance, and in-the-field type connections.

Welded, headed studs are designed to resist direct tension, shear, or in the usual case, the combination of the two. The design equations given in the Handbook are applicable to studs, which are welded to steel plates or other structural members, and embedded in unconfined, cracked or uncracked concrete (Anderson & Meinheit 2007a).

It is assumed that the steel plates are of sufficient thickness to prevent significant plate deformation and adequately transfer the applied load to the studs. In addition, the in-place connector design strength should be taken as the smaller value based on computing both the concrete and steel characteristic capacity for the anchorage configuration. Cracking is assumed to cause a reduction in capacity, similar to that in ACI Appendix D. No cracked concrete tests were conducted.

4 HIGHLIGHTS FROM THE RESEARCH RESULTS

4.1 Steel stud capacity

As presented in their paper (Anderson & Meinheit 2001), the authors clearly showed that steel failure in tensile and shear is only governed by the area of the stud shank and ultimate tensile strength of the stud steel (\(F_{ut}\)). This is attributed to the welding metallurgy affecting the headed stud mechanical properties in the heat-affected zone (HAZ) and a slightly greater stud area in the weld flash region.

Therefore, the steel capacity for a headed stud in tension and shear is identical. This realization may appear new; however, the compositely designed steel-concrete members have essentially used the same capacity in tension and shear since the early 1970s. The shear failure shown in Figure 1 occurs at a load dictated by the tensile ultimate strength.

4.2 Tension

As stated earlier, there is a substantial database of tension tests on headed studs and embedded bolts. WJE’s review of headed stud data in Phase 2 of the WJE/PCI research shows that the ACI provisions for calculating

![Image](image-url)

Figure 1. Steel failure of a headed-stud anchorage loaded in shear.
the single anchor concrete breakout capacity are representative of headed stud behavior. Provisions for edges and spacing using the CCD model are reasonable and generally conservative, except for the case where there is an anchor spacing influence in two directions. In this case, the CCD design model is slightly unconservative (no more than 10 percent) for anchor spacings that are less than about 2$h_{ef}$.

4.3 Shear

The WJE/PCI research program developed new design shear strength provisions for headed stud anchorages governed by a concrete breakout failure. The PCI design provisions are calibrated based on WJE experimental testing of headed-stud anchorages, which is permitted by the ACI Code. Figure 2 shows the different edge conditions for shear, discussed further in the following sections.

4.3.1 Front edge

The front edge condition represents a majority of shear-loaded connections found in engineering practice. Figure 3 shows a photograph of a typical front edge concrete breakout. The analyses of test data lead to a simpler design equation for the single stud breakout capacity. Unlike the ACI CCD model, the PCI equation is not a function of the anchor diameter or the effective embedment depth; their influence on headed stud capacity is not as significant as the edge distance.

For a multiple-stud connection with more than one anchor row perpendicular to the shear force direction, the breakout surface and hence capacity was found to be defined by the position of the rear or back stud row. The concept of Back Edge Distance (BED) for design was introduced in the PCI design procedure. The photograph in Figure 4 shows the rear stud clearly controls the location of the breakout crack formation; no parallel-to-stud-line splitting cracks occurred prior to failure. The ACI design provisions are conservative relative to the database developed from the WJE/PCI research testing.

4.3.2 Corners

The corner is considered to be a special case of an anchorage loaded toward the front-edge, but located sufficiently close to two intersecting edges such that a different concrete breakout path occurs, as seen in Figure 5. Corner tests showed the cattycorner stud, or stud diagonally opposite the geometric corner (see Figure 6) defined the concrete breakout capacity. The research found that the headed-stud corner influence is greater than the ACI model implies. Moreover, wide spacing between individual studs in the anchorage can initiate a “zipper-type” failure behavior, directing

Figure 2. Edge conditions for an anchorage loaded in shear.

Figure 3. Front edge concrete breakout representing a common load condition for shear.

Figure 4. Concrete breakout through the rear stud for a front edge loading condition.
4.3.3 **Side edge**

Side-edge conditions exist when the shear load is parallel to the free edge but the anchor(s) are close enough to the free edge to cause a breakout of the free edge parallel to the direction of the shear. The photograph in Figure 7 shows a side edge breakout for a two-stud connection. A new single-stud, side-edge breakout capacity equation was developed.

The ACI design procedure for side edge breakout was found to be very conservative for small side-edge distances when compared to the WJE/PCI developed database. The ACI design approach and equations for side edge breakout were based on limited testing of small diameter, single anchors; no group influences were considered because of the lack of test data at the time.

4.3.4 **Back edge**

The authors, to their knowledge, have not found any discussion of anchors near a free edge and loaded such that shear force is directed away from the free edge. For this condition of pure shear, testing found the back-edge distance has no influence on the headed-stud connection capacity, provided the anchor is not susceptible to pryout. At very small edge distances, as small as $4d_s$, the failure was consistently a steel shearing failure; this edge distance is well within the minimum concrete cover requirements for reinforcement protection.

4.3.5 **In-the-field and pryout**

When a headed-stud anchorage is sufficiently away from all edges, termed *in-the-field* of the member, the anchorage capacity is consistently governed by the steel stud(s), provided certain conditions exist with the stud geometry. If the stud is short and stocky, a concrete breakout failure known as concrete pryout can occur, as illustrated in Figure 8.
Sufficient test data exists in the literature to propose a new concrete pryout capacity equation for headed stud anchorages (Anderson & Meinheit 2005, 2007b). The geometric characteristic of the headed stud that dominates the pryout capacity is its stiffness. The diameter is representative of the stiffness of the anchor, which was experimentally found as controlling the pryout capacity.

4.4 Combined tension and shear action
Phase 2 of the WJE/PCI research explored combined tension and shear loading on a stud group. A test representing the attachment of a structural steel member to an embedded steel plate with headed studs was tested. Present design provisions for capacity analysis use a tri-linear interaction equation or diagram to describe the behavior, with truncation limits for minimum tension and shear. Because there are many different failure modes in tension and shear, one single interaction diagram representing all the different failure modes will make some combined loading designs liberal and others conservative.

This becomes a concern when steel failure may govern one capacity, while concrete breakout governs the other capacity. Instead of examining these failure modes as mutually exclusive failure behaviors, the authors have explored the combined action as a separate failure mode subject to modification by the level of tension or shear on the anchorage.

The authors present analyses of combined test data indicating that the failure in combined loading if not near an edge would be reasonable predicted by the tension breakout capacity. When the anchorage is closer to an edge, the failure again appears as a tension type concrete breakout.

Use of the tri-linear or an elliptical interaction design equation works for most cases of the data investigated. The case where the tri-linear equation is less conservative is when there is the possibility of a front edge concrete shear breakout failure in addition to a concrete tension breakout. Further refinements are still needed for this case.

5 SUMMARY
The WJE/PCI headed stud research initiative has produced an alternate shear design procedure, which better represents the behavior of headed-stud anchors. This design procedure also conforms to the ACI 318 Building Code, Appendix D requirements. The PCI Design Handbook – 6th Edition (PCI 2004) recognizes different types of failure modes associated with a headed-stud anchorage depending upon the type of edge condition, connection geometry, and the edge distances in relation to the connection.

The front edge breakout mode was contained in previous editions of the PCI Design Handbook, yet has been refined through this WJE/PCI research. In addition, the corner concrete breakout mode has been found to have a greater influence and revised connection capacity equations are presented. In the 6th Edition of the PCI Design Handbook, the concept of a side edge breakout has been introduced, as it was part of the WJE/PCI test program. Capacity equations for a connection adjacent to a side edge are presented for the first time in this PCI Design Handbook.

Tension design of headed stud anchorages follows the ACI Appendix D approach for the present. The design equations were found by WJE to be good representations of headed stud behavior in tension.

REFERENCES
ACI Committee 318—ACI 318. 2002. Building Code Requirements for Structural Concrete (ACI 318-02) and Commentary (ACI 318R-02), American Concrete Institute, Farmington Hills, Michigan.