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Design of anchor reinforcement for seismic tension loads

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ABSTRACT

This paper presents a study of cast-in anchors in reinforced concrete subjected to both monotonic and cyclic tension. Laboratory tests using 25 mm [1 in.] diameter anchor bolts showed that the code-conforming anchor reinforcement may not ensure anchor steel failure though it effectively prevented concrete breakout. Based on the observations and other tests in the literature, recommendations for the design of anchor tension reinforcement were proposed, which consists of (1) load-carrying reinforcement in the direction of the anchors; (2) crack-controlling reinforcement in all directions that have a limited edge distance; and (3) local confining reinforcement near the anchor head if side-face blowout may control the failure. The proposed anchor reinforcement was proven effective using additional laboratory tests. Further studies are needed to verify the reinforcement design for anchor connections.

1. Introduction

Anchor connections are a critical component of load transfer between steel and concrete members affecting structural performance during earthquake events [1,2]. Cast-in anchors may experience steel fracture and/or concrete breakout failure when subjected to a tension force [3–5]. The failure modes are mainly dependent upon the embedment depth (h_{ef}) when the anchor bolt is placed in plain concrete. Breakout failure is brittle and thus not a preferred failure mode for the anchors in seismic zones [6]. Engineers are recommended to consider steel reinforcement by building codes [7] and design guides [8,9] to improve the behavior of anchors likely controlled by concrete breakout.

It has been well documented that the potential failure region near headed stud anchors be confined using steel reinforcement [10]. The existing reinforcement for concrete anchors in the technical literature is summarized in Fig. 1. Two types of reinforcement are allowed in the building codes [7] and design guides [8]: specifically designed reinforcement (known as anchor reinforcement) for cast-in anchors and the existing reinforcement near the anchors in a reinforced concrete member (known as supplementary reinforcement). With a goal of restraining potential concrete breakout cracks, supplementary reinforcement is not designed to transfer the full tensile capacity of anchors into concrete. The effect of supplementary reinforcement has been well studied [11,12], and the corresponding analysis methods have been proposed. For example, the existing design methods assume that the concrete breakout, shown in shaded areas in Fig. 1a, c, and d, occurs before the reinforcement takes effect. With the cracks, the tensile capacity of the anchors is provided by the reinforcement in the same direction the anchors, and the tensile capacity of the reinforcement can be affected by available development lengths [10,11].

Anchor reinforcement in this study is that specifically designed and detailed such that the reinforced anchors achieve their full design capacities. U-shaped hairpins are specified in the current building codes and design guides. In addition, reinforcing bars placed near anchor bolts have been expected to create loading transferring paths through a splice mechanism (Fig. 1c, e, and f), and explained using strut-and-tie models (STMs). Few experimental tests have been available to verify the effectiveness of these anchor reinforcement, especially under simulated seismic loading.

2. Literature review

Very limited studies in the literature have focused on the behavior of anchor reinforcement and reinforced anchors. However, the literature review below includes a variety of related studies because concrete anchors are widely used in many applications in construction. Specifically, conceptual designs in the literature and the studies, in which headed anchors were embedded in reinforced concrete members, in which some reinforcing bars may have improved the anchor behavior/capacities. Observations from these tests are used to complement those made in this study, based which, an improved design method is proposed.

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Nomenclature

c_{a1}	front edge distance of anchor
d_a	anchor diameter
d_b	reinforcement diameter
d_s	stirrup diameter
f_c	measured concrete compressive strength
f_c'	specified concrete compressive strength (27.5 MP [4000 psi] in the study)
f_y	specified yield strength of steel (414 MPa [60 ksi] in the study)
h_{ef}	embedment depth of anchor bolts

foundation to the column reinforcement, as illustrated in Fig. 1e. The same model was also used to determine the lateral bursting force that leads to side face blowout failure. In the tests of column base connections in foundation beams, Baba et al. [17] treated closed stirrups near the headed anchors as anchor reinforcement, and applied STMs in explaining the load transfer. More importantly, a separate strut-and-tie model was used to visualize the load transfer from the bottom of the closed stirrups to the rest of the structure: column base plate in compression, as illustrated in Fig. 1f.

2.2. Existing experimental studies

There are limited tests available in the literature focusing on the verification of the above recommended anchor reinforcement. Focusing on the concrete breakout capacity of large diameter anchors, the tests by Lee et al. [18] included two test groups with four or eight No. 8 U-shaped hairpins, located within $0.2h_{ef}$ and the other $0.35h_{ef}$ from the test anchors. The No. 8 hairpins were assumed fully developed below the anchor head through a length of $14d_b$ with hooked ends. Note that these specimens were referred as "reinforced specimens," which leads to the term "reinforced anchors" in this paper. The hairpins can be treated as supplementary reinforcement because they were not proportioned to carry the anchor steel capacity in tension. The tests indicate that hairpins close to the test anchor are more effective than those located farther. The authors also indicated that the reinforcement should be proportioned to carry 100% of the applied load, and the design strength for the reinforcement should consider bond failure of reinforcement in the breakout cone. Berger [12] further studied the effect of supplementary reinforcement, and proposed a new capacity model, which considers contribution from both concrete and steel reinforcement. The tensile capacity of the reinforcement was calculated based on its bond capacity. Sharma et al. [11,19] extended the investigation to groups of four anchors. Instead of hairpins, closed stirrups were used as supplementary reinforcement in this latest study.

There are tests in the literature with headed studs placed in reinforced concrete members. The existing reinforcement in the members was not specifically designed as anchor reinforcement; however, observations from these tests provide relevant and valuable information to the subject of this study. For example, closed stirrups were provided in one of the two tension tests of headed studs for use in composite construction by Saari et al. [20]. The No. 3 stirrups at a spacing of 89 mm [3.5 in.] and longitudinal bars at all corners formed a reinforcing cage

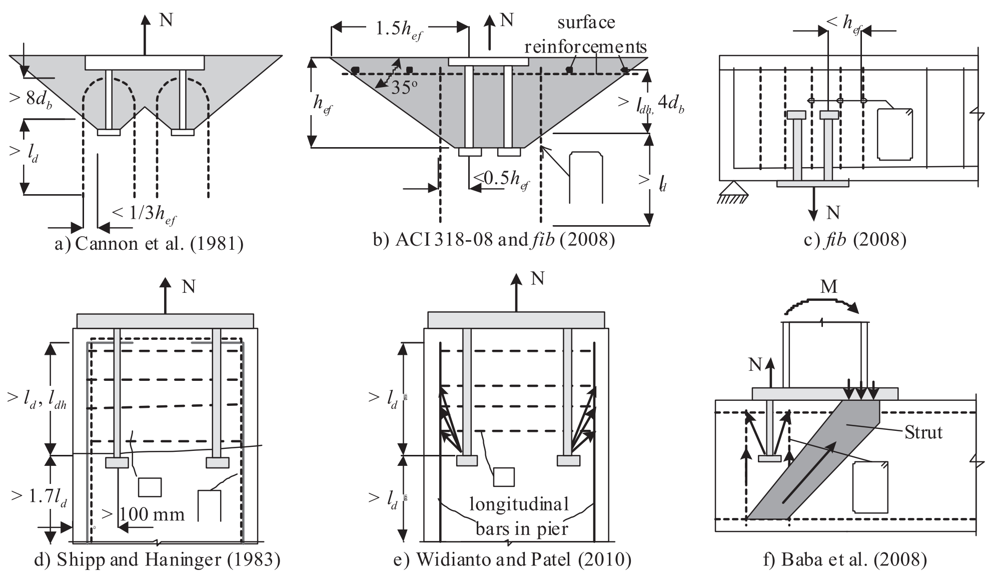

Fig. 1. Schematics of existing anchor tension reinforcement.

2.1. Existing design recommendations

The recommendations on the design of anchor tension reinforcement are summarized in Fig. 1. Cannon et al. [13] suggested simple hairpins for preventing potential breakout cones as shown in Fig. 1a. To achieve direct force transfer (similar to rebar splicing), hairpins are required to be placed symmetrically within $1/3h_{ef}$, measured from the edge of the anchor head, where h_{ef} is the embedded depth. A similar recommendation was adopted by CEB (1997) and ACI (2008) with a larger effective range ($0.5h_{ef}$), measured from the center of anchors, as shown in Fig. 1b. The European committee for standardization (2009) further increased this effective range to $0.75h_{ef}$. Critical to this study, stirrups in beams have been allowed by *fib* (2008) to transfer tensile forces from anchors installed at the bottom of the beam to the compression zone of the beam, as illustrated in Fig. 1c.

Cannon et al. [13] also recommended spiral reinforcement for each anchor in tension to prevent "lateral bursting," now known as side face blowout failure. In an application of U-shaped hairpins to the connections between steel columns and their concrete foundations, shown in Fig. 1d, Shipp and Haninger [14] recommended closed ties at a small spacing (e.g. 150 mm [6 in.]) to encase the anchor bolts. This critical measure may have been recommended after the study by Hasselwander et al. [15], in which many specimens, without confining reinforcement, failed in concrete side-face blowout.

Strut-and-tie models (STMs) have been used in the analysis and design of reinforcement for concrete anchors. For example, STMs are used to demonstrate the effectiveness of hairpins, and the needs for crack-controlling reinforcement [4,5,7,8]. Widianto and Patel [16] explained the load transfer from headed anchors embedded in a column