Transactions of the SMiRT 27
Yokohama, Japan, March 3-8, 2024
Division V

PULL-OUT STRENGTH ASSESSMENT OF HEADED ANCHOR IN CONCRETE USING MEASURED AND THEORETICAL FAILURE ANGLES

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ABSTRACT

An anchor system in the nuclear power plants (NPPs) is typically employed for fastening the system equipment. Hence, the assessment of the concrete anchor pull-out strength is required for the safety management of installed facilities when an extreme event like earthquake occurs. Basically, the pull-out strength is assessed by ACI 318 design code based, however, it requires considerably low strength reduction factor which ranges from 0.45 to 0.75. Thus, the design code allows the high uncertainty of estimation of the anchor pull-out strength influenced by anchor head size, embedment length, concrete strength, aggregate type, boundary condition, etc. To reduce the uncertainty and provide better predictability, it needs to investigate more accurate prediction method. In this study, a finite element analysis is performed using the cohesive zone model (CZM) to assess the pull-out strength of headed anchor in concrete according to the failure angle. A monotonic loading test was conducted using a concrete block installed a headed anchor at the center. The experimental pull-out strengths are compared with computational analysis with the two cases of failure angle, i.e., measured and theoretical angles. Consequently, it is found that CZM analysis with the measured angle captures the hardening response while the result with the theoretical angle provides conservative pull-out strength against the experimental test.

INTRODUCTION

In the standard for structural design of concrete anchors, the calculation of anchor pull-out strength generally follows the Concrete Capacity Design (CCD) method by Fuchs et al. (1995). Since the anchor design criteria include strength reduction factors ranging from 0.45 to 0.75 according to ACI 318 (2019), it is evident that the low reduction factors lead to a cautious estimation of anchor pull-out failure due to the high uncertainty. One of uncertain factors is the failure cone angle. CCD method involves determining an equivalent section based on concrete compressive strength and an anchor failure angle of 35°. In the experimental test, however, the failure cone angle cannot be specified constantly because the concrete cone fracture happens with the uncertainty of internal (heterogeneous material property) or external (experimental setup and loading condition) matters. Thus, the anchor pull-out strengths are differently obtained according to the failure cone angles, which the measured cone angle must be differing from the theoretical failure cone angle. To reduce the uncertainty and provide better predictability, it needs to investigate more accurate prediction method. In this study, a finite element (FE) analysis method using cohesive zone modelling (CZM) is employed, which can simulate crack propagation in fracture of concrete around the anchor. Consequently, the experimental pull-out strength is compared between the measured and theoretical cone angles, and the accuracy of computational results is discussed.

EXPERIMENTAL PROGRAM

In this study, the experimental data performed by Jeon et al. (2023) is utilized to compare the computational results with the experimental results. The brief description on the experimental program is explained in this section.

Materials

The concrete was mixed with water to cement ratio (w/c) of 42.5 % corresponding design strength of 40 MPa. For the workability, a superplasticizer was applied. Table 1 shows the mixing proportions of this study. The anchor steel bar has the nominal yield strength of 500 MPa (SD500), while the anchor head is fabricated with SS275.

Table 1: Mixing proportions.

w/c (%)	S/a (%)	Air (%)	Unit weight (kg/m^3)				
			Water	Cement	Sand	Gravel	Admixtures*
42.5	47	4.0	170	400	810	914	3.2 (0.8%)

* Superplasticizer

Fabrication and Test of the Specimens

Concrete anchor specimens were fabricated using plain concrete blocks measuring 600 × 600 × 200 mm. Holes are spaced 100 mm apart for securing the specimens to the testing machine. Anchor steel was positioned at the center of the concrete block with embedment lengths of 70 mm. The circular anchor had a diameter of 50 mm, and the anchor steel had a diameter of 16 mm. To vertically align the anchor steel, a steel bar extended from the circular anchor to the bottom of the anchor block. To prevent mechanical friction around the extension during pull-out loading, plastic bubble wrapping was applied. Figure 1 illustrates the geometry. The number of specimens was two. A tensile preload of 1.0 kN was imposed through the hydraulic actuator, followed by the application of force under displacement control at a rate of 0.02 mm/min. The force applied and the displacement of the anchor block were measured. To address potential slip between the anchor steel bar, the digital image correlation (DIC) method (Sutton et al., 1986) was employed. Random speckle pattern in relation with a quality measure (Park et al., 2017) was generated on the steel bar to evaluate the displacement of the anchor steel bar.

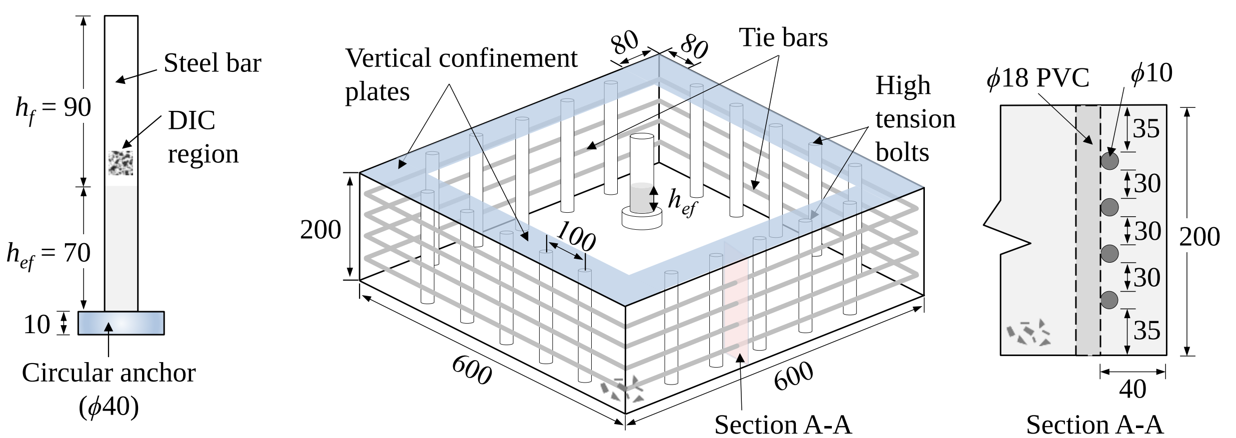

Figure 1. Geometry of the anchor specimens (mm in unit)

To assess the fracture energy of plain concrete, a three-point bending (TPB) beams were fabricated and three samples were tested using a universal testing machine (UTM) with the 250 kN capacity. The dimensions of the concrete beam were 700 × 150 × 80 mm, with an initial notch length (a_0) of 50 mm and a span (s) to depth ratio (D) of 4, as illustrated in Figure 2. A Crack Opening Displacement (COD) gauge was positioned at the notch between two knife wedges, and an initial preload of 0.5 kN was applied. The load was applied under closed-loop control with a COD rate of 0.05 mm/min. Additionally, six numbers of cylindrical specimens were fabricated to measure the compressive strength, indirect tensile strength, and elastic modulus of the concrete.

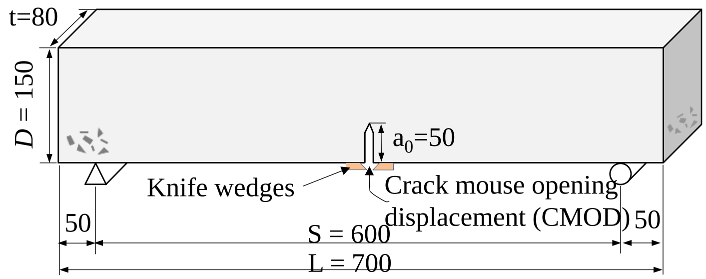

Figure 2. Geometry of the anchor specimens (mm in unit).

COHESIVE ZONE-BASED FINITE ELEMENT MODELLING

For the anchor pull-out analysis, an axis-symmetric condition is employed, as depicted in Figure 3. The concrete material is treated as linear elastic, and the cohesive zone model captures the nonlinear anchor failure process of concrete. The failure domain is discretized into linear rectangular continuum elements, while four-node cohesive surface elements are inserted along the potential failure angle, i.e., measured angle of 26.2°, and theoretical angle of 35°. Concerning the bonding between concrete and the anchor head, no resistance is assumed on the bottom and side surfaces of the anchor head. The anchor steel bar and head are described by a bilinear elasto-plastic model with the yield strengths of 554 MPa and 265 MPa, respectively. The finite element mesh has17,412 elements and 17,813 nodes.

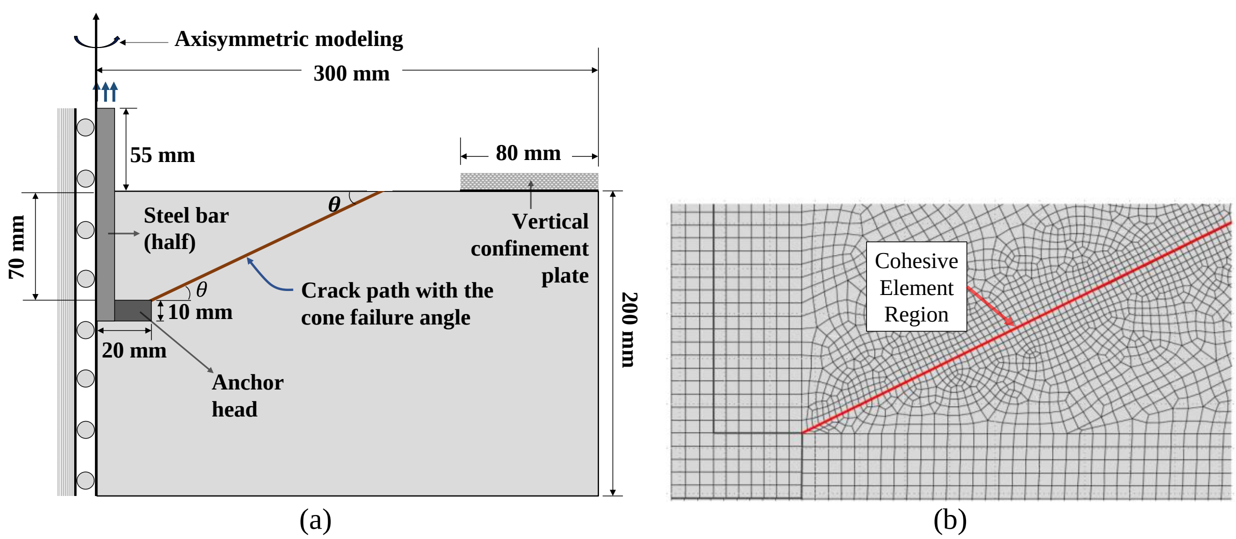

Figure 3. FE analysis modelling:(a) Geometry and boundary conditions and (b) Finite element mesh with cohesive zone modelling.

COMPUTATIONAL RESULTS

The finite element analysis results are compared with the experimental test result, as shown in Figure 4. Both cases of the failure angle provide the good agreement with the pull-out strength of the experimental result. The result based on the measured cone angle exhibits the hardening behavior, which captures the experimental responses, while the result using the theoretical cone angle results in the softening behavior in the load-displacement relations.

Additionally, the pull-out strength is compared with the nominal strength (N_{cb}) specified in the design codes of ACI-318 (2019). For the case involving cast-in anchors and normal strength concrete, the design equation is provided when the minimum edge distance exceeds the critical edge length, i.e., $c(a_{min}) > 1.5\, h_{ef}$. The nominal strength is given as

$$N_{cb} = 12.5\sqrt{f_c'}{h_{ef}}^{1.5} \tag{6}$$

where f_c' is the compressive strength of concrete, and the units of N_{cb}, f_c', and h_{ef} are N, MPa, and mm, respectively. The estimated nominal pull-out strength is 51.1 kN, which is significantly lower than the measured strength. This is because the design equation provides a conservative pull-out strength. It is evident that this is due to the highly uncertain behavior of pull-out failure.

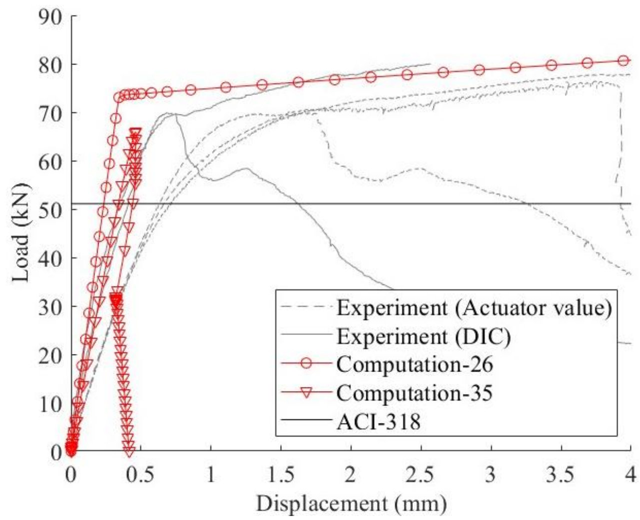

Figure 4. Experimental and computational analysis results for the cone angle of 26° and 35°

CONCLUSION

For more accurate prediction of pull-out failure, a cohesive zone-based finite element analysis is employed. The computational framework can simulate crack propagation of concrete around the headed anchor while capturing the pull-out strength and post-peak load behaviors. The computational results demonstrate that a potential crack path (i.e., cone failure angle) can significantly affects the load-displacement responses. Furthermore, in this study, the design expression significantly underestimates the pull-out strength because it does not directly account for the fracture resistance.

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