Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7-8, 2026

Development of a Large-scale Test Program for Investigating Concrete Breakout Strength in Deeply Embedded Anchors

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***Keywords :** cast-in-place anchor, concrete breakout strength, capacity of anchor, seismic fragility, deeply embedded anchor

1. Introduction

In Korean nuclear power plants (NPPs), most safety-related equipment is anchored to the concrete basemat using cast-in-place (CIP) anchor bolts. Under seismic loading, failure of the anchorage system is more frequently observed than failure of the equipment itself. Compared with steel anchor failure, concrete-related failure modes—particularly concrete breakout—exhibit significantly greater uncertainty due to material variability and complex stress distributions.

Current prediction models for the concrete breakout strength of anchors are primarily based on experimental databases. However, available test data are limited for deeply embedded anchors, especially for embedment depths exceeding 25 inches. Such deep embedments are commonly used for heavy safety-related equipment, including emergency diesel generators (EDGs), pumps, and storage tanks in NPPs.

Given the scarcity of experimental data in this embedment range, additional large-scale testing is necessary to improve the reliability of strength predictions, develop refined predictive models for deeply embedded anchors, and evaluate their seismic margin.

This paper presents the development of a large-scale experimental test program aimed at investigating the concrete breakout strength of deeply embedded CIP anchors. The specimen design and experimental setup are described in detail. The experimental results obtained from this program will be reported in future work.

2. Test Program

The anchor and concrete block were designed to experimentally investigate the concrete breakout strength of a deeply embedded CIP anchor subjected to monotonic tensile loading.

2.1 Anchor

Fig. 1 illustrates the configuration of the anchor. The anchor diameter D and the embedment depth h_{ef} were designed as 8.26 cm (3.25 in.) and 76.2 cm (30 in.), respectively. The diameter d and thickness t of the anchor head plate are 16.52 cm (6.5 in.) and 8.26 cm (3.25 in.), respectively. The embedment depth 76.2 cm (30 in.) was selected as the maximum feasible depth considering the loading capacity and geometric constraints of the test facility. The anchor material was specified as ASTM A193 Grade B7, with a nominal yield strength of 655 MPa and an ultimate tensile strength of 795 MPa.

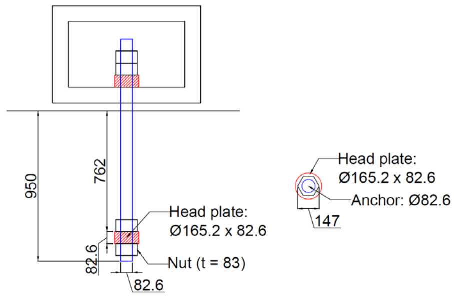

Fig. 1. Configuration of the anchor

The nominal steel tensile strength of the anchor, N_{sa}, is calculated using Eq. (1) in accordance with ACI 349 provisions [1].

$$N_{sa} = A_{se,N} f_{uta} = \frac{\pi \times 82.6^2}{4} \times 795 = 4258 \text{ kN} \quad (1)$$

where $A_{se,N}$ is the effective cross-sectional area of a single anchor in tension, and f_{uta} is the ultimate tensile strength of anchor.

The nominal pullout strength of the anchor, N_p, governed by bearing of the head against the concrete, is calculated as Eq. (2) [1].

$$N_p = 8 A_{brg} f'_c = 8 \times \frac{\pi \times 165.2^2}{4} \times 27 = 4627 \text{ kN} \quad (2)$$

where A_{brg} is the net bearing area of the head of anchor bolt and f'_c is the specified compressive strength of concrete.

2.2 Concrete block

The specified compressive strength of concrete was designed as 27 MPa (4000 psi), which is typically used for nuclear power plant (NPP) basemat structures.

Based on the compressive strength and embedment depth, the nominal concrete breakout strength in tension, N_{cb}, can be estimated using Eq. (3) [2].

$$N_{cb} = 4.4 f_c'^{3/4} h_{ef}^{1.6} = 2240 \text{ kN} \quad (3)$$

The predicted concrete breakout strength is smaller than both the nominal steel strength and the pullout strength. Therefore, the expected governing failure mode is concrete breakout.

ASTM E488-22 [3] specifies standard test methods for determining the strength of anchors in concrete elements. According to ASTM E488-22, the minimum required clear distance from the anchor to the test support for tension loading is $2h_{ef}$, and the test member thickness shall be at least $1.5\,h_{ef}$. Accordingly, the specimen dimensions were determined to satisfy these requirements. Minimum reinforcement was provided to control thermal and shrinkage cracking without significantly influencing the breakout behavior. Fig. 2 shows the configuration of the concrete block specimen.

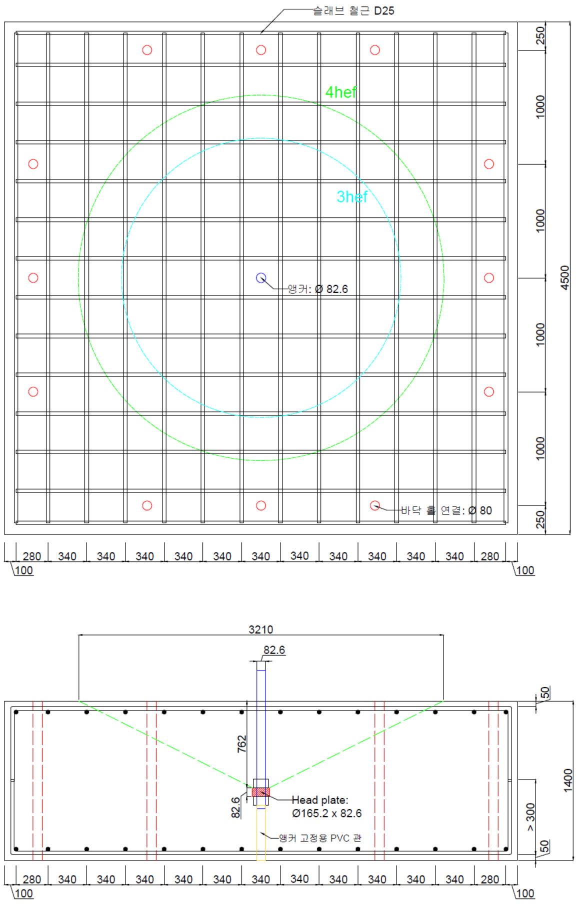

Fig. 2. Configuration of the concrete block specimen

In addition, flexural stresses induced by the self-weight of the specimen during lifting and transportation were evaluated. The connection between the specimen and the strong floor of the test facility was also verified to ensure adequate stability and safety during testing.

2.3 Instrumentation and Material Testing

Fig.3 presents the instrumentation plan for measuring the displacement and strain of the anchor during testing. Two linear variable differential transformers (LVDTs) were installed to measure axial displacement, and strain gauges were attached to the anchor shank to monitor strain development under tensile loading.

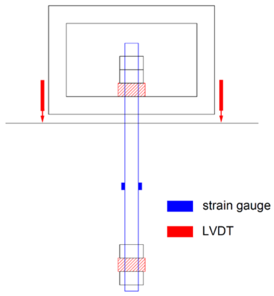

Fig. 3. Instrumentation plan for displacement and strain measurement

The compressive and tensile strengths of concrete were measured using standard cylinder specimens at various curing ages. In addition, after completion of the anchor test, core samples were extracted from six locations of the test specimen, as shown in Fig.4, to determine the in-situ compressive strength of the concrete.

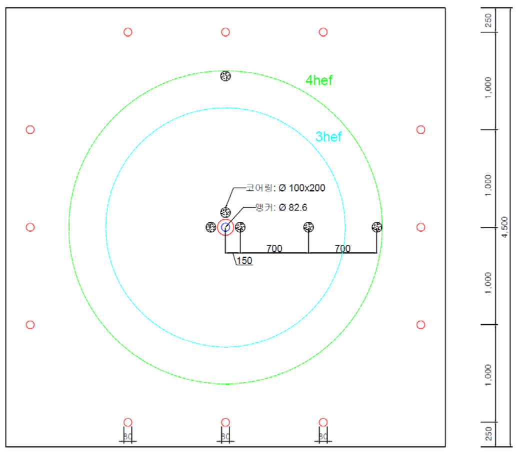

Fig. 4. Coring locations for compressive strength measurement

3. Conclusions

A large-scale test specimen consisting of a deeply embedded CIP anchor and a concrete block was designed to investigate the concrete breakout strength under tensile loading. The specimen dimensions and reinforcement details were determined in accordance with ACI 349, EPRI 3002012994 and ASTM E488-22 requirements to ensure that concrete breakout would govern the failure mode.

Given the large size and weight of the specimen, special considerations were taken in the design stage to prevent potential issues related to fabrication, handling, transportation, and installation. Structural checks were performed to ensure safety during lifting and testing.

The experimental results to be obtained from this test program will be presented in a subsequent paper. The findings are expected to contribute to improving prediction models for deeply embedded CIP anchors and to provide fundamental data for seismic fragility of safety-related equipment in nuclear power plants.

REFERENCES

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