An experimental study on the tensile concrete breakout capacity of deeply embedded cast-in-place anchors for equipment in nuclear power plant

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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 an experimental study on the tensile concrete breakout capacity of deeply embedded CIP anchors for equipment in NPPs. The test plan and results are described in detail. A preliminary modification of the prediction model is proposed, which will be further refined in future work through analytical parametric studies.

2. Test Plan

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.

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 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.

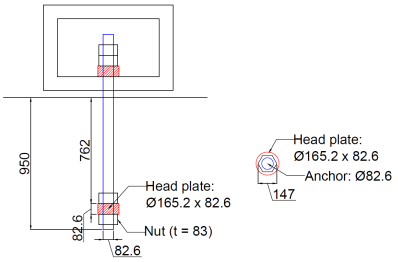


Fig. 1. Configuration of the anchor

The dimensions of concrete block in which the anchor is embedded were determined to satisfy the requirements of ASTM E488-22 [1]. 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 $1.5h_{ef}$. Fig. 2 shows the configuration of the concrete block specimen.

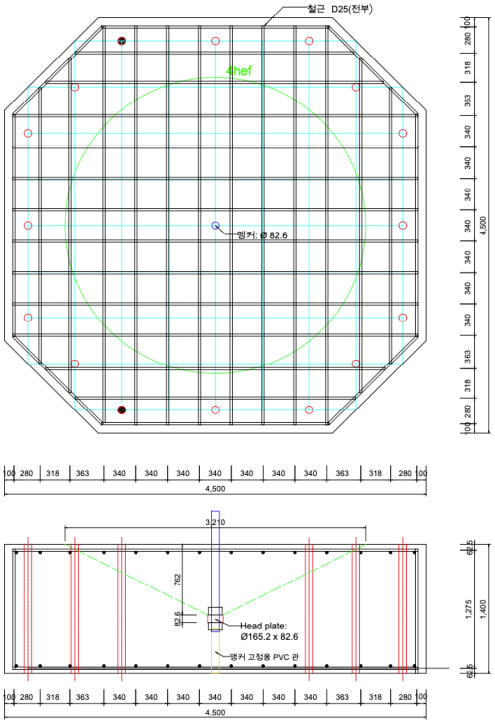


Fig. 2. Configuration of the concrete block specimen

3. Test Results

Fig. 3 illustrates the test setup and the condition of the specimens during and after loading. While circular surface cracks were clearly visible, the full concrete breakout cone could not be observed due to the presence of surface reinforcement.



Fig. 3. A specimen during and after the experiment

Table 1 summarizes the experimental concrete breakout strengths alongside the predicted values, calculated based on the concrete compressive strength at the time of testing. The predicted concrete breakout strength in tension, N_P, was estimated using Equation (1), as suggested in EPRI 3002012994 [2].

$$N_P = 4.4 f_c'^{3/4} h_{ef}^{1.6} \text{ (lb)} \quad (1)$$

where f_c' is the compressive strength of the concrete (in psi), and h_{ef} is the effective embedment depth of the anchor (in inches).

Table 1 Concrete breakout strength of CIP anchors installed in uncracked concrete

Test No.	f_c' (MPa)	Test, N_T (kN)	Prediction, N_P (kN)	Test/Prediction (N_T / N_P)
#1	33.8	3,059	2,647	1.155
#2	36.6	3,186	2,812	1.133
#3	36.6	3,615	2,812	1.276

As shown in the table, the experimental strengths exceeded the predicted values by 13% to 28%. Consequently, this indicates that the current predictive models yield conservative estimates for deeply embedded CIP anchors.

4. Modification of Prediction Model

Table 2 summarizes the experimental results compiled from the literature for anchors with deep embedment depths. By combining the data from Tables 1 and 2, Equation (1) was modified using the test results for deep embedment depths (mostly 300 mm or greater), as illustrated in Figure 4. Additional data are currently being collected to further refine the prediction model, which will be updated in future work.

Table 2 Test results from the literature

f_c' (MPa)	h_{ef} (mm)	N_T (kN)	Reference
26.1	316	490.5	KAERI M30 [3]
		522.5	
		515.2	
		524.2	
32.2	200	325.9	KAERI pilot [4]
		304.4	
37.7	300	621.9	
		629.7	
34.2	400	1012.9	
		980.7	
32.2	635	1982.1	Lee et al. [5]
37.7		2097.8	
38.0		2232.6	
39.8		2367.3	
36.7	889	3145.8	
36.2		3249.0	
35.7		3249.9	
32.2		3313.0	
37.6	1143	5008.7	
36.0		5417.9	
36.6		5595.9	
36.9		5689.3	

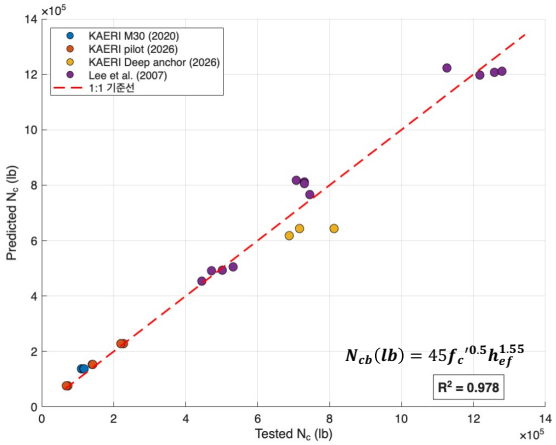


Fig. 4. Comparison of tested and predicted concrete breakout strengths using the modified model equation

5. Conclusion

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 experimental strengths exceeded the predicted values, which indicates that the current predictive models yield conservative estimates for deeply embedded CIP anchors. Therefore, a preliminary modified model was proposed through regression analysis using the test results from this research and data from the literature for anchors with deep embedment depths. In future work, additional test data and analytical

results will be collected to further update the model equation.

The findings of this research are expected to contribute to improving prediction models for deeply embedded CIP anchors and to provide fundamental data for evaluating the seismic fragility of safety-related equipment in nuclear power plants.

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