Experimental Evaluation of Tensile Capacity and Ductility in Cast-in-Place Anchors with Anchor Reinforcement

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1. Introduction

In nuclear power plants, anchors connecting safety-related equipment to concrete structures play a critical role in maintaining structural integrity and seismic safety. Under tensile loading, the load-carrying capacity of these anchors is frequently governed by concrete breakout failure, which typically exhibits a sudden and brittle response. Numerous experimental studies have established that the inclusion of anchor reinforcement contributes significantly to enhancing the tensile capacity of concrete anchors. Furthermore, if the anchor reinforcement is properly engaged to resist sufficient tensile load, the inherent ductility of the steel rebar itself can also be effectively utilized to prevent abrupt collapse. However, these beneficial effects on tensile capacity and ductility enhancement are not explicitly incorporated into current design codes, often resulting in overly conservative evaluations. To address these limitations, this experimental study investigated the tensile behavior of cast-in-place anchors provided with anchor reinforcement, aiming to analyze their tensile capacity and ductility characteristics.

2. Test Plan

Table 1 summarizes the key test parameters of the anchor tensile tests planned in this study. The primary variables include the anchor embedment depth (h_{ef}), the diameter of the anchor reinforcement (d_{ar}), the distance between the anchor and the anchor reinforcement (s_{ar}), and the number of legs of the anchor reinforcement (n_{ar}).

The anchor embedment depths are set to 200, 300, and 400 mm, designated as the H2, H3, and H4 series, respectively. The anchor reinforcement diameters are planned to be 13, 16, 19, and 22 mm. The spacing between the anchor and the anchor reinforcement is designed to be 100, 150, 200, and 300 mm. While the standard number of anchor reinforcement legs is set to four, six legs are incorporated specifically for the H3-D19-S100-N6 and H4-D22-S100-N6 specimens.

The target compressive strength of concrete is planned to be 30 MPa. To ensure concrete breakout

Table I: Test Variables

Specimen	Embedment depth (h_{ef}) [mm]	Anchor reinforcement		
		Bar size	Distance from anchor (s_{ar}) [mm]	Number of legs (n_{ar})
H2-D0	200	-	-	-
H2-D13-S100		D13	100	4
H2-D16-S100		D16	100	4
H2-D16-S150		D16	150	4
H2-D16-S200		D16	200	4
H2-D19-S100		D19	100	4
H3-D0	300	-	-	-
H3-D16-S100		D16	100	4
H3-D19-S100		D19	100	4
H3-D19-S150		D19	150	4
H3-D19-S200		D19	200	4
H3-D19-S300		D19	300	4
H3-D19-S100-N6		D19	100	6
H3-D22-S100		D22	100	4
H4-D0	400	-	-	-
H4-D19-S100		D19	100	4
H4-D19-S200		D19	200	4
H4-D22-S100		D22	100	4
H4-D22-S100-N6		D22	100	6

failure rather than anchor tensile failure during testing, high-strength anchor steel with nominal yield and ultimate strengths of 720 MPa and 860 MPa, respectively, will be used. The anchor diameters are planned to be 44.5 mm, 57.2 mm, and 63.5 mm for the H2, H3, and H4 series, respectively. To prevent pullout failure, a circular anchor head will be installed at the embedded end of the anchor, with head diameters of 100 mm, 120 mm, and 130 mm for the H2, H3, and H4 series, respectively. Grade SD400 rebar was used for the anchor reinforcement, with measured yield strengths ranging from 430.4 to 511.5 MPa depending on the rebar diameter.

3. Test Results

3.1 Load-displacement curves

Figure 1 shows the load-displacement curves of the H2 series specimens. The plain specimen without anchor reinforcement, H2-D0, exhibited an average peak load of 426.1 kN. In contrast, the specimens reinforced with anchor reinforcement demonstrated an increased peak load ranging from 591.4 to 639.1 kN—representing a 38.8% to 50.0% increase compared to H2-D0—with the exception of H2-D16-S200, which had a distance of 200 mm between the anchor and the anchor reinforcement. For the H2-D16-S200 specimen, the peak load was 464.9 kN, reaching 109.1% of the capacity observed in H2-D0 (a 9.1% increase). This

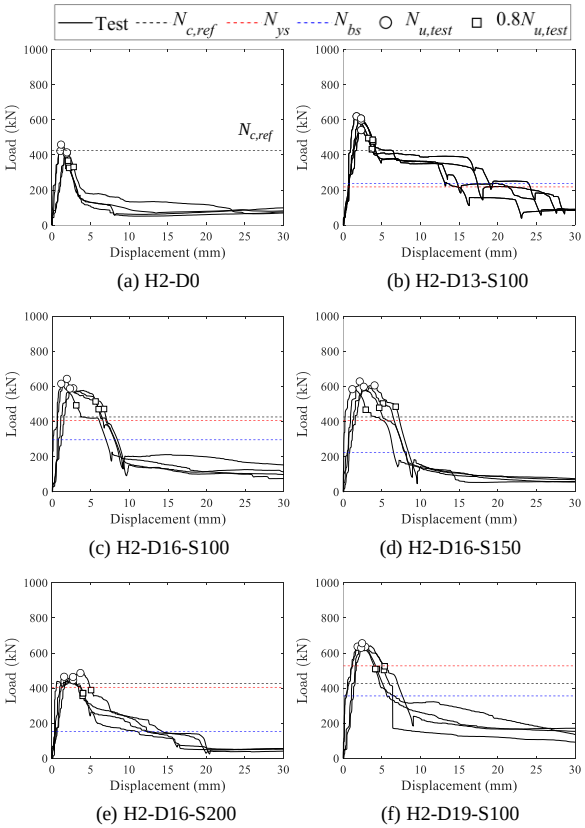


Fig. 1. Load-displacement curves for the H2 series specimens

trend was similarly observed in both the H3 and H4 series.

Furthermore, in the absence of anchor reinforcement, a brittle concrete breakout failure occurred, accompanied by a rapid decrease in load. Conversely, when anchor reinforcement was provided, the rate of load degradation post-peak load slowed significantly, demonstrating a noticeable enhancement in ductile behavior.

3.2 Ductility

To analyze the contribution of anchor reinforcement to ductility, the ductility factor was calculated based on the load-displacement curves. Figure 2 illustrates the evaluation concept for the displacement ductility factor (μ_Δ). Following the equivalent elastoplastic approach proposed by Park (1989), the displacement ductility factor (μ_Δ) was calculated as the ratio of the ultimate displacement (Δ_u) to the yield displacement (Δ_y). Here, Δ_y was determined by extrapolating the secant stiffness at 75% of the peak load ($0.75N_{u,test}$) to the peak load level, and Δ_u was defined as the displacement corresponding to a post-peak load degradation to 80% of $N_{u,test}$.

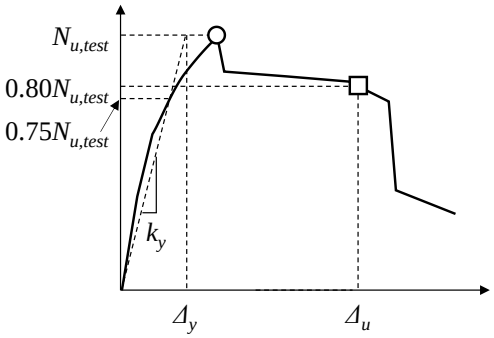


Fig. 2. Definition of displacement ductility factor based on equivalent elastoplastic approach (adapted from Park, 1989)

Figure 3 shows box plots of the displacement ductility factors for the H2 and H3 series specimens. Within identical test variables, the four repeated specimens exhibited relatively high variability in ductility. Nevertheless, the specimens provided with anchor reinforcement clearly exhibited larger ductility factors compared to the unreinforced D0 series.

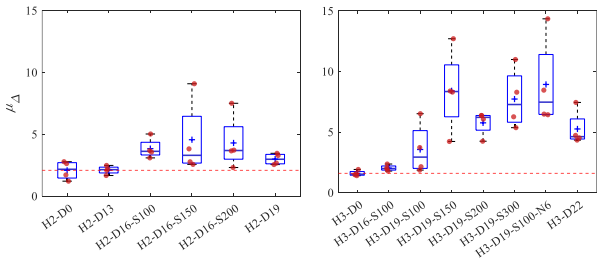


Fig. 3. Distribution of displacement ductility factors for H2 and H3 series specimens

4. Conclusions

In this study, an experimental investigation was performed to evaluate the tensile behavior of cast-in-place anchors provided with anchor reinforcement. While plain anchor specimens without reinforcement exhibited sudden, brittle concrete breakout failure with a rapid post-peak load drop, the inclusion of anchor reinforcement significantly slowed post-peak load degradation, demonstrating a clear transition toward ductile structural behavior. Furthermore, the provision of anchor reinforcement effectively increased the peak tensile capacity compared to unreinforced specimens across all test series. Overall, the test results confirm that anchor reinforcement not only enhances tensile capacity but also effectively mitigates brittle breakout failure by imparting substantial structural ductility.

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