Finite Element Modeling and Sensitivity Analysis of Head-Plated M30 CIP Anchor for Nuclear Power Plants

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1. Introduction

Safety-related equipment in nuclear power plants (NPPs), must maintain their functional integrity under seismic loading conditions. Cast-in-place (CIP) anchors with head plates are widely adopted to secure such equipment to concrete foundations in NPPs [1].While the Concrete Capacity Design (CCD) methodology in ACI 349-13 provides a widely accepted framework for estimating concrete breakout strength, it characterizes anchor capacity primarily as a function of embedment depth [2]. The influence of head plate geometry on local stress distribution, confinement, and crack propagation beneath the anchor head is not explicitly incorporated as an independent design variable. As a result, the degree to which CCD predictions align with actual behavior of head-plated CIP anchors remains a subject warranting further numerical investigation.In this study, a three-dimensional finite element (FE) model is developed for a head-plated M30 CIP anchor installed in the ESW pump system foundation of an NPP. The Concrete Damage Plasticity (CDP) model is employed to capture crack initiation, damage evolution, and post-peak softening behavior of concrete [3,4]. A systematic sensitivity analysis covering mesh size, dilation angle, compressive recovery factor, and tension softening index is conducted to identify optimal model parameters. The validated model serves as the foundation for a subsequent probabilistic investigation of failure mode transition under material uncertainty and varying embedment depths.

2. FE Modeling of Head-Plated M30 CIP Anchor

A 1/4 symmetric FE model was developed in ABAQUS to reduce computational cost while maintaining accuracy. The model consists of a concrete block (1,400 × 1,400 × 500 mm), the M30 anchor (diameter 30 mm, embedment depth 316 mm), and a square head plate (120 × 120 × 12 mm). Symmetry boundary conditions were applied along the two orthogonal symmetry planes, and the bottom surface was fully fixed. Tensile loading was applied via vertical displacement at the top of the anchor. Surface-to-surface contact was employed with a Coulomb friction coefficient of 0.4 and soft contact formulation in the normal direction to simulate progressive contact engagement beneath the head plate.

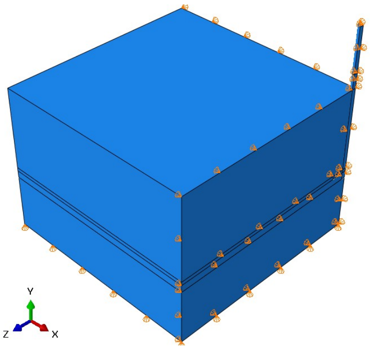


Fig. 1. FE model of head-plated M30 CIP anchor and boundary conditions.

3. Sensitivity Analysis and Validation

3.1 Mesh Size

Element sizes ranging from 14 mm to 24 mm were evaluated. As the mesh was refined, the peak tensile strength decreased and converged once the element size reached 18 mm or smaller, with differences among 20, 18, 16, and 14 mm meshes within approximately 1%. Accordingly, an element size of 18 mm was selected as the optimal mesh size balancing accuracy and computational efficiency.

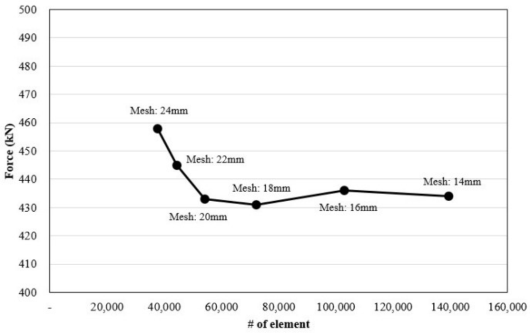


Fig. 2. Mesh sensitivity.

3.2 Dilation Angle

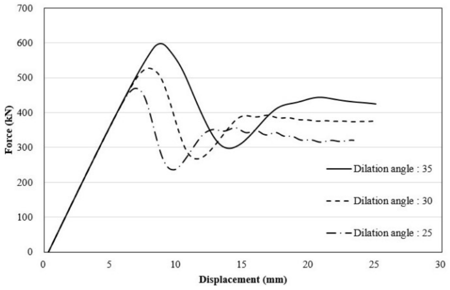
Analyses were performed with dilation angles of 25°, 30°, and 35°. Increasing the dilation angle produced a noticeable increase in peak tensile strength due to enhanced plastic volumetric expansion and shear transfer capacity, while the initial stiffness showed limited sensitivity. The dilation angle governs the dilatancy behavior of concrete during post-yield deformation and was calibrated against the experimental response.

3.3 Compressive Recovery Factor

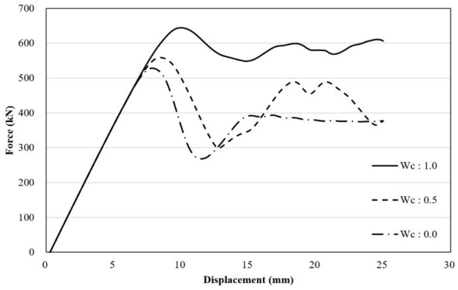
The compressive recovery factor wc (0.0, 0.5, 1.0) governs stiffness recovery after crack closure. Higher values of wc produced greater peak strength and elevated post-peak load levels, attributed to enhanced compressive stiffness recovery that prolongs the bearing effect beneath the head plate. Both peak and residual load increased as wc increased from 0.0 to 1.0.

3.4 Tension Softening Index

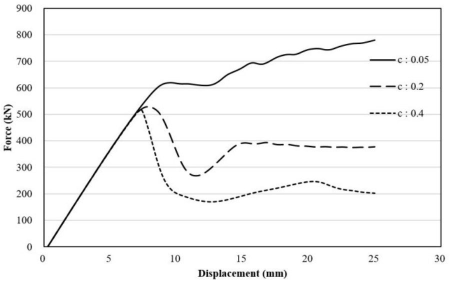
The tension softening index c in the Izumo model (0.05, 0.2, 0.4) controls post-cracking energy dissipation [5]. A higher value (c = 0.4) yielded a more brittle response due to steeper softening, while a lower value (c = 0.05) resulted in an unrealistically ductile response. The intermediate value c = 0.2 best reproduced the experimentally observed breakout behavior.



(a) Dilation anlge



(b) Compressive resovery factor



(c) Tension softening index

Fig. 3. Effect of parameters on load–displacement response.

3.5 Validation

Based on the sensitivity study, the final CDP parameter set was selected as: dilation angle 27°, compressive recovery factor wc = 0.0. Fig. 4 compares the FE and experimental load–displacement responses. A marginal discrepancy of approximately 1.6% was observed between the FE-predicted peak load (483 kN) and the experimental result (491 kN), demonstrating the model's high fidelity in capturing the maximum concrete breakout capacity. The predicted tensile damage initiates near the anchor head and propagates toward the concrete surface, consistent with the experimentally observed breakout cone failure pattern as shown in Fig. 5.

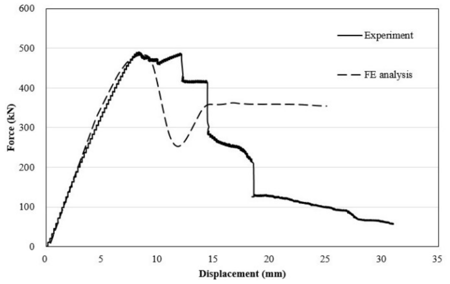
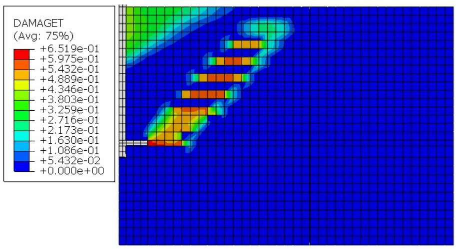
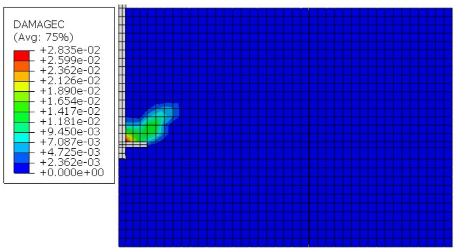


Fig. 4. Comparison of load–displacement response: FE analysis vs. Experiment.



(a) Tensile damage



(b) Compressive damage

Fig. 5. Damage results

5. Conclusions

This study developed and validated a high-fidelity 3D FE model for a head-plated M30 CIP anchor in an NPP ESW pump system. A comprehensive sensitivity analysis of CDP parameters—mesh size, dilation angle, compressive recovery factor, and tension softening index—was conducted to ensure reliable model calibration. The validated model (peak load error: 1.6%) accurately captures the concrete breakout failure mechanism, with tensile damage propagating from the anchor head to the concrete surface consistent with experimental observations. The calibrated model provides a reliable basis for subsequent probabilistic analysis of failure mode transition under material uncertainty and varying embedment depths.

Acknowledgments

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