Review of Failure Mechanism of Tensile Anchors in Concrete

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1. Introduction

Various types of anchors are widely used in fastening the equipment and pipe to transfer tensile and shear load into concrete structures of nuclear power plant. Except for the torque-controlled expansion anchors, failures of them including cast-in-place (CIP) anchor produce a concrete cone with the slope of around 35 degrees from its head edge to concrete surface. As the tensile load increases, circumferential cracking starts first at the anchor head edge and progresses stably towards the concrete surface. The concrete crack is growing under mixed failure mode conditions, therefore the load bearing capacity of the anchors closely depends on the fracture properties of concrete. For reference, the load bearing capacity of the expansion anchors depends on the internal and external friction of anchors, but the failure mechanism is judged to be similar to that of the CIP anchors.

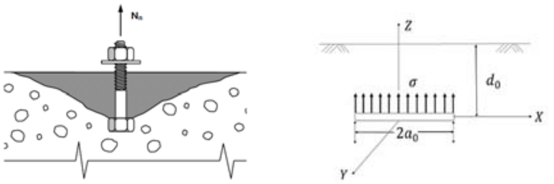
In nuclear power plant, medium and large-sized anchors with an embedment depth of over 50 mm are widely used, and their bearing load capacity is determined by the fracture properties of concrete. It has also been clearly demonstrated through a number of experimental and numerical research results that there is a size effect in the failure load of the anchors embedded into concrete.

In this study, the bearing load capacity of the headed anchor is reviewed by the linear elastic fracture mechanics (LEFM) and the numerical analysis approaches.

2. Theoretical Background

When an external force acts on an anchor bolt, the load generates a uniformly distributed reaction force on the upper surface of anchor head. As the load increases, concrete cracking at the anchor head edge starts and progresses in a stable manner towards the concrete surface. Eligehausen et al. (1989) derives the LEFM formula by idealizing an essential three-dimensional crack growth problem into a two-dimensional approximation. For the derivation, the anchor head in concrete is considered a half space containing a penny-shape cracks with a diameter of $2a_0$ and an effective depth of d_0 as shown in Fig. 1.

This penny-shape crack is propagated as the uniformly distributed load on the upper surface of anchor head is increased, and the stress intensity factors of K_I and K_{II} at the edge of the penny-shape crack are proposed by Zhukovskii (1982) and Karihaloo (1982) on the basis of LEFM. They represent a crack growth and propagation criteria; a crack under mixed mode condition of fracture mode I and mode II grows when $K_I = \sqrt{EG_f}$ and it grows in the direction where the mode II component is zero (K_{II}=0).



(a) CIP anchor (b) Penny-shape crack

Fig. 1. Idealization of anchor in concrete

Elgehausen et al. (1993) show that the bearing load capacity of anchor can be predicted by the formula derived on the basis of LEFM. Eq. (1) reflects the size effect of concrete fracture based on the LEFM theory according to the embedment depth of anchors.

$$\text{Fu} = a_1\sqrt{EG_f}d^{3/2} \tag{1}$$

Except for very shallow depths of embedment of d_0/a_0 equal and less than 5, the value of a_1 is approximately 0.617. An equivalent formula based on LEFM is presented in ACI 349 appendix B (2001).

3. Numerical Analysis

Numerical analysis of anchor is performed using MASA3 program which consists of microplane fracture model and crack band theory. All the inelastic behavior is characterized on the microplane by the stress-strain boundary, and it is possible to localize strain to simulate tension, compression and shear failures as a discontinuous function in smeared crack model. Therefore, this fracture model is a useful for idealizing the interface elements between anchor bolt and concrete block under fracture modes I, II and III.

The crack band model is based on the theory that the inelastic strain in uniaxial behavior localizes into a single element which depends on its length, and in three dimension, inelastic strain in general localizes into a band of elements running across the mesh. Therefore, a numerical analysis result is greatly affected by the size of the element of the finite element model, and the effect can be eliminated by introducing the tensile failure energy of concrete (G_f) into the continuum equation. The tensile and compressive fracture energies are defined as Eq. (2) and Eq. (3). In general, the compressive fracture energy is 100 times the tensile fracture energy.

$$G_f = A_f\,h = constant \tag{2}$$

$$G_C = A_{fC}\,h = constant \tag{3}$$

Where, A_f and A_{fC} represent the area of uniaxial tension curves in tension and compression, respectively, and h represents an average size of element related to crack band.

In this study, tensile fracture simulations of anchor in concrete are performed on seven types of small anchor mainly used in nuclear power plant such as Table 1, and the analysis results are compared with the calculated load bearing capacities using Eq. (1) and equation of ACI 349 appendix B (2001).

Table 1. Outline of anchors

Designation	Stud Product (in.)				d_o/a_o in Eq. (1)
	Shank		Head		
	Dia.	Length	Dia.	Height	
T44	1/2	3.69	1	0.312	7.38
T46	1/2	5.69	1	0.312	11.38
T48	1/2	7.69	1	0.312	11.38
T58	5/8	7.69	1.25	0.312	11.38
T68	3/4	7.63	1.25	0.375	12.21
T78	7/8	7.63	1.375	0.375	12.21
T86	1	5.63	1.625	0.5	6.93

Fig. 2 shows a typical 1/4 symmetric finite element model combined with anchor shank, interface element, and concrete block element. And the analysis is performed with a displacement control of 0.05 mm/step.

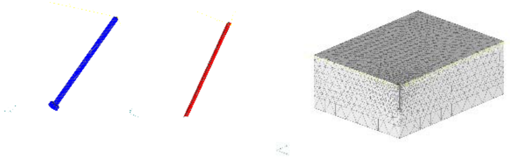


Fig. 2. Finite element model for anchor I concrete

4. Comparison Results and Summary

Fig. 3 shows strain contours at the peak load bearing capacity and the post-peak load behavior. As shown in the figures, the angle of propagated concrete crack is roughly measured to be in the range of 30 to 40 degrees. The peak load bearing capacity appears at the moment when the concrete crack starts near the anchor head, and the load gradually decreases as the concrete crack progressed to the concrete surface.

The relationship between load and displacement at anchor is shown in Fig. 4. The slope of curve depends on the combined effect of anchor stiffness and concrete damage level, and the load bearing capacity increases gradually as the effective embedment length increase, while the ratio of increment is not a linear relationship. This phenomenon means that the size effect of concrete fracture appears according to the embedding depth.

Table 2 represents comparison results of the peak load according to the finite element analysis, the fracture mechanics-based theoretical equation(Eq.1), and the design specification in ACI 349. The ratio of the bearing load capacity shows that the results of the fracture analysis and Eq. (1) calculation are similar, but the ACI 349 design criteria represents considerable safety conservatism. Although not covered in this study, these results needs to be referred to anchors to which the performance-based design method is applied.

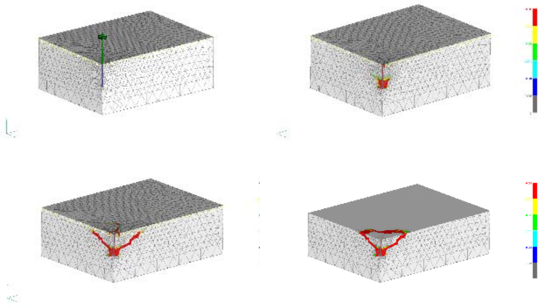


Fig. 3. Strain contours with increasing anchor load

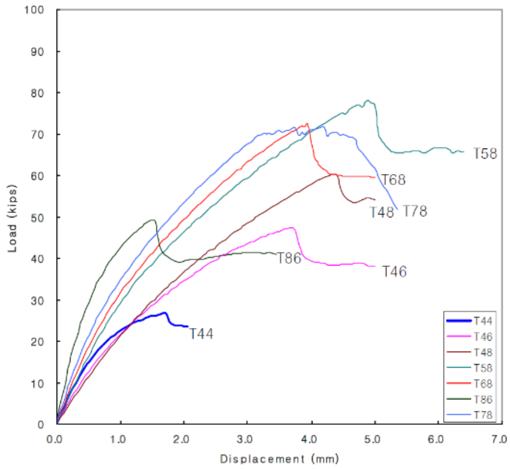


Fig. 4. Load-displacement relationships of anchor

Table 2. Comparison results of the capacity of anchors

Designation	FEM(a)	LEFM(b)	ACI349(c)	a/b	a/c
T44	26.8	24.3	15.7	1.10	1.7
T46	47.3	46.5	28.9	1.01	1.6
T48	60.2	73.1	44.5	0.82	1.4
T58	78.1	73.1	44.5	1.06	1.8
T68	72.5	72.1	44.5	1.01	1.6
T78	71.6	72.1	44.5	0.99	1.6
T86	49.3	45.5	28.9	1.08	1.7

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