Failure Mechanism for Large-Sized Grouted Anchor Bolt under Tensile Load

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ABSTRACT

Non-shrinkage grouted anchor bolts were used to consider the constructibility in the Yonggwang Nuclear Power Plant. The pullout strength of bonded anchor is influenced by factors such as bond strength, concrete strength, grout strength, and pre-formed hole (block-out) size. Thus, the possible failure mode and pull-out strength of grouted anchor used in the above nuclear power plant should be explored for the practical prediction. In order to simulate the behavior of grouted anchor bolt in the Yonggwang Nuclear Power Plant, 5 mock-up test specimens were cast with the same conditions as the actual anchor bolt constructed in the tank foundation. A 2-1/2 inches diameter anchor bolt with 2 ft 2-3/8 inches embedded depth was used and preformed block-out for grout is introduced to evaluate the effect on the capacity of grouted anchor bolt.

Based on the mock-up test results, the bond strength was appeared to be greater than the required strength of the concrete. Thus, failure by pull-out test is to be governed by a combination of tension failure of the concrete resulting in a partial depth cone-shaped spall and bond failure at the grout concrete interface in the low portion of the block-out. The measured de-bonding length, de-bonding forces and pull-out strength are compared with the theoretical predictions of the analytical method and the values of design in accordance with ACI 349 code. To simulate such a structural behavior and failure mode of grouted anchor bolt, nonlinear finite element analysis of such a pullout is also performed. The predictions are compared with the mock-up test results and those from other research results. The nonlinear analysis code ABAQUS is used with the principle of fracture and contact failure mechanics.

INTRODUCTION

Grouted anchors are generally used when the loads are greater than can be carried by post-installed anchor or as replacements for post-installed anchors that could not be set properly or failed during load testing. Therefore, laboratory tests on grouting of anchor bolts have been performed for smaller sizes of bolt than 1-inch with the hole type of less than 3 inches [1]. A number of large sized grouted anchor bolts, however, are often adopted to make convenient at installation of large-sized tank foundations in nuclear power plant. For this purpose, the condensate storage tank of the Yonggwang Unit 5 and 6 used a large size of grouted anchor bolt of 2-1/2 inches diameter, 8-inches by 8-inches hole and 27 inches hole depth.

Since grouted anchors are required to transfer loads the same as cast-in-place anchors, the appropriate design and anchorage requirements for cast-in-place anchors are applicable. Especially, the anchor bolts used in the safety-related tank foundation are required to design per the requirements in ACI 349 Appendix-B[2]. However, grouts are frequently used their own characteristics and the pull-out strength of bonded anchor is influenced by factors such as bond strength, concrete strength, grout strength and pre-formed hole size. Also, the behavior of large sized grouted anchor bolt designed per the design procedure provided for small sized grouted anchorage may not be corresponded to test results. Therefore, the ACI 349 Appendix-B requires some tests to verify their required properties and load transfer capabilities between steel and grout or grout and concrete and so on.

The objective of this research was to explore the possible failure mode and pull-out strength of grouted anchor that was incorporated in condensate storage tank. To accomplish this objective, five specimens considering the same conditions as those actually installed were established at test site. To simulate such a structural behavior and failure mode of grouted anchor bolt, nonlinear finite element analysis of such pull-out test specimen was also performed. This paper presents the results of pull-out tests and comparative numerical analyses of grouted anchor bolt and provides a basis for safety of grouted anchors per the requirements defined in ACI 349 Appendix-B.

DESIGN BASIS OF GROUTED ANCHOR

The same mechanisms of failure as for cast-in-place anchor are usually incorporated in the design of grouted anchors under tensile loading except for bonding failure between the grout and concrete. Three major types of failure were generally reported under ultimate tensile loading: bolt failure, plug pull-out, and concrete cone failure[3]. The typical failure mechanism for a grouted anchor which does not exhibit bolt failure was known as a combination of tension failure of the concrete resulting in a partial depth cone-shaped spall and bond failure at the grout concrete interface in the low portion of the hole. Figure 1 shows schematically this type of failure mechanism considered in the design of condensate storage tank.

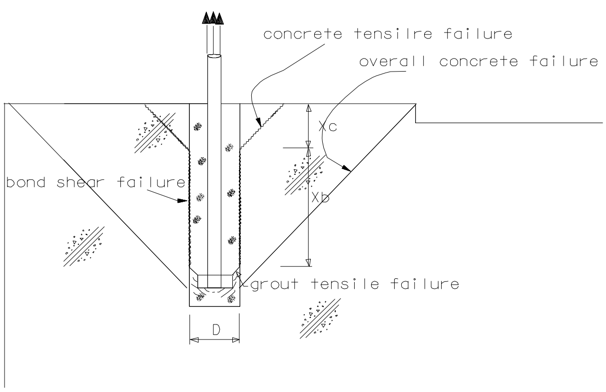


Figure 1 Possible failure mechanism of grouted anchor bolt

Figure 2 Pull-out mock-up test specimens

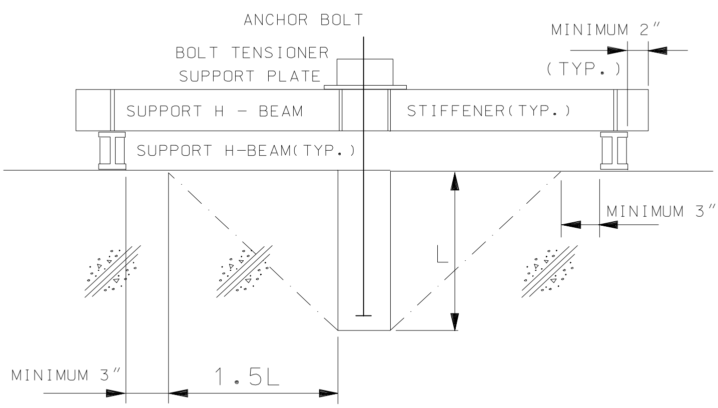
The procedure adopted in the construction of grouted anchor is: (1) block-outs are first pre-formed during concrete pouring construction, (2) insert anchor bolts adjusting to the field location of tank, and (3) finally fill non-shrinkage grout into block-out. A type of 2-1/2 inches ASTM A36 bolts embedded 27 inches was designed to install into concrete with a compressive strength of at least 4500psi. A commercial grout, Masterflow 870 Non-shrinkage Grout and a threaded anchor rod with an end nut were used. 77 grouted anchors of this type were circumferentially arranged at the bottom of condensate storage tank to resist the load transferred from the super-structure (circular tank) including fluid. In case that a combination of tension failure of the concrete resulting in a partial depth cone-shaped spall and bond failure at the grout concrete interface in the lower portion of the block governs the capacity of grouted anchor, the total design strength including bond strength, T_{bond} was calculated as:

$$T_{bond} = \left[(2X_c + D) - D^2 \right] f_t + 4 \cdot D \cdot U \cdot X_b \tag{1}$$

where variables X_c, D and X_b are as shown in Figure 1 and U is nominal bond strength per unit area. The pure portion of bond strength is second part of the above equation and the calculated value is 134.4 tons.

TEST PROGRAM

Pull-out mock-up tests on the grouted anchor threaded rod with an end nut were conducted to focus on the verification of grouted anchor per the ACI 349 Appendix-B. The values for all parameters including the embedment depth and size of block-out, anchor bolt diameter and concrete strength used in these tests are exactly same as those installed in the foundation of condensate storage tank. The apparatus for pullout testing of grouted anchor is schematically shown in Figure 3(a). Tensile loading was applied axially by means of a loading frame, hydraulic puller, and a hydraulic head as shown in Figure 3(b). The bearing reactions were located so that the reaction load was applied to the surrounding concrete at least 6 ft-8 inches away from the edge of block-out for grout being tested. This is to avoid overlap of the anticipated failure surface assuming an inclination between the failure surface and surface of the concrete member of about 35 degrees suggested from the concrete capacity design (CCD) approach.



(a) Schematic view of testing apparatus

(b) Photo of testing apparatus

Figure 3 Testing apparatus for pull-out tensile test

Specimen Preparation

A large concrete block shown in Figure 2 was constructed for these pull-out mock-up tests. The block was 3 ft deep with the same reinforcing arrangements as those installed in the foundation of condensate storage tank. The plan dimensions of the block was 36 ft by 5 ft 6 inches. Concrete with a specified minimum 28 day compressive strength of 4500 psi was used. The concrete strengths at the time of testing were generally greater than the specified minimum strength.

Twelve sets of block-out for non-shrinkage grout were made with 2 ft spacing the same as that in actual design to consider the effects of neighbored grouted block-out. Five of twelve sets were only installed anchor bolt with an appropriate spacing in a concrete block so that the assumed failure surface could develop without damaging to adjacent grouted anchors. The size of each block-out for grout is 8 inches by 8 inches with 2 ft 3 inches depth. All anchors for these results were 2-1/2 inches nominal diameter ASTM A36 threaded rod with an end nut. The embedment depth of anchor bolt is 2 ft 2-3/8 inches and the length of projection is 2 ft 2-3/8 inches. The commercial non-shrinkage grout, Masterflow 870 GK, the same as that in the condensate storage tank foundation.

According to field test, the actual average compressive strengths of concrete at 7days and 28 days are 5419psi and 7180psi, respectively. The actual average compressive strength of non-shrinkage grout at 7days and 21 days are 7550psi and 11100psi, respectively. The bond strength of non-shrinkage grout, Masterfolw 870, is 40kgf/cm^2, and the modulus of elasticity of steel, A36 is 29x10^6 psi and poisson' s ratio is 0.3.

Testing Procedure and Measurement

Each grouted anchor was first tested in tension until the minimum required tensile load 50 tons with an increment of 7.5 tons to confirm the grout and concrete structure integrity. Then each grouted anchor bolt was retested in tension until failure or peak load. Tensile load was applied to the grouted anchors using a hydraulic ram with an electric pump providing pressure. Load was applied slowly in each loading stage to the anchor with 7.5 tons of uniform load increment the same as that for first tensile test. Load was measured with a load cell and checked with a pressure gage. At each top of the anchor bolt an extensometer was mounted and readings taken simultaneously for equal loading intervals. The failure surface was photographed before and after removing the spalled concrete cover.

TEST RESULTS

Behavior under Tensile Load

The relationship between load and displacement was approximately linear at the lower load. Figure 4 shows load-displacement curves for five anchors under tensile load applied until 50 ton. Three of five specimens of grouted anchors were tested in tension until failure or peak load. Two types of grouted anchor failure were observed from these pullout tests. As the load increases, a little reduction in stiffness is appeared to start after around 17 tons and then more reduction was observed around 50tons and 110 tons. Figure 5 from results for test specimen No. 3 and No. 5 show a typical behavior for the reduction.

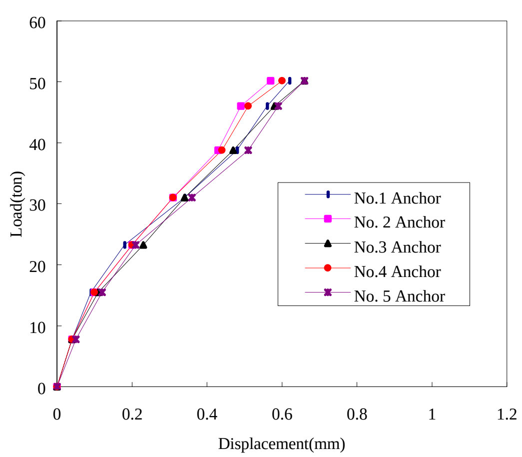


Figure 4 Load-displacement behavior to required design load

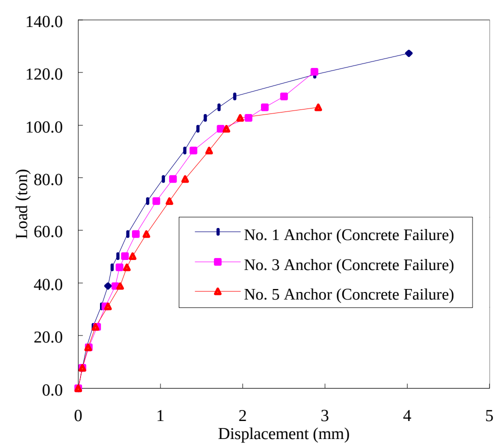
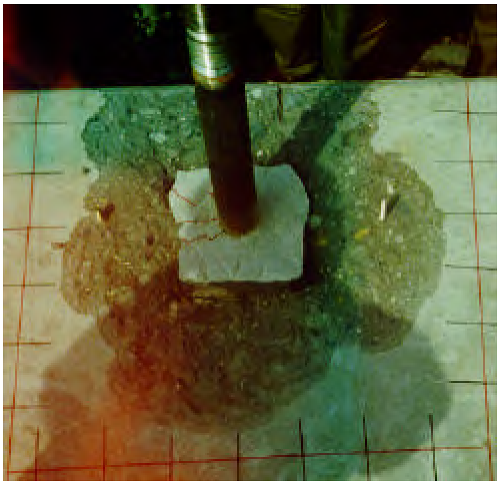


Figure 5 Load-displacement behavior until ultimate load

Thus, test specimens No. 3 and No. 5 could be judged that tensile failure of grout was occurred at the lower portion of the grout block and then bonding failure between grout and concrete and tensile failure of concrete were subsequently appeared. The threaded part of No. 5 specimen was abraded during tensioning and thus load versus displacement after about

100 tons of load was differed from those for No. 1 and No. 3. The tension failure of the concrete resulting a partial depth cone-shaped spall was appeared as shown in Figure 6. The failure surface is very large, but the failure depth of concrete seems to be very shallow. The tensile failure of concrete appeared to be restrained by the reinforcement near at top surface.



(a) Anchor specimens No. 3

(b) Anchor specimen No. 5

Figure 6 Typical pull-out failure of grouted anchors

NUMERICAL MODELING OF PULLOUT ANALYSIS

Finite Element Model

To simulate a failure mechanism of grouted anchorage system for pullout test, a linear and a nonlinear finite element model were established as shown in Figure 7. The element used for both linear and nonlinear finite element model of non-shrinkage grout anchorage system is the four-node axi-symmetrical plain strain element in the commercial code ABAQUS[4]. A number of non-linear spring elements with shear and compressive behavior were adopted in the non-linear finite element model to simulate de-bonding behavior. The linear elastic finite element model was used to explore the overall behavior for pullout load. Boundary conditions imposed on the model correspond to restraint of translation in the radial direction on vertical boundary along axis, and restraint of translation in vertical and radial directions along the bottom boundary of the model.

Menetrey-Willam's concrete failure model with non-associated plastic flow was introduced to evaluate the nonlinear behavior of non-shrinkage grout and concrete after post-cracking. As aforementioned, nonlinear shear and compressive spring elements were modeled to account for bonding and de-bonding effects at interface of concrete and non-shrinkage grout. Shear spring stiffness corresponding to bonding strength was calculated by equation (2) and the stress-strain relationship shown in Figure 8 was assumed. The bond shearing-stress distribution along the concrete-grout interface decreases exponentially with depth[3], but the shearing-stress distribution varying with depth was not considered in the finite element model.

$$K_v = \frac{E_b}{2(1+n_b)t_b} \tag{2}$$

where K_v is the vertical spring stiffness. And E_b, $\tilde{o}_b$ and t_b are the elastic modulus, poisson' s ratio, and thickness of concrete, respectively.

To simulate the resistance of grout for compression, a spring element corresponding to the elastic modulus of non-shrinkage grout was modeled. The effective bonding surface between concrete and grout was assumed an interface area excluding upper and lower portions corresponding to tensile failure regions of concrete and grout. The 40kgf/cm^2 of de-bonding stress at concrete-grout interface were considered in the analysis and this value was from test results. Since a failure cone pulled from a block-out hole is largely in a fracture mode II loading, the compressive failure of those materials were not considered and thus assumed to be within elastic state.

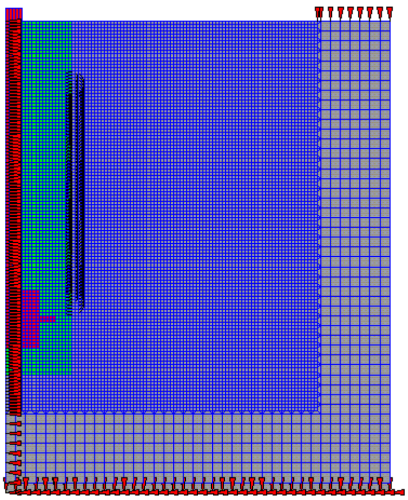


Figure 7 Finite element model for grouted anchor

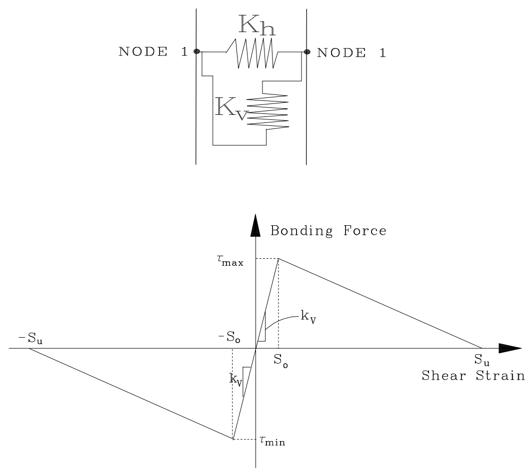
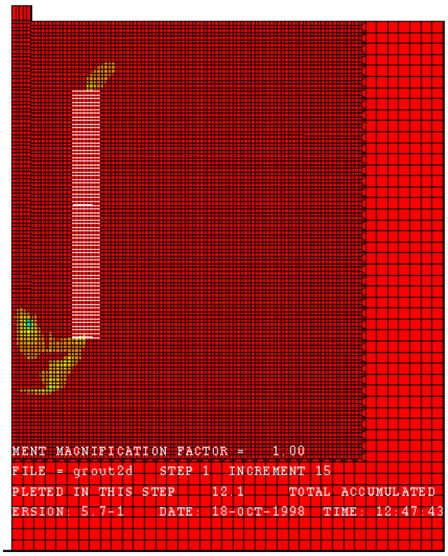


Figure 8 Shear spring(Kv) behavior for bonding failure

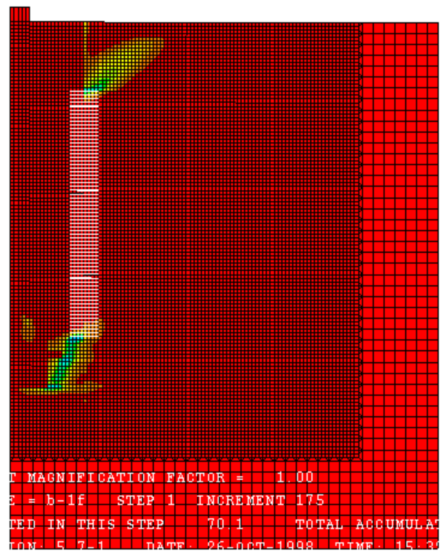
Results from Finite Element Analyses

The linear elastic analysis, which assumes a perfect bond condition between the non-shrinkage grout and concrete, shows that the critical stress was locally concentrated around the edge of anchor head. This shows very similar behavior to the extensive test results for cast-in-place anchor bolts. The failure of cast-in-place anchorage system has been generally reported to initiate at outside edges of anchor head [5]. The load-displacement relationship of grouted anchor from linear elastic analysis simulated well to the test results until 50 tons of load on the anchor. Nonlinear analysis results indicate that the concrete fracture process in the pullout mock-up test begins with the development of a primary cracking system from the upper corner of the anchor head. This primary crack initially propagates towards the lower portion of concrete-grout interface and it initiates de-bonding crack when it encounters concrete-grout interface. As the loading was increased, de-bonding crack rapidly propagates along the interface of concrete and grout, resulting in the initiation of tension failure of the concrete with a partial depth cone-shaped spalling.

Figures 9 and 10 also show that the grouted anchorage system was appeared to be damaged by the combination of grout tensile failure, bond slip failure and concrete tensile failure with large displacement. The concrete tensile failure initiated at a depth of 4.5 inches with an angle of about 20 degrees relative to the horizontal surface. This observed angle as shown in Figure 9 differs slightly from those of other researches[5], 25 to 45 degrees, but it agrees well with the behavior observed in the pull-out mock-up test. The stress distribution of elements at lower portion of grouted block-out indicates a tensile failure region at stresses approaching 0.65ksi on the 18.5 tons of load. The predicted load-displacement relationships of anchor bolts are shown in figure 11 and also compared with those from pullout mock-up tests. From the comparisons, the analytically predicted results agree well with pullout mock-up test data until 62 tons. Further reduction in stiffness, however, occurred in mock-up test than numerical analysis after about 62 tons of load. It is also indicated that load-displacement curves derived from numerical analyses are abruptly changed around at ultimate state, while test results gave continuous load-displacement performance until a ultimate load. It may be seen that the assumption of uniform shearing-stress distribution along the concrete-grout interface leads to the abrupt break-out with sharp stiffness reduction in the numerical analysis.



(a) At about 60% of ultimate load



(b) At the ultimate load

Figure 9 Typical strain contours under pull-out tensile load

The tensile strength of grout has not been usually considered in the design of ultimate capacity of grouted anchor bolt. The ultimate capacity of grouted anchor bolt was, however, appeared to be influenced by the tensile strength of grout[1]. Thus, to evaluate the influence of material properties on the ultimate capacity of non-shrinkage grout anchor, the finite element model was analyzed for various tensile strength of concrete and grout, and bond strength of grout. Figure 11 typically shows that grouted anchor capacity depends on the strength of grout. That is, in case that the tensile strength of the non-shrinkage grout is assumed to be much greater than that of the concrete, the predicted failure mechanism for non-shrinkage grouted anchor will be changed to the full-depth concrete spalling. Therefore, the results above indicated that the contribution of tensile strength of grout be considered in the design of ultimate capacity of grouted anchorage system.

CONCLUSIONS

Based on the mock-up test and numerical analysis results, the following conclusions can be made about the large-sized grouted anchorage performance for pull-out tensile loading:

1) A large-sized grouted anchor adopted in Yoggwang Nuclear Plant has the sufficient margin of safety against the minimum tensile load required in the design.

2) The usual failure mechanism of large-sized grouted anchor was a combination of bonding failure between concrete and grout and concrete tensile failure similarly to that of small size grouted anchor.

3) The shape of concrete tensile failure around surface seems to be restrained by the reinforcement near top surface and thus limited to the cover depth.

4) The crack of the grouted anchor was initiated at the outside edge of anchor head and then propagated toward the lower portion of concrete-grout interface. Thus, the tensile strength of grout affects on the ultimate capacity of anchorage system and thus should be considered in the practical design of actual capacity.

5) A proposed analysis method considering the material nonlinear behavior and bonding behavior is applicable to the prediction of the ultimate capacity of the grouted anchorage system. But additional research needs to present exactly the bonding shear distribution at the concrete-grout interface varying with depth of anchor.

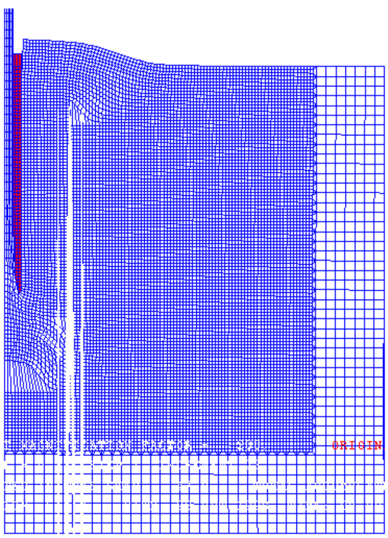


Figure 10 Deformed shape at ultimate state

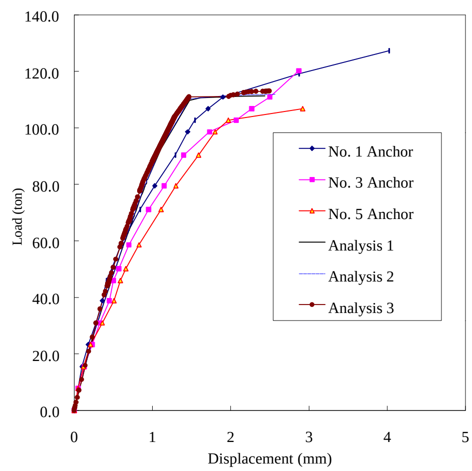


Figure 11 Comparison between numerical analyses and tests

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