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Post-installed anchor bolts subjected to tension

Y. Hosokawa
Department of Architecture, University of Tokyo, Japan

ABSTRACT: The performance of post-installed anchors, which have commonly been used in seismic retrofit of existing reinforced concrete buildings by adding new in-filled shear walls, was ivestigated in a series of experimental efforts. Reliability of metal expansion anchors in their pull-out stiffness and strength was improved by application of pre-loading at their installation. Pull-out stiffness and strength of bonded chemical anchors were improved by cleaning their installing holes with nylon or wire brush. The new installtion technique of the post-installed anchors is shown to increase the lateral resistance of a structure retrofitted with post-cast shear walls.

1 INTRODUCTION

Adding infilled shear walls to existing reinforced concrete buildings is a common seismic retrofitting method in Japan. Such post-cast shear walls are connected to existing frames with post-installed anchor bars or bolts. Details or numbers of post-installed anchors are designed according to the Guidelines for Repair and Retrofit Design of Existing Reinforced Concrete Buildings(1977). The strength of post-cast shear walls is estimated lower than that of monolithic shear walls in the guidelines because many tests showed (a) slip failure along the boundary between a post-cast shear wall panel and the surrounding frame or (b) pull-out of connecting anchors from the surrounding frame. The lateral resistance of the retrofitted frame-wall increased with the pull-out resistance of anchors.

In this paper, the performance of two types of anchor, i.e., metal expansion anchors and bonded chemical anchors, is studied. The following two techniques are introduced to generate sufficient pull-out stiffness and strength of the metal expansion anchor; (a) widening of expanding angle of the expander and (b) pre-loading technique at installation. The influence of cleaning method on the stiffness and strength is discussed for the bonded chemical anchor.

2 BACKGROUND

Since the pull-out resistance of post-installed anchors was unreliable, such anchors have not been used in connections where they would resist pull-out actions. When post-installed anchors were used for the repair of seismically damaged structures or the seismic retrofit of existing structures, the number of anchors was determined on the basis of direct shear strength of the cross section of anchor bolt. The dowel resisting mechanism was solely expected by Aoyama (1984) as a role of anchors.

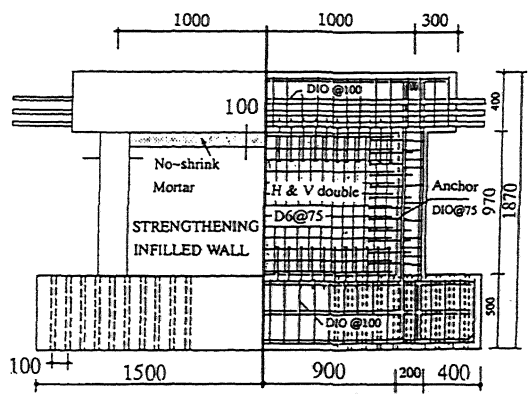

Figure 1. Elevation and reinforcement details of post-cast shear wall

Shiohara et al. (1985) pointed out the importance of the pull-out resistance of post-installed anchors on the basis of tests of post-cast shear wall specimens. The joints between a post-cast shear wall panel and its surrounding frame were carefully constructed to develop monolithic characteristics (Fig.1); (a) the column and beam surface was roughened more than 5 mm in depth before placement of the post-cast wall concrete, (b) no-shrink mortar was injected into the space under the beam after casting the wall panel, (c) the post-installed anchors were provided with sufficient lapping length within the wall panel and anchorage length within the boundary beams and columns. The post-cast shear wall specimens, constructed in this manner, developed the stiffness and resistance equivalent to the monolithic shear frame-wall specimen.

An analytical method was developed by Shiohara (1986) to calculate the resistance of a monolithic shear wall with the boundary frame using the truss analogy

with tie and strut forces. The method was applied in the analysis of post-cast shear wall specimens (Fig.1), and the pull-out resistance of the anchor bolts was a conclusive factor to determine the shear wall strength.

3 ANCHOR SPECIMENS FOR PULL-OUT TESTS

Table 1. Properties of material

Metal Expansion Anchors

Compressive strength of concrete	Mpa	16,17,25,30
Yeiled strength of anchor bolts	Mpa	UC Anchor:580
		DE Anchor:630
Diameter of anchor bolts	mm	16
Embedment length	mm	48,80,112,144
Minimum cross section	cm^2	UC Anchor:145.6
		DE Anchor: 99.8
Testing method	Pull-out test	

Bonded Anchors

Compressive strength of concrete	Mpa	18,22
Yeiled strength of re-bar	Mpa	370
Embedment length	mm	80,128,200
Testing method	Bond test,Pull-out test	

3.1 Metal Expansion Anchors

Three types of metal expansion anchors were tested.

(a) DE anchor (Fig.2.a): An ordinary type in Japan, which resists pull-out action by friction and interlock mechanism between concrete and expander surface at the top of an anchor bolt. The expander is expanded by knocking the plug of an angle of 7 to 8 degrees. The pull-out stiffness and strength of this type were likely to scatter, depending on concrete rigidity or the condition of expander.

(b) UC anchor (Fig.2.b): Developed to increase the interlock with concrete by enlarging the expanding angle of a plug. The bottom of installing hole is enlarged in a cone shape with a special drill so that the expander copuld easily expand to fit into the hole at a wider angle.

(c) BU anchor (Fig.2.c): Specially prepared for the current study. Simulating broken concrete pieces in the hole during construction. The expanded shell tends to deform inward at the hole bottom so that the interlock between concrete and expander becomes loose after installing of anchor by knocking.

3.2 Bonded chemical anchors

Bonded chemical anchors (Fig.2.d) usually used for seismic strengthening in Japan are of capsule type with polyester or epoxy compounds. Test specimens were prepared as following: Standard embedment length was chosen to be 8 times bar diameter. Deformed bars of grade SD295 (nominal yield strength: 3Mpa) and a nominal diameter of 16 mm were used as anchor re-bars. The diameter of a drill edge used in drilling holes was 20 mm. Assuming the pull-out resisting mechanism of bonded anchors was similar to the bonding mechanism of deformed bars, the bond stress distribution along anchor re-bar was determined from the measured strains along the anchor. An embedment length of 12.5 times anchor diameter was given to some specimens to investigate an influence on bond characteristics.

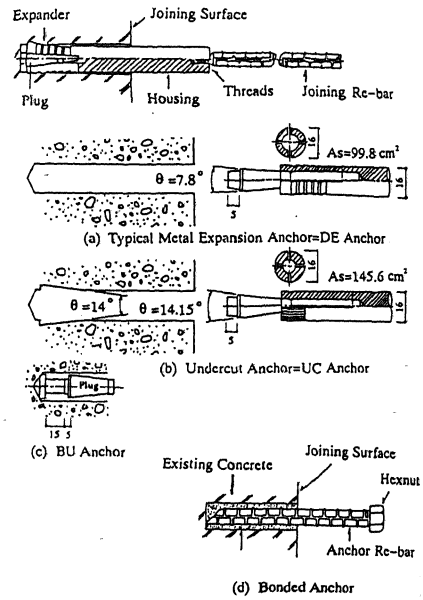

Figure 2. Detail of post-installed anchors

In the pull-out test, three cleaning methods of the installing hole were chosen as a main parameter to influence the bonding stiffness and strength; i.e., (a) vacuuming the hole, (b) brushing the concrete surface in the hole with a nylon brush after vacuuming and (c) brushing with a wire brush after vacuuming. The diameter of a wire brush fitted to an electromotive drill was 5 mm larger than the diameter of an installing hole.

Effect of cleaning methods similar to the above has already been investigated by Luke et al.(1985).

4 TESTING PROCEDURE

Anchor specimens were installed in a concrete block as shown in Fig. 3. The dimensions of the concrete block were 1200 x 1200 x 450 mm or 900 x 900 x 400 mm, large enough to avoid the influence by flexural cracks or partial cracks near an edge.

The loading system is illustrated in Fig. 4. Each specimen was pulled by a 20 KN center hole hydraulic ram. Pull-out displacement was measured by electric displacement transducers. The diameter of the reaction stand was wide enough to avoid confinement of the concrete in the region of a diameter equal to the depth of the anchor (Fig. 4.a).

Bond tests of adhesive chemical anchors were carried out by the apparatus shown in Fig. 4.b. Bond of the re-bar was cut from the concrete surface to 50 mm in

depth in order to eliminate the influence of confinement from the loading apparatus near the concrete surface.

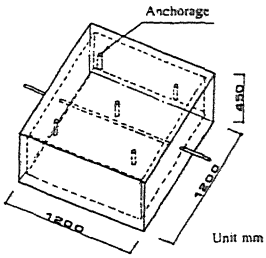

Figure 3. Concrete test block installed with anchors

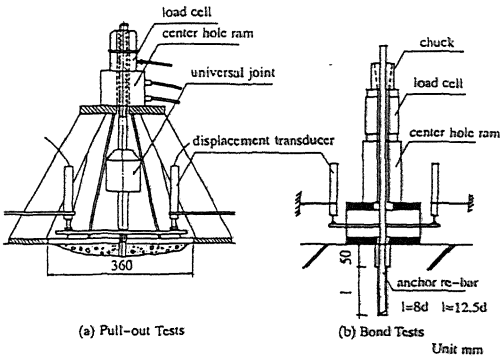

Figure 4. Loading system

5 TEST RESULTS

5.1 Metal Expansion Anchors

Typical pull-out load and displacement relations of the DE anchors and the UC anchors are compared in Fig. 5. In the DE anchor, large pull-out displacement was observed with load ; displacement at maximum resistance was as large as 15 mm, and the decay in resistance after the maximum was drastic. While in the UC anchor, both initial stiffness and maximum resistance were high; the decay in resistance after the maximum was gradual. In both anchors, cracks in concrete surface were not observed at the maximum resistances. Initial cracks were observed at a pull-out displacements of 16 mm.

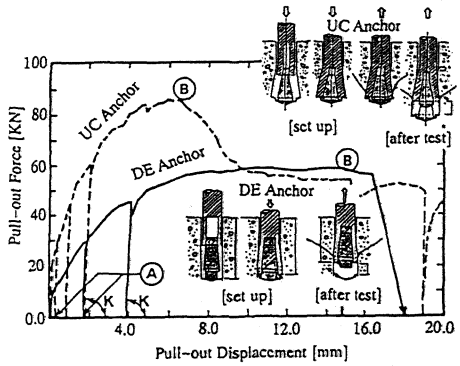

Figure 5. DE and UC anchors

Influence of embedment length or concrete strength to pull-out load-displacement relationship is demonstrated in Fig.6. A horizontal line represents the yield strength of joining re-bar. The DE anchor did not yeild for an embedment length less than seven times the diameter. On the other hand, the pull-out resitance of the UC anchor exceeded the yield strength of the joining re-bar, for an embedment length more than five times the bar diameter.

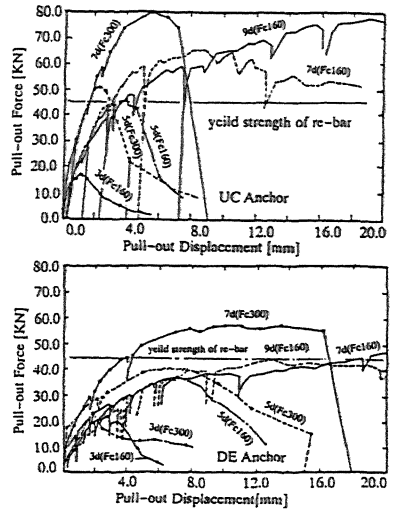

Figure 6. Effect of embedment length and concrete strength

The behavior of a UC anchor under one way loading and unloading simulating seismic situation is shown in Fig. 7. Loading and unloading were repeated five times at the design load and then five times at twice the design load. The load-displacement relation was almost linear during unloading and reloading. A drawback of the metal expansion anchor is the scattering of its stiffness and strength values, but can be corrected by making use of the preloading to a given level.

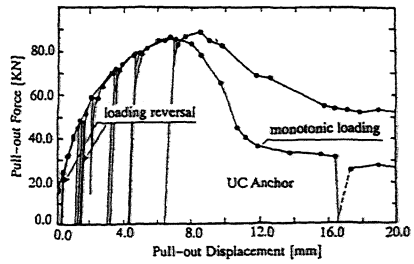

Figure 7. Restoring force characteristics of metal expansion anchor

Stiffness under reloading is compared in Fig. 8. The ordinate represents tension load and the abscissa pull-

out displacement shifting residual displacements under one way loading reversals to the origin. The reloading stiffness up to the previous maximum load coincided with the initial elastic stiffness. This simple but important characteristic can be applied to correct unreliable magnitude in stiffness and strength of metal expansion anchors; i.e., after installing an anchor, the preloading should be applied to a certain load level before the usage. The load level, called assurance load, may be decided in relation to the design load.

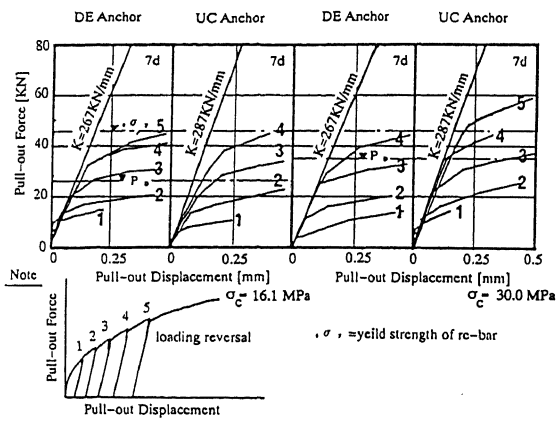

Figure 8. Comparison of stiffing for restoring force

Elasticity under reloading as shown in Figs. 7 or 8 implies perfect interlock between concrete and anchor. An idealized interlocking condition is illustrated in Fig. 9. Friction force and bearing force were assumed to act on the surface between the anchor and concrete. The concrete around the anchor would fail in bearing under the pull-out action, but the ground concrete powder produced by crushing would be compacted and hardened enough to resist the pull-out action(by Luts (1967). As the pull-out action increased, bearing region of the concrete would spread and finally the pull-out resistance would reach the maximum. Pull-out strength due to such bearing resisting mechanism T_1 was assumed to be presented by the following equation:

$$T_1 = N \cdot \sin(\alpha + \phi)/\cos\phi \qquad (1)$$

Where, N: bearing strength of concrete (assumed equalto $12\sigma c$,in which σc : compressive strength of concrete), α : angle of the plug, and ϕ : Angle of friction ($\tan\phi = \mu$,was assumed equal to 0.4).

The pull-out strength could be defined for the cone failure given in the following equation:

$$T_2 = Ac\sqrt{\sigma c} \quad \text{(Unit: KN, cm)} \qquad (2)$$

$$\text{Where,} \quad Ac = \pi\, le(le + da), \qquad (3)$$

$$le = l - da, \qquad (4)$$

T_2: pull-out strength due to cone shape failure. Ac:effective rojected area of cone shape, σc compressive strength of concrete, l: embedment length, le:effective length, and da: anchor diameter.

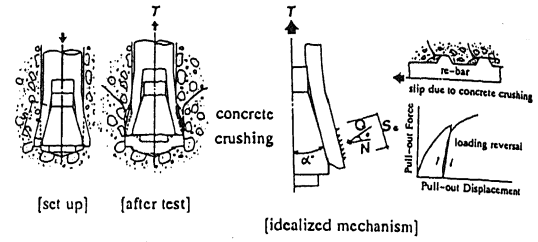

Figure 9. Tensile mechanism of expansion anchor

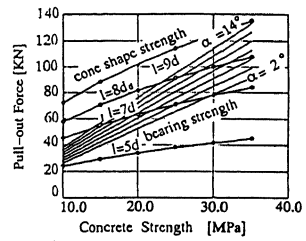

Figure 10. Pull-out load and concrete compressive strength relationship

Calculated pull-out strengths for the cone shape failure and the bearing failure are compared in Fig. 10. The abscissa represents the concrete strength. In the cone shape failure, the embedment length was varied from five to nine times anchor diameter. In the bearing failure, the angle of plug was varied 2 to 14 degrees. In case of shallow embedment and small plug angle, the pull-out strength was decided by the cone shape failure, while in case of deep embedment and large plug angle, it was decided by the bearing failure.

The change in observed pull-out strength and failure mode by embedment length is plotted in Fig. 11. Test data were grouped by the embedment length. Horizontal lines are calculated strength for each failure mode. For both DE and UC anchors, only cone shape failure was observed when embedment length was short. Fracture of anchor re-bar was observed when embedment length was 9 times diameter in the DE anchor and 7 times in the UC anchor. Bearing failure was observed only in the UC anchor when the embedment length was more than 7 times diameter. Therefore, the pull-out strength of the metal anchor whose anchorage is stiff must be calculated based on bearing failure.

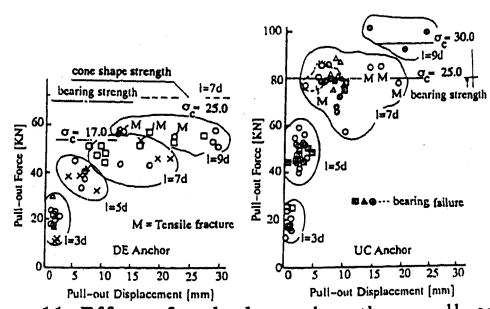

Figure 11. Effect of embedment length on pull-out displacement

Any obstructive, pieces such as broken concrete, falling into the installing hole during construction, would deteriorate the performance of anchor. The BU type anchor was tested under simulating the such condition. The pull-out load-displacement relation is compared to that of DE anchor in Fig. 13. The pull-out stiffness of the BU anchor was siginificantly low. This fact means it is dangerous to regard completion of installing as completion of anchor construction. However, as shown in the figure, the preloading technique is effective to insure sufficient stiffness.

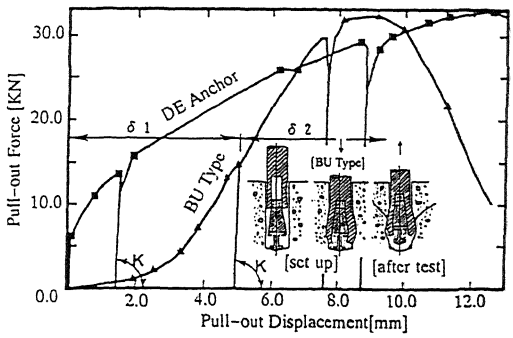

Figure 12. Comparison of load-slip relationship for typical anchor and BU type anchor

Thus, stiffness and strength of metal expansion anchors are not assured by only installing. The loading and unloading technique is necessary to generate their sufficient stiffness and strength, secured within a limit range. Metal expansion anchors should be designed based on assurance load.

5.2 Bonded Chemical Anchor

The location of strain gauges to investigate bond performance is illustrated in Fig. 13.(a). Observed strain distribution for each cleaning method is shown in Fig. 13.(b) and (c). Strain of each specimen distributed linearly along anchor re-bar at lower load steps, demonstrating uniform bond stress. However, in higher load steps, the effect of cleaning method was revealed in the strain distribution. Anchor re-bar did not yield in the case of only vacuuming, while the re-bar yielded in the case of brushing with nylon brush or wire brush.

Pull-out load-displacement relations observed for each cleaning method are shown in Fig. 14. In the case of cleaning by vacuuming only, significantly large displacement occurred before anchor re-bar yielded. Anchors whose hole was cleaned by brushing developed high stiffness and strength. This accounted especially for the wire brush.

Average of bond strength for each cleaning method was 10 Mpa when only vacuuming, 12.5Mpa when brushing with a nylon brush and 14Mpa when brushing with a wire brush.

Observed failure modes of adhesive chemical anchor under a pull-out action are generally classified as the following: (1) cone shape failure, (2) bond failure, (3) combined mode of the above (1) and (2), (4) adhesive fracture and (5) anchor re-bar fracture. In case (2), the pull-out strength was lowest.

The range of bond stress of specimens failed in combined mode of the cone shape failure and the bond failure in this series of tests was 10.8 - 11.9Mpa for an effective embedment length.

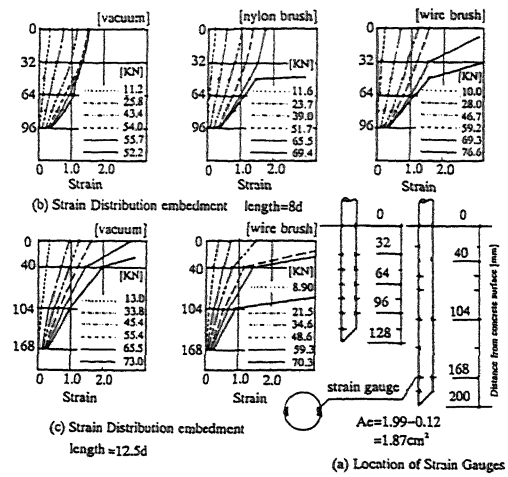

Figure 13. Strain distribution in an embedment re-bar

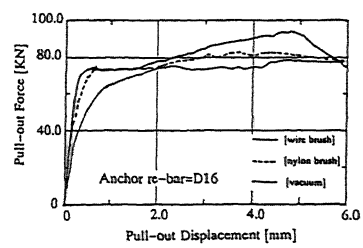

Figure 14. Effect of cleaning methods on load-slip relationship bonded anchors

A cross section of specimens failed in the cone shape failure is illustrated in Fig. 15(a). The depth of a cone was measured by vernier at every 2 cm. Based on this observation, each length necessary to calculation of pull-out strength was defined as shown in Fig. 15(b).

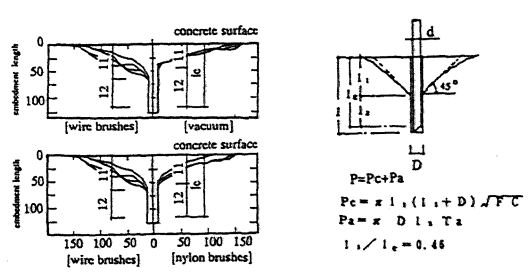

Figure 15. Observed failure patterns for each cleaning methods and idealized combination cone and bond failure.

Supposing the combined failure mode of the cone shape failure and the bond failure as a general failure mode, the pull-out strength of an adhesive chemical anchor P was defined as the sum of strengths of each failure mode:

$$P = Pc + Pa \quad (5)$$

$$\text{Where, } Pc = \pi\, l_1(l_1+D), \quad (6)$$

$$Pa = \pi\, D\, l_2, \quad (7)$$

$l_1/le = 0.46$ (observed average value),
Pc: Pull-out strength due to cone shape failure,
Pa: Pull-out strength due to bond failure,
l_1: Cone depth, l_2: Bond length,
le: Effective embedment length,
Bond stress (assumed 12.5Mpa here).

Observed pull-out strength and calculated strength are compared in Fig. 16. The pull-out strength may be predictable by the method.

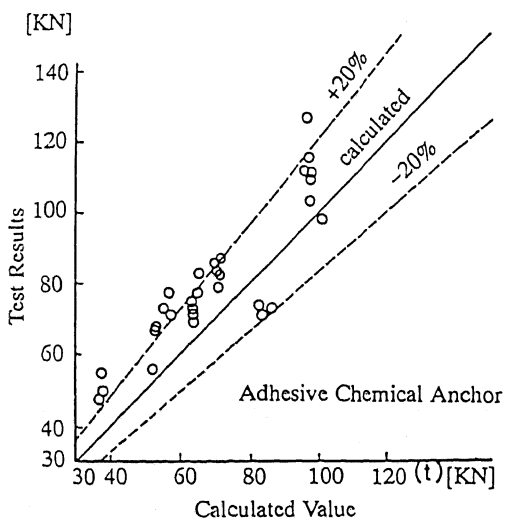

Figure 16. Comparison between calculated strength and observed strength

6 CONCLUSIONS

Post-installed anchors were difficult to use for seismic retrofit of important structures because of the lack of reliability in their performance. However, a series of pull-out tests proved that the reliability could be improved. Such improved anchors will contribute to the increase of seismic resistance of strengthened structures especially when used for post-cast shear walls.

Main findings obtained from pull-out tests of metal expansion anchors are summarized as follows;

(1) Hardening interlock between concrete and the top of anchor by pulling out up to a necessary load makes it possible for a metal expansion anchor to generate elastic stiffness surely in load range below the pull-out load. The finish of this loading work should be regarded as Completion of anchor construction.

(2) The undercut type anchor (UC anchor) with wide angle expander installed into the hole whose bottom was drilled to spread in cone shape develops higher stiffness and strength.

(3) When estimating pull-out strength of metal expansion anchor, it is necessary to suppose not only cone shape failure but also bearing failure of concrete near the top of anchor.

Test results of adhesive chemical anchors are concluded as follows.

(1) In order to assure the adhesive chemical anchor develops pull-out strength up to yield strength of its re-bar, it is necessary to certify the bond strength is more than 12Mpa by field bonding test.

(2) Cleaning the installing hole is important to make the anchor generate sufficient stiffness and strength. Brushing with wire brush whose diameter is larger than the hole diameter is very effective.

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