Outline of Japanese Guideline for influence of the embedment length and the edges on tensile resistance of post-installed bonded anchor

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SUMMARY:
This paper describes and comments on AIJ Design Guideline 2010 of post-installed bonded (adhesive) anchor. This paper presents tension tests to clarify the influence of the embedment depth and the edges on the tensile behavior of the single post-installed bonded anchor. The 4 parameters of the test are established; embedment length (l_e = 7d_a, 14d_a and 21d_a; d_a: anchor diameter), edge configuration (anchorage at an edge, a corner and thin member), edge distance and adhesive system (glass capsule type, film soil type and injection type). In those tests, we investigated failure mode and failure load of bonded anchor close to the edge(s), and discussed about resistance of anchor to tensile load. Further, the method to estimate the tensile strength (failure load) of single-anchor or anchors in the group was proposed with the influence on edge(s). The method in bond failure type is modelled based on a uniform bond stress, and the uniform bond strength is evaluated with reduction coefficient which considered the number of edge and the edge distance.

Keywords: post-installed bonded anchor, tensile resistance, embedment length, edge distance, guideline

1. INTRODUCTION

This paper describes and comments on AIJ Design Guideline 2010 of post-installed bonded anchor. In Japan, post-installed anchors are mainly used for fastening of equipment. However, some are used for connection of structural member, and many of them are being used for connection of structural members for strengthening existing buildings. Therefore, it is recommended to using bonded anchors for fix structural anchors, and they are widely used for seismic strengthening work.

In those cases, the embedment length of post-installed bonded anchor is generally designed from 7 to 10d_a (d_a: anchor diameter) (JBDPA RC Guideline 2001, AIJ Design Composite Construction 1985), and differs from that of cast-in-place-system (of 30 to 40d_a) (AIJ Standard RC 1999). The reason is that the failure load of post-installed bonded anchor is not evaluated with the edge influence appropriately.

It means that the tensile strength of bonded anchor in concrete cone-failure type is evaluated with the actual projected area and that in bonded (pull-out) failure type is not evaluated with edge influence. So, the target of this paper is to clarify the influence of embedment length and edge(s) on the tensile behavior of single post-installed bonded (adhesive) anchor. Further, the aim of this paper is to estimate the tensile strength of post-installed bonded anchor from tests.

2. OUTLINE OF TEST

2.1. Specimen

Details of specimens are shown in Table 1 and Figure 1. Those 79 specimens were prepared for the test. Bonded anchors were installed in hardened concrete blocks. The concrete blocks were unconfined and were un-cracked.

The following 4 parameters were established; embedment length, edge configuration, edge distance and bonded type. The embedment lengths were $7d_a$ (d_a: anchor diameter, 133mm), $14d_a$ (266mm) and $21d_a$ (399mm). The edge configuration meant number of edge, were Center (no edge), 1-edge (anchorage at an edge) and 2-edge (corner and both sides: anchoring thin member). The edge distances were 75mm and 150mm. The type of bonded anchor was adhesive system; Glass capsule type (G-Type), Film foil type (F-Type) and Injection type (I-Type). The compounds of bonded anchor were epoxy acrylate. The installation of adhesive anchor was as follows;
1) For G-type and F-type, capsule (glass capsule or film foil) was placed in the clean hole drilled in to concrete and then anchor rod was driven in mechanically by hand drill until the required embedment depth.
2) For I-type, bonding material (delivered separate chambers of the injection cartridge) was injected into the hole and then the anchor rod was inserted manually. The mixing process of the bounding material is carried out in the mixing spiral of the top of the cartridge extension during the insertion.

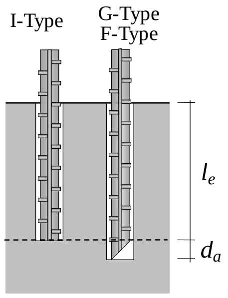
Post-installed anchor rod was deformed bar (D19: diameter was 19mm.) and high strength steel (yield strength was 685N/mm^2 level). The diameters of hole drilled in to concrete were 24mm (I-type, F-type) or 25mm (G-type). Concrete strength of this test were 29-36 N/mm^2.

2.2. Load system

Figure 2 shows a diagram of the test apparatus used to perform the tensile test. Concrete was not confined by the load system. A tensile load was produced by a hydraulic rum in combination with a hand pump. The reaction load was transferred to the concrete through a steel frame. The steel frame was separated 200mm (about $7d_a$), 300mm (about $14d_a$), and 400mm (about $21d_a$) from the anchor rod. Tensile loads were measured using a load cell and top of anchor displacements (d_1, d_2) were measured with displacement transducers.

Table 1. Parameter of Test

Bond-Type	l_e	Edge	Edge distance $C=C_1=C_2=C_3$
G-Type	$7d_a$(133mm) $14d_a$(266mm) $21d_a$(399mm)	Center 1-Edge 2-Edge (Both Sides) 2-Edge (Corner)	75mm 150mm
I-Type			
F-Type	$7d_a$(133mm) $14d_a$(266mm)		



Sumple of l_e

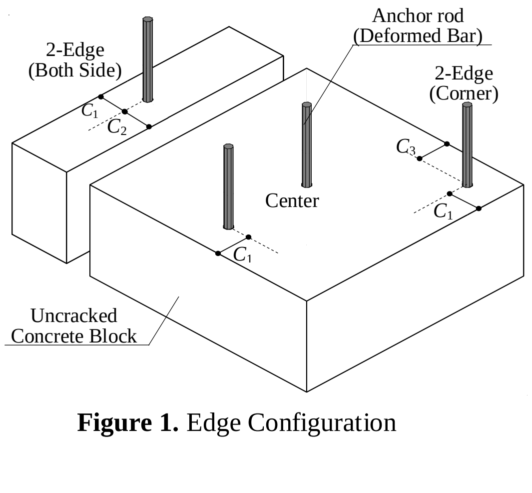


Figure 1. Edge Configuration

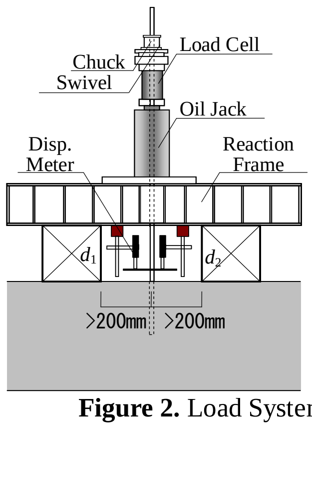


Figure 2. Load System

3. TEST RESULT

3.1. Failure mode

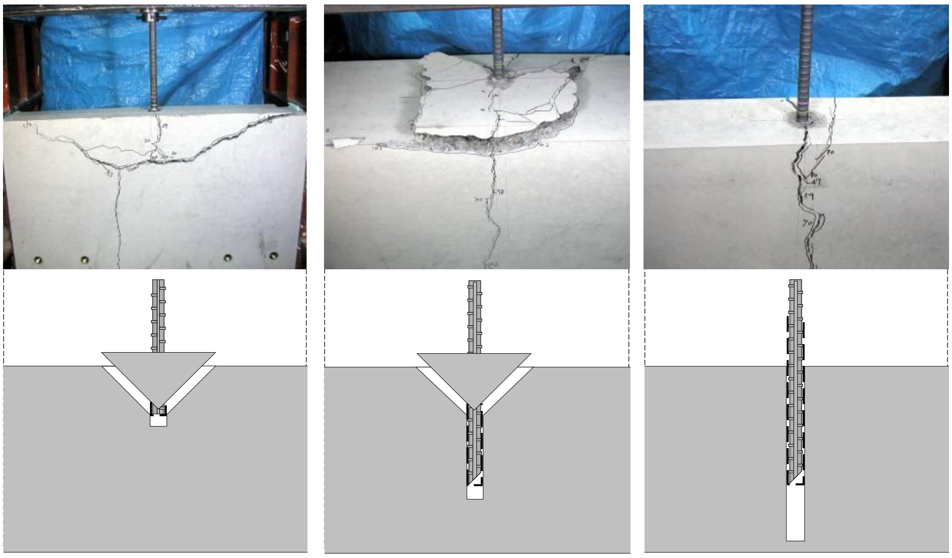
In the tests four types of failure modes were obtained which are shown in Figure 3 and listed in Table 2 as a concrete cone failure (C), a bond failure with a concrete cone (BC), a bond split failure with a concrete cone (BSC) and a bond split failure (BS). For shallow embedment (le = 7d_a), the failure mode appeared a concrete cone failure (C). For deeper installation (le = 14d_a, 21d_a), failure resulted in a bond (or bond split) failure with a shallow concrete cone (BC, BSC). Some of anchoring in thin member (2-Egde both sides) was a bond split failure. A typical failure mode of anchor surface after loading is shown Figure 4. In G-Type, the failure mode of anchor surface was steel/adhesive interface.

On the other hand, since resin had adhered to the concrete, the failure mode of anchor surface in F, I-Type was adhesive/concrete interface. The concrete cone length versus embedment length is showed in Figure 5. The embedment length has small influence on the concrete cone lengths, which were dispersed 10-130 mm (Ave.63mm).

Table 2. Test result and calculated value

Parameters			Test Result						Calculation	
l_e [mm]	Edge[*1]		G-Type Load [kN]	G-Type mode[*2]	F-Type Load [kN]	F-Type mode[*2]	I-Type Load [kN]	I-Type mode[*2]	Load[*3] [kN]	mode[*2]
$7d_a$	C	-	74[*6]	CC	122[*6]	CC	98[*6]	CC	84[*6]	CC
	1	75	57[*6]	CC	77[*5] 91[*6]	CC CC	52[*5] 63[*6]	CC CC	65[*5] 69[*6]	CC CC
	2C	75	52[*6]	CC	71[*6]	CC	49[*6]	CC	55[*6]	CC
	2B	75	63[*6]	CC	53[*5] 80[*6]	CC CC	45[*5] 64[*6]	CC CC	50[*5] 54[*6]	CC CC
	1	150	83[*6]	CC	84[*5] 120[*6]	CC CC	69[*5] 55[*6]	CC CC	79[*5] 84[*6]	CC CC
	2C	150	63[*6]	CC	97[*6]	CC	71[*6]	CC	84[*6]	CC
	2B	150	86[*6]	CC	81[*5] 108[*6]	CC CC	64[*5] 82[*6]	CC CC	79[*5] 84[*6]	CC CC
$14d_a$	C	-	150[*6]	BC	270[*5] 261[*6]	BC BC	168[*5] 192[*6]	BC BC	188[*5] 209[*6]	B B
	1	75	130[*6]	BSC	160[*5] 198[*6]	BS BSC	143[*5] 130[*6]	BC BC	120[*5] 134[*6]	B B
	2C	75	135[*6]	BSC	128[*6]	BSC	109[*6]	BSC	86[*6]	B
	2B	75	97[*6]	BSC	66[*5] 101[*6]	BS BSC	61[*5] 116[*6]	BSC BSC	77[*5] 82[*6]	B B
	1	150	132[*6]	BSC	192[*5] 227[*6]	BC BSC	170[*5] 150[*6]	BC BC	147[*5] 163[*6]	B B
	2C	150	181[*6]	BSC	180[*6]	BSC	161[*6]	BC	128[*6]	B
	2B	150	155[*6]	BSC	105[*5] 195[*6]	BSC BSC	102[*5] 160[*6]	BSC BSC	115[*5] 122[*6]	B B
$21d_a$	C	-	268[*6]	BSC	-	-	257[*5] 279[*6]	BC SF	278[*5] 280[*6]	CC SF
	1	75	258[*6]	BS	-	-	192[*5] 172[*6]	BC BSC	165[*5] 178[*6]	B B
	2C	75	x[*4]	x[*4]	-	-	x[*4]	x[*4]	111[*6]	B
	2B	75	105[*6]	BS	-	-	70[*5] 116[*6]	BS BSC	98[*5] 106[*6]	B B
	1	150	278[*6]	SF	-	-	235[*5] 248[*6]	BC BC	191[*5] 207[*6]	B B
	2C	150	x[*4]	x[*4]	-	-	x[*4]	x[*4]	142[*6]	B
	2B	150	242[*6]	BS	-	-	124[*5] 219[*6]	BSC BSC	132[*5] 142[*6]	B B

*1 C: Center, 1: 1-Edge, 2C: 2-Edge(Corner), 2B: 2-Edge(Both Side)
*2 CC: Concrete Cone Failure, B: Bond Failure, BC: Bond Failure with a Concrete Cone,
BSC: Bond Split Failure with a Concrete Cone, BS: Bond Split Failure, SF:Steel Failure
*3 Calculated. *4 Impossible Loading, *5 Concrete Strength f_c=29N/mm^2, *6 f_c=35N/mm^2



concrete cone failure (CC) | bond split failure with a concrete cone(BC, BSC) | bond split failure (BS)

Figure 3. Failure mode of single bonded anchor

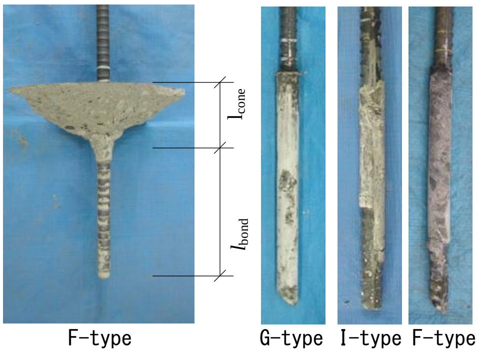


Figure 4. Failure mode (l_e=14d)

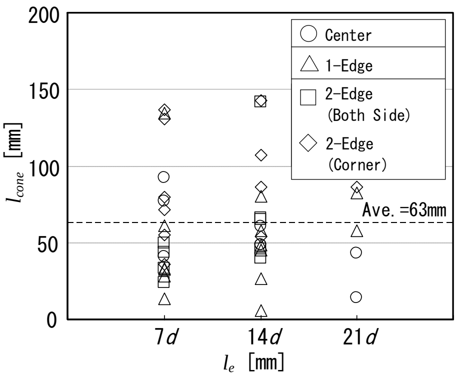


Figure 5. Concrete cone length versus l_e

3.2. Tensile load – displacement relationship

Figure 6 shows a typical tensile load – displacement relationship of 1-edge l_e=14d_a in comparison with adhesive system (G-type, F-type and I-type). The adhesive system has no influence on elastic stiffness and failure load of F-type was about 5-10% larger than that of G, I-types. Therefore, the result shows small influence of adhesive system on the tensile behavior of bonded anchor.

Figure 7 shows typical tensile load – displacement relationship for embedment length l_e. The embedment length had little effect on elastic stiffness, and the failure load increased as the embedment length increased. Additionally, since the bond length increased, the displacement in failure load was larger with increasing the embedment length.

Figure 8 shows typical tensile load – displacement relationship for edge configuration. Although stiffness was variable, influence of the edge configurations on stiffness was not observed. The failure load was larger in order of 2-edge (Both sides), 2-edge (Corner), 1-edge and Center. Furthermore, with increasing edge distance, increase of the failure loads was observed.

3.3. Influence of embedment depth and edge on failure load

Table 2 shows failure load and Figure 9 shows failure load versus embedment depth (in c =75mm). For all adhesive system (G-Type, I-Type, F-Type), the value of failure load was dispersion, but the failure load of bonded anchor increased almost linearly in proportion to the embedment depth. Furthermore, the failure load was larger at the smaller number of edge surface, and at the larger edge distance.

3.4. Bond resistance to tensile load (strain distribution)

Figure 10 shows a typical strain distribution of anchor rod versus embedment length with increasing load. The gradient of strain became large gradually with increasing load. Since a shallow concrete cone failure occurred, the gradient of strain distribution near concrete surface decreased. After shallow concrete cone failure, bond length (section where gradient of strain existed) was deeper. Further, the strain distributions at failure load were almost linear in bond length, so the bond stress was almost constant throughout the bond length in failure load.

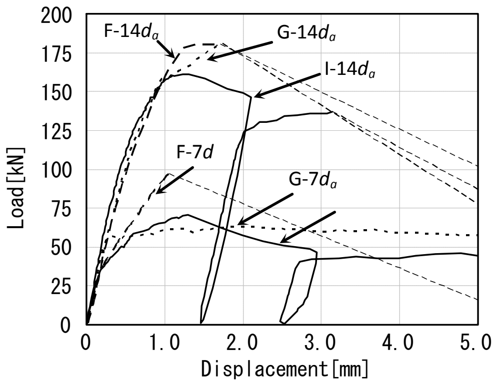


Figure 6. Load-Displacement for Bond-Type (150mm, Corner)

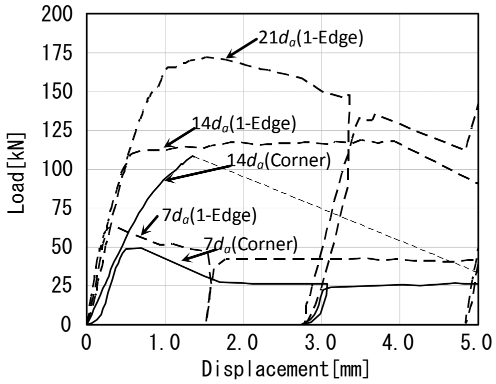


Figure 7. Load-Displacement for l_e (75mm, I-Type)

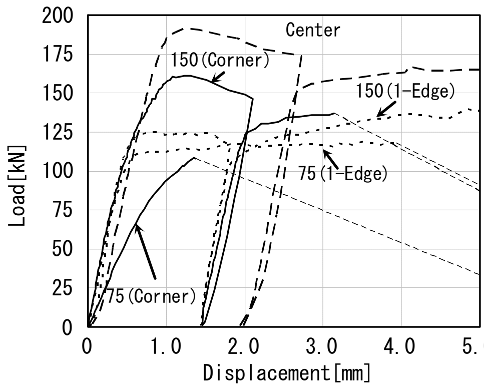


Figure 8. Load-Displacement for Edge(s) (I-Type, 14d)

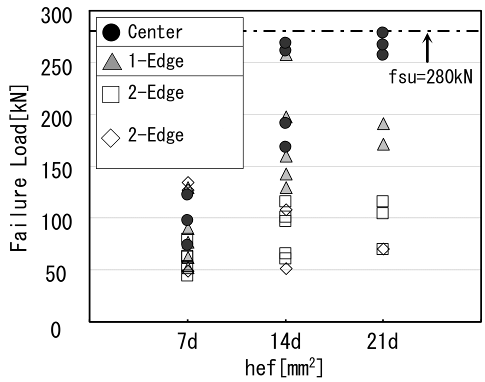
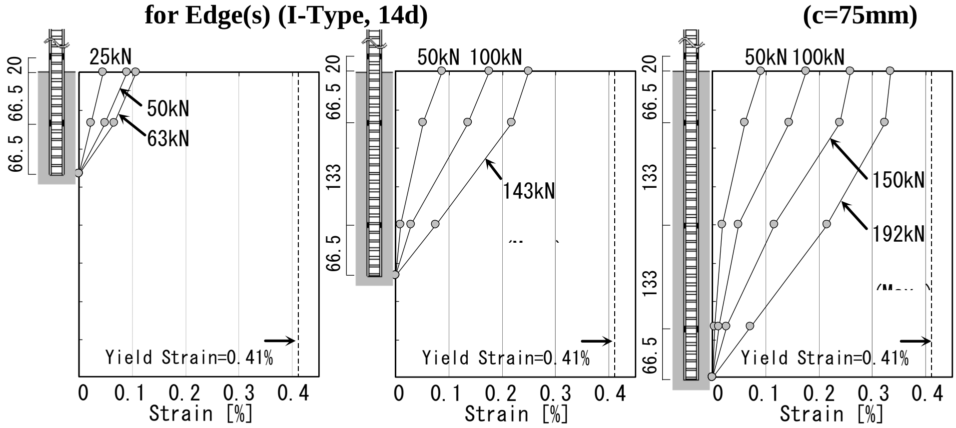


Figure 9. Failure Load versus l_e (c=75mm)



I-Type, 1-Edge (75mm)

Figure 10. Strain distribution

4. DESIGN METHOD OF BONDED ANCHOR CLOSE TO EDGE(S)

The design method suggested in AIJ Guideline 2010 for failure load of a bonded anchor. In this guideline, in view of the findings from the results of experiments involving effective embedment lengths of $7d_a$ to $21d_a$, the strength of a bonded anchor is evaluated in terms of the strength determined by the yielding of the anchor rod and the strength determined by adhesion, and strength reduction due to the group effect is evaluated by reducing the bond strength between the anchor rod and the concrete.

Eq. (2) and Eq. (3) give the tensile failure load of a bonded anchor. The allowable tensile force p_a for a bonded anchor secured in preplaced concrete shall be taken to be the value calculated from Eq. (2) or the value calculated from Eq. (3), whichever is smaller. Eq. (2) calculates the value of steel failure mode and Eq. (3) gives the tensile failure load of bond failure, is simple model based on a uniform bond stress.

The value of concrete cone failure mode with the actual projected area is given by reference (JBDPA RC Guideline 2001, AIJ Design Composite Construction 1985) is not considered in this guideline, because the cone length had little influence on the failure load of a bonded anchor in deeper embedment. In addition, this simple bond model is assumed that the failure surface could occur either at the steel/adhesive or adhesive/concrete interface. The allowable tensile force pa is given by Eq. (1).

$$p_a = \min.(p_{a1}, p_{a3}) \quad \text{(N)} \tag{1}$$

$$p_{a1} = \phi_1 \cdot {}_s\sigma_{pa} \cdot {}_{sc}a \quad \text{(N)} \tag{2}$$

$$p_{a3} = \phi_3 \cdot \tau_a \cdot \pi \cdot d_a \cdot l_{ce} \quad \text{(N)} \tag{3}$$

where:

p_{a1} = allowable tensile force for bonding anchor determined by yielding of anchor rod (N)

p_{a3} = allowable tensile force determined on the basis of bonding (N)

ϕ_1 = reduction coefficient determined by steel failure
= 2/3 (long-term allowable force), 1.0 (short-term allowable force)

ϕ_3 = reduction coefficient determined by concrete failure
= 1/3 (long-term allowable force), 2/3 (short-term allowable force)

${}_s\sigma_{pa}$ = tensile strength of anchor rod where ${}_s\sigma_{pa} = {}_s\sigma_y$ provided that ${}_s\sigma_{pa} = \alpha_{yu} \cdot {}_s\sigma_y$ when the upper limit tensile force (N/mm^2) in the case where yielding of anchor bolt is guaranteed is calculated

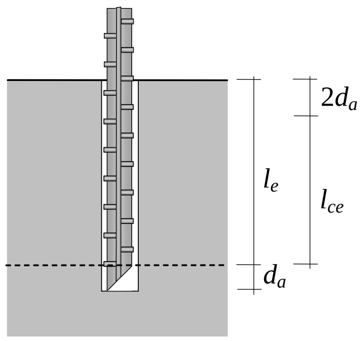


Figure 11. l_e and l_{ce}

α_{yu} = reduction coefficient (1.25 or greater) for standard-specified yield point strength allowing for variability of material strength of anchor rod

${}_s\sigma_y$ = yield strength of anchor rod (N/mm^2)

${}_{sc}a$ = cross-sectional area of anchor rod, calculated as the cross-sectional area of the non-threaded portion of the shank or the effective cross-sectional area of the threaded portion, whichever is smaller (mm^2)

d_a = diameter of anchor rod (mm)

l_e = effective embedment length of anchor-rod (mm) $\leq 10d_a$

l_{ce} = effective embedment length of anchor-rod for calculating p_{a3} (mm)
= $l_e - 2d_a$ ($l_e \leq 10d_a$)

τ_a = uniform bond strength to tensile force of bonded anchor taking into account edge distance and anchor spacing

$$= \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \tau_{bavg} \quad \text{(N/mm}^2\text{)} \tag{4}$$

α_n = reduction factor for bond strength due to edge distance and anchor spacing, calculated from Eq.(5) (n = 1, 2, 3); two surfaces with the smallest dimensions to be taken into account

$$= 0.5 + 0.5\frac{c_n}{l_e} \quad (5)$$

where (c_n/l_e) is taken to be equal to 1.0 if $(c_n/l_e) \geq 1.0$, and l_e is taken to be equal to $10d_a$ if $l_e \geq 10\ d_a$.
τ_{bavg} = nominal uniform bond strength (N/mm^2)

$$= 10\sqrt{Fc/21} \quad (6)$$

F_c = concrete compressive strength (cylinders) (N/mm^2)
c_n = edge distance or 1/2 of anchor spacing a (= a_n/2, a_n= anchor spacing)

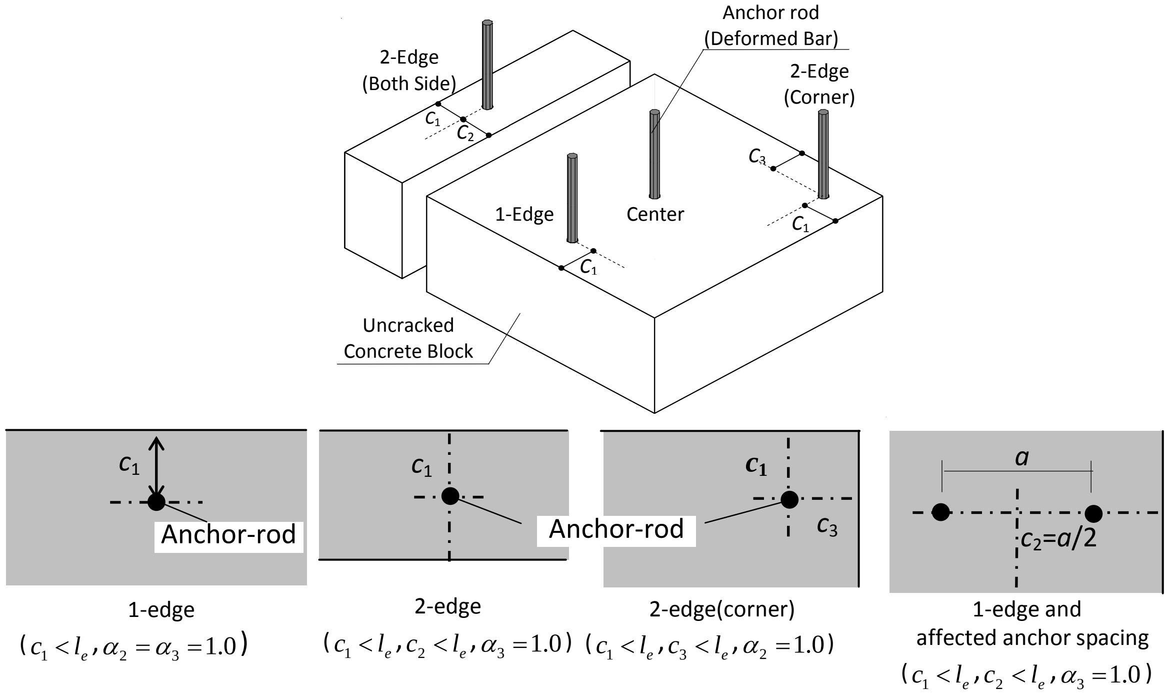


Figure 12. Edge-type and Anchor-spacing

The allowable tensile force for a bonded anchor is given as the value calculated from Eq. (7) or the value calculated from Eq. (9), whichever is smaller. The value calculated from Eq. (7) is the allowable tensile for determined by yielding in tension of the anchor bolt, and the value calculated from Eq. (9) is the allowable tensile force determined by adhesion. These are determined by applying the ultimate strength equations of Eq. (7) and Eq. (9), respectively.

In the case of a bonded anchor with a small embedment length, the influence of cone failure is great, and the method of using three equations including Eq. (8) may be used as for headed anchor bolts. It is thought, however, that the failure mode that determines the ultimate strength is determined by bond failure in a non-concrete-cone section, regardless of effective embedment length.

$$p_1 = {}_s\sigma_{pa} \cdot {}_{sc}a \ \text{(N)} \quad (7)$$

$$p_2 = {}_c\sigma_t \cdot A_c \ \text{(N)} \quad \text{for} \quad {}_c\sigma_t = 0.31\sqrt{F_c} \ \text{(N/mm}^2\text{)} \quad (8)$$

where: A_c = actual projected area affected by edge(s) (Figure 15) (mm^2)

$$p_3 = \tau_a \cdot \pi \cdot d_a \cdot l_{ce} \quad (9)$$

Figure 13 shows representative examples of the relationships between values calculated from (P_1), (P_2) and (P_3) and the effective embedment length l_e. This figure is an experimental result in case the edge distance is fully secured. When the effective embedment length l_e is used as the embedment length for strength calculation, l_{ce}, P_2 determined by cone failure tends to take the smallest value until $8d_a$ or so is reached. When, however, the embedment length for strength calculation obtained by subtracting two times the anchor bar diameter ($l_{ce} = l_e - 2d_a$) is used in view of bond deterioration, the value is determined by bond failure even in the range in which the effective embedment length is small (less than $8d_a$). In this guideline, therefore, the tensile strength of a bonded anchor rod is evaluated in terms of the strength determined by yielding of the anchor rod and the strength determined by adhesion.

The allowable bond strength of Eq. (3) is given by multiplying the embedment length for strength calculation, l_{ce}, by the average bond strength, τ_a. This is based on the assumption that tension is resisted by the average bond stress that is uniform over the embedment length for strength calculation. Figure 10 shows measured anchor bar strain distributions for effective embedment lengths (l_e) of $7d_a$, $14d_a$ and $21d_a$. At $l_e = 21d_a$, the strain distribution at the maximum strength is linear except in the bond deterioration zone near the pulled end of the bar.

Cook et al. showed that the average bond stress until le reaches $25d_a$ or so (Cook et al. 1998). Because the effective embedment length le of a bonded anchor is usually not greater than $25d_a$, this guideline uses the bond strength calculation method based on the average bond strength τ_a.

The average bond strength τ_a of Eq. (4) is determined by multiplying the basic average bond strength τ_{bavg} by α_n, which is an influence factor for edge distance and the number of anchors (group effect). The basic average bond strength τ_{bavg} is the bond strength of a bonded anchor free from the influence of edge distance and the group effect and is an experimentally determined strength. The maximum value is $10\sqrt{F_c/21}$, and this value is reduced to 90% if lightweight concrete is used.

The basic rule of post-installed bonded anchors is to secure an edge distance (c) of $10d_a$ or more and a steel bar spacing (a) of $20d_a$ or more. If the edge distance or the anchor spacing mentioned above cannot be secured, the average bond strength τ_a is reduced by use of the reduction factor α_n of Eq. (5). The reduction factor α_n is calculated by using the edge distance c.

In Eq. (4), the basic average bond strength τ_{bavg} is multiplied by the reduction factor α_n once if there is only one free edge, twice if there are two free edges (two opposite edges, two adjoining edges). If two or more anchor rods are placed close together and tensile force and shear force act in a similar manner, their mutual influence on their bond properties is allowed for in the form of the group effect. The tensile strength reflecting the group effect is calculated by multiplying the strength of the lowest-strength rod in the rod group by the number of rods.

To calculate the tensile strength of a single rod, if the anchor spacing is $20d_a$ or less, $c = a/2$ is assumed and the basic average bond strength τ_{bavg} is reduced by using an edge distance reduction factor. If both the free edge effect and the group effect are involved, the basic average bond strength τ_{bavg} is multiplied by an edge distance reduction factor for the number of times such influence occurs.

In this guideline, in connection with cone failure, edge distance (free edge effect) and anchor spacing (group effect) are allowed for in design by using the effective horizontal projected area. Similarly, in connection with bond failure, the free edge effect and the group effect are allowed for in design by using the reduction factor mentioned above instead of the effective horizontal projected area.

Comparison between the failure load of test and the calculated values is shown in Figure 15. In figure 15, the uniform bond strength (τ_a) of the edge(s) is not considered the influence ($\tau_a = \tau_{bavg}$). In concrete cone (C) failure mode (embedment depth $7d_a$), the ratios of test values to calculated values are 0.65 to 1.49 (average 1.05). In bond failure mode (BC, BSC, BS), the calculated values of "Center" are agreed with the tests result (average 1.07), but the ratios of test values to calculated values are 0.45 to 1.07 in anchoring close to edge (1-edge, 2-edge).

Therefore, the uniform bond strength is reduced by reduction coefficient. The Eq.(5) reduction coefficient α_n was suggested from pullout test in reference (Nakano and Matsuzaki 2002). The uniform bond strength (τ_a) is given by proposed Eq.(10) to (12). The uniform bond strength of "2-edge (Corner and Both sides)" is calculated using twice the reduction coefficient α_n.

$$\tau_a = \tau_{bavg} \qquad (\mathrm{N/mm^2}) \qquad \text{for } c \geq l_e \text{ (no edge)} \tag{10}$$

$$\tau_a = \alpha_1 \cdot \tau_{bavg} \qquad (\mathrm{N/mm^2}) \qquad \text{for 1- edge} \tag{11}$$

$$\tau_a = \alpha_1 \cdot \alpha_2 \cdot \tau_{bavg} \qquad (\mathrm{N/mm^2}) \qquad \text{for 2- edge} \tag{12}$$

In Figure 16, all test results are compared with the values given by design formulas, and the calculated value is listed in table 2. In "2-edge (Corner and Both sides)", the ratio of test values to calculated values are 0.71 to 1.57 (average 1.21), so all calculated value agree with test results by the suggested method. Also, the method can predict the failure (Concrete cone or bond) mode of tests.

Figure 17 shows a pull-out experiment in which a group of bonded anchor rods was pulled out. As shown in Figure 17(a), in the experiment, tensile force was applied uniformly to four deformed steel bars (D19). The anchor rods were uniformly spaced (150 mm), and the strength-affecting factors considered in the experiment were (1) the type of anchorage (cast-in-placed, injection type), (2) embedment length l_e (= $7d_a$, $14d_a$, $21d_a$), (3) free edge (1, no free edge (center)) and (4) edge distance (75 mm ($3.5d_a$), 150 mm ($7d_a$)). Figure 17(b) compares the calculated values calculated by taking into account the edge distance and anchor spacing with the measured values. Evaluation is made as in the single-bar tensile test by using 1/2 of the anchor spacing a as the edge distance c (c = b/2).

5. CONCLUSION

The conclusions in this paper are as follows:
1) For shallow embedment ($l_e = 7d_a$), the failure mode appears a concrete cone failure. For deeper embedment ($14d_a$, $21d_a$), failure results in a bond (or bond split) failure with a shallow concrete cone.
2) The failure load of bond failure type and the embedment depth have a linear relationship. The failure load decrease as the number of edge increase, and increase as the edge distance lengthen.
3) In failure load, the bond stress is almost constant throughout the bond length.
4) The method to estimate the tensile strength (failure load) of an anchor is proposed with the influence on edge(s) and anchor spacing. The method in bond failure type is model based on a uniform bond stress, and the uniform bond strength is evaluated with reduction coefficient which considered the number of edge and the edge distance.

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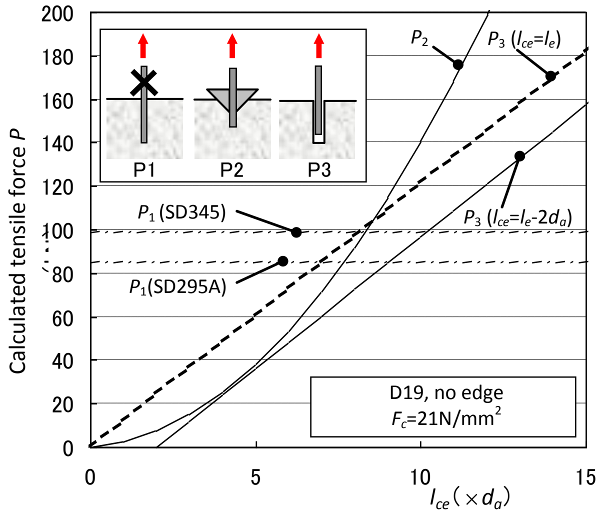


Figure 13. Tensile force and l_{ce}

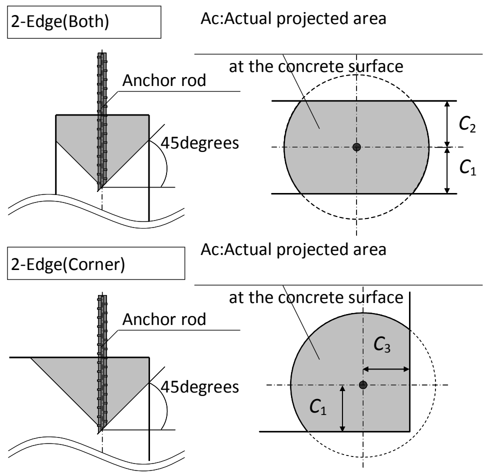


Figure 14. Actural projected area

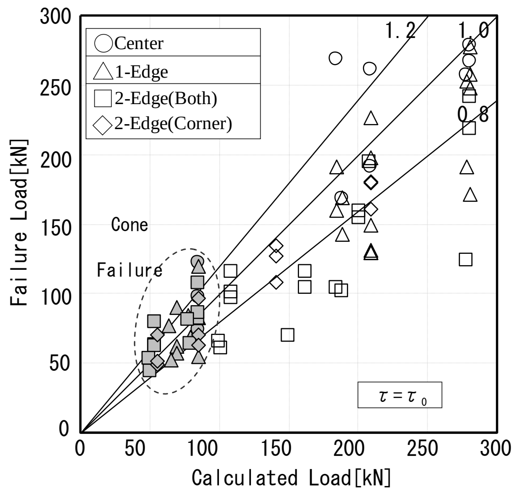


Figure 15. Calculation compared with test (case1: $\tau_a = \tau_{bavg}$)

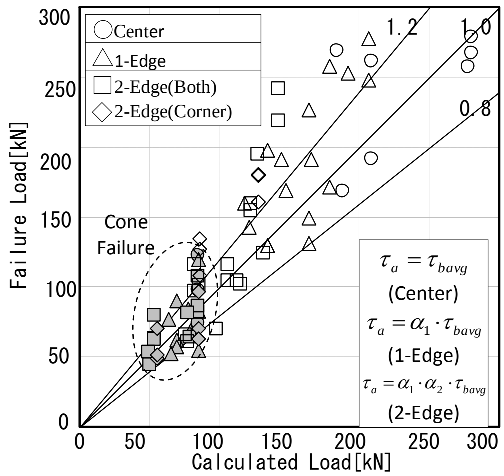
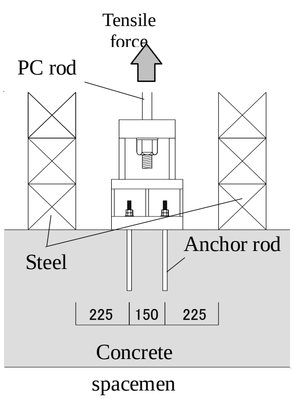
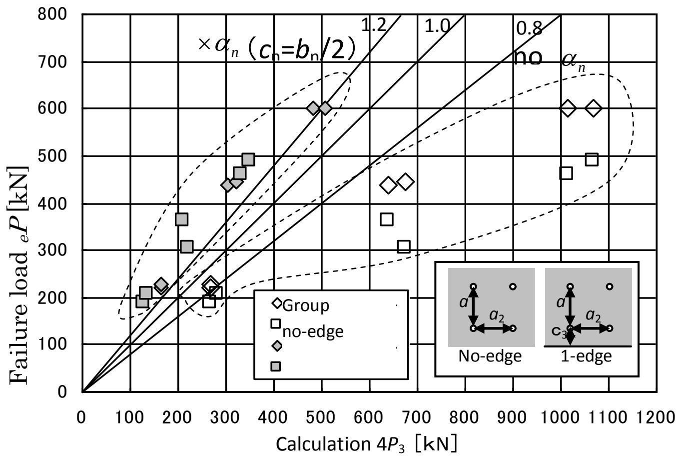


Figure 16. Calculation compared with test (case3: $\alpha_1 \cdot \alpha_2 \cdot \tau_a = \tau_{bavg}$)



(a) Load system



(b) Calculation compared with

Figure 17. Tensile result of group anchor