論 文

[2106] An Experimental Investigation on Shear Strength of Anchor Bolt Group

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1. INTRODUCTION

In practice anchor bolt is subject to shear as well as pull-out force. There have been a number of studies (1-5) on shear strength of single anchor bolt, in which failure modes are disclosed and formulae for strength prediction are presented. These failure modes are (i) concrete failure with wedge cone, (ii) concrete failure without wedge cone, (iii) concrete failure with pull-out cone, and (iv) bolt steel failure in shear. For the anchor bolt embedded in unreinforced concrete, when the embedment length, l_e is deep enough to prevent the concrete failure with pull-out cone, one of the other three failure modes will be seen according to the given combination of the anchor bolt diameter, d_b and the edge distance, d_e like shown in Fig. 1. Although some studies have been conducted on group anchor bolt, they were mainly to investigate the pull-out strength. The authors, therefore, had conducted an experimental study on double bolt anchorage under shear and revealed the effects of the anchor bolt spacing normal to the loading direction, s and the edge distance (6). In this previous study concrete failure with wedge cone among the four failure modes was largely investigated because the shear strength with this failure mode was considered to be influenced most by arrangement of anchor bolts.

This study is a continuation of the authors' previous study (6), in which bolt line of double bolt anchorage are taken to be both normal and parallel to the loading direction. The minimum spacing of anchor bolts to have no effect of the spacing on the shear strength of concrete failure with wedge cone is experimentally disclosed. Futhermore, effects of testing conditions, such as support condition of concrete block, loading plate size, initial torque for anchor bolt, and concrete casting direction, on the shear strength are discussed.

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2. OUTLINE OF EXPERIMENT

All together twenty-one single bolt anchorages and thirty double bolt anchorages were embedded in ten unreinforced concrete blocks measuring 450 x 800 x 3500 mm (height x width x length). All the anchor bolts used were ordinary mild steel with nominal ultimate tensile strength of 42 MPa, nominal diameter of 16 mm, length of 300 mm and hexagonal head. The embedment length of 200 mm was chosen so as to prevent concrete failure with pull-out cone. The concrete was ready-mixed concrete with crushed rock whose maximum size was 20 mm. During the loading, the concrete block was either fixed on the testing floor (Holding Condition A) or held down by transverse reaction beams (Holding Condition B) as shown in Fig. 2. For Holding Condition A the loading direction was horizontal and the anchor bolts were placed in the direction of concrete casting. The loading direction for Holding Condition B, however, was vertical (upwards) and the anchor bolts were placed in the direction normal to concrete casting. Two types of loading plates were used (see Table 1). The load was applied through those loading plates by hydraulic jacks and measured by load cells. Two load cells were installed for double bolt anchorage to measure the load of each bolt separately. Tightening torque on test bolt was measured before the loading. Bolt line of the double bolt anchorage was either normal or parallel to the loading direction. The edge distance was defined always as the minimum distance from the bolt center line to free edge of the concrete block measured in the loading direction.

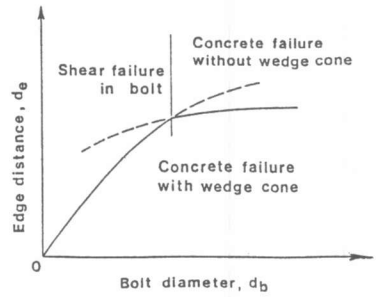


Fig. 1: Failure Modes

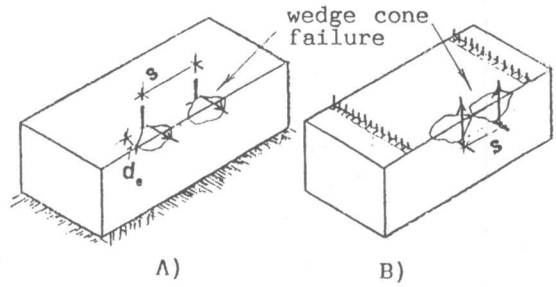
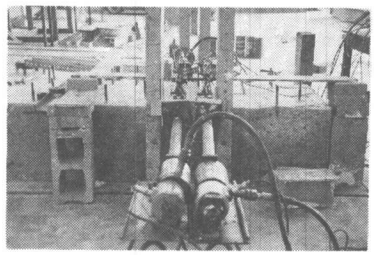


Fig. 2: Holding Condition A,B



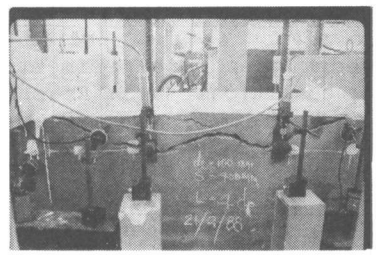


Fig. 3 : Test set-up

3. TEST RESULTS AND DISCUSSION

3.1 EFFECT OF SUPPORT CONDITION OF CONCRETE BLOCK

In this study, Holding Condition A of the concrete block was applied chiefly instead of Holding Condition B used in the authors' previous study (6). Therefore, the effect of support condition of the concrete block on the shear strength was investigated. Increase in the bolt-to-reaction beam distance, d_r from 2 d_e to 8 d_e under Holding Condition B decreases the shear strength as shown in Fig. 4. This fact agrees with the results in the previous study. The bolt-to-reaction distance shorter than $2d_e$ is considered to produce significantly large shear strength, while it can be said that the shear strength is constant for the bolt-to-reaction distance longer than 8 d_e. For the case of the bolt-to-reaction distance, $2d_e$ with edge distance of 100 mm cracking was found beneath the reaction beam, which means insufficient reaction force. It is possible, therefore, that the actual shear strength in this case is greater than the observed. On the other hand, the effect of width (100 mm) of the reaction beam was considered to exist in the case of the bolt-to-reaction distance, 2 d_e with edge distance of 50 mm. Because of the width, the failure crack surface was very steep and then the shear strength could become greater.

Holding Condition A can be considered to be Holding Condition B with an infinite bolt-to-reaction distance. It was predicted, therefore, that the shear strength with Holding Condition A was as small as that with the bolt-to-reaction distance of 8 d_e. The test results, however, indicate that the shear strengths with Holding Condition A were greater as shown in Fig. 4. The reason of this fact could be found in difference of the concrete casting direction relative to the bolt axis. For Holding Condition A, failure surface is nearly parallel to the casting direction, but nearly normal for Holding Condition B. Because of possible segregation in fresh concrete, the tensile strength of concrete in a plane normal to the casting direction (the case of Holding Condition B) may be less than that in a parallel plane (the case of Holding Condition A).

3.2 EFFECTS OF LOADING PLATE AND TORQUE FOR TIGHTENING BOLT

In order to measure the shear force of each bolt for double bolt anchorage a rather small loading plate was used for each bolt. The size of this plate (Type A) is much smaller than that in the authors' previous study (Type B). The effect of the loading plate size, therefore, was carefully examined by varying torque for tightening bolt. Figure 5 clearly indicates that clamping force induced by torque increases the shear strength and that the greater loading plate provides the greater shear strength. And it is also observed that this plate size effect is more emphasized as edge distance increases. (see the differences between S1 and S17 and between S8 and S21). It could be partly because of additional clamping force induced by elongation of anchor bolt during the test. Figure 5 also shows that a very big torque for tightening could reduce the shear strength. From the foregoing test results there could be observed the effects of clamping force, which introduces the frictional force between the loading plate and concrete block and the tensile stress in concrete surrounding the bolt.

Table 1 Specimens and Test Results

specimen	concrete strength f_c' MPa	edge distance d_e, mm	spacing s, mm	bolt-to-reaction distance	torque kN-mm	type of loading plate(1)	measured shear strength V_u, kN	$V_u\sqrt{20/f_c'}$	remark
S1	19.86	50	-	∞	22.6	A	12.4	12.4	
S2	21.05	50	-	$12d_e$	22.6	A	8.9	8.7	
S3	21.05	50	-	$8d_e$	22.6	A	6.7	6.5	
S4	21.05	50	-	$4d_e$	22.6	A	9.1	8.9	
S5	21.05	50	-	$2d_e$	22.6	A	25.0	24.4	
S6	19.86	100	-	∞	22.6	A	34.0	34.1	
S7	21.19	100	-	$8d_e$	22.6	A	25.8	25.1	
S8	28.00	100	-	$4d_e$	22.6	A	29.5	24.9	
S9	21.19	100	-	$2d_e$	22.6	A	34.4	33.4	
S10	21.19	50	-	$4d_e/6d_e$	22.6	A	12.5	12.1	
S11	21.19	50	-	$4d_e/8d_e$	22.6	A	10.7	10.4	
S12	21.19	50	-	$4d_e/12d_e$	22.6	A	13.1	12.7	
S13	21.19	50	-	$4d_e/28d_e$	22.6	A	10.5	10.2	
S14	21.05	50	-	∞	0	A	9.8	9.6	
S15	21.05	50	-	∞	45.2	A	14.7	14.3	
S16	27.00	50	-	∞	67.8	A	12.9	11.1	
S17	21.05	50	-	∞	22.6	B	16.1	15.7	
S18	21.05	50	-	∞	45.2	B	18.9	18.4	
S19	21.05	50	-	∞	67.8	B	16.9	16.5	
S20	19.86	100	-	(2)	22.6	A	35.9	36.0	
S21	28.00	100	-	$4d_e$	22.6	B	38.4	32.5	
D1	27.00	50	150	∞	22.6	A	23.2	20.0	
D2	27.00	50	300	∞	22.6	A	27.3	23.5	
D3	27.00	50	400	∞	22.6	A	28.1	24.2	
D4	27.00	50	500	∞	22.6	A	29.0	25.0	
D5	27.00	50	150	∞	22.6	A	19.0	16.4	(3)
D6	27.00	50	300	∞	22.6	A	20.6	17.7	(3)
D7	27.00	50	400	∞	22.6	A	22.0	18.9	(3)
D8	27.00	50	500	∞	22.6	A	28.0	24.1	(3)
D9	15.57	50	100	$4d_e$	22.6	A	14.8	16.8	
D10	15.57	50	200	$4d_e$	22.6	A	20.0	22.7	
D11	15.57	50	300	$4d_e$	22.6	A	21.0	23.8	
D12	15.57	100	300	$2d_e$	22.6	A	52.1	59.0	
D13	27.00	100	300	$4d_e$	22.6	A	62.6	53.9	
D14	15.57	100	300	$6d_e$	22.6	A	48.2	54.6	
D15	15.57	100	400	$2d_e$	22.6	A	58.0	65.7	
D16	27.00	100	400	$4d_e$	22.6	A	68.0	58.5	
D17	15.57	100	400	$6d_e$	22.6	A	51.2	58.0	
D18	27.00	50	50(4)	∞	22.6	A	25.2	21.7	
D19	21.19	50	50(4)	∞	22.6	A	23.4	22.7	
D20	19.86	50	100(4)	∞	22.6	A	21.6	21.7	
D21	21.19	50	100(4)	∞	22.6	A	26.1	25.4	
D22	27.00	50	200(4)	∞	22.6	A	29.0	25.0	
D23	27.00	50	300(4)	∞	22.6	A	30.8	26.5	
D24	19.86	100	50(4)	∞	22.6	A	52.2	52.4	
D25	21.19	100	50(4)	∞	22.6	A	45.5	44.2	
D26	19.86	100	100(4)	∞	22.6	A	54.8	55.0	
D27	21.19	100	100(4)	∞	22.6	A	46.7	45.4	
D28	21.05	100	200(4)	∞	22.6	A	68.4	66.7	
D29	19.86	100	260(4)	∞	22.6	A	67.2	67.4	
D30	21.19	100	300(4)	∞	22.6	A	61.6	59.8	

Note: (1) A: 40 x 40 x 23, B: 125 x 500 x 25 (heigh x width x thickness, in mm)
(2) Holding condition of the concrete block followed that in Klingner, et. al's study (2).
(3) Uneven load for each bolt (the smaller load = the greater load - 2 kN
(4) Bolt line was in the loading direction.

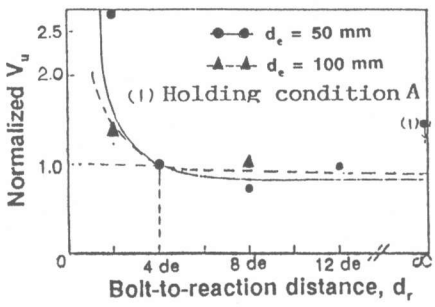


Fig. 4 : Effect of support condition

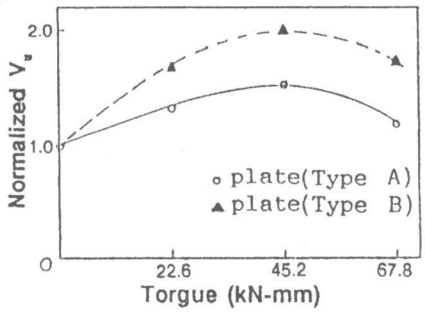


Fig. 5 : Effect of plate size and torque

3.3 EFFECTS OF ANCHOR BOLT SPACING

It was clearly observed for Holding Condition A that the shear strength of double bolt anchorage increased as the bolt spacing increased for the both cases of the bolt line normal and parallel to the loading direction. The minimum spacings to avoid interaction between the bolts, or to have the shear strength twice as much as that of single bolt anchorage, are around 8 d_e for the bolt line normal to the loading direction and 2 d_e for the bolt line parallel to the loading direction as seen in Fig. 6. The wedge cone was generally found surrounding only one bolt for large spacings in the case of the bolt line normal to the loading, while the wedge cone was always observed to include only the bolt closer to the free edge of the concrete block for the bolt line parallel to the loading except for specimens D24 and D25.

For Holding Condition B the bolt spacing was observed to have similar effect. In Fig. 7 indicating increase in the shear strength with the spacing, however, the observed shear strengths with large spacings were greater than twice the single bolt anchorage strength. The reason could be found in the test results of specimens S10 to S13. They are single bolt anchorage with the bolt-to-reaction distance, 4 d_e on one side and 6 d_e or longer on the other side. Their shear strengths all are greater than that with the bolt-to-reaction distance, 4 d_e on the both sides. For the double bolt anchorage specimens D10 and D11, the bolt-to-reaction distances for each bolt are 4 d_e/8 d_e and 4 d_e/10 d_e respectively. Because of those uneven bolt-to-reaction distances, the shear strength would be greater than twice the single bolt anchorage when the bolt spacing is large enough to avoid the interaction effect. The reason of the greater shear strength with the uneven bolt-to-reaction distances could be that the greater compressive force acting on the close reaction beam can delay the occurrence of failure cracking. The effect of this compressive force at reaction beam seems to be less significant, because the strengths with the bolt-to-reaction distance of 2 d_e are less than those with 4 d_e as shown in Fig. 7.

The shear strengths of double bolt anchorage in the previous study (6) were significantly less than those in this study. The reason may be uneven loading between two bolts as pointed in the previous study. To prove this the tests were conducted under the uneven loading (see Table 1). The test results are given in Fig. 8, in which it is clearly seen that the uneven loading condition reduces the shear strength significantly.

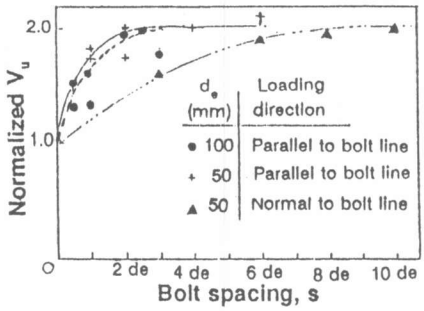


Fig. 6: Effect of bolt spacing (Holding condition A)

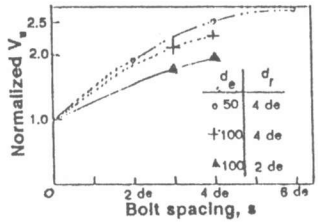


Fig. 7: Effect of bolt spacing (Holding condition B)

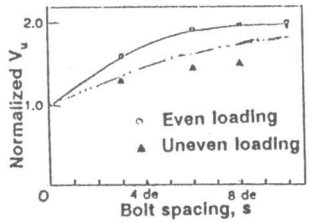


Fig. 8: Effect of load sharing between bolts

4. CONCLUSIONS

The shear strength of double bolt anchorage increases with increase in the bolt spacing for the both cases of the bolt line normal and parallel to the loading direction, and becomes twice as much as the single bolt anchorage strength for the bolt spacing of 8 d_e or more in the case of the bolt line normal to the loading and for 2 d_e or more in the case of the bolt line parallel to the loading. The clamping force of the bolt and the frictional force between the loading plate and the concrete block affect the shear strength.

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