Lateral Blow-Out Failure of Headed Studs Near a Free Edge

by J. Furche and R. Elingehausen

Synopsis: Pullout tests with headed studs placed near a free edge have been carried out. In most of the tests blow-out failure occurred. On the basis of this and other available test results an empirical equation for calculating the failure load was derived. The equation takes into account the influence of the edge distance, the concrete strength and the load bearing area. The equation for calculating the failure load shows good agreement with the test results. The equation for calculating the critical edge distance at which the failure mode changes to steel rupture or to concrete cone failure is given. The values for critical edge distance are different from the values in ACI 349, Appendix B, because of the ACI 349 overestimates the concrete capacity for large edge distances.

Keywords: Cover; embedment; failure mechanisms; loads (forces); pullout tests; studs; tension

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INTRODUCTION

The capacity of tension loaded headed studs depends on the material properties of the stud, the compressive and tensile strength of the concrete, and the size of the concrete member. The failure can be caused by rupture of the steel, by anchor pullout or, given a sufficiently high steel capacity, by concrete failure. Various types of anchor failures are shown in Figure 1.

A splitting of the concrete member can be expected if the member dimensions are small. If the member is sufficiently large, a concrete cone is formed if the bolts are set at a sufficiently large distance away from the edge. However, when the bolts are placed near the edge, the size of the concrete cone decreases with decreasing edge distance and the failure load decreases accordingly. These modes of concrete failure have been investigated quite thoroughly. The failure load of the headed stud for these modes of failure can be calculated by equation (1) /1/:

$$F_u = \chi_m \cdot 17.3 \cdot \sqrt{f_c'} \cdot l_d^{1.5} \tag{1}$$

with (see Fig. 2)

F_u = average tension failure load [N]
f_c' = concrete cylinder compressive strength [N/mm²]
l_d = embedment depth [mm]
m = edge distance [mm]
χ_m = reduction factor for close-to-edge anchorages
$= 0.3 + 0.7 \cdot m / (1.5 \cdot l_d) \leq 1$

If the ratio of edge distance to embedment depth is very small, a lateral blow-out in the area of the bolt head is likely. This mode of failure has rarely been investigated up to now. The equations for calculating blow-out failure loads proposed in literature and the values calculated for given conditions differ to a large extent. Therefore, the behaviour of single headed studs installed in uncracked concrete that exhibit blow-out failure is the subject of this paper.

LITERATURE REVIEW

According to /1,2/, lateral blow-out failure is caused by the quasi hydrostatic pressure in the area of the head, which produces a lateral force $Z = \alpha.F$ (Fig. 2). At failure the following equation applies:

$$F_u = Z_u / \alpha \qquad (2)$$

with Z_u = resisting force to lateral bursting
α = ratio between lateral force and tension load

According to /2/, the resisting force Z_u to lateral bursting is based on a uniform tensile strength $f_t = 0.33 \sqrt{f_c'}$ acting on the projected area of the failure cone with an angle of inclination of 45° starting from the bolt head. The ratio between the lateral force and the tension load is based on only a few tests, assuming $\alpha = Z/F = 0.25$. With these assumptions the following equation for the maximum load in the case of a blow-out failure applies:

$$F_u = 1.04/\alpha \cdot m^2 \cdot \sqrt{f_c'} \qquad (3)$$

with $\alpha = 0.25$

In /1/, it is assumed that the resistance Z_u can be calculated according to equation (1) when l_d is substituted by the edge distance m. The ratio $\alpha = Z/F$ was evaluated from the results of tests and was found to be $\alpha = 0.25$ to 0.6. Thus

$$F_u = \frac{1}{\alpha} \cdot 17.3 \cdot m^{1.5} \cdot \sqrt{f_c'} \qquad (4)$$

with $\alpha = 0.25$ to 0.6

According to /3/, the maximum load for blow-out failure can be calculated with equation (5).

$$F_u = 356 \cdot m \cdot \sqrt{f_c'} \qquad (5)$$

Based on 47 pull-out tests on anchors in a heavily reinforced concrete specimen, equation (6) was proposed for calculating the failure load for close to the edge anchorages /4/.

$$F_u = 11.6 \cdot A_b \cdot \sqrt{f_c'} \cdot (0.7 + \ln(c/a)) \tag{6}$$

with A_b = net bearing area [mm^2]
c = clear side cover of the bolt [mm]
a = width of shoulder [mm]

In the tests blow-out failures occurred only for small edge distances, while for larger edge distances spalling of the complete concrete cover was observed. Therefore, equation (5) predicts the blow-out failure load only for small edge distances. However, the critical edge distance, at which a change of the failure mode occurred,is not given in /4/.

According to all equations, the blow-out failure load increases in proportion to the concrete tensile strength. The influence of edge distance or side cover load on the failure load is assumed very differently. In equations (3) to (6) the failure loads increase with varying proportionality with edge distance m. Under the same conditions the failure loads predicted by the four equations vary considerably. The important influence of the load bearing area on the failure load is only taken into account by equation (6).

EXPERIMENTAL INVESTIGATIONS

Thirty five tests on single headed studs were performed /5/. While the bolt diameter (d = 25 mm) and the concrete strength (cylinder strength f_c' = 26.4 N/mm^2, splitting tensile strength f_t = 2.5 N/mm^2) were kept constant, parameters such as embedment depth l_d, edge distance m, width of shoulder a, or head diameter were varied. To model undercut anchors some tests with an angle of inclination of the bolt head $\gamma < 90^0$ (compare Fig. 2) were tested in addition. The complete program is given in Table 1.

The strength of the specially manufactured headed studs was high (> 700 N/mm^2) to exclude a steel failure. The studs were cast into the top side of large unreinforced concrete blocks (height/width/length = 0.7m/ 0.8m to 1.2m /3m to 3.6 m) with the heads down. The shafts were lubricated with oil to minimize the bond between steel and concrete. The anchors were spaced such that a concrete cone with a diameter equal to 3 l_d was possible.

The anchors were loaded by a closed loop servo-hydraulic testing machine (Fig. 3). The displacement of the hydraulic jack was increased by 0.8 mm/sec. During the test, the tension load F, the anchor displacement s and the lateral concrete displacements v were measured continuously by a data acquisition system and stored on a disk.

TEST RESULTS

All headed studs with an edge distance m = 60 mm and an embedment depth $l_d \leq 200$ mm and one headed stud with $l_d = 300$ mm exhibited a concrete cone failure. A blow-out failure was observed for the remaining 28 tests. Figure 4 shows a typical failure mode. While the concrete in the area of the head had broken out, the concrete in the direction of loading was undamaged.

In Figure 5 the size of the lateral blow-out at the concrete surface is plotted for anchors with $l_d = 400$ mm. The diameter of the lateral concrete cone was 6 to 8 times the edge distance m.

Figure 6a shows a load-displacement curve that is typical for a blow-out failure. In Figure 6b the concrete displacements perpendicular to the concrete surface (i.e. in the direction of the lateral force) are plotted. Positive displacements indicate a bulging of the concrete surface. Because the test was done under deformation control, the descending branch of the load-displacement curve and the concrete deformations after reaching the peak load could be measured. The transducers that measured the concrete displacements were connected to a rigid steel structure (see Fig. 3). During testing, the specimens were slightly tilted. This explains the measured negative displacements at the beginning of the test. At peak load, the concrete close to the head (measuring points 2 to 4) started to bulge. The concrete far away from the head measured at points 1 and 5 did not deform.

In Figure 7, the measured failure loads for anchors with a constant edge distance and head diameter are plotted as a function of the embedment depth. For an embedment depth $l_d < 200$ mm, the failure load increases according to equation (1). The failure load is almost constant for $l_d \geq 300$ mm.

Figures 8 to 10 show the influence of the edge distance, load bearing area and angle of inclination of the anchor head on the failure load. In each test series, only one selected parameter was varied at a time.

The failure load increases almost linearly with increasing edge distance (Fig. 8). According to Figure 9, the failure load depends significantly on the load bearing area. Furthermore, for anchors with an angle of inclination of the anchor head $\gamma = 90°$, a smaller failure load was measured than for headed studs with $\gamma = 90°$ (Fig. 10). The reduction for headed studs with $\gamma < 90°$ was about 50%. This result can be explained by the larger lateral forces of inclined heads. It should be taken into account when dealing with undercut anchors.

EVALUATION OF TEST RESULTS

The results of tests with headed studs ($\gamma = 90°$) showing a blow-out failure and the results given in /6/ were evaluated together. In the latter tests, the concrete strength was almost constant ($f_c' = 25$ N/mm^2). The following varied: edge distance (m = 75 mm to 175 mm), bolt diameter (d = 30 mm to 50 mm) and the width of shoulder (a = 7.5 mm to 15 mm). This variance resulted in a variation of the bearing area A_b (A_b = 880 to 3060 mm²). The embedment depth was large enough to ensure a blow-out failure. The tests were done under load control. Altogether 51 tests with blow-out failure are available.

According to equation (4), for a constant value of α, the load causing a blow-out failure increases in proportion to $m^{1.5}$. However, the test results show (Fig. 8) that the failure load increases only linearly with edge distance m. This behaviour can be explained by an increasing factor α with increasing pressure under the head.

To check this assumption, the ratios $\alpha = Z_u/F_u$ are plotted as a function of the ratio p_u/f_c' in Figure 11. The lateral resistance Z_u was calculated with equation (1), substituting l_d by m. The pressure under the head is given by $p_u = F_u/A_b$ with F_u = measured failure load. According to Figure 11, the factor α increases with increasing pressure under the head on an average from $\alpha \approx 0.2$ ($p_u/f_c' \approx 4$) to α 0.4 ($p_u/f_c' \approx 15$). For ratios p_u/f_c' > 15 the factor α should approach a limiting value. The scatter of the test results is large. Alpha ratios depend on the equation used for calculating resistance Z_u. Assuming that the lateral resistance does not increase with $m^{1.5}$ as assumed in Equation (1) but with m^2, then different values for α would be calculated.

Assuming

$$\alpha = 0.1 \cdot \sqrt{p_u/f_c'} \tag{7a}$$

with $p_u = F_u/A_b$

to describe the average test results and inserting equation (7a) in equation (4) we get

$$F_u = 31 \cdot m \cdot A_b^{1/3} \cdot f_c'^{\,2/3} \tag{7b}$$

According to equation (7b), the failure load increases linearly with the edge distance m. The influence of the concrete strength on F_u is larger than usually assumed. Whether this is correct cannot be checked, because the concrete strength was not varied in the test program. Additional tests should be performed to study the influence of f_c' on the failure load F_u.

A detailed analysis of the test results showed that the influence of the bearing area A_b was slightly underestimated by equation (7b). Therefore, a multiple regression analysis was performed assuming that F_u is proportional to $\sqrt{f_c'}$. The following equation to calculate the average failure load emerged after rounding up the exponents:

$$F_u = 16.8 \cdot m \cdot \sqrt{A_b} \cdot \sqrt{f_c'} \tag{8}$$

Equation (8) is based on 51 tests with single headed studs with a near constant concrete compressive strength where 40 mm $\leq$ m $\leq$ 175 mm, 22 mm $\leq$ d $\leq$ 50 mm and 250 mm² < A_b < 3000 mm². The calculated failure loads show good agreement with the measured values (Fig. 12). On an average the ratio $F_{u,\,test}/F_{u,\,calc.}$ = 0.99 with a coefficient of variation V = 11%. The 5% fractile of these results is given by equation (9).

$$F_{u,5\%} = 13.4 \cdot m \cdot \sqrt{A_b} \cdot \sqrt{f'_c} \qquad (9)$$

According to equation (8) the failure load increases with $\sqrt{A_b}$. In Figure 13 the failure load of all 51 available tests normalized by the factor $m.\sqrt{f'_c}$ is plotted as a function of the load bearing area. It shows that the influence of the load bearing area on the failure load is correctly taken into account by equation (8).

Equation (8) is valid for anchors in uncracked concrete. If the concrete is cracked due to tensile stresses caused by external loads or restraint of deformations, a reduction of the failure load must be expected. Further investigations should be performed.

For anchor groups close to the edge an overlapping of the lateral failure cones will occur, if the anchor spacing is smaller than the diameter of the cone. According to Figure 5, a conservative estimate of the critical spacing can be assumed to be s_c = 6 m. For smaller spacing the failure load should be reduced. The reduction should be investigated in further tests.

In the 51 tests with blow-out failure, the ratio of edge distance and embedment depth was $m/l_d \leq 0.33$. The critical edge distance, m_c, at which the failure mode changes from a blow-out to a concrete cone failure can be evaluated by equating equation (1) with equation (8):

$$m_c = 0.3 \cdot l_d/(\sqrt{A_b/l_d} - 0.5) \qquad (10)$$

In Figure 14, the ratio m_c/l_d is plotted for two common anchor types (d_1 = 19 mm, a_1 = 6.4 mm; d_2 = 25 mm, a_2 = 8 mm) as a function of the embedment depth. For edge distances smaller than the limiting value, a blow-out failure will occur. Figure 14 demonstrates that the ratio of critical edge distance to embedment depth depends significantly on the anchor type and the actual embedment depth. Therefore, a constant value for the critical ratio m/l_d independent of the stud size cannot be given.

According to /2/, the ratio, bearing area/shaft area, must be at least 1.5. Assuming this value and provided that the embedment depth is large enough to exclude a concrete cone failure, the edge distance at which a rupture of the steel might occur is given by equation (11).

$$A_s \cdot f_{ut} = 16.8 \cdot \sqrt{f'_c} \cdot \sqrt{A_b} \cdot m_s \qquad (11a)$$

$$m_s = f_{ut} \cdot d \,/\, (23.2 \cdot \sqrt{f_c'}) \qquad (11b)$$

with m_s = edge distance at which the failure mode changes blow-out to steel rupture [mm]
f_{ut} = steel tensile strength [N/mm^2]
$A_s = d^2 \cdot \pi/4$ [mm^2]
d = bolt diameter [mm]
A_b = load bearing area = $1.5 \cdot A_s$

Equation (11) is based on the average blow-out failure load (equation (8)) and safety considerations are not taken into account. Using the 5% fractile of the test results (equation (9) and applying a strength reduction factor $\phi = 0.85$ as proposed in /2/, equation (12) will be obtained.

$$m_s = f_{ut} \cdot d \,/\, (15.7 \cdot \sqrt{f_c'}) \qquad (12)$$

COMPARISON WITH LITERATURE

In Figure 15 the failure load according to equation (8) is plotted as a function of the edge distance m. The figure applies for a concrete strength $f_c' = 25\ N/mm^2$. Because the failure load depends on the bearing area, the same anchor types as in Figure 14 are used. For comparison, the failure loads according to equations (3) to (6) are plotted as well. In equation (4) an average value for α ($\alpha = 0.4$) was taken.

According to equations (3) and (4), the failure load increases with m^2 or $m^{1.5}$ respectively. Because the tests demonstrated a smaller influence of the edge distance, equations (3) and (4) overestimate the failure load for large edge distances. This is especially true for anchors with a small bearing area.

According to equation (5), the failure load is proportional to the edge distance m, but independent of the bearing area A_b. The calculated values are situated between the lines valid for equation (8) with a small and a large bearing area, respectively. Equation (5) and (8) are identical for a bearing area $A_b = 450\ mm^2$.

Equation (6) takes into account the influence of the bearing area on the failure load, but underestimates the influence of the edge distance. This can be explained: the tests in /4/ exhibited blow-out failure only for small edge distances. However, for small values of m (m < 50mm), the failure loads according to equation (6) approach the values given by equation (8).

SUMMARY AND RECOMMENDATIONS

(1) Headed studs close to an edge may fail by forming a local lateral cone in the area of the anchor head (blow-out failure). The blow-out failure load depends on the edge distance, the bearing area of the anchor head and the

concrete strength. Equations (8) and (9) can be used to calculate the average failure load or the 5% fractile with sufficient accuracy (Fig. 12). The blow-out failure load is independent of anchorage depth (Fig. 7).

(2) The critical edge distance, m_c, at which the failure mode changes from blow-out to concrete cone failure, depends on the embedment depth and the load bearing area (equation (10) and Fig. 14). Therefore, no constant value m_c/l_d can be given. For practical values of the load bearing area and the embedment depth, the critical values are between $m_c/l_d = 0.2$ and 0.4.

(3) Provided that the embedment depth is large enough to exclude a concrete cone failure and assuming a bearing area according to /2/ ($A_b = 1.5\ A_s$), the critical edge distance required to ensure a steel failure is given by equation (11) and equation (12) respectively. Equation (11) is based on the average test results while equation (12) takes safety considerations into account.

(4) According to ACI 349, Appendix B /2/, the blow-out failure load is proportional to m^2 (equation (3)). However, according to tests, the failure load increases linearly with increasing edge distance (Fig. 8). Therefore, ACI 349 overestimates the concrete capacity for large edge distances (Fig. 15).

(5) The influence of anchor spacing and of cracks in the concrete caused by external loads or restraint of deformations on the blow-out failure load, requires further investigation.

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TABLE 1 -- TEST PROGRAM

m	a	A_b	γ	Number of tests				
				Embedment depth l_d [mm]				
mm	mm	mm²	°	100	200	300	400	500
40	7.5	766	90				3	
60	│		↑	3	3	3	5	3
80	7.5	766	│				3	
60	3	264	↓				3	
↑	10	1100	90				3	
↓	7.5	766	20				3	
60	7.5	766	5				3	
			Σ	3	3	3	23	3

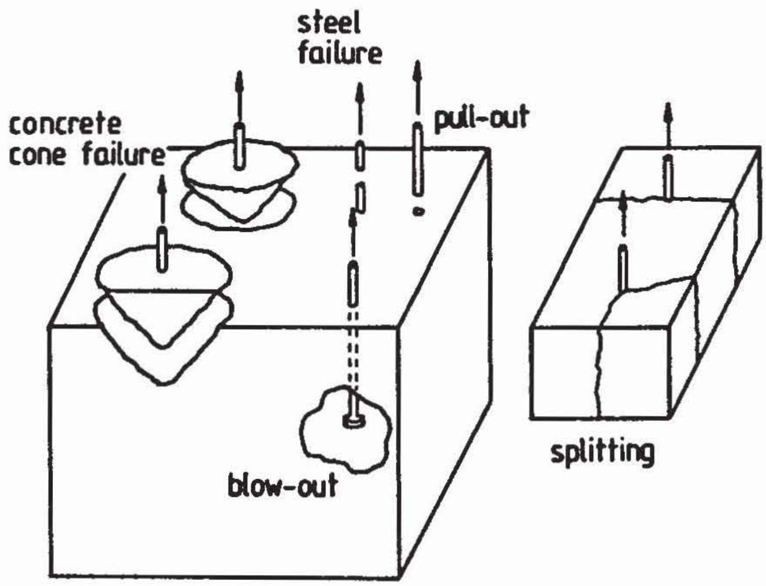

Fig. 1--Failure modes of single fastenings

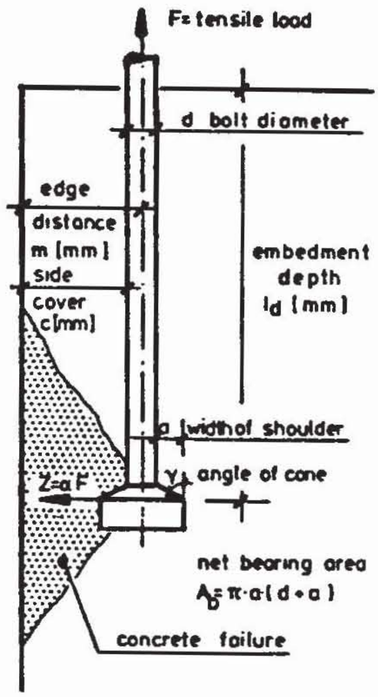

Fig. 2--Lateral blow-out by lateral force

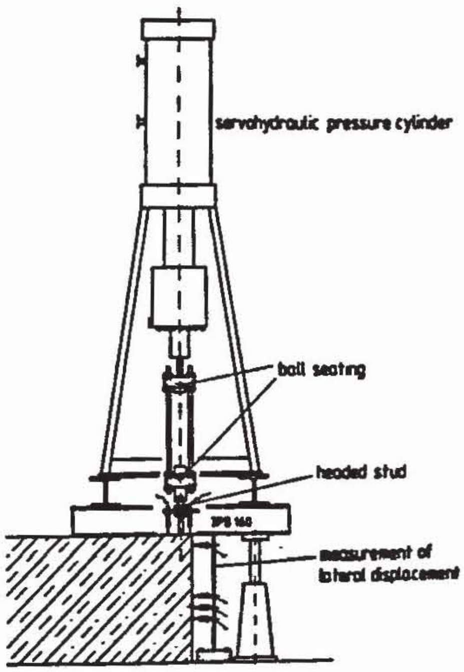

Fig. 3--Test equipment

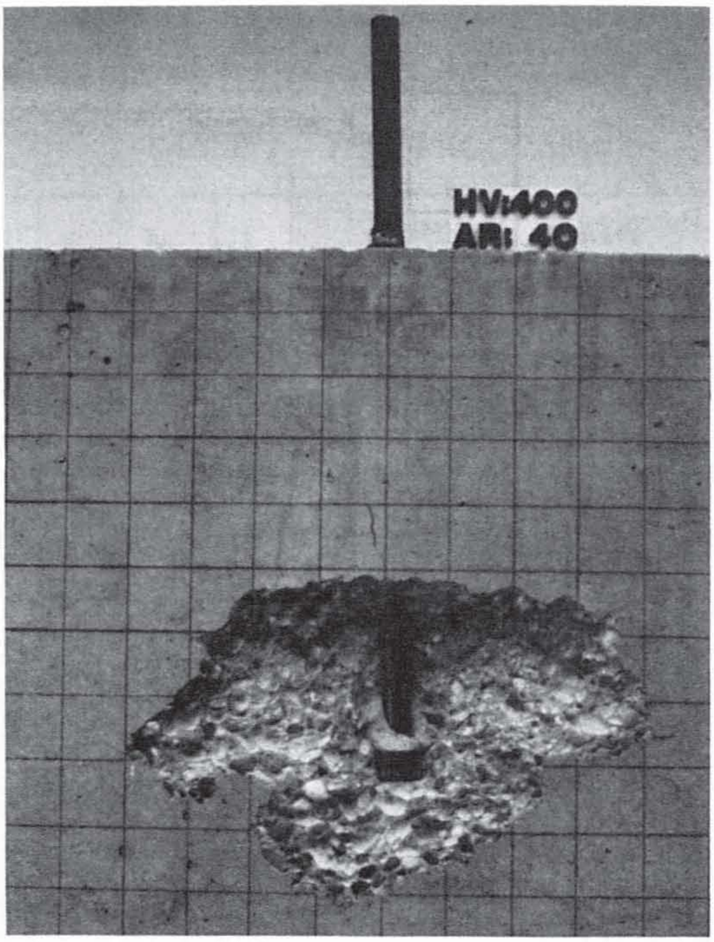

Fig. 4--Typical local blow-out at the side of the test block

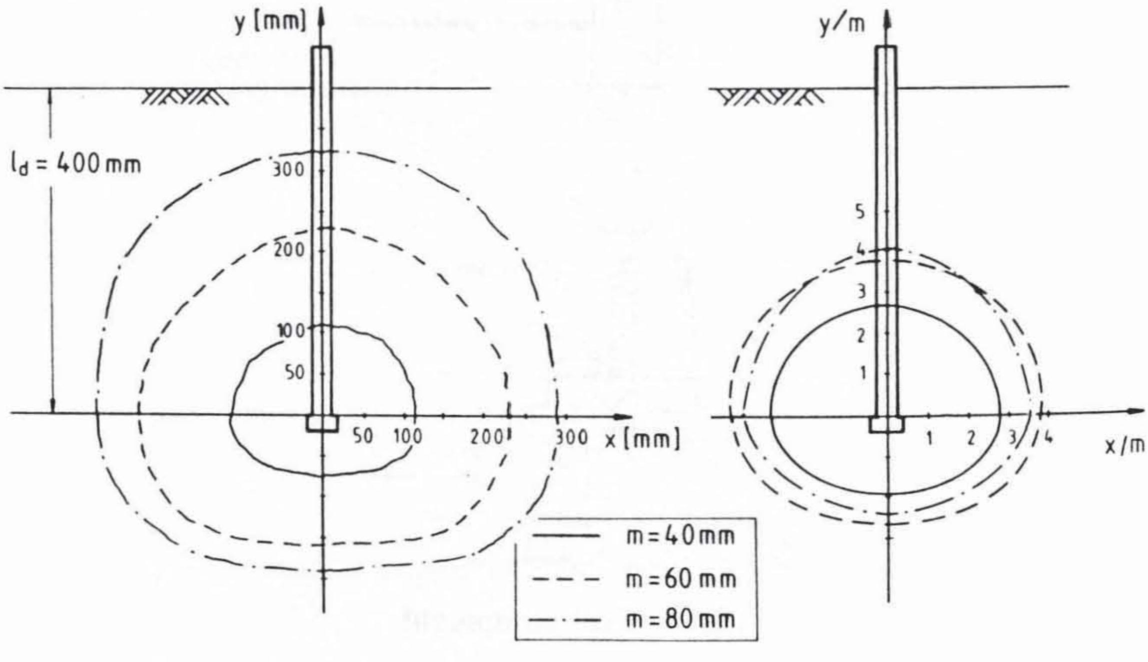

Fig. 5--Size of the lateral break-out bodies

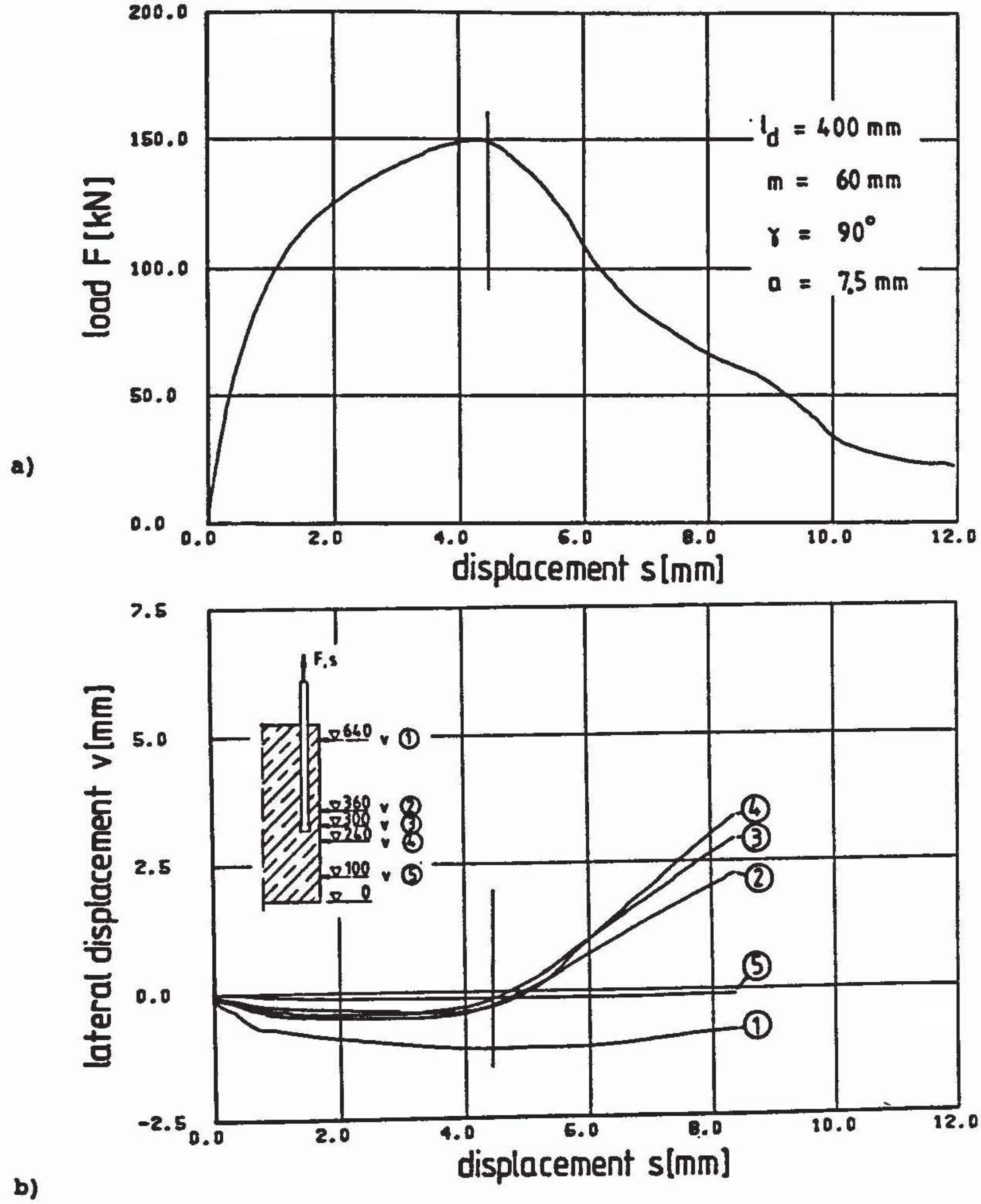

Fig. 6--Typical load-displacement curves and concrete deformations at blow-out

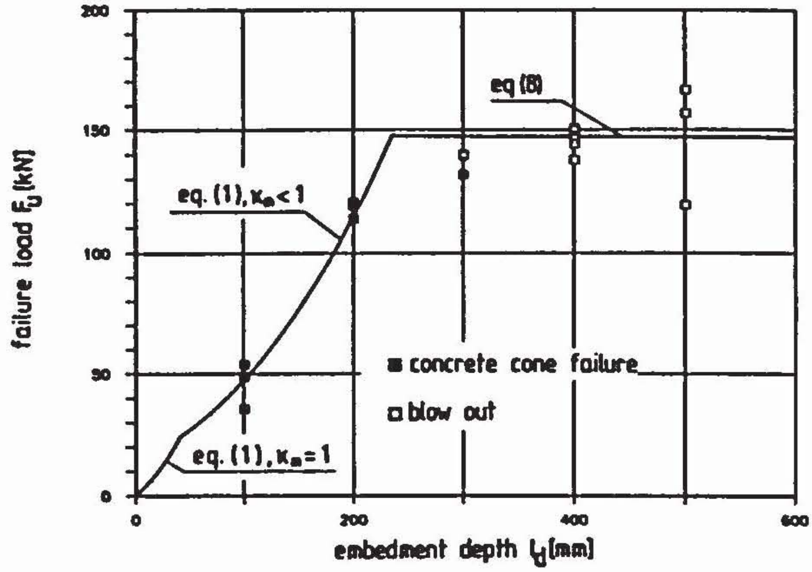

Fig. 7--Failure load F_u in relationship to embedment depth l_d (m = 60 mm, γ = 90°, A_b = 766 mm^2, f'_c = 26.4 N/mm^2)

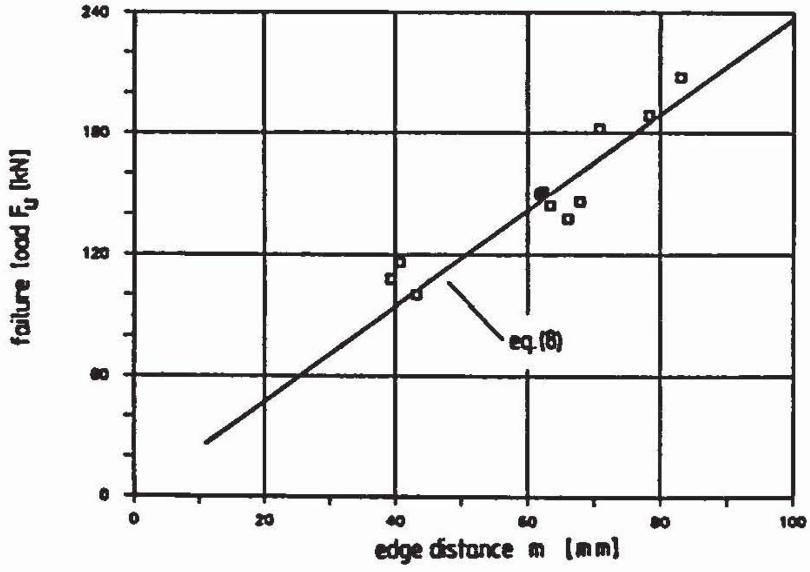

Fig. 8--Failure load F_u in relationship to edge distance m (γ = 90°, A_b = 766 mm^2, l_d = 400 mm, f'_c = 26.4 N/mm^2)

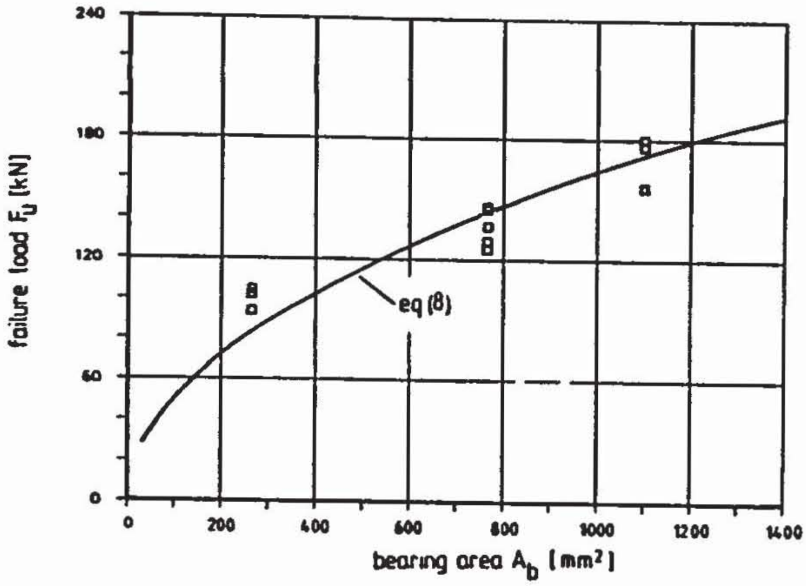

Fig. 9--Failure load F_u in relationship to load bearing area A_b
(γ = 90°, m = 60 mm, l_d = 400 mm, f'_c = 26.4 N/mm²)

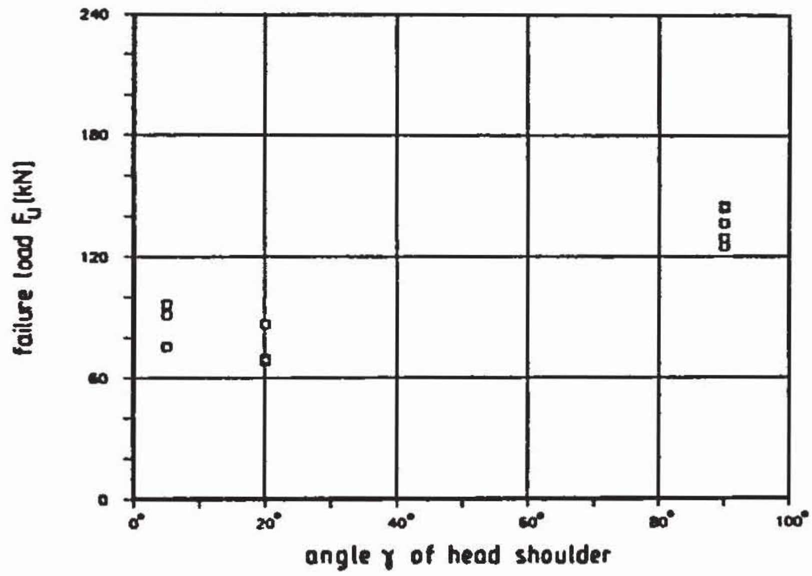

Fig. 10--Failure load F_u in relationship to the angle of inclination γ
(A_b = 766 mm², m = 60 mm, l_d = 400 mm, f'_c = 26.4 N/mm²)

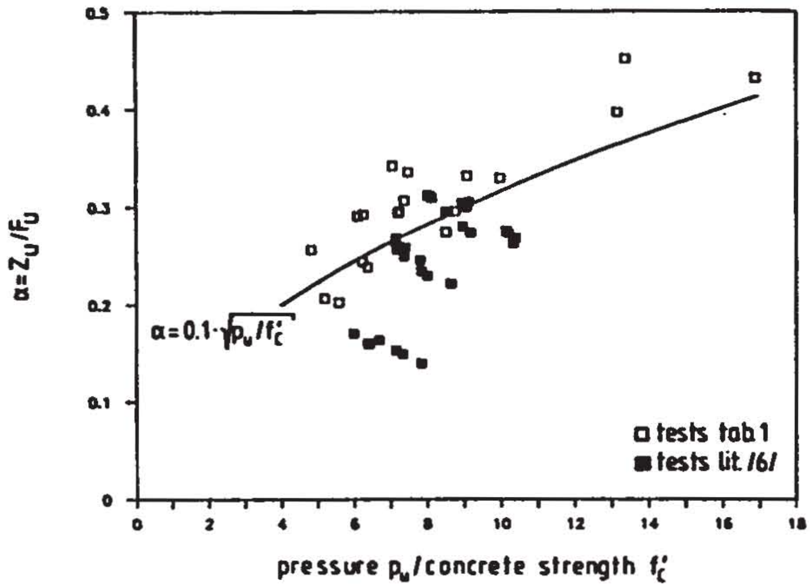

Fig. 11--Ratio α between lateral force and tensile load as a function of the ratio between the pressure in the load bearing area and concrete strength

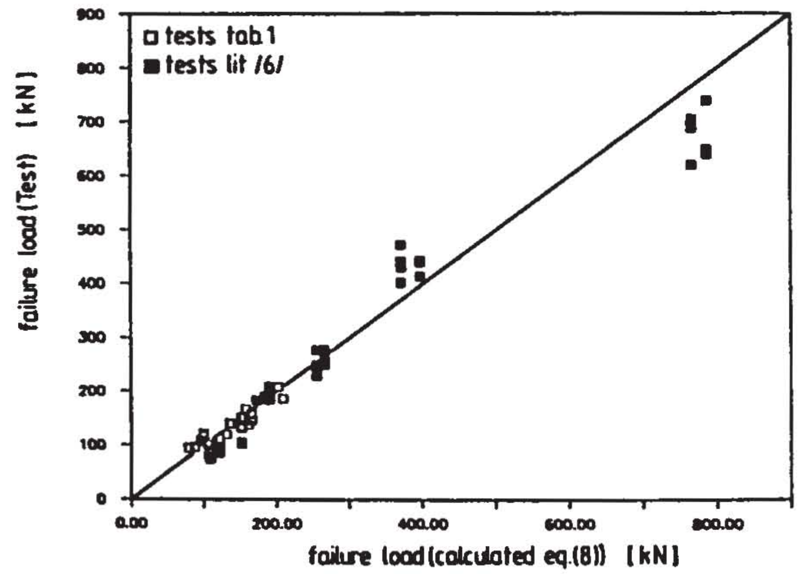

Fig. 12--Relationship of the measured failure load to the calculated maximum load [equation (8)]

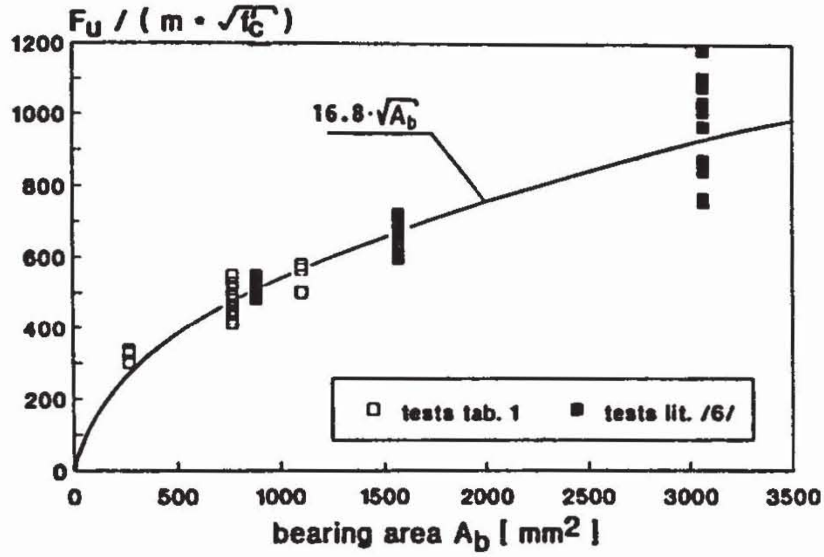

Fig. 13--Influence of the load bearing area on the failure load

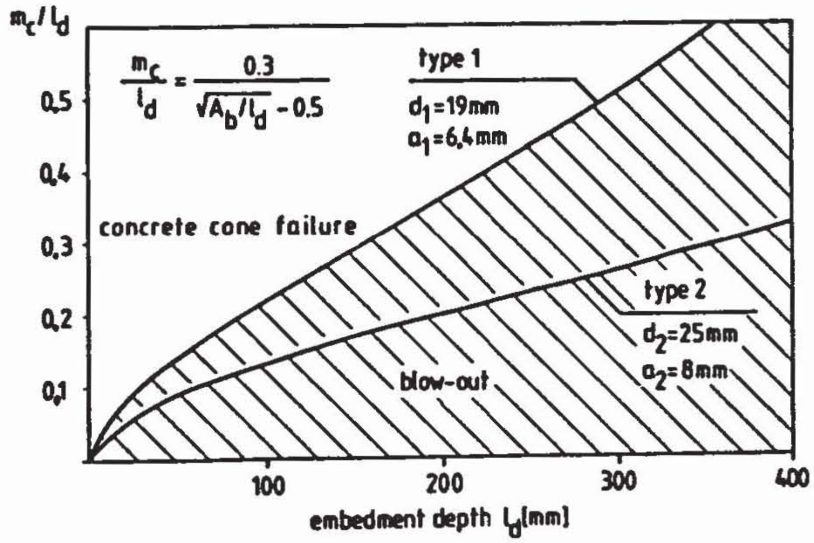

Fig. 14--Critical edge distance m_c to embedment depth l_d ratio as a function of the embedment depth

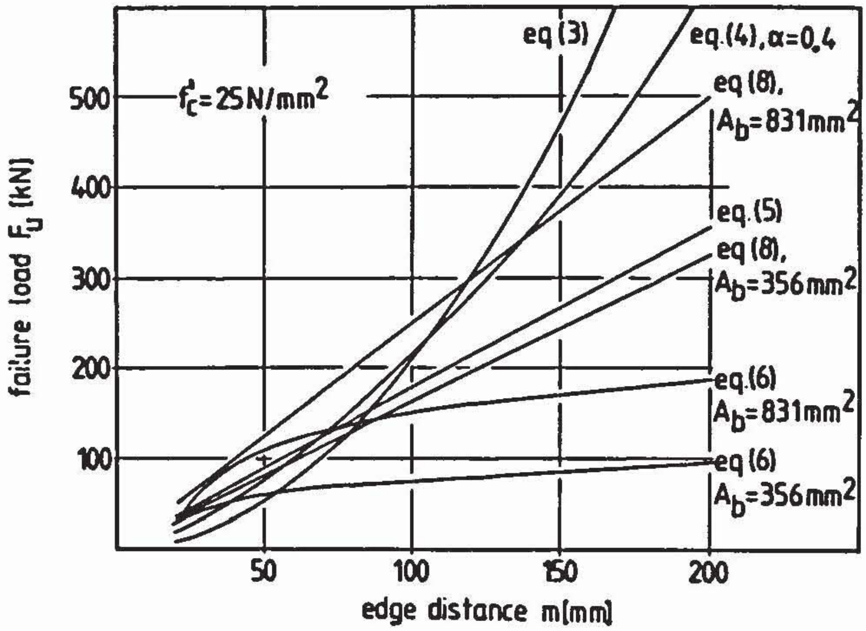

Fig. 15--Average blow-out failure load according to different equations