Behaviour of Fasteners Under Monotonic or Cyclic Shear Displacements

by E. Vintzéleou and R. Eligehausen

Synopsis: An experimental program was carried out to investigate the behaviour of metallic fasteners (undercut, torque controlled expansion and chemical anchors) embedded in cracked concrete and subjected to shear displacements.

The results show that the behaviour of all three types of anchors under shear displacements is similar. Fasteners situated close to an edge and loaded towards the edge exhibit brittle concrete failure. Cyclic loadings are possible only for displacements which are much lower than the values corresponding to the monotonic peak load. Fastenings away from an edge will cause steel failure with large displacements. During cyclic loading, a severe force-response degradation was observed. Empirical formulae are proposed to predict the strength of anchors, as well as strength degradation during cyclic loading.

Keywords: Cracking (fracturing); cyclic loads; failure; fasteners; hysteresis; shear properties

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INTRODUCTION

Metallic fasteners are widely used in many applications, including earthquake prone areas (e.g. fixing of facade elements on reinforced concrete structural elements, connections between structural elements, e.g. column to foundation). Other promising fields of application of fasteners are repair and strengthening techniques such as anchorage of additional reinforcement to old concrete of damaged elements, connections between old and new concrete to repair and/or strengthen structural elements.

However, the safe and economic use of fasteners in seismic zones should be based on appropriate design methods, taking into account the specific conditions under which fasteners have to function:

a) Since earthquakes induce cyclic displacements to the structure, the behaviour of fasteners under cyclically imposed deformations should be studied.

b) The probability that a fastener used in seismic zones will be situated in a crack is relatively high, especially for fasteners installed in regions where plastic hinges are expected to form during the earthquake. Therefore, the behaviour of fasteners embedded in cracked concrete and subjected to cyclic actions should be investigated.

c) The fastening system has to exhibit some ductility. The required ductility depends on the seismicity of the zone (i.e. on the expected maximum induced displacement), as well as on whether fasteners are installed within or outside the critical regions of the structure. Therefore, fastening systems should be designed for ductility as well as for strength.

The main aspects of behaviour and design of fasteners under seismic conditions constitute the subject of a research project which is undertaken jointly by the Institute for Building Materials, University of Stuttgart in Stuttgart, and the Laboratory of Reinforced Concrete, National Technical University in Athens. This paper, presents a part of this program which specifically deals with the behaviour of fasteners under shear actions under the conditions a) and b).

RESEARCH PROGRAM AND TEST SET-UP

Investigated Parameters

The test program is summarized in Table 1. Metallic fasteners were subjected to either monotonic or cyclic shear displacements. In order to account for the high probability of a fastener to be situated in a crack, most fasteners were embedded in cracked concrete. The crack was parallel to the direction of loading, and its width was varied between 0.10 mm and 0.80 mm. For comparison, tests in uncracked concrete were performed as well.

It is well known that the shear behaviour of anchors installed close to the edge of the concrete and loaded towards the edge is considerably improved by suitably arranged and anchored reinforcement /1/. However, since in several applications the presence of such reinforcement near the fastener cannot be guaranteed, the unfavourable case of anchors without any reinforcement transverse or parallel to the loading direction was investigated.

Three types of anchors were tested: chemical anchors, torque controlled expansion anchors, and undercut anchors (Fig. 1). The anchor thread diameter was equal to 12 mm (M 12). The embedment length for undercut and expansion was 80 mm and for chemical anchors it was 100 mm. The bolt strength was $f_{su} \approx 850$ MPa for undercut and expansion anchors and $f_{su} \approx 530$ MPa for chemical anchors.

Under tension loading, the expansion and undercut anchors showed satisfactory behaviour in cracked concrete. In contrast, the performance of tensioned chemical anchors in cracked concrete was poor /4/. The edge distance (see Figure 2a) of the fasteners varied between 80 mm and 150 mm.

Two loading histories were applied:

a) Monotonically increasing shear displacements were applied after the maximum force-response of the fastener had been reached. Thus, the falling branch of the shear force-shear displacement relationship was also recorded. The results of the monotonic tests were used as a reference for the evaluation of test conditions for the cyclic tests.

b) Cyclically imposed shear displacements: The fastener was subjected to full displacement reversals between $\pm\lambda\Delta u$ up to an approximate stabilization of the force-response. Here Δu was the shear displacement corresponding to the maximum monotonic shear resistance, and λ was varied between 0.33 and 2.00. Subsequently, monotonically increasing displacements were imposed.

Specimens and Testing Procedure

The specimens, concrete blocks 3.20 m long, 0.55 m wide and

0.30 m thick (Fig. 2a), were cast horizontally in wooden forms. Ready-mixed concrete, composed of crushed limestone aggregate with maximum diameter of 30 mm, and Portland cement, was used. During hardening of the concrete, the specimens were kept wet. After demoulding, no special curing was provided to the specimens, which remained in the laboratory up to the time of testing (concrete age about 6 weeks). The mean compressive strength of the concrete (measured on 12 cylinders 150/300 mm at the time of testing) was $f'_c = 25$ MPa, while its splitting tensile strength was $f_t = 3.0$ MPa.

Before casting, metal sheets 0.30 mm thick, spaced at 280 mm, were placed in the mould to serve as crack initiators (see Figure 2a, b). The specimens were reinforced with six deformed bars 18 mm in diameter.

The following testing procedure was used (Fig. 2):

a) The specimen was placed in the testing frame. To avoid bending, it rested on a steel "I" beam (Figure 2b). The six longitudinal reinforcing bars were bolted to a steel plate "A" (Fig. 2a), which was connected to four steel rods "B". These rods, passing through the frame "E", were bolted on a steel beam "C". Between the beam "C" and the frame "E" a hydraulic jack "D" was placed to allow for the application of axial tension to the specimen. At the other end of the specimen, the longitudinal reinforcing bars were bolted to the testing frame.

b) The specimen was subjected to axial tension until hairline cracks (width $w \approx 0.05$ mm to 0.10 mm) opened, mainly at the crack initiators. The crack widths were measured by means of a dial gauge (measuring length 100 mm) placed in locating discs glued before the test on the upper face of the specimen to both sides of each crack initiator (see Fig. 2c).

c) The tensile load was released and fasteners were installed into the hairline cracks. The sleeve of each expansion anchor was shortened so that it was flush with the concrete surface after correct installation. In contrast, the sleeves of the undercut anchors extended above the concrete surface and were flush with the loading plate "I" (Fig. 2c).

d) The tension load was re-applied and cracks were opened to a pre-selected width. The crack width was kept constant throughout the test by adjusting the tension load accordingly.

e) To prevent the specimen from moving laterally out of the testing frame when shear displacements were applied to the anchor, two metallic tubes "H" (see Fig. 2a) were bolted between the specimen and the reaction beam "F". The distance between the fastener and each tube was approximately 300 mm.

f) After placing the loading plate "I" a transducer was installed to measure the shear displacement of the anchor (Fig. 2c). A sheet of teflon was placed between the loading plate and the upper face of the specimen to reduce friction.

g) Shear displacements (monotonic or cyclic) were imposed by a servo-controlled hydraulic jack "G", and the shear force-shear displacement relationship was recorded with an x-y recorder.

TEST RESULTS

The main test results are summarized in Tables 2 and 3.

Failure Modes

Under monotonic and cyclic actions, two modes of failure were observed:

a) Concrete failure: A concrete cone with an angle of approximately 120° formed (Fig. 3) at the maximum shear response. An abrupt decrease in capacity was observed after loss of the concrete cover for the fastener. In some tests of undercut anchors with c = 150 mm, crushing of the concrete in front of the anchor occurred before the formation of the failure crack (Fig. 4).

b) Steel failure: Fracture of the anchor bolt occurred at the maximum force response, preceded by conchoidal crushing of the concrete in front of the anchor (Fig. 5).

The mode of failure depended on the edge distance, on the diameter and embedment depth of the anchor, and on the member thickness, as well as on the strength of the steel and the concrete. Within this program (compare Tables 2 and 3), concrete failure was observed for undercut anchors with c ≤ 150 mm and for expansion anchors with c = 80 mm and for some anchors with c = 150 mm. A steel failure was observed for most expansion and all chemical anchors with an edge distance c = 150 mm.

Shear Force-Shear Displacement Relationships

In Figure 6 some shear force-shear displacement relationships for monotonic loading, typical for the two failure modes, are shown.

It may be observed that all fasteners undergo an initial shear displacement without mobilization of any shear resistance. This can be explained by the existence of an initial gap between the anchor and the loading plate due to a slightly oversized hole. Furthermore, for expansion and undercut anchors the diameter of the drilled hole at the concrete surface is larger than the outer sleeve diameter. Therefore, some displacement must take place before the anchor contacts the surrounding concrete.

In Figure 6a it may be seen that in case of a concrete failure (c = 80 mm) the V-Δ-relationship is practically linear up to peak load. In contrast, for steel failure (c = 150 mm), the initial linear part of the V-Δ curve is followed by a considerably non-linear curve when yielding of the anchor occurs (Fig. 6b, 6c). Therefore, the shear displacements at peak load of anchors with c = 150 mm are much higher than for anchors with c = 80 mm.

In both types of failure (separation of a concrete cone or fracture of the anchor), the load-displacement curve after peak load dropped almost vertically.

In Figure 7 some typical V-Δ curves obtained from the cyclic tests are presented. For comparison the monotonic envelope is plotted as well.

All anchors tested under cyclic deformations exhibited the following common features:

a) For anchors with c = 80 mm, there is a pronounced asymmetry of the hysteresis loops in the two loading directions (Figure 7a). This can be explained by the different concrete cover of the fastener in the two loading directions.

b) For all types of anchors a considerable force-response degradation during cycling was recorded. This degradation was more pronounced in the early loading cycles.

c) The pinching effect was very significant in both loading directions. Thus, even during the second reversal, relatively large shear displacements were necessary for the mobilization of the force-response of the anchor. As a consequence, the area within the hysteretic loops (and therefore the hysteretic damping) was very small.

d) For displacements larger than the peak values during cyclic loading (maxΔ <Δu), the monotonic envelope is reached again and is followed thereafter. This behaviour occurs for both failure modes. Therefore, cyclic loading has no significant effect on the maximum anchor shear resistance and on the corresponding shear displacements, if cyclic loading is performed between shear displacements smaller than the value corresponding to the monotonic peak resistance.

DISCUSSION OF TEST RESULTS

Influence of Crack Width on the Maximum Force-Response

a) Concrete Failure

In Figure 8 the values of the maximum shear force V_u are plotted as a function of the widths of the cracks in which the anchors were installed. The figure is valid for expansion and undercut anchors with an edge distance c = 80 mm. It can be observed that the strengths of undercut and expansion anchors do not differ significantly. This finding agrees with /2/. Furthermore, as noted before, cyclic loading between displacements maxΔ < Δu does not decrease the failure load. As can be seen, the shear resistance V_u decreases with increasing crack width. The reduction is about 30% for crack widths $w \geq 0.3$ mm. The same reduction was observed in /2/.

b) Steel Failure

In Figure 9 the maximum shear response values V_u are plotted against the widths of cracks in which expansion or chemical anchors were installed. The V_u-values obtained from cyclic tests are also included. For comparison, the shear failure loads predicted by equation (3) /7/ are plotted as well.

$$V_u = 0.6 \cdot A_s \cdot f_{su} \qquad (1)$$

where

A_s = stressed area of the anchor
f_{su} = tensile strength of steel

Although the number of test results is rather small, it seems that the maximum mobilized shear resistance is independent of the crack width and is not influenced by cyclic loadings applied previously. The failure loads predicted for expansion anchors agree satisfactorily with the measured values. However, for chemical anchors the measured failure loads are on an average about 10% smaller than the predicted value. This might be due to the fact, that because of the high bearing stresses on the loaded side of the anchor, the concrete crushes and a combined shear/bending failure of the anchor shank occurs near the concrete surface. Thus, the shear load required to fail the anchor in this combined mode is less than that required to fail it in pure shear.

Influence of Edge Distance on the Concrete Failure Load

In Figure 10 the concrete failure loads measured in cracked concrete ($w \geq 0.3$ mm) are plotted as a function of edge distance. For comparison, the failure loads predicted by the empirical equation (2) proposed in /2/ are plotted as well.

$$V_u = \chi_w \cdot 1.1\,(l_d/d_s)^{0.2} \cdot \sqrt{d_s} \cdot \sqrt{f'_c} \cdot c^{1.5} \ [N] \qquad (2)$$

with

χ_w = 1.0 uncracked concrete
= 0.7 cracked concrete, $w \geq 0.3$ mm
l_d = embedment depth
d_s = diameter of the anchor sleeve (undercut and expansion anchors) or diameter of the drilled hole (chemical anchors)
f'_c = concrete compression test at time of testing measured on cylinders d/h = 150/300 mm
c = edge distance [mm]

Width l_d = 80 mm, d_s = 18 mm, and f'_c = 25 MPa one gets

$$V_u = 22.0 \cdot c^{1.5} \qquad (3)$$

Equations (2) and (3) are valid for a member depth $h \geq 1.4\ c$. For thinner members the failure load will be reduced /2/. As explained above, eqn. (2) is also valid for anchors subjected to cyclic actions, provided no fatigue failure occurs.

From Figure 10 it may be seen that the average shear resistance of the "fastener-concrete" system can be predicted satisfactorily by eqn. (2). For n = 18 tests, on an average the ratio $V_{u,\ test}/V_{u,\ predicted}$ is 1.03 with a coefficient of variation V = 15%.

Note that the concrete failure loads increase in proportion to $c^{1.5}$ which can be explained by the size effect /3/. Similar behaviour was found for the concrete cone failure load of tension anchors, which is proportional to $l_d^{1.5}$ (l_d = embedment depth) /4,5/. In /6/ it is assumed that the concrete failure load is proportional to the area of the failure surface, which is a function of c^2 (shear loading) or l_d^2 (tension loading) respectively. When compared with the presented test results, the influence of the edge distance on the shear resistance of anchors failing the concrete is overestimated by this assumption.

Influence of Concrete Cover on the Shear Displacement at Failure

In Figure 11 the shear displacements Δ_u at failure are plotted as a function of the edge distance c. The shear displacement at failure increases with increasing edge distance. For edge distances $c \leq 120$ mm, the Δ_u-c relationship is almost linear while for larger edge distances a significant increase of the Δ_u-values is recorded. This is associated with the change of the failure mode from concrete failure ($c \leq 120$ mm) to steel failure (c = 150 mm). It should also be noted that the tests did not show a significant influence of cycling on the shear displacements at failure.

Influence of Cycling on the Force-Response

In Figure 12 the force-response during the n-th displacement reversal, normalized to the force-response of the first cycle (V_n/V_1), is given as a function of the number of cycles. In the figure the results of all cyclic tests are plotted independently of the crack width and the edge distance of the anchor, since no clear influence of these two parameters on the hysteretic behaviour of fasteners was observed. During cyclic loading, no failure occurred and during the subsequent loading either a steel or a concrete failure was observed depending on the edge distance. Therefore, the strength and stiffness degradation was due to the local deterioration of the concrete at the loaded side of the anchor and no significant influence of the maximum load on the response degradation was found. This agrees with previous cyclic tests on dowels /8/.

Although the scatter of the measured V_n/V_1 values is quite large, the following empirical formula might be used to estimate the expected force-response during the n-th displacement reversal ($n < 10$):

$$V_n = V_1 \left[1 - \delta \sqrt{n-1}\right] \qquad (4)$$

where

δ = 0.11 for undercut anchors
0.13 for expansion anchors
0.17 for chemical anchors

CONCLUSIONS

The test results with undercut, torque controlled expansion and chemical anchors presented in this paper allow the following conclusions:

(1) The behaviour of the three types of anchors under monotonic and cyclic shear loading was similar in spite of the fact that their behaviour under tension loading is rather different, especially in cracked concrete.

(2) Fastenings with a small edge distance fail by breaking out a concrete cone. The failure load can be predicted with sufficient accuracy for practical purposes by eqn. (2). It increases in proportion to $c^{1.5}$ (c = edge distance) and decreases with increasing crack width w. For $w \geq 0.3$ mm the failure load is about 70% of the value measured in uncracked concrete.

(3) Fastenings with a large edge distance fail by rupture of the steel, usually preceded by crushing of the concrete in front of the anchor. The corresponding edge distance depends on anchor diameter and steel strength as well as concrete strength and member thickness. The failure load can be predicted by equation (1). For the tested anchors it was almost independent of the crack width.

(4) In both types of failure the load-displacement curve after peak load was almost vertical. Therefore, meaningful cyclic loading can only be imposed between displacements smaller than the value corresponding to peak load.

(5) During cyclic loading between displacement values $\Delta max \leq 0.75\ \Delta_u$, considerable force-response degradation took place and a very pronounced pinching effect was observed. This behaviour was independent of the failure mode. Torque controlled expansion anchors and especially chemical anchors seemed to be more sensitive to cyclic actions than undercut anchors.

(6) For displacements larger than the maximum value during cycling, the monotonic envelope is reached again and followed thereafter. Therefore, cyclic actions between $\Delta max \leq 0.75\ \Delta u$ have no significant influence on the shear resistance and the displacement at peak load. This is valid for concrete and steel failure. Therefore, equations (1) and (2) are also valid for anchors under cyclic excitations.

7) It should be noted, however, that steel failure (which may be ensured by providing sufficient edge distance or,

alternatively, by adequate placing of sufficient transverse reinforcement) is associated with large shear displacements. Hence, when the anchor is designed to fail by fracture of the steel, the tested anchors might be used also in seismic zones, provided that the expected maximum shear displacement to be imposed to the anchor is smaller than the value corresponding to peak load.

NOTATIONS

A_s - stressed cross-sectional area of the anchor
c - edge distance in the loading direction
max Δ - maximum shear displacement during cycling
Δu - shear displacement corresponding to the maximum shear response V_u under monotonically increasing displacments
f_c' - concrete compressive strength measured on cylinders 150/300 [mm]
f_{su} - tensile strength of steel
n - number of full displacement reversals
V_1 - force-response during the first cycle
V_n - force-response during the n-th cycle
V_u - maximum mobilized shear response
w - width of the crack in which an anchor is installed

CONVERSION FACTORS

1 mm - 0.0394 in
1 kN - 0.225 kips
1 MPa - 145psi

REFERENCES

/1/ Klingner, R.E., Mendonca, I.A., Malik, I.B.: "Effect of Reinforcing Details on the Shear Resistance of Anchor Bolts under Reversed Cyclic Loading", ACI-Journal, Jan./Feb. 1982, pp. 3-12.

/2/ Fuchs, W. and Eligehausen, R.: "Tragverhalten von Befestigungselementen im gerissenen Beton unter Querzugbeanspruchung" (Behaviour of Fastening Elements in Cracked Concrete Under Shear Loading). Report No. 1/41-89/15, Institut fur Werkstoffe im Bauwesen, University of Stuttgart, July 1989, in German.

/3/ Bazant, Z.P.: "Size Effect in Blunt Fracture: Concrete, Rock, Metal", ASCE Journal of Engineering Mechanics 110 (4), pp. 518-535.

/4/ Eligehausen, R., Fuchs, W. and Mayer, B.: "Tragverhalten von Dübelbefestigungen bei Zugbeanspruchung" (Load-bearing Behaviour of Anchor Fastenings in Tension). Betonwerk + Fertigteil-Technik, 1987, Heft 12, and 1988, Heft 1, in German and English.

/5/ Eligehausen, R. and Ozbolt, J.: "Size Effect in Anchorage Behaviour", Will be published in Proceedings, ECF8 Fracture Behaviour and Design of Materials and Structures, Turin, Oct. 1990.

/6/ ACI 349-76: Code Requirements for Nuclear Safety Related Concrete Structures, Appendix B: Steel Embedments. ACI Journal, Aug. 1978.

/7/ Eligehausen, R. and Fuchs, W.: "Tragverhalten von Dübeln unter Quer- und Schrägzug sowie Biegebelastung" (Load-bearing Behaviour of Anchor Fastenings Under Shear, Combined Tension and Shear or Flexural Loading). Betonwerk + Fertigteil-Technik, 1988, Heft 2, pp. 448-456.

/8/ Vintzéleou, E. and Tassios, T.P.: "Behaviour of Dowels under Cyclic Deformations", ACI Structural Journal, Jan./Feb. 1987, pp. 18-30.

TABLE 1 -- TEST PROGRAM

Anchor Type	Edge Distance c [mm]	Crack Width w [mm]	Loading History [1]	Number of Tested Anchors
Undercut Anchor	80	0.00	M	3
		0.10	M	1
		0.20	M	1
		0.30	M	1
		0.40	M	1
		0.80	M	1
		0.40	$\pm 2\Delta_u$	2
		0.40	$\pm 0.33\Delta_u$	1
		0.40	$\pm 0.75\Delta_u$	1
	120	0.10	M	1
		0.20	M	1
		0.40	M	1
		0.80	M	1
		0.10	$\pm 0.40\Delta_u$	2
		0.40	$\pm \Delta_u$	2
		0.80	$\pm 2\Delta_u$	1
	150	0.00	M	1
		0.30	M	1
		0.30	$\pm 0.33\Delta_u$	1
		0.30	$\pm 0.75\Delta_u$	1
		0.35	$\pm 0.33\Delta_u$	1
Torque Controlled Expansion Anchor	80	0.00	M	1
		0.20	M	1
		0.30	M	1
		0.40	M	1
		0.20	$\pm 0.5\Delta_u$	1
	150	0.00	M	4
		0.20	M	2
		0.00	$\pm 0.67\Delta_u$	1
		0.00	$\pm 0.5\Delta_u$	1
		0.25	$\pm 0.5\Delta_u$	1
		0.35	$\pm 0.5\Delta_u$	1
		0.40	$\pm 0.5\Delta_u$	1
		0.60	$\pm 0.5\Delta_u$	2
Chemical Anchor	150	0.30	M	2
		0.25	$\pm 0.5\Delta_u$	1
		0.40	$\pm 0.5\Delta_u$	2
		0.40	$\pm 0.67\Delta_u$	3

[1] M: monotonically imposed shear displacements, loading towards the edge

$\pm\lambda\Delta_u$ (λ = 0.33-2.00): full shear displacement reversals between the extreme values $+\lambda\Delta_u$, $-\lambda\Delta_u$, where Δ_u is the displacement corresponding to the maximum shear force under monotonic loading

$+\Delta_u$: shear loading towards the edge (first half cycle)

TABLE 2 -- RESULTS OF MONOTONIC TESTS

Type of Anchor	w [mm]	c [mm]	1) V_u [kN]	2) Δ_u [mm]	Mode of failure
Undercut	0.00	80	25.8	5.6	Concrete
	0.00	80	20.2	5.0	"
	0.00	80	25.4	4.0	"
	0.10	80	20.6	4.9	"
	0.20	80	17.4	3.2	"
	0.30	80	14.8	2.8	"
	0.40	30	10.8	2.3	"
	0.80	80	16.0	3.2	"
	0.10	120	30.0	5.3	"
	0.20	120	25.6	4.9	"
	0.40	120	28.8	5.9	"
	0.80	120	29.2	4.5	"
	0.00	145	50.7	15.2	"
	0.30	145	44.0	16.3	"
Expansion	0.00	80	22.6	8.0	Concrete
	0.20	80	20.8	7.4	"
	0.30	80	19.4	6.8	"
	0.40	80	16.0	5.8	"
	0.00	150	44.7	15.3	"
	0.00	150	40.6	14.5	"
	0.00	150	45.0	15.0	Steel
	0.00	150	40.0	20.3	Concrete
	0.20	150	47.3	19.0	"
	0.20	150	45.0	16.5	Steel
Chemical	0.30	150	26.0	15.0	Steel
	0.30	150	24.0	15.0	"

1) V_u: maximum shear response
2) Δ_u: shear displacement at maximum shear response

TABLE 3 -- RESULTS OF CYCLIC TESTS

Type of Anchor	w [mm]	c [mm]	$\lambda = \frac{\max\Delta^1}{\Delta_u}$	2) V_u [kN]	3) Δ_u [mm]	Mode of failure
Undercut	0.40	80	2.0	17.2	2.3	Concrete
	0.40	80	2.0	17.4	2.3	"
	0.40	80	0.33	23.0	3.5	"
	0.40	80	0.75	18.0	3.4	"
	0.10	120	0.4	36.0	6.3	"
	0.10	120	0.4	35.7	6.8	"
	0.40	120	1.0	30.6	4.9	"
	0.40	120	1.0	30.0	5.6	"
	0.80	120	2.0	37.4	6.7	"
	0.30	150	0.33	46.5	16.0	"
	0.35	145	0.33	47.2	19.0	"
	0.30	150	0.75	40.5	8.5	"
Expansion	0.20	80	0.50	24.3	12.0	Concrete
	0.00	150	0.67	42.0	18.0	Steel
	0.00	150	0.50	45.7	15.0	"
	0.26	150	0.50	40.7	14.0	"
	0.35	150	0.50	46.4	19.0	"
	0.42	150	0.50	44.4	17.0	"
	0.60	150	0.50	36.0	22.5	"
	0.60	150	0.50	44.0	19.0	"
Chemical	0.25	150	0.50	22.7	14.0	Steel
	0.40	150	0.50	28.7	13.0	"
	0.40	150	0.50	19.3	15.0	"
	0.40	150	0.67	20.2	13.0	"
	0.40	150	0.67	26.7	8.0	"
	0.40	150	0.67	23.2	11.0	"

1) max Δ: maximum displacement during cyclic loading
2) V_u: maximum shear response
3) Δ_u: shear displacement at maximum shear response

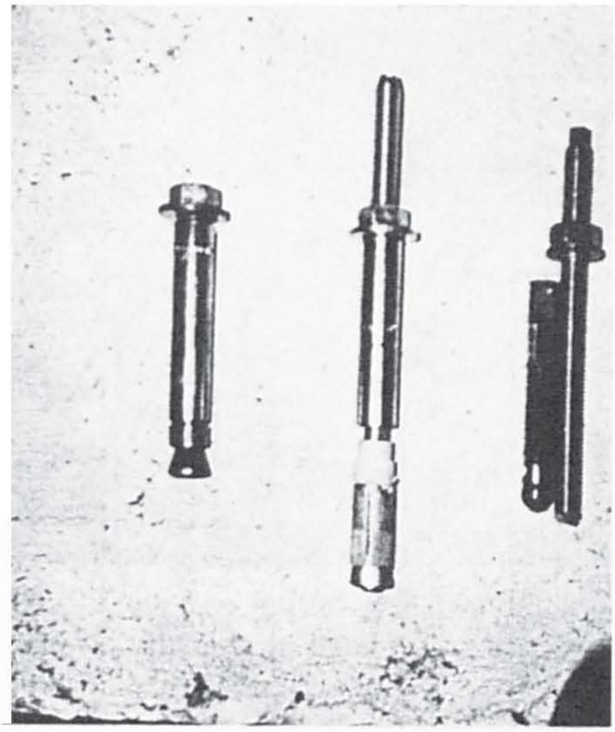
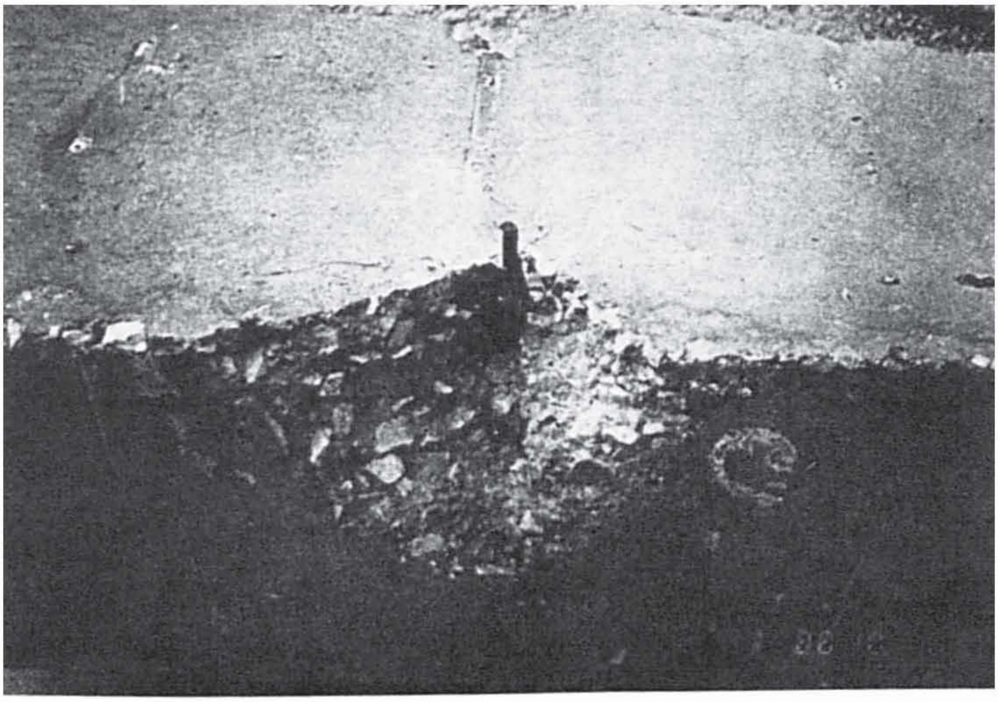


Fig. 1--Types of anchors tested
a) Undercut anchor
b) Torque controlled expansion anchor
c) Chemical anchor



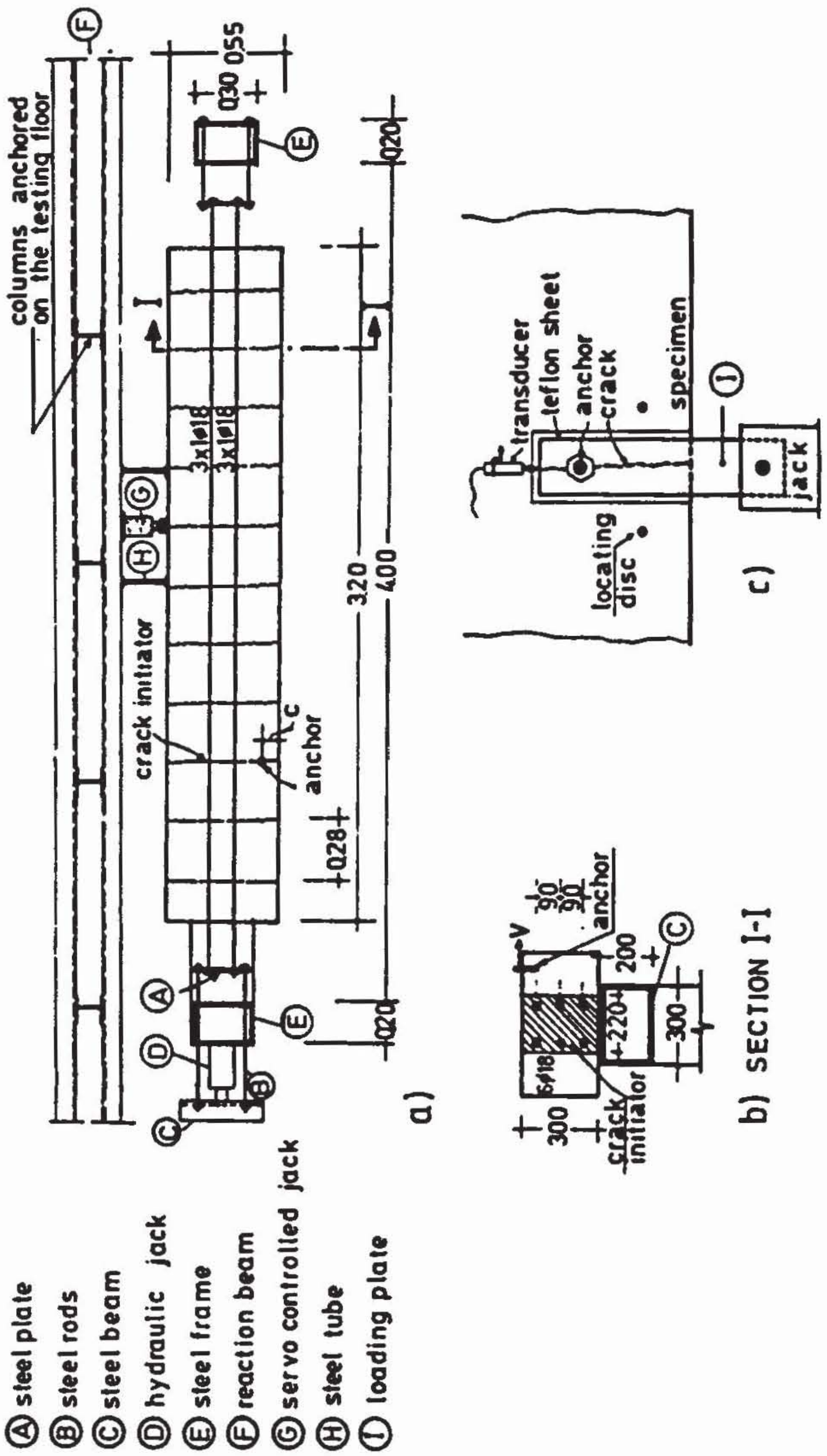


Fig. 2--Test set-up

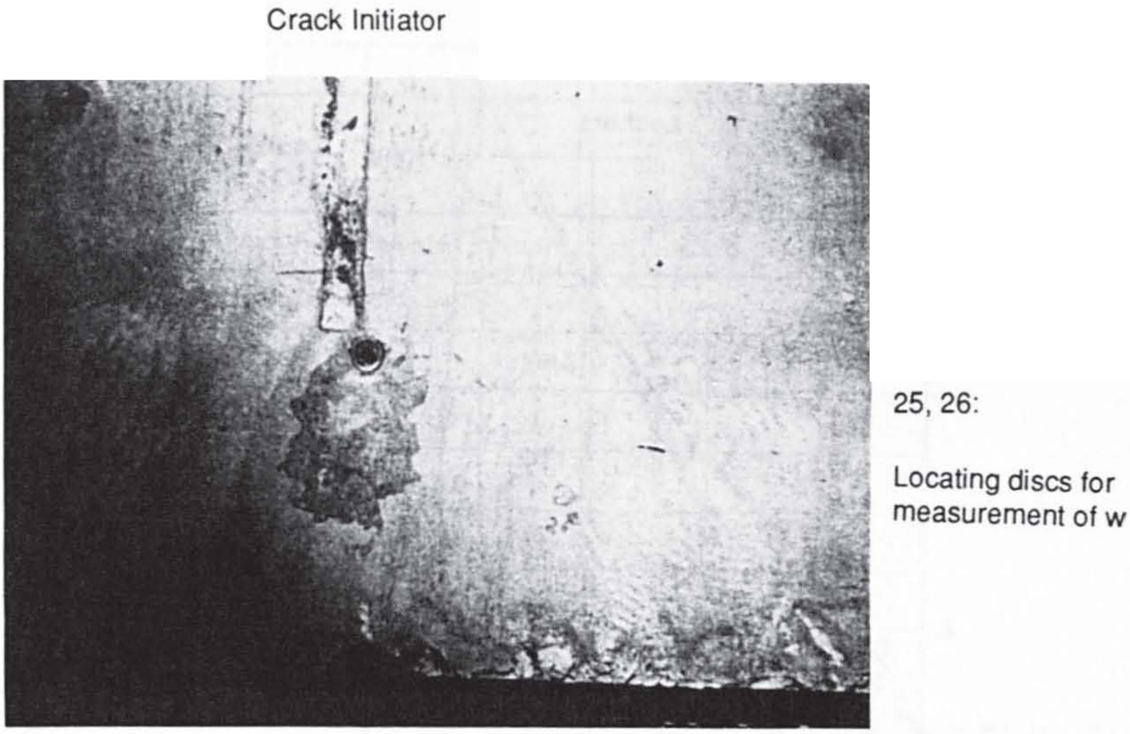


Fig. 4--Concrete failure preceded by some concrete crushing in front of the anchor

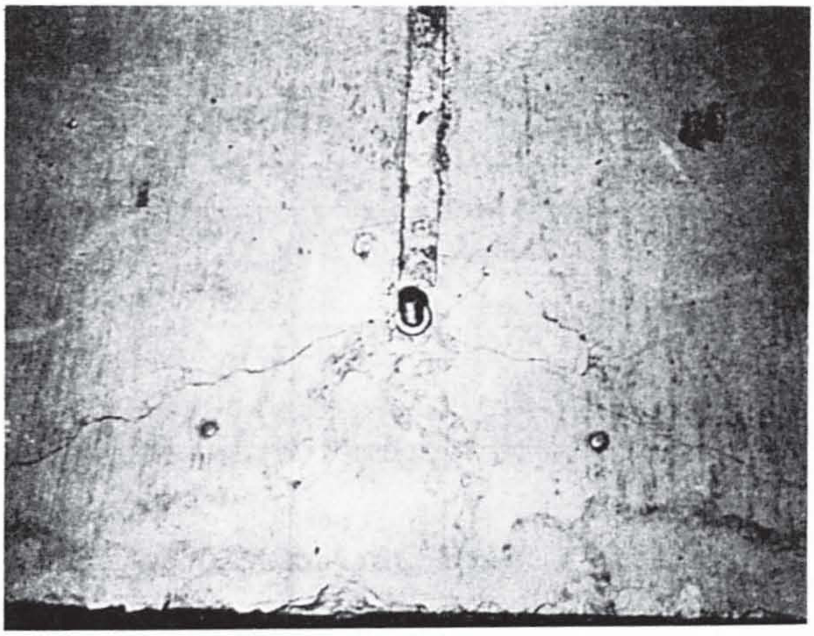


Fig. 5--Steel failure preceded by concrete crushing in front of the anchor

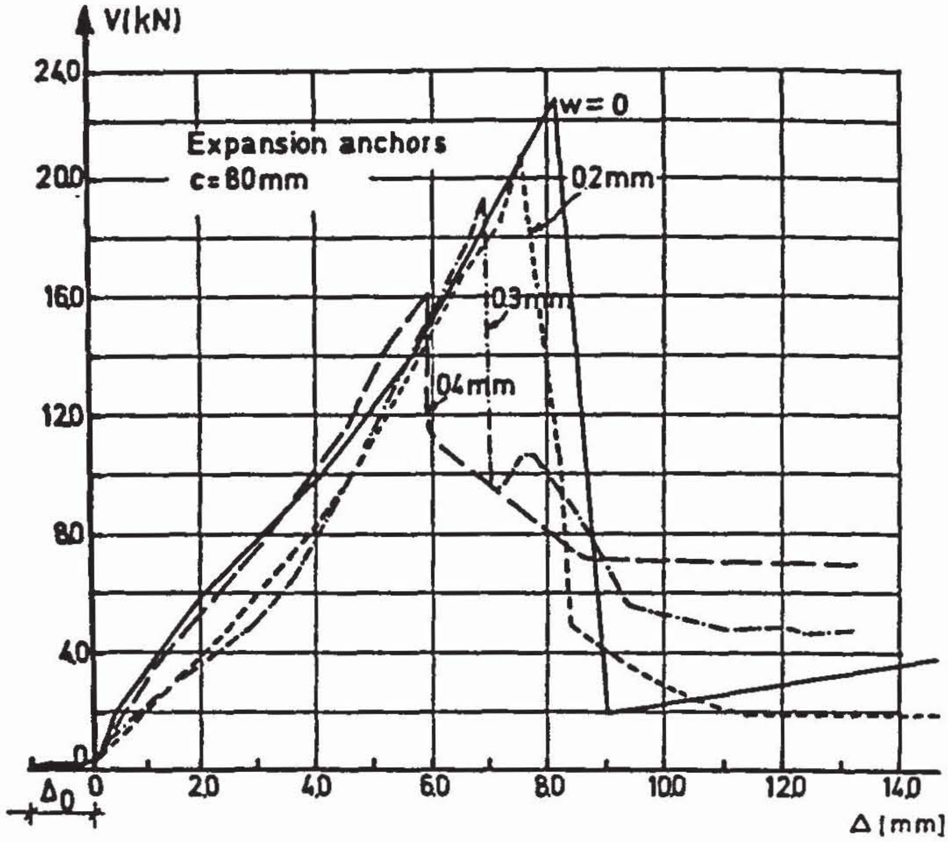


Fig. 6a--Typical shear force versus shear displacement relationships under monotonic loading, a) expansion anchor, c = 80 mm, concrete failure

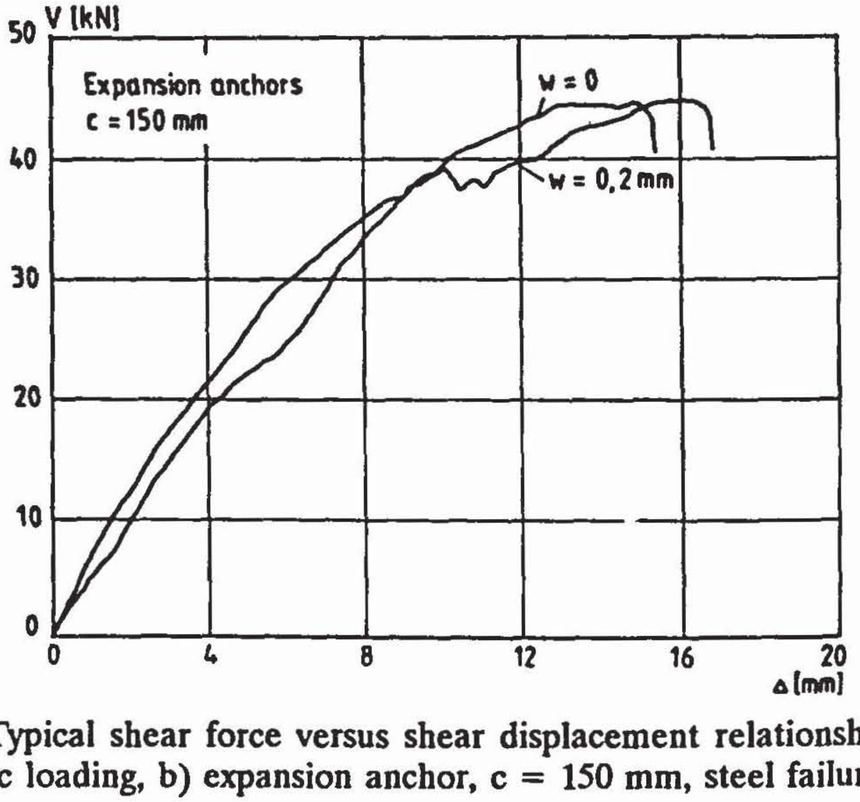


Fig. 6b--Typical shear force versus shear displacement relationships under monotonic loading, b) expansion anchor, c = 150 mm, steel failure

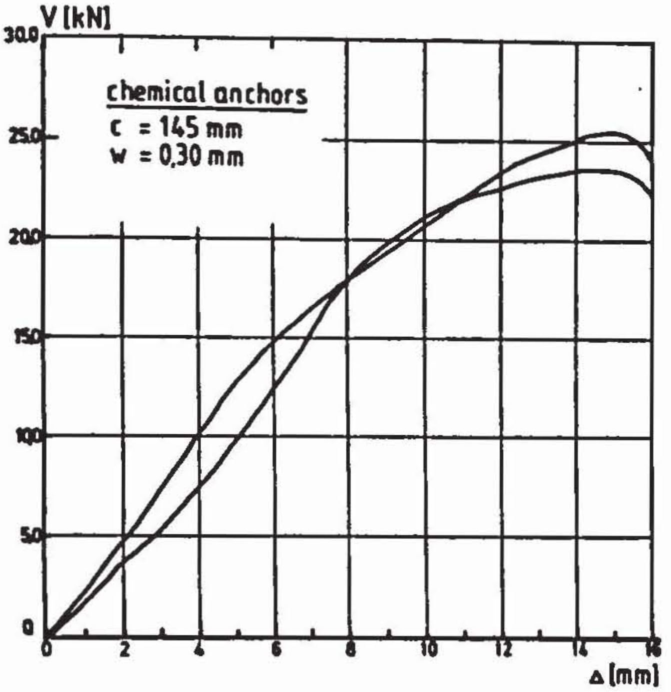


Fig. 6c--Typical shear force versus shear displacement relationships under monotonic loading, c) chemical anchor, c = 150 mm, steel failure

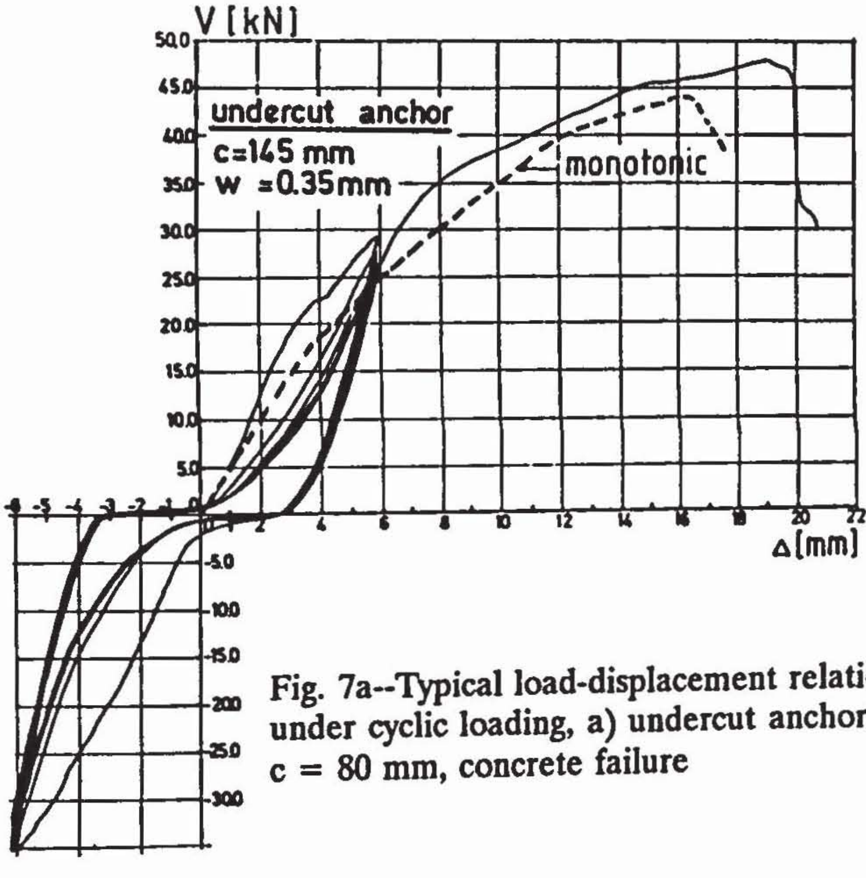


Fig. 7a--Typical load-displacement relationships under cyclic loading, a) undercut anchor, c = 80 mm, concrete failure

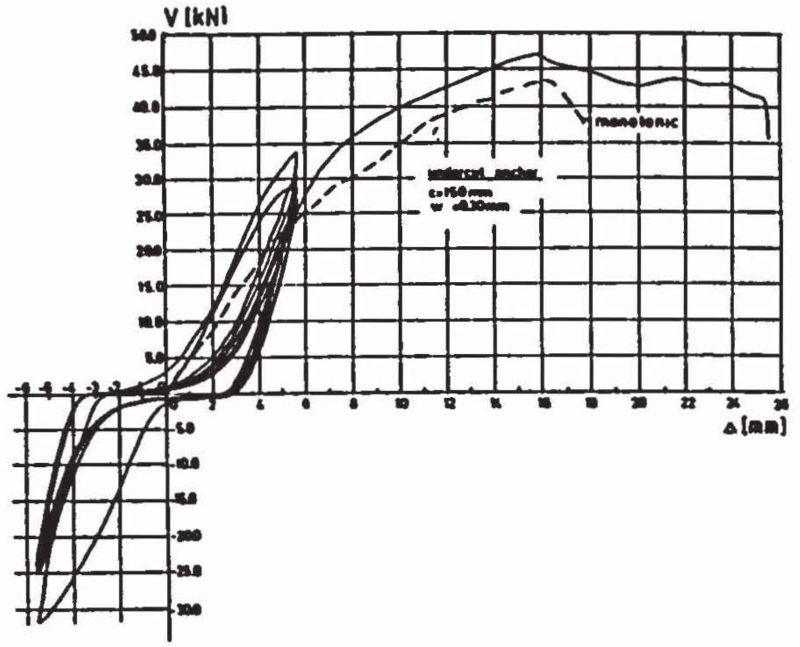


Fig. 7b--Typical load-displacement relationships under cyclic loading, b) undercut anchor, c = 150 mm, concrete failure

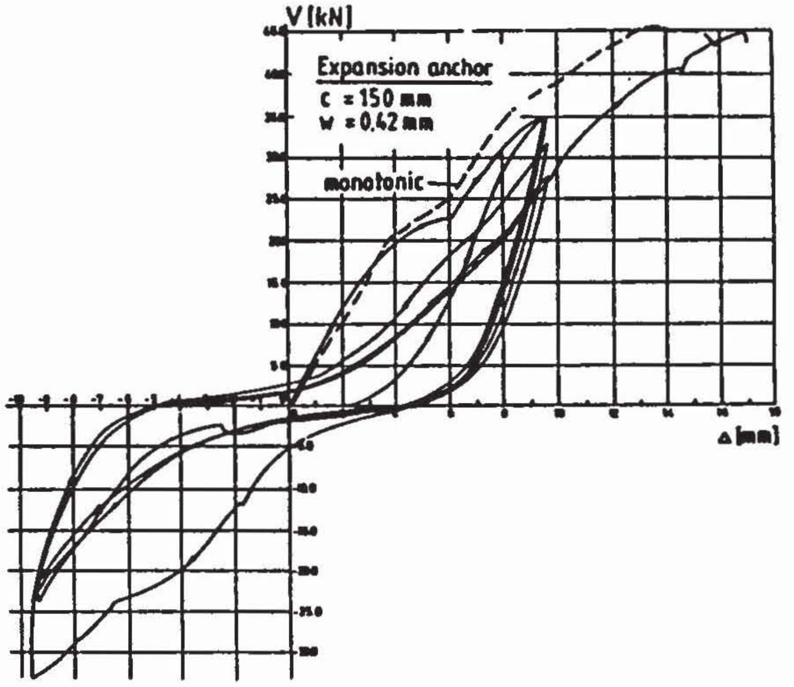


Fig. 7c--Typical load-displacement relationships under cyclic loading, c) expansion anchor, c = 150 mm, steel failure

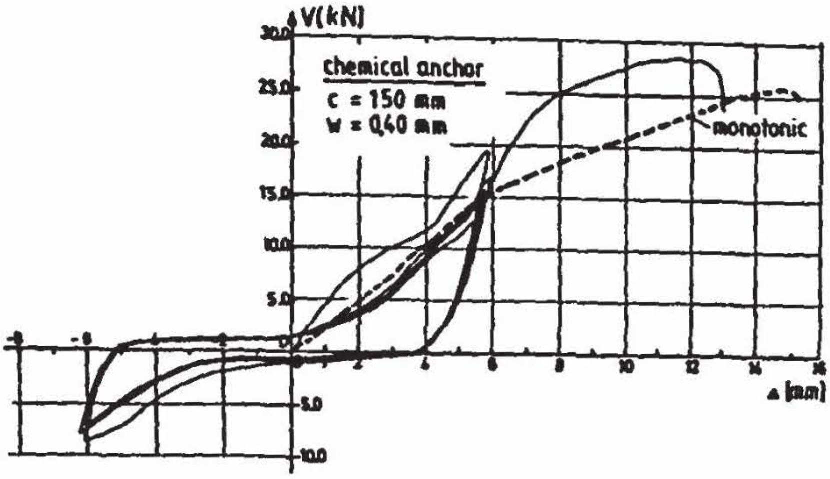


Fig. 7d--Typical load-displacement relationship under cyclic loading, d) chemical anchor, c = 150 mm, steel failure

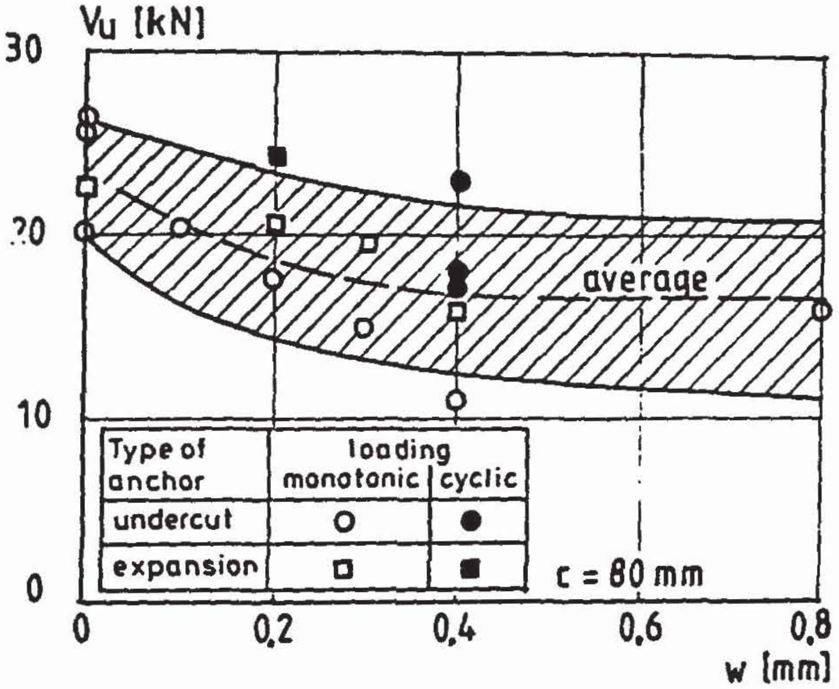


Fig. 8--Influence of crack width on anchor shear resistance, concrete failure

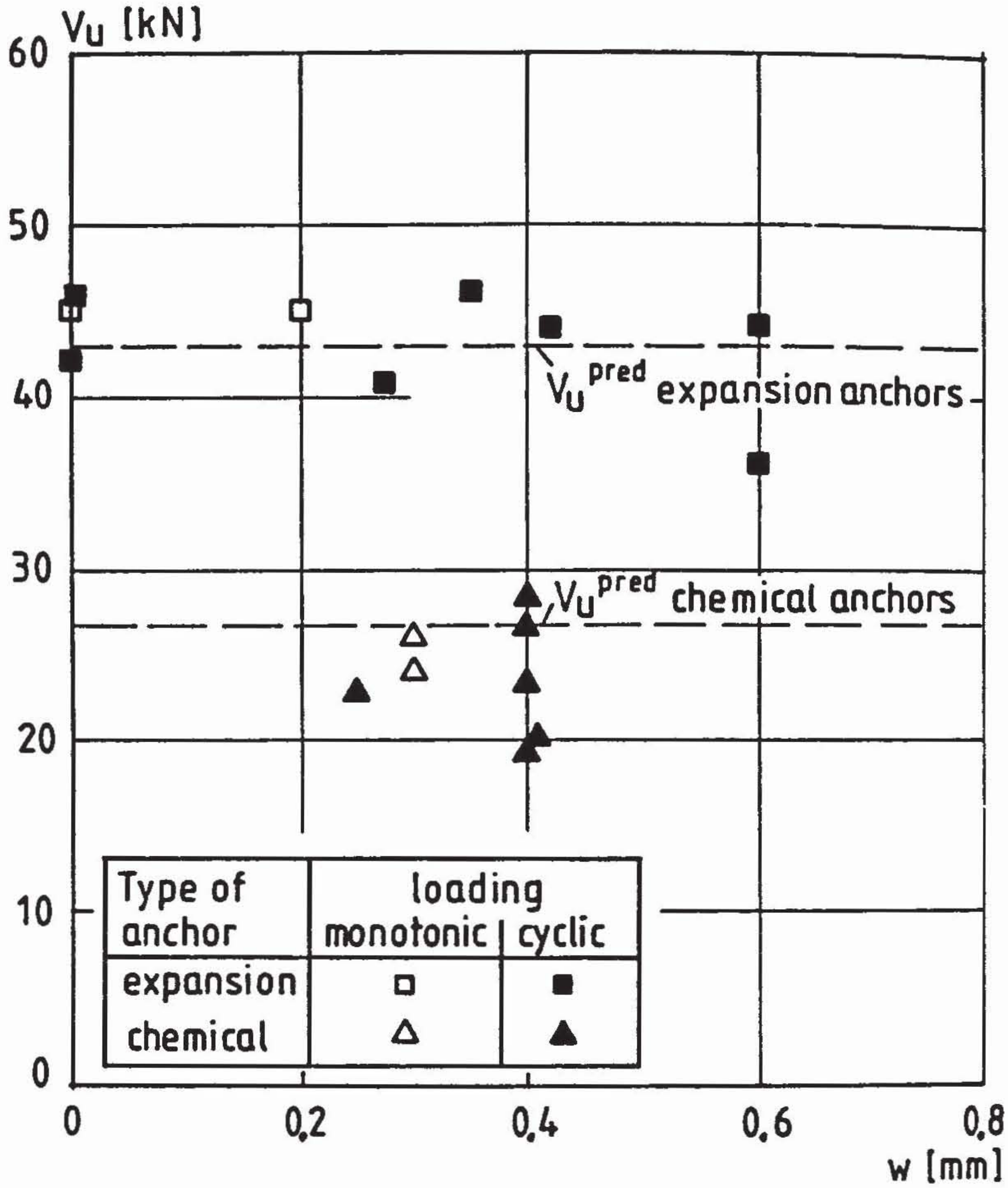


Fig. 9--Influence of crack width on anchor shear resistance, steel failure

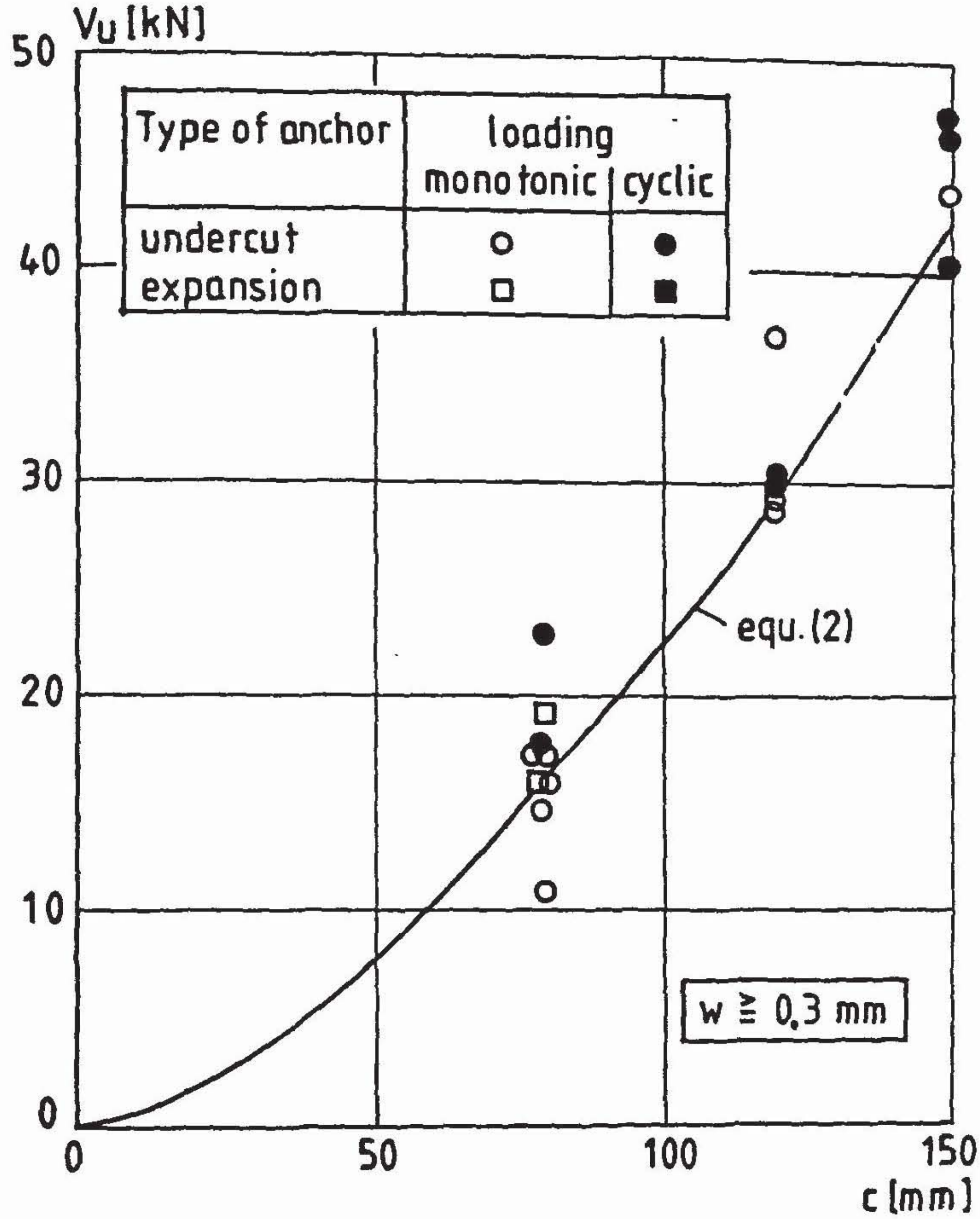


Fig. 10--Influence of edge distance on anchor shear resistance in cracked concrete (w ≥ 0.3 mm), concrete failure

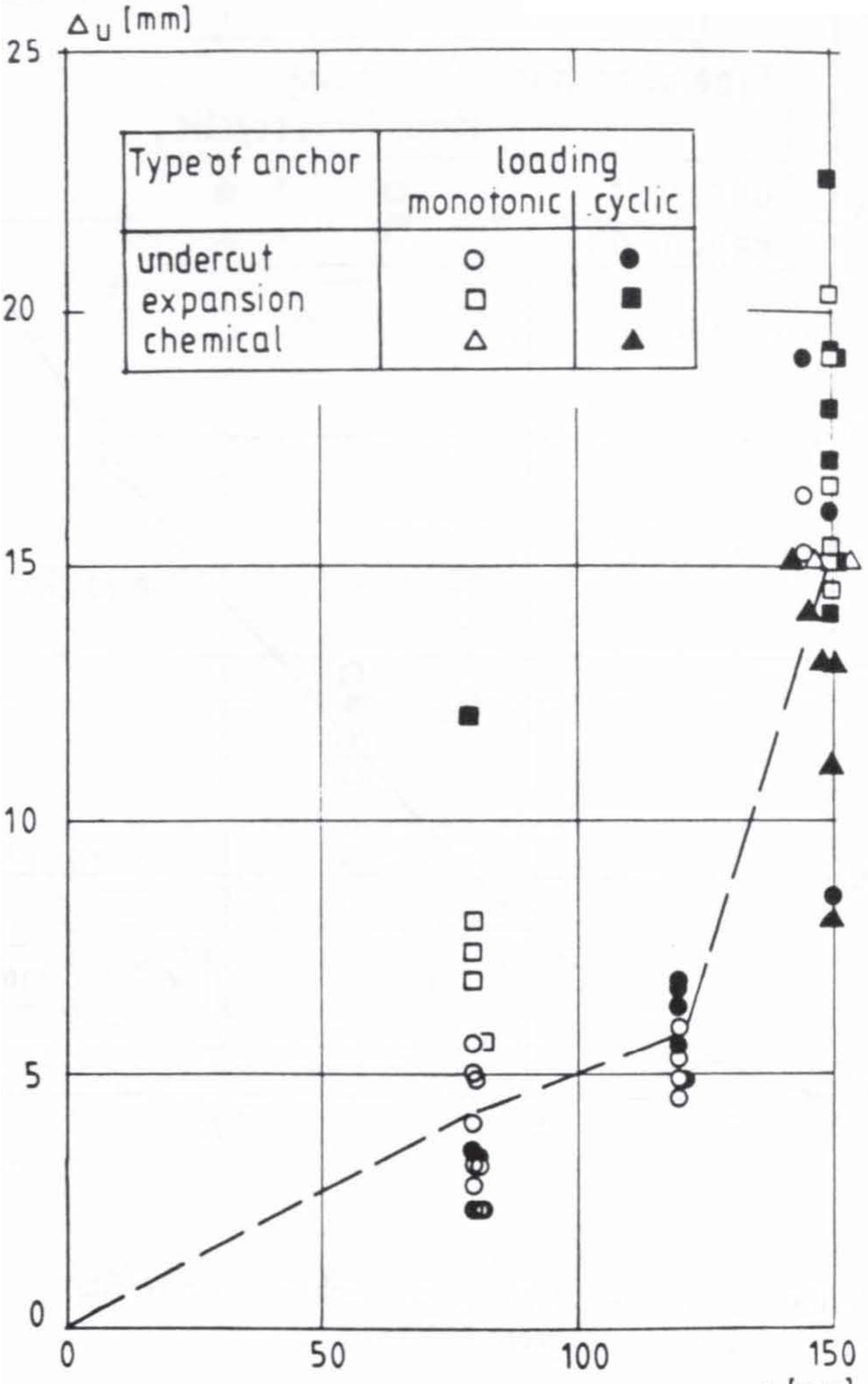


Fig. 11--Displacement at failure as a function of concrete cover

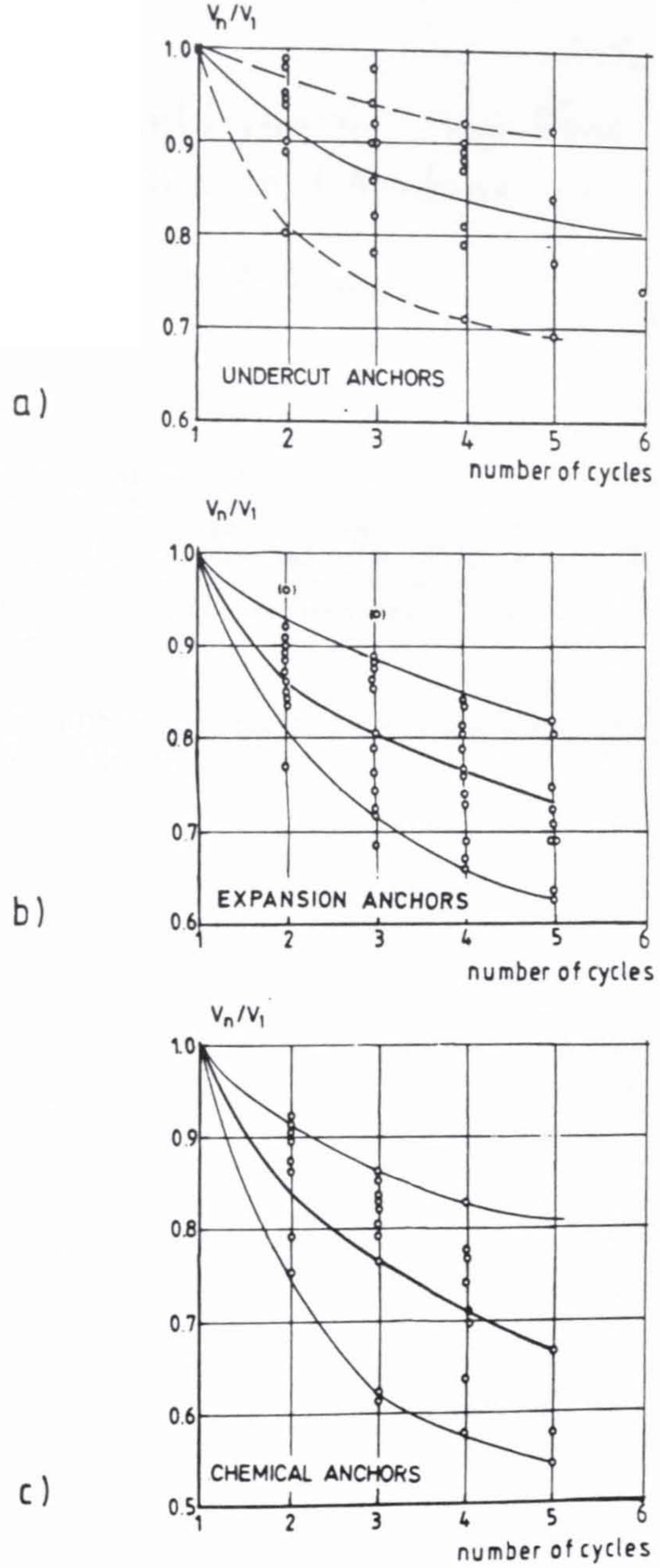


Fig. 12--Force response degradation due to cyclic loading