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FATIGUE BEHAVIOUR OF ANCHOR BOLTS IN CONCRETE

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Abstract
Fatigue behaviour of anchor bolts has been studied by means of pull-out tests carried out on concrete slabs. Three types of anchorage have been tested by applying sinusoidal shaped loading cycles.

Analysis performed with fatigue behaviour of anchorage according to the maximum cyclic load. Damage propagation is studied as a function of the number of loading cycles. Energy dissipated of cycles, compliance and displacement of anchorage have been chosen to study anchorage behaviour.

Experimental results have shown a relationship between the displacement in static tests and the displacement in dynamic tests. Therefore by means of the static pull-out test, it is possible to point out the fundamental feature that governs the cyclic behaviour.

1 Introduction

There has been a growing interest in the fatigue behaviour of anchor bolts subjected to cyclic loading because of its increasing use in structures.

The study of the anchorages is an effective tool to understand the mechanical interaction between concrete and steel. Therefore, in order to explain this interaction in the presence of fatigue it is necessary to analyze simple types of anchorage under cyclic loads.

The purpose of this investigation is to provide more data on the response of anchor bolts to cyclic loading.

In this paper an experimental research about short anchor bolts in concrete carried out at the Fracture Mechanics and Non Destructive Tests Laboratory - Structural Engineering Department of Politecnico di Torino (Cadoni, 1994) is reported.

The anchorage fatigue failure has been investigated by means of pull-out tests carried out on concrete slabs by applying sinusoidal shaped loading cycles to three types of anchor bolts previously embedded in the casting.

The anchorage geometries have been studied in order to emphasize the different types of concrete brittle failure, with crack propagation, concrete failure due to diffused damage and bond failure.

2 Testing programme

The tests have been carried out on concrete slabs 500x500x150 mm sized, with a short anchor bolt in the middle. The tests were performed by means of an MTS with maximum load of 250 kN. A large diameter contrast ring (500 mm) was used in order not to affect the cracking surface, in both static and dynamic tests.

Compressive strength, R=24.7 MPa, was evaluated on cubes (with 160 mm long sides). The determination of the secant modulus, E=20380 MPa, and of fracture energy, G_F=62 N/m, were performed on a 160x160x500 mm prism and 100x100x840 mm notched prisms, respectively.

It should be pointed out that before the tests, the slabs and test pieces were kept for 30 days at a temperature of about 20°C at a relative humidity of approx. 65%.

Static pull-out tests were performed by imposing a constant velocity of the load application point of $d\eta/dt=5\cdot10^{-6}$ m/s. Instantaneous displacement, η, was calculated as the arithmetical mean of η_1 and η_2 values measured by two inductive transducers placed in a diametrically opposed position with respect to the anchor bolt (Fig. 1). The measuring points of the transducers on the surface of the slab and on the testing machine were chosen so as to minimize possible displacement errors due to clearance in the mechanical connection or elastic strains in the materials. A large diameter contrast ring (500 mm) was used so as not to affect the cracking surface, in both static and dynamic tests.

Dynamic tests were carried out by applying a sinusoidal loading cycle with a frequency of 1Hz.

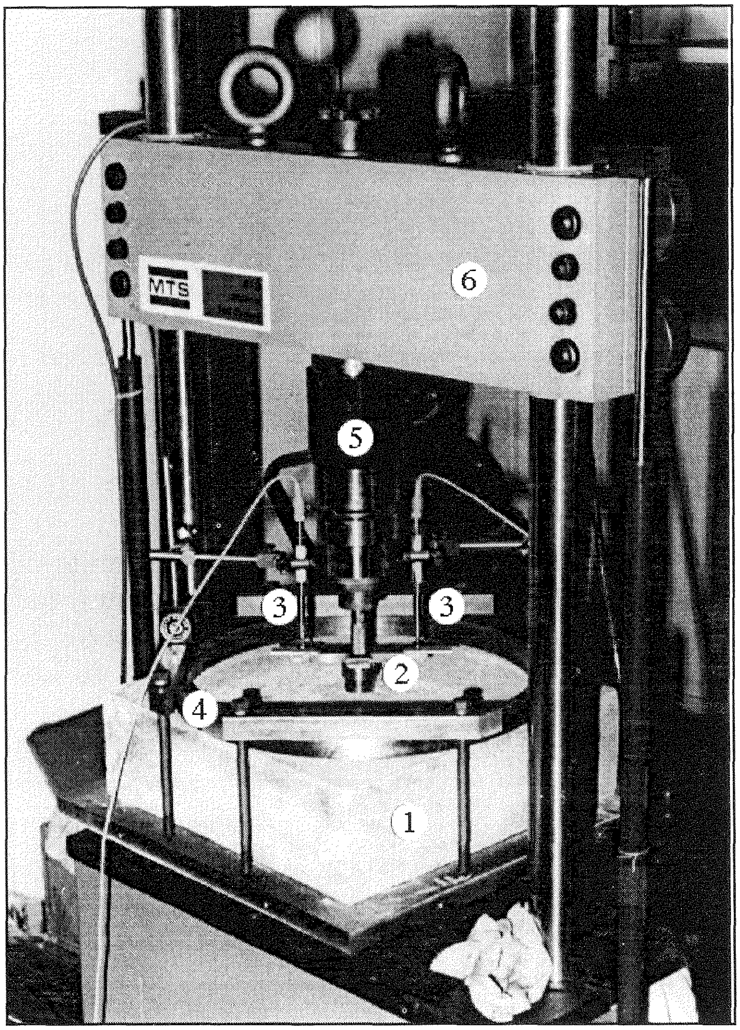

Fig. 1. Layout of testing equipment: 1. Specimen; 2. Extractor; 3. LVDT; 4. Contrast ring; 5. Load cell; 6. MTS

Maximum load, P_{max} , was kept constant throughout the test. Force-displacement diagrams (P,η) were recorded according to the following procedure: a) recording the first loading/unloading cycle by keeping the load increase rate constant; b) recording the (P,η) loading/unloading diagram after N_0, N_1, N_2, ..., N_i fatigue cycles.

The three types of anchorage are shown in Fig. 2. The anchor bolts were embedded at 40 mm while the rod and ribbed bars were embedded at 10 cm. All three types had a nominal diameter of 16 mm .

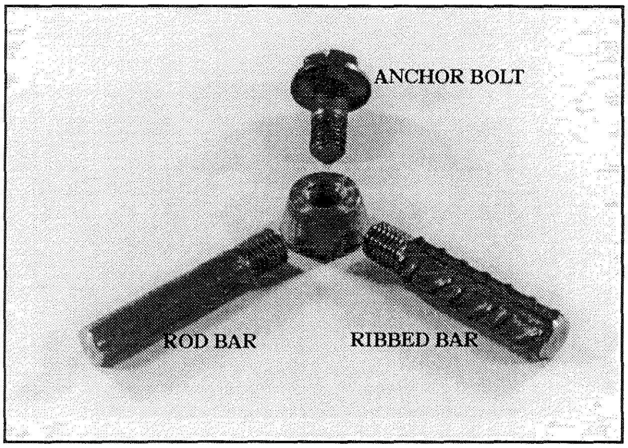

Fig. 2. Anchorage geometries chosen

3 Test results and discussion

As the number of cycles increases the anchorage subjected to fatigue loading shows progressive damage. The fatigue damage is a consequence of increasing internal cracking in concrete. In Fig. 3 the variation of the cycle shape during the fatigue test of anchor bolt is shown.

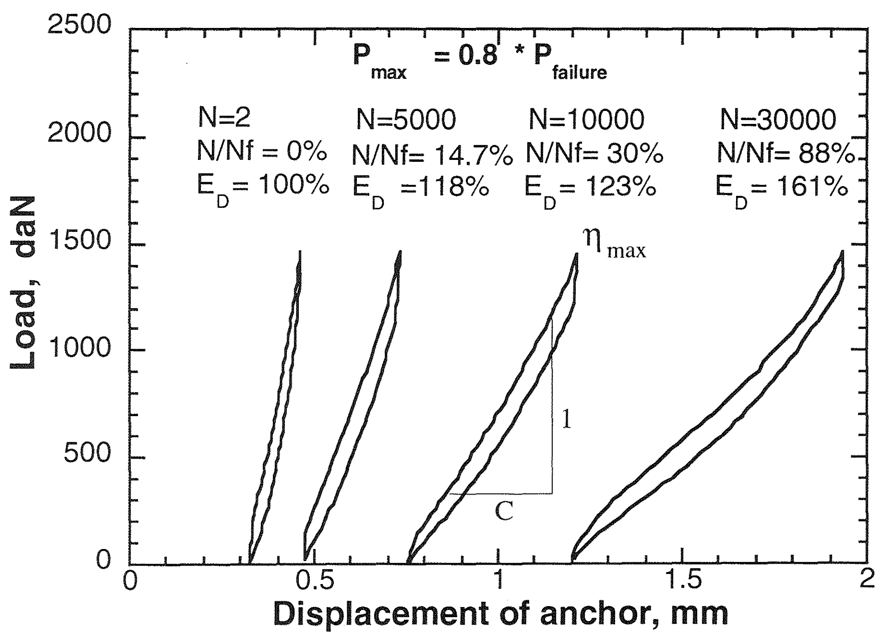

Fig. 3. Variation of cycle shape in fatigue test.

The anchorage behaviour is strongly influenced by its geometry. The substantial difference is located in the damage types produced during the anchorage life. Consequently the anchorage life is strictly connected to damage developed. According to the brittle or ductile failure of anchorage its geometry must be strictly considered.

Energy dissipated (E_D) of cycles, compliance (C) and displacement of anchorage (η_{max}) have been chosen to study anchorage behaviour.

In the case of anchor bolt the energy dissipated decreases after the first cycles, and increases steadily thereafter, up to failure. This does not occur for the rod and ribbed bars, where the energy dissipated continues to decrease, as shown in Fig. 4. The same behaviour was observed for the compliance of anchorage (Fig. 5).

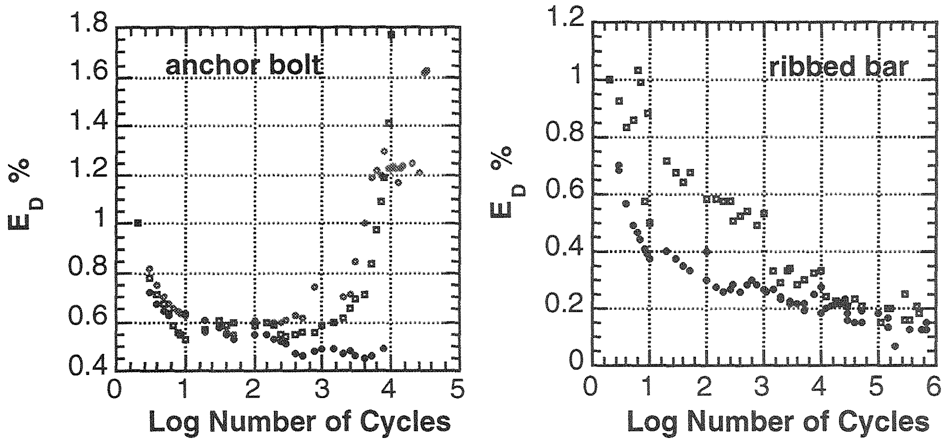

Fig. 4. Energy dissipated per cycles referred at 2° cycle vs number of cycles of two types of anchor

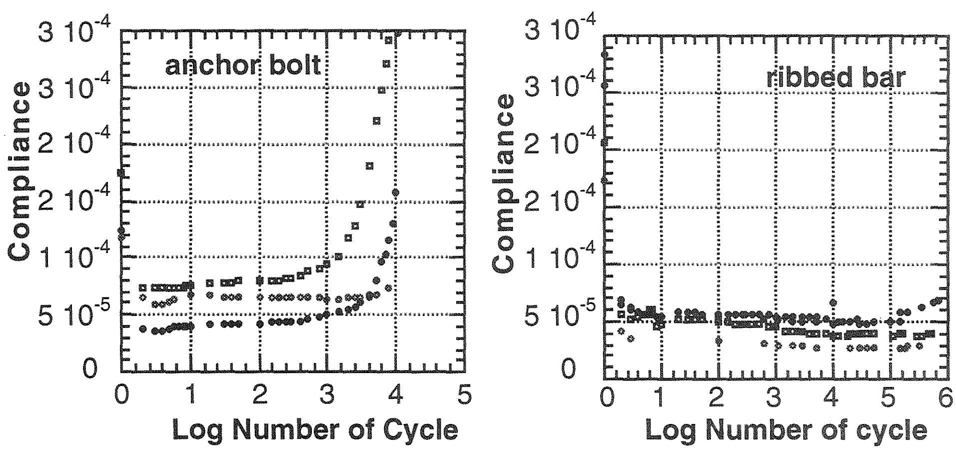

Fig. 5. Compliance vs. number of cycles of two types of anchor

Strain evolution and stiffness degradation with the number of cycles in anchor bolts were found to be similar to those of normal concrete.

Fig. 6 shows that all the three anchorage geometries have a similar displacement behaviour.

In the case of anchorage the displacement of anchor bolt appears in suitable quantity so as to check a fatigue process (Shah, 1984).

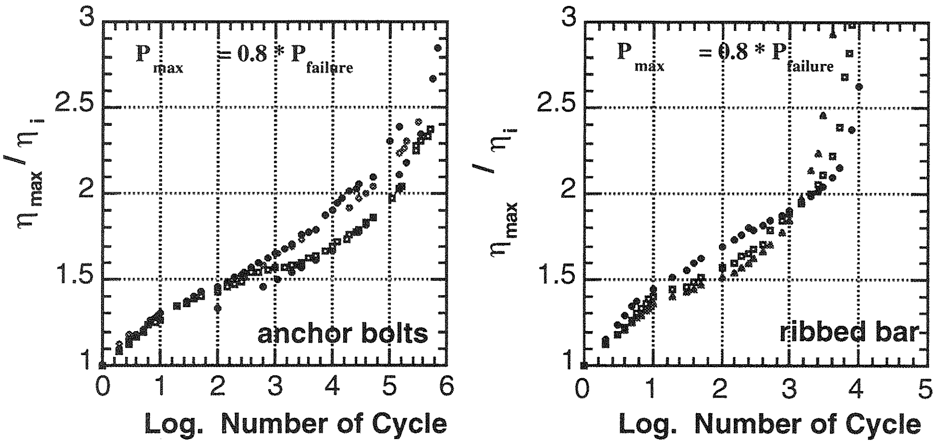

Fig. 6. Displacement referred at first cycle as a function of number of cycles of two types of anchor

These three parameters clearly indicate that the increase of damage with cyclic loading is highly nonlinear therefore the Miner's hypothesis is not valid for the structural element examined.

The anchorage fatigue life may be predicted more effectively through a relationship based on the increase in the displacement of the load application point, η_{max}, as a function of the number of cycles rather than through a relationship based on the crack propagation velocity as a function of the number of cycles as in metals (Bocca et al., 1992).

4 Fatigue effect on pull-out test

The fatigue influence on pull-out test was studied through a comparison between the pull-out tests before and after a certain number of cycles.

In pull-out tests of anchor bolts involving a contrast ring of considerable size compared to bolt depth, concrete failure is caused by a tensile stress field localized at the end of the bolt head, as a consequence this is the area where both the main crack and the micro cracking zone are initiated. In pull-out tests of rod and ribbed bars the failure is caused by the failure of the chemical link between steel and concrete, and the diffused damage of the concrete provoked by the ribbed bar, respectively.

Table 1 summarises the data obtained from pull-out tests.

Table 1. Testing results

anchor types	$P_{fail.}$ [daN]	$P_{fail,av}$ [daN]	$\eta_{fail.}$ [mm]	$\eta_{fai,av}$ [mm]	W_f [N·m]	$W_{f,m}$ [N·m]	Cycles applied N	$P=\%P_u$
	1800		0.297		41.96		1	100
	1877		0.197		38.44		1	100
	2075	1868	0.373	0.310	40.80	39.44	1	100
anchor bolt	1593		0.248		34.60		1	100
	1997		0.435		41.40		1	100
	2033		0.652		42.77		20000	68
	2016		0.568		37.02		200000	68
	2236		0.424		22.17		463000	68
	2806		0.361		170.94		1	100
	2766	2421	1.012	1.093	188.74	171.21	1	100
	1895		1.628		141.90		1	100
ribbed bar	2218		1.369		183.24		1	100
	2626		0.722		419.32		500000	56
	2638	2625	0.409	0.364	290.87		150000	84
	2608		0.251		247.30		700000	72
	2628		0.075		288.01		311000	80
	694		0.039		31.57		1	100
	1364		0.040		60.18		1	100
	597	841	0.090	0.077	21.82	58.41	1	100
rod bar	613		0.058		98.65		1	100
	1027		0.057		79.83		1	100
	407		0.054		7.28		40000	40
	688		0.093				300000	40

In order to emphasize the different damage mode only the first part of the pull-out diagram, as a parameter for the anchorage behaviour study, is considered.

In Figs. 7-8-9 dimensionless load - displacement curves for three types of anchorage are drawn. It can be noted that the elastic phase in the static test is terminated before of the 30% of the failure load. This occurs for all three geometries but their global behaviour is somewhat different. In fact, it is possible to observe gradual damage in the ribbed bar while this is not verified in the others. In the anchor bolts and in the bar behaviour two phase are present: one elastic and another of linear damage. In the anchor bolts the linear damage is provoked by stable cracking propagation and in the rod bars this is due to friction between steel and concrete with the possibility of instantaneous or unstable slipping.

The fatigue effect on the pull-out tests increases the deformation at failure making the structural element more ductile.

By the comparison between the static and cyclic behaviour it is evident that there is a relation between them.

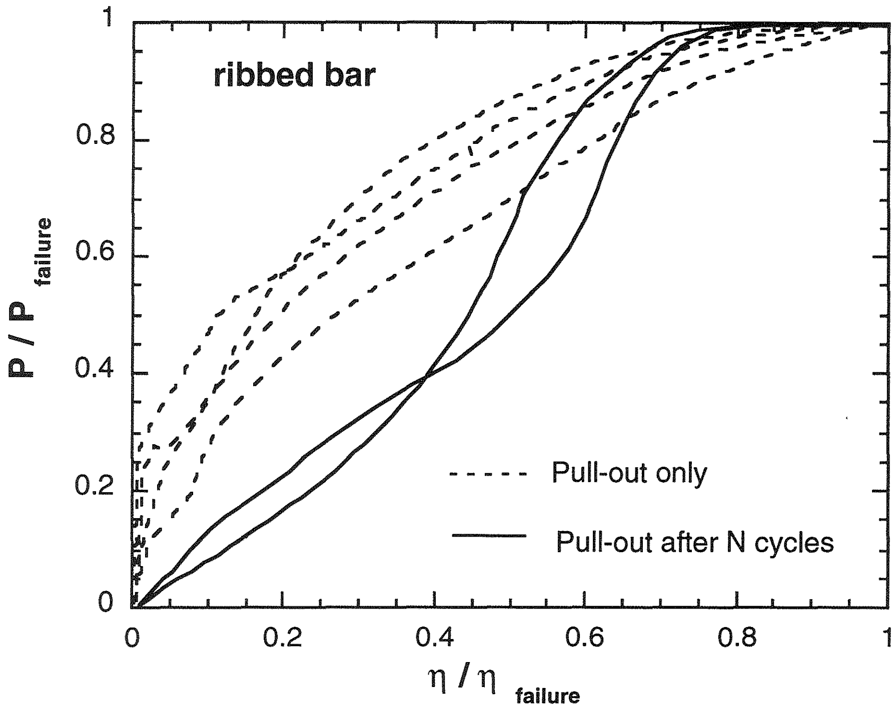

Fig. 7. Dimensionless load versus dimensionless displacement

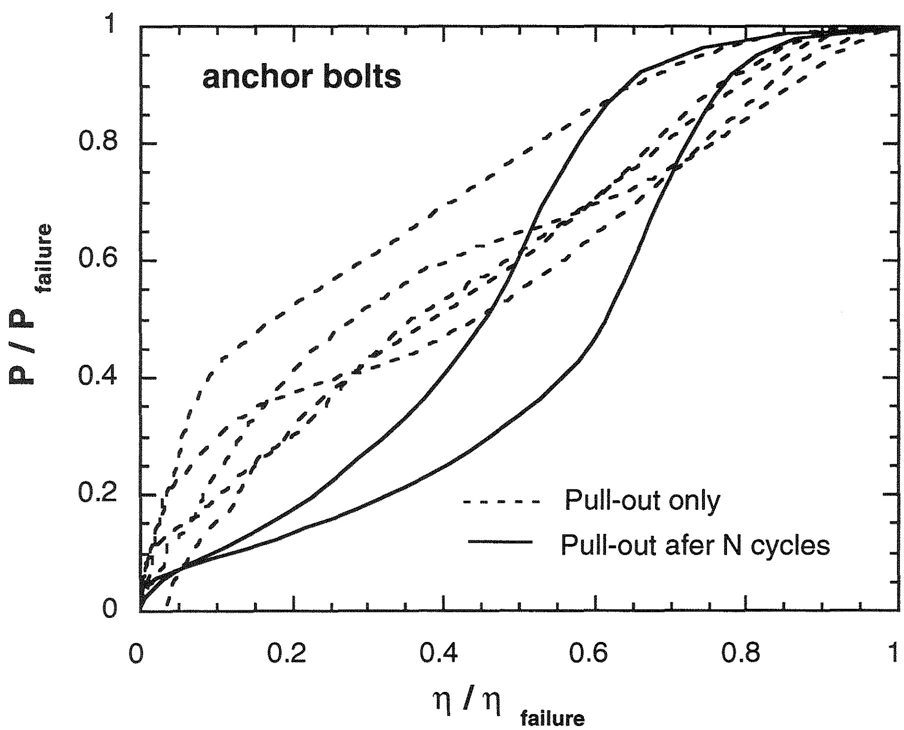

Fig. 8. Dimensionless load versus dimensionless displacement

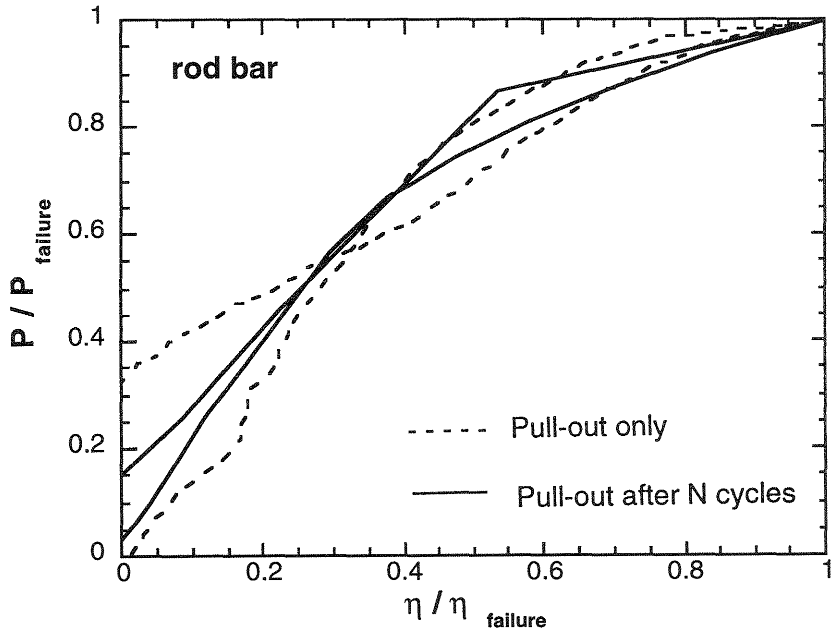

Fig. 9. Dimensionless load versus dimensionless displacement

The experimental results have shown that it is possible to verify, also for this structural element, that a relationship between the displacement in static tests and the displacement in cyclic tests exists. In fact the descending branch in a static test can be considered as the failure envelope in a fatigue test (Hordijk, 1991). It can be seen that the displacement for the last loop, more or less, coincided with the descending branch of the static test.

In Table 2 the results on the comparison between the failure displacement in static test and the displacement recorded at the end of secondary branch end in the cyclic test are reported.

Table 2. Comparison between displacements from static and cyclic test

Nome	η failure, static [mm]	ηfailure, cyclic [mm]	P_{max}=% P_f	N_f
anchor bolt	0.310	0.365	60	15000
		0.327	68	40000
		0.561	78	2500
		0.496	89	4000
		0.320	68	12250
		0.312	84	5000
ribbed bar	1.093	0.748	80	150000
		0.914	72	150000
		1.061	84	5000

This fact confirms the assumption made by Balázs (1986) on the stress-slip behaviour of bar pulled out of the concrete.

As a result of this hypothesis it is possible to point out the fundamental feature that governs the cyclic behaviour by means of the static pull-out test. The maximum displacement is represented by the intersection of the line at predetermined percentage of load and the descending branch of static pull-out test. However in the fatigue life of anchorage it is better not to exceed the displacement at static failure because in this case the processing at fatigue is in the unstable zone.

5 Conclusions

Experimental results have shown that the different fatigue behaviours of anchorage depend strongly on its geometry. By comparing the load-displacement curves it is observed a relationship between displacement in static and dynamic tests exists. Therefore by means of the static pull-out test, it is possible to point out the fundamental feature that governs the cyclic behaviour.

The selected variable trends show how only the displacement is able to mark the presence of fatigue process and consequently the others should not be chosen as the process control parameter.

6 References

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