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Fastening systems under seismic loading conditions

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ABSTRACT: New construction work, the installation process for equipment or machinery and especially the strengthening and repair measures in existing structures increase the demand in post-installed anchoring systems. Safety relevant anchoring needs to be strictly designed for safety margins comparable to overall structural seismic design levels. This paper describes the philosophy behind a new concept for the seismic testing and design of anchors.

1 INTRODUCTION

In new construction and especially in strengthening and repair procedures a lot of structural and non-structural elements, mechanical and electrical equipment, pipes, etc. have to be joined or connected to the concrete by means of post-installed mechanical or chemical anchors. In many safety-related applications not only dead load and static forces have to be taken into account but also dynamic excitations. Although the causes for dynamic forces in civil and mechanical engineering application are very different, this broad variety may be classified in three main load-specific categories, namely:

- fatigue
- earthquake (low-cycle fatigue)
- shock

Tab. 1 summarizes the principal criteria of the three loading categories (see also Ammann, 1983 and Bachmann/Ammann 1987):

Table 1. Characteristics of dynamic forces

	categories of dynamic excitations		
	Fatigue	Earthquake	Shock
N. of cycles	$N < 2 \cdot 10^6$	$10 < N < 10^3$	$1 < N < 20$
Strain rate	$10^{-5} < \dot{\varepsilon} < 10^{-3}$	$10^{-3} < \dot{\varepsilon} < 10^0$	$10^{-2} < \dot{\varepsilon} < 10^2$
Causes	o traffic o machinery	o earthquake	o impact o blast wave o collapse of support

Single anchors or anchor groups have to withstand these loading conditions. According to Fig. 1, a pulsating or an alternating type of loading may occur. The force applied to the anchor induces either pure tension, pure shear or a combined shear-tension excitation. For most anchors, the worst conditions are pure shear applied as an alternating load.

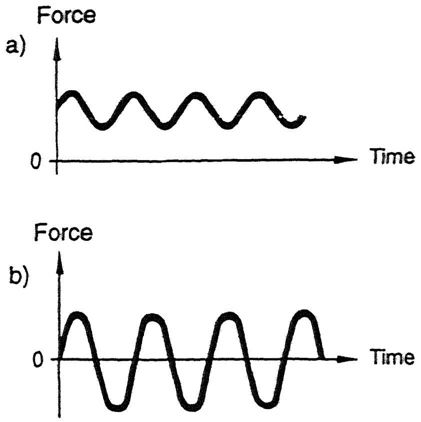

Figure 1. Pulsating a) and alternating b) force-time functions (Hilti, 1991)

This paper is focussed on the earthquake type of loading and summarizes the results of a study to evaluate a design procedure for seismically excited anchor and to establish a design-relevant test procedure. The investigation is limited to medium and heavy-duty anchors but for both mechanical and chemical anchors.

The fatigue and shock type of loading can be treated similarly. Corresponding investigations for fatigue and static longterm behaviour of anchors are presented in (Ammann, 1992).

2 MECHANICAL BEHAVIOUR OF ANCHORS

Only some specific information on the force-deformation characteristics is discussed (for further details see CEB, 1991).

A correctly designed and properly made fastening displays elastic behaviour under the working load. On loading and relieving the anchor the displacement is reversible. It is an advantage for the anchor to undergo a large amount of displacement before it reaches its ultimate load. In the case of force-controlled expansion anchors, for example, follow-up expansion of the anchor under load is a visible sign of overloading.

The pre-tensioning force F_v, the clamping force F_K (the force with which the part fastened is pressed against the base material) and the external working load imposed on the part fastened, F_A, act together in the overall system.

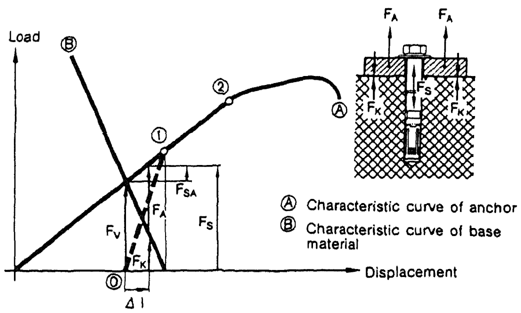

Figure 2. Anchor diagram of a force-controlled mechanical anchor

A so-called anchor diagram (Fig. 2) depicts idealistically the forces and displacements of a pre-tensioned anchor fastening subjected to a tensile load.

If an external working load, F_A, is applied to an anchor fastening which has been pre-tensioned with a certain force, F_v, the bolt will be loaded additionally by an amount, F_{SA}.

$$F_S = F_v + F_{SA}$$

At the same time, the load acting on the base material in the zone affected by the clamping force of the bolt, F_K, decreases. The point at which the force acts also shifts by an amount, Δl. Once an anchor has been pretensioned to a force F_v, it displays elastic behaviour on being reloaded to the pre-tension level.

The force-displacement curve of the bolt head when it is subjected to an external load F_A, follows the line 0 - 1. At point 1, the clamping force is cancelled out and the anchor has to take up any further increase in force in full. At point 2, force-controlled expansion anchors expand a second time (follow-up expansion). If the force is further increased, the failure or ultimate load is reached. Due to creep and relaxation processes the inital pre-tensioning force is decreasing by a large amount. Retorquing can regain the inital value (for details see Ammann, 1992).

If the fastening is subjected to lateral loading, it is, as a rule, sized for shear and possibly bending. However, particularly in the case of heavy-duty fastenings, the lateral force is often transmitted to the base material by friction, owing to the existing high force clamping the part fastened against the base material. Only when the frictional resistance is not sufficient to take up the working load the part fastened will move until the anchor takes up the remaining lateral force.

The performance of anchors subjected to dynamic loading can be improved decisively by pre-tensioning. This fact is extremely important in fatigue type conditions with upper load levels not exceeding working load levels (see Ammann, 1992). In case of earthquake type loading however it is possible that the high load levels exceed the present pre-tensioning force by far, inducing therefore follow-up expansion which reduces the level of pre-tensioning. Fig. 3 shows very clearly this decrease in pre-tensioning level and the necessary follow-up expansion process of a Hilti HSL M16 anchor due to a pulsating tensile force with upper levels beyond the actual pre-tensioning level. This level is characterized by the very pronounced kink in the force-deformation curve.

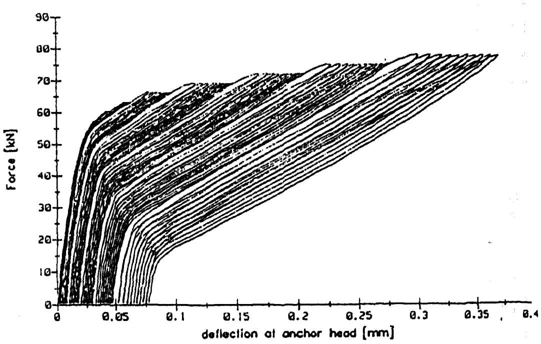

Figure 3. Decrease in pre-tensioning force due to a pulsating tensile force (10 cycles/step) in a Hilti HSL M16, torqued to 200 Nm (static allowable working load is 32 kN)

In case of earthquake type loading, it is therefore advisible not to count for positive pre-tensioning effects if the level is overpassed. In addition it is most likely that due to earthquake forces the concrete subground may crack leading to an immediate loss of pre-tension and therefore to a reduction of the ultimate failure load of the anchor compared to uncracked conditions. The influence of crack width on the mechanical behaviour of anchors is widely discussed in (CEB, 1991).

3 SEISMIC DESIGN OF ANCHORS

The philosophy for the seismic design of anchors tries - as close as possible - to be in line with the design procedure for civil engineered structures (EC 2, EC 8, 1990). The semi-probabilistic approach for safety evaluation, as formulated in the Eurocodes provides ultimate loadbearing capacity according to the comparison of the design values for resistance (strength R_d) and actions (S_d):

$$S_d \leq R_d$$

Partial safety factors connnect the design values with the corresponding characteristic values for actions and strength/resistance:

$$S_d = \gamma_S \cdot S_K$$
$$R_d = R_K / \gamma_R$$

The seismic actions (design level) can be determined with relevant seismic codes and/or specific dynamic calculations. The earthquake resistance for anchors has to be based on corresponding tests. This leads to:

$$\text{(seismic test level}/\gamma_R) \geq S_{design}$$

with a proposed $\gamma_R = 1.5$

Determination of the design actions:
Anchors under consideration are used for safety relevant fixations to attach so-called secondary systems like installations, equipment or structural elements to concrete or masonry structures. The seismic action and the number of relevant load cycles that these anchors will experience depend on the response of the secondary systems to the seismic input motion of the primary structure at the position of attachement. The seismic response of the primary system at different floor levels is governed by the seismic ground input motion and by the dynamic behaviour of the structure. It is well known from standard earthquake engineering practice that primary structures - depending on their dynamic behaviour - may suffer much larger accellerations compared to the seismic ground motion. This is again true for the response of the secondary system which has also to be considered as dynamic system . All these response characteristics depend very much on the accelleration level, duration and frequency content of the seismic ground motion, the dynamic response characteristics of the primary system (eigenfrequencies, floor level, damping, etc.), the dynamic behaviour of the secondary system (eigenfrequencies, damping) and the behaviour of the attachments. Fig. 4 shows as an example the dynamic amplification of a primary and secondary system to a specific ground motion.

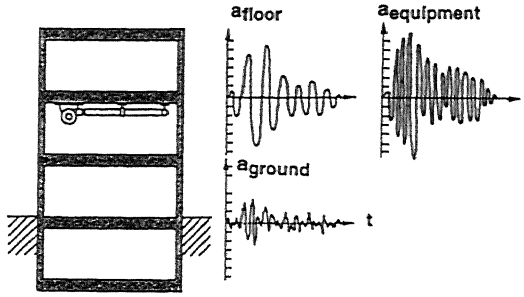

Figure 4. Earthquake loading conditions

It must be recognized that most national earthquake codes and standards only provide design spectra for the primary structural system. Only limited information exist on floor response spectra as a seismic input motion for the response of the secondary systems. As a first approximation, peak floor response accelleration values may be obtained based on code design spectra for the primary structure with the first structural eigenmode to be dominant and taking the distribution of the accelleration along the structure's hight into account. For specific safety relevant secondary systems, it is often necessary to generate first artificial ground motions fitting the code spectra values and second to determine the time histories at specific levels of the primary structure as input to calculate design spectra for secondary systems. The resulting design spectra are strictly elastic. It is recommended to use a damping ratio for secondary systems not exceeding 2 % of critical damping.

If the secondary system is rigid and rigidly connected to the primary structure the accelleration would be strictly identical (see Fig. 5). If the system is flexible the inertial response of the equipment might be strongly increased and depends on the resulting eigenfrequency of the secondary system. A third situation may exist where the equipment or the attachement of the equiment to a base-plate undergo plastic deformation limiting the resulting inertia force to a given level (ductility approach). In this case elastic response reduction taking ductility into account can be introduced similarly to code provisions for ductile primary systems. These three, basic secondary element configurations are summarized in Fig. 5 together with the resulting design actions and their qualitative probability density distributions. Assuming the same type of anchors for all three configuration it is obvious that the flexible system leads to the highest probability of failure. The design actions as indicated in Fig. 5 are valid only for rigid attachements of the baseplate to the primary system. The forces on the anchors are then strictly that computed for the equipment.

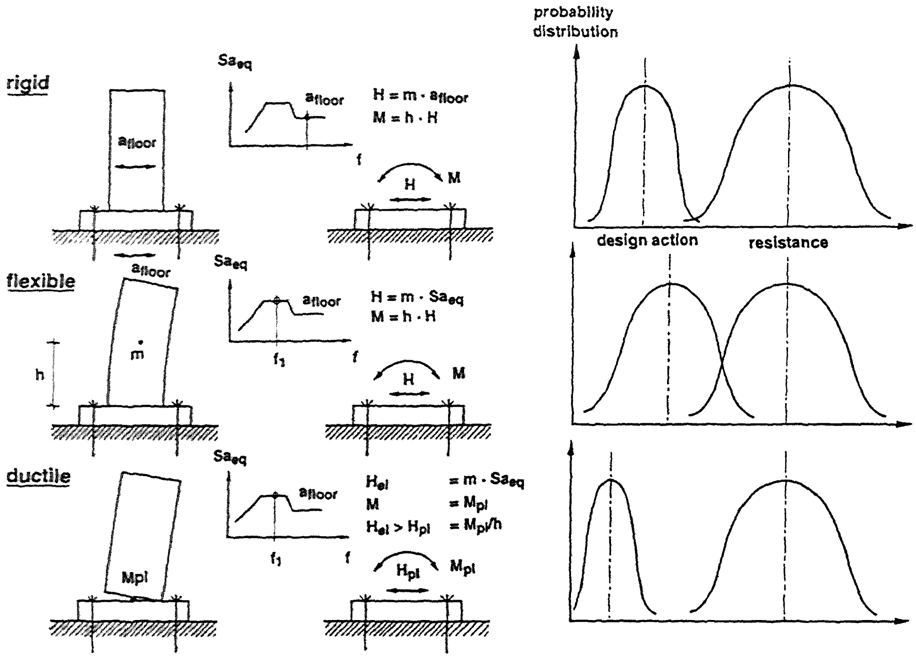

Figure 5. Design configurations for the equipment with m = mass of equipment, h = distance from center of gravity to base-plate, S_{aeq} = equipment response accelleration, M_{pl} = plastic moment, H = shear at base plate

In general the attachement itself can be subdivided also into the three categories rigid, flexible and ductile (see Fig. 6). Flexible and ductile attachements lead to rocking and/or sliding motions. Fig. 6 shows the resulting forces for rocking motions. The sliding motion (Fig. 7) leads to highly non-linear actions. For post-installed anchors and assuming that the base-plate may transfer some friction forces (Tang, 1983) has defined three action stages namely (Fig. 7):

1. elastic response when friciton is not exceeded,
2. free movement when the equipment slides through the gap (constant friction)
3. impact when the movement is brought to rest at contact

The first stage is fully elastic and the second stage is limited by the frictional resistance. The peak value of the sharp spike as a result of the impact for the third stage is highly indeterminated since it depends on the width of the gap, the acceleration level, the frequency of the excitation and the stiffness of the bolt, etc. Stage 2 and 3 are particularly dominating in the case of limited shear resistance which is primarily dependent upon the dynamic friction factor which in turn is strongly dependent on the actual pre-tensioning of the anchor bolt. According to Fig. 3 the level of pre-tensioning is reduced if the applied load level exceeds this internal force.

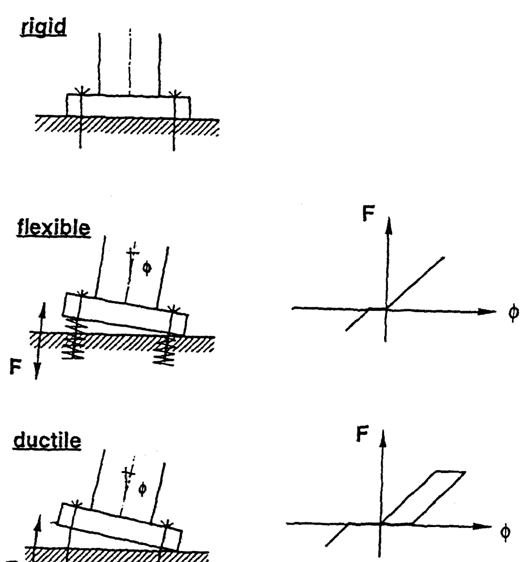

Figure 6. Rocking motion

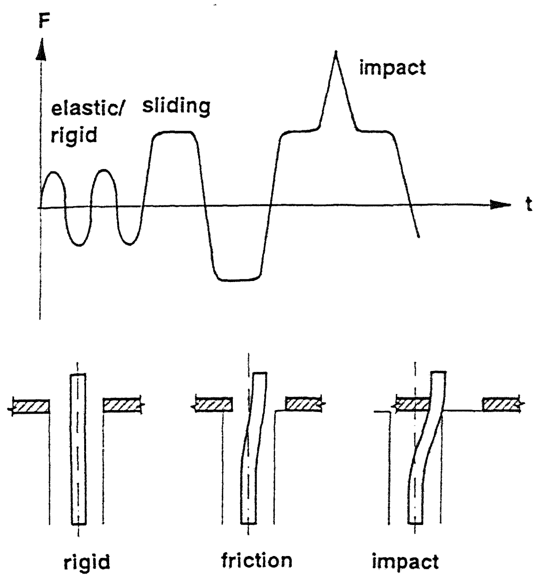

Figure 7. Sliding motion

Determination of the resistance

The earthquake resistance of anchors can only be determined under specific test conditions. To assure seismic qualification, it is therefore necessary to subject the anchor to a defined number of seismic cyles which will be representative for the number of times the peak accelleration amplitude will likely occur during an earthquake. The number of load cycles depend on the duration and frequency content of the earthquake and on the dynamic response of the primary and secondary structures. As is well known from strong motion recordings, an earthquake time-history as input motion for the primary structure shows three phases:

- initial phase of a few seconds duration with increase in accelleration from rest to peak value amplitudes
- strong motion phase with high amplitude accellerations
- decaying phase down to zero accelleration

Since the anchors under consideration attach the equipment to the primary structure, the number of seismic cycles that these anchors will experience must be determined from the response of the equipment to the seismic motion of the primary structure. Based on (Trifunac, 1975), (Vanmarke, 1980) and (Seed, 1976) a total event duration of 90 seconds has been chosen with a total of 270 load cycles, corresponding to a dominant frequency of 3 Hz. To follow the three phases mentioned above, four different load levels have been adopted leading to the characteristic test procedure for pulsating and alternating forces shown in Fig. 8. This test procedure primarily focusses on the strong motion phase with a total of 90 cycles at maximum level, therefore being much more severe than an earlier proposal by (Tang, 1983) for seismic anchor tests with 30 cycles at maximum level.

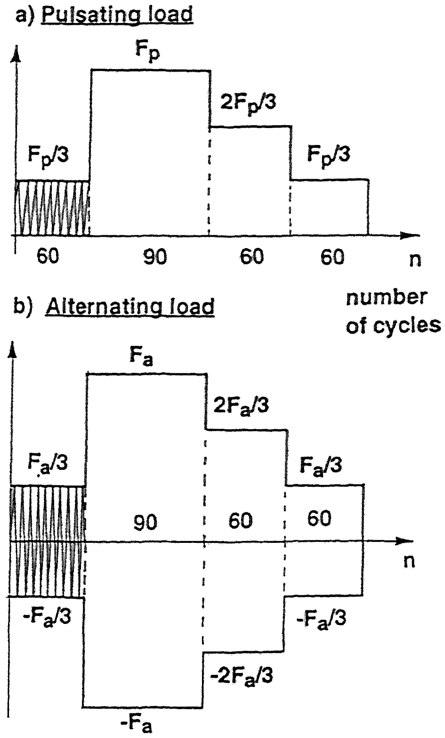

Figure 8. Test procedure for a) pulsating forces, b) for alternating forces

The applied load levels F_p and F_A in Fig 8 are deduced from static ultimate load levels and based on mean ultimate failure values (F_u 50%), leading to an earthqake test level of

$$F_{EQ} = \begin{cases} F_p = x \cdot F_u 50\% \text{ for pulsating} \\ F_A = y \cdot F_u 50\% \text{ for alternating} \end{cases}$$

tests with x and y depending on the type of anchor and the load-direction. Fig. 9 shows as an example an HSL-TZ M8 (see Hilti, 1991) with the cyclic (pulsating) dynamic load-deformation characteristic compared to the static behaviour for pure shear. Although a 100 cycles per load-step have been applied up to failure, the envelope of the dynamic test is very close to the static load-deformation curve. For this type of anchor for example x will be chosen as 80 % of the mean ultimate failure value leading to a maximum test level of approximately $F_p = 2.5\ F_{AWL}$.

4 RECOMMENDED TEST PROCEDURE

The previously described seismic anchor force is applied with a computer controlled servo-hydraulic 250 kN cylinder. The tests run under force-controlled conditions. Depending on the corresponding displacements of the anchor head, the frequency of the sinusoidaly applied force has to be decreased to ensure correct feed-back control of the servo-hydraulic system. Tests on anchors with small displacements should run at a frequency around 3-10 Hz, a decrease in frequency may be necessary for larger displacements of the anchor, e.g. under alternating shear forces, and may go down to 0.5 Hz.

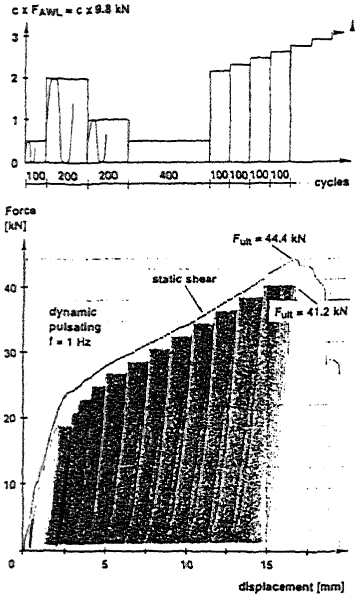

Figure 9. Seismic, pulsating shear test of a Hilti HSL-TZ M8 force-controlled mechanical anchor, increasing test level (100 cycles), compared with static force-displacement behaviour.

The anchors have to be set according to the supplier's setting prescription. The concrete used should have a compressive strength around 35-45 N/mm^2. Special attention has to be drawn on the torque-moment applied for pre-tensioning the anchors. Due to creep and relaxation (see Ammann, 1992) the anchor pre-tension drops down to 30-40 %. Therefore, the dynamic tests should run at 30 % of the prescribed and initially achieved torque-moment. Anchors with special devices, like e.g. disk-springs to maintain the anchor pre-tension may be run at higher pre-tension levels (80%).

5 ANCHOR ACCEPTANCE CRITERIA

The seismic qualification of an anchor based on the previously described tests depends on the required performance according to Figs. 5-7. Anchors which are used for ductile attachements according to Fig. 6 or 7 have to show stabilized displacements (see Fig. 9). As an example the total displacement of the anchor head after the test in pure tension may not exceed 10 % of the depth of embedment. Anchors used for rigid and limited flexible attachements can only be achieved with pre-tension ensuring a permanent clamping force. This pre-tension will only be possible to maintain with disk-springs. Corresponding tests have to be run at lower levels than the pre-tension.

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