INFLUENCE OF FATIGUE LOADS IN TENSION ON SHORT CAST-IN-PLACE ANCHORS IN CONCRETE

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Abstract
In the modern civil engineering field the anchorages play a very important role. In fact, the standardization of industrial process, like precasting industry, puts in evidence the need to develop modular elements. For the connections of these elements can be used: anchoring industrial systems (chemical anchors, undercut anchors, ecc.), cast-in-place anchors (designed before the casting of concrete). These anchors are often short cast-in-place anchors. They are used for fixing anchored panels, for fixing other elements to structure (publicity panels for example), or for fixing operating machine to ground. The anchors are subjected to cyclic loads. In particular, in the case of blocking operating machine, problematic of fatigue is present and can be predominant.
In this paper the fatigue behaviour of three types of short cast-in-place anchors is described. For this research have been used: anchor bolt, ribbed and rod bar. The experimental results permit to describe the evolution of some variables like displacement, stiffness, dissipated energy during the fatigue life.
The correlation between the load-displacement curve during the static pull-out test and the cyclic behaviour of anchor is also discussed.

1. Introduction
The great development of anchor bolts and their direct appliance in the field of structural engineering, has pointed out the necessity of knowing their behaviour under not usual loading case. In particular with the appearing of new types of structures (off-shore, high towers, ecc.) the anchors are often subjected to fatigue load.
A short anchor is usually defined as one whose embedded length is insufficient to develop tensile yield in the bolt. They are normally used in the connection between structural members.
For this research [1] have been used: anchor bolt, ribbed and rod bar. Cast-in-place steel anchors, threaded rods with nuts and washers at the bottom, which are widely used
throughout the world, are here considered as the short anchor to study the fatigue behaviour of concrete. The ribbed and rod bar have been chosen in order to emphasize the diffused damage and bond failure, respectively.

The fatigue failure of these anchors has been investigated through pull-out tests carried out on concrete slabs by applying sinusoidal shaped loading cycles to anchors previously embedded in the casting.

2. Experimental technique

The tests were performed on 40 anchors embedded, before the casting, in as many concrete slabs sized 500*500*150 mm. Only one type of micro-concrete, having the composition and mechanical properties given in Table 1, was tested. Compressive strength, R, was evaluated on standard cubes. The determination of secant modules, E, and fracture energy, $G_f$, were performed on 160*160*500 mm prism and 100*100*840 mm notched prisms, respectively.

Table 1 - Material

<table>
<thead>
<tr>
<th>Composition</th>
<th>400 kg/m³</th>
<th>1700 kg/m³</th>
<th>0.50</th>
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</thead>
<tbody>
<tr>
<td>cement CEM I 42.5</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>alluvional sand with 0-8 mm diameter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>water/cement ratio</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressive strength, R</td>
<td>25 MPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young's modulus, E</td>
<td>20.4 GPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fracture energy, $G_f$</td>
<td>62 N/m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Before the tests, the slabs and tests pieces were kept for 30 days at a temperature of about 20°C at a relative humidity of approx. 65%. The pull-out tests were performed by means of an MTS with maximum load of 250 kN by imposing a constant velocity of the load application point of $\eta = 5 \cdot 10^{-6}$ m/s.

Instantaneous displacement, $\eta_1$, was calculated as the arithmetical mean of $\eta_1$ and $\eta_2$ values measured by two LVDT (linear variable displacement transformer) transducers placed in a diametrically opposed position with respect to the anchor bolt.

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 play 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.

The fatigue tests were carried out by applying a sinusoidal loading cycle with a frequency of 1 Hz. Maximum load, $P_{max}$, was kept constant throughout the test.

Load-displacement diagrams were recorded keeping the load increase rate constant at the first loading/unloading cycle and after $N_0$, $N_1$, $N_2$, ..., $N_i$ fatigue cycles.

The anchor bolts were embedded at 40 mm while the rod and ribbed bars were embedded at 60 mm. All three types had a nominal diameter of 16 mm.
3. Failure mode of short cast-in-place anchors

The potential failure modes of a short anchor bolt can be of four kinds according to the materials and geometrical characteristics. The first mode is obtained by the pulling out of the rod and it depends exclusively on the interface quality between the two materials, the inadequate anchor length and the absence of the washer at the bottom. The second mode is the typical one which shows the concrete frustum cone shape failure. The third mode is half way between the two and mixed-mode named. In the fourth we finally have the threaded rod failure. This occurs in case of high anchor lengths or high resistance concretes. There is another ‘structural’ failure mode that is the splitting of the member due to the loading anchor.

In the typical failure (extraction of cone) of anchor bolts, due to axial-symmetric conditions, the crack more over enucleate at the top edge of the washer. As is known, in pull-out tests involving a contrast ring of considerable size compared to bolt depth, concrete failure is caused by a tensile stress field localised at the end of the bolt head, as born out by the fact that is the area where both the main crack and the micro-cracking zone are initiated. Moreover, the stress field produced by support reactions turns out to be negligible compared to the stress field close to the stem. In this case, a tensile stress field around the bolt heads triggers off the crack and, when static tests are considered, brittle behaviour is observed during collapse. The load-bearing capacity depends on the fracture energy and the tensile strength of concrete. By using smaller diameter contrast rings or different types of anchorage, such as those commonly used in the building industry, a brittle-ductile, or ductile behaviour is observed instead, that is to say, friction or hooping phenomena, due to the presence of reinforcement, or interlocking effects, etc. occur alongside with diffused micro and macro-cracking that enhance the ductility of the material [2].

The presence of a head or lateral pressure in short anchor permits a more uniform distribution of the shear stress and a better transferring of loads. The drawback is that this type provokes a brittle failure of concrete.

In the rod and ribbed bar the transferring of loads depends on hardly to the interface condition between anchor and concrete but in the case of short anchor it is ever present the slipping failure (that is more or less brittle).

In the case of anchor bolts, the fatigue collapse process evolves in two states: the initial phase, in which appears little local crack that arriving to a sufficient dimension develops, and a second phase in which the last one increases up to failure.

In the case of ribbed bar, it should take into account that during the fatigue life the stress are not uniformly distributed along the anchorage; this fact implies a new stress distribution during the load sequence and to failure with high interlocking effect.

The geometry of anchors is very important for the failure analysis of anchors.
4. Evolution of the mechanical behaviour during fatigue life of anchors

During the fatigue life the short anchor shows a variation of some variables that indicate a progressive damage [3-4]. The variables chosen as tool for checking the fatigue process were the energy dissipated of cycles, compliance and displacement of anchorage.

The fatigue process can be subdivided in three zone corresponding to the three known states. Considering the displacement of anchors as variable the state can be defined as follows:

- State I is the rapid increase of displacement up to 10% of the life
- State II is the stable growth between 10% and 80% of the life
- State III is the rapid increase up to failure

In Fig. 1 the dimensionless displacement versus dimensionless number of cycles (fatigue life) is shown.

![Fig. 1 - Dimensionless displacement vs. dimensionless number of cycles](image)

The fatigue effect on anchors depends on several factors as anchorages type, the concrete around, the presence of stress state or reinforcements near the anchors, the confinement, the load history of loads in time, the maximum stress and so on.

The shape of cycles change a little bit for each cycle. In Figs. 2, 3, 4 the variation of cycles shape for the three types of anchors are shown.
Analysing the variation of the cycle is possible to study the evolution of the variable chosen for the damage process in fatigue. In Figs. 5 and 6 are shown the displacement of anchor bolt and ribbed bar, respectively.

In Figs. 7 and 8 are described the evolution of the compliance and the energy dissipated per cycles during the fatigue life of anchor bolts.

The energy dissipated per cycles in the case of anchor bolts decreases during the firsts cycles, and increases steadily thereafter, up to failure. For the rod and ribbed bars, this does not occur.

The same behaviour was observed for the compliance of anchorage.

The displacement of anchorage seems to be the most suited feature that can be used as variable to check the fatigue process.
Fig. 3 - Evolution of the cycle shape during fatigue life (ribbed bar)

Fig. 4 - Evolution of the cycle shape during fatigue life (rod bar)
Fig. 5 – Displacement/displacement at first cycle vs. log number of cycles curves of anchor bolts

Fig. 6 – Displacement / displacement at first cycle vs. log number cycles curves of ribbed bar
Fig. 7 – Compliance vs. log number of cycles curves of anchor bolts

Fig. 8 – Energy dissipated per cycle vs. log number of cycles curves of anchor bolts
5. Correlation between static and cyclic behavior of anchor bolt.

The displacement, more generally the deformation, gives the possibility to understand if the fatigue process is in a stable or an unstable zone.

Does exist a link between the static and cyclic deformation? The answer can be positive. The same conclusion [5] was reached through a theoric-experimental study that described a local approach to fatigue concrete.

The descending branch of the load-displacement curve of static pull-out test could be the boundary for the displacement in fatigue tests.

As it has been reported before, the load-displacement curve during the cycles shows damage that consists of a decrease of slope with respect to the displacement axis hence, increase of compliance for the whole system.

The failure occurs when the cyclic load-displacement intersects the descending branch of the static pull-out curve.

It should be considered that is necessary to make some comments before verifying this hypothesis. It is difficult to know the exact pull-out curve for each type of anchor. In fact, each anchor possesses its own curve, in the sense that this depends on numerous factors as the concrete composition, the disposition of particular aggregate near the anchor, the modality of extraction and so on. It must be considered that the deduction and the hypothesis are referred to a mean behaviour; therefore, with a statistic dispersion that in some cases can be elevated, more caution is necessary.

The same difficulties are encountered when one wants to establish the bearing capacity of anchor or the displacement at failure.

The displacement that corresponds to the displacement of maximum load in static pull-out load has been considered as the end of linear growth of displacement, after the non linear growth begins up to reach the point of intersection with descending part of static pull-out test where the failure occurs. The same hypothesis for the description of τ-slip law of bars embedded in concrete [6] was also used.

The tests on anchor bolts have shown a behaviour similar to Hordijk’s observations.

Therefore, it is possible to define a failure criterion based on displacement because a relationship between the static and dynamic deformation (or displacement) recorded in static and cyclic tests respectively exists.

As a result of this hypothesis, it is possible to point out the fundamental features that govern 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 the static pull-out test. However, in the fatigue life of anchor it is better not to exceed the displacement at static failure because in this case the process of fatigue is in the unstable zone.
6. Conclusion

The type of anchor have to be considered when it is subjected to cyclic load. The experiments have shown a non linear damage of anchorage during the fatigue life. The damage is influenced by anchor geometries thus one needs to consider this aspect in anchor type choice, especially if subjected to cyclic load. By comparing the evolution of load cycles it is possible to say that the most suited feature for the control of fatigue process is the displacement. The relationship between displacement in static and cyclic tests exists, therefore, by the load-displacement recorded during the static pull-out test, it is possible to point out the fundamental features that govern the cyclic behaviour. As result, the anchor fatigue life may be predicted more effectively through a relationship based on the increase in the displacement of the load application point 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 [2].

7. References.