Finite element modeling of anchor subjected to static and cyclic load

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ABSTRACT: This research work deals with the study of the behavior under monotonic and alternate shear loads of a single steel bolt anchored in a concrete slab. The aim is to predict the failure modes and the failure loads on the one hand and to compare the anchor behavior under static load versus alternate load on the second hand. The study is based on a numerical resolution using the finite element method. Different types of non linearity are considered in the model: non-linear behavior laws for steel and concrete, geometrical non linearity due to the large displacements and non linearity due to the contact conditions.

1 INTRODUCTION

Metal anchor bolts are frequently used in modern construction in order to assure the connection between different building components and to allow loads transmission between different elements of a structure. Over the past 30 years, much research work has been carried out on anchors at European and International level (Klinger et al. 1982, Hawkins 1987, Mesureur et al. 1993, Eligehausen et al. 1993, ETAG 1997, Elighausen et al. 2006). The majority of the design models and methods proposed for this type of anchors are based on a statistical empirical approach. Practice and tests have shown that they are not always predictive although the values obtained are on the safe side.

The origin of this problem is that different failure modes can arise in relation to the values of the different parameters involved (the anchor characteristics and their support, the spacing between anchors, the distance to edges and the direction of the applied force). The current available models are only predictive for a restricted range of parameters.

While the qualification methods of anchors under static shear loads have been improved significantly over the past years, relatively few information exists about anchors under seismic loads (Klingner et al. 1982, Vintzeleou & Eligehausen 1991, Rodriguez 1995, David et al. 2005, Hoehler 2006). Consequently, it appeared necessary to investigate the behavior of anchors subjected to monotonic and alternate shear loads.

This research work deals with the study of the behavior under monotonic and alternate shear loads of a single expansion anchor. The aim is to predict the failure modes, the failure load and the global load-displacement behavior on the one hand and to compare the anchor behavior under static load versus alternate load on the second hand. The study is based on a numerical simulation using the finite element method. Different types of non linearity are considered: non-linear behavior laws for steel and concrete, geometrical non linearity due to the large displacements and non linearity due to the contact conditions. A specific damage model has been adopted for the cyclic behavior of concrete.

2 CONCRETE DAMAGE MODEL

Concrete exhibits a non-linear stress strain behavior mainly because of progressive micro-cracking and void growth. The development of micro cracks results in a degradation of the material stiffness and apparition of inelastic strains. For our modeling, the cracking progress in concrete is modeled using the damage model MODEV developed at the Scientific and Technical Center for Building CSTB (Mounajed et al. 2002, Ung Quoc 2003) and implemented in the finite element software CAST3M developed by the French Atomic Energy Commission CEA. This model has been established within the framework of the damage theory (Lemaitre & Chaboche, 1988).

The MODEV damage model takes into account the specific nonlinear effects involved in the deterioration process of concrete such: unilateral effect and stiffness recovery due to the cracks closure, inelastic strains, and the coupling between damage and inelastic strains.

Considering the complexity of cement based materials behavior, the model was kept as simple as possible with few parameters in order to insure a an easy experimental identification. This allows the model to be used for engineering design of concrete structures.

By analogy with Mazars's model (Mazars 1984), 2 equivalent strains representing respectively the local sliding and the crack opening are introduced. They are related to deviatoric part of the strain tensors and hydrostatic one. The model considers two independent scalar damage variables, corresponding respectively to each degradation mechanisms. Each damage variable has its own evolution law.

To improve mesh objectivity, the tensile and the compressive fracture energy are introduced in the damage evolutions laws by analogy to Hillerborg's fictitious crack approach (Hillerborg et al., 1976).

The adaptation of MODEV model for cyclic loading as well as the identification of its parameters has been presented in (Si Chaib et al., 2006).

The validation of the model under cyclic loading has been conducted by using a test described in literature (La Borderie 1991). A confrontation between simulated and experimental results has been carried out. The test corresponds to a reinforced concrete beam, subjected to a flexural cyclic load. The beam has 1700mm of length, 200mm of cross section height and 150mm of width. The span distance is about 1500mm. Steel reinforcement is composed of 4 longitudinal high adherence steel, and six stirrups, three at each beam end, to overcome failing under shear load. The beam is subjected to cyclic loading at the mid span as described in figure 1.

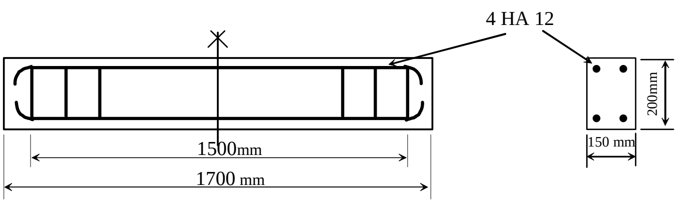


Figure 1. Schematic representation of reinforced beam geometry

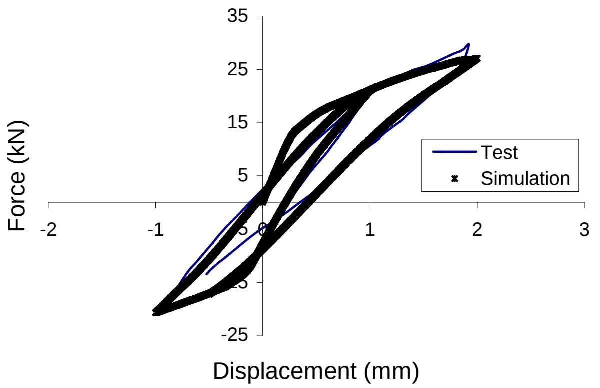


Figure 2. Global response of the reinforced beam under cyclic loading

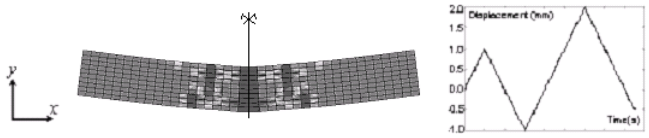


Figure 3. Damage profile of the reinforced beam and history of loading

The global force-displacement curve is plotted in figure 2. The comparison between test and simulation results shows a good agreement with both load estimation and residual strain. The damage profile is shown in figure 3.

The objectivity of the model with regard to the mesh size has been carried out.

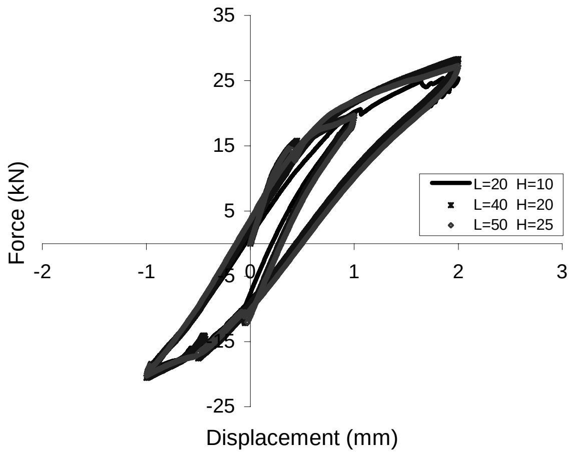


Figure 4. Global response of the reinforced beam under cyclic loading for different mesh sizes

Figure 4 shows simulation results, for the reinforced concrete beam, under cyclic loading, with 200 elements (length 20, height 10), 800 elements (length 40, height 20) and 1250 elements (length 50, height 25). It can be seen that these results both in terms of estimated load and inelastic strains are closer to each other. Objectivity according to different meshes is acceptable.

3 EXPANSION ANCHOR UNDER MONOTONIC SHEAR LOAD

A mechanical expansion anchor is placed in a C20/25 concrete with an embedment depth of 80 mm located far from any edges and subjected to monotonic shear load. The anchor dimensions are given in table 1.

Table 1. Anchor dimensions

External diameter	Effective embedment depth	Thickness*
mm	mm	mm
18	80	25

* Thickness of the fixture

3.1 *Mesh generation and material properties*

8-nodes isoparametric hexahedral elements have been adopted for the three dimensional finite elements mesh. Additional 4-nodes isoparametric tetrahedral elements are added to the configuration. In order to obtain correctly the higher stress gradient around the anchor, we used a high mesh density in this area. Due to symmetry, only a half of the mesh has been modeled. Figure 5 shows the principal parts of the mesh.

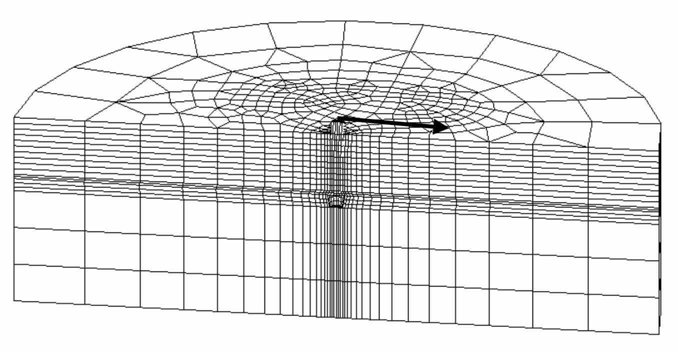


Figure 5. Global mesh

The shear force is simulated by a horizontal displacement applied, on the backside of the fixture. Concrete and steel properties are given in table 2.

Table 2. Concrete and steel properties

	Concrete			Steel	
	MPa	-	J/m²	MPa	-
Young Modulus	35000	-	-	210000	-
Poisson's ratio	-	0.2	-	-	0.24
Compr. Streng.	28	-	-	-	-
Tensile strength	3.5	-	-	-	-
Hardening modul.	-	-		2000	-
Fracture energy	-	-	80	-	-
Yield stress	-	-	-	600	-
Failure stress	-	-	-	900	-

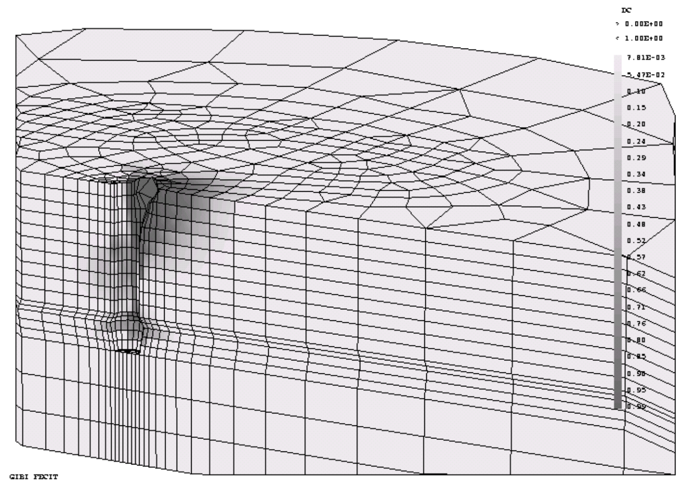
To solve such complex non-linear problem, the full Newton Raphson's method has been adopted. The computation is carried out in quasi static.

The contact phenomenon between steel and concrete interfaces is taken into account.

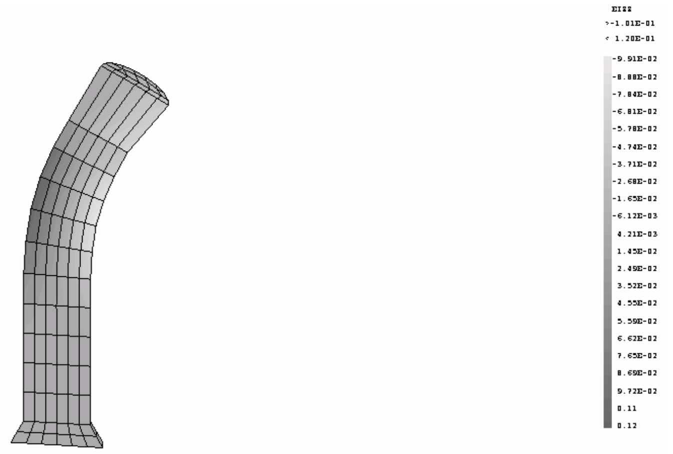
In the presence of large relative displacements between solids in contact (e.g. in the case of steel and concrete) the problem becomes highly non-linear.

Different methods can be used for numerical contact resolution. In our case, we used the double Lagrange multipliers method. Coulomb's smooth friction law has been used and the friction coefficient between steel and concrete is taken equal to 0.30.

An elasto-plastic model, with the Von Mises criterion has been adopted for the anchor behavior.



(a)



(b)

Figure 6. The failure occurs by a local concrete damage in front of the anchor followed by a steel failure: (a) deviatoric damage in the concrete structure (b) plastic strains (zz) in the anchor.

3.2 *Results*

The tests have shown that the fracture of an anchorage under shear loading is governed by the geometrical and by the mechanical properties of the anchor and its support. For a semi-infinite medium implantation, the failure may occur with concrete damage (pry-out for small embedment length) or steel failure accompanied by spalling at the concrete surface. In this study the failure occurs by the second mechanism mentioned above.

The comparison between the test results and the numerical simulation shows that the FE results are in good agreement with the tests results. In particular, the numerical simulations shows that the failure occurs by a local concrete damage in front of the anchor (Fig. 6) followed by a steel failure. The steel failure is caused by an important bending of the anchor. This bending is responsible of the excessive stresses and plastic strains in the anchor. In figure 6b and Figure 7 are respectively plotted the plastic strain and the Von Mises equivalent stress in the anchor.

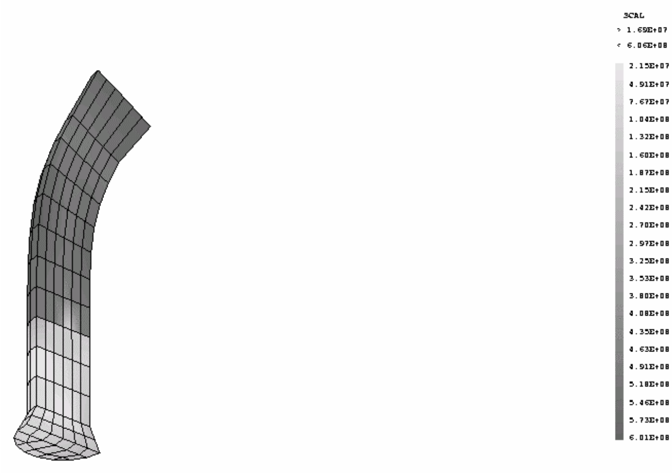


Figure 7. Von Mises equivalent stress in the anchor.

The ultimate load capacity of the anchor and the corresponding displacement comply with the experimental results as shown in figure 8.

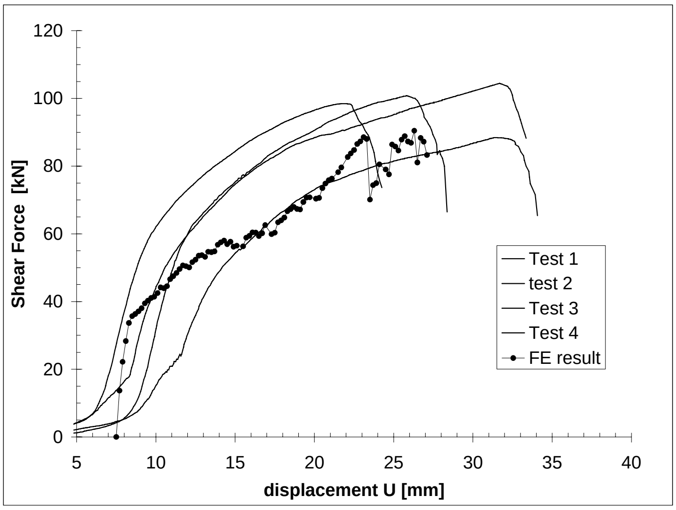


Figure 8. Load displacement curves: shear failure experimental and simulation results.

4 ALTERNATE SHEAR LOAD

Alternate shear test has been simulated on the same anchor described above. 4 alternating displacement controlled shear cycles were performed before loading the anchor to failure. The maximum displacement corresponds to a 50% of the ultimate shear capacity of the anchor. Figure 9 shows the adopted loading pattern.

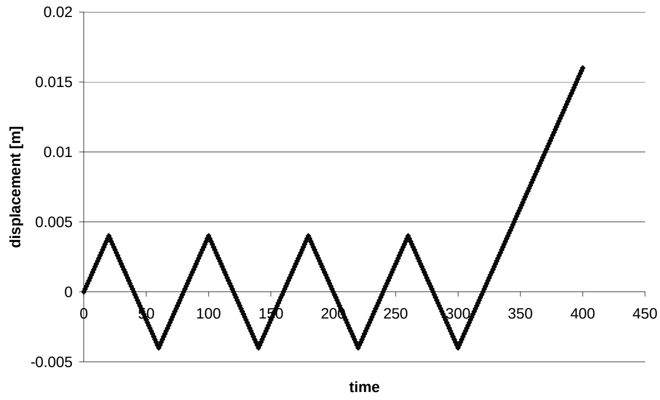


Figure 9. Alternate shear loading pattern (displacement controlled)

The alternate shear simulation shows (Fig. 10) that the local damage surrounding the anchor is more important compared to the damage obtained under shear load (for the same load level). This result complies with the experimental tests performed at CSTB (David et al. 2005) as shown in figure 11. It is also noticed that the local damage increases during the cycles particularly in the depth, bellow the upper surface of the slab (Fig. 12).

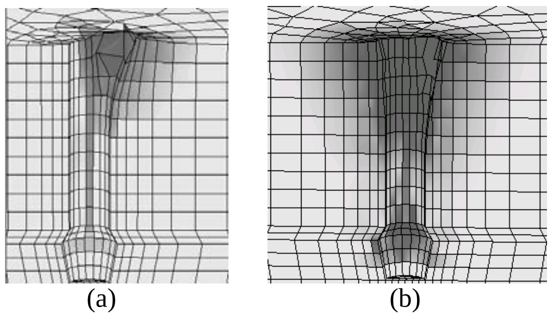


Figure 10. Local damage around the anchor: mono-tonic load (a) and alternate load (after 4 cycles) (b).

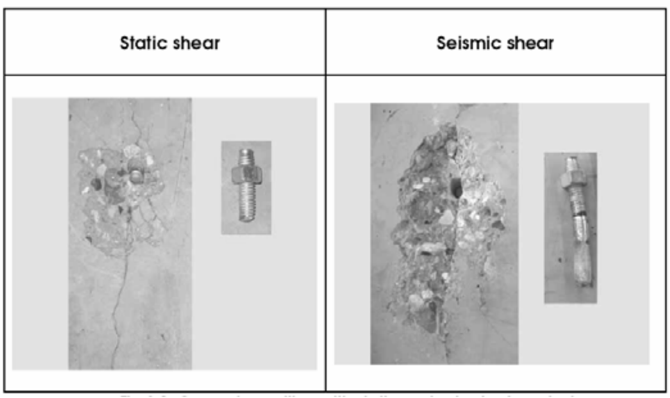


Figure 11. Local damage around the anchor with static and alternate shear tests (David et al. 2005).

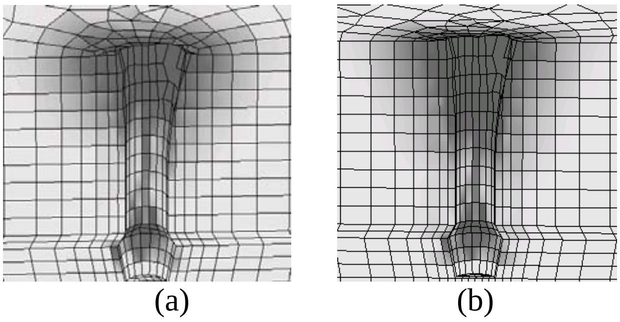


Figure 12. Local damage around the anchor : after one cycle (a) and after 4 cycles (b).

The load displacement curve, plotted in figure 13, points up the apparition of hysteresis loops during cycling. It points up also the substantial decrease of the shear stiffness with cycling.

Figure 14 illustrates the force degradation ratio (Vn/V_1) in the n^{th} cycle as a function of the number of cycles. This degradation is due to the local damage of the concrete surrounding the anchor. This result complies with the experimental tests performed by (Vintzeleou & Eligehausen 1991).

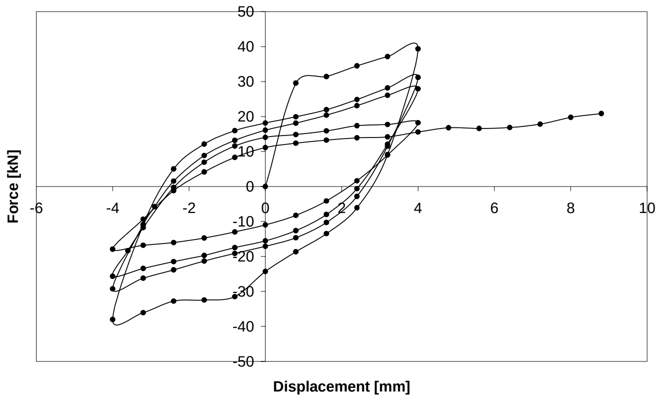


Figure 13. Load displacement curve: alternate shear simulation.

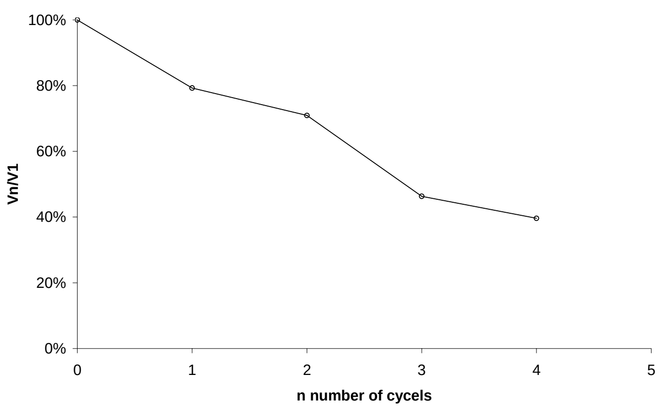


Figure 14. Force degradation ratio due to shear cycling as a function of the number of cycles.

5 CONCLUSION

The three-dimensional modeling of an anchorage to concrete using metal anchor bolts has been achieved under static and cyclic shear loads. Different types of non linearity have been considered: non-linear behavior of steel and concrete, large displacements and contact conditions. A specific damage model, developed at CSTB and implemented in the finite element software CAST3M, has been adopted for the static and cyclic behavior of concrete.

The results of the monotonic shear simulation are summarized as follows:

– The failure occurs by a local concrete damage in front of the anchor followed by a steel failure.
– The steel failure is caused by an important bending of the anchor.
– The ultimate load capacity of the anchor and the corresponding displacement comply with the experimental results.

The key results for the alternate shear load are summarized as follows:

– For the same load level, the local damage surrounding the anchor is more important compared to the damage obtained under shear load.
– The local damage increases during the cycles.
– Apparition of hysteresis loops during cycling.
– The degradation of the shear force increased with increasing number of cycles.

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