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NUMERICAL ANALYSIS OF FASTENERS USED IN CIVIL ENGINEERING STRUCTURES

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Abstract

When it comes to providing connection between different components, post installed mechanical fasteners can always offer a suitable solution. Their level of performances is nevertheless a concern, due to the consequences it may cause if they were inappropriately chosen. In order to avoid unexpected low performance of the fasteners, it is important to have a good knowledge regarding the mechanical behavior of fasteners to guarantee the durability and the efficiency of the structure. This issue can be raised in the case of French nuclear power plants, where the decision to extend the duration of life is at stake. In addition, except for newly installed anchors, most fasteners used in nuclear power plants have not been specifically qualified to demonstrate their capacity to support seismic loading. In recent years, CSTB (Centre Scientifique et Technique du Bâtiment) carried out experimental tests on fasteners used in nuclear power plant. The results showed that the shear capacity of these anchors subjected to seismic load is relatively low with respect to a static loading, which highlighted a need to study in more details their behavior. It should be noted that these qualifications were not requested when the fasteners were installed.

The scientific approach is to use two additional modeling techniques to assess the fasteners behavior with seismic loading: At the fasteners scale, the concrete crack will be explicitly described by a discrete model and at the structure scale, a simplified model using generalized variables will be developed to represent the non-linear behavior of the fasteners. The parameters of this model will be defined by the discrete model. In this paper, only the part at the scale of fasteners is presented.

In order to complete the experimental results, a numerical study is proposed, in this paper, to predict the behavior and the capacity of the fasteners under various loading. This study was done using a discrete element method, which allows to explicitly represent the cracks induced by the seismic event and the associated mechanisms (initiation, propagation, closure and unilateral effect, friction). After a brief description of the discrete model, the new meshing procedure, taking into account complex geometries, is presented. Then, 2D and 3D numerical results carried on headed stud for static loads are discussed. Finally, they are compared against experimental data. The discussion focuses on the capacity and the limitation of a 2D numerical model to predict the behavior of fasteners and the necessity to move to a 3D modeling.

Keywords: *Concrete, Fastening, Discrete model, Friction, Contact.*

1. Introduction

In structural and construction applications, mechanical anchors are used to ensure the connection between different structural elements, allowing the transfer of external loads toward base materials.

Anchor systems are distinguished by two main factors. The first one is the installation method and the second one is the transmission way of external forces toward base material. Generally, anchor systems are divided into two categories: cast in place and post-installed fasteners.

In order to extract the maximum potential and performance out of the fastening elements, a deep knowledge of their behavior under static and dynamic loading is necessary.

Experimental tests and empirical formulas are used to give a clear understanding regarding anchors behavior. It is worth noting that these experiments do not question the physical state of these anchors or how they may adapt during loading.

Nowadays, numerical simulations have been frequently used in the field of fastening technology. Recently, they were even confirmed as a valuable complement for any experimental result. Moreover, simulations can offer a wide understanding and even giving us a new perspective regarding the behavior of the studied material under different conditions. In addition, it can also reduce numbers, duration, and costs of experimental tests and help to estimate the seismic capacity of fasteners that couldn't be tested anymore.

However, the behavior of fasteners is a very complex problem due to its non-linearity. That behavior can be affected by numerous factors (large deformations, the contact surface between the anchor and the base material, geometric non linearity...). Over the last few decades, numerical simulations have been conducted to study the behavior of fasteners under various types of loading for a better understanding of their failure mechanism. In this context, two-dimensional and three-dimensional model were used to solve anchors problems. The finite element method was the most employed one. This modeling aims to reproduce realistically the anchor-concrete behavior.

For example, Ottosen (1981) carried out some tests on a headed stud in order to determine the compressive strength of concrete using a nonlinear finite element method. Cervenka and Pulk (1992) concentrating on the behavior of headed anchors in concrete. In their research, they considered a perfect adhesion between anchors and concrete. In addition, Long (1996) evaluated the behavior of anchors by using commercial simulation software (ABAQUS). Etze (1997) studied the failure behavior of a pulled out anchor, the steel part was not modeled but it was replaced by an applied displacement at the upper surface of the anchor head. Furthermore, Nienstedt and Mattner (2001) used their own simulation tools to study the tensile behavior of mechanical fasteners. The investigation of the anchors performance under static and cyclic loads was conducted by Boussa et al. (2007).

Nevertheless, most of these previous researches are based on a continuum mechanism that provides a global study without giving a fine description regarding the cracks process. For this reason, a discrete element model (DEM) is used instead of a finite element model (FEM) to represent a discontinuous material. For this purpose, DEAP (Discrete elements analysis program) aimed in this study to attain a clearer insight into the structural behavior. DEAP is a combination of a lattice model and a particular model. The lattice model has been proposed by Hrennikof (1941). The medium is represented by a group of beams or springs that can allow the transfer of force between the nodes. This model is unable to study the closure phenomena of cracks once they are opened.

Regarding the particular model, it was introduced by Cundall (1979) in order to study the behavior of granular materials. It discretizes the material to several particles and it models the interactions between particles.

In order to assess the behavior of these fasteners in seismic loading, the proposed scientific approach is to use two additional modeling: At the fasteners scale, the concrete crack will be explicitly described by a discrete model and at the structure scale, a simplified model using generalized variables will be developed to represent the non-linear behavior of the fasteners. The parameters of this model will be defined by the discrete model.

In this paper, the purpose is to demonstrate the capabilities of the beam-particular model (DEAP) for the analysis of the anchor's behavior in concrete during the setting and loading process.

The anchor and the concrete are presented through polygonal (polyhedral) particles in 2D (3D) linked together by beams that follow Euler-Bernoulli theory. Once two particles are not linked by a beam and are in contact, penetration and sliding are authorized between these two in order to represent the closure of cracks.

2. Model Description

DEAP is a particular discrete model originally developed by Delaplace (2008) and then extended by Vassaux et al. (2015) and Vassaux et al. (2016) to study the behavior of quasi-fragile materials, such as concrete. This discrete model represents a continuous medium by a finite number of rigid particles linked together through Euler-Bernoulli beams. Cohesion and contact efforts are the two types of interactions between the particles. The cohesive forces are provided by the set of beams joining the rigid particles by their centers.

These efforts take into account the cohesive behavior of the studied material. At this step, DEAP is similar to a lattice model. Later, the contact efforts are added to consider some mechanisms such as crack closure and aggregate interlocking. If two overlapping particles are not connected by a link or if the beam joining them initially was broken and removed during simulation, the particles will come into contact. Contact efforts, resulting from the penetration of these two particles and coulomb friction generated by the sliding caused between them, will be represented.

A brittle behavior is assigned to the set of beams used in the model. A breaking threshold P_{ij} is imposed and it depends on the axial strain and the flexion of the beam. When P_{ij} is reached, the breaking of the beam will be allowed (brittle fracture), it will be removed from the model and a micro-crack will be formed on the common side of both particles previously connected by this beam. The breaking threshold used in DEAP is that proposed by Herrmann and Roux (1990) [eq. 1]:

$$P_{ij} = \left(\frac{\varepsilon_{ij}}{\varepsilon_{ij}^{cr}} \right) + \left(\frac{|\theta_j - \theta_i|}{l_{ij}\theta_{ij}^{cr}} \right) \geq 1 \quad (1)$$

where ε_{ij}^{cr} and θ_{ij}^{cr} are the critical strain and the critical rotation of the beam i-j respectively.

Moreover, for a good representation of a quasi-brittle material such as concrete, a Weibull probability density function is introduced to the model to dissipate more energy and hence produce more micro-cracks in the material. More details are presented in Delaplace (2008), Vassaux et al. (2015) and Vassaux et al. (2016).

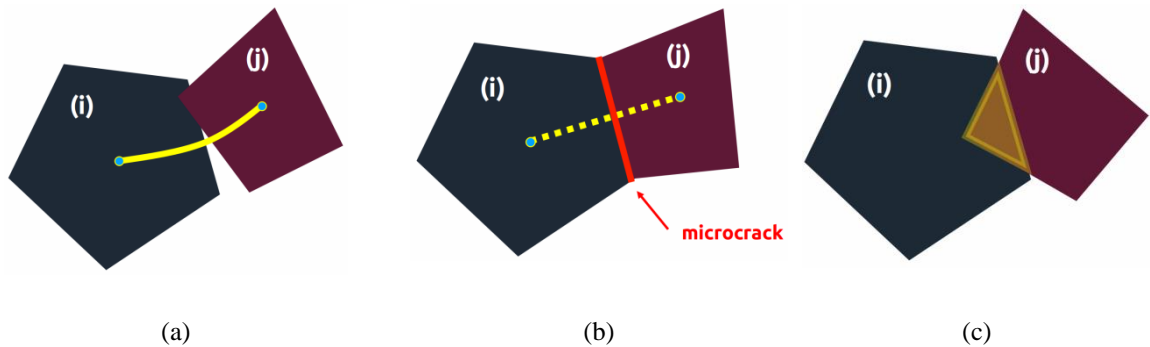


Figure 1. (a) Two cohesively linked particles (b) Rupture of link between the two particles (c) Two overlapping particles in contact

3. Mesh generation

For an anchor installed in concrete, a bad representation of the interface conducts a bad behavior and performance. For this reason, the steel-concrete interface must be well reproduced to avoid the appearance of any frictional efforts much higher than the ones in the real case. In other words, on the macroscopic scale, two types of friction should be distinguished: Coulomb law friction and geometric friction related to roughness. The first type can be adjusted by modifying the parameters. In contrast, the friction associated with roughness completely depends on the geometric representation and it cannot be modified. Hence, the need to generate correctly the contour of the surface.

For this purpose, a new meshing procedure has been developed to follow the VoroCrust method introduced by Abdelkader et al. (2012). This surface meshing exhibits two initial steps: (1) The reconstruction of the surface bounding (2) the generation of random nodes within the contour. VoroCrust algorithm can guarantee a good meshing quality for the generation of a Voronoi mesh. Furthermore, ghost nodes, required for the meshing, located near the edges are generated automatically outside the geometry.

Meshing algorithm is the following:

1. Discretization and generation of a set of points P_i along the contour M of the geometry (fig. 2 (a)).
2. Definition of circles B_i centered at each sample P_i with a proper radius r_i (fig. 2(a)).
3. Definition of a set of points $U_i = UB_i$ (fig. 2(a)).
4. Random generation of points inside the geometry using the method Poisson Disk Sampling proposed by (Dunbar and Humphreys, 2006) (fig. 2(b)).
5. Delaunay triangulation calculation of the set of points (fig. 2(c)).
6. Computation of Voronoi polygons (fig. 2(d)).

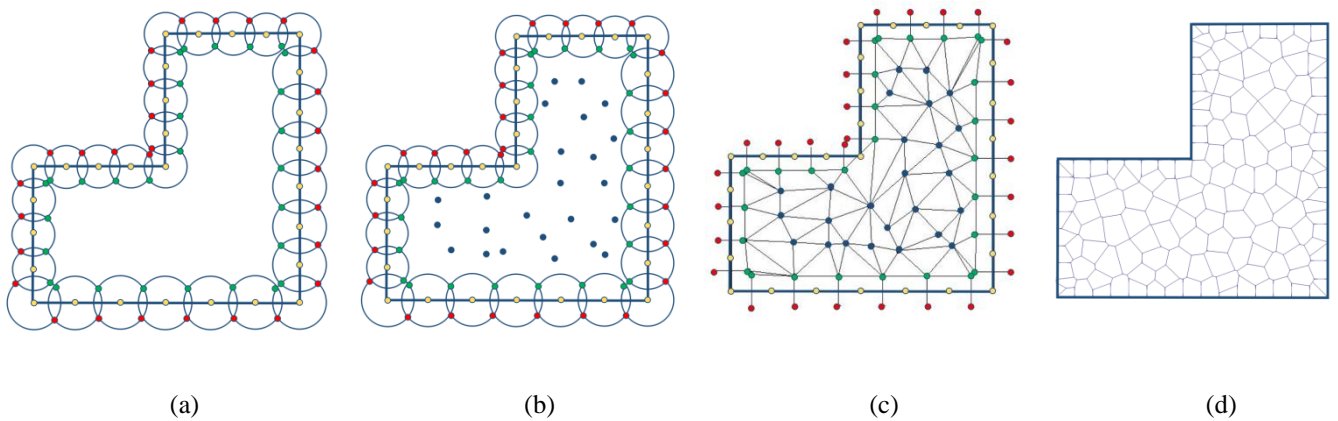


Figure 2. (a) steps 1-2-3 (b) step 4 (c) step 5 (d) step 6

4. Numerical Simulation

The numerical simulations presented here were built using DEAP to model the pull-out behavior of a headed stud placed in the concrete. This simulation is performed assuming the plane constraints hypothesis.

At the anchor scale, discrete modeling is used to represent the degradation of the concrete. In the simulation, two distinct materials with different mechanical properties as well as different friction coefficients were taken into consideration (steel-steel, concrete-concrete, steel-concrete). Figure 3 shows the discrete model of the anchor system. A pull-out test applied to a headed stud of type M20*160 (20 mm in diameter and 160 mm in length) is investigated. The geometry is generated using the meshing procedure presented in section 3. Horizontal and vertical displacements are blocked at a distance equal to $2 \cdot h_{ef}$ from the center axis of anchor to represent the support installed above the concrete during the experimental tests.

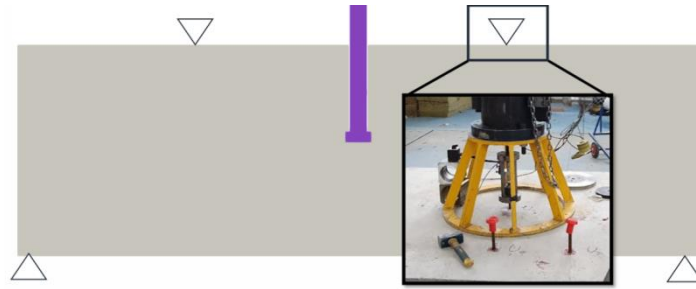


Figure 3. Model of anchor system

4.1. Simulation results

Figure 4 illustrates the displacement field of the anchor subjected to an applied displacement greater than the recommended one during the pull-out process. A concrete cone failure is obtained numerically of dimensions very close to that of the experiment test ($189 \times 152 \times 100$ vs $185 \times 161 \times 100$ mm³ respectively). On the other hand, quantitatively, the resistance obtained is very far from the real resistance of the anchor. This difference might be due to the inability of the plane constraints hypothesis to solve this type of problem.

4.2. Comparison with FE model (CAST3M)

This part aims to know whether to keep using DEAP2D or switch to a 3D version. For this purpose, a comparison was done in this section between DEAP and the finite element code CAST3M. The same geometry and the same boundary conditions were reproduced using CAST3M. Elastic behavior is assigned to the anchor and a Mazar's damage model is adopted for the concrete to take into account the degradation of the material. Three models have been studied: plane constraints simulations, axisymmetric simulations and three-dimensional model. In this study, adherence was applied between the screw head and the concrete. A spacing is assumed between the rod of the screw and the drilled hole. For the plane constraints simulation, the behavior and the maximal effort of the anchorage are very far from the experimental results. In contrast, in axisymmetric and three-dimensional simulations, the stiffness and the effort obtained numerically are close to that obtained experimentally with a concrete cone failure. Therefore, the hypothesis of plane constraints is not valid for studying anchor's behavior. This result was expected given the symmetries of the problem. It is important to note that axisymmetric conditions can be used for this specific problem but the classical loadings undergone by an anchor do not necessarily present this symmetry (especially in the case of shear loading).

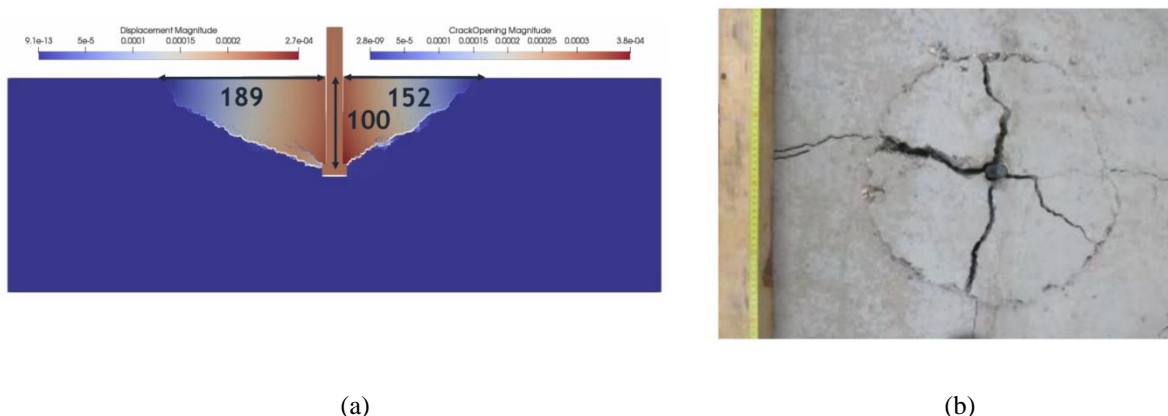


Figure 4. Concrete cone failure (a) DEAP (b) experimental tests

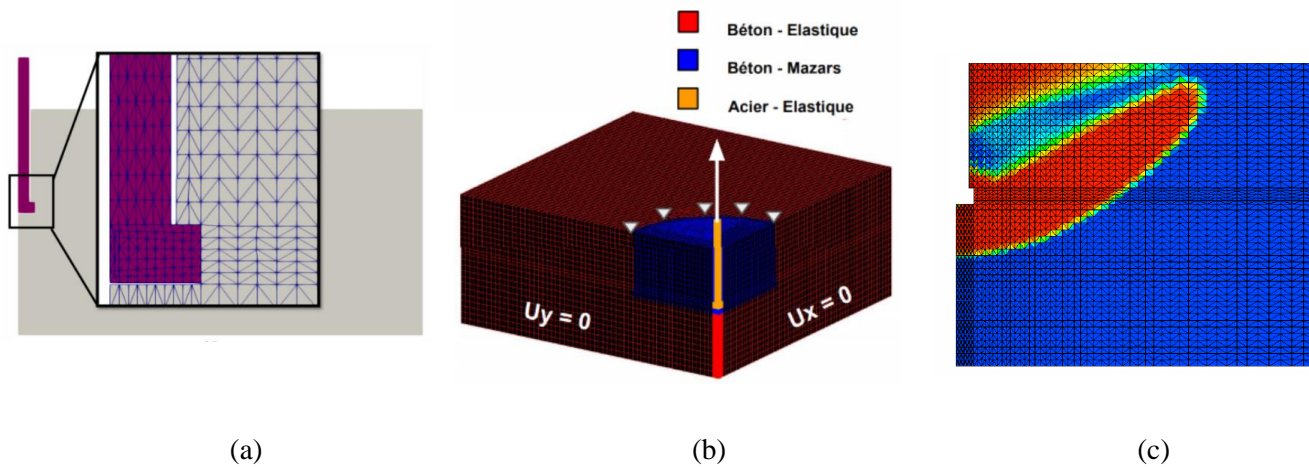


Figure 5. FE model for anchor system (a) in 2D (b) in 3D (c) axisymmetric results

5. Conclusions and perspectives

Good knowledge regarding the behavior of installed anchors in concrete is required for a safe design in structures. The two-dimensional modeling of an anchor system using a headed stud has been conducted under static tension loads. In this paper, a discrete model analysis is used for this aim. Experimental results carried out by the CSTB were chosen to be compared with the numerical simulation.

The following conclusions can be drawn from this study:

- The two-dimensional modeling based on the constraints plane hypothesis represents well the failure mechanisms. On the other side, it has a limitation on the prediction of the anchor's capacity.
- Axisymmetric simulations using a finite element program are compatible with the experimental tests. A concrete cone failure occurs and the model can reproduce the pull-out behavior of anchors. But those simulations are limited to specific cases.
- Concerning the three-dimensions, the results show compatibility with the experimental pull-out tests.

For this reason, a 3D version of DEAP will be developed in the near future for a better understanding of anchor applications under static and cyclic loads.

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