NUMERICAL ANALYSIS OF SCREW ANCHOR FOR CONCRETE

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Abstract: Concrete screws are one of the post-installed anchors and relatively new as a fastening product for concrete. For better understanding the working principle and for efficiently developing innovative screw anchors, numerical simulation is applied to study the failure mechanism and load carrying capacity of concrete screws. The loading process during pullout tests and the pressure distribution along the screw at different load steps are investigated. The relation between damage in concrete and pressure distribution is revealed.

1 INTRODUCTION

In order to develop innovative fastening products for concrete, a deep knowledge on the failure mechanism of concrete during setting and loading processes is very important. As is well known, numerical simulation is a powerful tool for the purpose, even though, due to the complexity of concrete, the simulation of concrete under complex loading condition is still a challenging research field. During the last two decades the Corporate Research & Technology of Hilti Corporation has been focused on the research in this field to continuously improve the simulation capability for supporting the development of Hilti fastening products. With the aid of simulation, the understanding of fastening systems and the knowledge on the failure mechanism of screws during setting and loading processes are impressively improved. This establishes the basis for developing high quality products and reducing the development time. In this study, a special type of anchor, namely concrete screws, is investigated. The tensile loading process is simulated with the aim of revealing the failure mechanism of the concrete screw. Moreover, the pressure distribution on the thread along the screw is analyzed. From the pressure analysis at different load steps, the pressure distribution and its influence on the damage of concrete during pullout loading is explored. The relation between concrete damage and pressure distribution is presented. The analysis results are valuable to better understand the working principle and the failure mechanism of concrete screws and offer more information for design engineers to innovatively improve the design of screw anchors.

2 SCREW ANCHOR FOR CONCRETE

The screw is a traditional fastening technique for construction materials like metal and wood. During the 1990s this technique was introduced to concrete as a post-installed anchor. In the last decade, the demand in the construction market for concrete screws has grown significantly, which greatly promotes the innovative development of screw anchors for concrete [1-3]. Figure 1 shows some typical concrete screws developed by Hilti Corporation during last few years.

Figure 1: Typical concrete screws developed by Hilti Corporation.

Concrete screws are one of the post-installed anchors. Compared to other traditional post-installed anchors for concrete, such as the undercut anchor, the expansion anchor and the bonded anchor, the screw anchors have some evident advantages. Apart from others, the main advantages of the concrete screws are the single component, fast installation, removability, and cost effectiveness. For the installation of concrete screws, a cylindrical hole has to be drilled in concrete. A power device or a screw-wrench is applied to drive the screw into the borehole. During the setting process the thread of the screw cut into the wall of the predrilled hole to create the mechanical interlock. This interlock ensures that the applied loads are transferred from anchor to concrete. Since concrete is a brittle material, the dust due to drilling could remain in the borehole. Before installation of the screw, the borehole has to be cleaned. A schematic instruction on correctly setting a screw anchor in concrete is shown in Figure 2.

The main function of screw anchor is to transfer the applied loads from the fixed element to the concrete through the mechanical interaction between concrete and the thread of the screw [3]. The load transfer mechanism is similar to that of reinforced bars cast into concrete, whereby the flanks of the screw thread act in a similar manner as the ribs of the reinforcing bars. However, a big difference compared to reinforced bars is that the screw anchors are post-installed into concrete. Therefore the damage to concrete during setting process may reduce the area of the mechanical interlock.

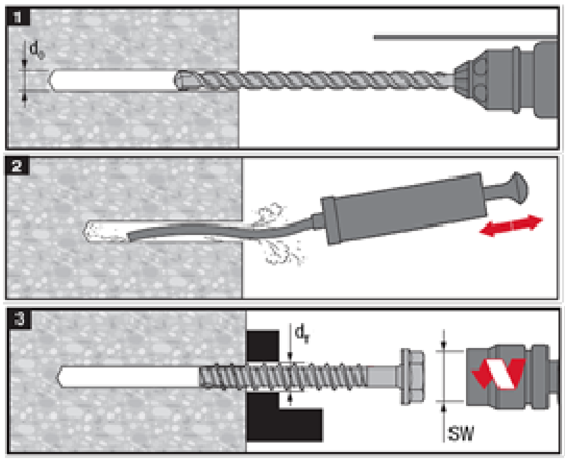

Figure 2: Setting instruction of a concrete screw [4].

The failure mode of a concrete screw under tensile loading can occur as a concrete cone failure, a concrete shear failure or a combined concrete cone and shear failure. The failure mode depends on the anchor geometry, boundary conditions, and concrete properties. Normally the concrete cone failure occurs for the undercut anchors, in which the failure is dominated by the tensile strength and fracture energy of concrete [5], while shear failure occurs for the bonded anchors, in which the shear resistance of bonded material dominates [6]. For concrete screws the typical failure mode is the combined failure as shown in Figure 3. The working principle of this kind of anchor is a combination of the functions of both undercut anchors and bond anchors.

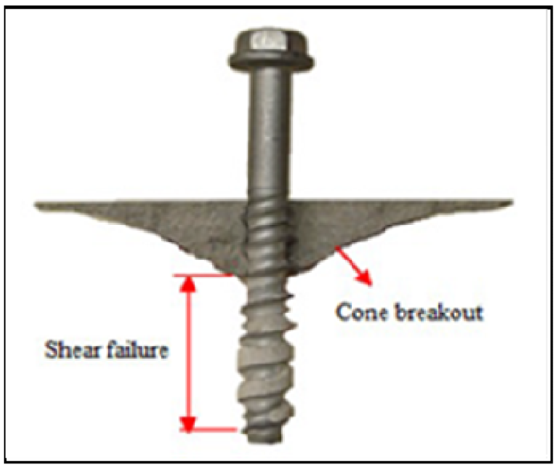

Figure 3: Typical failure mode of a concrete screw.

3 SIMULATION SET-UP

The simulation set-up for a pullout test of a screw anchor in concrete is shown in Figure 4.

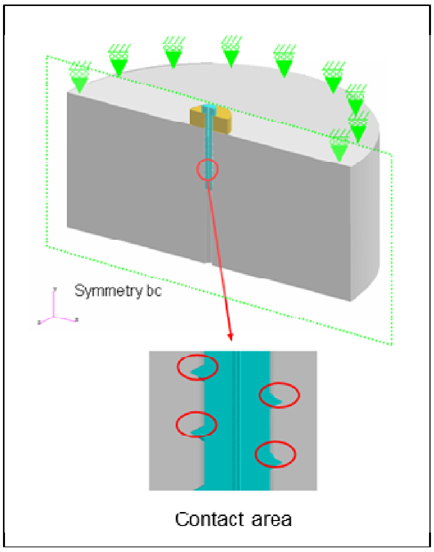

Figure 4: Simulation set-up of a concrete screw.

The tensile load is applied at the head of screw. The resistance boundary conditions are applied on the top surface of the concrete block. The distance between the applied boundary and the anchor center is larger than 1.5 times anchor length. Three components are presented in the simulation model: concrete block, screw anchor and fastened steel plate. To save computational cost, only half of the system is simulated and the symmetry boundary condition is introduced. The symmetry boundary condition is, theoretically, not applicable due to the shape of helix. Taking into account some preliminary simulations and the fact that the helix influence is very local, after comparison of the simulated failure processes to experimental data, the symmetry condition for screw is accepted.

In order to simulate the interaction between concrete and screw, the penalty contact model is used, as shown in Figure 4. The friction coefficients are defined based on experimental data. The applied tensile load is transferred from anchor to concrete through the contact on the surfaces of the thread.

The numerical investigation is conducted using a nonlinear finite element program developed by Hilti Corporation. A typical finite element mode for the simulation is shown in Figure 5.

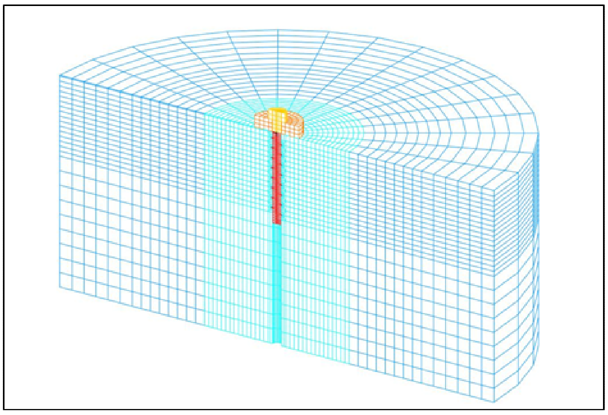

Figure 5: FE mode of concrete screw.

The pre-stress is applied in the upper part of the screw to simulate the stress situation due to the anchor`s installation. The value of the pre-stress is defined on the applied torque moment in experiment. Pullout load is controlled by the displacement at the top surface of the screw to capture the softening behavior of the structure. The concrete material is modeled with a damage plasticity model. The most important features of concrete under uniaxial tension, uniaxial compression and confined compression are included in the model. The crack band method is used for the objectivity with respect to different finite element meshes [7]. A typical benchmark to validate the simulation system has been published in previous work [8]. For all simulations in this study, the material properties for concrete are as listed in Table 1. The screw anchor and steel plate are modeled as an elasto-plastic material and the material parameters are shown in the same table.

Table 1: Material properties

Material	Concrete	Steel
Young’s modulus [MPa]	30303	210000
Poisson’s ratio	0.2	0.3
Tensile strength [MPa]	2.22	
Compressive strength [MPa]	26.9	
Yield strength [MPa]		750
Fracture energy [N/mm]	0.06	

4 NUMERICAL ANALYSIS

4.1 Pullout loading process

A typical screw anchor for concrete under pull-out loading is numerically investigated. The objective is to reveal the relation between concrete damage or failure modes and the load-displacement curve. The material properties, loading, and boundary conditions stay the same as described in the previous section. The simulated load-displacement curve with damage patterns in several typical loading steps is presented in Figure 6.

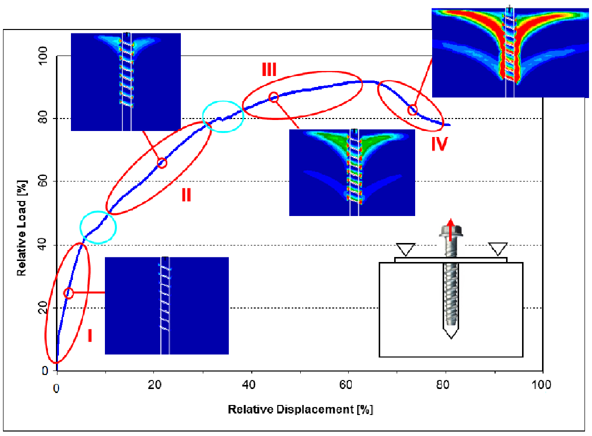

Figure 6: Concrete screw under tensile loading.

From the performance of the load-displacement curve in the figure, it is clear that the stiffness of the structure varies from strong to weak. Based on the variation of the structure stiffness, the curve can be divided into four phases as indicated by red lines in Figure 6. In order to check the damage situation in concrete, the damage patterns in four different phases are plotted out and presented in the figure. In the following, some comments on four phases are made.

Phase I: The load-displacement curve is almost linear with a strong stiffness. Only some micro-damage near thread is observed in the concrete. No crack is formed.

Phase II: The load-displacement curve is evidently bent and the structure stiffness becomes weaker. More damage appears and a localized crack is observed at the top portion of the concrete.

Phase III: The load-displacement curve is flattened and the structure stiffness becomes very weak. Strong damage appears in the concrete near the thread. The crack in the top portion of the concrete has been propagated, meanwhile another crack in the concrete near the bottom of screw is observed.

Phase IV: The load-displacement curve shows softening and the structure stiffness becomes negative. The damage near thread in the lower part of the screw connects together and forms a shear band. The crack in the top portion of concrete is strongly localized and a clear combined failure mode is formed. The crack at the bottom of the screw is slightly propagated, but finally it would be stopped with the localized combined failure mode.

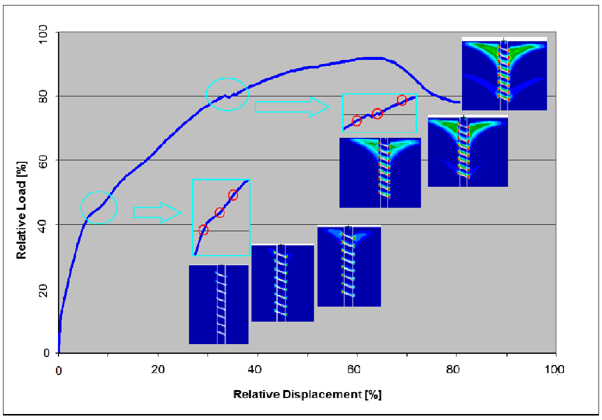

Figure 7: Concrete screw under tensile loading.

In order to understand why the stiffness varies in different phases, two small areas near the switch point of two phases are selected for detailed investigation. The selected areas are shown in Figure 7. The damage patterns before, at, and after the switch points are plotted on the same figure. From the damage patterns in Figure 7, it is clear that the reason of varied stiffness in different phases is due to the formation of new cracks. Between the first phase and the second phase, one crack in the upper part of the screw was created, and then another one was initiated at the bottom of the screw between the second phase and the third phase. Due to the formation of new cracks in the concrete, the structure becomes weaker and the stiffness of the system is reduced.

4.2 Pressure distribution

To better understand the failure mechanism of a concrete screw, the distribution of pressure on the surfaces of thread along screw is investigated. With the increasing of pullout load, some damage to concrete near the thread is formed. Meanwhile, the pressure on the surfaces of the thread should be correspondingly re-distributed. In theory, the total value of the pressure in the vertical direction represents the applied tensile load. The shape of the pressure distribution along the screw should help us understand how the screw anchor interacts with the concrete. In this section, the pressure on the surfaces of the thread is measured based on the simulation described in the previous section. The relation between the pressure distribution and the failure process is then analyzed.

4.2.1 Definition of pressure

In the simulation, the tensile load was applied on the top of screw anchor. The applied load is transferred from screw to concrete by the thread inside the concrete. The thread is considered to be separated based on the pitch, and the pressure within one pitch is calculated to represent the value in the section. Consequently, the loads in each section of thread are different. In order to calculate the pressure, the force for this section has to be defined. The definition of the force in each section is shown in Figure 8.

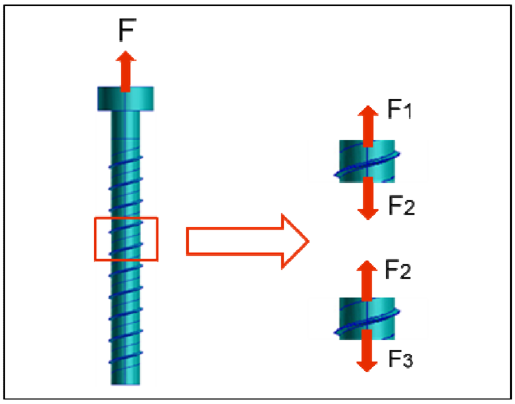

Figure 8: Forces in a section of the screw anchor.

As shown in the figure, the total applied load on the top of screw is F. The force transferred from the second section of the thread is calculated as follows:

$$F_{12} = F_1 - F_2 \qquad (1)$$

where F_{12} is the force applied to the section, F_1 is the force applied to the section above, and F_2 is the force applied to the section below.

The pressure is defined as the force per unit area applied in the direction perpendicular to the surface on the thread. As shown in Figure 9, the normal force on the thread is defined as a function of thread angle and applied load in the section, and calculated as follows:

$$F_{N12} = F_{12} \cos\alpha \qquad (2)$$

where F_{N12} is the normal force to the surface of thread, α is the thread angle, and F_{12} is the force applied to the section as defined in equation (1). Finally, the pressure can be calculated as a function of the normal force and the thread area in the section.

$$P_r = F_{N12} / A \qquad (3)$$

Where P_r is the pressure, F_{N12} is the normal force, and A is the contact area between concrete and thread.

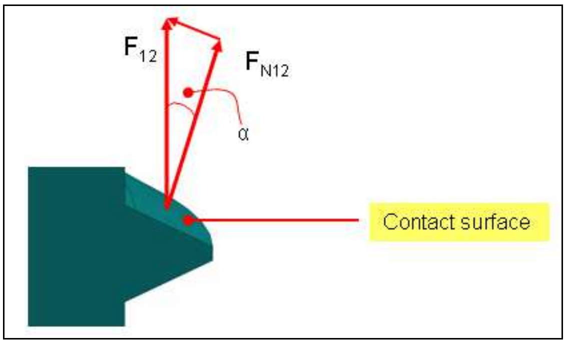

Figure 9: Schematic representation of the normal force.

4.2.2 Pressure distribution along the screw

In the study, the pressure distributions in all load steps are analyzed. Here, only the pressures in some critical load steps are presented. Figure 10 shows the positions of selected load steps in the load-displacement curve.

The first selected load step (step A) is located in the first phase of the load-displacement curve. The second one (step B) is located at the end of the first phase, where the first crack is created. The third one (step C) and the fourth one (step D) belong to the second and third phases in the load-displacement curve. The fifth (step E) is located at the maximum load point and the last one (step F) is in the area of the softening phase.

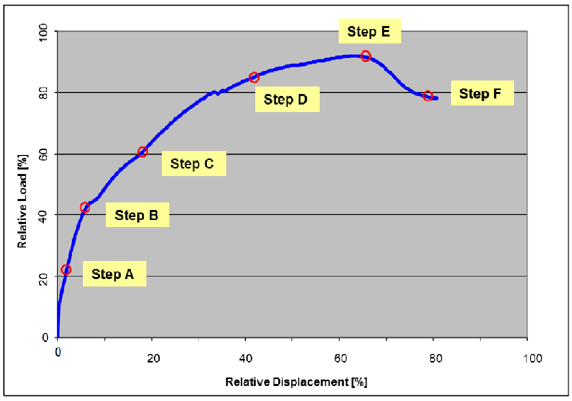

Figure 10: Selected load steps.

The calculated pressure distributions on the thread along the length of the screw are given in Figure 11. The horizontal coordinate in the figure represents the length of the screw.

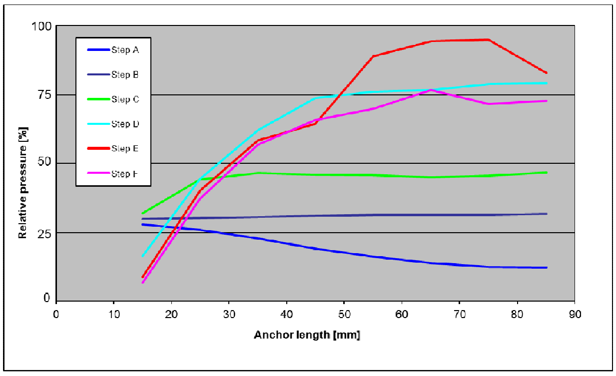

Figure 11: Pressures on thread along screw.

From Figure 11, some comments on the pressure distribution can be made as follows.

Load step A: This load step belongs to the first phase in the load-displacement curve as shown in Figure 6. In this load step, no visible crack was observed. The maximum pressure appears at the first thread from the top surface of the concrete. Towards the bottom of the screw, the pressure decreases gradually. This means that, in this load step, the thread in the upper part of the screw play a greater role than those in the lower part.

Load step B: This load step is located at the end of the first phase, just before the first crack appears. The interesting observation is that the pressure in this load step shows uniform distribution along the screw. This means that this load step is a critical level. As soon as the applied load passes this level, a visible crack is created, as observed in Figure 7.

Load step C: This load step belongs to the second phase in Figure 6. At this load step, the first crack has been formed and propagated. The pressure distribution at this load step appears uniform except at the first thread, where the pressure is evidently lower than those on other threads. The lower pressure at the first thread is caused by the propagation of formed crack.

Load step D: This load step belongs to the third phase. At this load step, two cracks have been formed and propagated. The pressure distribution at this load step appears very different. For the thread in the upper part of the screw, the pressure increases towards the bottom of the screw. For the other threads, the pressure distribution looks uniform. From the pattern of concrete damage, it can be seen that the first crack started from the area between third and fourth threads. A concrete cone was gradually formed as the crack propagated to the surface of concrete. Some threads at the upper part of screw are included inside of the concrete cone, which results in the reduction of the pressures on these threads. For the other threads, the pressures are almost uniform with a relatively high value.

Load step E: This load step is at the maximum point of the load-displacement curve. At this load step, the concrete cone has been completed and the shear resistance in the lower part of screw has reached to the limit of concrete shear strength. The concrete failure mode presents a combined failure. The pressure distribution clearly shows that the main applied load is resisted by the shear failure part of the screw, and the shear strength of concrete dominates the loading capacity.

Load step F: This load step belongs to the fourth phase. At this load step, the combined failure mode has been formed and the crack at the bottom of the screw is about to be closed. The pressure distribution in the shear-dominant part is reduced due to the shear failure occurring in the concrete. The pressure in the concrete cone area stays almost the same as in load step E.

5 CONCLUSIONS

In this study, the screw anchor for concrete is numerically investigated. Based on the simulated load-displacement curve, the loading process is divided into four phases. The damage and crack patterns in different phases are inspected. More detailed study shows that the reason for the phase's variation is the formation of new cracks in the concrete. From the pressure analysis at different load steps, the variation of pressure distribution during pullout loading is analyzed. The relation between damage patterns in the concrete and the pressure distribution is revealed. The analysis results are valuable for a better understanding of the working principle and failure mechanism of concrete screws.

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