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Experimental evaluation of tensile behaviour of single cast-in-place anchor bolts in plain and steel fibre-reinforced normal- and high-strength concrete

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Cast-in-place anchor bolts embedded in plain and steel fibre-reinforced normal- and high-strength concrete members were subjected to monotonic tensile loads. The influence of the concrete member thickness, concrete strength, and the addition of steel fibres to the concrete mixture, on the anchorage capacity and performance was evaluated. The experimental results were evaluated in terms of anchorage capacity, anchorage ductility and stiffness as well as failure mode and geometry. Furthermore, the validity of Concrete Capacity (CC) method for predicting the tensile breakout capacity of anchor bolts in plain and steel fibre-reinforced normal- and high-strength concrete members was evaluated.

The anchorage capacity and ductility increased slightly with increasing member thickness, whereas the anchorage stiffness decreased slightly. In contrast to the anchorage ductility, the anchorage capacity and stiffness increased considerably with increasing concrete compressive strength. The anchorage capacity and ductility also increased significantly with the addition of steel fibres to the concrete mixtures. This enhanced capacity and ductility resulted from the improved flexural tensile strength and post-peak cracking behaviour of steel fibre-reinforced concrete.

The average ratio of measured strengths to those predicted by the CC method for anchors in plain concrete members was increased from 1.0 to 1.17 with increasing member thickness. In steel fibre-reinforced concrete, this ratio varied from 1.29 to 1.51, depending on the member thickness and the concrete strength.

1. Introduction

Fastening systems, which use the mechanical interlock as a load transfer mechanism to convey external loads to concrete structures, typically fail via concrete-related failure modes, such as concrete cone breakout and concrete splitting. Concrete splitting failure may occur when an anchor is placed in a relatively thin concrete member or very close to adjacent anchor/s or concrete free edges. Concrete cone breakout failure is characterized by the formation of a cone-shaped fracture surface in concrete at the anchoring zone. This failure mode is fairly common for various types of anchors under tensile loads. Previous numerical and experimental studies on single cast-in-place anchor bolts under tension loads showed that the concrete cone circumferential cracking initiates at approximately 30% of the ultimate load. In addition, the concrete cone crack growth is stable up to the ultimate load [1]. It was observed that at ultimate load, concrete cone cracks do not reach the concrete surface. The ratio of the length of concrete cone cracks at ultimate load to the side length of a full-cone envelop varies from 0.5 to 0.25 with increasing anchor embedment depth [1]. As the deformation at ultimate load is exceeded, the concrete cone crack growth become unstable and the full-cone envelop forms completely with increasing deformations at post-peak load.

In general, concrete cone breakout and splitting failures are characterized as brittle failures because the load-displacement curves associated with these failures decline sharply after peak load, due to rapid and unstable propagation of concrete cracks. For these brittle failure modes, the full tensile capacity of concrete is utilized, thereby resulting in concrete cracks at the anchoring zone.

Steel failure may also occur if steel in the anchor experiences a tensile stress that exceeds its ultimate tensile strength while the concrete remains undamaged. This failure is considered a ductile-failure mode and is rarely observed but may occur if the steel in the anchor is ductile and if the anchor embedment depth

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is extremely large. In addition, a ductile failure for cast-in-place headed anchors may also be achieved if the concrete contains reinforcement in the anchoring zone.

Compared to the ordinary concrete (i.e. non-fibre-reinforced), Steel Fibre-Reinforced Concrete (SFRC) has shown improved flexural tensile strength, residual flexural tensile strength and post-peak cracking behaviour [2]. Several studies showed that the use of SFRC material leads to an improved structural capacity and performance (i.e. increased flexural, shear and punching resistance, increased flexural stiffness, improved ductility, and reduced crack widths and crack spacing) compared to ordinary concrete [3–5].

It is expected that fastening systems that are susceptible to brittle-concrete failures may have an improved anchorage capacity and performance when they are placed in SFRC members. Although currently the use of SFRC has become popular in practice, the structural behaviour of fastening systems in SFRC has not been fully investigated.

Over the last few decades, several investigations, via experiments and numerical simulations, of various anchorage systems in Normal-strength Plain Concrete (NPC) have led to the development of theoretical and empirical models for predicting the failure load of these systems [1,6–12]. The tested anchors were, however, all embedded in NPC members and, hence, the proposed models may underestimate the anchorage capacity in SFRC members. In addition, concrete compressive strength for most of the tested anchors considered in the previous studies was <50 MPa, albeit in a short number of tests it was up to 70 MPa. However, the current design standards and guidelines allow designing fastening systems in high-strength concrete with compressive strength of up to 70 MPa [13–17].

High-strength concrete is, by nature, more brittle than normal-strength concrete. As investigations on fastenings in this material have rarely been reported, further experimental evaluations of fastenings in concrete members with compressive strengths >50 MPa are recommended.

In addition, the influence of global bending stiffness of the concrete member (e.g. member thickness and surface reinforcement) and size of anchor-head on the anchorage capacity and performance is neglected by the current models for predicting the tensile bearing capacity of fastenings. Nilforoush et al. [18,19] have, via numerical simulations, recently shown that (i) the tensile breakout capacity of headed anchors increases with increasing the member thickness or size of anchor-head, and/or if surface reinforcement is present, (ii) the anchorage is governed by the concrete splitting failure, rather than the concrete cone breakout failure, if concrete member is relatively thin and unreinforced.

The use of high-strength SFRC may allow the design of relatively thin structural concrete members for loads corresponding to normal-strength concrete and, hence, its use is becoming common practice. Although theoretical models were developed for the design of such members, further investigations of anchorage behaviour in relatively thin high-strength SFRC are required.

In this paper, the influence of the member thickness, concrete strength, and steel-fibre addition to the concrete mixture, on the tensile breakout capacity and performance of cast-in-place headed anchors is experimentally investigated. Nineteen single cast-in-place headed anchors were tested in plain and steel fibre-reinforced normal- and high-strength concrete members. The experimental results are presented in terms of load-displacement curve, anchorage ultimate load, anchor displacement at the ultimate load and at the load corresponding to the initiation of concrete cone circumferential cracking (i.e. considered as 30% of the ultimate load), anchorage stiffness and ductility, and failure mode and geometry. In addition, the validity of the Concrete Capacity (CC) method for predicting the tensile breakout capacity of anchor bolts in plain high-strength concrete and steel fibre-reinforced normal- and high-strength concrete is evaluated. Furthermore, another experimental study is ongoing to evaluate the influence of member thickness, anchor head size and surface reinforcement on the tensile breakout capacity of headed anchors. The test results will be presented and discussed in detail in a separate paper.

2. Current models for tensile capacity of anchor bolts in concrete

In the case of steel failure, the resistance of an anchor is directly proportional to the steel strength and the cross-sectional area of the anchor shaft. Although the failure load associated with this failure is quite simple and well understood, the established theoretical model for determining the failure load associated with concrete splitting failure is more complex. In fact, the failure load for splitting failure of a particular anchor type is often determined by approval tests.

The failure load associated with concrete cone breakout can be reasonably calculated via the Concrete Capacity (CC) method (referred to as the Concrete Capacity Design (CCD) method in the US), proposed by Fuchs et al. [12]. The CC method, which is a basic model for predicting the tensile breakout capacity of fastening systems in concrete, has been incorporated into (i) several design standards in the US (e.g. ACI 349-01 [13] and ACI 318-08 [14]), (ii) various design-oriented documents in Europe (e.g. CEB Design Guide [15] and CEN/TS 1992-4 [16]), and (iii) internationally in the *fib* Bulletin 58 [17]. Based on the CC method, the mean tensile breakout capacity of a single cast-in-place anchor, unaffected by concrete free-edge influences or overlapping cones of adjacent anchors, can be evaluated from:

$$N_{u,m} = k\sqrt{f_{cc}}h_{ef}^{1.5} \quad (1)$$

where $N_{u,m}$: mean concrete cone breakout capacity of a single anchor [N], f_{cc}: concrete cube compressive strength [MPa], h_{ef}: anchor effective embedment depth [mm], and k: empirical factor [$N^{0.5}/mm^{0.5}$] of 15.5, obtained from several tests on cast-in-place undercut and headed anchors in uncracked concrete members. The CC method assumes a concrete cone angle of ~35°, with respect to the concrete surface, which leads to an idealized projected cone area of $\sim 3.0h_{ef} \times 3.0h_{ef}$ on the concrete surface [12].

3. Experimental program

The experimental study was performed in the laboratory of the Division of Structural and Fire Engineering at Luleå University of Technology (LTU), Sweden. A total of nineteen single cast-in-place anchor bolts were subjected to monotonic tensile loading. Testing parameters, such as the concrete member thickness, concrete compressive strength, and the addition of steel fibres to the concrete base material, were considered. Four different test series were considered in this experimental program (see Table 1 for matrix of experimental program). The typical geometry of the test specimens, including both the side and top views, is shown in Fig. 1. The test specimens were designed to fail via brittle-failure modes associated with concrete (the designed tensile strength of the steel anchor bolts was sufficiently high to prevent steel failure). In all test series, a single anchor bolt with an effective embedment depth of h_{ef} = 220 mm was placed in the center of a concrete slab. The length (L) and width (W) of concrete slabs for all specimens were identical ($L = W$ = 1300 mm), whereas the height of concrete slabs (H) varied from 1.5 to 3.0 times the anchor embedment depth (i.e. H = 330, 440 and 660 mm).

In series (i)–(iv), the anchor bolts were tested in Normal-strength Plain Concrete (NPC) members, Normal-strength steel Fibre-Reinforced Concrete (NFRC) members, High-strength Plain