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Failure modes and tensile strength of screw anchors in non-cracked concrete

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Failure Modes and Tensile Strength of Screw Anchors in Non-Cracked Concrete

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Abstract

Screw anchors are widely used in applications such as fastening base plates in steel and metal construction, formwork and bracing, structural steel applications, railings and handrails. At present, researchers and design engineers rely on the Concrete Capacity Design (CCD) method to predict the strength of screw anchors under the tensile loading as the only method available in literature. In CCD method, the underlying assumption is that the concrete cone and combined concrete cone and pull-out failure modes are the main failure mode for anchors, whereas, previous studies have demonstrated that pull-out is also a very common failure mode of screw anchors. In this paper, experimental results of more than 180 tests on one particular type of screw anchors are studied to better understand their behaviour under tensile loading. Experimental results are classified based on the observed failure modes. New equations are proposed to predict the tensile capacity of this particular type of screw anchors associated with each of the above mentioned dominant failure modes for the first time. The experimental results are compared with the predicted values by the CCD method and specifications provided by the anchor manufacturer. It is also shown that in majority of cases, the CCD method overestimates both the experimental results and the specifications given by the manufacturer.

Keywords:

Screw anchors; failure mode; tensile strength; cone failure; pull-out failure; combined failure; non-cracked concrete.

1. Background

Screw anchors rely on mechanical interlock between anchor threads and concrete grooves that are formed during installation to develop their tensile resistance. Interlock between the anchor and substrate is also the main load transfer mechanism in the case of headed studs and undercut anchors, where the interlock occurs mainly at the tip of the anchor. In the case of screw anchors, such an interlock takes place over a number of threads of the anchor. As such, screw anchors can sometimes exhibit a behaviour similar to that of chemical anchors where the load is transferred to the substrate along the embedment depth, instead of only at the tip of the anchor.

The resistance provided by the interlock between the anchor threads and grooves in the substrate material may vary from one screw anchor to another depending on several parameters such as: (i) the diameter of the anchor core/shank relative to the diameter of threads, i.e. the protrusion of the anchor into the substrate; (ii) the thread shape and pitch; (iii) the embedment depth of the anchor; (iv) the concrete (substrate) mechanical properties such as the compressive and tensile strength; (v) mode I and mode II fracture energies; (vi) age of concrete at the time of installation/loading, especially in the case of early aged concrete, and (vii) installation method, i.e. manual versus impact wrench can also alter the behaviour and failure mode of an anchor (see Section 4).

Research by Kuenzlen and Eligehausen [1] indicated that the applied torque during installation can also change the tensile capacity of anchors. They demonstrated that excessive applied torque during installation could damage the concrete grooves and hence reduce the tensile capacity of the anchor. In some cases, such excessive torque can cause shearing-off of the threads or the head of the screw anchor leading to the steel failure mode (also see Section 4).

Kuenzlen and Eligehausen [1] conducted 500 tests on three types of screw anchors. Anchors of 8–18 mm diameter were installed in concrete of cylinder compressive strength of 25.5 MPa (using a factor of 0.85 to convert the cube strength to cylinder); the embedment depth varied between 30 and 110 mm. They observed little variation between the tensile capacity of screw anchors of the same embedment depth and different diameters, and did not detect any meaningful effect associated with the type of threads of screw anchors of the same diameter and embedment depth.

However, the experimental results from a more recent study by Stuart, Harrison, et al. [2] on four types of screw anchors showed a strong correlation between the anchor (thread) type and the tensile capacity of anchor. They noted the largest concrete cone depths were related to one type of screw anchors which had the least thread protrusion into the concrete, i.e. minimum difference between the shank diameter and thread diameter. This particular anchor was threaded over the full length. With an exception of one anchor which failed due to excessive torque applied during installation, all anchors failed due to a combined pull-out and cone failure mode (hereafter referred to as combined failure mode for simplicity), with an average cone depth ranging between 30% and 66% of the nominal embedment (Figure 1). When the concrete grade was changed from C20/25 (with compressive strength range of 25-35 MPa) to C50/60 (with compressive strength range of 55-65 MPa), there was only 18% increase in the tensile capacity of one type of anchors, whereas it was as high as 61% for another type. The exact concrete compressive strengths, and the details of how such variations could be explained, e.g. detailed record of failure modes, were not reported.

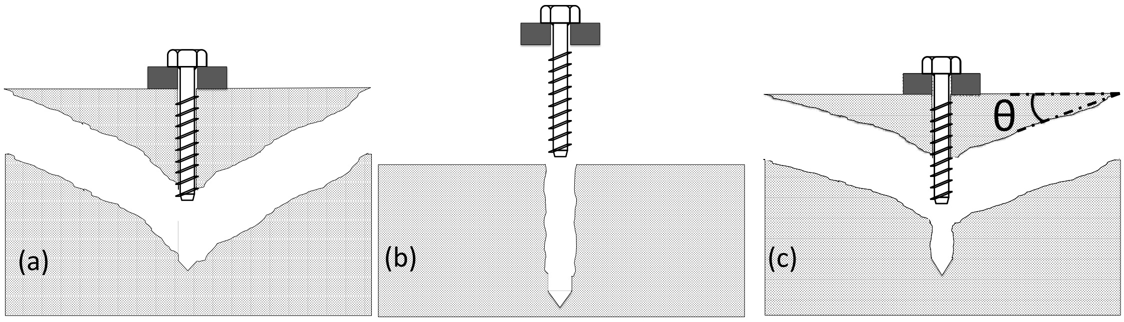

Figure 1: Screw anchor common failure modes under tensile load (a) concrete cone failure, (b) pull-out failure, (c) combined pull-out and cone failure

Mohyeddin, Gad, et al. [3], who tested three different types of anchors in two classes of concrete also found out that there was at least a 20% variation in the tensile strength of anchors of different types. They observed that cone failure was the least common failure mode in general, and showed that the recurrence of individual failure modes may also depend on the type of anchor.

Kuenzlen and Eligehausen [1] observed two failure modes in their tests: cone failure for shorter embedment depths, and combined failure mode for deeper embedment depths. Based on their experimental results, they extended the Concrete Capacity Design (CCD) method, Eq.1, which was initially developed for expansion, undercut and stud anchors, to predict the tensile capacity of the three types of screw anchors that they tested:

$$N^U_0 = 14.6 * h_{ef,1}^{1.5} * f_{cm}^{0.5} \quad \textbf{Equation 1}$$

where N^U_0 is the tensile strength/capacity of the screw anchor (N), f_{cm} is the cylindrical compressive strength of concrete (N/mm^2), and $h_{ef,1}$ is the reduced effective embedment depth given by Eq. 2 (mm):

$$h_{ef,1} = 0.85 * (h_{nom} - 0.5 * h - h_s) \quad \textbf{Equation 2}$$

where h_{nom} is the distance from the concrete surface to the tip of the anchor (nominal embedment depth), h is the distance between threads (thread pitch), and h_s is the distance between the tip of an anchor and its first thread. These parameters are shown in Figure 2. The effective embedment depth of screw anchors, h_{ef}, is defined as $h_{ef,1}$ without the consideration of the reduction factor of 0.85 in Eq. 2.

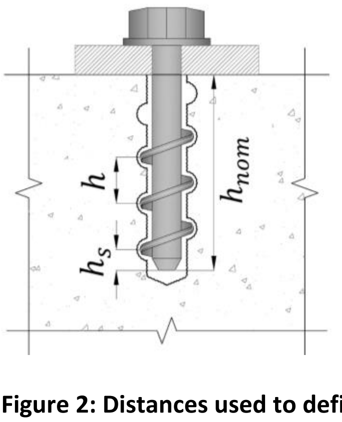

Figure 2: Distances used to define the effective embedment depth for a screw anchor

It should be noted that in order to expand the CCD method (Eq.1) to screw anchors, Kuenzlen and Eligehausen [1] included the results related to both cone failure and combined failure in their data analysis; it is for this reason that a reduction factor of 0.85 was incorporated in the definition of the "reduced" effective embedment depth, $\boldsymbol{h_{ef,1}}$, by Eq. 2. Therefore, it is expected that Eq. 1 would overestimate the tensile capacity of an individual anchor failing due to a combined failure mode, and underestimate the capacity of those failing due to a (pure) cone failure.

The above equation (with some minor variations) has since been the only equation used for predicting the tensile capacity of screw anchors as adopted by EN 1992-4 [4] and AS 5216 [5]. Olsen, Pregartner, et al. [6], who expanded the results by Kuenzlen and Eligehausen [1] by additional 353 tests on a wide range of screw anchors, suggested that Eq. 1 "on average" remains a safe choice to estimate the capacity of screw anchors. However, the ratio between the experimental and calculated strength of anchors installed in uncracked concrete with the nominal embedment depth of greater than 40 mm varied between approximately 0.5 to 1.75. Similar to the previous research, a detailed report on failure mode(s) was not provided.

More recent studies on screw anchors have demonstrated that pull-out is also a common failure mode of screw anchors. In comparison, Fuchs, Eligehausen, et al. [7] reported that pull-out failure mode is more ductile in behaviour compared to cone failure with the maximum tensile load occurring at relatively larger displacements in the case of undercut and expansion anchors. Similarly, Mohyeddin, Gad, et al. [8] reported a slightly more ductile behaviour of screw anchors which failed due to pull-out than those which failed due to combined failure. This can partly be related to the residual friction between the anchor and concrete when the anchor is pulled out of concrete after reaching the maximum tensile capacity, compared to a more brittle cone failure of concrete.

2. Objectives

As discussed earlier, Eq. 1 was developed based on the test results that include both cone and combined failure modes, and hence a constant reduction factor of 0.85 was applied to the definition of the effective embedment depth of screw anchors (Eq. 2). Furthermore, a designer would be completely dependent on the experimental values published by the manufacturer and/or in the ETA (European Technical Approval) of a product to assess the tensile capacity related to pull-out failure. The main objective of this article is to separate the test results based on their failure modes and assess their tensile capacities separately. An attempt has been made to propose separate equations to calculate the tensile capacity of an anchor associated with any of the above individual failure modes. The above objective would be of even more importance, if it was found that the recurrence of any of the failure modes was also sensitive to any of the geometric or material properties of the substrate or anchor, such as the anchor thread profile, embedment depth, anchor diameter, or any of the mechanical properties of substrate material (concrete). To reduce the number of variables, in this research any possible variations caused by the thread profile has been excluded, i.e. one anchor type has been used only.

One should further note that at the moment ETAs do not specifically report h or h_s values of an anchor, but rather a value for $h_{ef,1}$ to be used along with Eq. 1 (noting that these values may or may not be consistent with the original definition of $h_{ef,1}$ as given by Eq. 2). This, however, calls for another research to investigate the effectiveness of Eq. 2, given the current variety of screw anchors in the market. Obviously, if such $h_{ef,1}$ values do not match the values given by Eq. 2 (that a designer could physically measure/calculate), one would still be heavily dependent on the specifications given by manufacturers and/or ETAs to find the tensile capacity due to cone/combined failure modes (that are currently classified as one failure mode according to Eq. 1). This, however, is not the objective of the current research.

3. Dataset

Zinc plated screw anchors of different lengths (and embedment lengths) and diameters were used. Anchors were one-piece units with a finished hexagonal head including an integral washer, a dual lead thread and a chamfered tip. Table 1 summarises the results of the experimental results considered in this study. The dataset used in this paper is comprised of 112 tests that were conducted as part of the current study, and another 70 tests results available from the literature (Mohyeddin, Gad, et al. [8]), 60 of which were related anchors instlalled in early age concrete. These are marked in Table 1 and were installed in concretes of between 24 hours and 14 days age. The reason for including these tests in the dataset was to cover a wider range of concrete strengths for statistical analyses (Section 7). Further discussions on the effect of the age of concrete on the strength of anchors can be found in Mohyeddin, Gad, et al. [8], where it was shown that at early ages the tensile strength of concrete increases more rapidly compared to the compressive strength. However, it was shown that for both early age and old concretes the tensile capacity of anchors was more correlated to the compressive strength of concrete than the tensile strength; this is compatible with the findings of the regression analyses here, and hence the results of these 60 tests were included in the current study. As shown in Table 1, these 60 tests were conducted on M16 anchors only with one embedment depth. The dataset covers the whole range of the diameter of the one particular type of anchor that was selected for this study (except for the smallest diameter, 5 mm) and covers a wide range of the embedment depth and concrete strength. As mentioned earlier, in order to eliminate the variations due to the anchor type/thread type, all the anchors were of the same type from the same manufacturer. This is an important consideration in the current study, as it is not the intention of this article to look into the underlying assumption of Eq 2, i.e. the effective embedment only depends on h and h_s.

4. Test set-up and anchor installation

Unconfined test setup as per Figure 3 was used in all 182 tests conducted/reported in this study (noting that the same test setup was used by Mohyeddin, Gad, et al. [8]). A reaction frame with a clear span of 500 mm was utilised to support a hollow cylinder jack and a hollow load cell. According to EOTA TR048 [9], this span can be used for testing anchors with effective embedment depth of up to 125 mm. An electric pump was used for loading. A needle valve was used to control the loading rate and to apply the load slowly. Displacement was measured using a calibrated displacement transducer positioned on top of the head of screw anchor as shown in Figure 3 to measure displacement of anchor relative to the concrete surface during loading.

All screw anchors were installed as per the manufacturer's installation instructions. Holes were drilled using the relevant drill bits on the trowelled surface of slabs using a rotary hammer drill. Drill bits were regularly checked to ensure continued compliance as per EOTA TR048 [9]. Anchors were installed using an impact wrench up to just before the head of the anchor reached the top of the fixture. For consistency of installation, all anchors were tightened using a calibrated torque wrench to a maximum permissible torque value recommended by the anchor manufacturer. Only in the case of 6.5 mm-diameter anchors with the nominal embedment depth of 38 mm, the anchors were installed using a torque wrench for the whole depth. For all installation, two observers from two approximately orthogonal directions would check that the drill alignment is straight before drilling commenced and while drilling took place. The fixture, as shown in Figure 3b, included a square plate and one or more washers to provide a variety of embedment depths. Holes were cleaned using an air compressor and a vacuum before anchor installation.

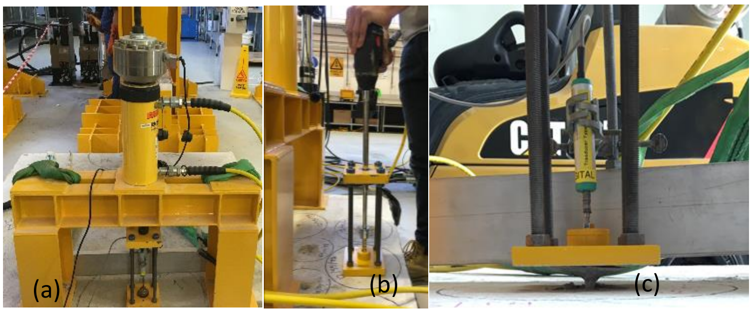

Figure 3: (a) Reacting frame, load cell, cylinder jack, displacement transducer and fixture, (b) anchor installation using an impact wrench, (c) displacement transducer

5. Substrate material

Five concrete slabs of 1400 mm × 1400 mm × 200 mm and one slab of 1400 mm × 1400 mm × 150 mm were cast for this study. In all cases the thickness of the slab was greater than double the embedment depth of screw anchors as per the requirement of EOTA TR048 [9]. Concrete was supplied from a local provider in the City of Perth in Western Australia. Normal class concrete, as specified in AS 1379 [10], with the maximum aggregate size of 20 mm and a slump of 80 mm made of general purpose cement (type GP), as per AS 3972 [11], was used. The compressive and tensile (splitting/Brazilian) strength of concrete were measured at the time of testing of anchors and are provided in Table 1.

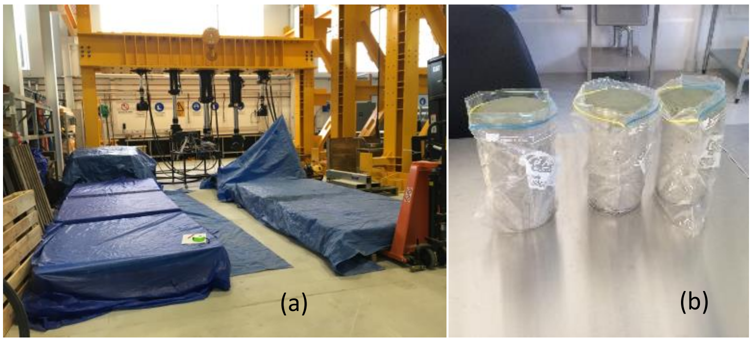

Figure 4: Covering slabs and cylinder samples after casting concrete

The concrete slabs were covered by plastic sheets straight after concrete was cast as shown in Figure 4a. All concrete cylinders were also cured under the same condition as that of the slabs to best represent the state of concrete slabs. The only exception was that cylinders were further covered with individual plastic bags before being covered by a large plastic sheet (Figure 3b). Sulphur capping was used for compressive samples as per AS 1012.9 [12]. Capping was carried out at least one hour prior to tests.

6. Anchor tests and failure modes

Out of 182 tests considered in this study, 107 anchors failed due to a combined failure mode, and 75 anchors failed due to pull-out (Figures 5a - b). This is consistent with the failure modes observed by other researchers (Olsen, Pregartner, et al. [6], Stuart, Harrison, et al. [2]). However, this is not consistent with the observations made by Eligehausen, Mallee, et al. [13] on failure modes; they expected pull-out failure to be observed only in cases where less than 80% of the embedment depth of anchor is threaded and the anchor is embedded for the standard anchorage depth. All the anchors considered in the current study had a threaded length greater than the nominal embedment depth (i.e. the full embedment length was threaded), except for anchors with the nominal embedment depth of 98 mm, where the threaded length was 95 mm. Since the difference is only 3% of the embedment depth, in all cases it was assumed that the full embedment depth is threaded.

For the classification of failure modes, the ranges previously applied by Mohyeddin, Gad, et al. [8] and Mohyeddin, Gad, et al. [14] were adopted for consistency. If the cone depth was less than 20% of the embedment depth, the failure mode would be defined as pull-out. This is mainly because of the surface effect that normally a small part of concrete would be damaged and stuck to the head of anchor without having any significance in terms of resistance. When the cone depth was between 20% and 85% of the embedment depth, it would be classified as a combined failure mode. Any cone depth greater than 85% of the embedment depth (which was not observed in this test series) would be considered as a full cone.

In three instances, the anchors of 6.5 mm diameter failed due to steel rupture (Figures 5c - e). Out of three cases, only one anchor with the nominal embedment depth of 79 mm broke off almost just below the head of the anchor (Figure 5c). In this case, the maximum tensile force was recorded at a very low displacement (0.8 mm), which may relate this failure to the quality of this particular anchor. The other two anchors ruptured almost at the concrete surface/just below the fixture (Figure 5d - e); the nominal embedment depths were 69 and 79 mm in these cases and the displacements at the maximum force were greater than 2.1 mm.

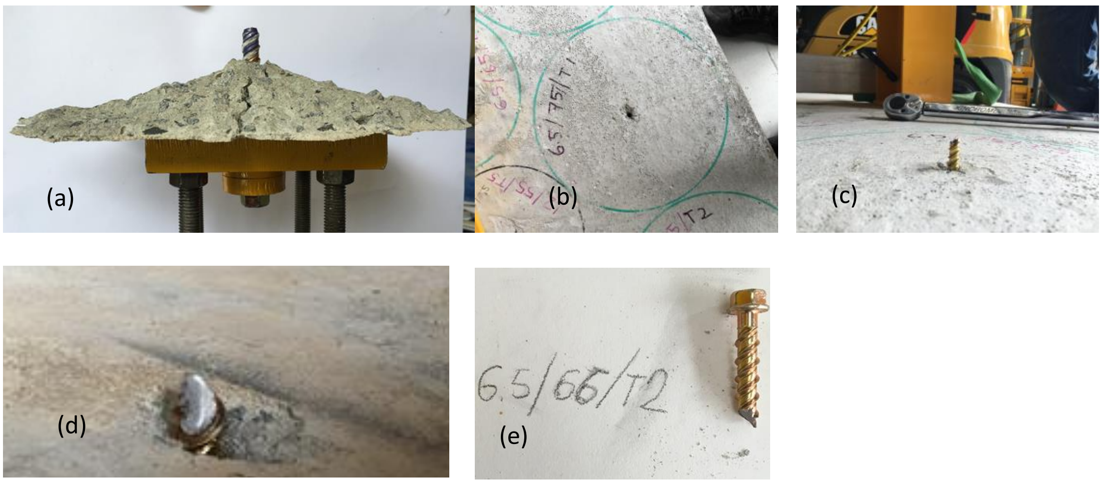

Figure 5: Failure modes (a) combined, (b) pull-out, (c) – (e) steel rupture

In the case of combined failure mode, the maximum loads were recorded at an average displacement of 2.4 mm, with minimum, maximum and coefficient of variation of 0.1 mm, 7.0 mm and 0.6, respectively. In the case of pull-out failure mode, these values were 2.8 mm, 0.1 mm, 8.0 mm and 0.6, respectively. This confirms the previous observation by Mohyeddin, Gad, et al. [8] that pull-out failure mode tends to exhibit a slightly higher displacement at maximum load compared to combined failure mode.

Figure 6 shows the recurrence of combined and pull-out failure modes against the anchor diameter, the nominal embedment depth and the compressive strength of concrete. According to Figure 6(a), pull-out failure constitutes a relatively large proportion of failure modes, i.e. more than 50%, when the anchors are at the two ends of the spectrum, i.e. 6.5 mm and 16 mm diameters; whereas in the middle range almost 75% of anchors failed due to combined failure mode. Based on Figure 6(b), one can conclude that as the embedment depth increases from ~40 mm to 80 mm, the recurrence of combined failure modes decreases from 90% to 50%, after which on average ~50% of anchors tend to fail due to pull-out failure. Figure 6(c) shows no correlation between the concrete compressive strength up to ~30 MPa and the recurrence of failure modes; for higher strengths, though, the combined failure mode becomes the dominant failure mode occurring in more than 75% of cases.

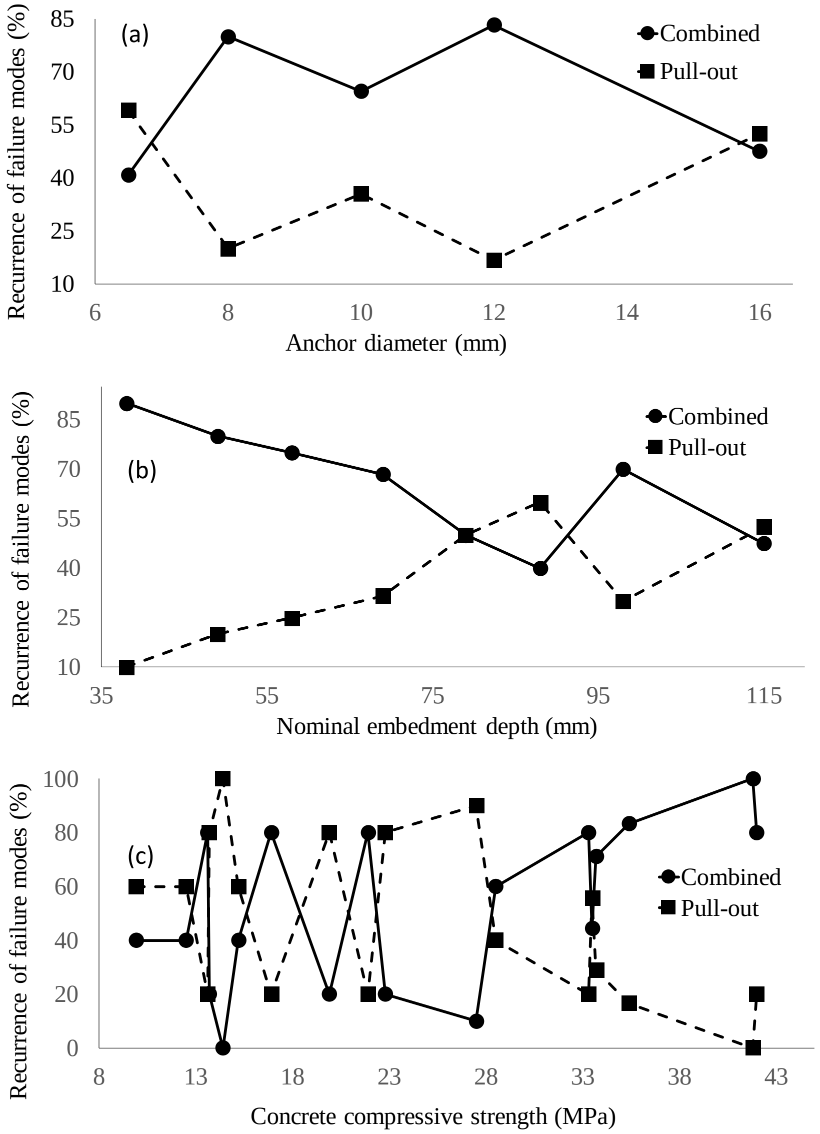

Figure 6: Recurrence of failure modes versus (a) anchor diameter, (b) nominal embedment depth and (c) concrete compressive strength

Table 1: Summary of experimental results for concrete properties and anchor results

Nominal Embedment Depth (mm)	Anchor Diameter (mm)	Average Compressive Strength f_{cm} (MPa)	Characteristic Compressive Strength f'_c (MPa)	Average Splitting Tensile Stress $f_{ct.sp}$ (MPa)	Average of Anchor Ultimate Strength $N^t_{Ru,m}$ (kN)*	Recurrence of Failure Mode#	Eq. 4 $N^{th}_{pullout}$ (kN)	Eq. 14 $N^{th}_{comb,min}$ (kN)	Eq. 1 N^U_0 (kN)	Average Capacity of Anchor Specified by Manufacturer (kN)**
38	6.5	33.7	24.1	2.7	6.5	Combined: 4	12.2	11.1	13.8	11.6
					7.3	Pull-out: 1				
					6.7 (15)	All tests: 5				
	8	33.7	24.1	2.7	9.5 (14)	Combined: 5	13.2	11.8	13.3	12.9
49	6.5	33.7	24.1	2.7	14.4	Combined: 3	16.0	15.0	20.1	N/A
					15.2	Pull-out: 2				
					14.7 (13)	All tests: 5				
	8	33.7	24.1	2.7	15.4 (12)	Combined: 5	17.5	16.1	20.3	17.5
	10	33.7	24.1	2.7	13.2	Combined: 4	19.2	17.2	19.7	17.6
					13.8	Pull-out: 1				
					13.3 (15)	All tests: 5				
58	6.5	33.5	23.9	2.8	22.6	Combined: 1	19.1	18.0	27.0	N/A
					16.8	Pull-out: 4				
					18 (16)	All tests: 5				
	8	33.5	23.9	2.8	22.4	Combined: 4	20.9	19.5	26.5	21.2
					19.3	Pull-out: 1				
					21.8 (8)	All tests: 5				
	10	35.4	25.8	2.8	18.0 (13)	Combined: 5	23.6	21.6	26.6	21.7
	12	35.4	25.8	2.8	19.4 (10)	Combined: 5	25.3	22.6	25.7	26.9
69	6.5	33.5	23.9	2.8	19.1	Combined: 1	22.9	21.9	35.5	N/A
					21.7	Pull-out: 3				
					27.9	Steel rupture:1				
					22.4	All tests: 5				
	8	33.5	23.9	2.8	29.9	Combined: 3	25.1	23.7	34.9	N/A
					27.5	Pull-out: 2				
					28.9 (13)	All tests: 5				
	10	35.4	25.8	2.8	28.4	Combined: 4	28.5	26.5	35.2	26.3
					30.3	Pull-out: 1				
					28.8 (14)	All tests: 5				
	12	35.4	25.8	2.8	29.5 (11)	Combined: 5	30.6	28.0	34.2	34.3
79	6.5	33.5	23.9	2.8	22.7	Pull-out: 3	26.4	25.3	43.9##	N/A
					23.8	Steel rupture:2				
					23.2 (15)	All tests: 5				
	8	33.5	23.9	2.8	35.7	Combined: 3	29.0	27.6	43.3	N/A
					30.6	Pull-out: 2				
					33.6 (13)	All tests: 5				
	10	35.4	25.8	2.8	32.8	Combined: 2	32.9	30.9	43.7	31.0
					35.2	Pull-out: 3				
					34.3 (9)	All tests: 5				
	12	35.4	25.8	2.8	33.6	Combined: 2	35.5	32.8	42.6	41.4
					35.3	Pull-out: 3				
					34.0 (14)	All tests: 5				
88	10	33.7	24.1	2.7	40.0	Combined: 2	36.0	34.0	50.6	34.9
					40.9	Pull-out: 3				
					40.5 (7)	All tests: 5				

	12	33.7	24.1	2.7	43.8	Combined: 2	38.8	36.3	49.5	45.7
					38.7	Pull-out: 3				
					40.8 (12)	All tests: 5				
98	10	33.7	24.1	2.7	45.9	Combined: 3	40.3	38.3	60.0	N/A
					44.4	Pull-out: 2				
					45.3 (11)	All tests: 5				
	12	33.7	24.1	2.7	45.5	Combined: 4	43.6	41.0	58.8	48.5
					50.2	Pull-out: 1				
					46.5 (9)	All tests: 5				
115	16	9.9^	0.3	1.2	29.0	Combined: 2	31.7	29.6	40.0	N/A
					33.8	Pull-out: 3				
					31.9 (14)	All tests: 5				
		13.7^	4.1	1.4	34.2	Combined: 1	37.3	34.8	47.0	N/A
					35.6	Pull-out: 4				
					35.4 (3)	All tests: 5				
		12.5^	2.9	1.3	38.4	Combined: 2	35.6	33.2	44.9	N/A
					37.0	Pull-out: 3				
					37.6 (6)	All tests: 5				
		14.4^	4.8	1.7	35.8 (4)	Pull-out: 5	38.2	35.6	48.2	N/A
		13.6^	4.0	1.6	37.9	Combined: 4	37.2	34.6	46.8	N/A
					35.2	Pull-out: 1				
					37.4 (12)	All tests: 5				
		16.9^	7.3	1.7	43.3	Combined: 4	41.4	38.6	52.2	N/A
					34.3	Pull-out: 1				
					41.5 (18)	All tests: 5				
		15.2^	5.6	1.5	36.8	Combined: 2	39.3	36.6	49.5	N/A
					44.0	Pull-out: 3				
					41.1 (12)	All tests: 5				
		21.9^	12.3	2.0	50.8	Combined: 4	47.2	44.0	59.4	N/A
					50.2	Pull-out: 1				
					50.6 (9)	All tests: 5				
		19.9^	10.3	1.7	51.1	Combined: 1	45.0	41.9	56.7	N/A
					44.5	Pull-out: 4				
					45.8 (13)	All tests: 5				
		28.5^	18.9	1.9	49.8	Combined: 3	53.8	50.1	67.8	55.9
					56.0	Pull-out: 2				
					52.3 (16)	All tests: 5				
		22.8^	13.2	2.1	36.4	Combined: 1	48.1	44.8	60.6	N/A
					46.7	Pull-out: 4				
					44.7 (11)	All tests: 5				
		33.3^	23.7	2.7	54.8	Combined: 4	58.1	54.2	73.3	60.9
					61.0	Pull-out: 1				
					56.0 (15)	All tests: 5				
		27.5	17.9	2.4	51.0 (8)	Pull-out: 5	52.8	49.3	66.6	54.8
		41.8	32.2	2.8	62.3 (16)	Combined: 5	65.1	60.7	82.1	69.8

*The average of all Coefficients of Variations for each class of concrete was below 0.15, which satisfies the requirements of EAD 330232-00-0601 [15].

Refer to Figure 1 for failure modes.

**Calculated and interpolated using allowable working loads provided by the manufacturer excluding the safety factor of 3.0 used by the manufacturer and considering a 10% increase on average to convert the characteristic values to average values, i.e. the figures reported in the table are allowable working loads multiplied by 3.10. Also, the concrete characteristic strength was used instead of the average compressive strength.

^ Early age concrete.

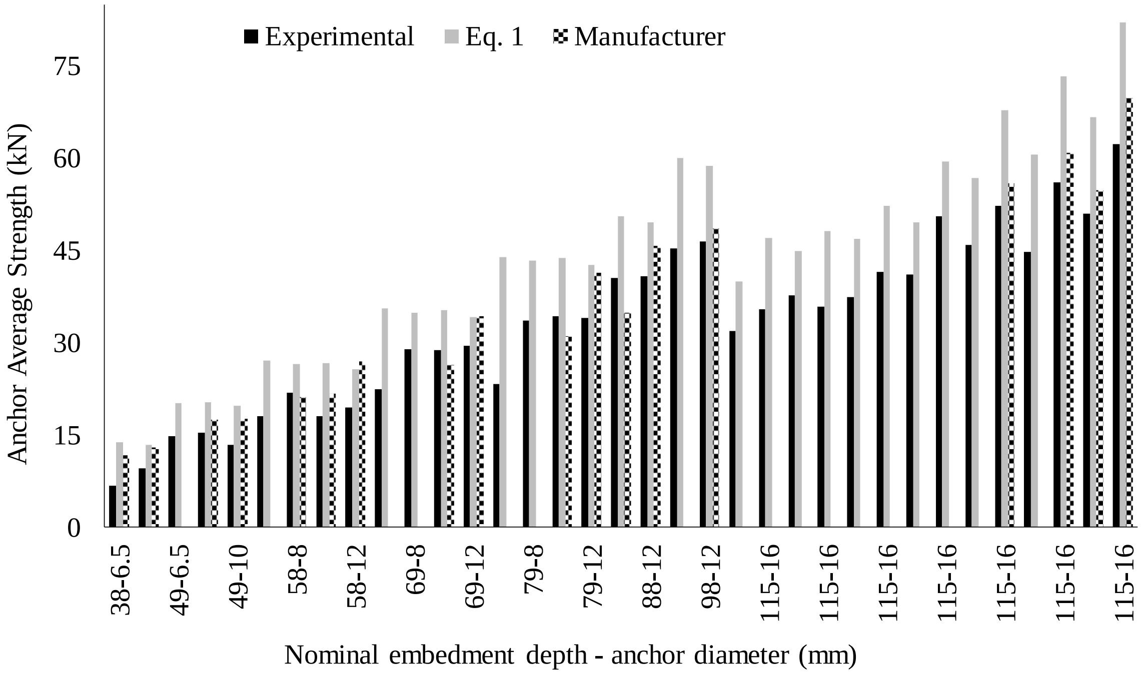

Figure 7: A comparison between the anchors experimental average strengths and suggested values by the manufacturer and literature

Figure 7 summarises the anchors experimental average ultimate strengths against those estimated based on the manufacturer's design data and the values calculated using Eq. 1. The measured values of h (thread pitch) and h_s (distance between the tip of an anchor and its first thread) used for calculating N^u_0 are given in Table 2.

Table 2: Measured physical dimensions of anchors

Anchor Diameter (mm)	h* (mm)	h_s* (mm)
6.5	5.0	0.5
8	6.0	0.7
10	7.2	1.0
12	9.0	1.3
16	11.6	2.0

* For h and h_s refer to Figure 2.

As shown in Table 1 and Figure 7, in some cases the experiments fall outside the range for which the manufacturer has provided design data, e.g. very low concrete strengths. For the range where an interpolation was accepted by the manufacturer, in ~25% of the cases the experimental results showed a higher strength than what was provided by the manufacturer. In another ~35% of the cases the experimental results were up to 10% less than the values given by the manufacturer; except for one case, the rest of the results (~40%) were less than 30% lower than the values given by the manufacturer. When interpreting these comparisons, however, one should note the assumptions made to back-calculate the manufacturer's average values, such as a 10% increase in characteristic strengths, and a linear interpolation between the given concrete strengths and embedment depths (allowed by the manufacturer). On the other hand, the experimental results are on average 24% lower than the values predicted by Eq. 1. This consistent overestimation is expected as discussed in Section

1, since the there was no full cone formation/cone failure in the experimental results of the current study, and hence the overestimation by Eq. 1. Furthermore, it is likely that the specific anchor used in this study had a thread profile substantially different from those of the range of anchors (three types) used by Kuenzlen and Eligehausen [1], and therefore the variation from the predictions by Eq. 1. In addition, Eq. 1 is based on the compressive strength of concrete measured using concrete cylinders of 150 mm diameter and 300 mm length. In this study cylinders of 100 m diameter and 200 mm length were used (i.e. common practice in Australia). There is no consensus in the literature on a specific conversion factor for the strengths measured using different cylinder sizes. AS 5216 [5], for instance, does not recognise any size effect on the compressive strength using the above two cylinder sizes. However, AS 1012.8.1 [20] does not allow the data from specimens of different sizes to be combined. According to very limited experience that authors have, any of the two sizes may reveal a smaller or higher strength, that is consistent with the findings of Vandegrift and Schindler [21]. Regardless of the source of such a variation between the experimental results and Eq. 1, one could suggest to replace the constant 0.85 in Eq. 2 with 0.70, i.e. ~20% reduction $h_{ef,1}$, to make Eq. 1 applicable to this particular anchor. The implication of such a correction factor is that Eq. 1 does depend on the anchor type (thread profile); this is more consistent with the findings of Stuart, Harrison, et al. [2], and contrary to the assumptions made by Kuenzlen and Eligehausen [1] (Section 1).

The average of the tensile strength related to combined and pull-out failure modes, where they both occurred in any 5 repeats of the same test, is compared in Figure 8. Based on this figure it is not possible to identify one or the other as the favourable failure mode in terms of the highest strength. One should also note that pull-out failure of a screw anchor (unless the anchor has improperly been installed leading to a premature pull-out failure) does require breakage of concrete (also see Section 7.1) and is not of a frictional behaviour similar to that of expansion anchors, in which case is not a desirable failure mode.

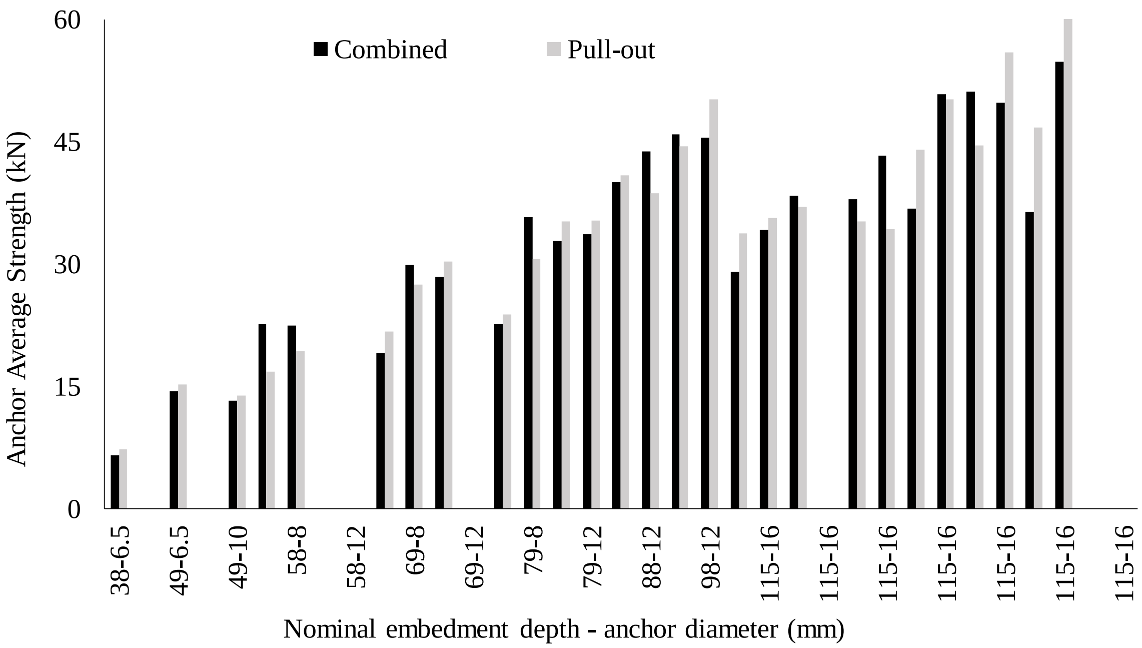

Figure 8: A comparison between the anchors experimental average strengths and suggested values by the manufacturer and literature

7. Calculating anchor strength according to the failure mode

As discussed in Section 1, the only equation available from literature to predict the tensile capacity of screw anchors, Eq. 1, is essentially based on CCD method and hence a cone mode of failure, but adjusted to also include combined mode of failure; this is through defining a reduced embedment depth (Eq. 2). In this study, it is attempted to separate the results according to failure modes for the first time, and propose different equations associated with any of the individual failure modes.

7.1 Pull-out failure mode

The pull-out failure mode can be related to the shear strength of the concrete entrapped in the space between the threads (Figure 9). The failure of concrete between threads, however, is not only due to the shear stresses in concrete. The interlock resistance is primarily created as the result of bearing/compressive stresses developed between the anchor threads and concrete grooves. Such compressive stresses are resisted by a combination of tensile, shear and compressive stresses on a shear area, $\boldsymbol{A_s} = \boldsymbol{\pi}(\boldsymbol{d} + \boldsymbol{p})\boldsymbol{h_{ef}}$, as shown in Figure 9. $\boldsymbol{A_s}$, is defined using $\boldsymbol{h_{ef}}$ rather than $\boldsymbol{h_{nom}}$, since there is no load transfer between the first thread and the tip of the anchor, $\boldsymbol{h_s}$; also the spiral shape of the groove results in a continuous change in the height of the shearing area from a maximum of $\boldsymbol{h_{nom}} - \boldsymbol{h_s}$ to a minimum of $\boldsymbol{h_{nom}} - \boldsymbol{h} - \boldsymbol{h_s}$, with an average of $\boldsymbol{h_{nom}} - \boldsymbol{h_s} - \mathbf{0.5}\boldsymbol{h}$ (i.e. $\boldsymbol{h_{ef}}$).

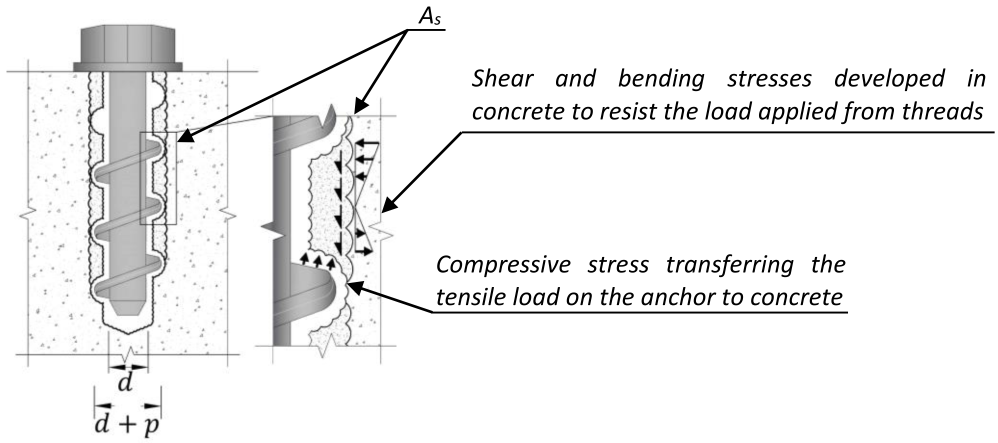

Figure 9: Simplified stress diagram explaining pull-out failure mode

Due to the facture of concrete, the size-effect, and the fact that stresses over the shear area, $\boldsymbol{A_s}$, are not constant, the relationship between the capacity of the anchor and $\boldsymbol{A_s}$ would be of a nonlinear nature. A regression analysis was carried out to find the best correlation between the ultimate strength of anchors which failed due to pull-out, $\boldsymbol{A_s}$, $\boldsymbol{f_{ct.sp}}$ and $\boldsymbol{f_{cm}}$ using Eq. 3:

$$\mathbf{N}^{\mathbf{th}}_{\mathbf{pullout}} = \boldsymbol{k_1}\boldsymbol{\pi}(\boldsymbol{k_d}(\boldsymbol{d} + \boldsymbol{p}))^{\boldsymbol{m}}(\boldsymbol{k_h}\boldsymbol{h_{ef}})^{\boldsymbol{n}}\boldsymbol{f_c^k} \qquad \textbf{Equation 3}$$

where $\boldsymbol{k_1}$, $\boldsymbol{k_d}$, $\boldsymbol{k_h}$, $\boldsymbol{m}$, $\boldsymbol{n}$ and $\boldsymbol{k}$ are constant, and $\boldsymbol{f_c}$ can be either $\boldsymbol{f_{cm}}$ or $\boldsymbol{f_{ct,sp}}$ in MPa, $\boldsymbol{d}$ is the nominal diameter of the anchor (drilled hole) in mm, $\boldsymbol{p}$ is the protrusion of the anchor threads measured with respect to $\boldsymbol{d}$ in mm (Figure 9), $\boldsymbol{h_{ef}}$ is the effective embedment depth in mm, i.e. the reduced embedment depth excluding the 0.85 reduction factor, and $N^{th}_{pullout}$ is the theoretical tensile capacity of the anchor related to the pull-out failure mode in N.

It was found out that without compromising the accuracy, a more practical version of Eq. 3 can be presented by enforcing a value of 1.0 for k_d and k_h, a power of 0.5 for d and f_{cm}, and a power of 1.0 for h_{ef}, and eliminating p (which is not readily available to the engineer/designer):

$$N^{th}_{pullout} = 23.5\, d^{0.5} h_{ef} f_{cm}^{0.5}\ ;\ R^2 = 0.896 \qquad \textbf{Equation 4}$$

where R^2 is the coefficient of determination. A power of 0.5 for d in Eq. 4, rather than 1.0 that was originally assumed in the definition of A_s, can partly be related to a size effect proportional to $d^{-0.5}$. The implication of such a size effect is that the concrete resistance increases at a lower rate than that of the available failure surface (Fuchs, Eligehausen, et al. [7]). This is also consistent with the size effect included in Eq. 1, which is proportional to $h_{ef,1}^{-0.5}$ (using $h_{ef,1}^{1.5}$ instead of $h_{ef,1}^{2}$ in this equation). Also, one should note that $f_{cm}^{0.5}$ in Eq. 4 is the only mechanical property of concrete representing all types of stresses involved in the pull-out failure mode as illustrated in Figure 6.

Olsen, Pregartner, et al. [6] further suggested that there could also be a nonlinear distribution of stress along the embedment depth, as the threads closer to the tip of the anchor tend to wear more during the installation process. In the case of the anchors that failed due to pull-out in the current study, such wear effect was not significant. This is shown in Figure 10 where both the linear and parabolic fits of the results present almost the same level of accuracy.

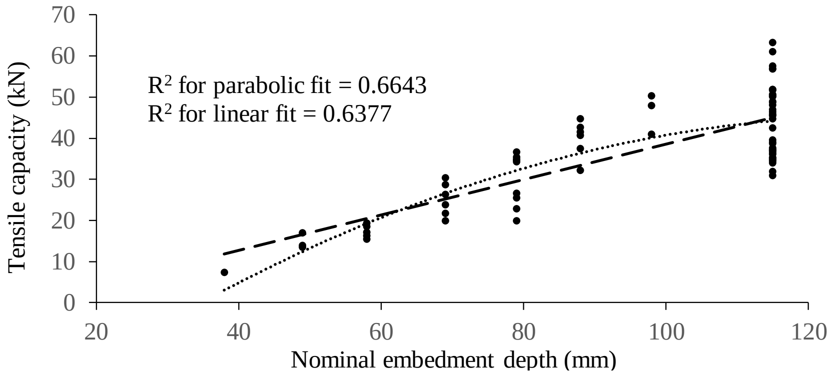

Figure 10: Tensile capacity of anchors failed due to pull-out

7.2 Combined failure mode

One way to calculate the capacity of anchors that failed due to a combined failure mode is to add the strength related to the pull-out failure of the bottom of the anchor along h_p (Figure 11), to that of the cone failure at the top of the anchor along h_{con} (Figure 11). To do this, one can use Eqs. 1 and 4 to calculate the strengths related to h_{con} and h_p, respectively. However, since h_{con} is the exact length of the anchor embedded in the concrete cone, $h_{ef,1}$ in Eq. 1 can be substituted by h_{con}. The rest of the embedment depth, i.e. h_p, can then be used in Eq. 4 to calculate the strength related to the pull-out failure at the bottom of the anchor as given by Eq. 5:

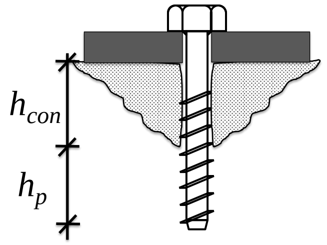

Figure 11: Defining h_p and h_{con} in a combined failure mode

$$\mathbf{N^{th}_{comb}} = \mathbf{23.5}\, \boldsymbol{d}^{\mathbf{0.5}}(\boldsymbol{h_p} - \mathbf{0.5}\boldsymbol{h} - \boldsymbol{h_s})\boldsymbol{f_{cm}^{0.5}} + \boldsymbol{k_2 h_{con}^{1.5} f_{cm}^{0.5}}$$ **Equation 5**

where $\boldsymbol{k_2}$ is constant and $\mathbf{N^{th}_{comb}}$ is the ultimate strength of the anchor due to a combined failure mode. The regression analysis of Eq. 8 leads to:

$$\mathbf{N^{th}_{comb}} = \mathbf{23.5}\, \boldsymbol{d}^{\mathbf{0.5}}(\boldsymbol{h_p} - \mathbf{0.5}\boldsymbol{h} - \boldsymbol{h_s})\boldsymbol{f_{cm}^{0.5}} + \mathbf{13.4}\, \boldsymbol{h_{con}^{1.5} f_{cm}^{0.5}}$$

$$\mathbf{N^{th}_{comb}} = (\mathbf{23.5}\, \boldsymbol{d}^{\mathbf{0.5}}\, \boldsymbol{h_{ef,p}} + \mathbf{13.4}\, \boldsymbol{h_{con}^{1.5}})\boldsymbol{f_{cm}^{0.5}}; R^2 = 0.885$$ **Equation 6**

The main shortcoming of Eq. 6 is that it includes two parameters $\boldsymbol{h_p}$ and $\boldsymbol{h_{con}}$, both of which are unknown when designing an anchor. However, this equation can be used to mathematically calculate the minimum strength, and also the strength related to the cone failure mode; these will be later discussed in Sections 7.3 and 7.4.

7.2.1 Relationship between compressive and tensile strength of concrete

Eq. 6 is similar to Eq. 1 in approximating the tensile strength of concrete related to the cone failure (at the top of the anchor) by $\boldsymbol{f_{cm}^{0.5}}$. However, this assumption is not in full agreement with some of the more recent studies (e.g. Mindess, Young, et al. [16], Smyrou [17], Smyrou, Blandon-Uribes, et al. [18]). A regression analysis was carried out to find the best fit between the tensile splitting and compressive cylindrical test results available from the current study. This regression analysis resulted in Eq. 7:

$$\boldsymbol{f_{ct,sp}} = \mathbf{0.244}\, \boldsymbol{f_{cm}^{0.684}}; R^2 = 0.945$$ **Equation 7**

Eq. 7 is also more consistent with the findings of Mohyeddin, Gad, et al. [8], Mohyeddin, Gad, et al. [19], and Eligehausen, Mallee, et al. [13] for concretes with $\boldsymbol{f_{cm}}$ < 70 MPa. However, substituting the tensile strength of concrete in Eq. 6 by Eq. 7, did not improve the value of R^2 for Eq. 6, and hence no changes were made to Eq. 6.

7.3 Cone failure mode

For an extreme case of $\boldsymbol{h_p} = 0$, one could apply Eq. 6 to calculate the cone failure strength, $\mathbf{N^{th}_{con}}$. This would lead to the following equation:

$$\mathbf{N^{th}_{con}} = \mathbf{13.4}\, \boldsymbol{h_{ef}^{1.5} f_{cm}^{0.5}}$$ **Equation 8**

Comparing Eq. 1 and Eq. 8, the constant in Eq. 8 is ~10% lower, and $\boldsymbol{h_{ef,1}}$ in Eq. 1 is substituted by $\boldsymbol{h_{ef}}$ in Eq. 8, which is ~18% larger. Considering both effects, Eq. 8 would overestimate the strength given by Eq. 1 by ~18% for an anchor failing due to cone failure. This is reasonable since Eq. 8 was developed as a potential equation for estimating the strength of anchors failing due to cone failure only, whereas Eq. 1 was developed based on the experimental results that included both cone and combined failure modes, and hence expected to give a lower tensile strength.

7.4 Anchor minimum strength

A comparison between Eqs. 4 and 6 shows that when $h_{con} \approx 3d$ the two equations give the same strength. This means that for such a cone size the strengths related to (pure) pull-out and combined failure modes are equal. Physically, this is a rather small cone, mainly formed in concrete paste with no significant contribution to the anchor strength. For any h_{con} greater than this, pull-out failure will be dominant (lower tensile strength).

Also, solving Eq. 6 for the minimum strength shows that at $h_{con} \approx 1.4d$ the strength related to a combined failure mode is less than that of a pull-out failure by $10.7 * d^{1.5} * f_{cm}^{0.5}$:

$$N_{min}^{th} = 23.5 d^{0.5} (h_{ef}) f_{cm}^{0.5} - 10.7\, d^{1.5} f_{cm}^{0.5} \qquad \textbf{Equation 9}$$

Similar to the previous case, a cone of **1.4*d*** deep is a rather small cone with almost no contribution to the anchor strength. However, such small cones are frequently observed in pull-out failure modes (Figure 12). Eq. 9 could explain why such cones are normally formed in pull-out failures (even if there were no variation in the concrete strength/quality at the top surface). This equation basically shows that the formation of such small cones on top leads to a lesser strength compared to when the full length of the anchor pulls out of concrete.

The above discussion supports the idea of assuming any failure with a small volume of concrete attached to the head of anchor (low values of h_{con}) as (pure) pull-out failure (also see Section 6).

Figure 12: Formation of small cones beneath the fixture in pull-out failure modes

7.5 Proposed equations specific to individual failure modes

Figure 13 shows a comparison between the experimental results, Eqs. 1, 4, 8 and 9. Since no cone failure was observed in this series of tests, both Eqs. 1 and 8 have overestimated the strength. The overestimation by Eq. 8 is greater compared to that of Eq. 1, as expected and explained in Sections 6 and 7.3. The average of ratio of the experimental results to those calculated using Eqs. 1, 4, 8 and 9 are 0.76, 0.96, 0.65 and 1.03, respectively, with a coefficient of variation of 0.15, 0.17, 0.15 and 0.17, respectively.

Table 3 gives a summary of the equations proposed for individual failure modes. As mentioned earlier, Eq. 6 is of no practical use, since it includes two unknown parameters which need to be experimentally determined. However, as it was demonstrated, it will give a strength which would fall between the values calculated based on Eqs. 4 and 8. Eq. 9 gives the absolute minimum tensile strength. This equation would be related to a pull-out failure mode accompanied by a small cone attached to the top of the anchor directly below the fixture (Figure 12).

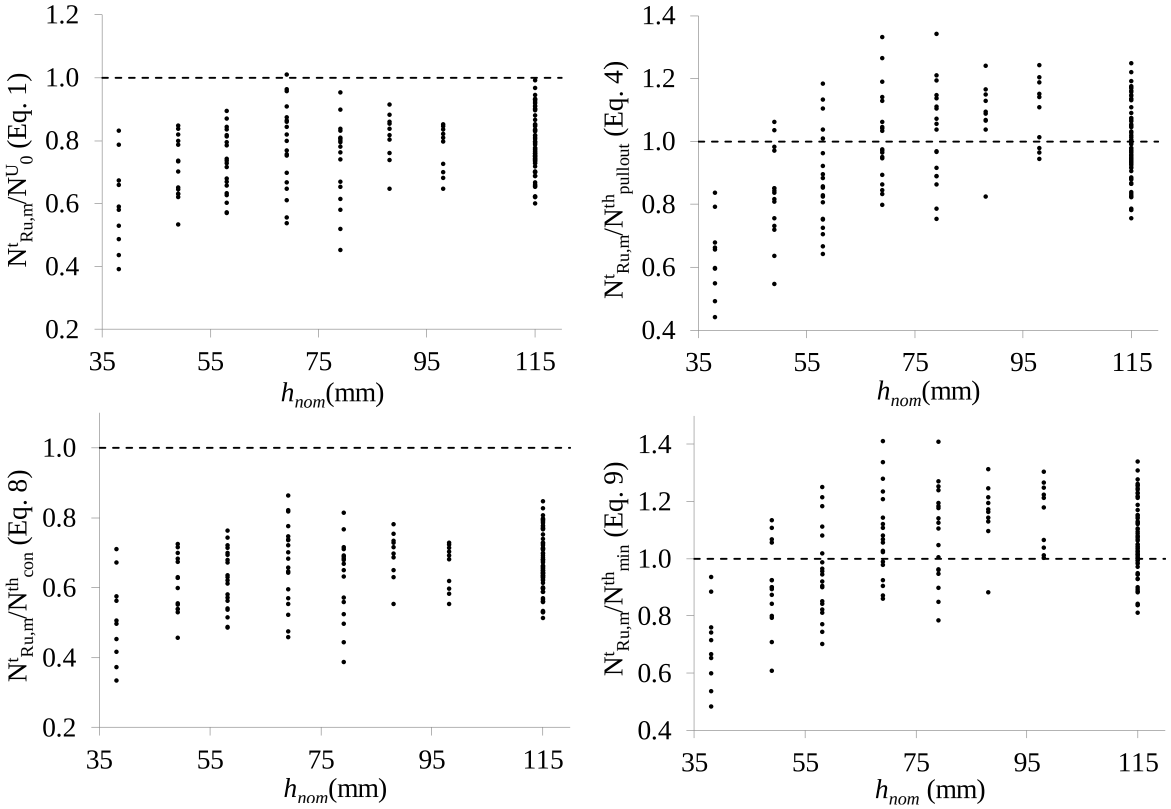

Figure 13: Comparison between experimental strengths and theoretical values

The equations given in Table 3 are proposed based on the full range of diameter and embedment depth for a specific type of a screw anchor. As discussed in Section 1, there is no consensus in the literature on whether or not the type of the screw anchor has a meaningful effect on the performance of the anchor under tensile loading. However, the more recent study by Stuart, Harrison, et al. [2] shows that the type of anchor and its threads do have an effect on the tensile performance of the anchor. Therefore, one should note that the equations provided in this article cannot be applied to other types of anchors, and such generalisation of the results is subject to further research.

Table 3: Equations proposed to predict the tensile capacity of screw anchors based on failure modes

Failure mode	Tensile capacity (N)
Pull-out (Eq. 4)	$N^{th}_{pullout} = 23.5h_{ef}d^{0.5}f^{0.5}_{cm}$
Combined (Eq. 6)	$N^{th}_{comb} = (23.5h_{ef,p}d^{0.5} + 13.4h^{1.5}_{con})f^{0.5}_{cm}$
Cone (Eq. 8)	$N^{th}_{con} = 13.4\, h^{1.5}_{ef}f^{0.5}_{cm}$
Minimum anchor capacity (Eq. 9)	$N^{th}_{min} = (23.5h_{ef} - 10.7d)d^{0.5}f^{0.5}_{cm}$

8. Summary and concluding remarks

Out the 182 tests considered in this study, about 60% of anchors failed due to a combined failure and the rest as the result of a pull-out failure mode. No concrete cone failure was observed. In three cases, anchors failed due to steel rupture; these were all 6.5 mm anchors, i.e. the smallest diameter tested in this study. This proves pull-out as the second common failure mode, and cone failure as the least expected failure mode. Up to an embedment depth of ~80 mm, the recurrence of pull-out failure increased with the increase in the embedment depth, beyond which its contribution was capped at an average of just below 50%. Pull-out also tended to be a more dominant failure mode for very small and very large diameters (6.5 mm and 16 mm); for the middle range diameters the combined failure mode covered the majority of failures (~75%). Even though for the concrete strengths below ~30 MPa there was no correlation between the concrete compressive strength and the likelihood of failure modes, for higher concrete strengths, the dominant failure mode was combined. Furthermore, it was not possible to favour any of the two common failure modes, combined and pull-out, in terms of their achieved ultimate tensile strength.

Where the design data from manufacturer was available, an approximate average ultimate strength was calculated (see Table 1 for assumptions). Comparing the experimental results with those of the manufacturer, in 60% of cases the experimental results fell in the range of ±10% of those given by the manufacturer. The remainder 40% of the experimental results were on average ~20% lower than the values given by the manufacturer. Such variations may be related to a larger population of results that are normally used by manufacturers to determine the design data, and also the variations in the concrete properties affecting the strength of anchors in addition to the characteristic compressive strength, such as the mix design and aggregates' size and distribution.

Table 3 summarises the equations derived for calculating the tensile strength related to each individual failure mode. An equation was also proposed to calculate the minimum tensile strength, which can be associated with a pull-out failure mode where a small cone forms at the top of the anchor (Eq. 9). For the anchors tested in this study, the minimum strength was on average 7% less than the pull-out tensile strength given by Eq. 4. Eq. 9 was also more conservative compared to the specifications given by the manufacturer by 9% on average. On the other hand, Eq. 1 from literature overestimated both the experimental and manufacturer's strengths by an average of 24% and 14%, respectively; as discussed in Section 6, there are multiple reasons for such a variation. Since the observed failure modes were mainly combined and pull-out, Eq. 9 is believed to be a more accurate equation to predict the (minimum) tensile strength of the particular anchors used in this study.

As an observation, the average of the angle of the cone with respect to the horizontal for combined failure mode (Figure 1) was measured as ~12˚. This is about one third of what is assumed in the CCD method for cone failure mode (35˚). However, this angle is subject to a large variation and in many cases includes the concrete crust that would have a large footprint in area at the top without necessarily contributing to the strength of concrete cone. Hence, more precise measurements need to be conducted before any solid conclusion can be made on the magnitude of this angle.

9. Future work

$f_{cm}^{0.5}$ in Eq. 4 represents all three types of stresses involved in the pull-out failure mode (Figure 9). As previously found in the case of cone failure (Eligehausen, Mallee, et al. [13]), other mechanical properties of concrete, such as the modulus of elasticity, or mode I fracture energy, might more accurately represent such a complex interaction of stresses on the shear area, A_s. This requires further studies; however, since other mechanical properties of concrete are not normally measured in practice, f_{cm} would still serve as a suitable mechanical property to represent the concrete material for design purposes.

When assessing the tensile strength of screw anchors, little attention has been paid to separating the experimental results related to each individual failure mode. On the other hand, there is no consensus in the available literature on the effect of thread profile on the tensile strength of screw anchors. Since there is a wide range of screw anchors currently available in the market, further study is required to examine the effect of thread profile on the equations proposed here (which were developed for individual failure modes). One way to advance the current study is to find additional product-specific correction/adjusting factors to take into account the potential variation in the tensile behaviour of different screw anchors. For the same reasons, Eqs. 1 and 2 from literature need to be re-assessed to ascertain their applicability to the broad range of available anchors.

As discussed in Section 8, the size of concrete cylinders used to determine the compressive strength of concrete may have some effect on the equations proposed here and the comparisons made with the values calculated using Eq. 1, and hence subject to further study.

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