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Shear strength of epoxy anchors embedded into low strength concrete

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HIGHLIGHTS

- ▶ Cyclic shear tests were conducted on anchors embedded to low strength concrete.
- ▶ The obtained results indicate that increasing the anchor diameter have decreased the shear strength.
- ▶ A decrease in shear capacity was observed for lower concrete strengths.
- ▶ A reduction factor is introduced depending on the bar diameter and concrete strength.
- ▶ Establishing an upper limit for the anchor bar diameter in the related standards is proposed.

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ABSTRACT

Chemical anchors are getting more frequently used to connect structural elements. The studies regarding the chemical anchors embedded in low strength concrete are very limited in the literature. However, the compressive strength of the concrete may be 10 MPa or lower in many strengthening applications. Steel bars having 12, 16 and 20 mm diameters have been selected as the anchor rod in this study. They have been embedded in to concrete blocks with 5.9 and 10.9 MPa compressive strength. Solvent-free epoxy based three component chemical adhesive has been used for the connection between concrete and anchor bar. The depth of holes is 10, 15 and 20 times that of the anchor diameter. The anchors have been embedded such that they are sufficiently away from the free edge so as not to cause any concrete failure. The load–displacement cycles of all anchors have been obtained by reversed cyclic tests with incremental displacement. The obtained results indicate that increasing the anchor diameter have decreased the shear strength. Even though the anchor damage has been caused by steel failure, a decrease in shear capacity was observed with the lower strength concrete.

1. Introduction

Anchors that are used to provide the connection between two different elements can be categorized under two categories as cast-in-place and post-installed anchorages. Post-installed anchorages could be manufactured using different methods such as mechanical, grout or chemical. The behavior of cast-in-place anchors [1] and post-installed mechanical anchors [2] have been studied considerably well in previous studies conducted in the past years. The design of cast-in-place anchorages [3] and mechanical anchorages [4] has been consigned to a reliable procedure as a result of these studies. Although the use of chemical adhesives in the construction sector goes back to late 1960s [5], the studies on the use of chemical anchors especially used for strengthening applications are relatively recent and a standard for specifying the design principles of such anchors has not yet been established, also under the influence of wide variety of materials [6].

Chemical anchors are embedded in the holes set up in the hardened concrete. The diameter of the drilled hole is at most 50% larger than that of the bar diameter [2]. Chemical adhesives are among the best solutions providing the bonding forces between the concrete and the steel [7]. Chemical anchors have begun to be widely used starting in the 1990s with the development of high resistance adhesives of polyester, vinylester and epoxy type [8,9]. Nowadays, many products are available in the market in terms of chemical adhesives. However, the bonding resistance of epoxy type products is usually higher than that of esther based products [10].

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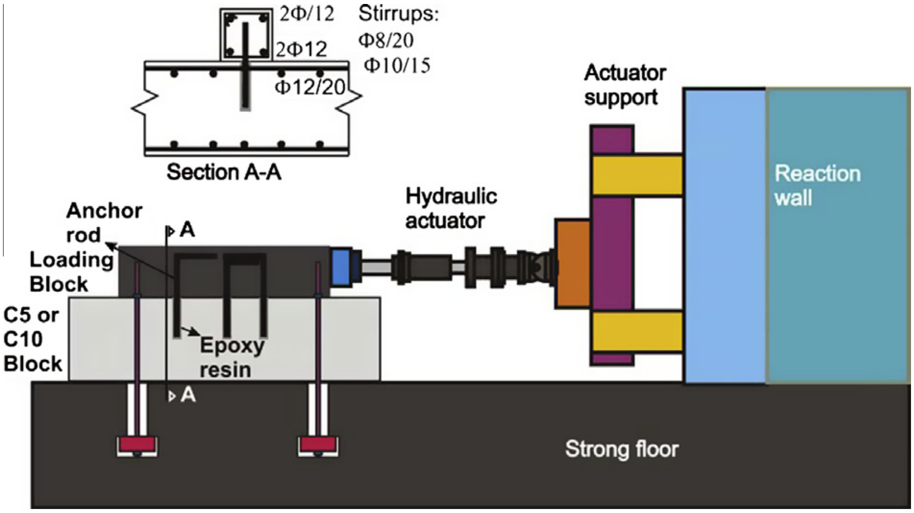


Fig. 1. Test setup and detailing of specimens.

Table 1
Properties of the test specimens.

Specimen name	Mean concrete compressive strength (MPa)	Anchor diameter (mm)	Embedment depth (mm)
C5D12L12	5.9	12	120
C5D12L18	5.9	12	180
C5D12L24	5.9	12	240
C5D16L16	5.9	16	160
C5D16L24	5.9	16	240
C5D16L32	5.9	16	320
C5D20L20	5.9	20	200
C5D20L30	5.9	20	300
C5D20L40	5.9	20	400
C10D12L12	10.9	12	120
C10D12L18	10.9	12	180
C10D12L24	10.9	12	240
C10D16L16	10.9	16	160
C10D16L24	10.9	16	240
C10D16L32	10.9	16	320
C10D20L20	10.9	20	200
C10D20L30	10.9	20	300
C10D20L40	10.9	20	400

Table 2
Concrete mixture (by weight).

Material (kg/m^3)	C5	C10	Loading block
0–5 Aggregate	1300	1235	1065
5–15 Aggregate	390	400	295
15–22 Aggregate	390	427	560
cement	100	185	310
Water	175	150	168
Additive (super fluidizer)	0.8	1.5	4.5

Table 3
Uniaxial strength of concrete and steel.

Material		Strength type (yield/tensile/compressive)	Mean strength (MPa)
Base concrete	C5	f_{c28}	5.9
	C10	f_{c28}	10.9
Loading block		f_{c28}	36.4
Anchor bars	Φ12	f_y	543
		f_u	628
	Φ16	f_y	534
		f_u	633
	Φ20	f_y	536
		f_u	657

f_c: compressive strength; f_y: yield strength; f_u: ultimate strength.

Table 4
Mix proportions and mechanical properties of the chemical adhesive.

Number of component	3
Mixture ratio	A/B/C
Weight	30/20/50
Volumetric	30/20/50
Mixture density (g/cm^3, 20 °C)	1.70–1.90
Pot life (min, 23 °C)	50–70
Tensile strength (N/mm^2)	16.9
Compressive strength (N/mm^2)	69.5
Modulus of elasticity (N/mm^2)	4500

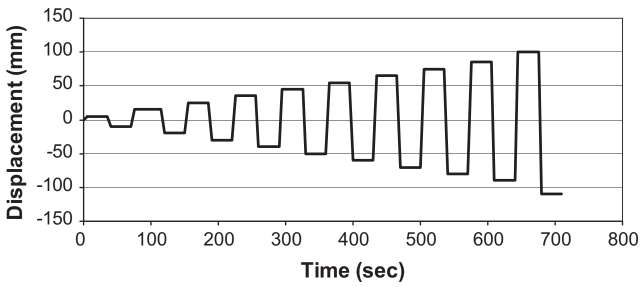


Fig. 2. Displacement profile applied to specimens.

Many parameters such as the cleanness of the drilled hole, the method of drilling, the humidity level of the concrete and temperature may affect the bond strength in addition to the type of adhesive [2].

The first studies on chemical anchors go back to the early 1980s [11]. Most parts of those studies are based on experimental studies for determining the tensile strength of the anchors. The effect of different factors on the anchor tensile strength has been investigated in those studies. Factors such as the adhesive thickness, the type of filler material added to the adhesive [12], the embedment depth [8], the anchorage diameter [13,14], the steel resistance [15], the edge distance [16] and the distance between the anchorages [17] have been investigated in parts of these studies. In some studies, it has been observed that the concrete

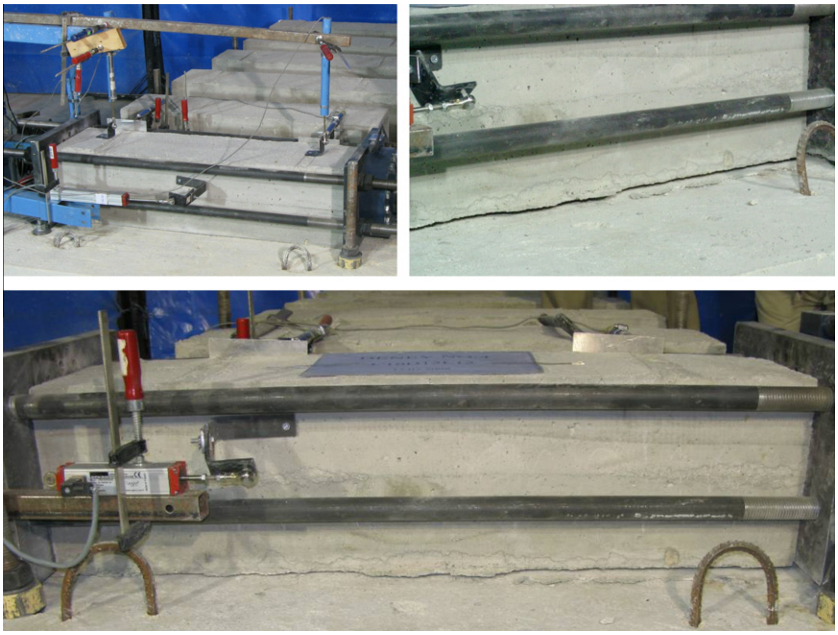


Fig. 3. Some views from the experiments.

strength and the type of aggregate were also taken into consideration [10,14]. A study investigating the behavior of both the single and the group anchors has been recently completed [2]. Studies are also present regarding the anchor tensile strength under dynamic loads in response to increases in the loading speed [18,19]. Some studies that have focused on the tensile behavior of chemical anchors are concerned with partially bonded anchors [1,20].

In addition to the studies on the subject of the anchorage tensile behavior, the studies on the topic of its shear behavior have been very limited. Only one study could be accessed on the shear behavior of chemical anchors [17]. Studies on this topic are mostly carried on mechanical and cast-in-place anchors [21,22]. In other conducted studies, the shear resistance of single anchors and double bolted group anchors [23] the shear-tension interaction [24] has been investigated. In another study on anchors near the free edge and the dynamic behavior of anchor groups [25] with and without hairpins have been used. The hairpinned samples were observed to have more resistance at the end of these experiments.

Basically concrete anchors attain load capacity by two failure modes as steel and concrete failure [26]. The steel failure determines the shear capacity of anchors that were embedded usually further away from the free edge. When shear stress is applied on the anchor, the steel rod embedded in the concrete is damaged through the bending behavior. At that moment, local crushing is observed in the concrete around the steel [27]. The concrete based failures take place as a breakout failure when the anchor is closer to the free edge and as a pryout failure when it is further away [3]. The 45° Cone [21] and concrete capacity design methods [28] to determine the capacities regarding these failure types were developed based on these available test data. The method presented in the PCI Design Handbook [29] is another method that may be used as an alternative [6]. In addition to these, several studies regarding the anchor strength determined from neural networks are also present [26,30].

In most of the previous studies, the anchors were embedded to normal or high strength concrete. However, in many buildings, concrete possessing lower strength values than these are encountered [31,32]. Therefore, the shear strength of chemical anchors on low strength concrete is still an important subject area. The shear behavior of chemical anchors has not been studied thoroughly. In this study, the behavior of epoxy bonded anchors embedded in low strength concrete under reversed cyclic shear loads is investigated.

2. Materials and methods

2.1. Test specimens

As it is known, many strengthening applications are performed on buildings that are made of low strength concrete. Because of that, in order to better represent the practice, the anchors have been embedded in concrete elements with low compressive strength [31,32]. Anchors were embedded in two concrete grades with different compressive strength, which are named as C5 and C10, in scope of the study. Other parameters that have been used in this study are the anchor bar diameter and the anchor depth. In this study, anchors of three different diameters, namely 12, 16 and 20 mm have been embedded in depths that are 10, 15 and 20 times of their diameters. A total of 18 test samples have been produced. The manufactured test samples have been cured under laboratory conditions. Following this, the holes where the anchor bars will be embedded have been drilled. The holes were cleaned by using pressurized air from an oil-free compressor. The anchor bars have been embedded in the concrete blocks using epoxy resin and necessary precautions have been taken in order for the bars not to move until the epoxy has gained strength. The embedded anchors were covered by a loading block. In situ cast concrete element having a 36 MPa average compressive strength has been used as the loading block. In order to decrease the effects of friction, as smooth a surface as possible was attained on the low strength base concrete. The dimensions and the reinforcement details of both the base and the loading block are given in Fig. 1. Totally, 18 test specimens were constructed and the shear experiments were conducted. The properties of the test specimens are given in Table 1.

The concrete mixtures that have been used for the construction of the test specimens are given in Table 2. The design mixes were aimed to obtain mean compressive strength of 5 and 10 MPa for C5 and C10 grade concrete. Concrete samples have been collected during the production of the test elements. Uniaxial compression tests were conducted on the samples. The strength of concrete and steel are given in Table 3. The uniaxial compression tests of concrete specimens indicated that the mean compressive strength of the samples was slightly higher than what has been initially aimed (Table 3). Mix proportions and mechanical properties of the epoxy are listed in Table 4.

2.2. Test system

The manufactured test samples have been supported on a strong floor and have been loaded by a hydraulic actuator mounted on the reaction wall. Reversed cyclic loads have been applied on the anchor specimens. The reversed cyclic displacement profile that has been used in the experiments is given in Fig. 2.

The loading system that has been applied on the test sample has been designed such that they are able to apply pushing force on both sides during successive load steps. In this way, the formation of tensile forces on the loading block has been prevented. Displacement transducers and load cells have been attached to the data acquisition system in order to record the displacements and the loads that the test elements have forced with. Some pictures from the experiments are given in Fig. 3.

3. Test results

The hysteresis curves for anchors under shear loading that have been embedded into C5 and C10 grade concrete are given in Figs. 4 and 5. The shear load capacity has been observed to increase with increasing diameters in the obtained curves, as it was expected. However, with increasing embedment depth, a significant change could not be observed in capacity except for the C5D12L24 sample. The hysteresis curves indicate that the anchorages possess different capacities for push and pull directions. Through the evaluation of capacities in both directions simultaneously, the mean strength of the anchorages in C5 blocks was determined as 291 MPa and it was determined as 334 MPa for the anchors embedded into C10 blocks. Here, the difference in strength between C5 and C10 blocks is approximately 15%.

The ultimate anchor shear capacities and their corresponding ultimate anchor strength are shown in Fig. 6. Anchor shear strength is found by dividing shear force capacity to the total bar area of each specimen. Evaluation of the shear capacity with respect to the anchor diameter indicated that the mean shear strength values were determined as 387 MPa, 302 MPa and 248 MPa for the 12, 16 and 20 mm bars, respectively. As it was seen, although an increase in shear force with increasing the bar area was observed, the maximum shear strength has occurred at lower levels for higher bar sizes. This situation could be evaluated in low strength concrete as the high diameter anchors causing greater local stresses. Taking 20 mm diameter anchors as the baseline, the increase in the strength of 16 and 12 mm diameter anchors were 21% and 56%, respectively.

Breakout damage was already not expected since the conducted tests were further away from the edge. The test element were thoroughly investigated prior to and following the tests and a pryout damage could not be detected either. All test elements have reached their bearing capacity through the steel failure and the local damages that occurred in the concrete.

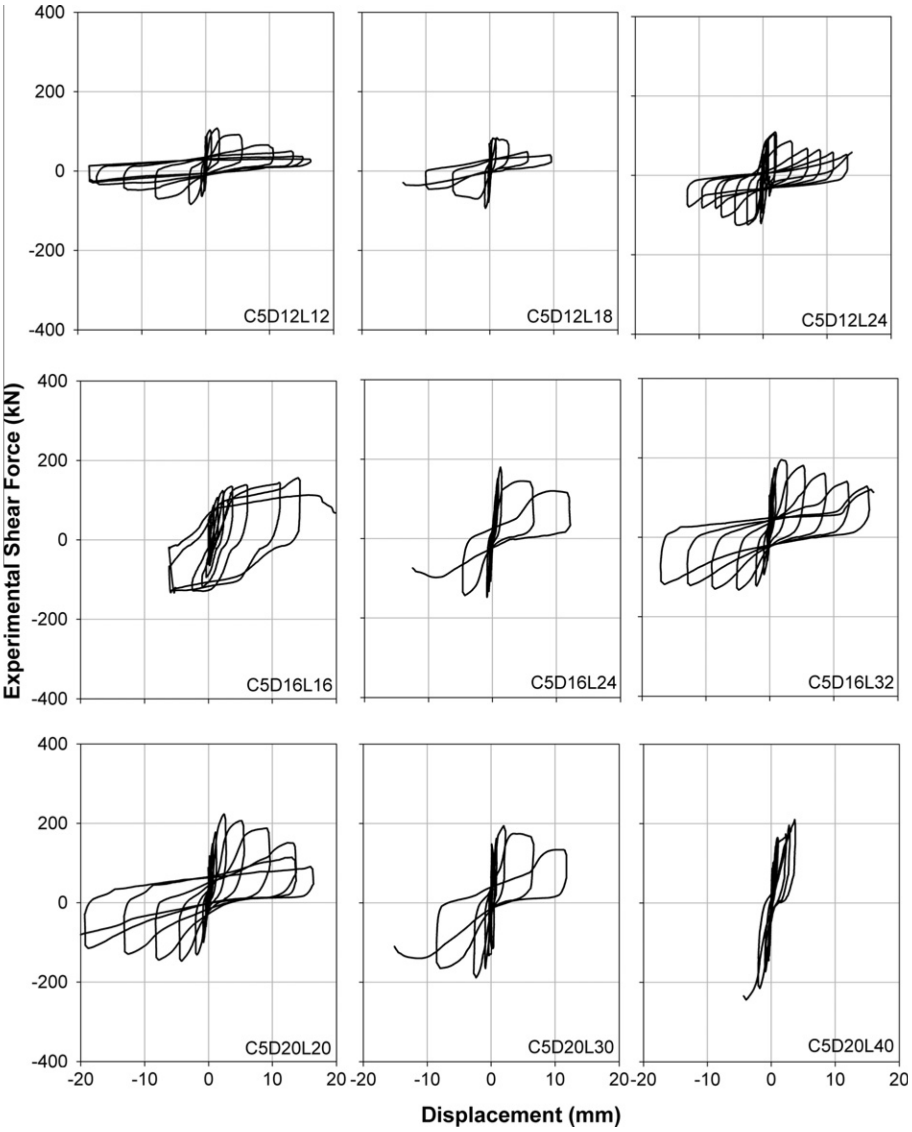


Fig. 4. Load–displacement curves for the C5-anchors.

4. Comparison of the experimental results with the anchor shear capacity per ACI318

4.1. ACI318 anchor design method for shear loads

In ACI318 Appendix D three different failure modes were defined upon reaching the anchor shear capacity: steel failure, concrete breakout failure of near edge anchors and concrete pryout failure. These modes of collapse are shown in Fig. 7. In situations where the anchor bars is closer to the edge, the ultimate concrete cone capacity generally governs the anchor capacity and where it is further away from the edge, the shear capacity of the anchor bar is the main determining factor.

Taking steel failure into consideration, the anchor shear capacity (V_{sa}) can be computed according to following equation:

$$V_{sa} = n \cdot A_{se} \cdot f_{uta} \tag{1}$$

Here n defines the number of anchors in the group, A_{se} stands for cross sectional area of an anchor (mm^2) and f_{uta} is the tensile strength of the anchor steel (N/mm^2).

In situations where the concrete failure occurred in anchors that were placed near the edge, the basic breakout capacity (V_b) and concrete breakout capacity (V_{cb}) can be obtained using Eqs. (2) and (3) for single anchors respectively. Those capacities are to be calculated using Eqs. (4) and (5) for group anchors. Effective anchor depth (l_e), bar diameter (d_o), distance to free edge (c_{a1}) in the direction of loading, concrete strength (f_c), area of expected failure surface of actual anchor or anchor group (A_{vc}) and that of a single anchor well away from the free edge (A_{vco}) are the effective parameters in the equations. Various reduction factors (ψ) are also utilized to take into consideration of edge effect, eccentricity and cracks.

$$V_b = 0.6\left(\frac{l_e}{d_0}\right)^{0.2}\sqrt{d_0}\sqrt{f_c'}(c_{a1})^{1.5} \tag{2}$$

$$V_{cb} = \frac{A_{vc}}{A_{vco}}\psi_{ed,v}\psi_{c,v}V_b \tag{3}$$

$$V_b = 0.7\left(\frac{l_e}{d_0}\right)^{0.2}\sqrt{d_0}\sqrt{f_c'}(c_{a1})^{1.5} \tag{4}$$

$$V_{cbg} = \frac{A_{vc}}{A_{vco}}\psi_{ec,v}\psi_{ed,v}\psi_{c,v}V_b \tag{5}$$

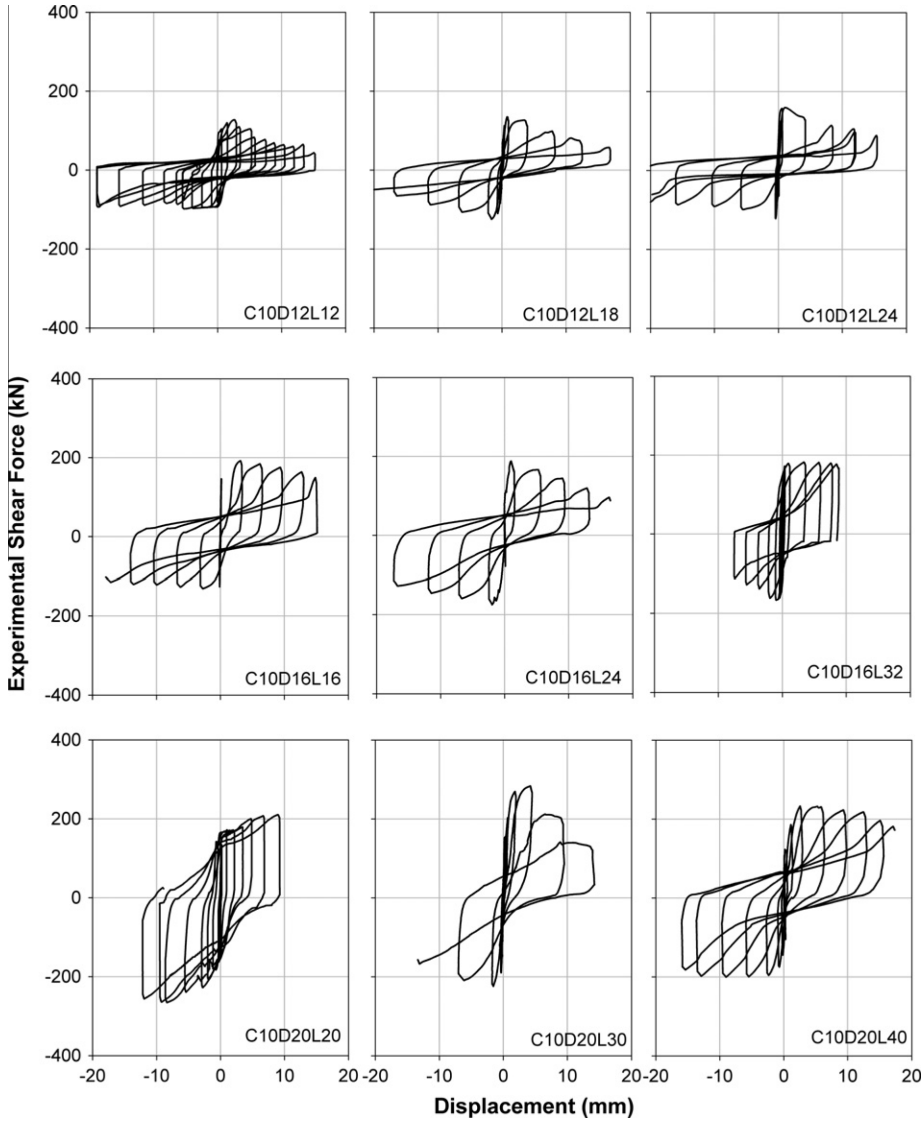


Fig. 5. Load–displacement curves for the C10-anchors.

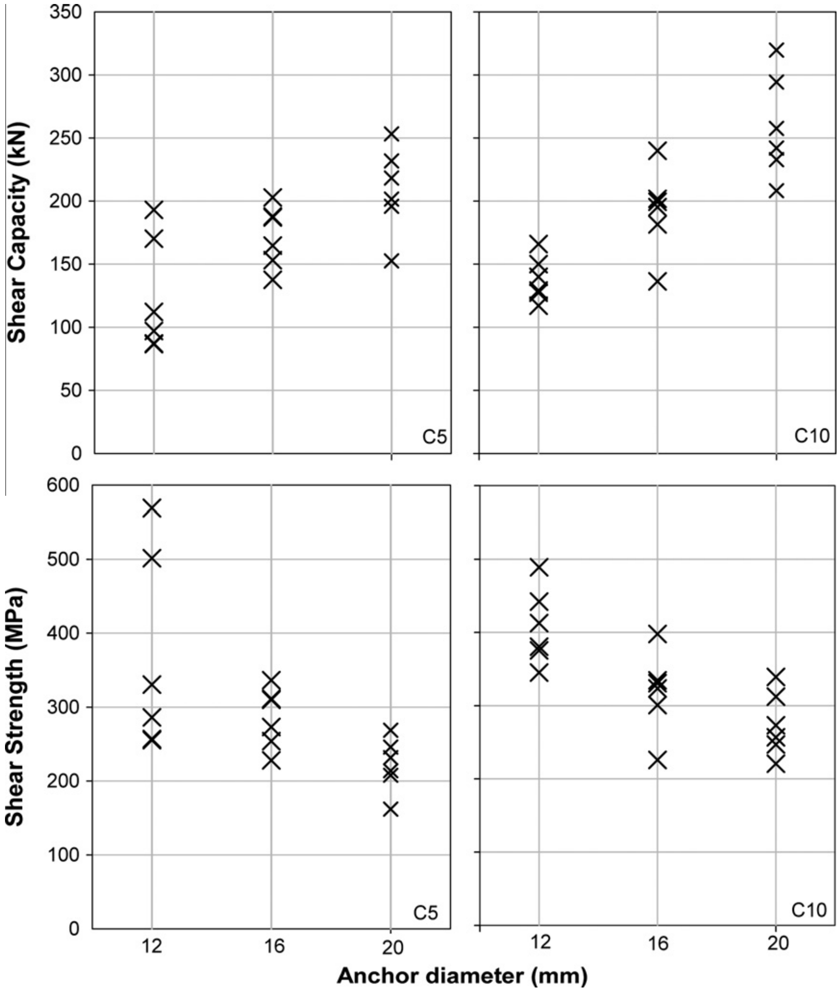
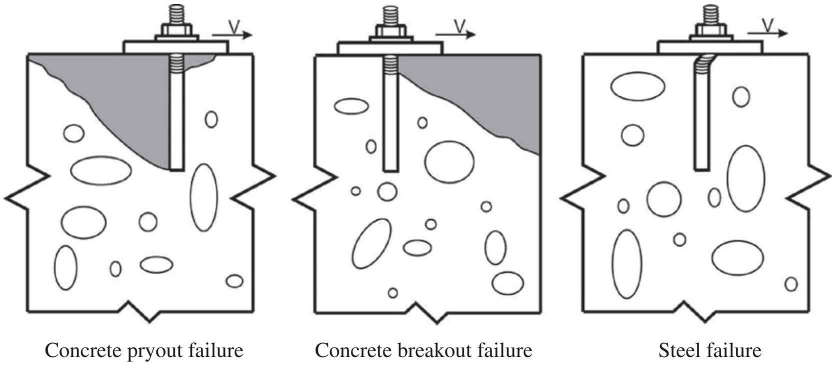


Fig. 6. Change in the ultimate anchor capacity and shear strength in response to bar size.



Concrete pryout failure Concrete breakout failure Steel failure

Fig. 7. Anchor failure modes under shear loading.

The formula that ACI318 provides for the pryout collapse of the concrete is shown in Eqs. (6) and (7) for single and group anchors respectively. The pryout capacity can be computed depending on the concrete breakout capacity that was given for the axial load (N_{cb} or N_{cbg})

$$V_{cp} = k_{cp}N_{cb} \quad \text{(for single anchors)} \tag{6}$$

$$V_{cpg} = k_{cp}N_{cbg} \quad \text{(for group anchors)} \tag{7}$$

Here k_{cp} is a constant that changes with embedment depth is proposed as 1.0 for shallow anchors ($h_{ef} < 65$ mm) and 2.0 for other effective depth values.

The ultimate shear capacity could be calculated for the three different collapse modes in the ACI318 method and the ultimate capacity would be determined taking the collapse mode with the lowest strength into consideration. This shear capacity is reduced by a strength reduction coefficient for design purposes. This reduction coefficient was given as 0.65

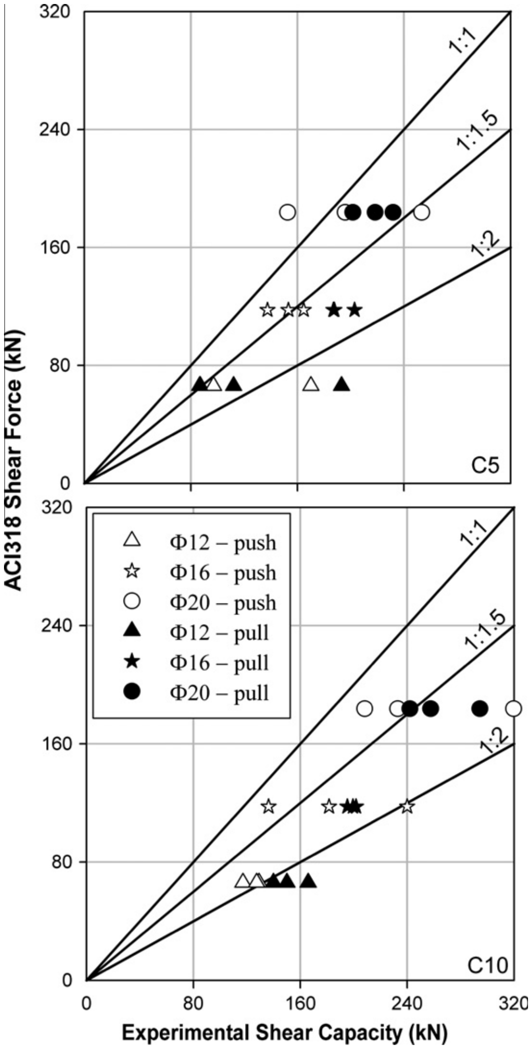


Fig. 8. Comparison of the experimental load capacities for the C5 and the C10 blocks with the ACI318 design shear forces.

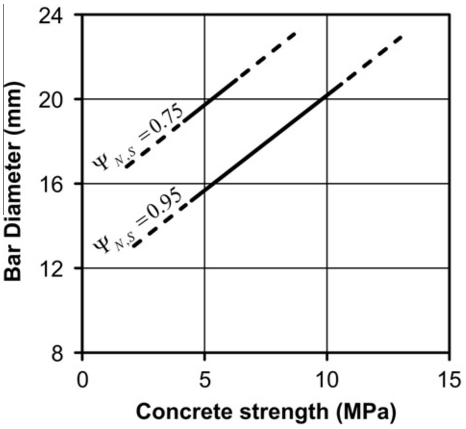


Fig. 9. Reduction factor ($\Psi_{N,S}$) for bar diameter and concrete strength.

in ACI318 for the ductile steel rods that have been used in this study.

Design shear strength of all test elements were determined in accordance with ACI318 using the method given above. The steel failure determines the shear capacity in all elements according to the ACI318 method. This result is also concordant with the experimental behavior.

4.2. Evaluation of the test data

The experimental results obtained from the anchor shear tests for the C5 and C10 concretes and the ACI318 design shear forces were compared in Fig. 8. Since the capacity values reached by the test samples in the push and pull directions were different, the ultimate load capacities attained by the anchors were given in the push and pull directions separately in the displayed figures. Since all anchorages were embedded well away from the edges, the dominant anchor behavior was failure of the steel. For this reason, the same design forces were calculated for the samples with the same bar diameter. Therefore, ACI318 design forces have formed three different levels in the figures for the 12, 16 and 20 mm bars from the bottom to the top.

Only one of the experimental capacity values was found to be lower than that of the design value obtained from ACI318. This behavior was observed for the C5 concrete and 20 mm bar (Fig. 8). In the given figures, it has been observed that the factor of safety calculated for the ACI318 formulae was higher for the C10 samples than the C5 samples. The average factors of safety for the ACI318 formula were found to be 1.49 and 1.71 for the C5 and C10 samples respectively.

The factor of safety decreased as the bar diameter increased. The factor of safety was more than 2 in some tests for both C5 and C10 samples for the 12 mm diameter anchors, whereas none of the 20 mm anchorages could attain that level of safety. The average factor of safety for the ACI318 design formula was determined as 1.88, 1.46 and 1.14 for the 12, 16 and 20 mm diameter anchors, for the C5 anchors respectively. These values have increased up to 2.09, 1.64 and 1.41 for the C10 anchors. If the acceptable average factor of safety is assumed to be 1.5, a reduction factor ($\Psi_{N,S}$) for bar diameter and concrete strength can be defined as given in Fig. 9. This reduction factor is to be used for the shear capacity reduction of anchors suffering from steel failure according to Eq. (8). As the experimental program does not include higher bar size, reduction factors are obtained for a limited region.

$$V_{sa} = \Psi_{N,S} \cdot n \cdot A_{se} \cdot f_{uta} \tag{8}$$

5. Conclusions

Considering the concrete classes and the materials that have been used, the following implications for anchors presenting steel failure under shear could be obtained from this study:

1. Although the load capacity of the adhesive anchors that have been embedded away from the edges increases with increasing diameter, the ultimate shear stress levels of the anchor bars decreased.
2. In order to provide the required anchor area, through the use of many small diameter anchors rather than fewer large diameter anchors, safer designs could be attained. This was especially the case for the low strength concrete. Establishing an upper limit for the anchor diameter in the related standard and regulations might also be useful.
3. The steel failure formula in ACI318 Appendix D provided safe results for low strength concrete, in the case of the anchors away from the free edge under shear loads.
4. The factor of safety of the ACI318 formula decreased as the anchor diameter increased. In addition, the average factor of safety was observed to decrease with decreasing concrete strength. For this reason, average factor of safety for the

20 mm anchorages embedded in C5 concrete was as low as 1.14 whereas it was found to be 2.09 for the 12 mm diameter anchors embedded in C10 concrete.

5. The factor of safety of the provided equation by ACI318 for steel failure mode dropped below 1.5 for 20 mm diameter anchorages in 10 MPa concrete, and was observed to be below this safety limit for both the 16 and 20 mm diameter anchors in 5 MPa concrete.
6. Adaptation of steel capacity formula is proposed. A new reduction factor is introduced to assure an average factor of safety of 1.5 depending on the bar diameter and concrete strength. However, more tests are needed to define reduction factors for bar diameters higher than 20 mm.
7. Through the use of anchor bars having larger diameters than 16 mm in low strength concrete, significant decreases in shear strength could be observed. In a necessity for the use of such bars, the verification of the design strength is required to be experimentally confirmed.
8. Having the embedment depth more than 10 times the bar diameter was not observed to have a significant effect on the shear strength of the anchor.
9. Assuming an average factor of safety of 1.5, a reduction factor ($\Psi_{N,S}$) depending on bar diameter and concrete strength is proposed for steel failure mode. The experimental program includes bar sizes between 12 and 20 mm and concrete strength was below 10 MPa. Therefore, the tests should be extended to get a better coverage of probable combinations.

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