Anchorage strength and ductility at various loading conditions

Aleksandr Shuvalov, Igor Gorbunov and Mikhail Kovalev

Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, Russia

E-mail: kovalyov.mike@gmail.com

Abstract. Article shows results of anchor pullout tests for two types of anchors: bent foundation anchor bolt and torque-controlled undercut anchor. Effective embedment depth is determined during research for bent anchors 16, 24 and 36 mm in diameter. Tests were carried out for 37 specimens with different embedment depth in a range from 150 to 650 mm. Load-displacement diagrams for static and cyclic dynamic pullout tests in uncracked and cracked concrete were acquired. Cyclic loading pattern simulated seismic loads. Test results for undercut anchors with diameter of 12, 16 and 20 mm and embedment depth of 125, 190 and 250 mm respectively allowed to estimate the influence of cracks in concrete and cyclic loads on ductility of anchor during pullout tests. It is stated that embedment depth required by regulatory documents for bent anchor bolt is higher than admissible embedment depth acquired in tests as a result of comparative analysis of design and optimal anchor bolt structure.

1. Introduction

Existing types of anchors [1,2] for structure elements and equipment can be in particular differentiated by the way they are installed for cast-in-place [3] and drilled-in anchors [4]. Drilled-in anchors are more common because of wide application field and setup processability. However, these anchors have several disadvantages compared to cast-in-place ones including high cost, installation requirements and inability of using big diameters due to structural properties and absence of experimental research of drilled-in anchors performance. For example, maximum recommended diameter for test conduction is 30 mm according to regulatory documents such as GOST R «Mechanical anchors for use in concrete. Test methods» [5].

The purpose of this research was the determination of the minimum effective embedment depth for anchor and its ductility in uncracked and cracked concrete under static and dynamic loads. Ultimate stresses and pullout loads were compared to design values which were determined by bolts steel strength. In this research bent foundation bolt was used as cast-in-place anchor (figure 1) [6]. Test results analysis for minimum embedment depth was done based on comparison with design depth [3].

Anchorage using torque-controlled undercut anchor was chosen according to specification [4]. Herein the goal was the determination of strength and ductility of anchor in uncracked and cracked concrete under static and dynamic pullout load at embedment depth shown in [4].
2. Methods and materials

Bent foundation bolts were installed into drilled holes in preformed concrete blocks (figure 1). Drilling was done using drilling device with diamond head. Table 1 shows sizes of drilled holes that were chosen depending on anchor diameter. Self-expanding cement-sand grout with strength grade B30 was used for anchor embedment in wells. Its expansion in unrestricted conditions was 0.06…0.08 mm/m

| Table 1. Geometry parameters for bent anchors cast in well |
|----------------------------------------------------------|
| Bolt diameter $d$, mm | 16 | 24 | 36 |
| Well depth $H_k$, mm | $H_0 + 10$ | $H_0 + 10$ | $H_0 + 10$ |
| Well diameter $D_k$, mm | 82 | 122 | 152 |
| Fixture thickness $t$, mm | 40 | 40 | 50 |

Figure 1. Cast-in-place bent foundation bolt

Minimum embedment depth for bolts from St3 steel in foundation for concrete grade B12.5 was $H_0 = 25d$. For different steel or concrete grades embedment depth $H_0$ was determined as follows:

$$H_0 \geq Hm_1m_2 \quad (1)$$

where $m_1 = 0.569$ – ratio between design tension strength of concrete grade B12.5 and of assumed concrete grade B30;

$m_2 = 185/145 = 1.276$ – ratio between design tension strength of assumed steel grade for bolts and of steel grade VSt3kp2.

Hole drilling for installation of torque-controlled undercut anchors (figure 2) was done till necessary depth $H_0$ [4] using drill bit with stopper.

Figure 2. Torque-controlled undercut anchor
Concrete blocks of various size with concrete grade B30 were used as base for anchor embedment. Steel strength for bent bolts was 450-500 MPa, for undercut anchors – 800-850 MPa. Sizes of concrete blocks were chosen depending on anchor embedment depth in order to allow unrestricted formation of concrete cone. Blocks were reinforced with structural reinforcement [6] to exclude failure of concrete base during crack formation.

Force from load frame to anchor was transferred using steel plate which was connected with hydrocylinders using steel stud bolts (figure 3). Specimens loading was done using rearranging load frame CFM Schiller equipped with MTS hydrocylinders.

![Figure 3. Rig for anchor pullout tests](image)

You should consider high probability that anchor is situated in crack when designing fastening of manufacturing equipment in seismic regions [7-10]. Crack formation was done using steel wedged elements. Crack width was monitored using dial displacement gauge with measuring sensitivity of 0.01 mm.

«Load-displacement» diagram was recorded during tests. Displacement measurement was carried out using linear displacement gage SPD-100C manufactured by Tokyo Sokki Kenkyujo with measurement limit of 100 mm and measuring sensitivity of 0.01 mm.

Seismic loading was simulated in cyclic load tests according to [11]. Table 2 show loading pattern (0≤N_{min}≤0.02N_{max}; N_{max}=0.75·N_{u,m}; N_{u,m} – ultimate pullout strength acquired in static tests with crack width of Δw=1,5 mm). Load frequency was 0.5 Hz.

![Table 2. Load amplitude for dynamic tests](image)

| N/N_{max} | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | Total |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|
| Number of cycles | 25 | 15 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 75 |

3. Test results
Table 3 shows embedment depth for anchor bolts depending on their diameter, structure, steel and concrete grades.
Table 3. Embedment depth for anchor depending on their structure

| Anchor structure         | Bent foundation bolts | Torque-controlled undercut anchor |
|--------------------------|-----------------------|-----------------------------------|
| Diameter by thread \( d \), mm | 16        | 24        | 36        | 12        | 16        | 20        |
| Embedment depth, mm      | Embedment depth by \([2]\), mm |
| By formula \( H_0=H\cdot m_1\cdot m_2 \) for steel grade 09G2S | 290        | 440        | 650        | -         | -         | -         |
| By test results for steel grade 09G2S | 200        | 300        | 440        | -         | -         | -         |
| Steel of undercut anchor | -         | -         | -         | -         | 125        | 190        | 250        |
| Concrete grade           | B30        | B30        | B30        | B30        | B30        |

Figures 4a, 5a, 6a show «Load-displacement» diagrams for bent foundation bolts 16, 24 and 36 mm in diameter under static load mounted in cracked and uncracked concrete with concrete grade B30. Figures 4b, 5b, 6b show «Load-displacement» diagrams for bent foundation bolts of the same diameters under dynamic load which simulated seismic load with following static loading till failure.

Figures 7a, 8a, 9a show «Load-displacement» diagrams for undercut anchors 12, 16 and 20 mm in diameter under static load mounted in cracked and uncracked concrete with concrete grade B30. Figures 7b, 8b, 9b show «Load-displacement» diagrams for undercut anchors of the same diameters under dynamic load which simulated seismic load with following static loading till failure.

Figure 4. «Load-displacement» diagrams for bent foundation bolt 16 mm in diameter: a) under static load; b) under dynamic load. Embedment depth – 200 mm.

Figure 5. «Load-displacement» diagrams for bent foundation bolt 24 mm in diameter: a) under static load; b) under dynamic load. Embedment depth – 300 mm.
Figure 6. «Load-displacement» diagrams for bent foundation bolt 36 mm in diameter: a) under static load; b) under dynamic load. Embedment depth – 440 mm.

Figure 7. «Load-displacement» diagrams for undercut anchor 12 mm in diameter: a) under static load; b) under dynamic load. Embedment depth – 125 mm.

Figure 8. «Load-displacement» diagrams for undercut anchor 16 mm in diameter: a) under static load; b) under dynamic load. Embedment depth – 190 mm.
Figure 9. «Load-displacement» diagrams for undercut anchor 20 mm in diameter: a) under static load; b) under dynamic load. Embedment depth – 250 mm.

4. Discussions
Anchorage strength was defined by ultimate tensile load for anchor bolt providing that concrete tensile and shear strength is assured. In its turn concrete strength depends on depth and reliability of anchor embedment.

Table 3 shows test and calculation results [3, 4] for anchors embedment depths. Effective embedment depth for bent foundation bolts was determined by gradual reduction of depth from values recommended in manual [3] till minimum value. Embedment depth value was counted as minimum (effective) if test for anchors with lesser embedment depth showed concrete cone failure for at least one specimen.

Tests showed that minimum admissible length for bent foundation bolts equals 67% of values required by [3].

Comparison of bearing capacity showed that torque-controlled undercut anchors guarantee more reliable embedment of anchor at required depth [4] than bent foundation bolts. Thus, bent foundation bolts 16 mm in diameter with 150 mm embedment depth and 450 MPa steel strength showed steel failure during tests. Transition to steel strength of 500 MPa led to concrete cone failure. Undercut anchors 16 mm in diameter in the same concrete grade (B30) with 190 mm embedment depth and 850 MPa steel strength show steel failure at approximately 80% higher load than for bent foundation bolts.

Tests showed that anchors the existence of cracks and dynamic loads do not reduce the bearing capacity for both types of excluding the case of bent foundation bolt 16 mm in diameter which required increase in embedment depth from 150 mm to 200 mm in tests with cracked concrete.

Threshold values for elastic strain stage for anchorage with bent foundation bolts lie in range from 1.0 mm to 1.5 mm at load of 0.67·N_{u,m}.

Tests showed that for bent foundation bolts the existence of crack does not affect anchor displacement during loading. Calculations indicate that on the strain stage with displacement of 6 mm relation between displacement from anchor strain to displacement from concrete equals 1:3.

Tests of torque-controlled undercut anchors showed that:
- for anchorage in uncracked concrete during elastic strain stage anchor displacement is defined by bolt strain – there are no cracks in concrete. Hereat load on the threshold of elastic strain equals 0.67·N_{u,m} (similar to bent foundation bolts);
- for anchors 16 and 20 mm in diameter the existence of crack and dynamic load essentially increases anchor ductility across the entire loading range. Displacement for undercut anchors 16 mm in diameter is four time higher than for bent foundation bolts (figure 10) at the same loading level of 0.5·N_{u,m} which is recommended for displacement estimation by [12]. There were anchor failures which occurred due to exceedance of maximum permissible displacement for maintenance conditions at load levels which were less than ultimate.
5. Conclusions

1. Minimum embedment depth for bent foundation bolts 16, 24 and 36 mm in diameter was acquired as a result of tests. Received data on anchor embedment depth after static tests was verified and adjusted after dynamic loading which simulated seismic loading. Minimum embedment depth is 67% of required by manual [3].

2. Crack existence in concrete led to increase in embedment depth for bent foundation bolts 16 mm in diameter in order to achieve steel failure.

3. Crack existence and dynamic load had almost no influence on ductility of bent foundation bolts.

4. Torque-controlled undercut anchors show high ductility in uncracked concrete at elastic strain stage – anchor displacement is determined only by anchor strain. Existence of cracks in concrete essentially increases ductility of undercut anchors from the beginning of loading.

References

[1] Klementev S V 2004 Chto my znaem ob ankerah i dyubelyah (Volgograd: OOO ORVIL) p 71.
[2] Kiselev D A 2010 Prochnost i deformativnost ankernogo krepezhka pri dejstvii staticeskoj i dinamicheskoi nagruzok dissertatsiya na soiskanie uchenoj stepeni k t n (Moscow: TSNIISK im V A Kucherenko) p 158.
[3] MDS 31 4 2000 Posobie po proektirovaniyu ankernyh boltov dlya krepleniya stroitelnykh konstruktsij i oborudovaniya k SNiP 2 09 03.
[4] STO 36554501 039 2014 Ankernye krepleniya k betonu s primeneniem ankerov HILTI. Raschyot i konstruirovanie.
[5] GOST R 56731 2015 Ankery mekanicheskie dlya krepleniya v betone. Metody ispytaniy.
[6] GOST 24379 1 2012 Bolty fundamentnye. Konstruktziya i razmery.
[7] Hoehler M S, Mahrenholtz P and Eligehausen R 2011 ACI Structural Journal 108 238-247.
[8] Mahrenholtz P and Eligehausen R 2015 Nuclear Engineering and Design 287 48-56.
[9] Rodriguez M, Lotze D, Gross J H, Zhang Y G, Klingner R E and Graves H L 2001 Structural Journal 98 511-524.
[10] Henzel J and Stork J 1990 Darmstadt Concrete 5 79–86.
[11] GOST R 58430 2019 Ankery mekanicheskie i kleevye dlya krepleniya v betone v sejsmicheskikh rajonah. Metody ispytaniy
[12] STO 36554501 052 2017 Ankernye krepleniya k betonu. Pravila ustanovleniya normiruemyh parametrov