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PULL-OUT BEHAVIOR OF CHEMICALLY BONDED DEFORMED BARS TYPICALLY USED DURING STRUCTURAL RETROFITTING

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ABSTRACT

In this experimental study, deformed bars were chemically anchored in low strength concrete and pull-out tests were carried out using a specially designed test setup, which allowed cone type concrete failure. The effects of several parameters, such as the depth of drilling holes, types of adhesives and surface condition of concrete in the hole, on pull-out behavior were investigated. For anchoring deformed bars in concrete, four different types of adhesives were used. The depth of the drilling holes varied between six to twelve times the bar diameter. The other test parameters considered were the humidity and dust condition of the concrete surface in the drilling hole. The experimental results are presented using bond strengths, bond stress-slip relationships and failure patterns.

Introduction

The tensile load transfer mechanism of a common type post-installed chemical anchor can be explained as the transfer of applied load on the anchor bolt to the concrete by the forces occurred on the anchor-adhesive-concrete interfaces. Different types of anchors may fail in different modes. There are five primary failure modes for anchors under tensile forces (ACI-355 1R-91): steel failure, pull-out failure, concrete splitting failure, concrete cone failure and spacing and edge cone failure (Fig. 1).

Numerous experimental (Eligehausen at al. 1984, Cook 1993) and analytical (Wisser at al. 2000, McVay at al. 1996) studies have been carried out for understanding the behavior of chemically bonded anchors. However, in most of these studies, the concrete compressive strengths are high with respect to the common concrete quality of existing buildings to be seismically retrofitted in Turkey, like many other locations. Although the concrete quality for new construction is not generally low, according to a large number of tests carried out on cores taken from existing buildings, the concrete compressive strength is generally determined to be 8-20 MPa for existing reinforced concrete structures in Turkey. Although, one would think that demolition of such structures are more rational than retrofitting these structures, considering the very large stock of existing buildings in such condition, and the financial, social and legal obstacles, structural retrofitting appears as the most adequate approach in most cases. Considering that chemical anchorages are very widely used in conventional retrofitting methodologies, research on the bond behavior of deformed bars, which are anchored in low quality concrete, is vitally important, particularly in the absence of sufficient data for the case of low strength concrete.

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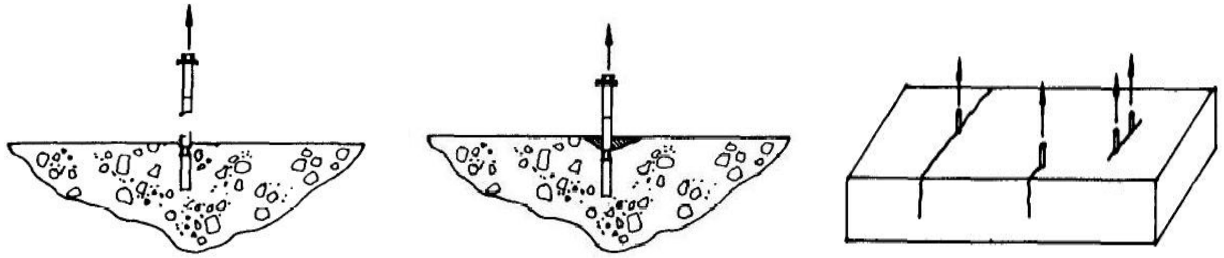

a) Steel failure b) Pull-out failure c) Concrete splitting failure

d) Concrete cone failure e) Spacing and edge cone failure

Figure 1. Primary failure modes for anchors under tensile forces (ACI-355 1R-91).

In this study, the pull-out behavior of deformed bars anchored in relatively low strength concrete using chemical adhesives was investigated experimentally. The average compressive strength of concrete, in which deformed bars were anchored, was 16.1 MPa. Four different types of adhesives, as well as four different anchorage depths were taken into account. According to Kaya (2004), the surface condition of the anchorage hole is among the main factors, which affects the bonding strength. Therefore, different surface conditions in terms of cleaning procedure and humidity were included in the testing program. Perfect clean and dry holes, surfacially cleaned dusty holes, which are assumed to represent poor application procedure on construction site, and holes with humid surfaces were used for representing different surface conditions in this study. According to test results, it was observed that the adhesive type, anchorage depth and the surface condition of the holes effected the anchor behavior significantly, resulting in different pull-out resistances and failure mechanisms. The test results are given by bond strengths, bond stress-slip relationships and failure patterns.

Materials

All anchors were installed in the cast-in-site large size concrete blocks, which were cast using a specially designed low strength ready mixed concrete. The concrete mix-proportion and fresh concrete characteristics are presented in Table 1 and 2, respectively. Standard concrete cylinders of 150×300 mm were tested under compression and average compressive strength and elasticity modulus of concrete at 70 days of age, when the pull-out tests were performed, were determined as 16.1 and 21800 MPa, respectively. For eliminating the effects of the reinforcement, concrete blocks were cast without reinforcement. As anchor bars, deformed bars of 20 mm diameter, as mostly used in practical applications were used. The mechanical characteristics of deformed bars are presented in Table 3. Four different types of adhesives, which are usually used in practical applications in retrofitting, were chosen. The characteristics of the adhesives are summarized in Table 4 and Table 5. The mechanical characteristics of adhesives were obtained by laboratory tests carried out in accordance with EN 196-1. M1 and M4 were epoxy based adhesives with different consistencies and packaging. M1 had pasty consistency and it could be applied with mortar guns. M4 was flowable and could be easily poured into the holes. On the other hand, M2 and M3 were ready to use cartridge packaged products, and could be used with less labor faults. Furthermore, M2 and M3 were fast setting adhesives and they allowed quick applications in retrofitting.

Table 1. Concrete mix design (kg/m^3).

Cement	Fly Ash	Sand	Water	Gravel	Admixture
170	45	1017	144	1081	1.51

Table 2. Slump test results.

	Test 1	Test 2	Test 3
Slump (mm)	200	160	200

Table 3. Tension test results for anchor bars.

	Diameter of Bar (mm)	Yield Strength (MPa)	Tensile Strength (MPa)	Ultimate Strength (MPa)
Specimen 1	19.20	478	797	732
Specimen 2	20.11	559	661	522
Specimen 3	19.13	464	789	710
Specimen 4	19.90	555	669	562

Table 4. Material properties of the adhesives.

	M1	M2	M3	M4
Comp. A (Resin) Comp. B (Hardener)	Epoxy Amine	Epoxy-acrylate Dibenzoyl-peroxide	Epoxy-acrylate Methylethylketone-peroxide	Epoxy Amine
Mixing Ratio (by weight) Comp. A / Comp. B	~ 3 / 1	~ 10 / 1	~ 10 / 1	~ 2 / 1
Packaging Comp. A: Comp. B:	3.75 kg 1.25 kg	345 ml Cartridge	345 ml Cartridge	5.00 kg 2.50 kg
Mixed Density (kg / liter)	1.70	1.70	1.70	1.55
Final Cure (20 °C)	7 days	1 days	1 days	7 days

Table 5. Compressive and flexural tensile strengths of adhesives (MPa).

	M1	M2	M3	M4
Average Compressive Strength*	75.6	90.8	69.9	83.0
Average Flexural Strength*	28.6	22.0	22.7	26.8

*Test were carried out on at least three specimens cured seven days under 12~13 °C.

Test Program

Test Variables

In total, 24 chemically bonded deformed bars were tested under pull-out forces. The average concrete compressive strength of the blocks, where deformed bars were anchored, is 16.1 MPa. Deformed bars with 20 mm diameter were used for anchoring in relatively low strength concrete blocks. The diameter of anchor hole was fixed at 26 mm, which was 6 mm wider than the anchor bar diameter. Adhesive types, anchor depths and surface conditions of anchor holes are the test variables in this study. Most commonly used adhesives in retrofitting were taken into account and they were coded as M1, M2, M3 and M4. M1 and M4 adhesives were moisture insensitive epoxies and M2 and M3 were fast setting, cartridge packaged epoxy-acrylates. For understanding the effects of the depth of the anchors, four different anchor depths were investigated in this study. The hole depths varied as 6Φ, 8Φ, 10Φ and 12Φ, where Φ is the diameter of the anchor bar. Three different surface conditions of anchor holes were included in testing program. These were dry and perfectly clean holes, which were assumed to represent ideal application, partly cleaned dusty holes, which were assumed to represent inadequate applications in practice, and properly cleaned but humid surfaces, which were assumed to represent the cases, where it was practically impossible to fully dry the surfaces of anchorage holes. The specimens were coded according to adhesive type, anchor details, hole diameter and depth, and the surface condition of the hole. For example, for the code M1Φ20x26x200-D; M1 is the type of adhesive, 20 is the diameter of anchored bar in mm, 26 is the diameter of the hole in mm, 200 is the depth of the hole in mm and D represents dusty surface condition. When the surfaces of the hole were kept humid around 48 hours before bonding, the letter ‘H’ was used in the specimen designation. The specimen characteristics, tensile strengths and failure types are presented in Table 6.

Preparation of Specimens and Workmanship

Seven concrete blocks were cast for anchor applications. The dimensions of these blocks were around 250×100×25~30 cm. Ten standard cylinder samples were prepared for compressive and tensile strength tests. Slump tests were made for evaluating the fresh concrete properties. For eliminating the splitting failure, spacing and edge cone failures, the anchors were separated with significant distances from each other and from edges depending on their depths. After determining the geometric positions of the anchors on the concrete blocks, all the anchor holes were drilled with pre-defined depths and diameters by using an electrical driller. After finishing the drilling, the surface preparation stage was started. For preparing the clean and dry holes, the holes were cleaned with an air gun as it is seen in Fig. 2. After removing the dust from the holes, a steel wire brush was used to remove the loose particles from the hole surface and roughening. For the last step, the holes were re-cleaned with air guns. For preparing the partly-cleaned dusty holes, only the dust remaining after the drilling job was removed by air gun. In humid holes, all the surface preparation steps for clean and dry holes were followed and than the cleaned holes were fully filled with water and kept in that position for 48 hours. After 48 hours, the water was taken out by using a small injector pump, and then the adhesive was applied.

Figure 2. Surface preparation steps of clean and dry holes.

Table 6. Characteristics of specimens and main test results.

Specimen	Adhesive Type	Anchor Diameter (mm)	Hole Diameter (mm)	Anchor Depth (mm)	Surface Condition	Failure Type	Tensile Load (KN)
M1Φ20x26x120	M1	20	26	120	Clean - Dry	Conc.	77.6
M1Φ20x26x160	M1	20	26	160	Clean - Dry	Combined	103.0
M1Φ20x26x200	M1	20	26	200	Clean - Dry	Combined	142.5
M1Φ20x26x240	M1	20	26	240	Clean - Dry	Combined	152.6
M1Φ20x26x120-D	M1	20	26	120	Dusty	Conc.	67.0
M1Φ20x26x160-D	M1	20	26	160	Dusty	Combined	106.3
M1Φ20x26x200-D	M1	20	26	200	Dusty	Combined	154.8
M1Φ20x26x240-D	M1	20	26	240	Dusty	Combined	154.6
M1Φ20x26x120-H	M1	20	26	120	Humid	Conc.	68.5
M1Φ20x26x160-H	M1	20	26	160	Humid	Combined	116.5
M1Φ20x26x200-H	M1	20	26	200	Humid	Combined	104.5
M1Φ20x26x240-H	M1	20	26	240	Humid	Combined	146.6
M2Φ20x26x120	M2	20	26	120	Clean - Dry	Conc.	49.3
M2Φ20x26x160	M2	20	26	160	Clean - Dry	Combined	95.3
M2Φ20x26x200	M2	20	26	200	Clean - Dry	Combined	99.5
M2Φ20x26x240	M2	20	26	240	Clean - Dry	Combined	82.6
M3Φ20x26x120	M3	20	26	120	Clean - Dry	Pullout	37.0
M3Φ20x26x160	M3	20	26	160	Clean - Dry	Pullout	58.6
M3Φ20x26x200	M3	20	26	200	Clean - Dry	Pullout	52.5
M3Φ20x26x240	M3	20	26	240	Clean - Dry	Pullout	72.8
M4Φ20x26x120	M4	20	26	120	Clean - Dry	Conc.	65.1
M4Φ20x26x160	M4	20	26	160	Clean - Dry	Combined	93.0
M4Φ20x26x200	M4	20	26	200	Clean - Dry	Combined	104.5
M4Φ20x26x240	M4	20	26	240	Clean - Dry	Combined	139.6

M1 and M4 adhesives had two component packaging system including hardener and resin. For preparing these materials, two components (hardener and resin) were mixed together with an electrical mixer until obtaining a homogenous consistency. M1 had a pasty consistency and it was filled into a mortar gun and applied into the hole by using the mortar gun. M4 could flow under its own gravity. Therefore, it was poured into the holes from a mixing pail. On the other hand, M2 and M3 were packaged in ready to use 345 ml cartridges with two tubes. After placing the cartridges into their own cartridge guns, the holes were filled with an adequate amount of adhesive. The filling process of the holes with M1 and M2 adhesives are shown in Fig. 3. After filling the holes with adhesives, the anchor bars were installed into the holes.


a) b)

Figure 3. Filling the holes with a) M1 and b) M2 adhesives, respectively.

Test Setup

The anchors were subjected to direct tensile forces by using a hydraulic jack, clamping system and a special three pod table. The three pod table was specially designed depending on the anchor geometry, possible concrete cone diameter and maximum tensile load to be applied. The hydraulic jack had a load capacity of 200 kN and it was used with a 500 kN capacity load cell. The steel clamping system was custom made for the deformed bars used in the tests. For measuring the deformations of the anchor, one TML CDP 50 type displacement transducer was used. Upward displacement was measured from a point, which was very close to the concrete surface. For data acquisition a TML-TDS-303 data logger was used. General appearance of the test setup is shown in Fig. 4.

Figure 4. Test setup.

Behavior of Specimens

During the tests, three different failure patterns were observed. The first failure type was concrete cone failure, which occurred in shallow anchors with depths of 6Φ in the case of M1, M2 and M4 adhesives. A typical concrete cone failure is shown in Fig. 5. The concrete cone diameters varied between 400–500 mm. In the case of M3 adhesive, all anchors failed due to pull-out failure in all depths. For these anchors, slipping initiated at approximately 50% of the pull-out strength of other anchors. The failure pattern of these anchors is shown in Fig. 6. The third failure mode was combined mode. In deep anchors, the concrete cone failure and the pull-out failure were combined. In this pattern, a concrete cone was formed with a depth of 50–100 mm from the concrete surface and the remaining part of the anchor was pulled out from the concrete. A typical combined failure mode is shown in Fig. 7.

Figure 5. Concrete cone failure in shallow anchors.

Figure 6. Pull-out failure of anchors bonded with M3 type adhesive.

Figure 7. Combined failure mode.

In combined failure mode, anchors bonded with M1 and M4 adhesives exhibited similar behavior and failure patterns, while for the case of anchors bonded with M2 adhesive, the pull-out mode was more dominant to concrete cone failure mode. Therefore, the concrete cone depths varied between 50–60 mm, where they were 80–100 mm for M1 and M4 used anchors.

Experimental Results

Although the failure patterns were similar for anchors in similar depths, the load–slip behavior was completely different from each other. In terms of strength, anchors bonded with M1 and M4 adhesives exhibited best performances, while anchors bonded with M2 adhesive exhibited relatively poor performance and the anchors bonded with M3 exhibited the worst. As it can be understood from the test results, adhesive type was a key factor, which was effective on the anchor performance and behavior. The load–slip behavior of the specimens was affected from the adhesive type, anchor depth and resulting failure pattern. The anchors bonded with M1 and M4 adhesives exhibited similar performances for different anchor depths. For these anchors, the tensile load increased until a limit in elastic state, and started to decrease dramatically with the bond failure as it is shown for M1 and M4 in Fig. 8 and Fig. 9, respectively. The failure patterns and performances of the anchors, bonded with moisture insensitive M1 adhesive, were not affected from the surface conditions of the holes, Fig. 10 and Fig. 11. As it can be seen in Fig. 10, in dusty conditions pull-out failure was more dominant in combined failure mode and the anchor behaved more ductile because of deteriorating friction forces around the anchor bar. This behavior can be explained with gradually decreasing bond strength in concrete–adhesive interface due to the transition media formed by epoxy, dust and loose particles between concrete and epoxy.

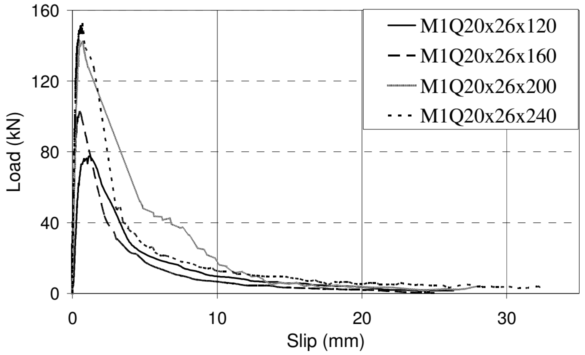

Figure 8. Load–slip relationships for anchors bonded with M1 adhesive in clean and dry conditions.

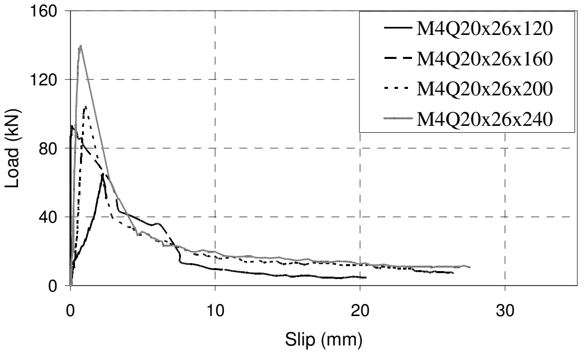

Figure 9. Load–slip relationships for anchors bonded with M4 adhesive in clean and dry conditions.

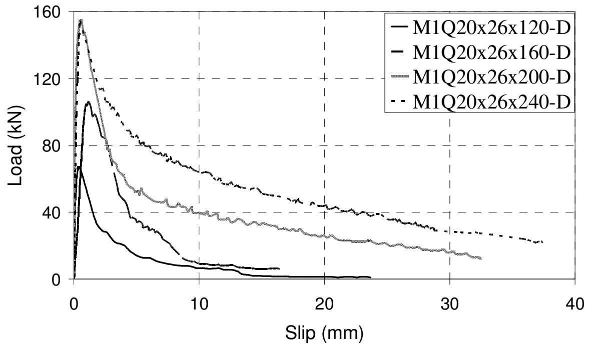

Figure 10. Load–slip relationships for anchors bonded with M1 adhesive in dusty surface conditions.

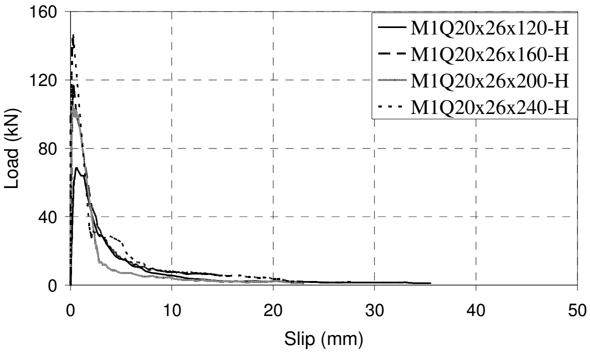

Figure 11. Load–slip relationships for anchors bonded with M1 adhesive in humid surface conditions.

On the other hand, in humid conditions, the anchors behaved more brittle without exhibiting significant slipping. The concrete cone failure was dominant in the anchors in humid conditions.

The anchors bonded with M2 adhesive had similar load–slip behavior, with a less steep descending branch, indicating a more ductile behavior. However, it should be noted that pull-out strengths were significantly lower than the cases of M1 and M4 adhesives, Fig. 12. The pull-out failure was dominant in combined mode because of the lower bond strength of the M2 adhesive with respect to M1 and M4 adhesives. Moreover, the anchors bonded with the M3 adhesive had a perfect pull-out failure in all depths under significantly lower tensile loads, as shown in Fig. 13. Although pull-out strengths were much lower, considering the highly ductile character of the behavior, this type of behavior may also be preferable for applications of seismic retrofitting, where ductility during seismic load reversals are vitally important. Undoubtedly, in this case, the relatively low tensile strength of the anchor should be taken into account.

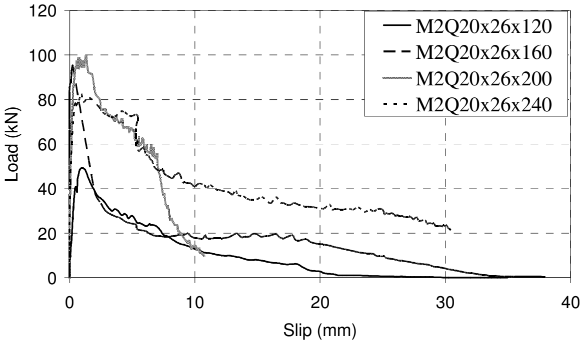

Figure 12. Load–slip relationships for anchors bonded with M2 adhesive in clean and dry conditions.

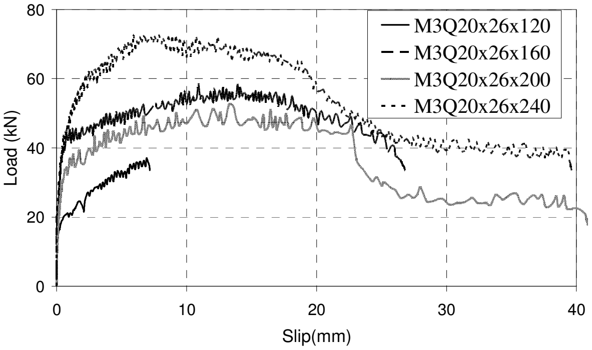

Figure 13. Load–slip relationships for anchors bonded with M3 adhesive in clean and dry conditions.

Conclusions

In this study, 24 deformed bars were anchored in relatively low strength concrete blocks using four different kinds of adhesives for different depths and surface conditions. These specimens were then tested under tensile loads using a specially designed loading apparatus, which allowed concrete cone failure if this was more critical than slipping of the anchored deformed bar. The test parameters covered the range of anchor depths, which are generally used during seismic retrofitting applications. The results are summarized as follows:

- Independent from the adhesive type, the tensile load capacity of the anchored deformed bars increased with increasing depth of the anchor.
- Different failure patterns and pull-out strengths were observed for different types of adhesives, although anchor depths and surface conditions were identical. Therefore, it is important to characterize the adhesive properties for realistically predicting the pull-out behavior of the anchor.
- The bond strength of the adhesive affected the failure pattern significantly. Adhesives with low bonding strength caused the anchor to fail in a perfect pull-out mode, whereas the adhesives with high bonding strength made the concrete cone failure dominant in combined failure modes.
- Surface conditions of the anchor holes were also effective on the behavior of chemically anchored deformed bars. Dusty holes, which were not properly cleaned, and humid hole surfaces particularly effected the post-peak branches of the load-slip relationships, effecting the ductility significantly.

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