MECHANICAL PROPERTIES OF CFRP ANCHORAGES

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ABSTRACT

MECHANICAL PROPERTIES OF CFRP ANCHOR DOWELS

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Due to inadequate lateral stiffness, many reinforced concrete buildings are highly damaged or collapsed in Turkey after the major earthquake. To improve the behavior of such buildings and to prevent them from collapse, repair and/or strengthening of some reinforced concrete elements is required. One of the strengthening techniques is the use of CFRP sheets on the existing hollow brick masonry infill. While using the CFRP sheets their attachment to both structural and non-structural members are provided by CFRP anchor dowels. In this study, by means of the prepared test setup, the pull-out strength capacities of CFRP anchor dowels are measured. The effects of concrete compressive strength, anchorage depth, anchorage diameter, and number of fibers on the tensile strength capacity of CFRP anchor dowel are studied.

Keywords: Strengthening, Carbon Fiber Reinforced Polymer (CFRP), Bonded Anchor, Bond Model, CFRP Anchor Dowel

ÖZ

CFRP ANKRAJLARIN MEKANİK ÖZELLİKLERİ

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Türkiye'de çok sayıda betonarme bina yeterli yanal rijitliğe sahip olmadığından ya ağır hasara uğramış ya da yıkılmıştır. Bu tür binaların davranışlarını iyileştirmek ve yıkılmalarını önlemek için betonarme binalardaki bazı taşıyıcı elemanların onarılması ve/veya güçlendirilmesi gerekmektedir. Uygulanan güçlendirme tekniklerinden birisi betonarme binalardaki tuğla duvarların üzerine karbon fiber takviyeli polimer (CFRP) tabaka kaplamaktır. Bu tarz güçlendirme tekniklerinde kullanılan CFRP tabakanın taşıyıcı ve taşıyıcı olmayan elemanlara bağlantısı CFRP ankrajlar sayesinde gerçekleştirilmektedir. Bu çalışmada, hazırlanan deney duzeneği yardımıyla kullanılan CFRP ankrajların betondan çekme dayanımı belirlenecektir. Bu çalışmada belirlenen parametreler beton dayanımı, ankraj derinliği, ankraj deliğinin çapı ve uygulanan CFRP tabakanın kalınlığıdır.

Anhtar Kelimeler: Güçlendirme, (CFRP), yapıştırılmış ankraj, kayma gerilmesi modeli, CFRP ankrajları

To my family and my love Aslı…

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A	Tensile stress area of the anchor
d	Anchor hole diameter
f_c	Concrete compressive strength
F_u	Ultimate strength of the anchor
h_{ef}	Embedment depth of the anchor dowel
k	Anchor constant
P_{CMPST}	Ultimate tensile capacity of epoxy coated CFRP sheet
P_{CONE}	Ultimate tensile capacity of the concrete failed by cone failure
P_{FRP}	Ultimate tensile capacity of CFRP sheet
w	Width of the CFRP sheet
σ	Tensile stress in concrete
σ_{ult}	Ultimate tensile stress of anchor
τ_{ave}	Average shear stress of the concrete

CHAPTER 1

INTRODUCTION

Structures should be constructed in such a way that they have enough capacity to carry the possible loads. Engineers must be very careful during the design stage of any structure. At the design stage, some of the loads can inadvertently be underestimated or ignored. Unintentionally created deficiencies during design and/or construction may cause catastrophic results when the structure is subjected to high level of loads. Due to these deficiencies, heavy damage or total collapse of RC buildings after major earthquakes has initiated the studies on the strengthening techniques of damaged and undamaged buildings. It has been observed that the basic reasons of catastrophic results after the earthquakes are the inadequacy in lateral stiffness, strength and ductility of the structure. To improve the seismic behavior of these buildings, to resist against earthquakes, strengthening procedures are needed. In general, strengthening is achieved by providing additional strength or ductility to the structure depending on the method. Various strengthening methods have been developed to reduce the effects of the earthquakes. Every method has some advantages and disadvantages. Depending on the condition of the structure, the optimal technique must be selected.

One of the widespread strengthening applications is inserting reinforced concrete (RC) infill walls to meet the lateral demands of the structure. Additional strength and lateral stiffness can be gained by this strengthening technique. Although the effectiveness of this technique has been approved in the last major earthquakes, the problem is the time needed for the application. This technique is also a disturbing process for the occupants. In other words, to apply this method, the structure should be empty. If there are some residents, they should be evacuated before the process begins.

By the improvements in technology, a new technique was developed in the strengthening of structures aiming less disturbance and less time consumption. For this purpose, fiber reinforced polymers (FRP), made of high-modulus fibers bonded with a resin matrix, has been increasingly used because of its superior properties. In comparison with steel, FRP possess many advantages such as high corrosion resistance, high strength to weight ratio, electromagnetic neutrality and ease of handling. The most common fiber types used and researched are made of glass (GFRP), aramid (AFRP), and carbon (CFRP) fibers.

The first applications of FRP in strengthening are seen in the retrofitting of damaged columns and beams which are individual members of a system. These members are wrapped with high strength new material FRP and this application is known as wrapping. Use of any wrapping technique provides additional bending moment capacity or lateral stiffness for individual members.

In recent studies, knowing that strengthening with FRP is successful for members of a system, it was used in rehabilitation of damaged structures with a new technique. In this new technique, the goal was the system improvement rather then member rehabilitation. This technique is called as seismic retrofit by carbon fiber sheet (SR-CF system). In SR-CF system, the surface of the existing hollow clay tile infill walls are covered with diagonally glued carbon fiber sheet providing that edges of the sheet are connected to the peripheral column, beam and floor using special connection details. With this method, the carbon fiber sheet behaves like a tensile bracing, and increases the shear resistance of the wall. Key issue in SR-CF application is the performance of the connection between the CFRP sheet and the peripheral structural members. Because, the aim of this strengthening technique is to provide that the infill wall can also resist against shear force with the help of the CFRP ties by transmitting the applied load to the frame members. And this can be possible with proper connection details. This is why connection is crucial. For this purpose, special devices namely, carbon fiber (CF) anchor dowels, were developed.

The behavior and tensile capacity of these special connections, namely CFRP anchor dowels need to be investigated for the success of this strengthening technique. In this study, direct tensile load capacities of CFRP anchor dowels are measured. During the tests, the effects of concrete strength, anchor embedment depth, anchor hole diameter, and CFRP sheet width on the tensile strength capacity of CFRP anchor dowels are studied.

It should not be forgotten that all strengthening applications are carried out in different structures having different characteristics. To reflect this phenomenon, tests were carried out with concrete blocks having three different compressive strengths to observe the efficiency of connection detail depending on the concrete quality. For the compressive strength, most commonly used concrete strengths of existing structures in Turkey were chosen. Similarly, to determine how deep the anchor dowel should be the embedment depth of the anchor dowel is chosen as an other test parameter. In addition, the sheet width of anchor dowel is chosen as a parameter to find out the efficiency of number of fibers, resisting the applied tensile load. And finally, hole diameter is designated as a variable to observe whether the amount of epoxy resin used to bond the anchor dowel to the RC frame has an effect on the behavior or not. For this purpose, a total of 176 tests were carried out in two parts with parameters mentioned above.

1.1 LITERATURE SURVEY

In the literature, there is no study on the direct tensile capacity of anchor dowels made of CFRP sheet. On the other hand, there are quiet many studies on steel anchor dowels and FRP rods. In the first part of this section, some of the researches conducted on these topics are presented. In the second part, the researches carried out with CFRP as a system improvement facility, are given with the related conclusions. The following studies are worth to mention because of their similarities in the parameters of affecting the behavior of the CFRP anchor dowels.

McVay et al [1] presented a sate-of-the-art report on elastoplastic finite element analysis for post installed chemically bonded steel anchor dowels. They carried out a series of computer based analysis, and then compared the results with that of experimental studies. The main parameter was the ratio of embedment depth to diameter. During the tests, this ratio varied between 5 to 8. A total of 18 experiments were conducted for fully bonded anchor dowels. The computer simulation revealed that the concrete cone failure was found to initiate at the concrete-adhesive bond interface and progress towards the surface as a tension zone.

Lynch and Burdette [2] studied the current design methods for calculating tensile and shear capacities of steel anchor dowels. They attempted to introduce a practical way of calculating the tensile capacity of multiple anchor dowels with overlapping shear cones. The aim of this research was to make a collection of information available about anchor dowel behavior in tension and shear for the purpose of structural design.

Cook and Klingner [3] determined the distribution of stresses (loads) between steel anchor dowels and concrete in a connection and proposed a mechanical model. The model was based on limit design theory. In design of multiple anchor dowels, authors followed three steps: Calculation of loads on the connection, distribution of those loads on the anchor dowels, design of each anchor dowel for its loads. In this study, authors mainly studied the distribution of the loads. They combined the existing knowledge of design for single anchor dowels and experimental results of multiple-anchor dowels. In the light of this knowledge, they presented a design procedure. Variables that affect the behavior of ductile multiple anchor dowel connection were: loading type (axial load, moment and shear), size of the steel attachment, size, number, location and type of anchor dowels, tension/shear interaction for a single anchor dowel, distribution of shear among the anchor dowels, distribution of tension among the anchor dowels.

Cook et al [4] studied the tensile capacities of threaded steel anchor dowels with 16 mm diameter for six different adhesive products. They carried out 97 tests. The main objective of this study was to develop a model for bond stress distribution to use in design procedures. For this purpose, fully bonded and partially bonded single anchor dowels were tested with varying embedments of 100 mm and 150 mm to examine the behavior of bond stress for different bonded lengths. This study pointed out that the capacities of a partially bonded anchor and fully bonded anchor which were in the same dimensions were almost the same for the chosen two different embedment depths. This shows that the contribution of concrete cone on the capacity can be neglected and elastic behavioral model can be used to determine the bond stress distribution and strength of adhesive anchor dowels made of steel.

In another study, Cook et al [5] carried out 280 tests to investigate the behavior of chemically bonded steel anchor dowels. Main objective of this study was to propose a behavioral model for bonded anchor dowels. All tests were conducted in concrete for a concrete compressive strength of 38 MPa. They proposed an equation to predict anchor capacity which is a function of the anchor hole diameter, shear stress between concrete and adhesive, and embedment depth of anchor by using elastic bond stress model. They compared the results found from bond stress model with the experimental data. Using the available test data and bond stress models, authors concluded that the behavior of the bonded anchor dowel can be divided into 3 parts. For shallow depths, concrete cone model is well suited. A combined cone-bond failure model using uniform bond stress can be used for anchor dowels having intermediate depths. And finally a combined cone-bond failure model is appropriate for anchor dowels of deep embedment depths.

Recently, Cook et al [6] presented a model to calculate the capacity of a single adhesive steel anchor dowel in uncracked concrete members. Data for this study was obtained from the ultimate tensile tests of single anchor dowels placed into clean, dry holes far from concrete edges. They made a summary about bond models for adhesively bonded steel anchor dowels. They also presented a bond model for evaluation of ultimate tensile capacity of an adhesively bonded steel anchor dowel. In the light of the investigations performed, authors concluded the following: The effect of concrete compressive strength on bond strength between adhesive anchor dowel and concrete is dependent on the product used for bonding.

Barnes and Mays [7] performed 15 tests to investigate the transfer of stress through a steel-concrete adhesive bond. These experiments were also followed by a finite element analysis. The main objectives of this research were: to examine stress and strain distributions for different anchor dowel lengths, to investigate the relationship between shear strain distribution and plate-adhesive thickness. The objectives of the finite element analysis were to validate the use of finite element analysis to confirm the trends derived from the experimental test program and to understand the stress transfer process in the concrete-adhesive-steel bonded joint. Authors reported that the shear stress in a steel-to-concrete adhesive joint is exponentially distributed.

Chen and Teng [8] made a review of the anchorage strength models in the literature and dealed with the anchorage failure modes. Knowing all the deficiencies of all the other models, the authors proposed a new model to find bond strength and effective anchor dowel length. In this new model, they used previous models in which they made some modifications from existing fracture mechanics. By the help of this new model, they calculated the effective bond length and bond strength. The authors stated that, concrete strength is the basic parameter that affects the bond strength and increase in the anchor dowel length can not increase the bond strength after a critical embedment depth. This length is called the effective bond length and the authors presented an equation for this length.

Zhang et al [9] presented a model of bonded anchor dowels for fiber-reinforced rods to calculate the bond stress and the tensile capacity of bonded anchor dowels. The bond strength values used in the calculations were determined from the pullout tests of 100 mm length anchor dowels. Besides, 200 mm and 350 mm were also used as bonded lengths. Authors modeled the bond stress distribution of bonded anchor dowels in three parts over the embedment length. According to this model, bond stresses due to the tensile forces exerted on the anchor dowel was not uniformly distributed. It changes through the length of anchor dowel that is divided into three parts in modeling. Authors pointed out the followings: Characteristic bond strength is related to neither the bonded length nor the load level. It is related to the surface conditions of the tendon and the mechanical properties of the grout. Anchor dowel length is the primary parameter that affects the bond stress distribution along the anchorage. Distribution is more uniform when the anchor dowel length is short. Increase in the length of the anchor dowel leads less uniformity in the stress distribution. They also conclude that the bonded anchor dowel specimens should be prepared less than thirteen times the diameter of the specimen in order to accurately determine the bond strength from pullout tests. Experimental and analytical results of anchor dowels having 100 mm bonded length, for which the ratio of embedment depth to the anchor diameter is between 12 and 13, showed a good agreement.

Benmokrane et al [10] studied the tensile characteristics, bond strength and pullout behavior of AFRP and CFRP rods embedded in cement grout. Variables which were changed during the tests were rod type, grout type, bonded length and anchor tube type. Beside these variables, authors also investigated the effects of surface geometry of FRP rods, properties of grout and stiffness of the concrete on the pullout capacity and maximum bond stress of cement grouted FRP anchor dowels. Authors stated that bond stress distribution is not uniform through the length of the anchor dowel and an increase in the bond length decrease the bond stress.

Drimousis and Cheng [11] carried out a series of push-apart tests of FRP sheets with bond lengths of 100 mm, 200 mm and 300 mm. Test results indicate that there was no significant change in the capacities due to the increase in bond length from 200 mm to 300 mm. This conclusion reveals that the load carrying capacity of a bonded anchor increases up to a limit after which the capacity does not increase. This limit is given the name effective bond length.

Chajes et al [12] conducted direct pull tests with FRP sheets, bond lengths ranging from 50 mm to 200 mm. Authors concluded that there exists a development length (effective length) beyond which no further increase in ultimate capacity can be achieved. Another conclusion they draw out is that the ultimate capacity is directly proportional to the bond length (h) up to the effective length limit.

Alexander and Cheng [13] studied the effect of bond length on the bond behavior using a series of 16 push-apart tests with FRP sheets. The bond lengths chosen for the investigation of the behavior were ranged from 50 mm to 175 mm. They proposed a bond stress vs. bond length relationship in which the effective bond length is 110 mm.

Maeda et al [14] conducted a research on the bond mechanism of CFRP sheets bonded to concrete. They concluded that bond lengths above 100 mm did not change the ultimate load, implying the existence of an effective bond length of 100 mm.

Ueda et al [15] investigated the bond strength characteristics of FRP sheets. The chosen parameters for this study were anchor dowel length, anchor technique, fiber sheet width, fiber sheet stiffness, and type of loading. The width of the CFRP sheets ranged from 10 mm to 200 mm. They observed that bond length longer than 100 mm did not contribute to the bond strength.

Bonded anchor dowels transfer the applied load by adhesion to concrete along the embedment depth. This phenomenon was studied by several researchers. Luke et al [16], made some investigations and suggested that the bond failure occurs prior to cone failure. In contrary to this suggestion, Cannon et al [17] offer that a shallow concrete cone observed prior to failure of the anchor dowel. However, a combined failure mechanism proposed by Collins et al [18] such that the shallow concrete cone and bond failure occurs at the same time. Throughout these studies, bond strengths are compared with a baseline test series but authors did not suggest any bond model in their studies. In 1991 Cook et al [19] studied the same parameters as previous ones. However, this time authors underlined the need of a bond behavior model which depends on the embedment depth of the adhesive anchor dowel.

Matsuzaki et al [20] conducted a series of experiments to investigate the effect of the reinforcement in the columns with spandrel walls (short column), which are strengthened with CFRP anchor dowels. The main parameters of the specimens include the existence of CF reinforcement (CFRP sheet and CFRP anchor), the thickness of a spandrel wall, the wall position. Cross sections of the columns are 300×300 mm and shear span ratio is 1.5. Specimens were tested under a constant axial force and subjected to cycling horizontal force. This study asserted that strengthening with CFRP anchor dowel system provides a great improvement in ductility.

Kobayashi et al [21] carried out an investigation about strengthening with CFRP sheets. They tried to develop a wrapping system for walls. For this purpose, CFRP-anchor dowel was used to make a connection between the CFRP-sheets through the wall. The authors observed that the strength and rigidity of the walls were also affected by the anchor dowel. The anchor dowels were applied between the walls and columns. It was demonstrated that a great amount of tensile capacity of CFRP sheet could be transferred through anchor dowels if a good detail was improved at the connection between sheet and anchor dowel. This study revealed that an increase in the capacity of CF-anchor dowel is not always expected even if the CFRP anchor length is increased.

As it is mentioned at the beginning of this chapter, development of a new promising strengthening method of undamaged existing buildings has been recently initiated at Middle East Technical University (METU) Structural Laboratory started to be investigated. In this context, Özcebe et al [22] investigated the behavior of the undamaged masonry walls strengthened with CFRP sheet. Different techniques were applied on seven two-story, one bay, 1/3 scale RC frames to obtain the most efficient CFRP application. All specimens were tested under quasi-static reversed cyclic loading. The conclusions drawn out from this study were: An increase in the strength was obtained with CFRP anchor dowels. The specimen strengthened with CFRP sheet using anchorages had a lateral strength two times that of reference frame.

Erdem et al [23] compared two types of strengthening techniques of RC frames. They used two-story three bay RC frame models having a scale of 1/3. They constructed two specimens. First one strengthened with RC infill and second one strengthened with CFRP that was bonded to exterior face of the hollow clay tile walls by using epoxy. The RC test frame was designed to have the common deficiencies observed in Turkey such as poor lateral strength, poor concrete quality and insufficient lateral reinforcement at member ends. Specimens were tested under a quasi-static reversed cyclic lateral load which was applied only at the second story level. During the tests, a vertical load of 9 kN was applied at the top of each second story column that has a cross-sectional area of 110×110 mm. In the specimen strengthened with CFRP, the CFRP sheets were extended and anchored to the frame with CFRP anchor dowels. This study revealed that the capacity of the specimens, in which CFRP was used for strengthening, depends on the quality and the number of CFRP anchor dowels.

Triantafillou [24] aimed to develop a basic understanding of mechanical behavior of masonry walls strengthened with bonded FRP laminates. Author constructed 12 masonry walls to investigate the short term strength of these walls. These 12 specimens were strengthened with FRP laminates. Half of the specimens were tested in in-plane bending while the other half was tested in out-of plane bending. This study revealed that the achievement of full-inplane flexural strength depends on proper anchorage.

Albert et al [25] studied unreinforced masonry walls. These walls were strengthened with FRP. Two types of FRP, namely CFRP and GFRP, were used in strengthening applications. In this experimental study, authors have chosen the following variables to investigate: type of FRP, layout of FRP, axial load and type of loading. Obtained test results were verified with an analytical study carried out by the authors. They concluded that an increase in the amount of FRP resulted in an increase in the stiffness.

1.2 METHODS TO DETERMINE THE CONCRETE CONE CAPACITY

In the literature, there are numerous methods to determine the tensile capacities of different anchors. In this section, TWO of these methods are going to be presented.

1.2.1 45 Degree Cone Method

The 45-degree cone method assumes that a constant tensile stress of $0.96\sqrt{f_c}$ acts on the projected area of a 45-degree cone radiating towards the free surface from the bearing edge of the anchor (Figure 1.1). Therefore, for a single tensile anchor far from free edges, the cone breakout capacity is determined by [26]:

$$P = 0.96\sqrt{f_c} \times h_{ef}^2 \times \left(1 + \frac{d}{h_{ef}^2}\right) \tag{1.1}$$

where f_c = specified concrete compressive cylinder strength (MPa),

d = diameter of anchor hole (mm),

h = effective embedment depth (mm).

1.2.2 CC Method

The concrete cone (CC) method, which is based on a large amount of test results and to some extent on fracture mechanics, computes the concrete cone capacity of a single tensile anchor far from edges as [27]:

$$P = k\sqrt{f_c}\,h_{ef}^{1.5} \tag{1.2}$$

The constant k given in equation 1.2 is equal to 15.5 for expansion and undercut anchors, and 17 for headed anchors. In the CC method, the breakout body is idealized as a pyramid with an inclination of about 35 degrees between the failure surface and the concrete member surface (Figure 1.2). As a result, the base of the pyramid measures $3h_{ef}$ by $3h_{ef}$.

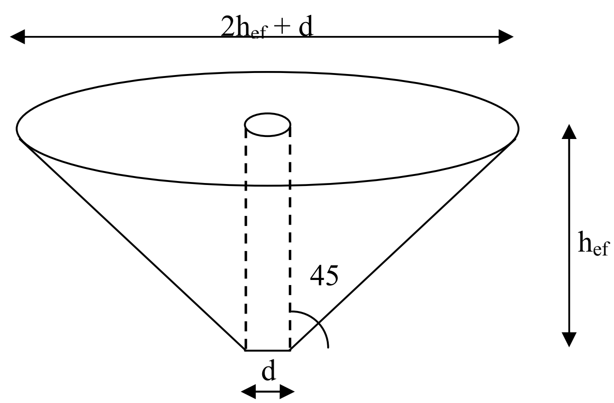

Figure 1.1 45-degree cone

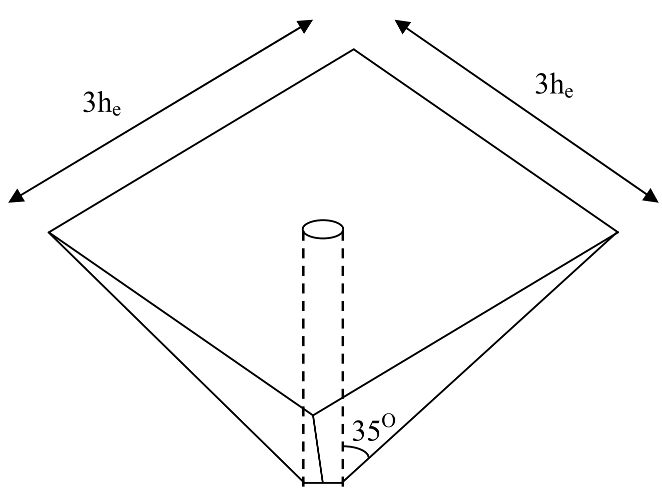

Figure 1.2 Pyramid with an inclination of 35 degree

1.3 OBJECT AND SCOPE

Previous studies reveal that in strengthening with CFRP, connections between the frame members and CFRP sheet are the crucial points. The effectiveness of the rehabilitation depends on a proper connection. Provided that the connection has sufficient strength, then the strengthening method is satisfactory. Key issue is to determine the number and the capacity of the anchor dowels that must be used for a proper connection in CFRP strengthening technique. The stress transfer from infill to the frame members is provided by the anchor dowels. The capacity of the anchor dowels needs to be known for a successful upgrade design.

The objective of this study is to investigate the uniaxial tensile capacity of the embedded CFRP anchor dowels. Tensile capacity of a single CFRP anchor dowel was investigated throughout the experiments. Parameters that affect the capacity of anchor dowels were CFRP sheet width, anchor bond length, anchor hole diameter and compressive strength of concrete. Tested anchor dowels were sufficiently far from free sides. The results obtained from this study provide experimental information for the design of adhesive CFRP anchor dowels.

Detailed information about the test specimens, instrumentation and test procedure is stated in Chapter II. Test results and failure types are listed in Chapter III. Finally in Chapter IV, important conclusions of the study are given.

CHAPTER 2

EXPERIMENTAL PROGRAM

In one of the previous studies carried out by Erdem et al [23] at METU Structural Mechanics Laboratory, CFRP was used to strengthen a model structure having hollow clay tile infill. CFRP strips were bonded on this hollow clay tile infill and were extended to the frame elements. The connection between the CFRP strip and the frame elements were achieved by CFRP anchor dowels (Figure 2.1). This study revealed that, although they are not the investigated parameters, the number and configuration of CFRP anchor dowels have a great effect on the behavior of CFRP application in strengthening. At the end of this study, the followings were recommended [23]:

- "Proper use of CFRP anchor dowels will lead to higher capacities with the strengthening,"
- "The quality and number of the CFRP anchor dowels should be increased,"
- "The application and design of the CFRP anchor dowels should be investigated."

In the present study, only the tensile capacity of the CFRP anchor dowels was investigated. Test elements and anchor specimens were prepared in order to observe the tensile capacity of a single adhesively bonded CFRP anchor dowel.

2.1 TEST SPECIMENS

2.1.1 Concrete Beams

In order to obtain the direct tensile load capacities of CFRP anchor dowels, 4 m long concrete beams with no lateral reinforcement, were used. For this purpose, three concrete beams were constructed. All of the concrete beams have a cross-section of 300 × 400 mm (Figure 2.2). As previously mentioned, one of the parameters investigated in this study was the concrete compressive strength. These concrete beams have three different 28 day compressive strengths, 10 MPa, 16 MPa and 20 MPa. In Figure 2.3, detail of these concrete beams is given.

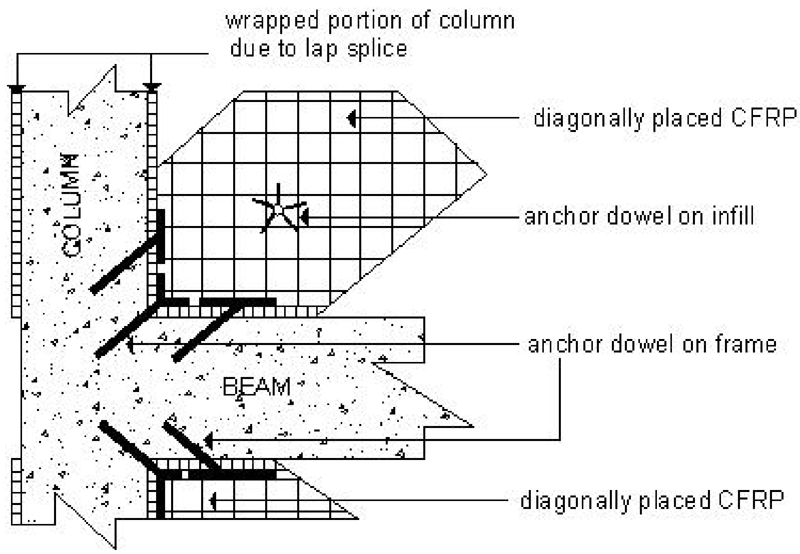

Figure 2.1 Application of CFRP anchor dowels in strengthening

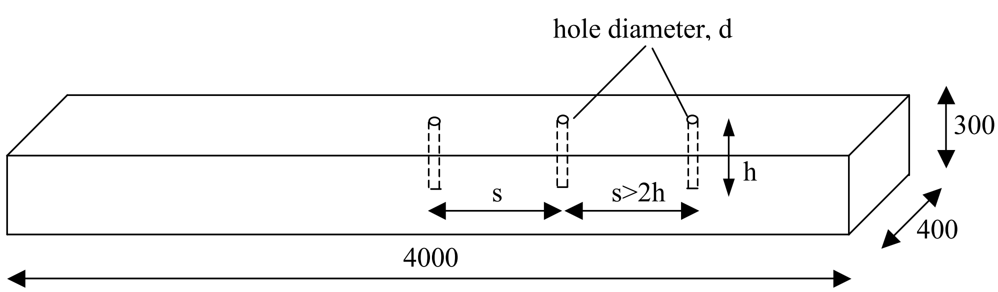

Figure 2.2 Schematic view of the concrete beam and installed anchor dowels (All dimensions are in mm)

Figure 2.3 Reinforcement detail of the beam

2.1.2 CFRP Anchor Dowels

CFRP anchor dowels were prepared using three different sheet widths (*w*) of 80 mm, 120 mm and 160 mm. During the preparation of CFRP anchor dowels, two distinct techniques were used namely Type 1 and Type 2.

2.1.2.1 Type 1

In the first series of tests, CFRP sheets were cut into two layers of equal width and equal height. Then, these soft CFRP sheets (Figure 2.4a) were rolled to have a cylindrical form (Figure 2.4b) with applying epoxy. To prevent the CFRP sheet bundle deviating from its cylindrical shape, rolled sheets were tied with CFRP fibers. CFRP sheets became ready to be used as an anchor dowel after 1 cm portion from the bottom of the rolled CFRP sheet is embedded into the epoxy resin and waited for one day (Figure 2.4b). The aim of the epoxy coated bottom part of the CFRP anchor dowel is to have a stiff part to maintain ease in installation. During the installation procedure, CFRP anchor dowels are pushed from the hardened end into the drilled and carefully cleaned holes by using a rod. All of the holes were cleaned by an air pump. After pouring enough epoxy resin into the clean, dry anchor hole, epoxy coated end of the CFRP anchor dowel was embedded into the concrete as seen in Figure 2.5a. The bond free part of the CFRP anchor dowel was also perfectly bonded to a steel rod to apply a tensile force (Figure 2.5b). The bond length of CFRP sheet bonded to tension steel rod is chosen so that it is enough to prevent sliding from the rod. A plane bar is used as tension steel rod and to prevent sliding, the bond length should be at least two times the embedment depth. Bond lengths less than embedment depths failed as slip from the steel rod. Another precaution to prevent the slip of CFRP sheet from tension steel was to use pipe clips along the bonded part. They were tightened to provide full bond between CFRP sheet and steel rod. These steel rods are used to transfer the applied load to the CFRP anchor dowel and it is not prolong into the hole. The diameter of the steel rod is chosen in such a way that it did not change the diameter of the cylindrical CFRP anchor dowels. Thus the outer diameter, as well as the inner diameter of the CFRP anchor dowel was achieved to be constant through its bonded lengths. During the curing of epoxy stiffener, a small amount of pre-loading was applied on the CFRP anchor dowels through the steel rod. Purpose of applying a small amount of pre-loading is to minimize the eccentricity along the CFRP anchor dowel during the loading process and to achieve a straight anchor dowel, i.e. to prevent any bulging just above the concrete surface.

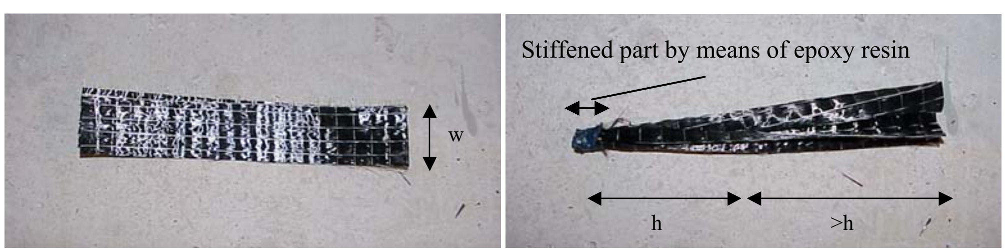

Figure 2.4 a)CFRP sheet (left) and b)CFRP anchor dowel (right)

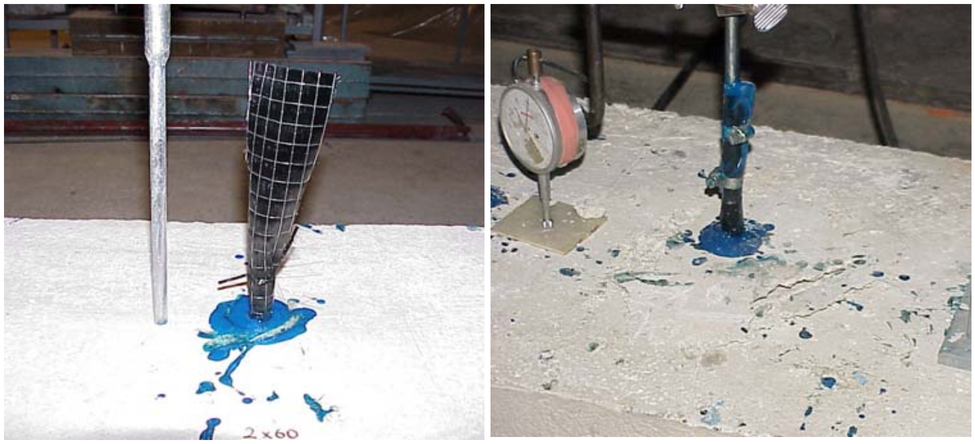

Figure 2.5 a)Anchor dowel in the concrete, b)Anchor dowel bonded to steel

2.1.2.2 Type 2

In the second type of anchors, the CFRP anchor dowels are prepared completely out of the hole and then installed into the concrete. This technique was developed after the first series of tests. In this technique, first the desired width of CFRP sheet is cut and coated with epoxy resin (Figure 2.6). Then, the epoxy coated CFRP sheet is bonded to the steel rod, through which the tensile load is applied, by rolling the sheet around the silicon rod through full embedment length of the CFRP anchor dowel (Figure 2.7). This technique is improved to have straight anchor dowels in which the fibers of the CFRP sheets are oriented in the same alignment. For this purpose, the same diameter steel and silicon rods were used while CFRP sheet was rolled around the steel and silicon rod (Figure 2.8). In these CFRP anchor dowels, there was minimal gap between steel and silicon rod. Then, the portion of the CFRP anchor dowel that is bonded to steel rod is tightened by carbon fibers to prevent slip failure (Figure 2.9). With the experiences gained through the first series of tests, deformed bars were used to transfer applied load to the CFRP anchor dowels instead of plane bars in this second technique. In most of the tests conducted with Type 2 CFRP anchor dowels bonded to plane bar ended with slip failure, which has no meaning in this study. To eliminate this undesired situation, the bond surface length was increased by choosing deformed bar as tension bar. The part of the anchor dowel that is rolled around the silicon rod is embedded into the drilled hole and bonded there. The length of the part rolled around the silicon rod is slightly longer than the embedment depth of the anchor. The reason why it is chosen longer is to prevent formation of less strength section at the nozzle of the hole where there can be stress concentration.

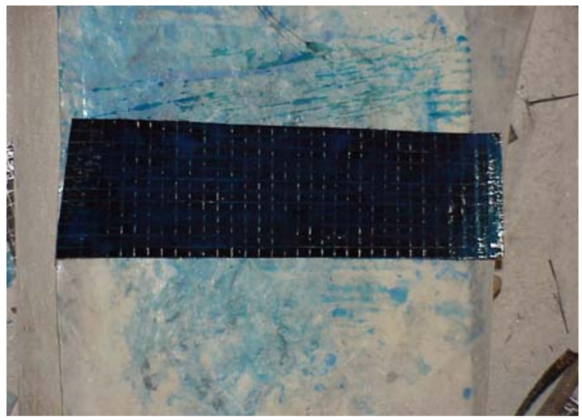

Figure 2.6 Epoxy coated CFRP sheet

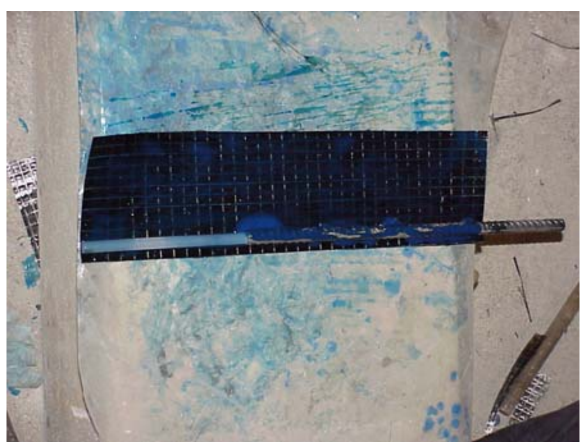

Figure 2.7 CFRP sheet is going to be rolled around silicon and steel rods

Figure 2.8 CFRP sheet is bonded to either of the steel or silicon rods

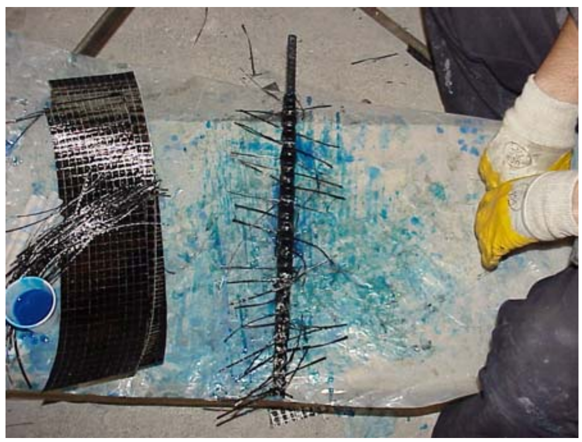

Figure 2.9 CFRP anchor dowel is tightened with carbon fibers

2.2 MATERIALS

2.2.1 Concrete

The concrete for the beam specimens were prepared in METU-Structural Mechanics Laboratory. Three different mixture designs were used aiming three different 28-day concrete compressive strengths. The mix proportions for the beams with 10 MPa, 16 MPa and 20 MPa compressive strengths are given in Table 2.1. In order to determine the compressive strength of the beams, standard cylindrical test specimens were prepared. Cylinders of 150 mm in diameter and

300 mm in height were used. These tests were also carried out in Structural Mechanics Laboratory. The averages of 28-day compressive strengths are given in Table 2.2. In this table, the minimum and maximum values of test day compressive cylinder test results are also presented. Concrete specimens and cylindrical specimens were cured at the room temperature to get its strength. Curing of the concrete was done by sprinkling for the test specimens and for the cylinder specimens.

Table 2.1 Mixture Proportions for 10 MPa, 16 MPa, and 20 MPa compressive strengths (for 1 m^3 concrete).

	10 MPa		**16 MPa**		**20 MPa**	
Material	**Mass (kg)**	**Proportion of weight (%)**	**Mass (kg)**	**Proportion of weight (%)**	**Mass (kg)**	**Proportion of weight (%)**
Cement	305	11.9	268	10.4	312	11.9
0-3 mm aggregate	487	19.1	1192	46.4	499	19
3-7 mm aggregate	973	38	848	33	998	38.1
7-15 mm aggregate	512	20	-	-	531	20.2
Water	281	11	262	10.2	281	10.8
Total	2558	100	2570	100	2621	100

Table 2.2 Results of cylinder compression tests

Specimen	**28 day f_c (MPa)**	**Test day f_c (MPa)**
1^{st} beam	10.7	10.7-11.3
2^{nd} beam	15.8	15.8-16.4
3^{rd} beam	19.4	19.4-20.1
4^{th} beam	10.2	10.2-10.5
5^{th} beam	16.3	16.3-16.5

2.2.2 Carbon Fiber Reinforced Polymer (CFRP)

In this study, MBrace produce C1-30 unidirectional fiber sheets were used. CFRP anchor dowels were composed of an epoxy based matrix and C1-30 carbon fibers. A two component, room temperature cure epoxy resin adhesive, namely saturant, is used as the component of the CFRP. Mechanical properties of C1-30 carbon fiber sheets and epoxy used in this experimental program are given in Tables 2.3 and 2.4, respectively.

Table 2.3 Mechanical Properties of C1-30 Carbon Fibers (provided by MBrace)

Property	Amount	Unit
Unit Weight	0.300	kg/mm^2
Effective Thickness	0.165	mm
Characteristic Tensile Strength	3,430	MPa
Characteristic Elasticity Modulus	230,000	MPa
Ultimate Strain	0.015	mm/mm

Table 2.4 Mechanical Properties of Adhesive (provided by MBrace)

Property	Amount
Compressive Strength	>80 MPa
Direct Tensile Strength	>50 MPa
Flexural Tensile Strength	>120 MPa
Elasticity Modulus	>3000 MPa
Ultimate Strain	>0.025

Adhesive anchor dowels transfer the load through the adhesive layer along the bond surface. Therefore, the important points for an adhesive anchor dowel are the quality and type of the adhesive. An epoxy adhesive is a synthetic compound consisting of an epoxy resin cross-linked with a curing agent. The epoxy resin is designated as compound A and the curing agent as compound B by the manufacturer. Epoxy adhesives are thermosetting polymers; that is, they require heat to cure. This heat is generated during the exothermic reaction between the epoxy resin and the curing agent. Epoxy adhesives are durable, have a long life, and undergo almost no shrinkage during curing. [3-6].

In the literature, there are different application techniques of adhesively bonded anchor dowels. In Figure 2.10 different types of adhesive anchor systems and types of adhesives are given. In this experimental study, for both of the anchor types, an injection type adhesive anchor application was chosen. Before the installation of the anchor dowel, a catalyzed resin is injected into the hole and then the anchor dowel is pushed into the hole.

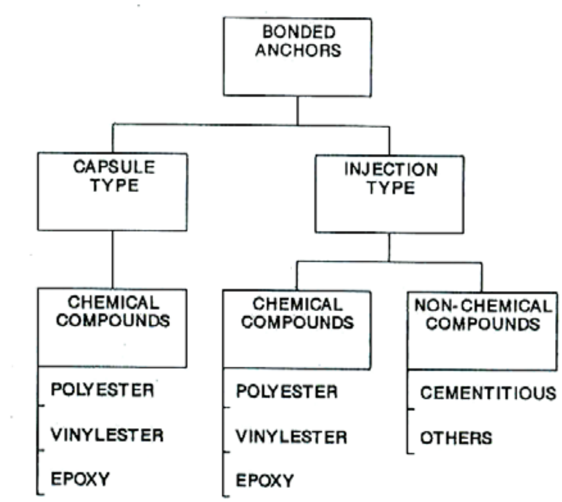

Figure 2.10 Typical types of adhesive anchor systems and types of adhesives [5]

While determining the tensile capacity of the CFRP anchor dowels, strength of CFRP composite should be evaluated rather than strength of C1-30 carbon fiber itself. For this reason, coupon tests were carried out to determine the tensile strength of the CFRP. These tests were conducted at METU-Materials and Construction Laboratory in previous studies [28] using the same type of carbon fibers and epoxy resin. Strips of 300×25 mm were prepared with a total thickness of 1.2 mm. The gage length during the tests was 165 mm. The maximum tensile strength of the CFRP sheet was obtained as 650 MPa with an ultimate strain of 0.01 mm/mm.

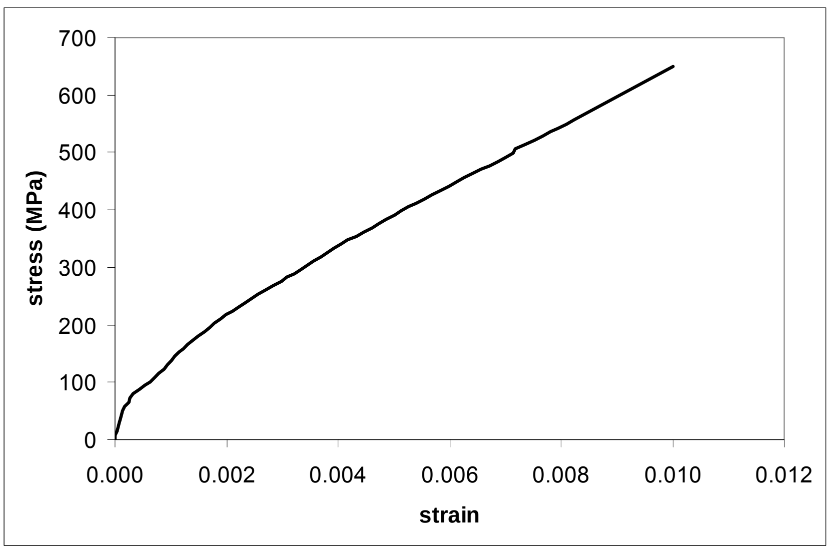

Figure 2.11 Result of coupon tests (Taken from [28])

2.3. INSTRUMENTATION AND TEST PROCEDURE

2.3.1 TEST SETUP

The steel frame which is prepared to apply a tensile force to the embedded anchor dowel is made of U-200 type steel section. The beam of the steel frame is 1 m long and was made up of two U-200 sections. These sections were placed back to back with a spacing between each other (Figure 2.12). These sections were fixed together using two bolts. This beam was placed on two columns having heights of 50 cm. These columns were also made up of two U-200 sections (Figure 2.13), which were welded together to form a box section. Beam was connected to the column by welding. The yield strength of these steel members is 500 MPa. The constructed loading frame is given in Figure 2.14.

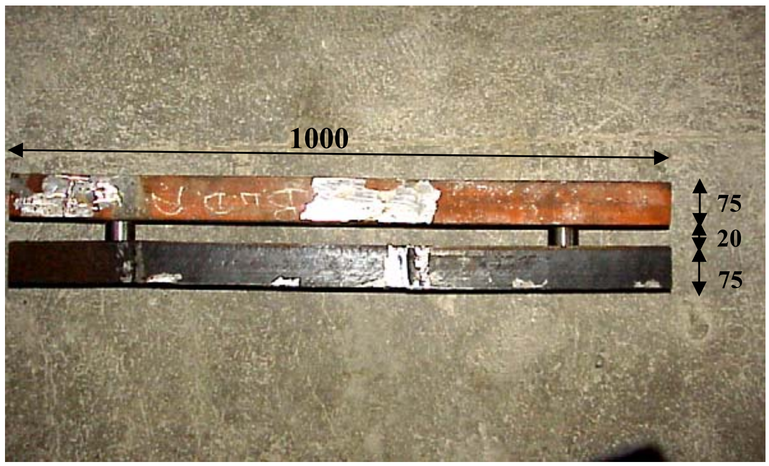

Figure 2.12 Two back-to-back connected U-sections (All dimensions are in mm)

Through the spacing between two U-200 steel sections seen in Figure 2.12, a steel rod is extended from the top of the load cell towards to bottom part of the loading frame. Between the load cell and the loading frame, a hollow core hydraulic jack is placed. The load was applied by means of hydraulic jack and the load was measured by means of the load cell. Capacity of the load cell was 200 kN. Applied load was transferred to the CFRP anchor dowels through the steel rod extending along the loading equipments. The elongations of the CFRP anchor dowels were measured by using a dial gage between the concrete block surface and bond free end of the anchor dowel. The load cell and the dial gage were connected to a data acquisition system.

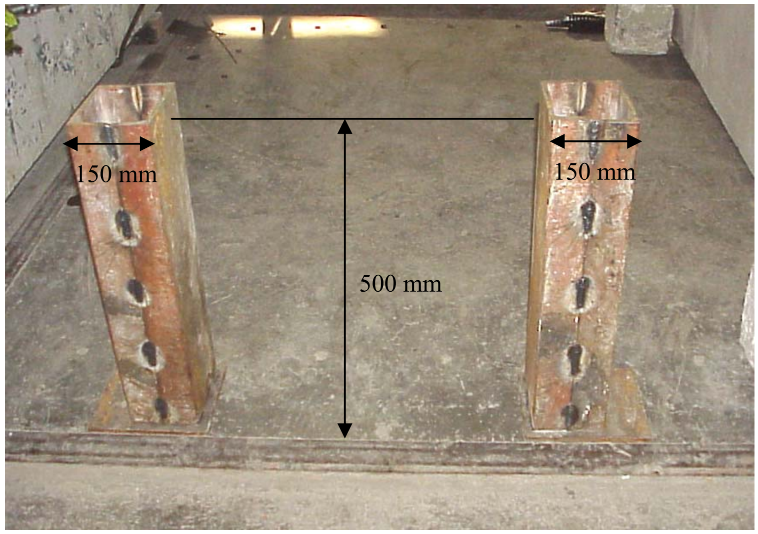

Figure 2.13 Two welded U-sections as columns

Figure 2.14 Loading frame

It is known that the capacity of an anchor dowel would increase if it is tested in a confined concrete block. The applied compression force exerted through the loading frame to form a tensile load in the anchor dowel will lead to higher bond capacity between the anchor and concrete block. To prevent this phenomenon, namely confinement effect, the loading frame was constructed in such a way that the loading does not affect the behavior of the anchor dowel. Since, the tension load was applied to the anchor dowels by applying compressive force to the concrete block by means of the columns of loading frame, the distance between two columns of loading frame is chosen far enough from the anchor dowels. In addition, the loading was applied at the middle of the loading frame to provide equal forces at each column. The schematic view of the test setup is given in Figure 2.15 while a picture of it is given in Figure 2.16.

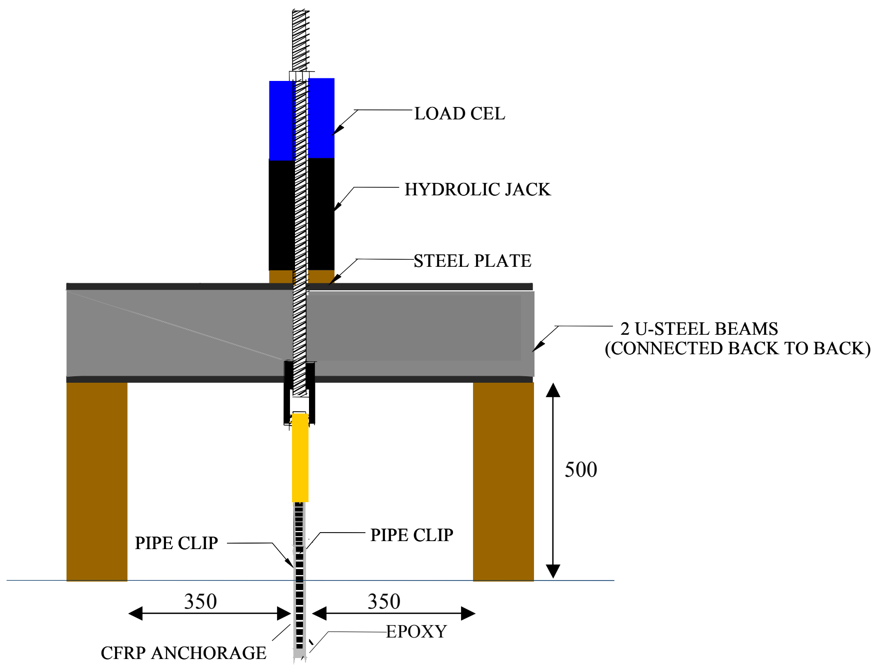

Figure 2.15 Test Setup (Dimensions are in mm)

Figure 2.16 Picture of the Test setup

CHAPTER 3

GENERAL BEHAVIOR OF ADHESIVE ANCHOR DOWELS UNDER TENSILE LOADS AND TEST RESULTS

Tensile capacity of an anchor dowel is limited with the tensile capacity of the concrete or with the tensile capacity of the anchor dowel itself. For both of the cases, there are numerous methods to determine the capacity of the anchor dowels. For the case in which the strength of the concrete is the main parameter to determine the capacity of the anchor dowel (shallow anchors), some of the available methods are namely concrete capacity (CC) method and 45-degree cone method. It should not be forgotten that all of the expressed models are based on some similar assumptions to simplify the calculations. One of these assumptions is the distance criteria between neighboring anchor dowels. The details about these methods are given in the part in which failure modes are described. To determine the capacity of a single anchor dowel, the spacing (s) between successive anchor dowels should be at least equal to twice of the embedment depth. Satisfying this criterion, the interaction between two different anchor dowels and most importantly, multiple anchor effect is eliminated.

As discussed in the literature survey, it has been seen that the anchor performance is related to the depth of the anchor dowel for an adhesive anchor dowel [3-6]. Throughout the tests performed with adhesive steel anchors and with CFRP sheets bonded to a surface by means of adhesives, researchers stated that the optimum depth of an adhesive anchor dowel is more or less 100 mm depending on the chosen parameters [3-6,9]. This depth is generally found out to obey the assumption of uniformly distributed bond stress. Beside the uniform stress distribution, researchers also showed that the behavior of an adhesive steel anchor dowel can be given by elastic stress distribution through the embedment depth. Most of the experimental studies conducted in the literature confirm that the tensile capacity of the bonded anchors does not increase after a critical depth. This depth is called effective depth. Expecting a similar behavior for adhesive CFRP anchor dowels, the embedment depths were chosen as 70, 100 and 150 mm to inspect the change in capacity of anchor dowels due to increase in embedment depth.

The load transfer between the anchor dowel and resin depends mainly on adhesion for an adhesive anchor dowel. Therefore, before the bonding process, anchor holes were cleaned carefully to achieve full adhesion between concrete and epoxy resin. To achieve this, compressed air was used to clean the bond surface. In addition to compressed air, bond surface was also cleaned by means of a wet tissue. It is important to have clean and dry holes before installation of CFRP anchor dowels to have a perfect bond between concrete and anchor. All of the holes are drilled vertically by means of rotator drilling process. The hole diameters were chosen to be greater than the anchor diameters at least with an amount of 2 mm to provide enough space for bonding. Having finished the drilling and cleaning processes, bonding the anchor dowel to the concrete was achieved by epoxy resin.

In this chapter, test results and observations made during the tests are presented. Before starting the presentation of the test results, observed failure modes are listed to give an idea about the failure mechanism of an adhesive CFRP anchor dowels. After the discussion about the failure modes, the test results are presented for Type 1 and Type 2 CFRP anchor dowels.

3.1 GENERAL BEHAVIOR OF ADHESIVE ANCHOR DOWELS

As well as the ultimate load capacity, another parameter that is proportional with the embedment depth of the anchor dowel is the failure type. One of the most important key parameters that should be taken into account during the design of an anchor dowel is the understanding of its behavior. Understanding anchor behavior is necessary in specifying the appropriate anchorage for a given application. This includes an understanding of failure modes and strength as well as load-displacement characteristics of various anchor types. In this section, the behavior of adhesive anchors is discussed.

3.1.1 FAILURE MODES

Anchors are primarily loaded through attachments to the embedded anchor dowels. The loading can be in tension and/or shear. They may also be subjected to bending depending on the details of shear transfer through the attachment. The behavior and failure modes of anchors in tension are of primary importance in this study.

There are four primary failure modes for adhesive anchor dowels which are subjected to pure tensile loading. These are

a) Anchor failure,
b) Concrete splitting failure,
c) Concrete cone failure,
d) Pull-out failure,
e) Spacing and edge cone failure.

The above mentioned failure types are schematically given in Figure 3.1.

3.1.1.1 Anchor Failure

The strength of anchor dowel controls failure when the embedment depth of the anchor is sufficient to preclude concrete failure and when the spreading forces are sufficiently high or the bearing area is sufficiently large to preclude an anchor slip failure. The failure mode (Figure 3.1a) is rupture of the anchor dowel with ductility dependent on the type of anchor and embedment depth. The ultimate strength can be determined by

$$F_u = A \times \sigma_{ult} \tag{3.1}$$

where A= tensile stress area,

σ_{ult} = ultimate tensile strength of anchor.

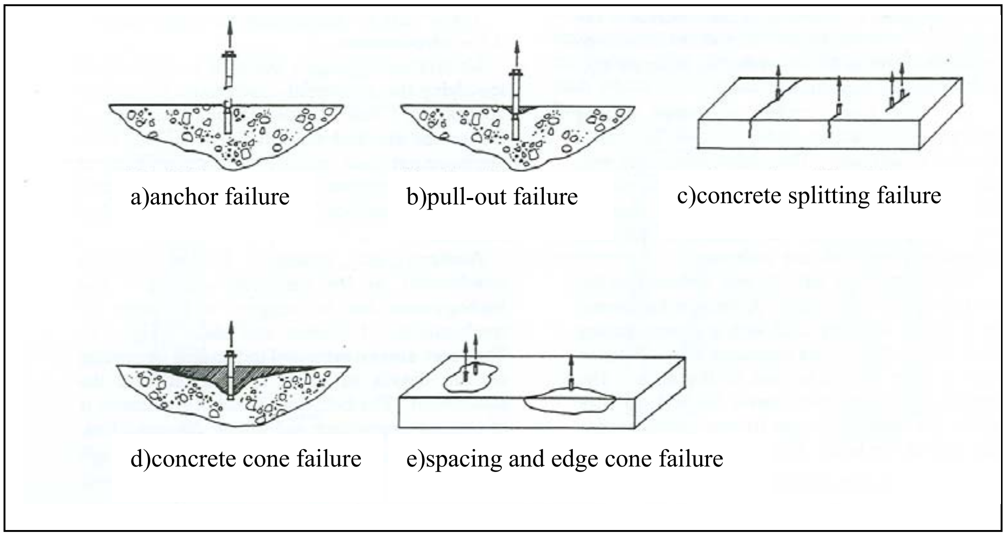

Figure 3.1 Typical failure modes of adhesive anchors loaded in tension [26]

For given material properties and anchor dimensions, this case defines the upper limit for the tensile load carrying capacity. If the embedment depth of the anchor dowel is sufficient enough so that the anchor would not fail due to tensile strength of concrete, then the corresponding failure is shown in Figure 3.2. In this type of failure behavior, the anchor dowel reaches to its maximum tensile capacity under the applied direct tension load. Since CFRP is a brittle material, this failure is very brittle.

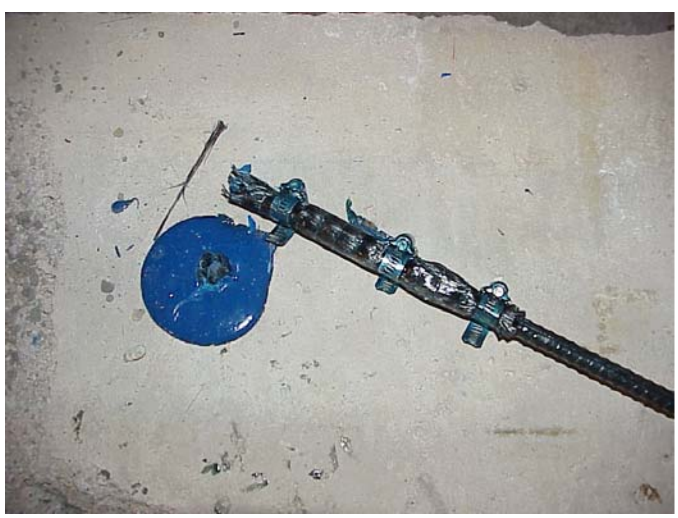

Figure 3.2 CFRP failure

3.1.1.2 Splitting Failure of Concrete

Splitting failure is characterized by the propagation of a crack in a plane containing the anchor. This failure mode will occur only if the dimensions of the concrete are too small, the anchors are placed too close to an edge or too close to each other (Figure 3.1c). The failure load is usually smaller than for a concrete cone failure. This type of failure has not been seen after taking necessary precautions to prevent it.

3.1.1.3 Concrete Cone Failure

When anchor load is transferred to concrete through bond development, maximum stress occurs near the surface and diminishes with depth. If the embedment depth of an anchor dowel is insufficient to develop the tensile strength of the anchor, then a pullout cone failure of the concrete is the expected failure mode (Figure 3.1d). In addition, when the spacing of anchors or location of an edge (Figure 3.1e) interfaces with the development of the full cone strength of an anchor, its capacity is reduced. Consequently, for the anchors, which do not have sufficient embedment depth to provide the failure of anchor itself, tensile capacity of the anchor dowel is limited with the cone capacity. For the case in which the tensile strength of the concrete is the main parameter to determine the capacity of the anchor dowel (shallow anchors), some of the methods which are widely accepted, are namely CC (concrete capacity) method and 45-degree cone method. It should not be forgotten that all of the expressed models are based on some similar assumptions to simplify the calculations. One of these assumptions is the spacing between neighboring anchor dowels. To eliminate the interaction between neighboring anchor dowels, the spacing (s) between successive anchor dowels are chosen at least equal to twice of the embedment depth.

In agreement with the definitions given above, when the embedment depth is shallow, the observed failure is due to tensile capacity of the concrete. In Figure 3.3, a picture of the concrete cone failure observed during the tests is given for an embedment depth of 50 mm.

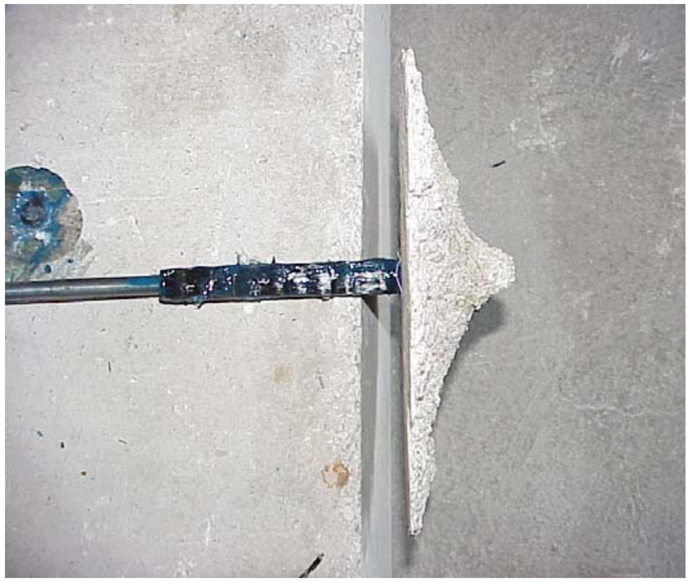

Figure 3.3 Concrete cone failure

3.1.1.4 Pullout Failure

Pullout failure (Figure 3.1b) is a typical failure mode for wedge anchors at moderate to deep embedment depths in lower strength concrete where the crushing of the concrete at the wedges allows the anchor dowel to pull through. The pullout capacity of adhesive anchors increases with increasing embedment depth. However, after a depth that is approximately equal to nine anchor diameters, the increase is not proportional to embedment depth [27]. This is due to high bonding effect resulting in high load transfer to the concrete at the top of the anchor. The bond stress is no longer uniform, and if the tensile load is sufficiently high, the failure initiates with a concrete failure in the upper portion of the concrete and then the bond fails in the remainder of the embedment depth. The bond stress distribution along the embedment depth of the anchor dowel prior to failure is given in Figure 3.4.

This failure type has been seen in some of the experiments done in this study. Figures 3.5 and 3.6 show the pictures of a pullout failure together with a slip and a concrete cone at the top. In Figure 3.5, the failure area can be seen clearly. This figure shows the importance of the spacing between neighboring anchor dowels. It is obvious that the anchors, which are too close to each other, can not provide the full capacity of the concrete.

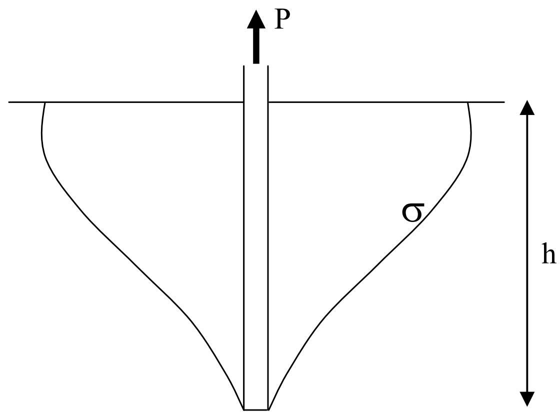

Figure 3.4 Bond stress distribution along embedment depth of the anchor

Figure 3.5 Pullout failure of CFRP anchor dowel

Figure 3.6 shows the inner part of the failed anchor dowel inside the crushed concrete. For this specific anchor dowel, embedment depth was 70 mm. At the upper part, near the surface, there occurs a shallow concrete cone with an approximate depth of 50 mm. The remaining 20 mm part fails due to slip of the anchor dowel from the concrete. Therefore, one can conclude that, the excessive amount of tensile load causes a bond failure between the epoxy resin and the concrete surface after the concrete cone has occurred.

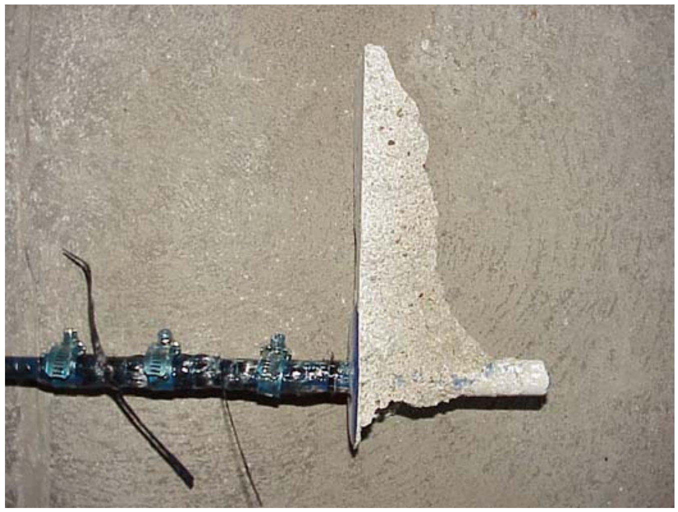

Figure 3.6 Side view of the failed CFRP anchor dowel

3.2 PREDICTION of TENSILE CAPACITY of CFRP ANCHOR DOWELS

After giving some detail about the failure mechanism of adhesive anchors, the prediction of tensile capacities of adhesive CFRP anchor dowels is going to be studied now. It will be better to start with the calculation of the tensile capacity of carbon fibers used in the preparation of CFRP anchor dowels. Tensile capacity of carbon fibers can be calculated using the following equation.

$$P_{FRP} = w \times t \times f_u \text{ (N)} \tag{3.2}$$

In equation 3.2, *w* is the width of the CFRP sheet, *t* is the thickness of the CFRP sheet in mm, and f_u is the characteristic tensile strength of the carbon fibers in terms of MPa. As it is given in Table 2.3, t is equal to 0.165 mm, and f_u is equal to 3,450 MPa.

One may want to compute the tensile capacity of the carbon fibers after the application of epoxy resin to the carbon fibers. This time, they form a composite material which has a stress-strain relation given in Figure 2.8. The maximum tensile stress is obtained as 650 MPa from this figure. The tensile capacity of this composite can be computed by equation 3.3 with the assumption that thickness is equal to 1.2 mm.

$$P_{CMPST} = w \times 1.2 \times 650 \text{ (N)} \tag{3.3}$$

Equations 3.2 and 3.3 are based on the capacity of the carbon fibers in a chosen sheet width. Similarly, the tensile capacity of CFRP anchor dowels can be calculated approximately by using the tensile capacity of the concrete, which is the typical case for second series of tests. By the help of the failure types discussed previously, tensile capacity of concrete can be computed by using a concrete cone which has a tensile strength of $0.33\sqrt{f_c}$. The tensile capacity of the concrete cone (Figure 3.7) can be calculated as:

$$P_{CONE} = 0.33\sqrt{f_c} \times h \times (d + h)\pi \qquad h < 50 \text{ mm}$$

$$P_{CONE} = 0.33\sqrt{f_c} \times 50 \times (d + 50)\pi + \tau_{ave} \times \pi \times d(h - 50) \qquad h > 50 \text{ mm} \tag{3.4}$$

In equation 3.4, f_c is concrete compressive strength, h is embedment depth of anchor dowel, d is hole diameter, and τ_{ave} is the average shear stress of the concrete through the embedment depth. In [26], it is stated that the average shear stress should be taken as 9 MPa for a concrete with 20 MPa compressive strength. In the light of this statement, τ_{ave} is taken as 4.5 MPa, and 7.2 MPa for concrete compressive strengths of 10 MPa and 16 MPa, respectively.

As it is seen from equation 3.4, for embedments deeper than 50 mm, P_{CONE} is added a new term to represent the bond failure after the 50 mm cone has occurred. The concrete cone depth is taken as 50 mm for all embedment depths based on experimental observations. The details about choosing the concrete cone depth as 50 mm will be discussed in the second part of the test results.

Equation 3.4 is obtained for a concrete cone with crack angle of 45 degrees. One may want to change these equations into a form in which the angle of crack pattern is also a variable. In that case, these two equations take the following forms.

$$P_{CONE} = 0.33\sqrt{f_c}\left(d + \frac{h}{\tan\theta}\right)\frac{\pi h}{\sin\theta} \qquad h < 50\,\text{mm}$$

$$P_{CONE} = 0.33\sqrt{f_c}\left(d + \frac{50}{\tan\theta}\right)\frac{\pi \times 50}{\sin\theta} + \tau_{ave} \times \pi d \times (h - 50) \qquad h > 50\,\text{mm} \qquad (3.5)$$

To normalize the ultimate tensile capacities obtained from tests, the capacity calculated by equation 3.2 is used. All the tensile capacities are normalized with the capacity of carbon fibers that have the same sheet width with the anchor dowels.

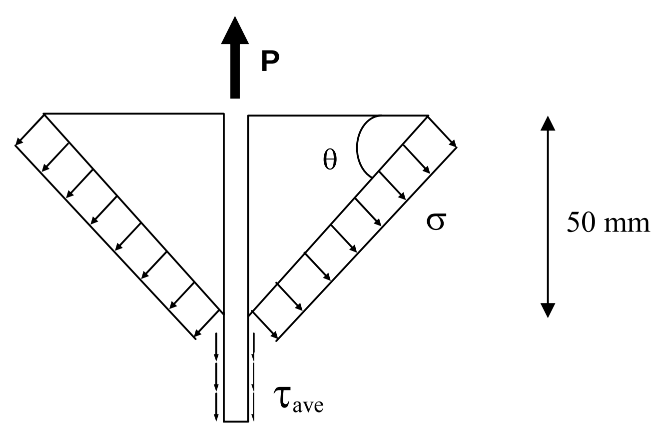

Figure 3.7 Stress distribution along the embedment depth of the anchor dowel

3.3 TEST RESULTS

3.3.1 Testing Scheme

The test results are going to be presented in two parts. In the first set of tests, 153 tests were conducted with three different concrete compressive strengths. However, the results of 127 tests are taken into consideration. The remaining 26 tests are excluded because of the undesired failures (slip from steel rod, and improper adhesive mixture) of the anchor dowels. In the following three tables, the distribution of the number of tests performed in the first set is given in detail.

In Table 3.1, number of tests carried out for different anchor hole diameters is given for a concrete compressive strength of 10 MPa. A total of 28 tests were performed for this concrete block.

Similarly, Table 3.2 presents number of tests conducted in a concrete with a compressive strength of 16 MPa. 42 tests were performed in this concrete block with three different anchor hole diameters of 12 mm, 14 mm, and 16 mm.

Table 3.1 Testing scheme for 10 MPa concrete compressive strength with three different anchor hole diameters (first series of tests).

		w in mm		
		80	120	160
h in mm	70	1	1	1
	100	1	1	1
	150	1	1	1

a) d=12 mm

		w in mm		
		80	120	160
h in mm	70	1	1	1
	100	1	1	1
	150	1	1	2

b) d=14 mm

		w in mm		
		80	120	160
h in mm	70	1	1	1
	100	1	1	1
	150	1	1	1

c) d=16 mm

A total of 47 tests were performed in a concrete block with compressive strength of 20 MPa. The distribution of the number of performed test for three different anchor hole diameters of 12 mm, 14 mm, and 16 mm is given in Table 3.3.

Table 3.2 Testing scheme for 16 MPa concrete compressive strength with three different anchor hole diameters (first set of tests).

		w in mm		
		80	120	160
h in mm	70	2	1	2
	100	1	2	1
	150	2	2	1

a) d=12 mm

		w in mm		
		80	120	160
h in mm	70	1	2	1
	100	2	2	1
	150	1	1	2

b) d=14 mm

		w in mm		
		80	120	160
h in mm	70	1	2	2
	100	3	3	1
	150	4	2	2

c) d=16 mm

Table 3.3 Testing scheme for 20 MPa concrete compressive strength with three different anchor hole diameters (first set of tests).

		w in mm		
		80	120	160
h in mm	70	2	2	1
	100	3	4	2
	150	6	1	1

a) d=12 mm

		w in mm		
		80	120	160
h in mm	70	1	1	1
	100	1	4	2
	150	1	1	1

a) d=14 mm

		w in mm		
		80	120	160
h in mm	70	1	4	2
	100	1	2	3
	150	2	1	1

a) d=16 mm

Number of available test results for the second series of tests in which the anchor dowels are prepared with a different technique, explained in Chapter II in detail, are presented in Table 3.4. For all of the anchor specimens tested in this second series, the CFRP sheet width was same for all specimens and equal to 120 mm. Hole diameter was 20 mm. Here, 17 tests were performed for two different compressive strengths of 10 MPa and 16 MPa. In this set of data, an additional embedment depth (h=50 mm) was chosen to reflect the behavior of the anchor that depends on the concrete failure.

Table 3.4 Testing scheme for 10 MPa and 16 MPa concrete compressive strengths for a sheet width of 120 mm (second series of tests).

	Number of Tests*	
Embedment depth (h)	**Compressive strength (f_c) = 10 MPa**	**Compressive strength (f_c) = 16 MPa**
50	3	2
70	3	3
100	3	3
150	3	3

*: CFRP sheet width (w) is 120 mm, anchor hole diameter (d) is 20 mm for all specimens

3.3.2 Test Results (Part 1)

In accordance with the previous part of this chapter, the test results are also given in two different tables. In Table 3.5, presented test results belong to first set of data. The properties of the CFRP anchor dowels are given under the name of identification of the performed tests in the first column of the table. Here, w is CFRP sheet width, h is embedment depth of CFRP anchor dowel, f is the 28 day compressive cylinder strength of the concrete, and d is the diameter of the anchor hole. In Table 3.5, the ultimate load capacities of each CFRP anchor dowels are given in kN. These ultimate tensile load capacities are normalized with the ultimate capacity of the carbon fibers obtained from equation 3.2 by using the specifications provided by the manufacturer. Table 3.5 also specifies the failure types of the CFRP anchor dowels corresponding to the observed failure loads.

Table 3.5 Results of first series of tests with the failure types and normalized values according to the capacity of the carbon fibers.

Identification of the performed tests	Ultimate tensile load applied to the anchor dowel (kN)	Ratio of the ultimate load to the capacity of carbon fibers	Failure Type
w80***h***70***f***10***d***12	18.7	0.41	CFRP rupture
w80***h***70***f***10***d***14	20.0	0.44	CFRP rupture
w80***h***70***f***10***d***16	16.4	0.36	CFRP rupture
w80***h***70***f***16***d***12	13.0	0.29	CFRP rupture
w80***h***70***f***16***d***12	20.1	0.44	CFRP rupture
w80***h***70***f***16***d***16	22.5	0.49	CFRP rupture
w80***h***70***f***20***d***12	12.8	0.28	CFRP rupture
w80***h***70***f***20***d***12	14.2	0.31	CFRP rupture
w80***h***70***f***20***d***14	16.4	0.36	CFRP rupture
w80***h***70***f***20***d***16	16.2	0.36	CFRP rupture
w80***h***100***f***10***d***12	25.4	0.56	CFRP rupture
w80***h***100***f***10***d***14	15.1	0.33	CFRP rupture
w80***h***100***f***10***d***16	16.4	0.36	CFRP rupture
w80***h***100***f***16***d***12	23.9	0.52	CFRP rupture
w80***h***100***f***16***d***14	15.7	0.34	CFRP rupture
w80***h***100***f***16***d***14	25.2	0.55	CFRP rupture
w80***h***100***f***16***d***16	17.7	0.39	CFRP rupture
w80***h***100***f***16***d***16	17.8	0.39	CFRP rupture
w80***h***100***f***16***d***16	24.3	0.53	CFRP rupture
w80***h***100***f***20***d***12	24.1	0.53	CFRP rupture
w80***h***100***f***20***d***12	25.2	0.55	CFRP rupture
w80***h***100***f***20***d***12	22.0	0.48	CFRP rupture
w80***h***100***f***20***d***14	21.5	0.47	CFRP rupture
w80***h***100***f***20***d***16	19.6	0.43	CFRP rupture
w80***h***150***f***10***d***12	20.6	0.45	CFRP rupture
w80***h***150***f***10***d***14	21.1	0.46	CFRP rupture
w80***h***150***f***10***d***16	21.7	0.48	CFRP rupture
w80***h***150***f***16***d***12	12.4	0.27	CFRP rupture
w80***h***150***f***16***d***12	20.1	0.44	CFRP rupture
w80***h***150***f***16***d***14	19.3	0.42	CFRP rupture
w80***h***150***f***16***d***16	10.8	0.24	CFRP rupture
w80***h***150***f***16***d***16	12.3	0.27	CFRP rupture
w80***h***150***f***16***d***16	20.1	0.44	CFRP rupture
w80***h***150***f***16***d***16	27.4	0.60	CFRP rupture
w80***h***150***f***20***d***12	22.3	0.49	CFRP rupture
w80***h***150***f***20***d***12	20.2	0.44	CFRP rupture
w80***h***150***f***20***d***12	17.1	0.38	CFRP rupture
w80***h***150***f***20***d***12	16.2	0.36	CFRP rupture
w80***h***150***f***20***d***12	30.0	0.66	CFRP rupture
w80***h***150***f***20***d***12	24.4	0.54	CFRP rupture

Table 3.5 Results of first series of tests with the failure types and normalized values according to the capacity of the carbon fibers (continued).

Identification of the performed tests	Ultimate tensile load applied to the anchor dowel (kN)	Ratio of the ultimate load to the capacity of carbon fibers	Failure Type
w80***h***150***f***20***d***14	25.7	0.56	CFRP rupture
w80***h***150***f***20***d***16	12.3	0.27	CFRP rupture
w80***h***150***f***20***d***16	24.8	0.54	CFRP rupture
w120***h***70***f***10***d***12	17.1	0.25	CFRP rupture
w120***h***70***f***10***d***14	16.1	0.24	Pullout failure
w120***h***70***f***10***d***16	15.1	0.22	Pullout failure
w120***h***70***f***16***d***12	21.5	0.31	CFRP rupture
w120***h***70***f***16***d***14	24.6	0.36	CFRP rupture
w120***h***70***f***16***d***14	25.1	0.37	CFRP rupture
w120***h***70***f***16***d***16	18.4	0.27	Pullout failure
w120***h***70***f***16***d***16	20.6	0.30	CFRP rupture
w120***h***70***f***20***d***12	15.6	0.23	CFRP rupture
w120***h***70***f***20***d***12	25.1	0.37	CFRP rupture
w120***h***70***f***20***d***14	21.2	0.31	CFRP rupture
w120***h***70***f***20***d***16	14.7	0.22	CFRP rupture
w120***h***70***f***20***d***16	16.1	0.24	CFRP rupture
w120***h***70***f***20***d***16	21.5	0.31	Pullout failure
w120***h***70***f***20***d***16	26.0	0.38	CFRP rupture
w120***h***100***f***10***d***12	32.9	0.48	CFRP rupture
w120***h***100***f***10***d***14	29.3	0.43	CFRP rupture
w120***h***100***f***10***d***16	30.0	0.44	CFRP rupture
w120***h***100***f***16***d***12	17.5	0.26	CFRP rupture
w120***h***100***f***16***d***12	22.7	0.33	CFRP rupture
w120***h***100***f***16***d***14	19.0	0.28	CFRP rupture
w120***h***100***f***16***d***14	29.3	0.43	CFRP rupture
w120***h***100***f***16***d***16	17.5	0.26	CFRP rupture
w120***h***100***f***16***d***16	32.5	0.48	CFRP rupture
w120***h***100***f***16***d***16	35.5	0.52	CFRP rupture
w120***h***100***f***20***d***12	24.7	0.36	CFRP rupture
w120***h***100***f***20***d***12	27.5	0.40	CFRP rupture
w120***h***100***f***20***d***12	27.1	0.40	CFRP rupture
w120***h***100***f***20***d***12	28.6	0.42	Pullout failure
w120***h***100***f***20***d***14	16.6	0.24	CFRP rupture
w120***h***100***f***20***d***14	17.1	0.25	CFRP rupture
w120***h***100***f***20***d***14	31.4	0.46	CFRP rupture
w120***h***100***f***20***d***14	23.5	0.34	CFRP rupture
w120***h***100***f***20***d***16	19.1	0.28	CFRP rupture
w120***h***100***f***20***d***16	20.1	0.29	CFRP rupture

Table 3.5 Results of first series of tests with the failure types and normalized values according to the capacity of the carbon fibers (continued).

Identification of the performed tests	**Ultimate tensile load applied to the anchor dowel (kN)**	**Ratio of the ultimate load to the capacity of carbon fibers**	**Failure Type**
w120***h***150***f***10***d***12	21.3	0.31	CFRP rupture
w120***h***150***f***10***d***14	32.3	0.47	CFRP rupture
w120***h***150***f***10***d***16	12.2	0.18	CFRP rupture
w120***h***150***f***16***d***12	20.6	0.30	CFRP rupture
w120***h***150***f***16***d***12	20.9	0.31	CFRP rupture
w120***h***150***f***16***d***14	22.9	0.34	CFRP rupture
w120***h***150***f***16***d***16	21.0	0.31	CFRP rupture
w120***h***150***f***16***d***16	22.5	0.33	CFRP rupture
w120***h***150***f***20***d***14	35.2	0.52	CFRP rupture
w120***h***150***f***20***d***16	28.9	0.42	CFRP rupture
w160***h***70***f***10***d***12	19.1	0.21	Pullout failure
w160***h***70***f***10***d***14	17.9	0.20	Pullout failure
w160***h***70***f***10***d***16	19.2	0.21	CFRP rupture
w160***h***70***f***16***d***12	20.4	0.22	Pullout failure
w160***h***70***f***16***d***12	28.5	0.31	CFRP rupture
w160***h***70***f***16***d***14	21.9	0.24	CFRP rupture
w160***h***70***f***16***d***16	25.1	0.28	CFRP rupture
w160***h***70***f***16***d***16	23.0	0.25	CFRP rupture
w160***h***70***f***20***d***12	21.3	0.23	CFRP rupture
w160***h***70***f***20***d***14	23.1	0.25	CFRP rupture
w160***h***70***f***20***d***16	13.7	0.15	CFRP rupture
w160***h***70***f***20***d***16	20.7	0.23	CFRP rupture
w160***h***100***f***10***d***12	21.6	0.24	CFRP rupture
w160***h***100***f***10d14	30.8	0.34	CFRP rupture
w160***h***100***f***10***d***16	31.3	0.34	CFRP rupture
w160***h***100***f***16***d***14	28.5	0.31	CFRP rupture
w160***h***100***f***16***d***16	28.4	0.31	CFRP rupture
w160***h***100***f***20***d***12	32.8	0.36	CFRP rupture
w160***h***100***f***20***d***12	33.2	0.36	CFRP rupture
w160***h***100***f***20***d***14	27.2	0.30	CFRP rupture
w160***h***100***f***20***d***14	31.2	0.34	CFRP rupture
w160***h***100***f***20***d***16	16.7	0.18	CFRP rupture
w160***h***100***f***20***d***16	22.4	0.25	CFRP rupture
w160***h***100***f***20***d***16	35.6	0.39	CFRP rupture
w160***h***150***f***10***d***12	29.4	0.32	CFRP rupture
w160***h***150***f***10***d***14	22.3	0.24	CFRP rupture
w160***h***150***f***10***d***14	29.9	0.33	CFRP rupture
w160***h***150***f***10***d***16	25.3	0.28	CFRP rupture

Table 3.5 Results of first series of tests with the failure types and normalized values according to the capacity of the carbon fibers (continued).

Identification of the performed tests	Ultimate tensile load applied to the anchor dowel (kN)	Ratio of the ultimate load to the capacity of carbon fibers	Failure Type
w160***h***150***f***16***d***12	27.5	0.30	CFRP rupture
w160***h***150***f***16***d***14	19.0	0.21	CFRP rupture
w160***h***150***f***16***d***14	27.3	0.30	CFRP rupture
w160***h***150***f***16***d***16	14.8	0.16	CFRP rupture
w160***h***150***f***16***d***16	29.4	0.32	CFRP rupture
w160***h***150***f***20***d***12	22.5	0.25	CFRP rupture
w160***h***150***f***20***d***14	23.9	0.26	CFRP rupture
w160***h***150***f***20***d***16	25.5	0.28	CFRP rupture

CFRP rupture is used to define the failure of the CFRP anchor dowel itself (failure type b). During the discussion of the effect of each parameter, only CFRP rupture results were used.

3.3.2.1 Effect of Anchor Hole Diameter (*d*)

During the installation of adhesive anchors, most of the adhesive manufacturers suggest a 2-3 mm free space between the anchor and resin to have an effective bonding. The load transfer mechanism of adhesive anchor dowels is different from that of mechanic or headed anchor dowels by the way how it transmits the applied tensile load. That is why the bond strength is important for an adhesive anchor dowel. The main idea to define the hole diameter as a variable is to determine the effect of the free space between the anchor dowel and concrete surface on the tensile capacity of the anchor dowels.

The procedure throughout the experiments for investigating the effect of the anchor hole diameter is to change the hole diameter while the other parameters remain unchanged.

In Figure 3.8, the variation of normalized tensile capacity over anchor hole diameter is given for anchor dowels with 80 mm CFRP sheet width, and 70 mm embedment depth. These anchors are embedded into a concrete beam, which has a compressive strength of 16 MPa. It is seen that anchor hole diameter has no significant effect on the normalized tensile capacities of the anchor dowels. Tensile capacities of the anchor dowels change between 45 to 50% of the capacity of the CFRP sheet in the same width. The tensile capacities increase very slightly with an increase in anchor hole diameters.

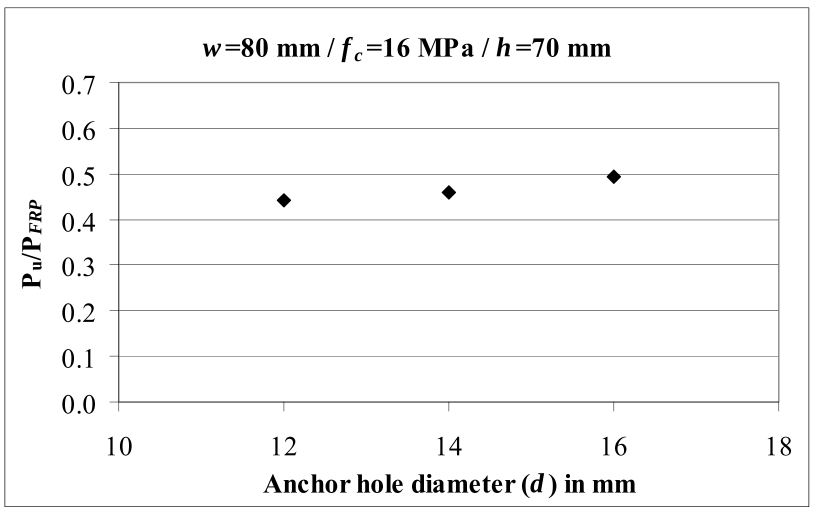

Figure 3.8 Normalized test results presented according to anchor hole diameter (*w*=80 mm, *h*=70 mm, and f_c=16 MPa)

Effect of hole diameter *d* on 10 MPa concrete block is discussed in Figure 3.9 for anchor dowels having sheet width of 120 mm, and embedment depth of 100 mm. Similar to Figure 3.8, the range of the normalized tensile capacities is between 45 to 50%. But, this time the tensile capacities decrease very slightly with an increase in anchor hole diameter.

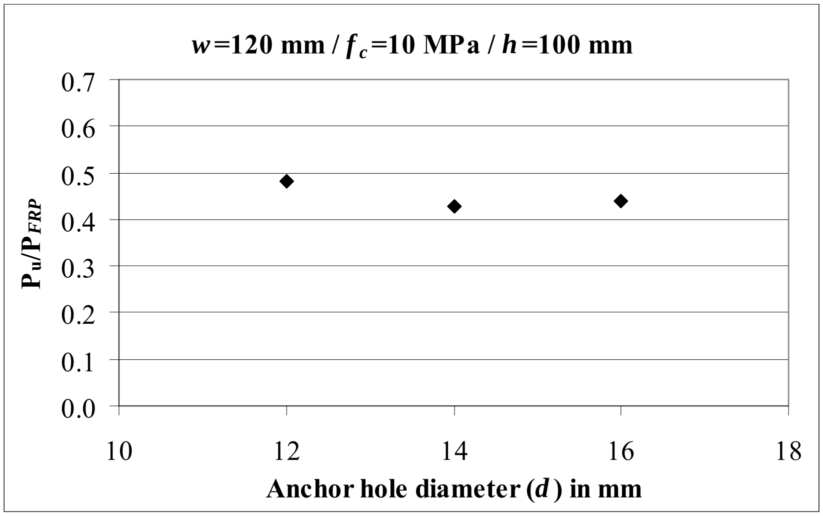

Figure 3.9 Normalized test results presented according to anchor hole diameter (*w*=120 mm, *h*=100 mm, and f_c=10 MPa)

Figures 3.8 and 3.9 clearly show that, providing enough free space for bonding, the anchor hole diameter has no significant effect on tensile capacities of CFRP anchor dowels. The experiments reveal that 2 mm free space for epoxy resin is enough for effective bonding.

3.3.2.2 Effect of Concrete Compressive Strength (f_c)

In previous studies [6,9,11,29,30], compressive strength of the medium, where adhesive anchor dowels were installed, has been chosen as a parameter influencing the capacity of the anchor dowels. Some of those studies indicate that the compressive strength does not have a significant effect on the capacity of the anchor dowel [29,30] while some of them designate that compressive strength is influential on the capacity of the adhesive anchor dowels [6,9,11].

In Figure 3.10, normalized tensile capacities versus concrete compressive strength is given. The data shown in this figure designates the behavior of the anchor dowels, which have 80 mm sheet width, 100 mm embedment depth, and 12 mm hole diameter. The normalized tensile capacities are 0.55, 0.52, and 0.53

for the compressive strengths of 10 MPa, 16 MPa, and 20 MPa, respectively. These values are close to each other in a range less than 5%.

In the same manner, Figure 3.11 presents the test results for a group of anchor dowel which have 160 mm sheet width, 100 mm embedment depth, and 14 mm hole diameter. There is no significant effect of concrete compressive strength on the tensile capacities of CFRP anchor dowels, provided that the concrete strength is within the range worked in this study. The normalized tensile capacities vary in between 0.30 and 0.32.

In the light of these limited test results, it can be said that the effect of compressive strength on the maximum load capacity of the adhesive CFRP anchor dowels is insignificant for concrete compressive strengths between 10 to 20 MPa. This result is also in agreement with the previous studies in literature [29,30].

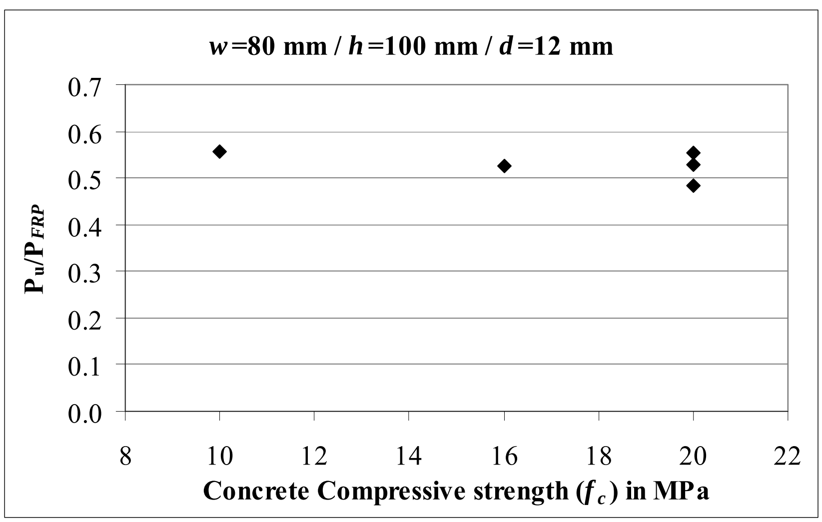

Figure 3.10 Normalized test results presented according to concrete compressive strength (*w*=80 mm, *h*=100 mm, and *d*=12 mm)

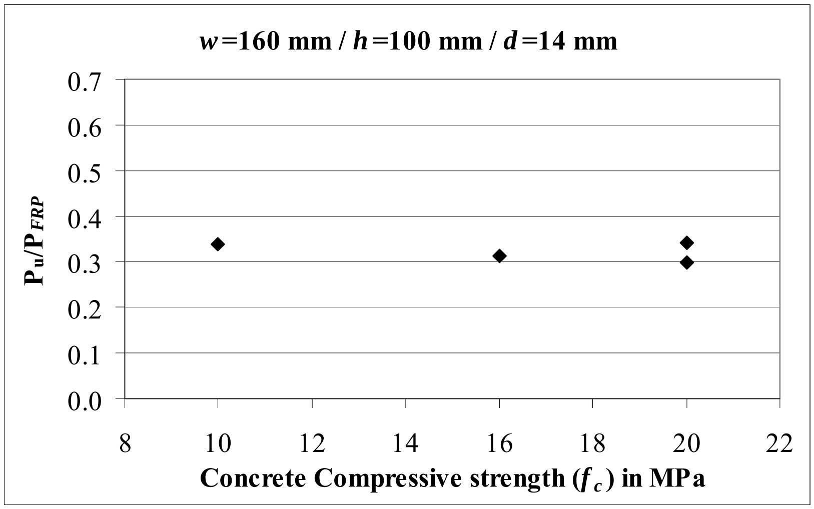

Figure 3.11 Normalized test results presented according to concrete compressive strength (*w*=160 mm, *h*=100 mm, and *d*=14 mm)

3.3.2.3 Effect of CFRP Sheet Width (*w*)

Capacity of a CFRP anchor dowel is related with the number of fibers in that dowel, thus CFRP sheet width. As expected, test results show that load capacity increases with an increase in sheet width. A wider anchor dowel contains more carbon fibers to resist applied tensile load. However, the behavior is not linearly proportional to the sheet width. In other words, the tensile capacities of the anchor dowels do not increase in the same amount with the sheet widths. This phenomenon is presented in the following figures by plotting the normalized tensile capacities against the CFRP sheet width.

The ultimate tensile capacities versus CFRP sheet width are plotted in Figure 3.12. When they are normalized according to the capacity of the carbon fibers in the same width, the ratios decrease from narrower to wider sheets. In Figure 3.13, normalized tensile capacities are given as a function of CFRP sheet width. All anchor dowels presented in this graph have 100 mm embedment depth, 12 mm hole diameter. They are installed into a concrete beam, which has a compressive strength of 20 MPa. This figure shows that the normalized capacity decreases although the tensile capacities increase. This shows that the tensile capacity does not increase in the same rate with the ratios of CFRP sheet widths. This is why the ratios decrease instead of being equal to each other. The normalized tensile capacity of an anchor dowel with 80 mm sheet width is obtained in average as 52 % of the carbon fibers with the same CFRP sheet width. This ratio is approximately equal to 40 % for an anchor dowel having 120 mm sheet width. Finally, as a result of the gradual fall in the normalized data due to increase in CFRP sheet width, the tensile capacity of anchor dowel that is 160 mm in width is obtained as 0.35.

Similarly, the same behavior can be seen in Figures 3.14 and 3.15. The tensile capacities of the anchor dowels are normalized with the tensile capacities of the carbon fibers, and plotted against CFRP sheet width. It is obvious that the data follows a trend which decreases with the increase in sheet width. Figure 3.15 gives the normalized values as 0.36, 0.31, and 0.25 for sheet widths of 80 mm, 120 mm, and 160 mm respectively. The corresponding tensile capacities of the data shown in Figure 3.15 are plotted in Figure 3.14. The tensile capacity increases due to increase in CFRP sheet width. However, the amount of increase in tensile capacities is not directly proportional to the ratio of the sheet widths. The amount of increment in tensile capacities is smaller than the amount of increment in CFRP sheet widths. This is the reason why the normalized tensile capacities decrease with increasing sheet widths.

3.3.2.4 Effect of Embedment Depth (*h*)

Most of the previous studies [3-6,9] that investigate the behavior of the anchor dowels are mostly interested in the effect of the embedment depth of the anchors. In the following numerous graphs, the normalized failure loads, according to tensile capacity of the carbon fibers, are given against the embedment depth of the anchor dowels.

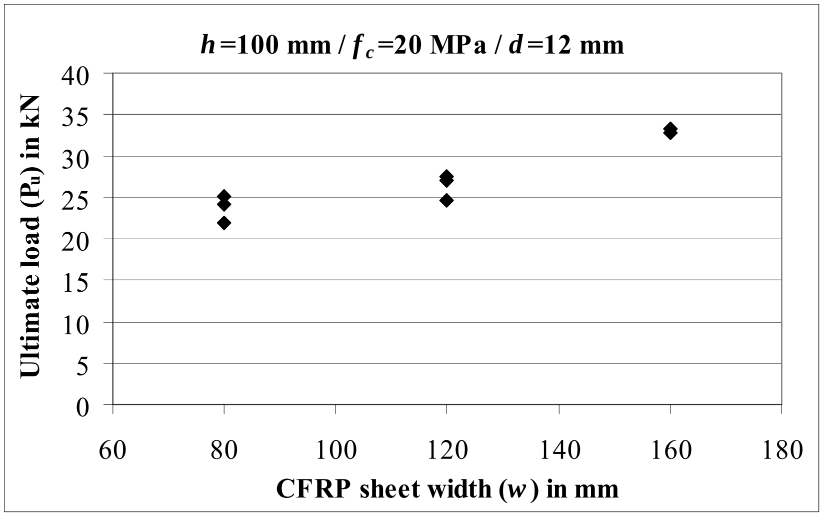

Figure 3.12 Test results presented according to CFRP sheet width (*h*=100 mm, *d*=12 mm, and f_c=20 MPa)

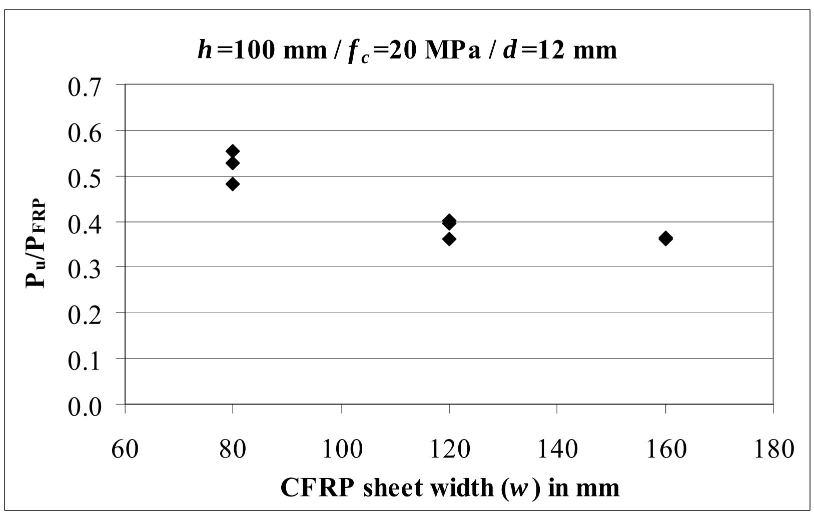

Figure 3.13 Normalized test results presented according to CFRP sheet width (*h*=100 mm, *d*=12 mm, and f_c=20 MPa)

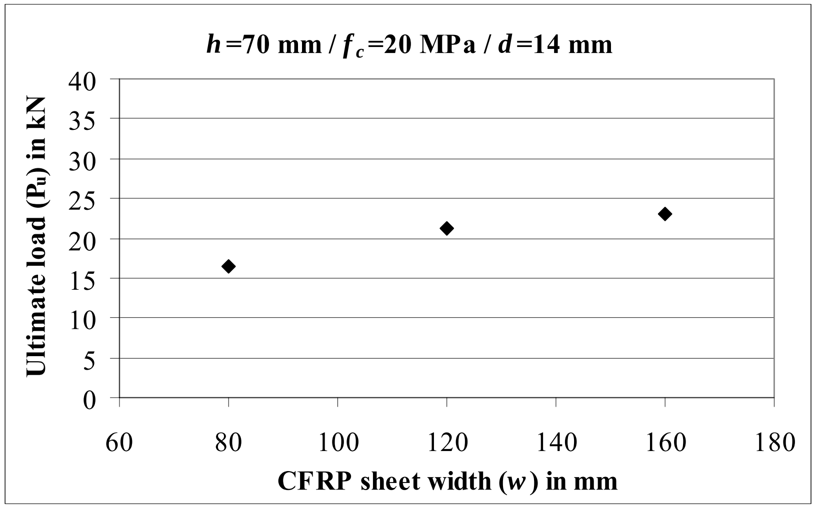

Figure 3.14 Test results presented according to CFRP sheet width (h=70 mm, d=14 mm, and f_c=20 MPa)

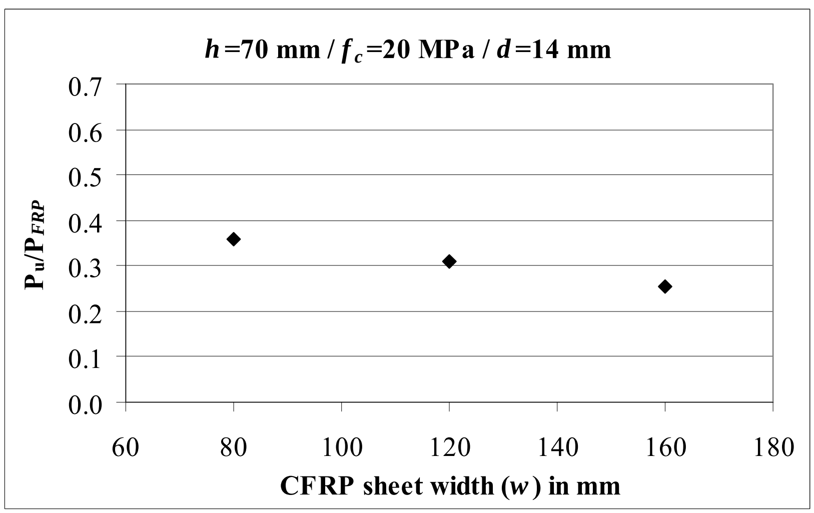

Figure 3.15 Normalized test results presented according to CFRP sheet width (h=70 mm, d=14 mm, and f_c=20 MPa)

Figure 3.16 gives the normalized test results of anchors having 80 mm sheet width and 12 mm hole diameter in a concrete of 20 MPa compressive strength. The anchor dowels having 70 mm embedment depth failed at approximately 30% of the tensile capacity of the carbon fibers. This ratio rises to about 50-55% for anchor dowels having 100 mm embedment depth. For the case in which the embedment depth is 150 mm, the normalized values change in a wide band between 35 and 65%. In average, the highest tensile capacity is obtained for an embedment depth of 100 mm.

Similarly, the normalized test results of anchors of 80 mm sheet width and 12 mm hole diameter in 16 MPa compressive concrete strength is shown in Figure 3.17. For anchor dowels having 70 mm and 150 mm embedment depth the tensile capacity obtained is the 30 to 45% of the capacity of the carbon fibers. The single point for anchor dowel with 100 mm embedment depth, gives approximately 50% of the tensile capacity of the carbon fibers.

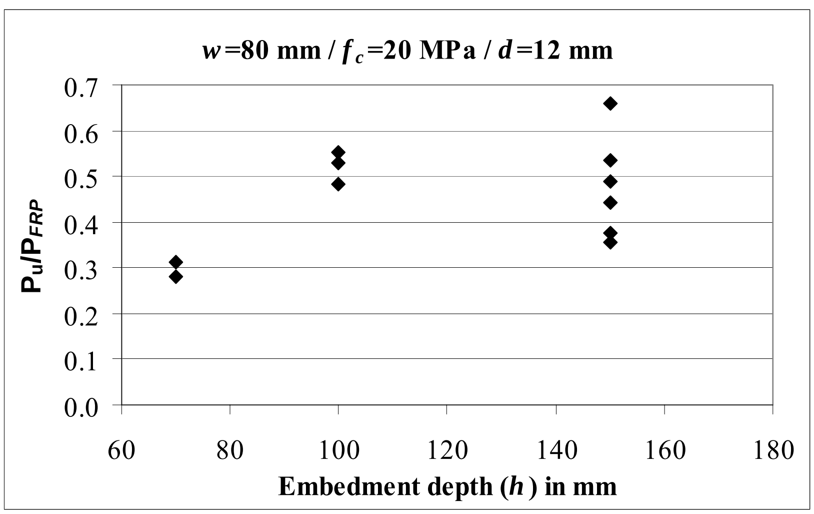

Figure 3.16 Normalized test results presented according to embedment depth (w=80 mm, d=12 mm, and f_c=20 MPa)

In Figure 3.18, normalized tensile capacities of CFRP anchor dowels are given as a function of embedment depth for w=80 mm, f_c=10 MPa, and d=12 mm. The tensile capacity of the anchor dowel with 70 mm embedment depth, normalized with the capacity of the carbon fibers, is nearly 0.40. This ratio is obtained for anchor dowels with 100 mm and 150 mm embedment depths as 0.55

and 0.45, respectively. In agreement with previous figures, the maximum tensile capacity holds for the embedment depth of 100 mm.

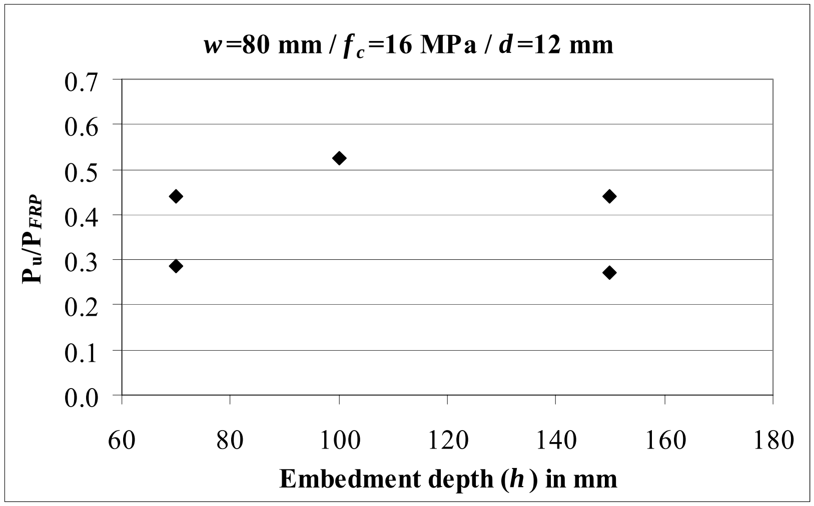

Figure 3.17 Normalized test results presented according to embedment depth (*w*=80 mm, *d*=12 mm, and f_c=16 MPa)

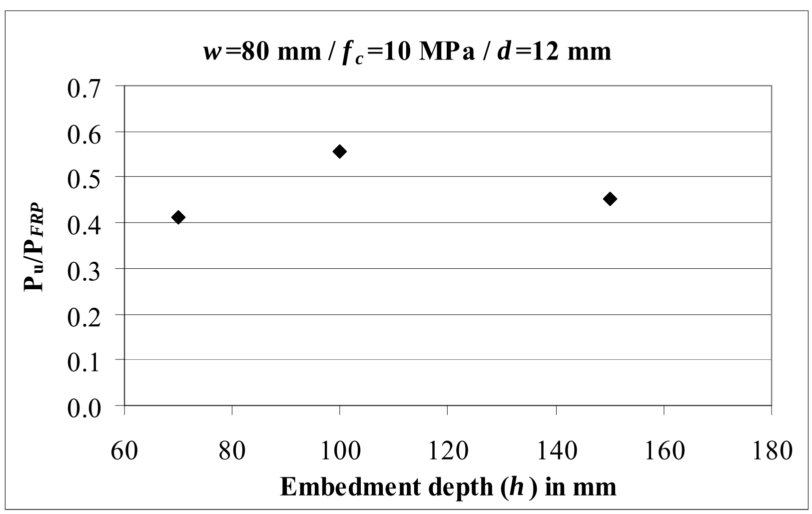

Figure 3.18 Normalized test results presented according to embedment depth (*w*=80 mm, *d*=12 mm, and f_c=10 MPa)

Figures 3.19, 3.20, and 3.21 also show the change in normalized tensile capacities for the anchor dowels with a CFRP sheet width of 160 mm. The data given in Figure 3.19 corresponds to the anchor dowels that have an anchor hole diameter of 14 mm. The compressive strength of the concrete into which the anchor dowels were installed is 20 MPa. The tensile capacities of the anchor dowels are approximately equal to 25%, 35%, and 25% of the tensile capacities of carbon fibers for embedment depths of 70 mm, 100 mm, and 150 mm, respectively. The maximum normalized value matches with the embedment depth of 100 mm.

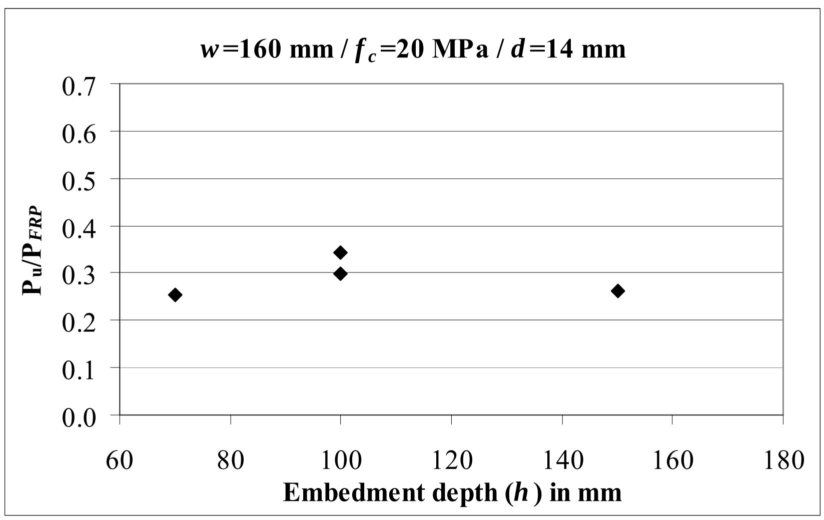

Figure 3.19 Normalized test results presented according to embedment depth (w=160 mm, d=14 mm, and f_c=20 MPa)

Figure 3.20 presents the test data of the anchor dowels having a CFRP sheet width of 160 mm and a hole diameter of 14 mm. These anchors were installed into a concrete beam which has a compressive strength of 16 MPa. As it is seen, the maximum normalized tensile capacity is in the range of 0.32 for the embedment depth of 100 mm. On the other hand, this ratio is equal to 0.25 for 70 mm embedment depth, and 0.28, in average, for an embedment depth of 150 mm.

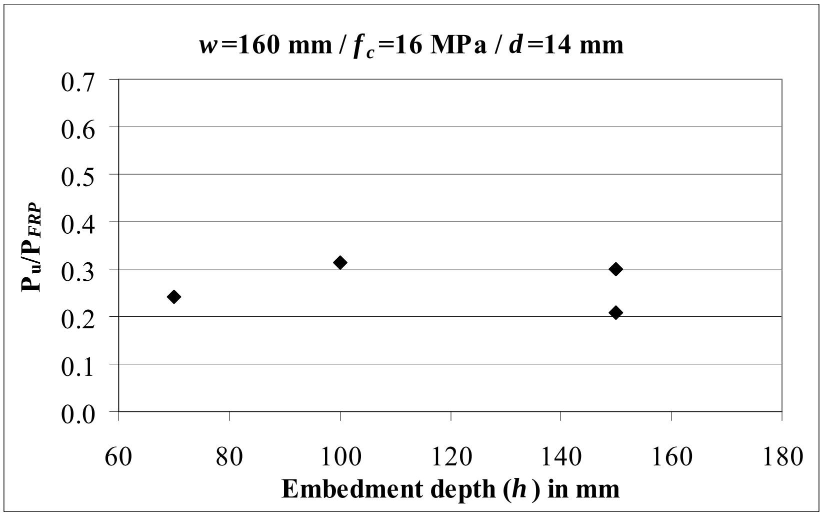

Figure 3.20 Normalized test results presented according to embedment depth (*w*=160 mm, *d*=14 mm, and f_c=16 MPa)

Test results for anchor dowels with 160 mm CFRP sheet width, 14 mm anchor hole diameter, and 10 MPa concrete compressive strength are presented in Figure 3.21. The maximum normalized tensile capacity is obtained for an embedment depth of 100 mm is approximately equal to 35% of the tensile capacity of the carbon fibers of 160 mm sheet width. This percentage decreases to 20 % for anchor dowel that has 70 mm embedment depth. 150 mm embedment depth gives an average normalized tensile capacity of 30 %.

In the light of these tests, and with the parameters chosen, 100 mm embedment depth looks like an effective embedment depth for CFRP anchor dowels inserted in concrete members having 10 to 20 MPa compressive cylinder strength. Anchor dowels with 150 mm embedment depth gives very close results with that of anchor dowels embedded into 100 mm.

In the literature, it was assumed that bond stress has uniform, linear or non-linear distributions along the embedment depth of an adhesively bonded anchor dowel [3,4]. According to these bond stress models, the ultimate load capacity of an adhesive anchor dowel increases when the embedment depth increases. However, the test results indicate that it is not true. If one assumes a uniform bond stress distribution along the anchor dowel, anchor dowels having 100 mm and 150 mm embedment depths will have capacities of 1.4 and 2.1 times that of anchor dowel with 70 mm embedment depth. Test results revealed that up to 100 mm embedment depth, uniform bond stress distribution is quite satisfactory. However, for embedment depths greater than 100 mm, this assumption is not valid.

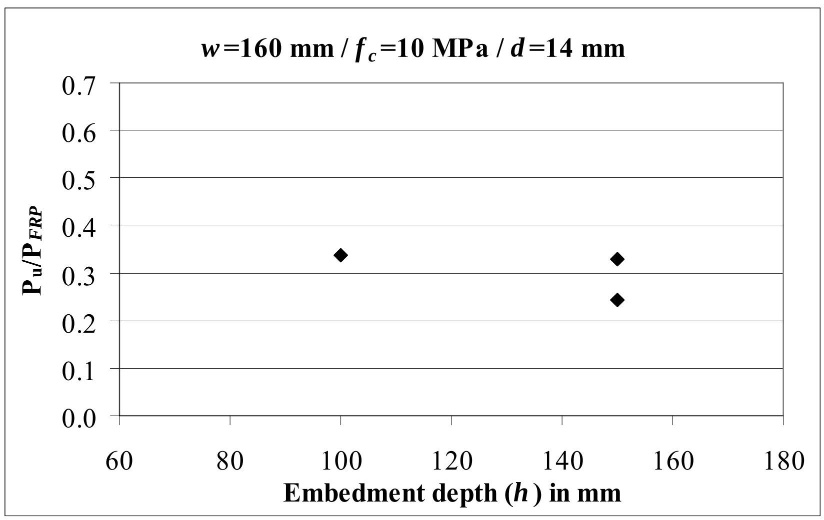

Figure 3.21 Normalized test results presented according to embedment depth (*w*=160 mm, *d*=14 mm, and f_c=10 MPa)

In the light of Figures 3.16 - 3.21, it might be said that there is an effective bond length concept beyond which the tensile load capacity does not increase with an increase in embedment depth (bond length) for adhesive CFRP anchor dowels. This effective length is found as 100 mm throughout the performed tests. This result is in agreement with that of Zhang et al [9]. They declared that the effective bond length is 100 mm for embedded FRP rods.

3.3.3 Test Results (Part 2)

At the end of first series of tests, observed tensile capacities have a large scatter. It is hard to come up with general conclusions through those results. For instance, the tensile capacities of the anchor dowels with 150 mm embedment depth are believed to be at least equal to the tensile capacity of the anchor dowel with embedment depth of 100 mm. However, in most of the cases the capacities are observed to be less than that of anchor dowels with 100 mm embedment depth. Additionally, as discussed under the name of failure types, the failure type of an adhesive CFRP anchor dowel depends mainly on the tensile strength of the concrete. So, it is expected to observe different failure types for different amounts of embedment depths and tensile loads. However, all the presented data has CFRP rupture in a high range of tensile load. To investigate these behaviors in detail, this second part of the study is carried out for only one CFRP sheet width and hole diameter, while the embedment depth changes from 50 mm to 150 mm, including 70 mm and 100 mm. This series is studied for two concrete beams. Two compressive strengths of concrete have been chosen, they were 10 MPa and 16 MPa. The experimentally obtained ultimate tensile capacities of the anchor dowels tested in this second series are given in Table 3.6 with the normalized values of tensile capacities and corresponding failure types.

3.3.3.1 Effect of Embedment Depth (*h*)

In this second series of tests, all of the tests are performed with anchor dowels having 120 mm sheet width and 20 mm hole diameter. These anchors were installed into two different concrete beams that have compressive strengths of 10 MPa and 16 MPa.

Figure 3.22 gives the normalized test results of anchor dowels installed into concrete beam, which has a compressive strength of 10 MPa. The anchor dowels having 50 mm embedment depth failed at approximately 21% of the tensile capacity of the carbon fibers. This ratio rises to about 30% and 43% for anchor dowels having 70 mm, and 100 mm embedment depths, respectively. For the case in which the embedment depth is 150 mm, the normalized values change very slightly when compared to tensile capacity of anchor dowels with 100 mm embedment depth. They have approximately 43% of the tensile capacity of the carbon fibers. This shows that the tensile capacity of the anchor dowels do not change when the embedment depth increases from 100 mm to 150 mm.

Table 3.6 Results of second series of tests with the failure types and normalized values according to the capacity of the carbon fibers.

Identification of the performed tests	**Ultimate tensile load applied to the anchor dowel (kN)**	**Ratio of the ultimate load to the capacity of carbon fibers**	**Failure Type**
w120***h***50***f***10***d***20	14.6	0.21	concrete cone failure
w120***h***50***f***10***d***20	15.06	0.22	concrete cone failure
w120***h***50***f***10***d***20	14.6	0.21	concrete cone failure
w120***h***70***f***10***d***20	25.6	0.37	Pullout failure
w120***h***70***f***10***d***20	22.3	0.33	Pullout failure
w120***h***70***f***10***d***20	20.1	0.29	Pullout failure
w120***h***100***f***10***d***20	35.5	0.52	Pullout failure
w120***h***100***f***10***d***20	29.4	0.43	CFRP rupture
w120***h***100***f***10***d***20	30.4	0.44	Pullout failure
w120***h***150***f***10***d***20	29.6	0.43	CFRP rupture
w120***h***150***f***10***d***20	31.4	0.46	CFRP rupture
w120***h***150***f***10***d***20	32.1	0.47	CFRP rupture
w120***h***50***f***16***d***20	16.0	0.23	concrete cone failure
w120***h***50***f***16***d***20	15.9	0.23	concrete cone failure
w120***h***70***f***16***d***20	27.93	0.41	Pullout failure
w120***h***70***f***16***d***20	26.46	0.39	Pullout failure
w120***h***70***f***16***d***20	26.17	0.38	Pullout failure
w120***h***100***f***16***d***20	41.65	0.61	Pullout failure
w120***h***100***f***16***d***20	34.99	0.51	Pullout failure
w120***h***100***f***16***d***20	35.38	0.52	Pullout failure
w120***h***150***f***16***d***20	37.04	0.54	CFRP rupture
w120***h***150***f***16***d***20	34.69	0.51	CFRP rupture
w120***h***150***f***16***d***20	35.77	0.52	CFRP rupture

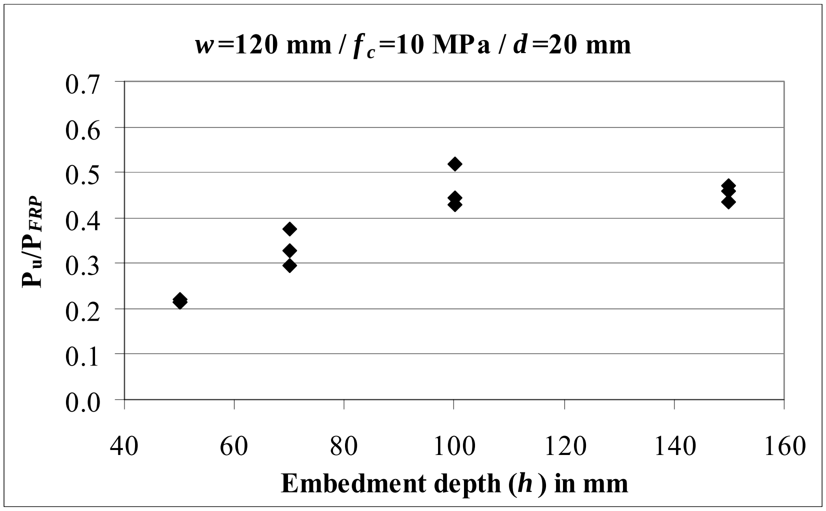

Figure 3.22 Normalized test results presented according to embedment depth (w=120 mm, d=20 mm, and f_c=10 MPa)

Similar to Figures 3.22, Figure 3.23 shows the change in normalized tensile capacities of anchor dowels installed into a concrete beam of 16 MPa compressive strength. The tensile capacities of the anchor dowels are approximately equal to 23%, 39%, and 51% of the tensile capacities of carbon fibers for embedment depths of 50 mm, 70 mm, and 100 mm, respectively. The tensile capacities of the anchor dowels increase due to increase in embedment depth up to 100 mm. On the other hand for embedment of 150 mm, the tensile capacity does not increase compared to tensile capacities of anchor dowels having 100 mm embedment depth. This result agrees with the inference for Figure 3.23.

These two figures (3.22 and 3.23), imply that there exists an effective embedment depth phenomenon in which the tensile capacity does not increase after a certain embedment depth. This critical depth is obtained as 100 mm throughout this experimental study.

Using equation 3.5, tensile capacities of the anchor dowels can be obtained for various crack patterns. When the angle of propagation of cracks is introduced to these two equations, following two figures are obtained. In Figure 3.24, the solid lines are drawn using the tensile capacity of a concrete beam having 10 MPa compressive strength. When the computed test results are plotted with the experimental tensile capacities, a band in which the upper limit corresponds to 55 degree and lower limit corresponds to 50 degree is obtained.

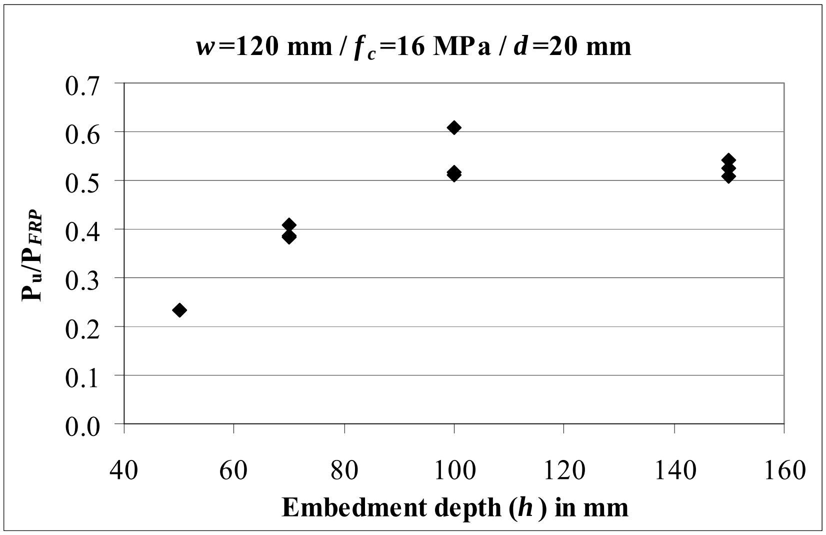

Figure 3.23 Normalized test results presented according to embedment depth (w=120 mm, d=20 mm, and f_c=10 MPa)

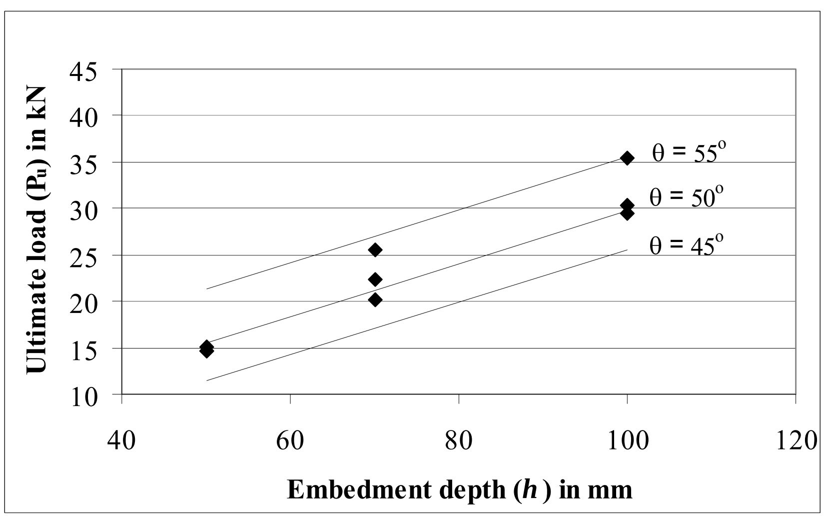

Figure 3.24 Ultimate loads with different crack patterns for 10 MPa concrete

Similarly, Figure 3.25 presents the tensile capacities computed by equation 3.5 for a concrete compressive strength of 16 MPa. In this case, the upper band is obtained as 50 degree while the lower limit is 45 degree.

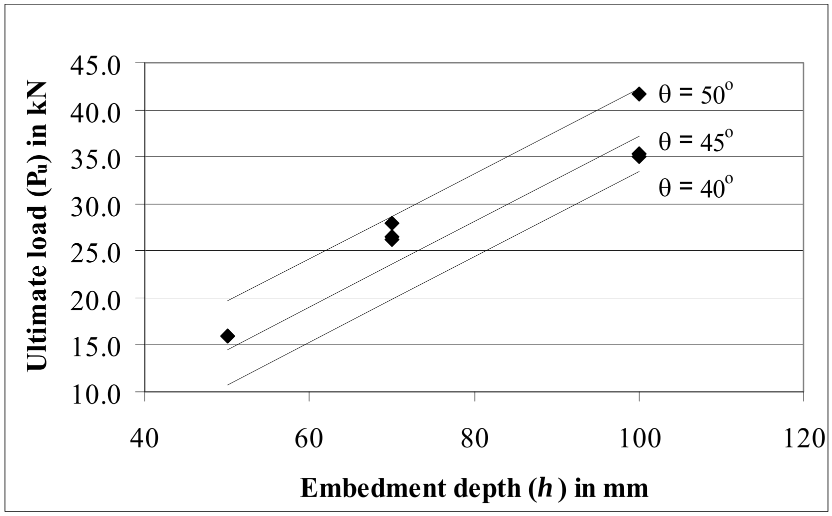

Figure 3.25 Ultimate loads with different crack patterns for 16 MPa

In the light of available test results, Figures 3.24, and 3.25, it can be said that the crack angle gets steeper when the concrete compressive strength decreases (Figure 3.7). The optimum crack angles are 50° and 45° for concrete compressive strengths of 10 MPa and 16 MPa, respectively.

3.3.3.2 Effect of Concrete Compressive Strength (f_c)

To understand the effect of concrete compressive strength on the behavior of adhesive CFRP anchor dowels, the results of this second series are also sorted such that the normalized failure loads are presented as a function of the compressive strengths.

Normalized test results for all embedment depths, namely 50 mm, 70 mm, 100 mm, and 150 mm, are presented in Figure 3.26. These anchor dowels have 120 mm CFRP sheet width and 20 mm hole diameter. The values for 50 mm embedment depth are so close to each other. The difference in tensile capacities of anchor dowels installed into 10 MPa concrete beam and 16 MPa concrete beam is negligible. This difference is obtained as 5% and 9% in average for the anchor dowels with 70 mm and 100 mm embedment depths, respectively. Finally, for embedment depth of 150 mm, this difference is approximately 5%.

In the light of this data, it can be said that the compressive strength of the concrete has an effect, which is in an increasing trend up to effective embedment depth, on the tensile capacity of the anchor dowels.

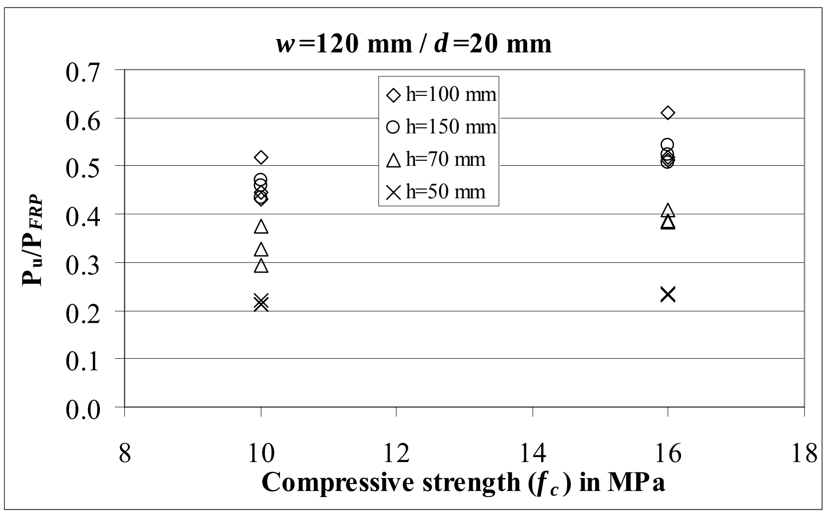

Figure 3.26 Normalized test results presented according to concrete compressive strength (*w*=120 mm, *d*=20 mm)

3.3.4 Determination of The Concrete Cone Depth

In the equations 3.4 and 3.5, concrete cone depth is taken as 50 mm. This depth is based on the experimental results and it is repetitive for all embedment depths. The figures of the anchor dowels failed as concrete cone failure or as pullout failure are given in Figures 3.27, 3.28, and 3.29 for embedment depths of 50 mm, 70 mm, and 100 mm, respectively. CFRP anchor dowels with embedments deeper than 50 mm have a shallow cone followed by a slip through the remaining part in failure. This phenomenon is also shown in these three figures. The concrete cone depth is equal to 50 mm for all of the CFRP anchor dowels with 50 mm embedment depth. It is equal to 48.5 mm for 70 mm embedment depth, while cone depth is 51.6 mm for 100 mm embedment depth. In the light of these results, in agreement with the observations stated in [3-6], the shallow concrete cone depth can be taken 50 mm.

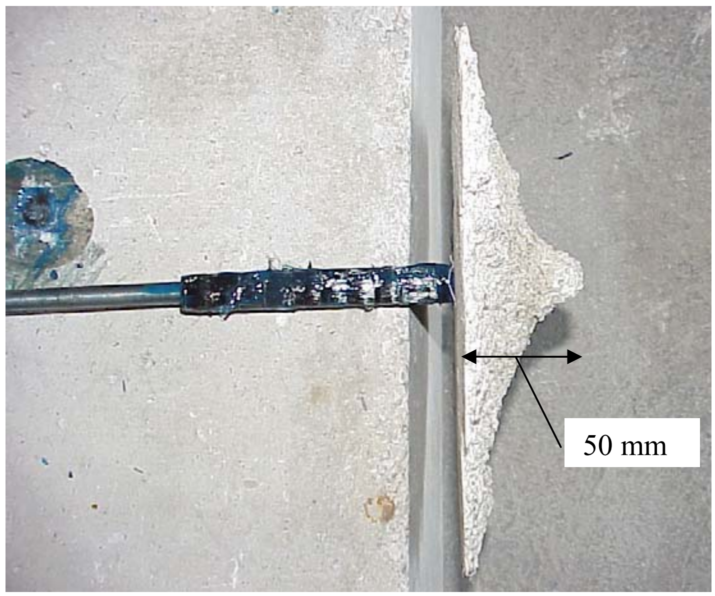

Figure 3.27 Concrete cone depth for an anchor dowel with 50 mm embedment depth

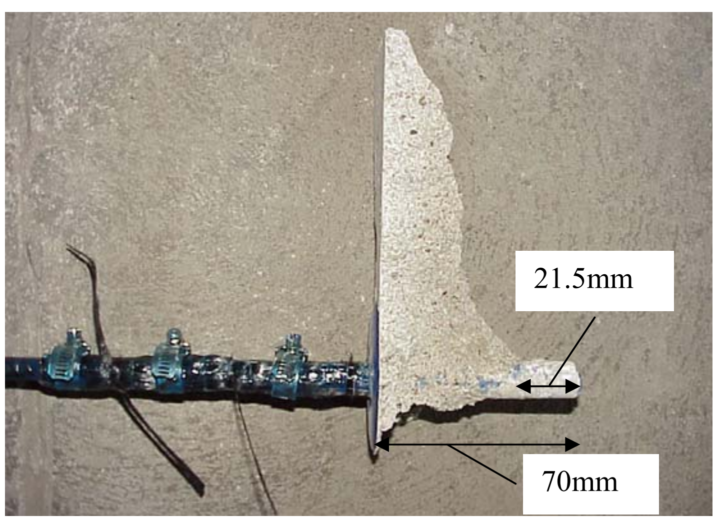

Figure 3.28 Concrete cone depth for an anchor dowel with 70 mm embedment depth

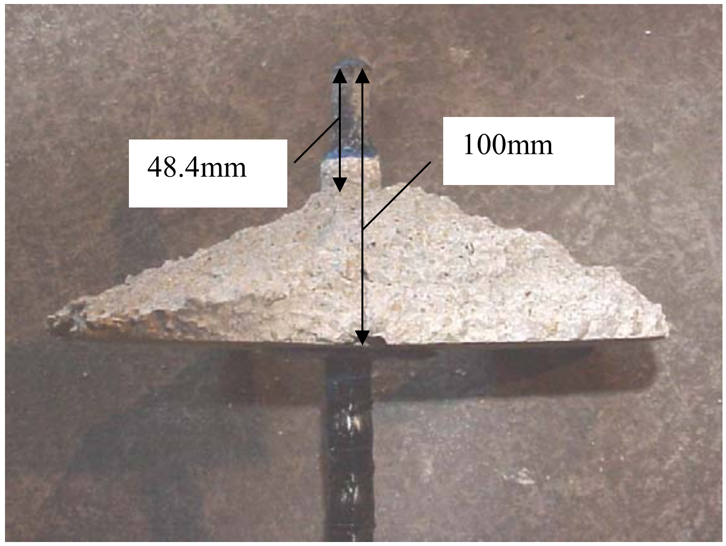

Figure 3.29 Concrete cone depth for an anchor dowel with 100 mm embedment depth

3.4 COMPARISON of TEST RESULTS WITH PREDICTED ONES

The comparison of the test results observed during the second series of tests with the predicted tensile capacities is given in Table 3.7. P_{FRP}, P_{CMPST}, and P_{CONE} are computed using the equations 3.2, 3.3, and 3.5, respectively. In second and third columns of Table 3.7, ultimate tensile loads of CFRP anchor dowels are normalized by the predicted tensile capacities. When P_{FRP} is taken into consideration, normalized tensile capacities are in between 0.21 and 0.52 for CFRP anchor dowels embedded into 10 MPa concrete. This variation is limited in between 0.23 and 0.61 for CFRP anchor dowels installed into 16 MPa concrete. In fourth and fifth columns of Table 3.7, the predicted tensile capacities according to P_{CONE} with the angles of 45 and 50 are used to normalize the experimental results. As it is shown in Figures 3.24 and 3.25, P_{CONE} should be used to determine the tensile capacities of CFRP anchor dowels with 50^o and 45^o for 10 MPa and 16 MPa concretes, respectively.

Table 3.7 Comparison of test results with predicted ones

	P_u/P_{FRP}	P_u/P_{CMPST}	P_u/P_{CONE} θ=45°	P_u/P_{CONE} θ=50°
w120/***h***50/***f***10/***d***20	0.21	0.17	1.27	0.94
w120/***h***50/***f***10/***d***20	0.22	0.18	1.31	0.97
w120/***h***50/***f***10/***d***20	0.21	0.17	1.27	0.94
w120/***h***70/***f***10/***d***20	0.37	0.30	1.49	1.21
w120/***h***70/***f***10/***d***20	0.33	0.26	1.30	1.05
w120/***h***70/***f***10/***d***20	0.29	0.23	1.17	0.95
w120/***h***100/***f***10/***d***20	0.52	0.41	1.39	1.20
w120/***h***100/***f***10/***d***20	0.43	0.34	1.15	0.99
w120/***h***100/***f***10/***d***20	0.44	0.35	1.19	1.02
w120/***h***150/***f***10/***d***20	0.43	0.35	0.75	0.68
w120/***h***150/***f***10/***d***20	0.46	0.37	0.79	0.72
w120/***h***150/***f***10/***d***20	0.47	0.37	0.81	0.73
w120/***h***50/***f***16/***d***20	0.23	0.19	1.10	0.81
w120/***h***50/***f***16/***d***20	0.23	0.19	1.09	0.81
w120/***h***70/***f***16/***d***20	0.41	0.33	1.19	0.97
w120/***h***70/***f***16/***d***20	0.39	0.31	1.12	0.92
w120/***h***70/***f***16/***d***20	0.38	0.30	1.11	0.91
w120/***h***100/***f***16/***d***20	0.61	0.49	1.12	0.98
w120/***h***100/***f***16/***d***20	0.51	0.41	0.94	0.83
w120/***h***100/***f***16/***d***20	0.52	0.41	0.95	0.84
w120/***h***150/***f***16/***d***20	0.54	0.43	0.62	0.57
w120/***h***150/***f***16/***d***20	0.51	0.40	0.58	0.53
w120/***h***150/***f***16/***d***20	0.52	0.42	0.60	0.55

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

During the last decade, fiber reinforced polymers (FRP) has been widely used to strengthen bridge girders, piers, columns of structures and masonry walls in wall bearing. Using carbon fiber reinforced polymers (CFRP) to strengthen the existing structures is relatively new and promising technique. While strengthening the existing structures CFRP sheet are applied on the hollow clay tile infill walls diagonally. In strengthening of the hollow clay tile infill by CFRP, CFRP anchorages are used both in masonry and in reinforced concrete members to provide a sufficient bond between the CFRP sheet and the masonry and the reinforced concrete member. Better connections lead higher energy dissipation and higher ductility. Thus, the capacity increase in the existing structure mostly depends on the load transferred through the CFRP anchor dowels, or simply the increase in capacity of the structure depends on CFRP anchor dowel capacity. In this experimental study, direct tensile capacities of CFRP anchor dowels were investigated for different parameters. Effect of CFRP sheet width, embedment depth of adhesive anchor dowel, hole diameter of anchor dowel and compressive strength of concrete on the uniaxial tensile capacity of the CFRP anchor dowels were determined.

Before the conclusions, the author is willing to strongly emphasize that the labor quality in these experiments is very important and it can significantly influence the results. Improper labor quality may cause misinterpretation of the test results. To minimize the effect of labor quality, there are a few key points to be carefully checked. First, while preparing the adhesive mixture, one must strictly obey the proportions mentioned by the manufacturer. Proper mixture means proper bonding and higher load capacities without failure of adhesive.

Second, anchors must be straight to transfer the applied load without any eccentricity. Any amount of eccentricity causes a decrease in the capacity. Additionally, the most important point is to provide a smooth connection just over the concrete where the unbonded part of the CFRP anchor dowel is bonded to tension steel. Any disturbance in the direction of the fibers in CFRP sheet, i.e. bulging due to improper connection of CFRP sheet to the tension steel, results in lower capacities. Because the applied load can not be transferred to the embedded portion of the anchor dowel directly.

In addition, to prevent slippage of the CFRP anchor dowel from the tension steel, either a deformed steel bar is used or sanding should be applied to a plain bar. Clips or fibers itself can be used to fix CFRP anchor to the steel bar.

4.1 CONCLUSIONS

Similar to test results, author wishes to present the conclusions also in two parts. Because, difference in preparation of two CFRP anchor dowels will lead different behaviors under the same conditions.

4.1.1 First Series of Tests

At the end of the first series of tests, the results have large scatter such that it is very hard to get a general conclusion. The most important point in these tests was experienced as the workmanship quality.

The only conclusion that can be drawn from the first series of test is that there is an effective embedment depth concept for CFRP anchor dowels. Beyond this depth, the tensile capacity of the dowels is not increased. The effective embedment depth for the studied parameters, appear to be 100 mm. this conclusion is in good agreement with the second series of tests also.

4.1.2 Second Series of Tests

In the light of the results obtained in the second series of tests, following conclusions can be drawn.

- For the embedment depth of 50 mm, uniaxial tension tests ended with a concrete cone failure. However, the anchor dowels with 70 mm and 100 mm embedment depths formed pullout failure with a shallow concrete cone at the top. The depth of this shallow cone is 50 mm also. On the other hand, CFRP rupture was observed for the dowels embedded into 150 mm.
- For the studied parameters, the maximum tensile load capacities are obtained for the CFRP anchor dowels which have 100 mm embedment depth. This indicates that there is an effective bond length beyond which load capacity does not increase. The increase in tensile load capacities can be assumed linear up to 100 mm embedment depth.
- For the shallow embedment depths, i.e. 50 mm, the effect of concrete compressive strength, in the range of 10 MPa to 16 MPa, on the tensile capacity of CFRP anchor dowel is not significant. However, as the embedment depth increases, the effect of concrete compressive strength becomes more significant.
- Equation 3.5 derived to predict the tensile capacity of CFRP anchor dowels embedded into concrete gives results close enough to experimental ones. The crack angle θ should be taken as 50^o and 45^o for 10 MPa and 16 MPa concrete compressive strengths, respectively.

4.2 RECOMMENDATIONS

The followings are recommended for the future studies:

- Investigate the behavior in which the bond free parts of the CFRP anchor dowels are bonded to a hollow clay infill wall through which the load is transferred to the anchor dowel.
- Investigate the behavior of multiple anchor systems.

- Investigate the effect of moisture in the drilled holes prior to anchor dowel installation.

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