TENSILE BEHAVIOR OF CHEMICALLY BONDED POST-INSTALLED ANCHORS IN LOW-STRENGTH REINFORCED CONCRETES

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ABSTRACT

TENSILE BEHAVIOR OF CHEMICALLY BONDED POST-INSTALLED ANCHORS IN LOW-STRENGTH REINFORCED CONCRETES

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After the 1999 Kocaeli Earthquake, the use of chemically bonded post-installed anchors has seen a great growth for retrofits in Turkey. Currently, chemically bonded post-installed anchors are designed from related tables provided by adhesive manufacturers and a set of equations based on laboratory pullout tests on normal or high strength concretes. Unfortunately, concrete compressive strengths of existing buildings, which need retrofit for earthquake resistance, ranges within 5 to 16 MPa. The determination of tensile strength of chemically bonded anchors in low-strength concretes is an obvious prerequisite for the design and reliability of retrofit projects.

Since chemically bonded anchors result in the failure of concrete, adhesive-concrete interface or anchored material, the ultimate resistance of anchor can be predicted through the sum of the contributions of concrete strength, properties of anchored material (which is steel for this work), and anchorage depth. In this work, all three factors and the predictions of current tables and equations related to anchorages are examined throughout site tests.

Keywords: Post-Installed Anchorages, Chemically Bonded Anchorages

ÖZ

SONRADAN YERLEŞTİRİLMİŞ KİMYASAL ANKRAJLARIN DÜŞÜK DAYANIMLI DONATILI BETONLARDAKİ ÇEKME DAVRANIŞLARI

Mazılıgüney, Levent
Yüksek Lisans , İnşaat Mühendisliği Bölümü
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Türkiye'de takviye işlerinde sonradan yerleştirilmiş kimyasal ankrajların kullanımı 1999 Kocaeli Depremi sonrasında büyük bir artış göstermiştir. Şu anda sonradan yerleştirilmiş kimyasal ankrajların tasarımı laboratuvar koşullarında normal ve yüksek dayanımlı betonlar üzerinde yapılan çekme deneylerine dayanan yapıştırıcı üreticilerinin sağladığı tablolar ve bir dizi denklemler kullanılarak yapılmaktadır. Oysaki deprem dayanımı için takviyeye ihtiyacı olan mevcut binaların beton basınç dayanımları 5 ile 16 MPa arasında değişmektedir. Takviye projelerinin tasarımı ve güvenilebilirliği için kimyasal ankrajların düşük dayanımlı betonlardaki çekme dayanımının belirlenmesi bariz bir gerekliliktir.

Kimyasal ankrajlarda kopmalar beton, yapışkan-beton ara yüzeyi veya ankraj edilen malzemede oluşabileceğinden, kimyasal ankrajın nihai dayanımı beton dayanımı, ankraj edilen malzeme (bu çalışma için çelik) özellikleri ve ankraj derinliğinin etkileri birlikte değerlendirilerek tahmin edilebilir. Bu çalışmada her üç etken ve ankrajla ilgili mevcut tablo ve denklemlerin tahminleri saha testleriyle incelenmiştir.

Anahtar Kelimeler: Sonradan Yerleştirilmiş Ankraj, Kimyasal Ankraj

To My Daughter “Nazlı Hilâl” And My Wife “Diler”

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LIST OF SYMBOLS

A Tensile stress area, cross sectional area of the anchor steel

A_e Effective stress area

c_1 Edge distance

d Diameter of the anchor

d_o Diameter of the hole

d_u Diameter of the anchor (head)

σ_{ult} Ultimate tensile strength of the anchor

f'_c Compressive strength of concrete measured on 150 mm x 300 mm cylinders

f_{ct} Concrete tensile strength

F_u Ultimate failure load

f_{u1} Ultimate failure load of a single anchor

f_{u2} Total failure load of two anchorages

f_{ut} Tensile strength of anchor steel

f_{te} Theoretical compressive strength

h_{ef} Effective embedment depth

l_e Embedment depth

R_{max} Maximum rebound number

R_{avg} Average rebound number

R_{min} Minimum rebound number

STIIIa Steel type IIIa

s_c Critical anchor spacing

s Distance between center of anchors

ϕ Strength reduction factor

τ_o Uniform failure stress

λ' Elastic constant

τ_{max} Maximum failure stress at the elastic limit

Ø Threaded rod diameter

σ_y Yield strength

σ_w Tensile strength

CHAPTER 1

INTRODUCTION

1.1 RESEARCH SIGNIFICANCE

The demand for more flexibility in the planning, design and strengthening of concrete structures has resulted in an increased use of metallic anchoring systems [1]. Anchors to concrete can be divided into two general categories as cast-in-place anchors and post-installed anchors. Cast-in-place anchors are installed before the concrete is cast; therefore they are generally used for predesigned facilities, usually for fixing or combining different items of a project which are made from different materials. Post-installed anchors are generally used for retrofit works, so they can also be called as retrofit anchors. While retrofit anchors are less well understood than cast-in place ones, they are more preferable since use of retrofit anchors allows greater flexibility in attachments to concrete [2]. Retrofit anchors can be fastened in almost any position desired by installing them in a hole drilled in hardened concrete [1]. The system of post-installed anchors includes adhesive, grouted, expansion, and undercut anchors. With the advent of the high strength bonding agents, however, the use of adhesive anchors has increased significantly, especially for retrofit works.

Existing concrete structures may require strengthening or stiffening in order to increase their ultimate flexural or shear capacity, or to control deflections and cracking [3] as well as to improve earthquake resistance. After the 1999 Kocaeli Earthquake, the use of chemically bonded anchors has seen a great growth for retrofits in Turkey. At the moment, no specific design codes are available for chemically bonded anchors. Currently, chemically bonded post-installed anchors are designed from related tables provided by adhesive manufacturers which involve a set of equations based on laboratory pullout tests on normal or high strength concretes. Unfortunately, concrete compressive strengths of existing buildings in Turkey, which need retrofit for earthquake resistance, ranges from 5 to 16 MPa according to data obtained from Ministry of Defense. Using the current tables and equations for low strength concretes causes many conflicts between the contractors and public authorities, since the predicted failure loads by this way are much greater than the actual values. Design engineers prefer to use large factor of safeties or large number of anchorages much more than needed. The determination of tensile strengths of chemically bonded anchors in low-strength concretes is an obvious prerequisite for the design and reliability of retrofit projects.

The objective of bonding-in or post-installing steel reinforcement in an existing reinforced concrete structure is to provide a connection between a new concrete element and the existing structure that is similar in strength and stiffness as cast-in reinforcement [4]. The technology of post-installed reinforcing bars is gaining increasing importance since these bars are being used frequently in horizontal, vertical, and overhead applications in rehabilitation and strengthening of existing structures. Application examples for post-installed chemically bonded anchors include [4]:

- Vertical connections, including new columns or piers, pile caps, or adding reinforcement for structural enhancement of vertical elements,
- Major structural repairs, including concrete remedial works and structural upgrading of columns, slabs, or beams,
- Structural connections to existing reinforced concrete walls or columns, including staircases, corbels, and cantilever connections such as balconies, access platforms, and landings,
- Concrete overlays, including bridge deck renovation and structural bonding across composite interfaces.

1.2 OBJECT AND SCOPE

Since chemically bonded anchors result in the failure of concrete, adhesive-concrete interface or anchored material, the ultimate resistance of anchor can be predicted through the sum of the contributions of concrete strength, properties of anchored material (which is steel ribbed bars (threaded rods) for this work), and anchorage depth. In this work, all three factors and the predictions of current tables and equations related to anchorages are examined throughout site tests.

The aim of this study is to determine the in situ performance of anchors at retrofit works with low concrete compressive strengths, so the most common anchor and adhesive type are chosen for site tests. The installation and pull-out tests are also performed as it is done on real retrofit works.

Background and literature survey of the study will be given in the second chapter by examining the types of anchoring devices, behavior of anchors, anchor design and factors affecting anchor performance. The experimental study will be given in the third chapter by examining the general description of the structure on which the tests are performed, the anchorage properties and the experimental program. Results and evaluation of the experimental work will be examined in the fourth chapter. Tensile behavior of anchors and effects of parameters on failure loads of anchorages will be given in the fourth chapter. Finally, conclusions and recommendations are given in the fifth chapter.

The specific terms and definitions used throughout the thesis study are given in Appendix A. The structural project layouts of the building on which the pull-out tests are performed are given in Appendix B. The data sheet of the adhesive used for anchorages is given in Appendix C and finally the project report of the statistical analysis performed with the software Minitab 14 is given in Appendix D.

CHAPTER 2

BACKGROUND AND LITERATURE SURVEY

2.1 TYPES OF ANCHORING DEVICES

Anchors in reinforced concrete structures are often used either in rehabilitation of existing structures or attaching an equipment to the base material. In addition the pull-out strength of an existing or a newly cast concrete can also be determined by the use of mechanical anchoring devices.

Anchors to concrete can be divided into two general categories as cast-in-place anchors and post-installed anchors.

2.1.1 Cast-in Place Anchors

Cast-in place anchor is an anchor that is installed prior to the placement of concrete and derives its holding strength from plates, lugs, or other protrusions that are cast into the concrete [5]. Cast-in place anchors provide less flexibility to the designer than post-installed anchors. There are three main groups of cast-in place anchors which are non-adjustable embedded anchors, bolted connections and adjustable anchors.

2.1.1.1 Non-Adjustable Embedded Anchors

These anchors may have an end attachment, such as a coil loop, head, nut, or plate, which will enhance anchorage properties and develop full potential strength by means of bond, and/or bearing, or both [6]. Typical examples of these anchors are shown below (Fig.2.1). In some cases, they are fastened to the formwork. Stud welded plates may be an example of this type (Fig.2.2). They develop their full strength by means of mechanical interlock.

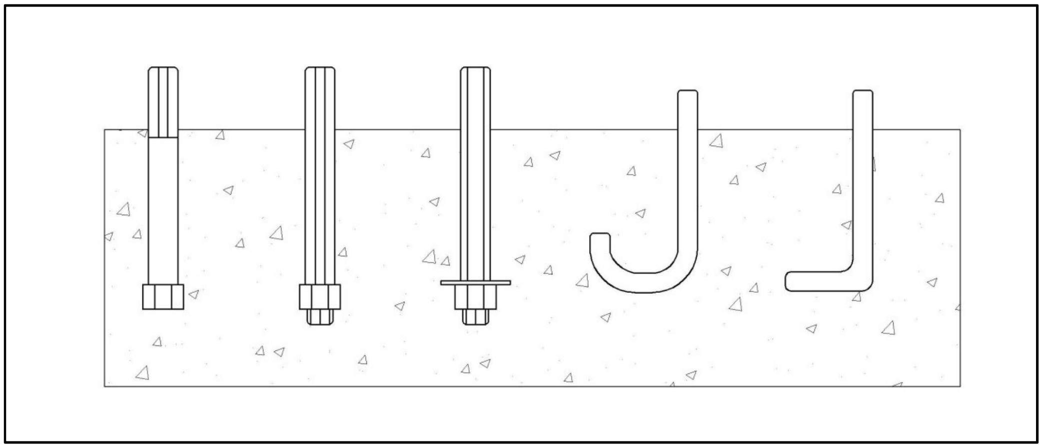

Figure 2.1 Examples of cast-in place anchors [6]

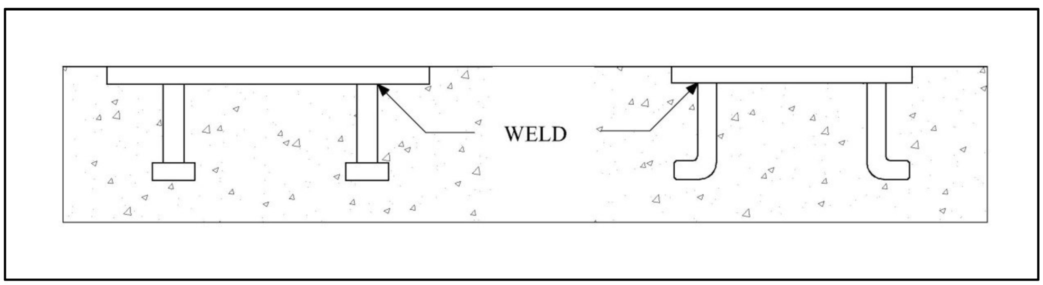

Figure 2.2 Examples of cast-in place anchors, welded studs [6]

2.1.1.2 Bolted Connections

These anchors consist of headed bolts, as embedded or through connectors [Fig.2.3]. These types of anchors develop their full strength by means of direct bearing of the bolt head to the concrete. The friction between the bolt and the concrete may often be totally eliminated by the use of a sleeve.

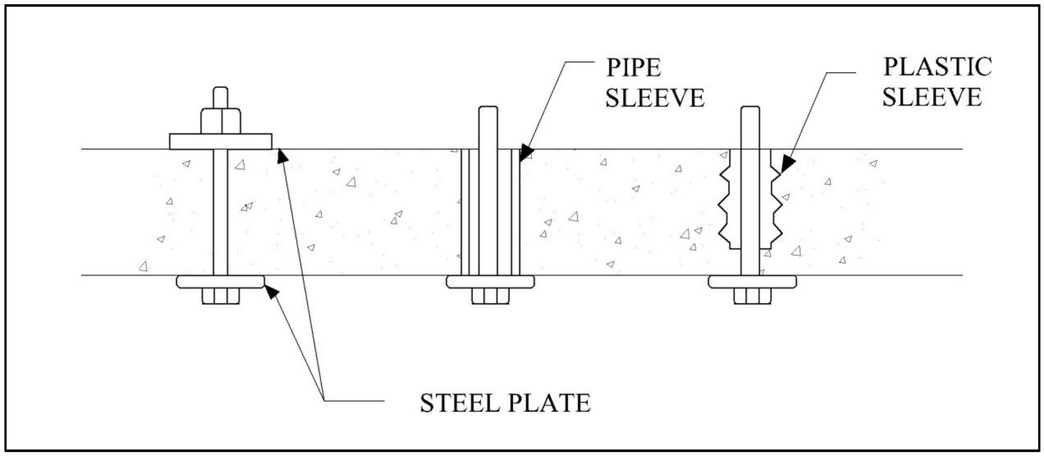

Figure 2.3 Bolted connections [6]

2.1.1.3 Adjustable Anchors

Adjustable anchors are normally used for attaching large machines or equipment bases and can be adjusted for lateral position or depth (Fig. 2.4). Usually, the concrete surrounding the anchor is cast after the positioning of the machine or equipment that it will carry.

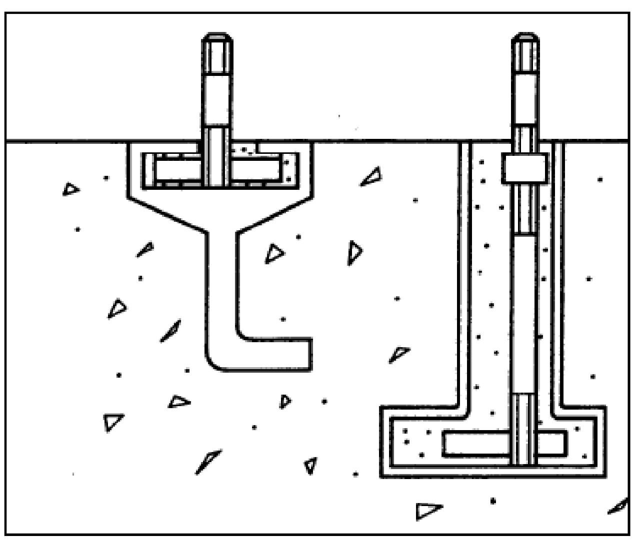

Figure 2.4 Adjustable anchors [6]

2.1.2 Post-Installed (Retrofit) Anchors

Post-installed anchors are installed in a hole drilled in the hardened concrete, but they differ from each other in their working principles. There are three main groups of post-installed anchors; as chemically bonded anchors, expansion anchors and undercut anchors. These three kinds of post-installed anchors are examined as individual parts in the thesis study.

2.1.3 Bonded Anchors

Bonded anchors transfer the load through the bond or adhesion between the anchor and walls of the drilled hole in hardened concrete. The hole is filled with resin or grout.

2.1.3.1 Chemically Bonded (Adhesive) Anchors

They are usually threaded rods (Fig.2.5) or deformed bars which are bonded in place with two-part chemical compounds of polyesters, vinylesters, or epoxies. The chemicals are usually available in four forms: glass capsules, plastic cartridges, tubes, or bulk.

Glass capsules are inserted into the drilled hole, and then broken by the anchor rod when it is rotated and hammered into place, thereby mixing two components to cause a chemical reaction.

The plastic cartridges are used with a dispenser and a mixing nozzle which mixes the two parts, initiating a chemical reaction while installing the compound into the drilled hole. The anchor rod is then inserted into the hole.

The tube type contains two components which are mixed by kneading the tube, placing the mixture into the hole, and finally, inserting the anchor rod into the hole.

The bulk systems predominantly use epoxies, which are either premixed in a pot and used immediately, or pumped through a mixer and injected, into the predrilled hole. The anchor is installed immediately afterward. Epoxies can be formulated to set up quickly or slowly (up to 36 hours curing time) [6]. In Turkey, two component bulk epoxies are the most widely used structural adhesives.

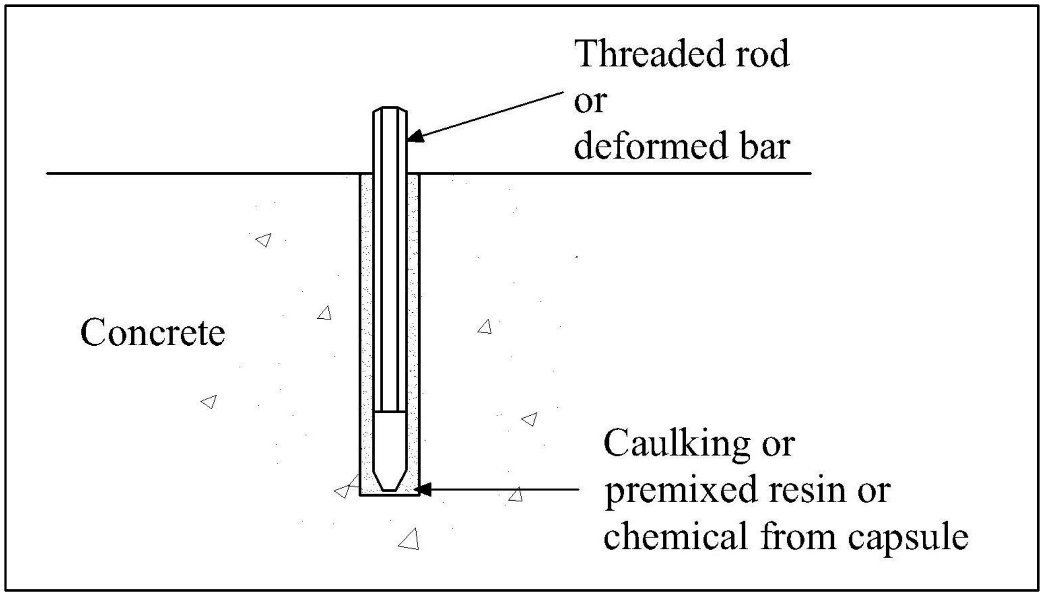

Figure 2.5 Chemically bonded anchor (threaded rod) [6]

2.1.3.2 Grouted Anchors

Grouted anchors are headed or headless bolts or threaded rods (Fig.2.6). They are set in predrilled holes with portland cement and sand grout or other commercially available premixed grout [6]. The diameter of the predrilled hole is at least 150 % larger than that of the anchor [7].

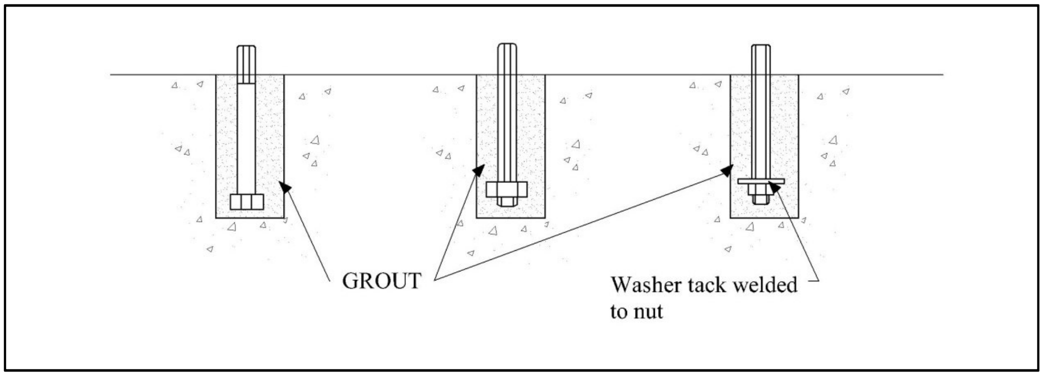

Figure 2.6 Grouted anchors [6]

2.1.4 Expansion Anchors

Expansion anchors are designed to be inserted into predrilled holes and then expanded by either tightening the nut (torque controlled expansion anchor) (Fig.2.7), or hammering the anchor (deformation controlled expansion anchor). The load transfer of the expansion anchors are based on the mechanical interlock between the anchors and the base material.

2.1.5 Undercut Anchors

Undercut anchors (Fig.2.8) transfer forces into the structure by mechanical interlock with the base material by directly bearing on the walls of the base material. They cause little or no expansion force in the concrete, but generate high tensile loading capacities [6].

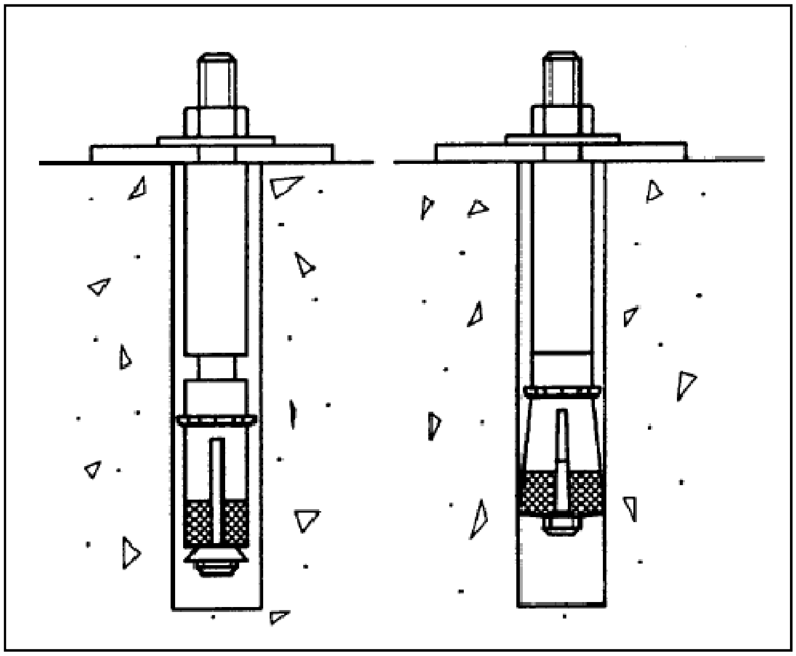

Figure 2.7 Torque controlled expansion anchor [6]

2.2 BEHAVIOR OF ANCHORS

Understanding anchor behavior is necessary in specifying the appropriate anchorage for a given application. This includes an understanding of failure modes and strengths as well as load displacement and relaxation characteristics of various anchor types [6]. Also, it requires an in-depth understanding of the physical phenomena involved in the complete process of setting and loading in building material, mainly in concrete [8]. This chapter covers chemically bonded post-installed anchor behavior in uncracked concrete.

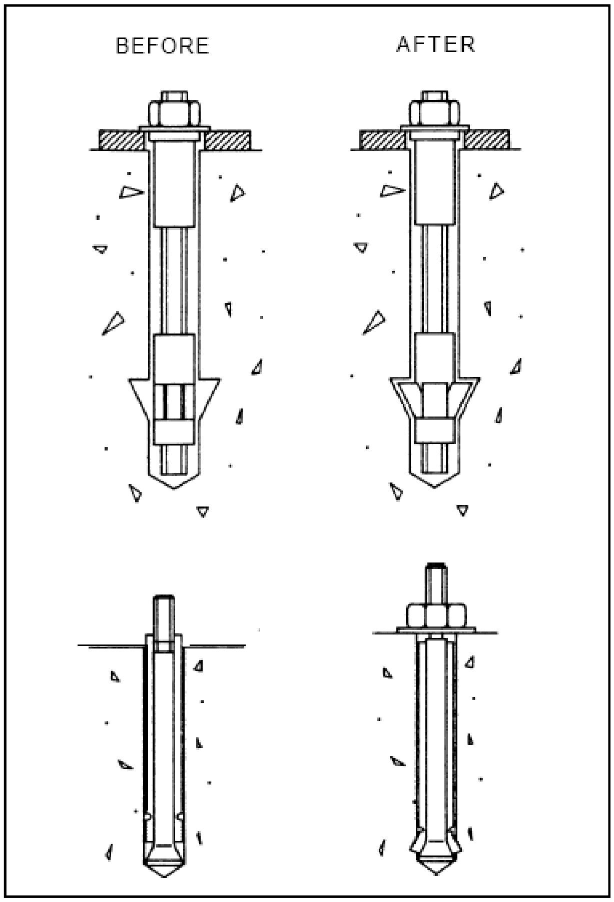

Figure 2.8 Undercut anchors [6]

2.2.1 Types of Loading

Anchors are loaded through attachments to the embedded anchor in tension and shear or combinations of both (Figure 2.9). Anchors may also be subjected to bending depending on the shear transfer through attachments. Dynamic loading may occur in pipelines, bridges, railway barriers and machine foundations. Fatigue loads and seismic loads may also act on anchorage systems.

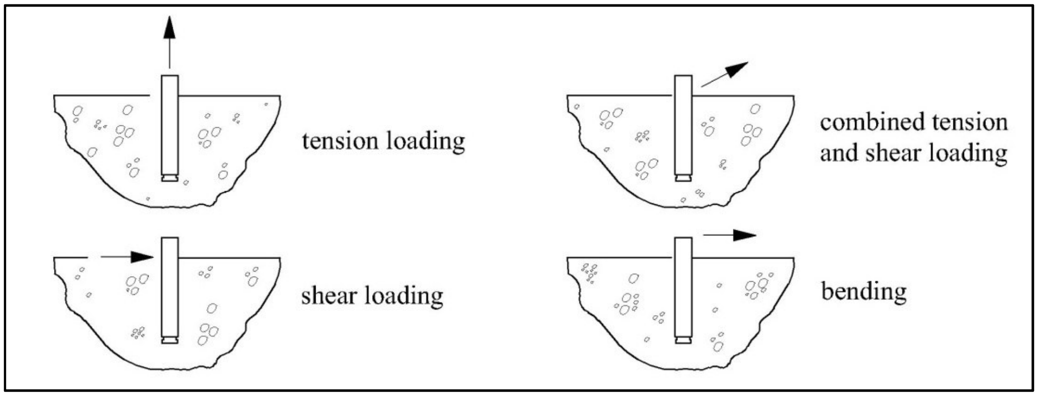

Figure 2.9 Possible loading types of anchors [6]

Behavior of the anchors under tensile loads will be examined in detail throughout the thesis study; therefore, a typical test apparatus for unconfined tensile testing is given in Figure 2.10, and a typical apparatus for confined tensile testing in Figure 2.11.

Unconfined tests allow an unrestricted formation of the rupture concrete cone. In confined tests concrete cone failure is eliminated by transferring the reaction force close to the anchor into the concrete [9]. It is known that the capacity of an anchor 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 will lead to higher bond capacity between the anchor and concrete block [10].

Tastani et al. [11] performed pull-out tests in order to examine the effect of external confinement and showed the confinement effect as showed in Figure 2.12.

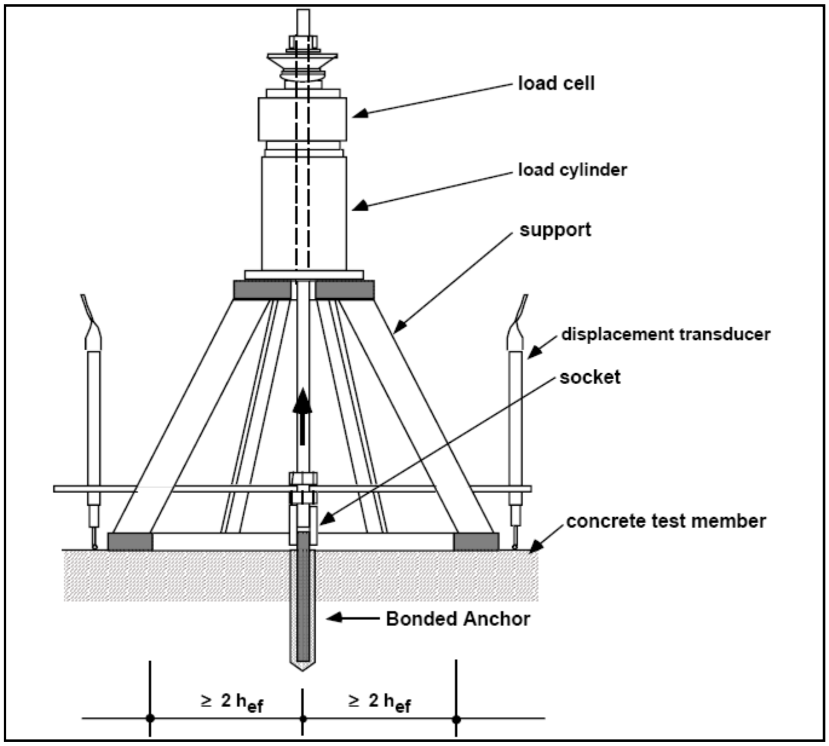

Figure 2.10 Unconfined tensile test apparatus [9]

2.2.2 Failure Modes under Tensile Loading

Loading type may be an important factor which influences the failure mode, but only the failure modes under tensile loading are examined throughout this study. There are five primary failure modes of anchors under tensile loading which are examined below. A typical bonded anchor with tensile loading can be seen in Figure 2.13.

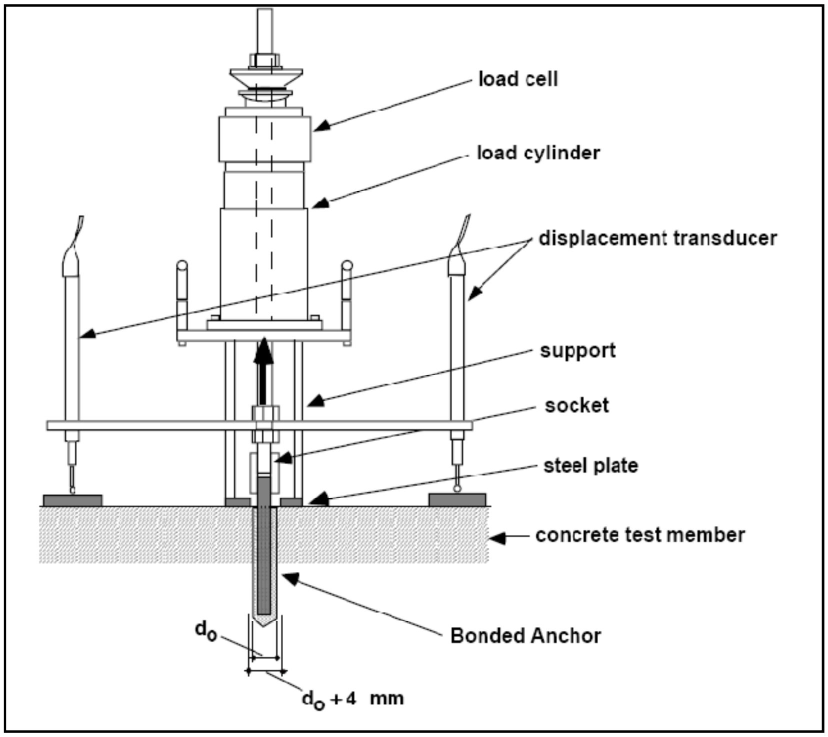

Figure 2.11 Confined tensile test apparatus [9]

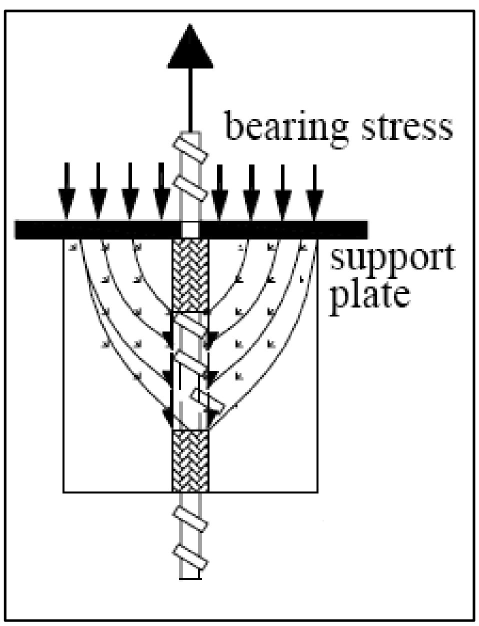

Figure 2.12 Schematic description of the confinement effect [11]

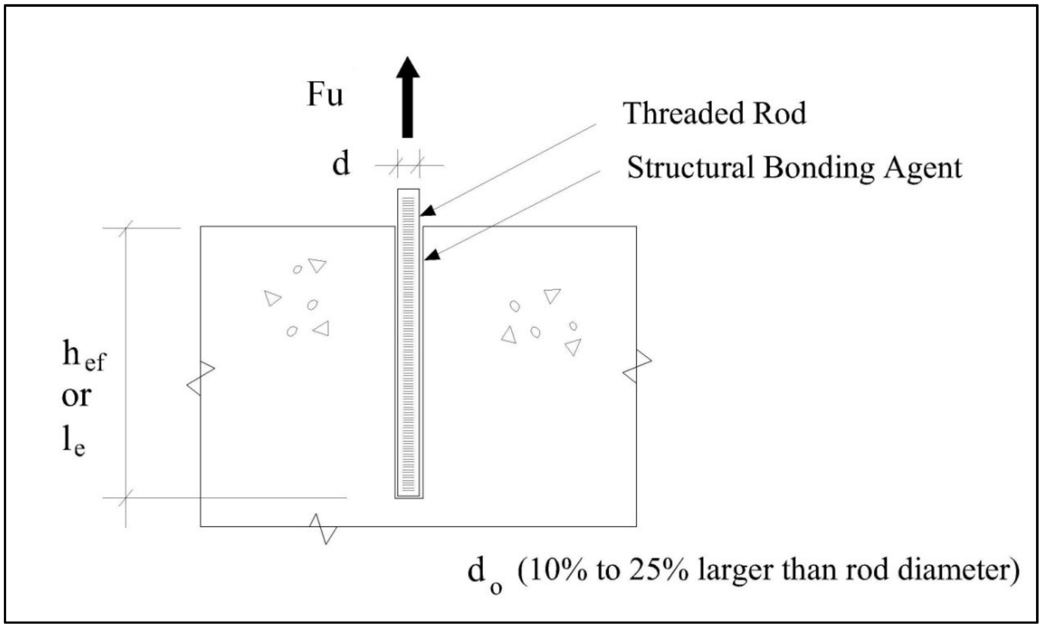

Figure 2.13 A typical bonded anchor with tensile loading [12]

2.2.2.1 Failure of Anchor Steel

Anchor steel failure (Fig.2.14) is characterized by yielding and fracture of steel rod and is likely to occur only with sufficiently long embedment depths [12, 13] with strong adhesives. To achieve this failure mode, the tensile strength of the anchor steel must be less than the strength associated with the embedded portion of the steel. The ultimate strength can be determined by

$$F_u = A\,\sigma_{ult} \tag{2.1}$$

where F_u = the ultimate strength of the anchor

A = tensile stress area, cross sectional area of the anchor steel

σ_{ult} = ultimate tensile strength of the anchor.

This failure mode defines the upper limit for the tensile load carrying capacity since the anchor steel reaches to its maximum tensile capacity under the applied tension load. Failure of the anchor under a tensile load is often not possible in retrofit works, as the embedment depth is usually kept minimal and the strength of the concrete is often low.

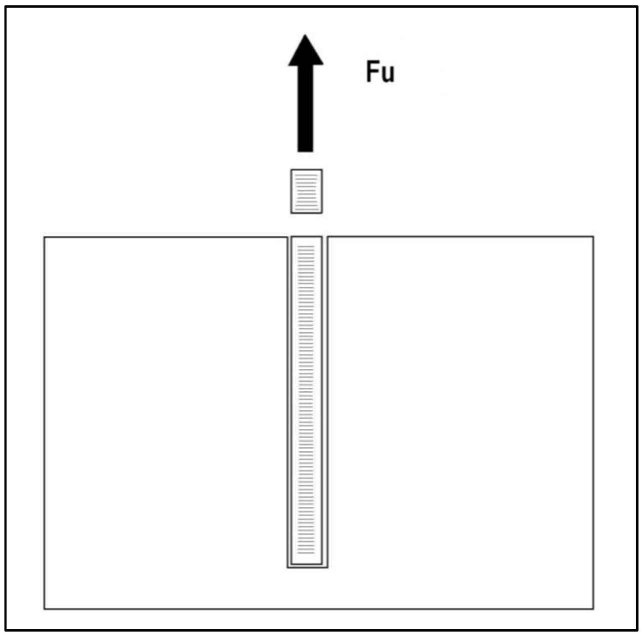

Figure 2.14 Failure of anchor steel [12, 13]

2.2.2.2 Pull-out of the Anchor

Pull out of the anchor failure is also called bond failure, or sometimes combined cone and bond failure which arte schematically provided in Figure 2.15. For embedments greater than 50-100 mm, the most commonly observed failure is characterized by the combined cone-bond failure mode with a shallow cone (usually less than 50 mm deep) attached to the top of the anchor [8]. In some installations, bond failure without a concrete cone (Fig.2.16) may occur if the bonded surface lacks adequate strength due to the adhesive itself, improper curing, or inadequate hole preparation [12, 13].

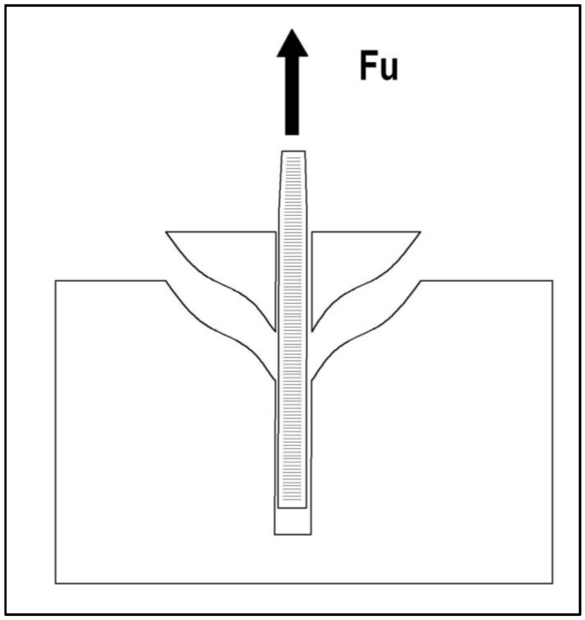

Figure 2.15 Combined cone-bond failure [12]

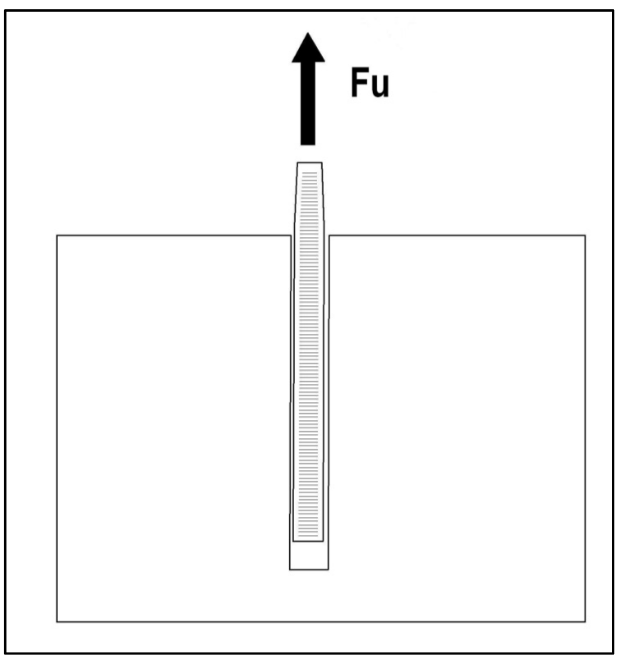

Figure 2.16 Bond failure without a concrete cone [12]

Cook et al. [12] showed that bond failure without a concrete cone (Fig.2.16) can occur when the top portion of the embedment length is debonded about 50 mm. Cook et al. [14] produced this failure by performing confined tension tests.

The pull-out capacity of the 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 [1]. 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 remaining embedment depth.

2.2.2.3 Concrete Cone Failure

When the embedment of an anchor or a group of anchors is insufficient to develop the tensile strength of the anchor steel, a pull-out cone failure of the concrete is the principal failure mode [6]. Concrete cone failure is observed in only shallow embedments (75 mm or smaller) [15] or a small concrete cone is observed as a result of the confinement created by the loading apparatus. Therefore it can be concluded that the failure mode of an anchor for embedments greater than 75 mm would not change by confined or unconfined testing, since the accepted failure mode is the combined cone-bond failure with a shallow cone attached to the top of the anchor, but the failure load would be greater for confined tensile tests because of the confinement effect.

The angle of the failure cone, measured from the axis of the anchor, varies along the failure surface and shows considerable scatter. In ACI 349-85 [16], the angle of the failure cone of bonded and expansion anchors was assumed as 45°. In ACI 349-01 [17], the angle of the failure cone of bonded and expansion anchors measured from perpendicular axis of the anchor axis is 35° (Fig. 2.17).

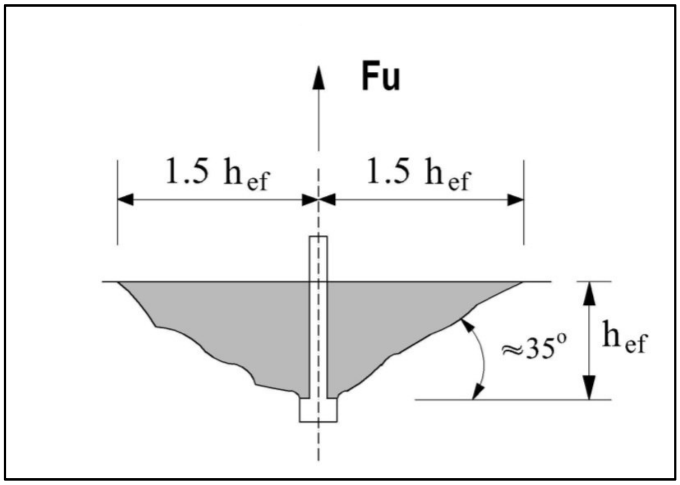

Figure 2.17 Concrete cone failure [17]

Consequently, when the embedment depth is shallow, the observed concrete cone failure is due to tensile capacity of the concrete, not the anchor steel.

2.2.2.4 Splitting of Concrete Failure

Anchors installed in thin, unreinforced slabs and beams may result in a split in the structural member where the concrete slab or beam fails in bending [18]. Splitting failure is characterized by the propagation of a crack in a plane containing the anchor. Splitting may lead either to complete split of the structural element, or to cracks between adjacent anchors or between the anchors or the edge (Fig.2.18). The failure load is usually smaller than that of a concrete cone failure.

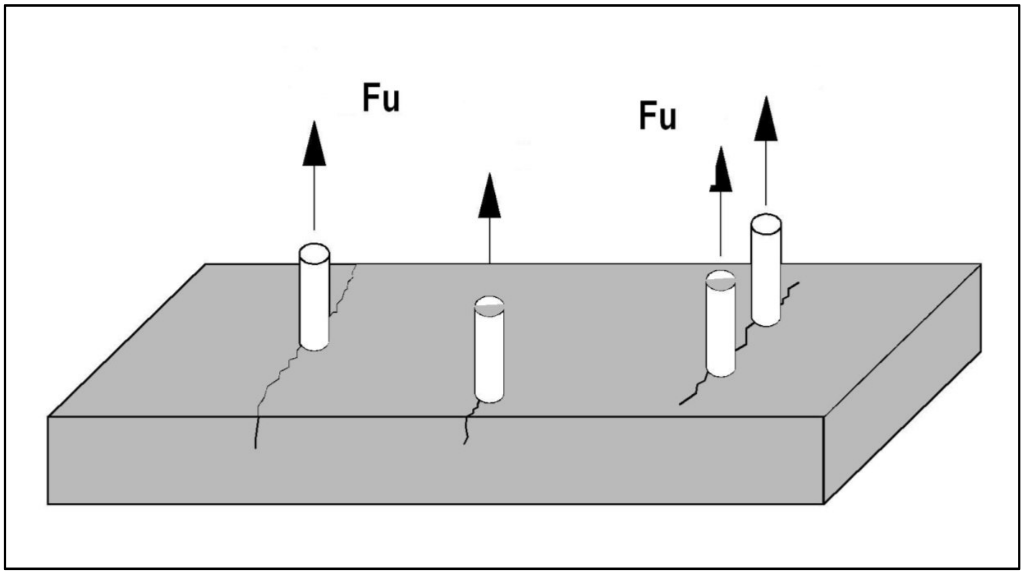

Figure 2.18 Splitting of concrete failure [17]

2.2.2.5 Spacing and Edge Cone Failure

If an anchor is located too close to an edge of a structural member or too close to another anchor, concrete cone that forms around the anchor extends to the edge or to the neighboring anchor causing spacing or an edge cone failure (Fig.2.19).

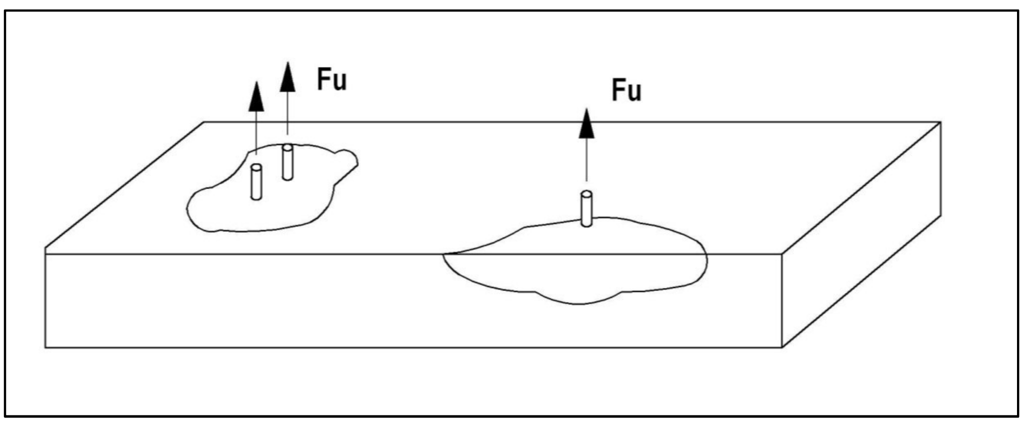

Figure 2.19 Spacing and edge cone failure [6]

2.3 ANCHOR DESIGN

Anchorages in concrete can be subdivided into three different working principles according to the load transfer mechanism, namely friction, keying and bonding [8]. For friction type anchors the tensile load is transferred from anchor to base material due to the friction created by expanded segments. Keying type anchors carry the tensile load by main keys at the end of anchor resulting in a concrete cone failure or in yielding of the steel rod. For bonding anchors the tensile load is transferred mainly due to the adhesive bond between anchor rod and concrete with a shear and concrete cone combined failure. In fact many anchors obtain their holding power from a combination of the three working principles.

The design philosophy of post-installed anchors shows a great variety not only in the design procedure but also in the estimation of ultimate capacity of anchors. This fact is owed to the basic differences in the design codes founded on the research being conducted in the U.S. and in Europe [19]. While research emphasis in European Union was largely based on failing of concrete, U.S. approach was to design ductile fastenings which meant ductile steel failure of anchorage [20].

The U.S. Nuclear Regularity Commission requires nuclear safety related structures to be able to sustain the most severe combination of loading conditions for a minimum number of cycles. ACI Committee 349 [17], thus required that all major connections and cast-in place anchorages be ductile and fail in anchor steel rather than concrete. For non-ductile post-installed and expansion anchors, the code requires a minimum safety factor of three based on the average of project testing for maximum combinations of loading conditions.

However, research in European Union was largely funded by anchor manufacturers. Correspondingly, research emphasis on testing anchors in Europe has largely been on failing of concrete since manufacturers of retrofit anchors designed the anchors to fail concrete, and expounded this feature to promote the quality of their product [21].

There are many different design methods available to predict the anchor capacity under tension. All of them are similar in philosophy, but basically change according to anchor type. Since all the methods (formulas) for obtaining anchor capacities under tension are empirical, there are some small differences between methods for same anchor types depending on the sets of experiments on which the methods are based on.

For expansion, undercut and adhesive anchors for which concrete cone failure is the governing failure mode, concrete capacity design (CCD) method is the most accepted one, and this method is examined shortly in this chapter. Previously, ACI 349-85 [61] had a different method than CCD, but the new form of ACI 349-85 [16] which is ACI 349-01 [17] has accepted the CCD method. ACI 349-85 [16] is also examined shortly in this chapter.

As mentioned before, concrete cone failure is observed in only shallow embedments (75 mm or smaller) [15]. For embedments greater than 50-100 mm, the most commonly observed failure is characterized by the combined cone-bond failure (Fig.2.15) mode with a shallow cone (usually less than 50 mm deep) attached to the top of the anchor [12]. Although, there is not an accepted method for combined cone and bond failures or pull-out failures, researchers have declared several empirical methods for obtaining anchor capacities under tension. The differences between these methods are also due to the sets of experiments on which the methods are based on. The methods related with combined cone-bond failure are also examined in this chapter.

2.3.1 ACI 349-85 Method

ACI 349-85 Appendix B [16] limits the tensile capacity of the cone failure of an anchor to a uniform stress of

$$f_{ct} = 4\phi\sqrt{f_c'} \quad (2.2)$$

where f_{ct} = concrete tensile strength (psi)

ϕ = strength reduction factor (used for design purposes)

f'_c = compressive strength of concrete measured on 150 mm x 300 mm cylinders (psi).

This uniform tensile stress is assumed to act on an effective stress area, A_e, which is defined by the projected area of stress cones radiating toward the attachment from the bearing edge of the anchor heads [16].

The ultimate failure load is then calculated by the following equation:

$$f_u = f_{ct} A_e \tag{2.3}$$

where f_u = ultimate failure load (lb)

A_e = effective stress area.

Additional information about ϕ can be found at ACI 349-85 [16].

Figure 2.20 represents the projected area of a single anchor loaded in tension.

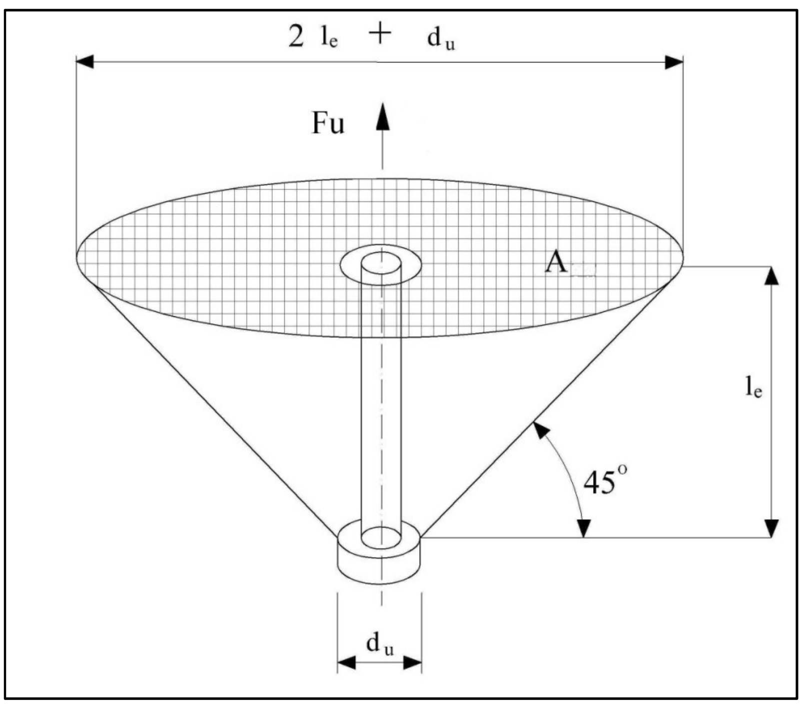

Figure 2.20 The projected area of a single anchor loaded in tension [1]

For a single headed anchor unlimited by edge or spacing (overlapping cones) effects, the effective area for anchors can be derived as:

$$A_e = l_e^2 \pi (1 + \frac{d_h}{l_e}) \quad (2.4)$$

where l_e = effective embedment depth (inch)

d_h = diameter of the anchor head (inch)

Substitution of equation 2.2 and 2.4 into equation 2.3 gives:

$$f_u = 4\phi\alpha\sqrt{f_c'}\, l_e^2 \pi (1 + \frac{d_h}{l_e}) \quad (2.5)$$

where f_u = ultimate failure load (lb)

SI equivalent of this formula is:

$$f_u = 1.043\phi\alpha\sqrt{f_c'}\, l_e^2 \pi (1 + \frac{d_h}{l_e}) \quad (2.6)$$

where f_u = ultimate failure load (N)

f'_c = compressive strength of concrete measured on 150 mm x 300 mm cylinders (N/mm^2)

l_e = effective embedment depth (mm)

d_h = diameter of the anchor head (mm)

In the new version of ACI 349-85 [16], which is ACI 349-01 [17], the angle of the failure cone of bonded and expansion anchors measured from perpendicular axis of the anchor axis is 35° (Fig.2.14). ACI 349-01 [17] has also accepted to use the CCD method which will be explained in the proceeding chapter.

2.3.2 Concrete Capacity Design (CCD) Method

The concrete capacity design method was proposed as an alternative to the ACI 349-85 method [1]. Under tensile loading, the concrete capacity of a single anchor is calculated assuming a 35° angle between the failure surface and surface of structural member. This verifies the observations that the horizontal extent of the failure surface is about three times the effective embedment depth [Fig. 2.21] [1].

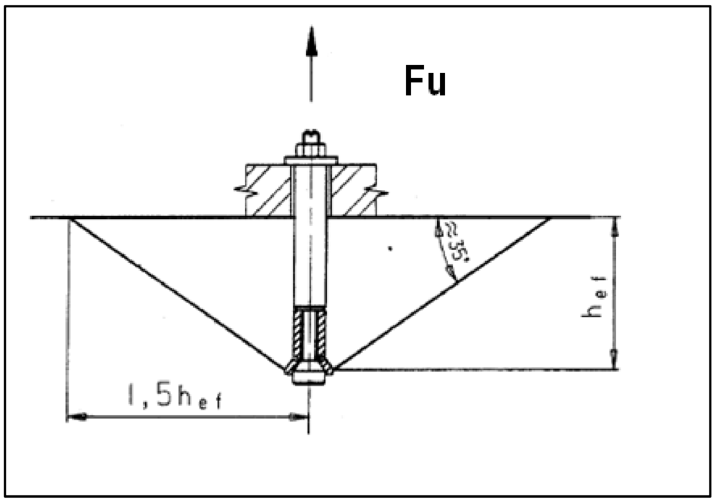

Figure 2.21 Idealized concrete cone assumed by CCD method [1]

The form of the equation for predicting the tensile capacity of a single anchor is given by Fuchs et al. [6] and Cook et al [22, 23].

$$f_u = 16.5\, l_e^{1.5}\sqrt{f'_c} \tag{2.7}$$

where f_u = ultimate failure load (N)

l_e = effective embedment depth (mm)

f'_c = compressive strength of concrete measured on 150 mm x 300 mm cylinders (N/mm^2)

2.3.3 Uniform Bond Stress Model and Elastic Bond Stress Model

Bond stress models include a uniform and an elastic bond stress models. Concrete cone failure is observed in only shallow embedments (75 mm or smaller) [15]. Therefore, the uniform bond-stress model is commonly used in design when the accepted failure mode is the bond failure which means the embedment length is more than 75 mm. The model is easy to apply since a uniform distribution along the anchorage length is assumed. It predicts the capacity of the anchor as a function of the uniform failure stress τ_o. The following equation is used to predict the failure load by uniform bond stress:

$$f_u = \tau_o \pi l_e d_o \tag{2.8}$$

where f_u = ultimate tensile load applied to the anchor (failure load) (N)

τ_o = uniform failure stress (N/mm^2)

l_e = effective embedment depth (mm)

d_o = diameter of the hole (mm)

The uniform bond stress model does not account for compatibility between the concrete, bonding agent, and threaded rod [12]. The elastic bond stress model has been proposed to address compatibility relationships between the concrete, bonding agent and the threaded rod for the bonded anchor [12]. The equation for the elastic bond stress model is:

$$f_u = \tau_{max} \pi d_o \left(\frac{\sqrt{d_o}}{\lambda'} tanh \frac{\lambda' l_e}{\sqrt{d_o}} \right) \tag{2.9}$$

where f_u, d_o, and l_e are same as above equation,

τ_{max} = maximum failure stress (N/mm^2) at the elastic limit

λ' = elastic constant which is dependent on the shear stiffness of the adhesive concrete system and axial stiffness of the threaded rod. λ' is independent of the hole diameter. The elastic constant is a stiffness property of the system, and is determined from the slope of load-displacement diagram [12].

The uniform and elastic bond stress models are shown in Figure 2.22.

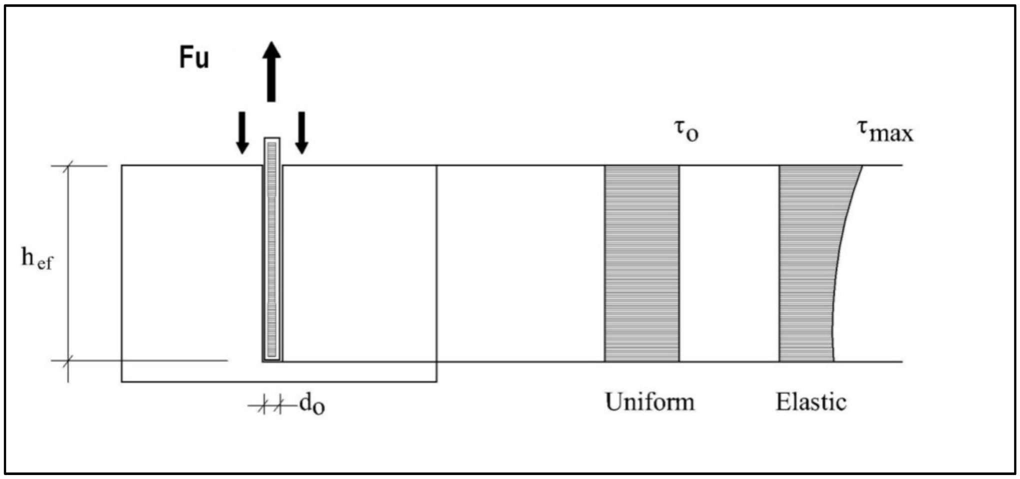

Figure 2.22 Uniform and elastic bond stress models [22]

Cook et al. [22] showed that the uniform bond stress model appears to be more appropriate than the elastic bond stress model. The use of the uniform bond stress model requires the evaluation of whether the anchor diameter (d) or the hole diameter (do) is most appropriate to use. Cook et al. [22] showed that there is a slight trend favoring anchor diameter but the results are not conclusive. The anchor diameter is preferred to be used throughout the thesis study.

For embedments greater than 50-100 mm, the most commonly observed failure is characterized by the combined cone-bond failure (Fig.2.12) mode with a shallow cone (usually less than 50 mm deep) attached to the top of the anchor [12]. Cook et al. [2] concluded that the contribution of the cone to the total strength of the anchor is minimal and can be neglected. Cook et al. [22] presented models assuming an effective embedment length equal to the actual embedment length less 50 mm (≅ 3d) to account for shallow concrete cone. Then the equation of the uniform bond stress model becomes:

$$f_u = \tau_o \, \pi \, d[l_e - 50\text{mm}(\text{or } 3d)] \tag{2.10}$$

where d = diameter of the anchor (mm) and the other terms are same as above expressions.

2.4 FACTORS AFFECTING ANCHOR PERFORMANCE

Factors that influence the bond strength of adhesive anchors can be classified as either internal or external. Internal factors (such as chemical formulation, manufacturing processes, and packaging) are generally beyond the control of the designer and installer [24]. Internal factors were not investigated in this study. External factors are generally beyond the direct control of the manufacturer, but usually can be accommodated by the designer and controlled by the installer [24].

2.4.1 Concrete Strength

When the capacity of the anchor is controlled by concrete properties, it is the tensile properties of the concrete which controls the failure modes of anchors. Tensile properties of the concrete are related to compressive properties, but the tensile-compressive strength relationship can be complicated by the influence of grain size, type and distribution of aggregate particles [25]. For this reason, construction practices which permit segregation of aggregate will increase the variability of tensile strength more than the compressive strength [20]. Segregation of the concrete is influenced by the slump, the height of drop of the concrete, and the amount of vibration during placement [26]. That is probably why the capacity of anchors may vary depending on their location on the structural member.

The capacity of an anchor usually increases with increasing tensile strength of the concrete until the capacity reaches to steel failure capacity of the anchor for shallow embedment depths. Cook et al. [22] showed that for concretes having compressive strengths of 20 MPa to 60 MPa, the effect of concrete strength on the capacity of adhesive bonded anchors is negligible for most products.

Eligehausen et al. [27] plotted the bond strength of cast-in-place and post-installed rebars as a function of concrete compressive strength (Fig.2.23) and showed that while the bond strength of cast-in-place rebars increases with increasing concrete compressive strength, the bond strength of post-installed bars increases only up to a concrete strength $f_{c,200}$ = 40 MPa.

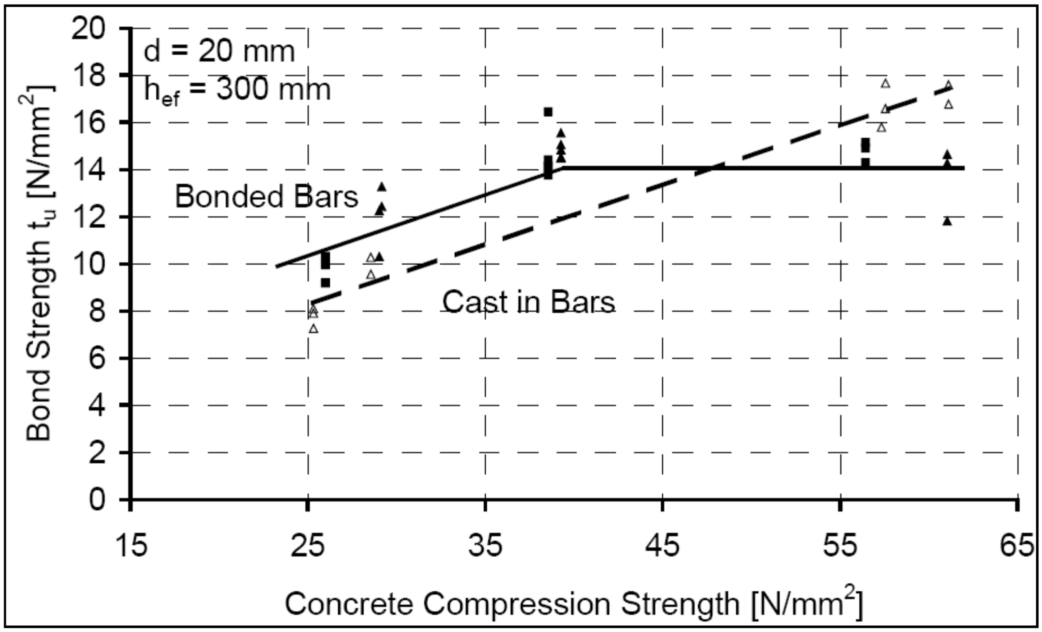

Figure 2.23 Influence of concrete compressive strength [27]

Gesoğlu et al. [28] studied the load-deflection behavior of adhesive and grouted anchors embedded in both plain and steel fiber reinforced normal (30 MPa) and high (60 MPa) strength concrete and concluded that the anchor capacity generally increased with the concrete strength even though the increment was not uniform for different types of anchors having various embedment depths. At small embedment depths, the concrete strength appeared to be more effective mainly because shallow anchors failed generally via concrete cone breakout. As the anchor embedment depth was increased, however, this beneficial effect was reduced due to shifting of failure mode of the anchors from concrete cone failure to pullout or steel failure.

2.4.2 Steel Strength

The type of steel used in anchorage is largely dependent on the type of the anchorage. For chemically bonded post-installed anchors, the most widely used steel type is threaded rebars. Steel failure is likely to occur only with sufficiently long embedment depths [12, 13]. To achieve this failure mode, the tensile strength of the anchor steel must be less than the strength associated with the embedded portion of the steel. When the steel failure is the accepted failure mode, it is obvious that the bond strength will increase with increasing tensile strength of the steel. Threaded rebars will have greater bond strengths than the unthreaded ones, especially when the bond failure is the accepted failure type. Çolak A. [29] claimed that the threaded rebars (or ribbed bars) significantly improve bond performance under seismic conditions.

Klingner et al. [30] claimed that nominal tensile capacity can reasonably be calculated as the product of the appropriate cross sectional area of the anchor times the specified minimum yield strength of the anchor steel.

Gesoğlu et al. [28] performed pull-out tests on steel fiber reinforced concretes and showed that the pull-out capacities of the anchors were not significantly affected by the addition of steel fibers into the concrete. The ultimate deflection and toughness, however, were greatly improved provided that the anchor failed through concrete breakout.

2.4.3 Edge Distance

If the anchor is placed too close to an edge of the concrete, the failure cone of the anchor will overlap with the edge and the failure load will be reduced. Then the failure type will be the edge cone failure. Therefore, the edge distance of the anchor should be enough to prevent edge cone failure.

ACI 349-85 [17], Appendix B recommends a minimum side cover or edge distance c_1 required to preclude edge failures which is:

$$c_1 = d_o \sqrt{\frac{f_{ut}}{3.54\sqrt{f_c'}}} \tag{2.11}$$

where c_1 = edge distance (mm)

d_o = diameter of the anchor (mm)

f_{ut} = tensile strength of anchor steel (N)

f_c' = compressive strength of concrete measured on 150 mm x 300 mm cylinders (N).

ACI 349-01 [17] recommends that the minimum edge distance for a post-installed anchor be based on the greater of

i) The minimum cover requirements for reinforcement, or

ii) The minimum edge distance requirements for the products as determined by field testing. Moreover, the minimum edge distance shall not be less than two times the maximum aggregate size.

2.4.4 Anchor Spacing

If the anchors of an anchor group are placed too close to each other, the failure cones of individual anchors will overlap and a common failure cone will be pulled out. The failure load will be reduced compared to widely spaced anchors [21]. Then the failure type will be the spacing cone failure.

When the concrete cone failure is the accepted failure mode, if the height of the failure cone is taken as equal to the anchorage length, or embedment depth, and its slope as 30°, an overlapping of the failure cones can be expressed when the actual spacing is smaller than the critical value, s_c, for full anchor capacity [20]. The critical anchor spacing is shown in Figure 2.24.

$$s_c = \frac{2l_e}{\tan 30} \cong 3.5l_e \tag{2.12}$$

where s_c = critical anchor spacing

l_e = embedment depth (length).

ACI 355 [6] proposes a coefficient called "χ" to reduce the ultimate failure load of anchor which does not have satisfactory anchor spacing for full anchor capacity. In this method the failure load of two-point anchorages results in:

$$f_{u2} = \chi_a f_{u1} \tag{2.13}$$

where f_{u2} = total failure load of two anchorages

f_{u1} = ultimate failure load of a single anchor

$\chi_a = 1 + \frac{s}{s_c} \leq 2$

s = distance between center of anchors

s_c = critical anchor spacing

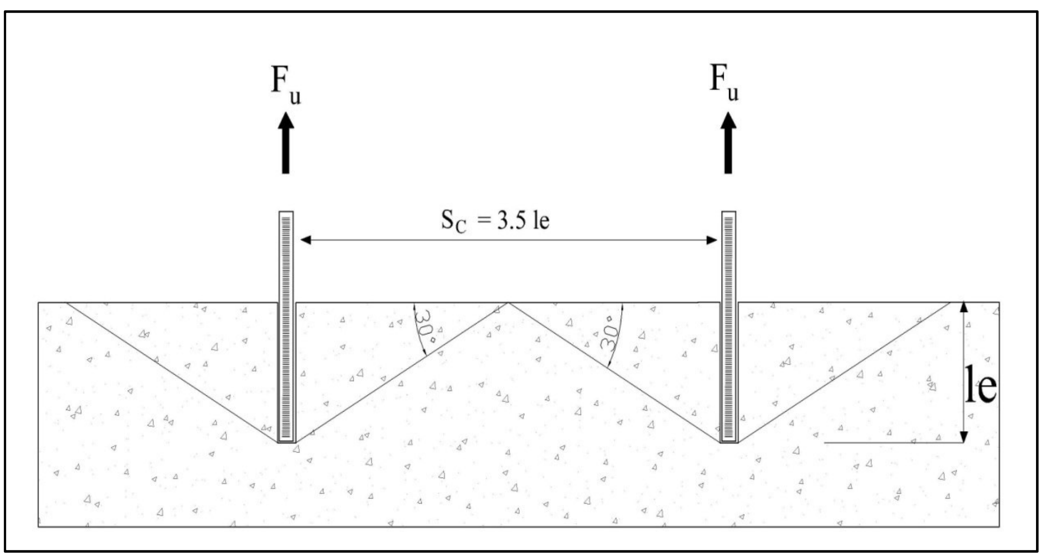

Figure 2.24 The critical anchor spacing

When the failure mode is the bond failure or combined cone-bond failure, anchor spacing is not that critical; therefore smaller anchor spacing may be used.

2.4.5 Embedment Depth

The testing of embedments deeper than 9 in. for individual anchors unaffected by the proximity of edges has largely been limited to steel failures [19]. The bond strength of the anchor increases with increasing embedment depth until when the steel failure becomes the governing failure mode.

Gesoğlu et al. [28] showed that the embedment depth was the most important parameter affecting the pullout capacity of the anchors. As the properties of the anchor and concrete were kept unchanged, the pullout capacity of the anchor increased almost linearly with the depth of the embedment into concretes.

Unterweger et al. [31] claimed that usually, the effective embedment depth is about 10 times larger than the diameter of the threaded rod or reinforcing bar for chemically bonded anchors.

Çolak A. [29] showed that the ultimate tension capacity of steel rods increases as the embedment length of steel rods rises. However, this increase is not linear. There is little increase in strength once a certain embedment length is reached. The other notable feature is that the ultimate tension capacity starts to deviate from linearity at bonded lengths above about 75 mm. This indicates that linear bond stress distribution is not correct for longer bonded lengths.

2.4.6 Thickness of the Structural Member

Anchors installed in thin, unreinforced slabs and beams may result in a split structural member where the concrete slab or beam fails in bending [18]. If the thickness of the structural member is less than the required amount, splitting of concrete failure may occur as the failure type. According to the European Union of Agreement, the thickness of the structural member must be at least 10 cm and twice the anchorage depth [19, 20].

CHAPTER 3

EXPERIMENTAL STUDY

After the 1999 Kocaeli Earthquake, the use of chemically bonded post-installed anchors has seen a great growth for retrofits in Turkey, but no specific design codes are available for chemically bonded anchors which are commonly used for retrofit works.

As mentioned earlier, chemically bonded anchors are designed from related tables provided by adhesive manufacturers which involve a set of equations based on laboratory pullout tests on normal or high strength concretes. Unfortunately, concrete compressive strengths of existing buildings in Turkey, which need retrofit for earthquake resistance, ranges within 5 to 16 MPa according to the data obtained from the retrofit works of Ministry of Defense . The determination of tensile strengths of chemically bonded anchors in low-strength concretes is an obvious prerequisite for the design and reliability of retrofit projects.

The aim of this study is to provide useful data for retrofit works in Turkey, so the most common anchor and adhesive type are chosen for site tests. The installation and pull-out tests are also performed as it is performed on real retrofit works. All tests are conducted on site conditions and on a real structure, a common type residential building. The site conditions and the experimental study performed are explained in detail in this chapter.

3.1 GENERAL DESCRIPTION OF THE STRUCTURE

3.1.1 Brief History, Location and Description of Site Conditions

The structure is a reinforced concrete residential building for the use of military officers in Tuzla, İstanbul. The structure was built in 1982, and the authorities decided to retrofit the building in order to improve the earthquake resistance. The retrofit and restoration cost of the building was more than 70 % of the reconstruction cost, therefore the building is decided to be demolished and rebuilt. Therefore, the building was available only for a limited time for the testing of anchorages.

The structure has a total of six stories (Fig.3.1), one basement, one ground, and four normal stories with two apartments on each story. The height is 2.80 m for each story. It is located on a 1^{st} degree earthquake zone. If this building was decided to be strengthened, columns would be coated and shear walls would be added to the structural system. All of these retrofit works would have been done by chemically bonded post-installed anchors.

Figure 3.1 The residential building on which the anchorages are tested

All of the anchorages and tests are performed on July, 2006 when the building was emptied for demolishing. The temperature of the city was around 30°C during day, and 15°C during night times.

Soil investigations of the building are also performed and the soil formation is found to be CL (low plasticity clay). The soil class is Z2 according to Earthquake Code, and there are no risks related with the soil conditions.

There is no apparent damage on the building. The structural projects layout of the building floors are given as Appendix A.

3.1.2 Concrete Properties

The compressive strength of the concrete used in the building is determined by taking core specimens (destructive method) and by determination of the rebound numbers of the concretes by using Schmidt Hammer (non-destructive method). All tests and calculations related with the tests were done according to TS 10465 [32], TS EN 12504-1 [33], and TS EN 12504-2 [34] by the technicians of İstanbul Kültür University. A military instruction MSY 319-6 [35] was also used for this structure.

According to the regulations, 3 core specimens and 60 Schmidt Hammer readings (Fig.3.2), all from the columns or the shear walls, were taken from each story. Therefore, a total of 18 core specimens and a total of 360 rebound numbers were obtained. The compressive strength test results of the core specimens, and the rebound numbers are given in Table 3.1. Last column of Table 3.1 lists the compressive strength test results of the core specimens and the compressive strengths estimated from the Schmidt hammer readings. The core strengths are marked in “bold”. The compressive strengths of the core specimens changed between a minimum of 5.7 MPa and a maximum of 17.5 MPa. The overall average concrete compressive strength of the building was calculated to be 12 MPa, but the concrete compressive strength of the building according to TS 10465 [32] was 5.3 MPa. The standard deviation is 3.29 MPa, so the compressive strength of the building is 8.7 MPa according to new Earthquake Code [36, 37] of Turkey.

Figure 3.2 Rebound numbers taken by Schmidt Hammer

3.1.3 Reinforcement Properties

The building was reinforced concrete, so the reinforcement properties were also examined by using destructive and non-destructive methods. The reinforcements observed for the columns are listed in Table 3.2. The structure is symmetric and the structural system is same for all stories, so the reinforcement properties should be the same for repeating columns.

Table 3.1 Evaluation of material properties

No	Story	Location	Schmidt Hammer Rebound Numbers										R_{min}	R_{max}	R_{avg}	f_{te} N/mm^2
1	Basement	S118(K1)	25	29	27	27	25	22	26	26	24	26	22	29	25,7	**8,6**
2		S119(K2)	32	30	28	30	28	36	30	27	29	31	27	36	30,1	**11,8**
3		1P6(K3)	33	34	33	35	34	32	33	31	33	32	31	35	33,0	**15,1**
4		1P3	25	21	25	28	21	26	23	28	23	25	21	28	24,5	8,6
5		1P7	27	28	26	30	27	27	25	27	30	29	25	30	27,6	10,7
6		1P8	32	33	30	30	34	32	27	28	25	32	25	34	30,3	13,1
7	Ground Story	S218(K4)	31	31	36	32	34	34	33	30	33	30	30	36	32,4	**15**
8		S219(K5)	30	29	29	31	27	28	28	27	33	30	27	33	29,2	**14,1**
9		2P6(K6)	36	25	36	31	36	27	27	25	25	33	25	36	30,1	**14,1**
10		2P3	32	28	30	30	28	28	32	30	30	26	26	32	29,4	12,2
11		2P7	29	35	35	29	29	37	38	35	40	30	29	40	33,7	16,7
12		2P8	26	28	23	26	29	31	31	27	31	31	23	31	28,3	11,3
13	1st Story	S318(K7)	21	23	23	21	21	21	20	21	22	22	20	23	21,5	**6,6**
14		S319(K8)	26	26	28	26	28	24	28	28	26	26	24	28	26,6	**10**
15		3P6(K9)	26	25	26	26	30	32	30	29	32	30	25	32	28,6	**11,9**
16		3P3	38	37	36	36	33	36	37	36	38	32	32	38	35,9	19,6
17		3P7	31	20	32	31	20	20	30	31	20	29	20	32	26,4	9,8
18		3P8	28	28	27	26	28	26	26	26	30	28	26	30	27,3	10,5
19	2nd Story	S418(K10)	26	28	28	26	26	28	28	28	29	28	26	29	27,5	**11,4**
20		S419(K11)	32	30	30	32	34	32	35	37	33	32	30	37	32,7	**14,8**
21		4P6(K12)	32	30	31	30	32	32	33	32	33	32	30	33	31,7	**13,4**
22		4P3	26	29	28	31	30	32	30	30	28	28	26	32	29,2	12,1
23		4P7	29	32	33	32	31	36	28	28	34	34	28	36	31,7	14,5
24		4P8	30	28	32	28	28	29	27	28	26	31	26	32	28,7	11,6
25	3rd Story	S518(K13)	33	35	33	35	34	33	31	33	34	33	31	35	33,4	**16,6**
26		S519(K14)	28	28	26	26	26	27	25	27	25	26	25	28	26,4	**7**
27		5P6(K15)	34	35	36	36	36	30	34	32	35	37	30	37	34,5	**17,5**
28		5P3	31	28	28	29	29	31	29	27	30	31	27	31	29,3	12,1
29		5P7	25	22	24	22	23	24	23	22	24	23	22	25	23,2	7,8
30		5P8	27	33	32	36	30	29	30	31	30	31	27	36	30,9	13,6
31	4th Story	S618(K16)	30	30	31	31	32	31	28	29	26	26	26	32	29,4	**14,2**
32		S619(K17)	30	31	31	30	31	28	31	29	28	31	28	31	30,0	**14,5**
33		6P6(K18)	18	19	17	20	20	20	22	22	18	20	17	22	19,6	**5,7**
34		6P3	24	21	25	26	24	25	21	21	27	23	21	27	23,7	8,1
35		6P7	27	30	26	27	28	26	26	25	29	27	25	30	27,1	10,4
36		6P8	20	22	21	20	21	22	24	23	22	24	20	24	21,9	7,1

Table 3.2 Reinforcement of columns

Column	Longitudinal Reinforcement	Lateral Reinforcement	Confinement Zone
S104	8Ø18	Ø8/250	NO
S105	8Ø18	Ø8/250	NO
S106	8Ø18	Ø8/240	NO
S109	8Ø18	Ø8/250	NO
S115	8Ø18	Ø8/240	NO
S119	8Ø18	Ø8/240	NO
S120	8Ø18	Ø8/230	NO

3.2 ANCHORAGE PROPERTIES

3.2.1 Steel Rebar

The most widely used anchor type for chemically bonded post-installed anchors is deformed steel bars (STIIIa) in Turkey. So, the most widely used deformed steel rebar diameters for retrofit works, 16 mm and 20 mm, are chosen for the tests performed at the site. Three specimens from each diameter are also tested for tensile properties in the Materials of Construction Laboratory of Middle East Technical University (METU). The tensile test results of steel are shown in Table 3.3.

3.2.2 Adhesive

The adhesive used is a solvent free, non-slump, two component epoxy resin called Sikadur-31. It is one of the most widely used adhesives for chemically bonded anchor applications, especially for retrofit works in Turkey. The product data sheet of Sikadur-31 is given in Appendix B.

Table 3.3 Steel tensile tests

Property	Unit	Ø16 mm Steel Rebars				Ø20 mm Steel Rebars			
		#1	#2	#3	Mean	#1	#2	#3	Mean
Diameter	mm	16.06	15.72	16.16	15.98	19.93	19.93	20.30	20.05
Yield Strength	MPa	440.53	556.13	449.60	482.08	496.72	509.36	551.71	519.26
Tensile Strength	MPa	566.43	647.17	593.11	602.24	622.44	654.03	709.36	661.98
Elongation	%	14.23	13.46	19.23	15.64	16.15	14.23	14.23	14.87

3.3 EXPERIMENTAL PROGRAM

3.3.1 Determining the Concrete Strengths

All the columns were not suitable for anchorage application, so the columns proper for the chemical anchorage application were chosen before the application. The columns that were chosen are listed in Table 3.4. Four of the chosen columns had core specimens taken. The compressive strengths of the columns from which core specimens were taken are known, but others are not. Taking core specimens again was not a practical way to determine the compressive strengths of the columns, since columns would be damaged by destructive methods. Instead, using the rebound numbers by correlating them with the compressive strengths of the core specimens was preferred.

Rebound numbers are measured according to TS EN 12504-2 [34] on the selected columns. 30 readings, 10 from top portion, 10 from center portion and 10 from the bottom portion are taken from each column by using Schmidt Hammer (Fig.3.2). First the plaster (cover) on the columns is removed, and then the column faces are cleaned by brushing with emeries. Schmidt Hammer is applied on clean surfaces. The rebound numbers of the columns are shown in Table 3.4.

A correlation between rebound numbers and compressive strengths is formed by using the known compressive strengths. The correlation formed can be seen on Figure 3.3.

Table 3.4. Rebound numbers of the columns used for testing the anchorages

COLUMN	PORTION	1	2	3	4	5	6	7	8	9	10	AVR.	COLUMN AVR.
S211	TOP	25	38	29	24	25	24	24	28	24	27	26.8	28.97
	CENTER	30	28	35	33	30	26	28	32	38	32	31.2	
	BOTTOM	28	30	31	25	29	30	28	30	30	28	28.9	
S218	TOP	37	32	32	36	32	34	32	31	31	32	32.9	32.50
	CENTER	28	32	28	32	32	33	38	33	35	31	32.2	
	BOTTOM	29	33	35	34	33	34	33	28	31	34	32.4	
S311	TOP	37	37	36	36	37	36	36	38	33	40	36.6	36.73
	CENTER	34	35	37	36	40	41	39	36	40	36	37.4	
	BOTTOM	33	34	38	40	40	36	36	34	36	35	36.2	
S312	TOP	24	30	32	28	34	30	25	29	29	27	28.8	28.23
	CENTER	32	28	27	29	29	27	27	27	27	33	28.6	
	BOTTOM	29	29	23	27	36	17	23	33	27	29	27.3	
S318	TOP	26	26	24	28	26	27	26	22	25	24	25.4	26.20
	CENTER	32	26	26	26	28	28	28	27	27	26	27.4	
	BOTTOM	26	26	25	26	26	25	26	24	27	27	25.8	
S412	TOP	27	33	28	34	33	37	31	30	29	28	31.0	32.90
	CENTER	34	33	39	35	32	34	36	35	36	34	34.8	
	BOTTOM	31	33	31	37	42	28	32	34	32	29	32.9	
S419	TOP	36	36	38	37	35	32	34	32	35	36	35.1	32.53
	CENTER	30	27	33	32	32	33	30	34	28	30	30.9	
	BOTTOM	28	32	32	30	36	31	31	30	30	36	31.6	
S511	TOP	29	31	31	31	30	29	31	26	30	38	30.6	29.17
	CENTER	27	27	27	32	32	30	28	30	28	26	28.7	
	BOTTOM	28	37	30	24	27	24	30	26	29	27	28.2	
S512	TOP	25	28	30	30	36	30	32	30	29	34	30.4	31.30
	CENTER	29	30	31	34	31	31	33	33	31	33	31.6	
	BOTTOM	29	32	34	33	31	31	31	33	34	31	31.9	
S519	TOP	31	30	29	31	31	30	28	28	30	29	29.7	28.43
	CENTER	30	30	31	30	26	32	30	32	31	30	30.2	
	BOTTOM	25	27	27	25	22	28	26	24	24	26	25.4	
S611	TOP	22	25	26	28	25	25	29	26	23	26	25.5	26.20
	CENTER	26	25	25	28	27	26	26	27	28	25	26.3	
	BOTTOM	28	26	27	27	25	25	30	28	24	28	26.8	
S612	TOP	30	33	24	34	25	25	24	26	37	38	29.6	29.00
	CENTER	28	28	27	30	32	28	33	28	30	30	29.4	
	BOTTOM	26	26	28	32	24	31	25	30	30	28	28.0	

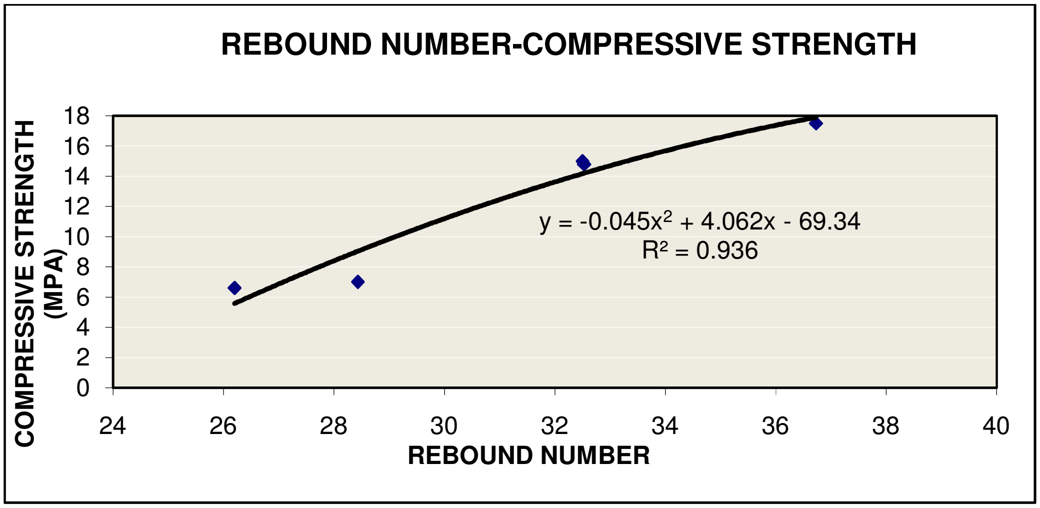

Figure 3.3 Correlation between rebound numbers and compressive strength

The compressive strengths of the concrete columns are calculated by using the correlation between rebound number and compressive strength presented in figure 3.3. The maximum value for the compressive strength is assumed to be 17.5 MPa which is the maximum value obtained on the building. The compressive strength of the concrete column is assumed to be same as the core specimen, if there is a core specimen taken from that column. Therefore, using the above mentioned approach, compressive strengths of the columns are calculated as presented in Table 3.5. The compressive strengths taken from core specimens are presented as "bold".

3.3.2 Determining the Anchorage Locations

The columns were grouped into two according to their compressive strengths, the ones having compressive strengths less than or equal to 10 MPa, and the ones having compressive strengths more than 10 MPa. This grouping is done to see, if any, the effect of compressive strength of the structural member on the performance of anchors. The groups were called low strength concretes and moderate strength concretes.

Table 3.5 Compressive strengths of the columns

Column	Average Rebound Number	Compressive Strength (MPa)
S211	28.97	10.56
S218	32.50	**15.00**
S311	36.73	17.50
S312	28.23	9.47
S318	26.20	**6.60**
S412	32.90	15.59
S419	32.53	**14.80**
S511	29.17	10.85
S512	31.30	13.71
S519	28.43	**7.00**
S611	26.20	6.19
S612	29.00	10.61

5 sets of experiments were performed from each anchor diameter, embedment depth, and concrete strength variations. For the tests, 2 types of anchor diameters (16 mm and 20 mm), 3 types of embedment depths (10Ø, 15Ø, and 20Ø), and 2 groups of concrete strengths (low strength and moderate strength) were chosen. So a total of 60 anchorage locations were determined accordingly. The distances between anchors are determined to be at least equal to the embedment depth (l_e) in order to prevent splitting failure of the concrete. All locations were determined and marked with a marker pen, and the anchor diameter, embedment depth, and concrete compressive strength properties of the anchorage were written next to the marked anchorage location (Fig.3.4). Also, the locations of the reinforcement bars of the columns were checked, in order to not collide with the reinforcement during drilling operation (Fig.3.4).

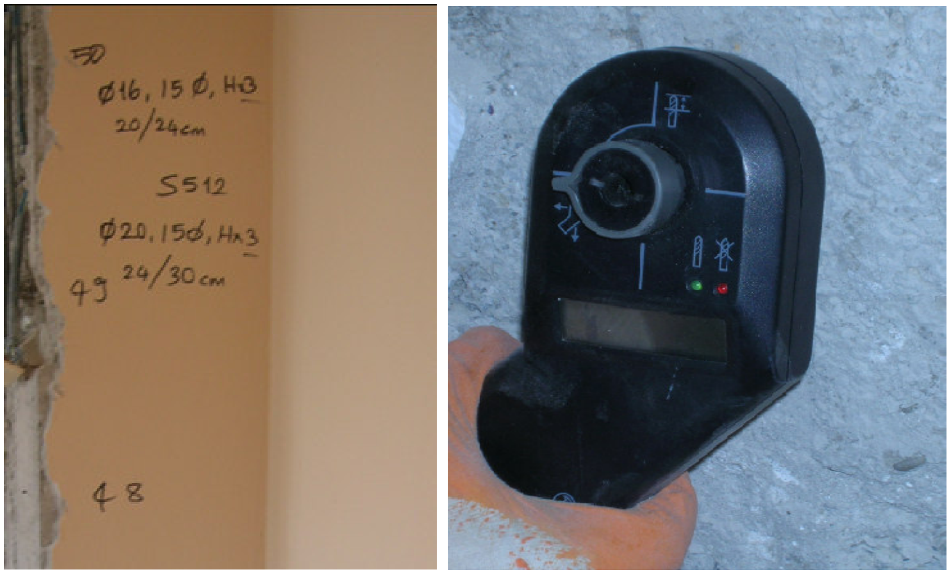

Figure 3.4 Determining the anchorage locations

3.3.3 Drilling of the Holes

The holes for the anchorages are all drilled by using a rotary hammer drill. The hole diameters for Ø16 anchors were drilled with a 20 mm diamond bit, and the hole diameters for Ø20 anchors were drilled with a 24 mm diamond bit as suggested in the MSY 319-6 [35], and as suggested by several manufacturers. All of the anchorage holes were drilled (without any inclination) at an angle of 90° to the surface (Fig.3.5).

Figure 3.5 Drilling of the holes

3.3.4 Cleaning of the Holes

The drilling process leaves loose concrete particles on the inside surface of the hole, creating a partial bond-breaker. The objective of cleaning is to improve the potential bond surface by removing these particles and exposing the pores with compressed air and a bristle brush [24].

After drilling the holes for the anchors, 4 sets from each group were cleaned by pumping first, then with a soft wire brush and with pumping again (Fig.3.6) as suggested in MSY 319-6 [35]. One set from each group was cleaned with only soft wire brush, so kept as moderately dirty in order to examine the effect of cleaning procedure on anchorage properties. Also, it was made sure that all of the holes were completely dry, and 4 sets (except the moderately dirty set) from each group were completely cleaned.

Figure 3.6 Cleaning of the holes

3.3.5 Mixing the Two Components of the Adhesive

The two components of the adhesive are mixed according to the manufacturer's recommendations. The two component system contained a premeasured package (can) of catalyst and a premeasured package (can) of resin. The entire package of the catalyst was added to a full can of resin and mixed by hand (Fig.3.7).

3.3.6 Placing of the Anchors

First the holes are filled manually by the adhesive, and anchors are covered with the adhesive. Then, anchors are placed into the holes by twisting slowly and taking the overflowing adhesive from the hole. The anchors are taken out from the holes by twisting slowly, and covered with the adhesive again. Finally, the anchors are placed into the holes again by twisting slowly (Fig.3.8). This procedure is the way suggested in MSY 319-6 [35]. By this procedure, it can be guaranteed that all of the volume between the anchor and the surfaces of the holes are filled with adhesive.

Figure 3.7 Mixing the two components of the adhesive

Figure 3.8 Placing of the anchors

The anchors were also marked for embedment depths before installation. The embedment depths were 10, 15 and 20 times the anchor diameter.

3.3.7 Pull-out Tests

Unfortunately, there is not a national standard about pull-out tests. Standard test methods for strength of anchors and testing bond performance are given in ASTM E 488 [5] and in ASTM E 1512 [38]. The testing apparatus used for site pull-out tests mostly matches with the requirements of these standards, but there were some missing points because of site conditions. The pull-out tests were preferred to be performed as it is applied on site conditions.

All of the anchorages are labeled and recorded first in order to distinguish their properties. They were, for example, marked as 16C10L or 20D15M, where first number, 16 or 20, designates for the anchor diameter in mm; second notation, C or D, designates for the Clean and Moderately Dirty holes respectively; the second number 10, 15 or 20 designates the embedment depth in terms of anchor diameter; and finally the last notation L or M designates the strength of the concrete as Low or Moderate, respectively.

Pull-out tests started at least 36 hours after the installation of the anchors. The pull-out test apparatus can be seen in Figure 3.9 and 3.10. The load was applied to the loading shoe through a high strength steel rod by using a hydraulic ram which was manually operated. A load cell was attached to the system and the failure loads were read from the load cell. Load was applied to the anchors until the maximum load was reached. The maximum loads read from the load cell for each test is recorded as the failure load.

Figure 3.9 Pull-out tests

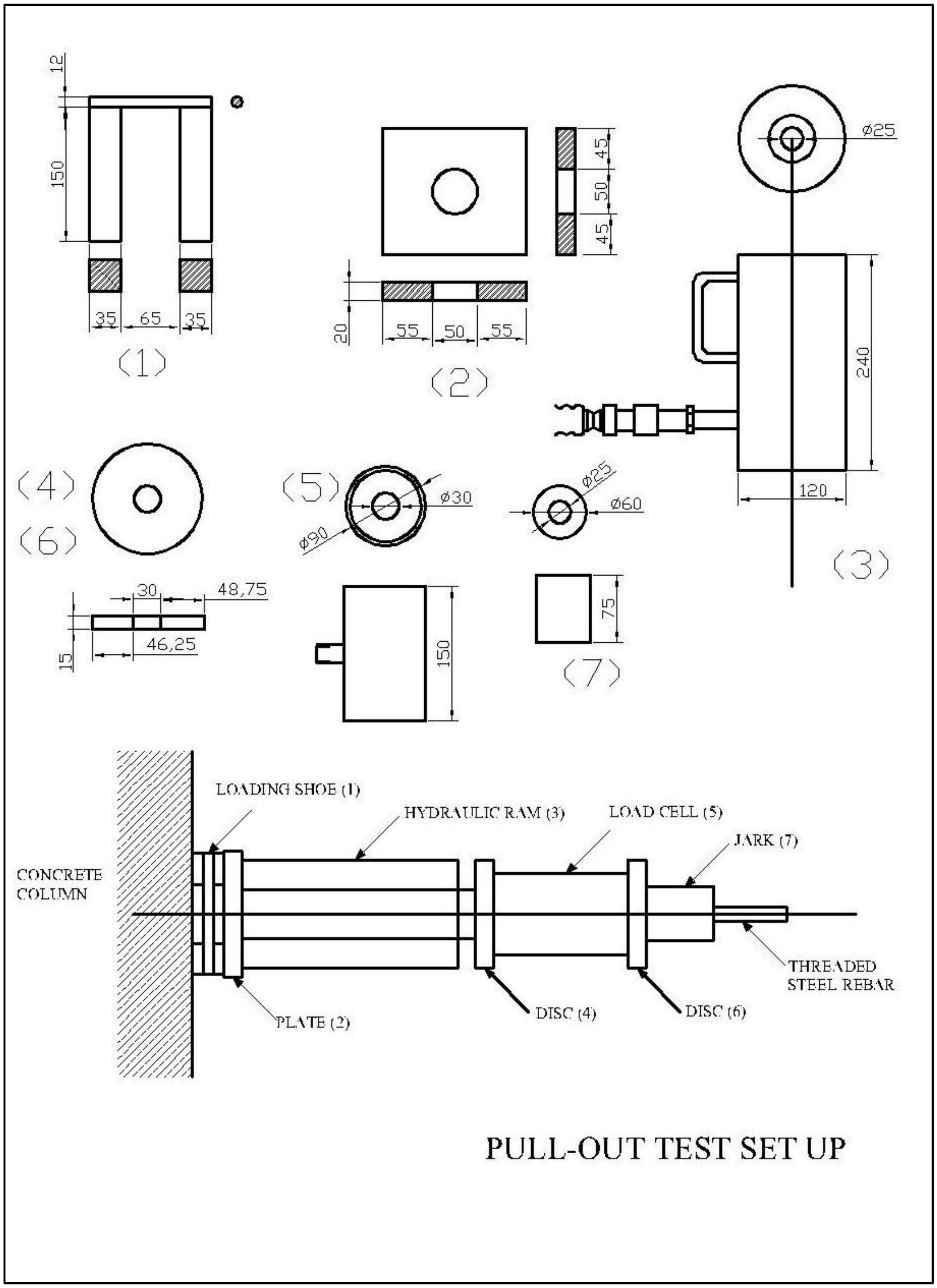

Figure 3.10 Pull-out test set up (measurements are in mm)

CHAPTER 4

RESULTS AND EVALUATION

4.1 TENSILE BEHAVIOR OF ANCHORS

4.1.1 Tensile Strengths of Anchors

The failure loads, tensile strengths and bond strengths of anchorages determined from the tests are provided in Tables 4.1 and 4.2 for the two anchor diameters tested. In those tables the first three columns represent the number, the label and the location of the anchorage. The compressive strength of the concrete column and the ultimate load that the anchorage was able to withstand are provided in the next two columns.

Tensile strengths and bond strengths of the anchorages are given in Table 4.3 and Table 4.4. Tensile strengths are calculated by dividing the failure load by the cross-sectional area of the anchor. Tensile strengths which are greater than the yield strengths of the anchors are indicated with bold letters in Tables 4.3 and 4.4. Bond strengths are calculated using equation 2.8 by taking the effective embedment depth 5 mm shorter than the actual embedment depth. Those two anchorages which are pulled-out without a concrete cone at the top of the anchor are no longer considered for the following discussions.

Table 4.1 Pull-out test results of anchors (Ø=16 mm)

No.	Anchorage Type	Anchorage Location	Column Compressive Strength (MPa)	Failure Load (N)
1	16C10L	S318	6.6	77695
2	16C10L	S318	6.6	71515
3	16C10L	S318	6.6	93195
4	16C10L	S318	6.6	63176
5	16D10L	S318	6.6	70142
6	16C10M	S218	15.0	83091
7	16C10M	S218	15.0	64550
8*	*16C10M*	*S218*	*15.0*	*25898*
9	16C10M	S218	15.0	59645
10	16D10M	S218	15.0	50816
11	16C15L	S611	6.2	85347
12	16C15L	S611	6.2	97315
13	16C15L	S611	6.2	93980
14	16C15L	S611	6.2	91233
15	16C15M	S611	6.2	89663
16	16C15M	S311	17.5	91527
17	16C15M	S311	17.5	79853
18	16C15M	S512	13.7	89958
19	16C15M	S512	13.7	104673
20	16C15M	S512	13.7	105556
21	16C20L	S211	10.6	73281
22	16C20L	S211	10.6	59743
23	16C20L	S211	10.6	95059
24	16C20L	S211	10.6	91233
25	16D20L	S211	10.6	103692
26	16C20M	S311	17.5	65433
27	16C20M	S311	17.5	81717
28	16C20M	S311	17.5	97806
29	16C20M	S311	17.5	93391
30	16D20M	S311	17.5	90056

(*) represents the bond failure without a concrete cone.

Table 4.2 Pull-out test results of anchors (Ø=20 mm)

No.	Anchorage Type	Anchorage Location	Column Compressive Strength (MPa)	Failure Load (N)
1	20C10L	S519	9.8	134593
2	20C10L	S519	9.8	164023
3	20C10L	S519	9.8	144501
4	20C10L	S519	9.8	169223
5	20D10L	S519	9.8	169517
6	20C10M	S419	14.8	155292
7	20C10M	S419	14.8	160099
8	20C10M	S419	14.8	157647
9	20C10M	S419	14.8	154213
10	20D10M	S419	14.8	128021
11	20C15L	S312	9.5	103103
12	20C15L	S312	9.5	122331
13	20C15L	S312	9.5	78480
14	20C15L	S312	9.5	128021
15	20D15L	S312	9.5	112128
16	20C15M	S412	15.6	124195
17	20C15M	S412	15.6	73085
18	20C15M	S512	13.8	150485
19	20C15M	S512	13.8	166672
20	20D15M	S512	13.8	165299
21	20C20L	S511	10.9	168830
22	20C20L	S511	10.9	177365
23	20C20L	S511	10.9	157451
24	20C20L	S511	10.9	151565
25	20D20L	S511	10.9	173441
26	20C20M	S412	15.6	157745
27*	*20C20M*	*S412*	*15.6*	*57094*
28	20C20M	S412	15.6	122919
29	20D20M	S412	15.6	165004
30	20D20M	S412	15.6	92312

(*) represents the bond failure without a concrete cone.

Table 4.3 Tensile and bond strengths of tested anchors (Ø = 16 mm)

No.	Anchorage Type	Anchorage Location	Column Compressive Strength (MPa)	Tensile Strength (MPa)	Bond Strength (MPa)
1	16C10L	S318	6.6	386.4	10.0
2	16C10L	S318	6.6	355.9	9.2
3	16C10L	S318	6.6	463.5	12.0
4	16C10L	S318	6.6	314.2	8.1
5	16D10L	S318	6.6	348.9	9.0
6	16C10M	S218	15.0	413.3	10.7
7	16C10M	S218	15.0	321.0	8.3
8*	*16C10M*	*S218*	*15.0*	*128.8*	*3.3*
9	16C10M	S218	15.0	296.7	7.7
10	16D10M	S218	15.0	252.7	6.5
11	16C15L	S611	6.2	424.3	7.2
12	16C15L	S611	6.2	**484.0**	8.2
13	16C15L	S611	6.2	467.4	8.0
14	16C15L	S611	6.2	453.8	7.7
15	16C15L	S611	6.2	446.0	7.6
16	16C15M	S311	17.5	455.2	7.8
17	16C15M	S311	17.5	397.2	6.8
18	16C15M	S512	13.7	447.4	7.6
19	16C15M	S512	13.7	**520.6**	8.9
20	16C15M	S512	13.7	**525.0**	8.9
21	16C20L	S211	10.6	364.5	4.6
22	16C20L	S211	10.6	297.1	3.8
23	16C20L	S211	10.6	472.8	6.0
24	16C20L	S211	10.6	453.8	5.8
25	16D20L	S211	10.6	**515.7**	6.6
26	16C20M	S311	17.5	325.4	4.1
27	16C20M	S311	17.5	406.4	5.2
28	16C20M	S311	17.5	**486.5**	6.2
29	16C20M	S311	17.5	464.5	5.9
30	16D20M	S311	17.5	447.9	5.7

(*) represents the bond failure without a concrete cone.

4.1.2 Failure Modes

All of the anchorage failures were bond failures, but two of the anchorages failed without a concrete cone forming at the top of the anchor. This failure mode may be due to improper placing of the anchor. These two anchors are not considered for progressing discussions. All other anchorages had failed with a small concrete cone at the top of the anchor as described in the “pull-out of the anchor” part (section 2.2.2.2) of this thesis. Splitting of the concrete failure did not occur at any of the anchorages which mean the spacing between the anchors was enough to prevent splitting of the concrete failure. The anchorages which were pulled-out without a concrete cone at the top of the anchor are indicated by italic letters in Tables 4.1 and 4.2.

Table 4.4 Tensile and bond strengths of tested anchors (Ø = 20 mm)

No.	Anchorage Type	Anchorage Location	Column Compressive Strength (MPa)	Tensile Strength (MPa)	Bond Strength (MPa)
1	20C10L	S519	9.8	428.4	11.0
2	20C10L	S519	9.8	**522.1**	13.4
3	20C10L	S519	9.8	460.0	11.8
4	20C10L	S519	9.8	**538.7**	13.8
5	20D10L	S519	9.8	**539.6**	13.8
6	20C10M	S419	14.8	494.3	12.7
7	20C10M	S419	14.8	509.6	13.1
8	20C10M	S419	14.8	501.8	12.9
9	20C10M	S419	14.8	490.9	12.6
10	20D10M	S419	14.8	407.5	10.5
11	20C15L	S312	9.5	328.2	5.6
12	20C15L	S312	9.5	389.4	6.6
13	20C15L	S312	9.5	249.8	4.2
14	20C15L	S312	9.5	407.5	6.9
15	20D15L	S312	9.5	356.9	6.1
16	20C15M	S412	15.6	395.3	6.7
17	20C15M	S412	15.6	232.6	3.9
18	20C15M	S512	13.8	479.0	8.1
19	20C15M	S512	13.8	**530.5**	9.0
20	20D15M	S512	13.8	**526.2**	8.9
21	20C20L	S511	10.9	**537.4**	6.8
22	20C20L	S511	10.9	**564.6**	7.2
23	20C20L	S511	10.9	501.2	6.3
24	20C20L	S511	10.9	482.4	6.1
25	20D20L	S511	10.9	**552.1**	7.0
26	20C20M	S412	15.6	502.1	6.4
27	*20C20M*	*S412*	*15.6*	*181.7*	*2.3*
28	20C20M	S412	15.6	391.3	5.0
29	20D20M	S412	15.6	**525.2**	6.7
30	20D20M	S412	15.6	293.8	3.7

(*) represents the bond failure without a concrete cone.

4.1.3 Comparison of Test Results with Predicted Values of Uniform Bond Stress Model

As can be seen from the product data sheet of Sikadur-31(Appendix B), the tensile strength of the adhesive is 15 MPa. The bond strength of the adhesive to steel is 20 MPa, and the bond strength of the adhesive to concrete is 3.5 MPa approximately. The uniform failure stress (τ_o) of the anchorages is a combination of these three strength values, but generally it is assumed to be equal to the tensile strength of the adhesive for confined tests, because confinement effect increases the bond strength of adhesive to concrete. The calculated bond strengths (τ_o) can be seen in Tables 4.3 and 4.4. The average bond strength for Ø=16 mm is 7.37 MPa. The average bond strength for Ø=20 mm is 8.5 MPa.

It can be concluded that uniform bond stress model is applicable for chemically bonded post-installed anchorages applied on low strength reinforced concrete structural members, but the uniform failure stress given in data sheets must be revised according to site applications and site tests for low strength concretes.

4.1.4 Comparison of Test Results with Predicted Values of CCD Method

CCD Method assumes a concrete cone failure and the calculations are based on this assumption. Equation 2.7 gives the concrete cone break out capacity of the anchorages. The failure modes observed during the tests are not concrete cone failures. The reason for comparison of the results is that the CCD method is accepted by public codes. MSY 319-6 [35] also use this method for the acceptance of the chemically bonded post-installed anchorages used for retrofit works. In fact, it has no meaning to use this method for site applications, since it is nearly impossible to establish unconfined tests for real site conditions, and the failure modes are almost always bond failures with a small concrete cone at the top of the anchor (combined cone and bond failure). This situation causes conflicts between the contractors and the public authorities. The average failure loads for different anchorages (clean ones) obtained from the site pull-out tests and the failure load values obtained by CCD method are given in Table 4.5 for comparison. It is clear that there is no correlation between the failure loads calculated with the CCD method and the test results.

Table 4.5 Comparison of test results with CCD method

No	Anchorage Diameter (mm)	Anchorage Depth (mm)	Column Compressive Strength (MPa)	Avg. Failure Load (N) (Test Result)	Failure Load (N) (CCD Method)	Predicted / Observed
1	16	160	6.6	76395	85790	1.12
2	16	160	15.0	69095	129333	1.87
3	16	240	6.2	91969	152632	1.66
4	16	240	17.0	85690	256637	2.99
5	16	240	13.7	100062	227154	2.27
6	16	320	10.6	79829	306931	3.84
7	16	320	17.5	84587	395119	4.67
8	20	200	9.8	153085	145948	0.95
9	20	200	14.8	156813	179539	1.14
10	20	300	9.5	107984	263840	2.44
11	20	300	15.6	98640	338524	3.43
12	20	300	13.7	158579	317457	2.00
13	20	400	10.9	163803	434799	2.65
14	20	400	15.6	140332	521191	3.71

4.2 EFFECTS OF PARAMETERS ON FAILURE LOADS OF ANCHORAGES

In order to draw meaningful conclusions from the collected data, statistical tools were also utilized throughout this study by the use of the statistical software Minitab 14. Relationships among the variables, concrete compressive strength, embedment depth, and anchorage diameter with respect to the response, failure load were drawn by using two different regression analysis procedures, named stepwise regression and response surface regression in order to draw absolute relations.

Regression analysis investigates and models the linear relationship between a response (Y) and predictor(s) (X). Both the response and predictors are continuous variables.

In particular, regression analysis is often used to:

- Determine how the response variable changes as a particular predictor variable changes,

- Predict the value of the response variable for any value of the predictor variable, or combination of values of the predictor variables.

Stepwise regression removes and adds variables to the regression model for the purpose of identifying a useful subset of the predictors. MINITAB provides three commonly used procedures:

- Forward selection, which involves starting with no variables in the model, trying out the variables one by one and including them if they are 'statistically significant'.
- Backward selection, which involves starting with all candidate variables and testing them one by one for statistical significance, deleting any that are not significant.
- Methods that are a combination of the above, testing at each stage for variables to be included or excluded.

Backward selection procedure is used for this study by including all the predictors (or variables) first into the analysis and eliminating one by one.

The main statistical tool of Minitab used in this research was “design of experiments” (DOE). Although as the name implies this tool is generally utilized for designing and planning the experiments for minimizing the effort to find out the significant variables of related responds, it is also used for analysing the relationship between responds and variables and for constructing empirical formulations and relations [39, 40].

Throughout this statistical study, “response surface design” was utilized as DOE tool. In fact, when response variable is a non-linear function of factors involved, response surface design is the most convenient tool for constructing empirical relationship between them [39, 40].

The “response surface design” was utilized only for exploration of empirical regression from the available data collected throughout the experimental study. In other words, it was not used for designing the experimental program; rather it was used for drawing empirical relations between responds and factors involved in this study. The backward selection procedure was also used for response surface regression analysis.

Throughout statistical analysis, a confidence interval (CI) of 90 % was selected. In other words, in analysis of variance (ANOVA), level of significance, i.e. the probability of error occurrence (α) was selected as 0.10. That means, p values less than 0.10 in ANOVA implies statistically significant factor.

4.2.1 Effect of Hole Cleaning

The box plot of failure load versus cleaning procedure of the hole can be seen in figure 4.1. It is necessary to mention again that all of the holes are cleaned before the location of the anchors, but one from each set of anchorages are cleaned only by wire brushes without pumping. Therefore, the notation D represents for moderately dirty (not completely dirty) anchorages. There are 25 clean and 5 moderately dirty anchorages for Ø = 16 mm; and there are 23 clean and 7 moderately dirty anchorages for Ø = 20 mm.

It can be seen from Figure 4.1 that the medians for the moderately dirty anchorages are slightly greater than the clean ones. It is also known from the test results that none of the moderately dirty anchorages failed without a concrete cone forming at the top of the anchor. The maximum and minimum values of failure loads are similar for Ø = 16 mm anchors, but the difference between the maximum and minimum values are greater for clean anchorages for Ø = 20 mm anchors. The only negative outcome is the deviations of failure loads (the difference between 25 % and 75 % values) are greater for moderately dirty anchorages for both types of anchors.

It can be concluded that pumping for hole cleaning of chemically bonded post-installed anchorages applied on low strength reinforce concretes has a minor effect on failure loads.

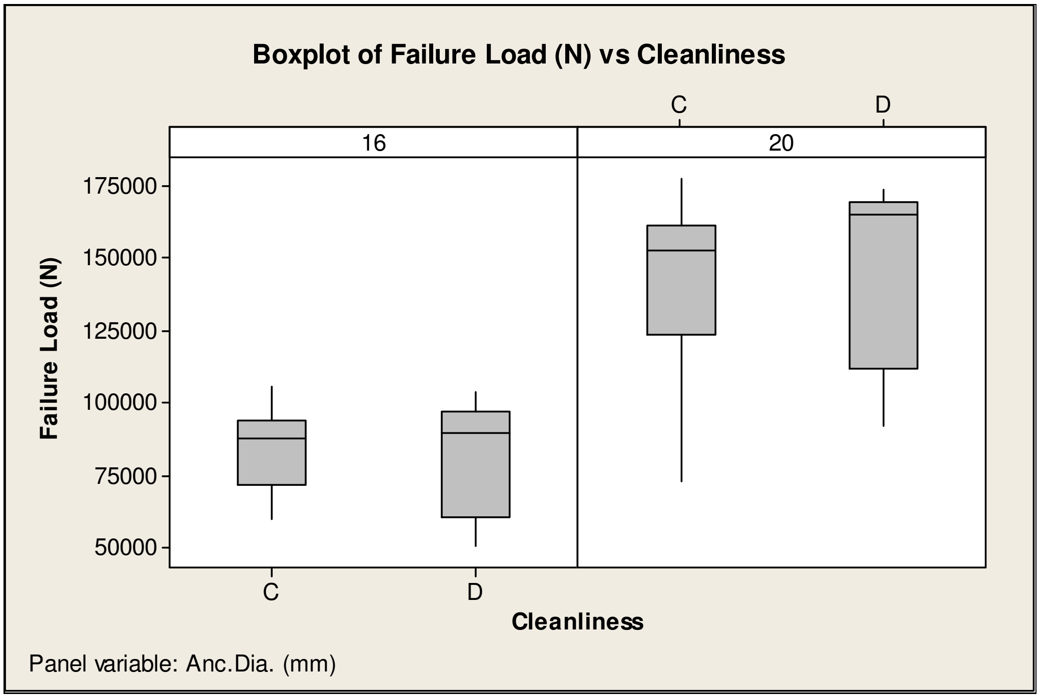

Figure 4.1 Box plot of failure load versus cleanliness

4.2.2 Effect of Concrete Compressive Strength

The scatter plot of the failure load versus column compressive strength can be seen in Figure 4.2. As seen from this figure, the compressive strength of the structural member does not seem to effect the failure load for both of the anchorage diameters tested. The statistical analysis was therefore conducted by a program called Minitab 14, and the project report formed by Minitab 14 is given in Appendix C. The p value of the column compressive strength found by stepwise regression analysis is 0.705 and the p value found by response surface regression analysis is 0.916. The p values found from the statistical analysis made by the clean anchorages only are 0.997 for stepwise regression analysis and 0.804 for response surface regression analysis. These p values mean that compressive strength of the structural member is outside the model predicted by statistical analysis.

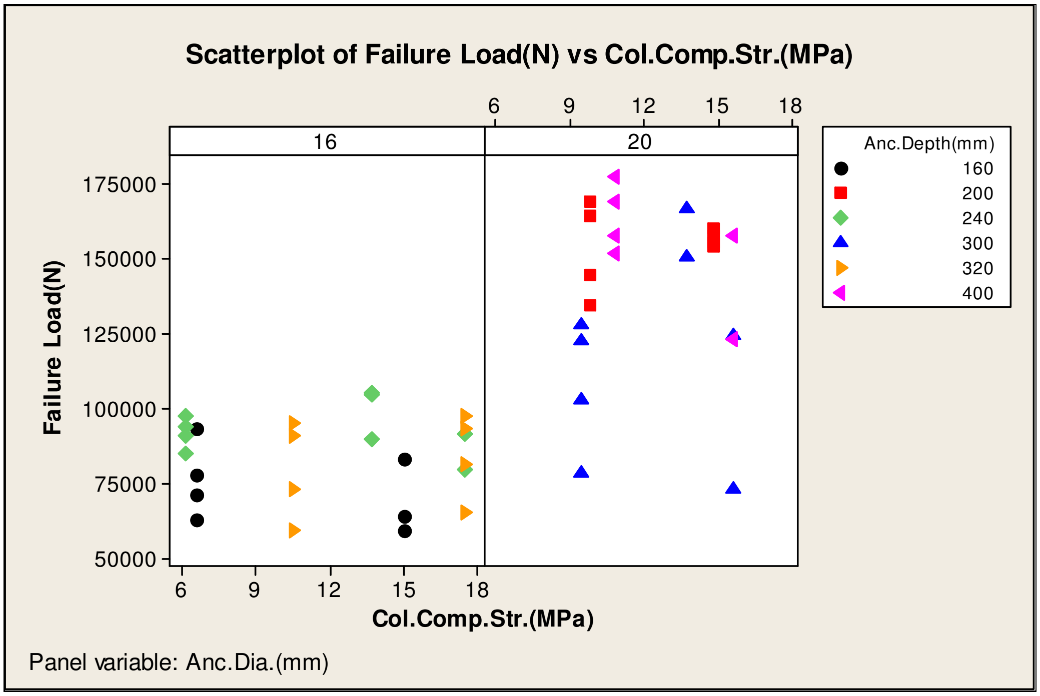

Figure 4.2 Scatter plot of failure load versus column compressive strength

Therefore, it can be concluded both from Figure 4.2 and from statistical analysis that there is not a meaningful correlation between failure load and compressive strength of the structural member for the chemically bonded post-installed anchorages in low strength reinforced concretes.

4.2.3 Effect of Embedment (Anchorage) Depth

The scatter plot of the failure load versus anchorage depth can be seen in figure 4.3. The project report of the statistical analysis made by Minitab 14 is given in Appendix C. The p value of the anchorage depth found by stepwise regression analysis is 0.499 and the p value found by response surface regression analysis is 0.138. The p values found from the statistical analysis made by the clean anchorages only are 0.796 for stepwise regression analysis and 0.346 for response surface regression analysis. These p values mean that anchorage depth is outside the model predicted by statistical analysis.

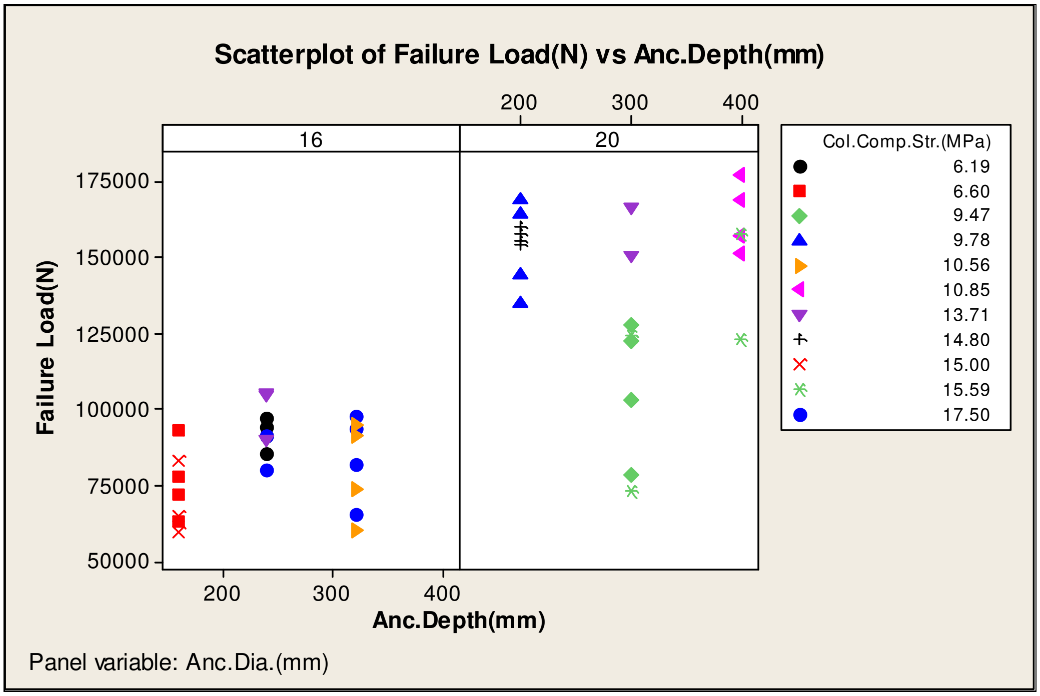

Figure 4.3 Scatter plot of failure load versus anchorage depth

The multiplication of anchorage depth with anchorage diameter has p values obtained from response surface regression analysis of 0.020 and 0.037 for full and clean only analysis respectively.

It can be concluded both from Figure 4.3 and from statistical analysis that there is not a meaningful correlation between failure load and anchorage depth for the chemically bonded post-installed anchorages in low strength reinforced concretes. It can not be concluded that the failure load will be greater with increasing anchorage depths for low strength concretes. But, it is clear that anchorage depth is more effective on the failure load than the compressive strength of the structural member. Also, it is obvious that the multiplication of the anchorage depth with anchorage diameter has a relatively strong effect on failure loads which forms a support for bond stress failure models.

4.2.4 Effect of Anchor Diameter

The scatter plot and of failure loads versus anchorage diameter can be seen in Figure 4.4. It is found from both the stepwise regression analysis and response surface regression analysis that anchorage diameter is the only meaningful and effective parameter with a confidence interval of 0.90. The R^2 is 63.1 % and the R^2(adj) is 62.4 % for response surface regression analysis of full data. The R^2 is 64.4 % and the R^2(adj) is 63.5 % for response surface regression analysis of clean only data. R^2(adj) is very similar to R^2, which means statically that the variation within the variable is quite low. In addition, R^2(adj) is a modified R^2 that has been adjusted for the number of terms in the model. If you include unnecessary terms, R^2 can be artificially high, whereas R^2(adj) may get smaller as unnecessary terms are included to the model [40].

The equation of the fitted line (or best line) for failure load versus anchorage diameter is:

$$F_u = -153053 + 14769d \quad (4.1)$$

where F_u = Ultimate failure load (N)

d = Diameter of the anchor (mm)

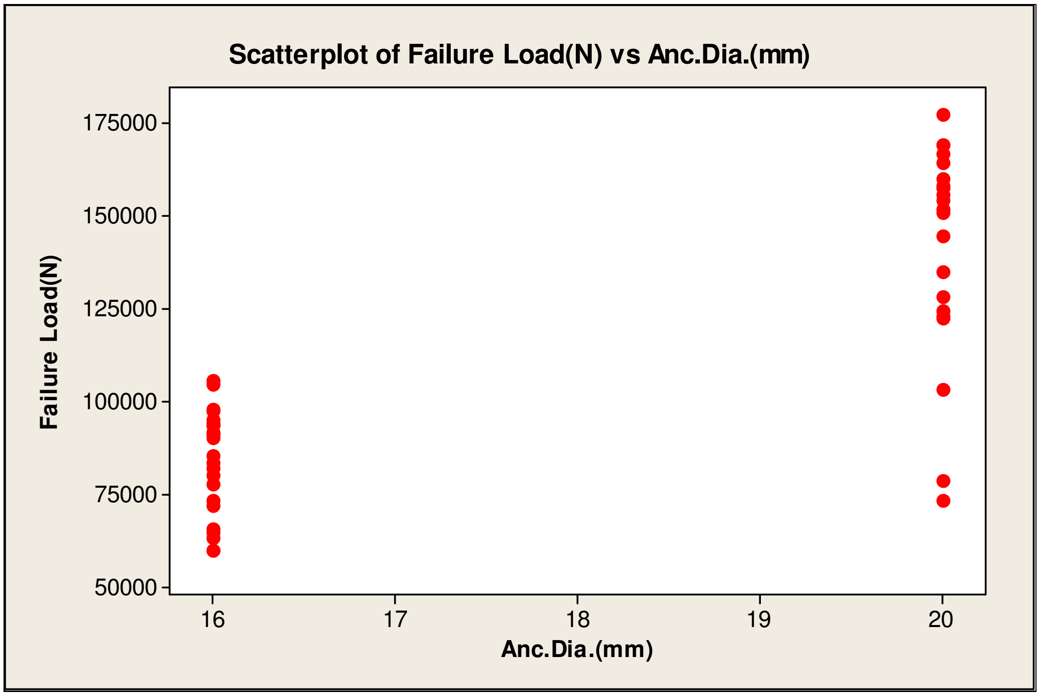

Figure 4.4 Failure load versus anchorage diameter

Even though the R^2 is not so high, regression analysis still give meaningful information about the factors affecting the failure load of anchorages. It can be concluded that anchorage diameter is the most effective parameter for the tensile behavior of chemically bonded post-installed anchorages in low strength reinforced concretes.

4.2.5 Comparison of Effects of Parameters

It is obvious that the most effective parameter on the failure load (or the pull-out load) is anchorage diameter for chemically bonded post-installed anchorages in low strength reinforced concretes. The multiplication of anchorage diameter with anchorage depth has a relatively strong effect which supports the bond stress models. The anchorage depth (or the embedment depth) is more effective than the compressive strength of the structural member, but it is still not meaningful for predicting the failure loads. Compressive strength of the structural member has no effect on the failure loads of chemically bonded post-installed anchorages in low strength reinforced concretes. There is a constant term with a meaningful p value found from the statistical analysis which means that there are some other factors contributing to the statistical model.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

A total of 60 site tests were conducted within the scope of this study. By examining the test results, the following conclusions and recommendations are inferred from this study.

5.1 CONCLUSIONS

Uniform bond stress model is applicable for chemically bonded post-installed anchorages applied on low strength reinforced concrete structural members, but the uniform failure stress given in data sheets must be revised according to site applications and site tests for low strength concretes.

Another alternative for predicting the failure loads of anchors can be using the bond strength of the adhesive to concrete as the uniform failure stress to be on the safe side. By this way, the failure loads obtained by confined pull-out tests would be assumed by a factor of safety of 2.

Yield strength of STIIIa steel is normally assumed as 420 MPa. It can be observed that tensile strengths of the anchorages are very close to or more than 420 MPa. It can be concluded that yield strength of the steel can be used for failure load assumptions with a proper factor of safety.

It is clear that there is no correlation between the failure loads calculated with the CCD method and the confined test results. Therefore, in site applications where the anchors are mostly tested in a confined manner, the allowable loads determined by the use of CCD method should not be used.

Pumping for hole cleaning of chemically bonded post-installed anchorages applied on low strength reinforced concretes has a minor effect on failure loads. The deviations of failure loads (the difference between 25 % and 75 % values) are greater for moderately dirty anchorages for both types of anchors.

There is not a meaningful correlation between failure load and anchorage depth for the chemically bonded post-installed anchorages in low strength reinforced concretes. Therefore, it can not be concluded that the failure load will be greater with increasing anchorage depths for low strength concretes.

It is obvious that the multiplication of the anchorage depth with anchorage diameter has a relatively strong effect on failure loads which forms a support for bond stress models.

Anchorage diameter is the most effective parameter for the tensile behavior of chemically bonded post-installed anchorages in low strength reinforced concretes.

5.2 RECOMMENDATIONS FOR FUTURE STUDIES

The author recommends the following subjects for future studies:

- The effect of confinement,
- The comparison of effects of wet and dry cleaning of the holes on anchorage performance,
- The effect of spacing on chemically bonded post-installed anchorages in low strength reinforced concretes,
- The effect of temperature on chemically bonded post-installed anchorages in low strength reinforced concretes,
- The behavior of chemically bonded post-installed anchorages in low strength reinforced concretes in cyclic tension tests,
- The bending performance of chemically bonded post-installed anchorages in low strength reinforced concretes,
- The comparison of behaviors of chemically bonded post-installed anchorages in low strength reinforced concretes with different adhesives.

This study was based on experiments performed on an existing building only on the limited time slot provided before the demolition of the structure. Therefore this study could be complemented on controlled lab specimens and with the following variables:

- Effect of confinement,
- Cleaning procedure,
- Spacing,
- Concrete compressive strength,
- Anchor diameter,
- Embedment depth.

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APPENDIX A - TERMS AND DEFINITIONS

The specific terms related to thesis study and their definitions are given below in alphabetical order.

Adhesive Anchor

A post-installed anchor that derives its holding strength from the chemical compound between the wall of the hole and the anchor rods. The materials used include epoxy, cementitious material, polyester resin, and other similar types [59].

Anchor

A steel element either cast into concrete or post-installed into a hardened concrete member and used to transmit applied loads, including headed bolts, headed studs, expansion anchors, undercut anchors, adhesive anchors or specialty inserts [62].

Anchor Pullout Strength

The strength corresponding to the anchoring device or a major component of the device sliding out from the concrete without breaking out a substantial portion of the surrounding concrete [62].

Anchor Spacing

The distance between anchors measured centerline to centerline, in mm (in.); also, the minimum distance between reaction points of the test frame [59].

Attachment

The structural assembly, external to the surface of the concrete, that transmits loads to or receives load from the anchor[62].

Brittle Steel Element

An element with a tensile test elongation of less than 14%, or reduction in area of less than 30%, or both [62].

Bonded Anchor

A fastener placed in hardened concrete or masonry that derives its holding strength from a chemical compound placed between the wall of the hole and the embedded portion of the anchor [60].

Cast in Place Anchors

An anchor that is installed prior to the placement of concrete and derives its holding strength from plates, lugs, or other protrusions that are cast into the concrete [59].

Chemically Bonded Anchor

A reinforcing bar or threaded rod inserted into a drilled hole (usually 10-25% larger than the diameter of the anchor) within hardened concrete with a structural adhesive acting as a bonding agent between the concrete and steel anchor [9].

Concrete Breakout Strength

The strength corresponding to a volume of concrete surrounding the anchor or group of anchors separating from the member [62].

Concrete Pryout Strength

The strength corresponding to formation of a concrete spall behind a short, stiff anchor with an embedded base that is displaced in the direction opposite to the applied shear force [62].

Curing Time

The minimum time from the end of mixing to the time when the anchor may be torqued or loaded (whichever is longer) [58].

Displacement

Movement of an anchor relative to the structural member. For tension tests, displacement is measured along the axis of the anchor, in mm [59].

Ductile Steel Element

An element with a tensile test elongation of at least 14% and reduction in area of at least 30% [62].

Edge Distance

Side cover distance or the distance from the centerline of an anchor to the nearest edge of a structural member, in mm; also, minimum distance from the centerline to the test frame [59].

Embedment Depth

Distance from the test member surface to the installed end of the anchor, in mm, prior to the setting of the anchor [59].

Effective Embedment Depth

The overall depth through which the anchor transfers force to or from the surrounding concrete. The effective embedment depth will normally be the depth of the concrete failure surface in tension applications. For cast-in headed bolts and headed studs, the effective embedment depth is measured from the bearing contact surface of the head [62].

Embedment

A steel component embedded in the concrete to transmit applied loads to or from the concrete structure. The embedment may be fabricated of plates, shapes, anchors, reinforcing bars, shear connectors, specialty inserts, or any combination thereof [62].

Expansion Anchor

A post-installed anchor that derives its holding strength through a mechanically expanded system which exerts forces against the sides of the drilled hole [59].

Open Time

The maximum time from end of mixing to when the insertion of the anchor into the bonding material shall be completed [58].

Post-Installed Anchor

An anchor that is installed after the placement and hardening of concrete [59]. It can also be called as *retrofit anchor*.

Projected Area

The area on the free surface of the concrete member that is used to represent the larger base of the assumed rectilinear failure surface [62].

Static Test

A test in which a load is slowly applied to an anchor according to a specified rate such that the anchor receives one loading cycle [59]. The tests done for the thesis study are static tests.

Structural Member

The material in which the anchor is installed and which resists forces from the anchor [59].

Tensile Test

A test in which an anchor is loaded axially in tension [59].

Undercut Anchor

A post-installed anchor that derives its holding strength from an expansion of an embedded portion of the anchor into a portion of the hole that is larger in diameter than the portion of the hole between the enlarged section and the surface of the structural member. The enlarged diameter section of the hole is predrilled or enlarged by an expansion process during setting of the anchor [59].

APPENDIX B - STRUCTURAL PROJECTS LAYOUT OF THE BUILDING

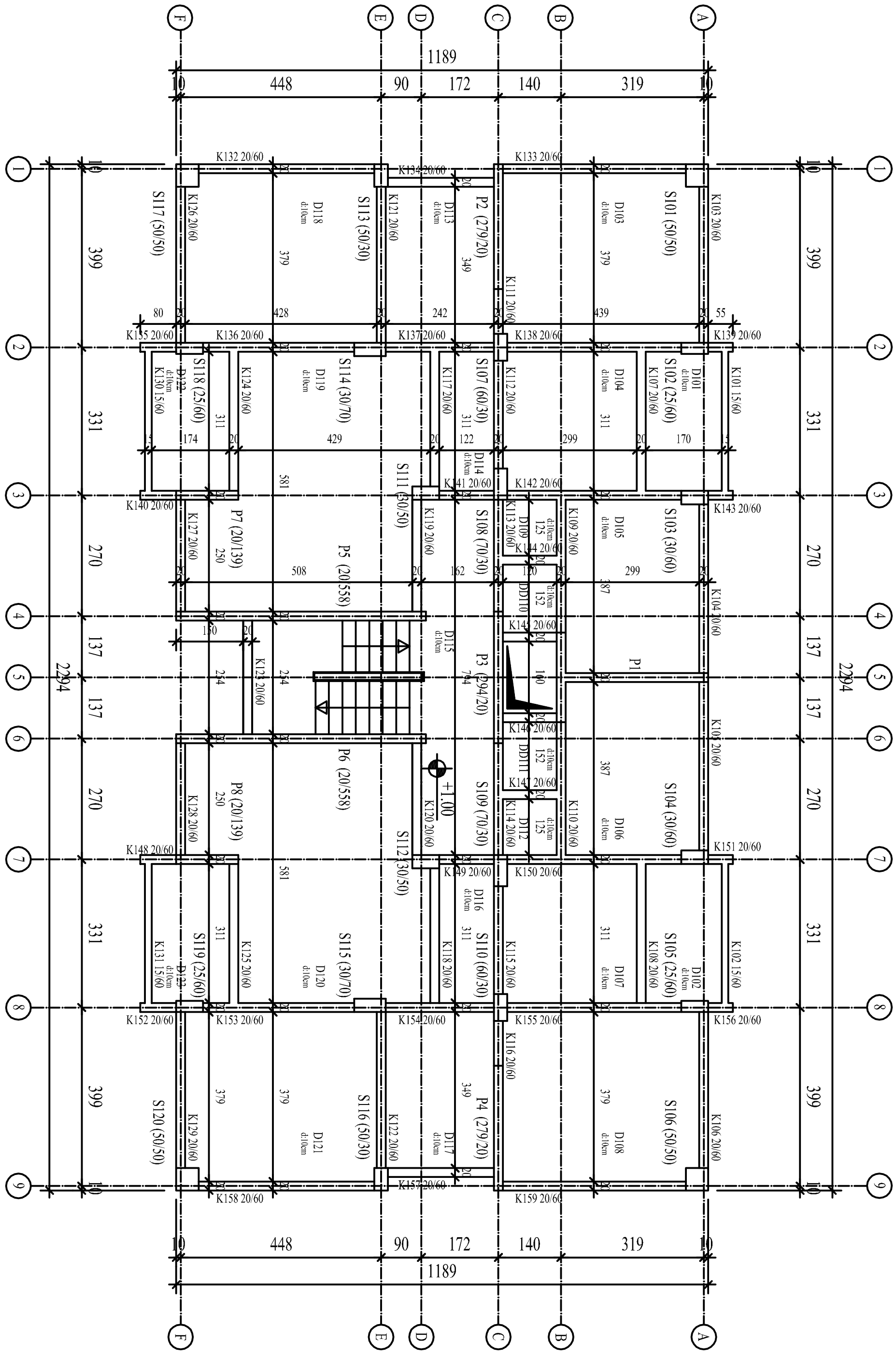

Figure B.1 The structural project of basement floor ceiling

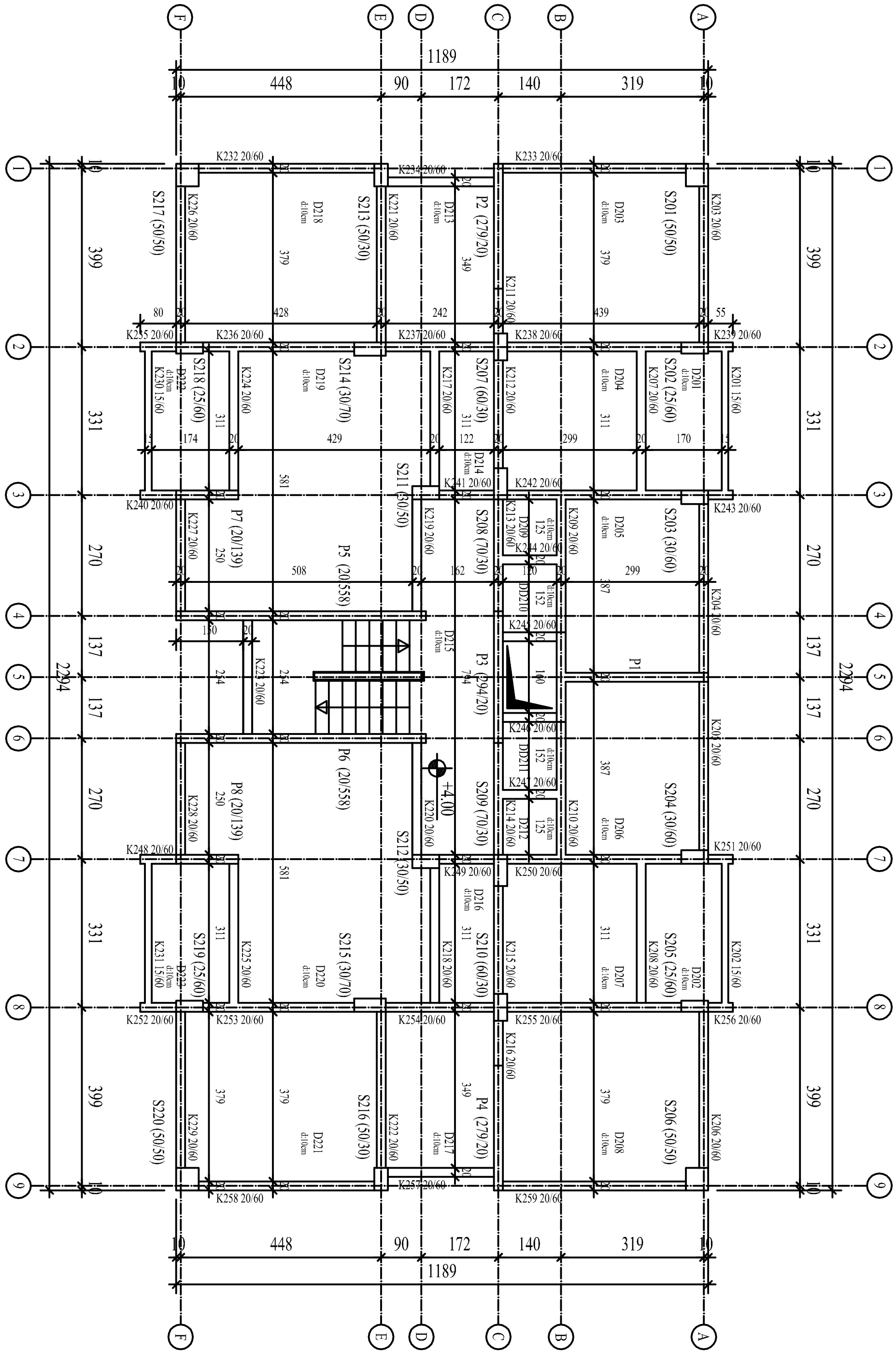

Figure B.2 The structural project of ground floor ceiling

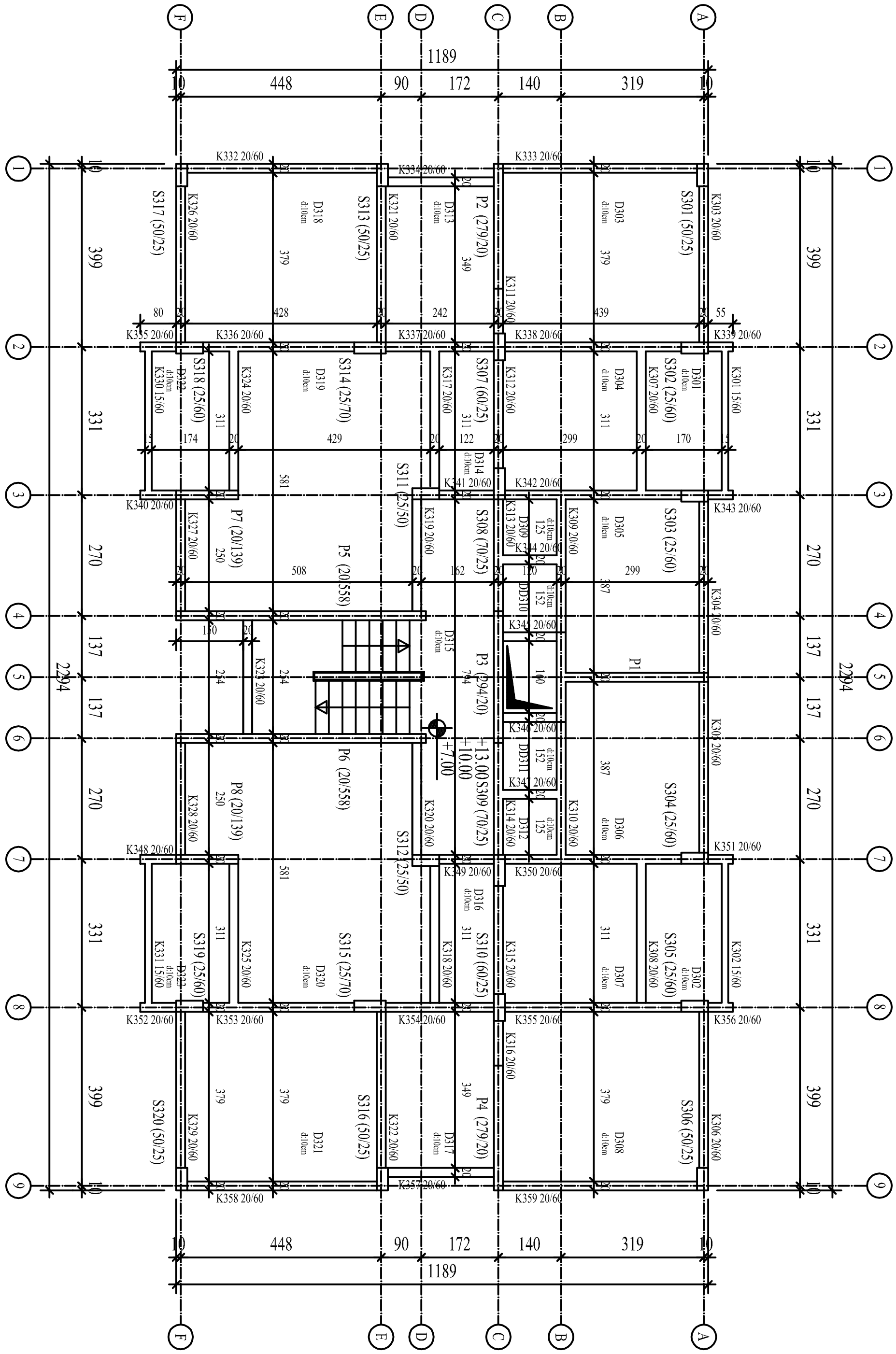

Figure B.3 The structural project of 1st, 2nd, and 3rd floor ceilings

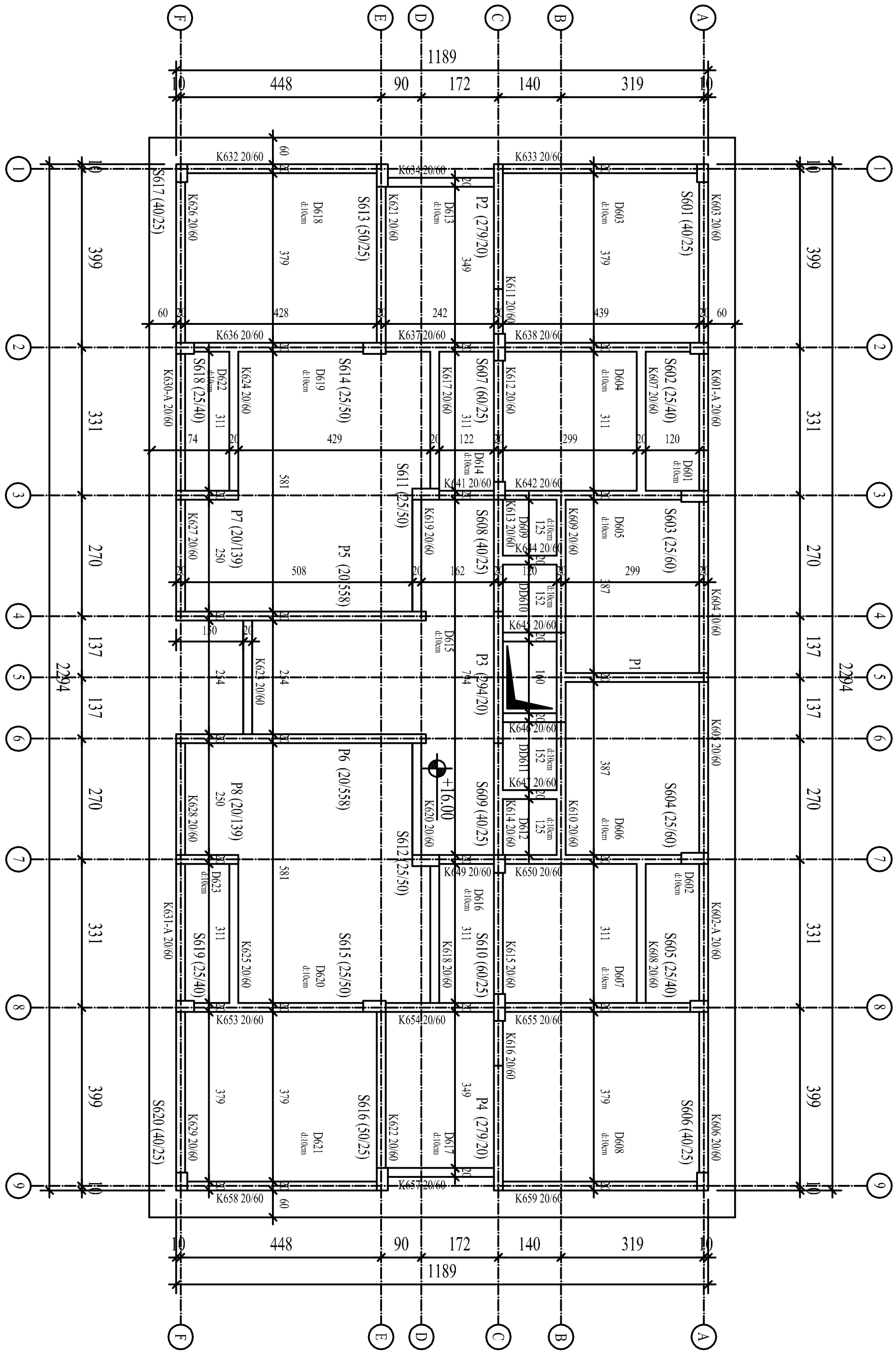

Figure B.4 The structural project of 4th floor ceiling

APPENDIX C – THE DATA SHEET OF THE ADHESIVE

Sikadur® 31

Non slump, epoxy resin adhesive mortar

Positioning Description

Sikadur 31 is a solvent free, non-slump, two component epoxy resin adhesive mortar containing carefully selected and blended high strength fillers. Its paste-like consistency, when mixed, allows for easy and versatile application.

Uses

Sikadur 31 can be used for:

- Grouting of steel reinforcement into existing concrete.
- Anchoring holding down bolts, steel plates, etc into concrete.
- As a thin layer levelling or scraping mortar.
- General bonding and adhesive work for concrete, steel, brickwork, stone, Hardiflex, timber, epoxy, etc.
- Ideal for bonding precast concrete pipe or culvert intersections.

Advantages

- Very easy to apply using either a trowel, spatula or mastic gun.
- Suitable for application to both dry and damp surfaces.
- Excellent non-sag properties for vertical and overhead work.
- Hardens without shrinkage.
- High abrasion resistance.
- Excellent adhesion to concrete, steel, timber and many other substrates.
- Approved for use in contact with potable water, once cured.
- Both components are different colours to ensure thorough mixing.

Product Data

Type: Thixotropic epoxy resin paste

Density: 1.7 kg/litre

Service temp: < 70°C

Application temp: + 5°C to + 30°C

Shrinkage: Negligible

Compressive strength 24 hours = 35-40 MPa approx.

(at 20°C): 7 days = 55-65 MPa approx.

Flexural strength: 22 MPa approx.

Tensile strength: 15 MPa approx.

Elastic modulus: 5.8 GPa approx.

Bond strength: Sandblasted Steel = 20 MPa approx.

Sandblasted Concrete = 3.5 MPa approx. (concrete failure)

Pot life (5 kg mix): Temperature (°C) 10°C 20°C 30°C

Minutes (approx.) 90 40 20

Application thickness: Up to 30 mm in one layer.

Specification &Test Compliance

• Tested in accordance with BS6319

• Complies with ASTM C881-78, Type 1, Grade 3, Class B & C.

• C/WRC approved for contact with potable water : WFBS listing number 8601065.

Packaging and Sizes

• Component A = Cream / Component B = Dark Grey / Concrete Grey colour when mixed.

• Supplied in 0.7 litre (1.2kg), 2.94 litre (5kg), and 26.5 litre (45kg) units (Comp. A & B)

Storage & Shelf Life

• Three (3) years in unopened original containers when stored in dry conditions between 5°C and 30°C.

• Sikadur 31, Component B has a dangerous goods classification for transportation: Haz., Class 8, UN No.1759, Haz., Chem 2X, Packing group III.

Application Conditions

Surface Preparation

• All concrete surfaces must be clean and free from any loosely adhering particles or contaminants such as dirt, oil, dust, grease, etc. All cement laitance should be removed by scabbling, sandblasting, etc.

• The prepared surface must be free from standing water.

• Steel surfaces must have all paints, films, oils, rust and other contaminants removed by grit blasting or similar. Apply Sikadur 31 immediately after blasting is completed to prevent rust from recurring.
• Epoxy surfaces must be mechanically abraded then washed clean with Sika Colma Cleaner. Allow to dry before applying Sikadur 31.

Mixing
• Add Component B to Component A at the correct ratio using a Sika mixing paddle attached to a low speed electric drill (max. 500 rpm). Mix together until a smooth streak free paste is achieved.
• Part batching of Sikadur 31 is not recommended unless strict measurement of the components, in accordance with the mix ratio of the factory proportioned pack, is observed and adhered to.

Application

Grouting of starters and bolts
• Sikadur 31 can be loaded into empty cartridges or directly into a Sika bulk dispensing gun. For best results gun apply the epoxy into the base of the prepared hole using a piece of tubing attached to the nozzle. This will ensure that any entrapped air is expelled when the starter or bolt is pushed into the hole, after the epoxy has been deposited.
• Temporary support of bolts and starters is required for overhead applications until the epoxy has gained sufficient adhesive strength.

Thin film bonding adhesive
• Apply Sikadur 31 to both prepared surfaces using a trowel or stiff brush. Push the components together ensuring that a continuous even film with a minimum thickness of 2 mm is achieved. Provide temporary support in vertical and overhead applications.

Levelling or scraping mortar
• Sikadur 31 can be applied to the prepared surface using a trowel or float. Ensure that the epoxy is well worked into the substrate. This is particularly important on damp surfaces.

• The ‘sticky’ non-slump nature of Sikadur 31 can make it difficult to achieve a smooth uniform finish when using a steel float. If necessary the float face may be wiped with Sika Colma Cleaner intermittently during finishing to help achieve a smooth finish. Do not under any circumstances apply Colma Cleaner directly to the surface of the epoxy.

• Sikadur 31 can be applied in layers up to 30 mm thick for each application. On vertical surfaces it will not sag in layers up to 10 mm thick.

Cleaning

• Clean all tools and equipment immediately after use with Sika Colma Cleaner.

• It is recommended that protective gloves and clothing be worn during application, however uncured Sikadur 31 may be removed from skin with Sikaflex Hand Cleaner or warm soapy water.

• Cured Sikadur 31 can only be removed mechanically.

Important Notes

• Do not apply Sikadur 31 to surfaces with standing water on them.

• When using compressed air to clean out drilled holes for starters and bolts it is essential that the hose be pushed to the base of the hole. This will ensure that any dust is blown up to the top and out of the hole. Check that the compressed air is clean and oil free.

• Sikadur 31 will not cure at temperatures below 5°C. Optimal application temperatures for Sikadur 31 are between 10°C and 30°C. The temperature at which Sikadur 31 is stored during the 24 hours before mixing will govern its pot life when mixed.

• To avoid shrinkage caused by exotherm Sikadur 31 should not be applied in layers greater than 30 mm thick per application.

• The information, and in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika’s current knowledge and experience of the products when properly stored, handled and applied under normal conditions. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users should always refer to the most recent issue of the Technical Data Sheet for the product concerned, copies of which will be supplied on request.

Handling Precautions

• Sika products are generally quite harmless, provided normal precautions are taken when handling chemicals. Avoid contact with foodstuffs and utensils. Avoid prolonged skin contact. Wear protective clothing, gloves, goggles etc. In the event of contamination wash thoroughly with water. If the eyes or mouth are affected wash with clean water and obtain medical attention immediately.

• For further information refer to the Sika Material Safety Data Sheet which is available on request.

• If in doubt always follow the directions given on the pack or label.

APPENDIX D – STATISTICAL ANALYSIS OF MINITAB 14

Minitab Project Report (Analysis of All Anchorages)

Stepwise Regression: Failure Load versus Anc.Dia. (mm; Col.Comp.Str; ...

Backward elimination. Alpha-to-Remove: 0.1

Response is Failure Load (N) on 3 predictors, with N = 58

Step	1	2	3
Constant	-150841	-153756	-153053
Anc.Dia. (mm)	14430	14426	14769
T-Value	8.85	8.92	9.78
P-Value	0.000	0.000	0.000
Col.Comp.Str.(MPa)	-330		
T-Value	-0.38		
P-Value	0.705		
Anc.Depth(mm)	29	25	
T-Value	0.68	0.61	
P-Value	0.499	0.541	
S	23303	23121	22993
R-Sq	63.44	63.34	63.09
R-Sq(adj)	61.41	62.01	62.43
Mallows C-p	4.0	2.1	0.5

Regression Analysis: Failure Load (N) versus Anc.Dia. (mm)

The regression equation is
Failure Load (N) = - 153053 + 14769 Anc.Dia. (mm)

Predictor	Coef	SE Coef	T	P
Constant	-153053	27339	-5.60	0.000
Anc.Dia. (mm)	14769	1510	9.78	0.000

S = 22992.7 R-Sq = 63.1% R-Sq(adj) = 62.4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	50605470450	50605470450	95.72	0.000
Residual Error	56	29605226926	528664767		
Total	57	80210697376			

Response Surface Regression: Failure Load versus Anc.Dia. (mm; ...

The following terms cannot be estimated, and were removed.

```
Anc.Dia. (mm)*Anc.Dia. (mm)


The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load (N)

Term                                   Coef  SE Coef       T      P
Constant                            -385098   145785  -2.642  0.011
Anc.Dia. (mm)                         31966    10374   3.081  0.003
Col.Comp.Str.(MPa)                    -1168    10969  -0.106  0.916
Anc.Depth(mm)                           687      456   1.507  0.138
Col.Comp.Str.(MPa)*                       7      412   0.018  0.986
  Col.Comp.Str.(MPa)
Anc.Depth(mm)*Anc.Depth(mm)               2        1   2.072  0.044
Anc.Dia. (mm)*Col.Comp.Str.(MPa)        173      529   0.327  0.745
Anc.Dia. (mm)*Anc.Depth(mm)             -78       32  -2.404  0.020
Col.Comp.Str.(MPa)*Anc.Depth(mm)        -11       17  -0.649  0.519

S = 22960   R-Sq = 67.8%   R-Sq(adj) = 62.5%


Analysis of Variance for Failure Load (N)

Source          DF       Seq SS       Adj SS      Adj MS      F      P
Regression       8  54379851454  54379851454  6797481432  12.89  0.000
  Linear         3  50886530614   5256473502  1752157834   3.32  0.027
  Square         2    428944190   2438180192  1219090096   2.31  0.110
  Interaction    3   3064376650   3064376650  1021458883   1.94  0.136
Residual Error  49  25830845923  25830845923   527160121
  Lack-of-Fit    5  14006081339  14006081339  2801216268  10.42  0.000
  Pure Error    44  11824764583  11824764583   268744650
Total           57  80210697376


Unusual Observations for Failure Load (N)

                 Failure
Obs  StdOrder   Load (N)         Fit    SE Fit    Residual  St Resid
 35        35  78480.000  134043.174  7942.763  -55563.174     -2.58 R
 38        38  73084.500  128968.438  8927.987  -55883.938     -2.64 R
 58        58  92312.100  141468.798  9510.004  -49156.698     -2.35 R

R denotes an observation with a large standardized residual.
```

Response Surface Regression: Failure Load versus Anc.Dia. (mm; ...

```
The following terms cannot be estimated, and were removed.

Anc.Dia. (mm)*Anc.Dia. (mm)


The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load (N)

Term                                   Coef  SE Coef       T      P
Constant                            -411234   120801  -3.404  0.001
Anc.Dia. (mm)                         33813     8623   3.921  0.000
Col.Comp.Str.(MPa)                     1320     7827   0.169  0.867
Anc.Depth(mm)                           647      435   1.486  0.143
Col.Comp.Str.(MPa)*                      12      408   0.029  0.977
```

Col.Comp.Str.(MPa)				
Anc.Depth(mm)*Anc.Depth(mm)	2	1	2.088	0.042
Anc.Dia. (mm)*Anc.Depth(mm)	-77	32	-2.404	0.020
Col.Comp.Str.(MPa)*Anc.Depth(mm)	-10	16	-0.590	0.558

S = 22754   R-Sq = 67.7%   R-Sq(adj) = 63.2%

Analysis of Variance for Failure Load (N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	7	54323541258	54323541258	7760505894	14.99	0.000
Linear	3	50886530614	10723529044	3574509681	6.90	0.001
Square	2	428944190	2426063975	1213031987	2.34	0.107
Interaction	2	3008066453	3008066453	1504033227	2.90	0.064
Residual Error	50	25887156119	25887156119	517743122		
Lack-of-Fit	6	14062391535	14062391535	2343731923	8.72	0.000
Pure Error	44	11824764583	11824764583	268744650		
Total	57	80210697376				

Unusual Observations for Failure Load (N)

Obs	StdOrder	Failure Load (N)	Fit	SE Fit	Residual	St Resid
35	35	78480.000	135317.705	6857.458	-56837.705	-2.62 R
38	38	73084.500	127569.404	7764.582	-54484.904	-2.55 R
58	58	92312.100	140610.173	9057.929	-48298.073	-2.31 R

R denotes an observation with a large standardized residual.

Response Surface Regression: Failure Load versus Anc.Dia. (mm; ...

The following terms cannot be estimated, and were removed.

Anc.Dia. (mm)*Anc.Dia. (mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load (N)

Term	Coef	SE Coef	T	P
Constant	-410765	118531	-3.465	0.001
Anc.Dia. (mm)	33731	8064	4.183	0.000
Col.Comp.Str.(MPa)	1527	3192	0.478	0.634
Anc.Depth(mm)	643	408	1.576	0.121
Anc.Depth(mm)*Anc.Depth(mm)	2	1	2.186	0.033
Anc.Dia. (mm)*Anc.Depth(mm)	-76	31	-2.480	0.016
Col.Comp.Str.(MPa)*Anc.Depth(mm)	-9	12	-0.758	0.452

S = 22530   R-Sq = 67.7%   R-Sq(adj) = 63.9%

Analysis of Variance for Failure Load (N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	6	54323106968	54323106968	9053851161	17.84	0.000
Linear	3	50886530614	10965781835	3655260612	7.20	0.000
Square	1	100548340	2425629686	2425629686	4.78	0.033
Interaction	2	3336028015	3336028015	1668014007	3.29	0.045
Residual Error	51	25887590408	25887590408	507599812		

Lack-of-Fit	7	14062825824	14062825824	2008975118	7.48	0.000
Pure Error	44	11824764583	11824764583	268744650		
Total	57	80210697376				

Unusual Observations for Failure Load (N)

Obs	StdOrder	Failure Load (N)	Fit	SE Fit	Residual	St Resid
35	35	78480.000	135312.276	6787.415	-56832.276	-2.65 R
38	38	73084.500	127574.555	7686.129	-54490.055	-2.57 R
58	58	92312.100	140637.060	8921.534	-48324.960	-2.34 R

R denotes an observation with a large standardized residual.

Response Surface Regression: Failure Load versus Anc.Dia. (mm; ...

The following terms cannot be estimated, and were removed.

Anc.Dia. (mm)*Anc.Dia. (mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load (N)

Term	Coef	SE Coef	T	P
Constant	-388645	114409	-3.397	0.001
Anc.Dia. (mm)	33698	8031	4.196	0.000
Col.Comp.Str.(MPa)	-802	858	-0.934	0.354
Anc.Depth(mm)	563	392	1.435	0.157
Anc.Depth(mm)*Anc.Depth(mm)	2	1	2.095	0.041
Anc.Dia. (mm)*Anc.Depth(mm)	-75	31	-2.459	0.017

S = 22438   R-Sq = 67.4%   R-Sq(adj) = 64.2%

Analysis of Variance for Failure Load (N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	54031625280	54031625280	10806325056	21.46	0.000
Linear	3	50886530614	10805053421	3601684474	7.15	0.000
Square	1	100548340	2209527322	2209527322	4.39	0.041
Interaction	1	3044546326	3044546326	3044546326	6.05	0.017
Residual Error	52	26179072097	26179072097	503443694		
Lack-of-Fit	8	14354307513	14354307513	1794288439	6.68	0.000
Pure Error	44	11824764583	11824764583	268744650		
Total	57	80210697376				

Unusual Observations for Failure Load (N)

Obs	StdOrder	Failure Load (N)	Fit	SE Fit	Residual	St Resid
35	35	78480.000	134408.483	6654.394	-55928.483	-2.61 R
38	38	73084.500	129499.855	7224.304	-56415.355	-2.66 R
58	58	92312.100	144165.365	7578.945	-51853.265	-2.46 R

R denotes an observation with a large standardized residual.

Response Surface Regression: Failure Load versus Anc.Dia. (mm; Anc.Depth(mm

The following terms cannot be estimated, and were removed.

Anc.Dia. (mm)*Anc.Dia. (mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load (N)

Term	Coef	SE Coef	T	P
Constant	-370497	112613	-3.290	0.002
Anc.Dia. (mm)	31955	7802	4.096	0.000
Anc.Depth(mm)	481	382	1.258	0.214
Anc.Depth(mm)*Anc.Depth(mm)	1	1	1.992	0.052
Anc.Dia. (mm)*Anc.Depth(mm)	-69	30	-2.307	0.025

S = 22411   R-Sq = 66.8%   R-Sq(adj) = 64.3%

Analysis of Variance for Failure Load (N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	4	53592126556	53592126556	13398031639	26.68	0.000
Linear	2	50807639836	10365554697	5182777348	10.32	0.000
Square	1	110985344	1993341202	1993341202	3.97	0.052
Interaction	1	2673501376	2673501376	2673501376	5.32	0.025
Residual Error	53	26618570821	26618570821	502237185		
Lack-of-Fit	1	5553845673	5553845673	5553845673	13.71	0.001
Pure Error	52	21064725147	21064725147	405090868		
Total	57	80210697376				

Unusual Observations for Failure Load (N)

Obs	StdOrder	Failure Load (N)	Fit	SE Fit	Residual	St Resid	
35	35	78480.000	132657.519	6377.406	-54177.519	-2.52	R
38	38	73084.500	132657.519	6377.406	-59573.019	-2.77	R
58	58	92312.100	146138.029	7270.203	-53825.929	-2.54	R

R denotes an observation with a large standardized residual.

Response Surface Regression: Failure Load versus Anc.Dia. (mm; Anc.Depth(mm

The following terms cannot be estimated, and were removed.

Anc.Dia. (mm)*Anc.Dia. (mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load (N)

Term	Coef	SE Coef	T	P
Constant	-278137	105411	-2.639	0.011
Anc.Dia. (mm)	21244	5807	3.658	0.001
Anc.Depth(mm)	502	392	1.280	0.206

Anc.Dia. (mm)*Anc.Depth(mm)   -26   21 -1.222 0.227

S = 23018   R-Sq = 64.3%   R-Sq(adj) = 62.3%

Analysis of Variance for Failure Load (N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	3	51598785354	51598785354	17199595118	32.46	0.000
Linear	2	50807639836	30767360529	15383680264	29.03	0.000
Interaction	1	791145518	791145518	791145518	1.49	0.227
Residual Error	54	28611912022	28611912022	529850223		
Lack-of-Fit	2	7547186875	7547186875	3773593438	9.32	0.000
Pure Error	52	21064725147	21064725147	405090868		
Total	57	80210697376				

Unusual Observations for Failure Load (N)

Obs	StdOrder	Failure Load (N)	Fit	SE Fit	Residual	St Resid
35	35	78480.000	142278.354	4278.308	-63798.354	-2.82 R
38	38	73084.500	142278.354	4278.308	-69193.854	-3.06 R
58	58	92312.100	140793.120	6940.332	-48481.020	-2.21 R

R denotes an observation with a large standardized residual.

Response Surface Regression: Failure Load versus Anc.Dia. (mm; Anc.Depth(mm

The following terms cannot be estimated, and were removed.

Anc.Dia. (mm)*Anc.Dia. (mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load (N)

Term	Coef	SE Coef	T	P
Constant	-153756	27515.9	-5.588	0.000
Anc.Dia. (mm)	14426	1617.1	8.921	0.000
Anc.Depth(mm)	25	41.5	0.615	0.541

S = 23121   R-Sq = 63.3%   R-Sq(adj) = 62.0%

Analysis of Variance for Failure Load (N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	2	50807639836	50807639836	25403819918	47.52	0.000
Linear	2	50807639836	50807639836	25403819918	47.52	0.000
Residual Error	55	29403057540	29403057540	534601046		
Lack-of-Fit	3	8338332393	8338332393	2779444131	6.86	0.001
Pure Error	52	21064725147	21064725147	405090868		
Total	57	80210697376				

Unusual Observations for Failure Load (N)

Obs	StdOrder	Failure Load (N)	Fit	SE Fit	Residual	St Resid

35	35	78480.000	142417.482	4295.923	-63937.482	-2.81 R
38	38	73084.500	142417.482	4295.923	-69332.982	-3.05 R
58	58	92312.100	144966.973	6068.621	-52654.873	-2.36 R

R denotes an observation with a large standardized residual.

Response Surface Regression: Failure Load (N) versus Anc.Dia. (mm)

The following terms cannot be estimated, and were removed.

Anc.Dia. (mm)*Anc.Dia. (mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load (N)

Term	Coef	SE Coef	T	P
Constant	-153053	27339	-5.598	0.000
Anc.Dia. (mm)	14769	1510	9.784	0.000

S = 22993   R-Sq = 63.1%   R-Sq(adj) = 62.4%

Analysis of Variance for Failure Load (N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	1	50605470450	50605470450	50605470450	95.72	0.000
Linear	1	50605470450	50605470450	50605470450	95.72	0.000
Residual Error	56	29605226926	29605226926	528664767		
Pure Error	56	29605226926	29605226926	528664767		
Total	57	80210697376				

Unusual Observations for Failure Load (N)

Obs	StdOrder	Failure Load (N)	Fit	SE Fit	Residual	St Resid
35	35	78480.000	142329.569	4269.639	-63849.569	-2.83 R
38	38	73084.500	142329.569	4269.639	-69245.069	-3.06 R
58	58	92312.100	142329.569	4269.639	-50017.469	-2.21 R

R denotes an observation with a large standardized residual.

Minitab Project Report (Analysis of Clean Anchorages Only)

Stepwise Regression: Failure Load versus Anc.Dia.(mm); Col.Comp.Str; ...

Backward elimination. Alpha-to-Remove: 0.1

Response is Failure Load(N) on 3 predictors, with N = 46

Step	1	2	3
Constant	-149481	-149518	-148863
Anc.Dia.(mm)	14391	14391	14538
T-Value	8.18	8.28	8.91
P-Value	0.000	0.000	0.000
Col.Comp.Str.(MPa)	-4		
T-Value	-0.00		
P-Value	0.997		
Anc.Depth(mm)	12	12	
T-Value	0.26	0.27	
P-Value	0.796	0.790	
S	22606	22341	22104
R-Sq	64.42	64.42	64.36
R-Sq(adj)	61.87	62.76	63.55
Mallows C-p	4.0	2.0	0.1

Response Surface Regression: Failure Load versus Anc.Dia.(mm); ...

The following terms cannot be estimated, and were removed.

Anc.Dia.(mm)*Anc.Dia.(mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load(N)

Term	Coef	SE Coef	T	P
Constant	-322036	161118	-1.999	0.053
Anc.Dia.(mm)	29424	11209	2.625	0.013
Col.Comp.Str.(MPa)	-3667	11788	-0.311	0.757
Anc.Depth(mm)	485	508	0.955	0.346
Col.Comp.Str.(MPa)* Col.Comp.Str.(MPa)	82	432	0.190	0.851
Anc.Depth(mm)*Anc.Depth(mm)	2	1	2.267	0.029
Anc.Dia.(mm)*Col.Comp.Str.(MPa)	295	576	0.512	0.612
Anc.Dia.(mm)*Anc.Depth(mm)	-74	35	-2.130	0.040
Col.Comp.Str.(MPa)*Anc.Depth(mm)	-15	19	-0.779	0.441

S = 22298 R-Sq = 69.5% R-Sq(adj) = 62.9%

Analysis of Variance for Failure Load(N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	8	41919454652	41919454652	5239931831	10.54	0.000
Linear	3	38852442539	4038430029	1346143343	2.71	0.059

Square	2	722239883	2644461831	1322230915	2.66	0.083
Interaction	3	2344772230	2344772230	781590743	1.57	0.213
Residual Error	37	18395941933	18395941933	497187620		
Lack-of-Fit	5	11112510790	11112510790	2222502158	9.76	0.000
Pure Error	32	7283431143	7283431143	227607223		
Total	45	60315396585				

Unusual Observations for Failure Load(N)

Obs	StdOrder	Failure Load(N)	Fit	SE Fit	Residual	St Resid
35	35	78480.000	129942.800	8685.096	-51462.800	-2.51 R
38	38	73084.500	129413.501	9802.404	-56329.001	-2.81 R

R denotes an observation with a large standardized residual.

Response Surface Regression: Failure Load versus Anc.Dia.(mm); ...

The following terms cannot be estimated, and were removed.

Anc.Dia.(mm)*Anc.Dia.(mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load(N)

Term	Coef	SE Coef	T	P
Constant	-317908	157601	-2.017	0.051
Anc.Dia.(mm)	28807	10589	2.720	0.010
Col.Comp.Str.(MPa)	-2309	9243	-0.250	0.804
Anc.Depth(mm)	456	478	0.954	0.346
Anc.Depth(mm)*Anc.Depth(mm)	2	1	2.328	0.025
Anc.Dia.(mm)*Col.Comp.Str.(MPa)	299	568	0.526	0.602
Anc.Dia.(mm)*Anc.Depth(mm)	-73	34	-2.167	0.037
Col.Comp.Str.(MPa)*Anc.Depth(mm)	-12	15	-0.844	0.404

S = 22013   R-Sq = 69.5%   R-Sq(adj) = 63.8%

Analysis of Variance for Failure Load(N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	7	41901586890	41901586890	5985940984	12.35	0.000
Linear	3	38852442539	5831341371	1943780457	4.01	0.014
Square	1	566798717	2626594069	2626594069	5.42	0.025
Interaction	3	2482345634	2482345634	827448545	1.71	0.182
Residual Error	38	18413809694	18413809694	484573939		
Lack-of-Fit	6	11130378552	11130378552	1855063092	8.15	0.000
Pure Error	32	7283431143	7283431143	227607223		
Total	45	60315396585				

Response Surface Regression: Failure Load versus Anc.Dia.(mm); ...

The following terms cannot be estimated, and were removed.

Anc.Dia.(mm)*Anc.Dia.(mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load(N)

Term	Coef	SE Coef	T	P
Constant	-364433	129269	-2.819	0.008
Anc.Dia.(mm)	31984	8620	3.710	0.001
Col.Comp.Str.(MPa)	2173	3562	0.610	0.545
Anc.Depth(mm)	394	459	0.858	0.396
Anc.Depth(mm)*Anc.Depth(mm)	2	1	2.333	0.025
Anc.Dia.(mm)*Anc.Depth(mm)	-71	33	-2.139	0.039
Col.Comp.Str.(MPa)*Anc.Depth(mm)	-10	14	-0.723	0.474

S = 21808   R-Sq = 69.2%   R-Sq(adj) = 64.5%

Analysis of Variance for Failure Load(N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	6	41767325500	41767325500	6961220917	14.64	0.000
Linear	3	38852442539	9746733451	3248911150	6.83	0.001
Square	1	566798717	2588173033	2588173033	5.44	0.025
Interaction	2	2348084244	2348084244	1174042122	2.47	0.098
Residual Error	39	18548071085	18548071085	475591566		
Lack-of-Fit	7	11264639943	11264639943	1609234278	7.07	0.000
Pure Error	32	7283431143	7283431143	227607223		
Total	45	60315396585				

Response Surface Regression: Failure Load versus Anc.Dia.(mm); ...

The following terms cannot be estimated, and were removed.

Anc.Dia.(mm)*Anc.Dia.(mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load(N)

Term	Coef	SE Coef	T	P
Constant	-338806	123578	-2.742	0.009
Anc.Dia.(mm)	31888	8568	3.722	0.001
Col.Comp.Str.(MPa)	-316	920	-0.343	0.733
Anc.Depth(mm)	294	435	0.675	0.503
Anc.Depth(mm)*Anc.Depth(mm)	2	1	2.264	0.029
Anc.Dia.(mm)*Anc.Depth(mm)	-69	33	-2.114	0.041

S = 21678   R-Sq = 68.8%   R-Sq(adj) = 64.9%

Analysis of Variance for Failure Load(N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	41518404667	41518404667	8303680933	17.67	0.000
Linear	3	38852442539	9549524460	3183174820	6.77	0.001
Square	1	566798717	2409429797	2409429797	5.13	0.029
Interaction	1	2099163412	2099163412	2099163412	4.47	0.041
Residual Error	40	18796991917	18796991917	469924798		
Lack-of-Fit	8	11513560775	11513560775	1439195097	6.32	0.000
Pure Error	32	7283431143	7283431143	227607223		
Total	45	60315396585				

Response Surface Regression: Failure Load(N) versus Anc.Dia.(mm); Anc.Depth(mm)

The following terms cannot be estimated, and were removed.

Anc.Dia.(mm)*Anc.Dia.(mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load(N)

Term	Coef	SE Coef	T	P
Constant	-331762	120546	-2.752	0.009
Anc.Dia.(mm)	31261	8280	3.775	0.001
Anc.Depth(mm)	257	417	0.616	0.541
Anc.Depth(mm)*Anc.Depth(mm)	2	1	2.270	0.029
Anc.Dia.(mm)*Anc.Depth(mm)	-67	32	-2.112	0.041

S = 21443   R-Sq = 68.7%   R-Sq(adj) = 65.7%

Analysis of Variance for Failure Load(N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	4	41462977976	41462977976	10365744494	22.54	0.000
Linear	2	38852433781	9494097768	4747048884	10.32	0.000
Square	1	560248524	2368467673	2368467673	5.15	0.029
Interaction	1	2050295671	2050295671	2050295671	4.46	0.041
Residual Error	41	18852418609	18852418609	459815088		
Lack-of-Fit	1	5966488663	5966488663	5966488663	18.52	0.000
Pure Error	40	12885929946	12885929946	322148249		
Total	45	60315396585				

Response Surface Regression: Failure Load(N) versus Anc.Dia.(mm); Anc.Depth(mm)

The following terms cannot be estimated, and were removed.

Anc.Dia.(mm)*Anc.Dia.(mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load(N)

Term	Coef	SE Coef	T	P
Constant	-227700	116865	-1.948	0.058
Anc.Dia.(mm)	18690	6452	2.897	0.006
Anc.Depth(mm)	313	436	0.717	0.478
Anc.Dia.(mm)*Anc.Depth(mm)	-16	24	-0.692	0.493

S = 22478   R-Sq = 64.8%   R-Sq(adj) = 62.3%

Analysis of Variance for Failure Load(N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	3	39094510303	39094510303	13031503434	25.79	0.000
Linear	2	38852433781	24780734189	12390367094	24.52	0.000
Interaction	1	242076522	242076522	242076522	0.48	0.493
Residual Error	42	21220886282	21220886282	505259197		

Lack-of-Fit	2	8334956336	8334956336	4167478168	12.94	0.000
Pure Error	40	12885929946	12885929946	322148249		
Total	45	60315396585				

Response Surface Regression: Failure Load(N) versus Anc.Dia.(mm); Anc.Depth(mm)

The following terms cannot be estimated, and were removed.

Anc.Dia.(mm)*Anc.Dia.(mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load(N)

Term	Coef	SE Coef	T	P
Constant	-101889	53865.9	-1.892	0.065
Anc.Dia.(mm)	14141	1751.1	8.076	0.000
Anc.Depth(mm)	-328	324.3	-1.012	0.317
Anc.Depth(mm)*Anc.Depth(mm)	1	0.6	1.061	0.295

S = 22309   R-Sq = 65.3%   R-Sq(adj) = 62.9%

Analysis of Variance for Failure Load(N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	3	39412682304	39412682304	13137560768	26.40	0.000
Linear	2	38852433781	33953577263	16976788632	34.11	0.000
Square	1	560248524	560248524	560248524	1.13	0.295
Residual Error	42	20902714280	20902714280	497683673		
Lack-of-Fit	2	8016784334	8016784334	4008392167	12.44	0.000
Pure Error	40	12885929946	12885929946	322148249		
Total	45	60315396585				

Response Surface Regression: Failure Load(N) versus Anc.Dia.(mm); Anc.Depth(mm)

The following terms cannot be estimated, and were removed.

Anc.Dia.(mm)*Anc.Dia.(mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load(N)

Term	Coef	SE Coef	T	P
Constant	-149518	29815.2	-5.015	0.000
Anc.Dia.(mm)	14391	1737.7	8.282	0.000
Anc.Depth(mm)	12	46.2	0.268	0.790

S = 22341   R-Sq = 64.4%   R-Sq(adj) = 62.8%

Analysis of Variance for Failure Load(N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	2	38852433781	38852433781	19426216890	38.92	0.000

Linear	2	38852433781	38852433781	19426216890	38.92	0.000
Residual Error	43	21462962804	21462962804	499138670		
Lack-of-Fit	3	8577032858	8577032858	2859010953	8.87	0.000
Pure Error	40	12885929946	12885929946	322148249		
Total	45	60315396585				

Response Surface Regression: Failure Load(N) versus Anc.Dia.(mm)

The following terms cannot be estimated, and were removed.

Anc.Dia.(mm)*Anc.Dia.(mm)

The analysis was done using uncoded units.

Estimated Regression Coefficients for Failure Load(N)

Term	Coef	SE Coef	T	P
Constant	-148863	29399	-5.063	0.000
Anc.Dia.(mm)	14538	1631	8.913	0.000

S = 22104   R-Sq = 64.4%   R-Sq(adj) = 63.5%

Analysis of Variance for Failure Load(N)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	1	38816670873	38816670873	38816670873	79.44	0.000
Linear	1	38816670873	38816670873	38816670873	79.44	0.000
Residual Error	44	21498725712	21498725712	488607403		
Pure Error	44	21498725712	21498725712	488607403		
Total	45	60315396585				