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STRENGTH AND RELIABILTY OF CHEMICALLY BONDED ROCK CLIMBING ANCHORS IN SANDSTONE

STEPHEN HAWKSHAW

SUPERVISOR

CHALLIS PROFESSOR JOHN CARTER

DEPARTMENT OF CIVIL ENGINEERING

The University of Sydney

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SYNOPSIS

There has been very little testing previously undertaken into the strength of chemically bonded rock climbing anchors in sandstone. This testing program was designed to increase the understanding of chemically bonded rock climbing anchors in sandstone.

A series of 81 tests were undertaken to determine the effect of different treatments to the anchor shaft, the relative strength of different adhesives, and the relative strength of various rock climbing anchor configurations in sandstone. The rock climbing anchors were tested in shear and tension and were installed with a polyester adhesive in the sandstone tests.

From the testing and literature review a number of recommendations and conclusions have been made.

Anchors should be treaded along their shafts to provide the maximum area for the adhesive to bind to. The threading was over twice as strong as the other shaft treatments tested.

Epoxy based adhesives are approximately twice as strong as polyester adhesives.

The strength of the rock climbing anchors in sandstone was found to be dependant on a number of factors. The shape of the anchors affected the failure mechanism and the strength. The strength of the anchors were compared to each other and recommendations were made into the appropriateness of the various configurations.

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Chapter One

INTRODUCTION

1.1 Purpose of Study

Activities that rely on permanent rock anchors are growing in popularity. These activities include rock climbing, abseiling and caving. With this increase in popularity comes an increase in the installation and use of permanent anchors. These anchors are subjected to various loads but none greater than those used in rock climbing. For this reason rock climbing anchors are the focus of this research.

There are two main uses for anchors in rock climbing. They are placed as 'runners' at various points on a 'climb', as 'lower offs' at the top of a 'climb' to enable easy descent, or as 'belay anchors' at intermediate stopping point of a 'multi-pitch climb'. In a rock climbing situation the greatest load is placed on an anchor when it is a 'runner' and a climber falls. The climber will fall twice the distance that they have climbed above their previous runner. Figure 1.1 shows typical uses for climbing anchors and the falls they are required to withstand.

Anchors are installed by climbers who, although experienced at climbing, do not always have an understanding of the strength of the particular anchor they are using. It is an aim of this study to test a variety of anchor shapes to compare their strength.

There is a large variety of anchors that are in use. The two main categories are chemically bonded (polyester, acrylic epoxy and epoxy resin) and mechanically fixed (expansion sleeves or undersized hole) anchors. Within these two categories, there are a number of different configurations that are used. Due to the soft nature of sandstone in the Sydney region, the use of mechanically fixed anchors is quite minimal owing to their tendency to work loose over time, among other reasons. This paper focuses on testing a variety of chemically bonded anchors and their elements to determine their strength in sandstone.

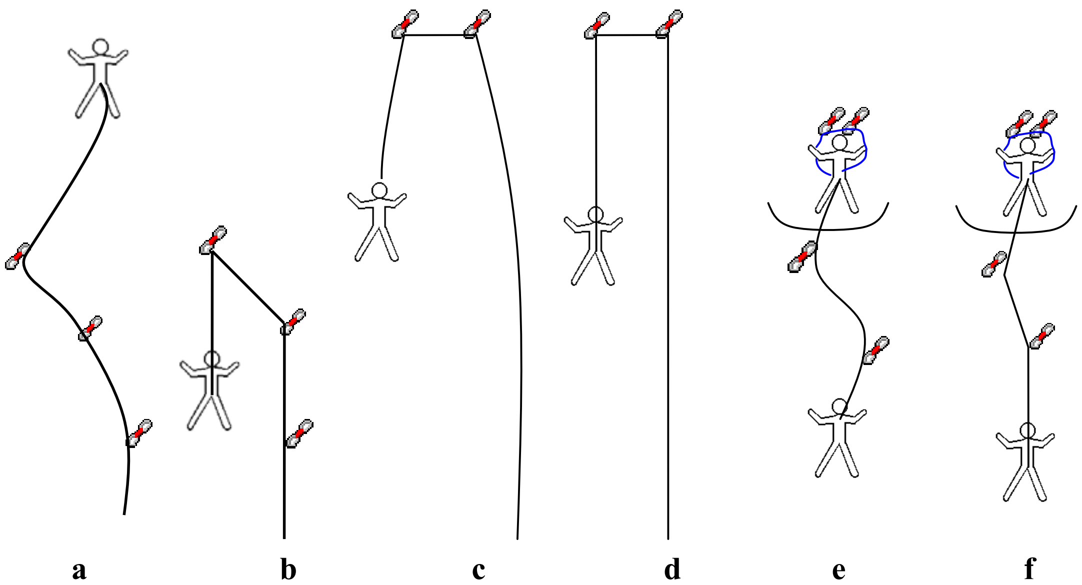

Figure 1.1

Different uses for anchors in rock climbing

a) *The anchors are used as 'runners' as the climber 'lead climbs' higher.*

b) *When the climber falls in a 'leading' situation [**a**] they fall twice the distance to their closest 'runner'. This scenario produces the highest loading on anchors.*

c) *Anchors being used as 'top rope' system.*

d) *The distance of a fall in a 'top rope' system [**c**] is small and there is minimal dynamic force.*

e) *Anchors used on a 'multi-pitch climb' as 'belay' anchors. The top climber is attached to the anchors and 'belays' the lower climber up with a 'top belay'.*

f) *The distance of a fall is small in a 'top belay' [**e**] situation.*

There has been a number of tests undertaken in concrete, but little literature is available on the strength of anchors in sandstone. The majority of tests that have been undertaken in the past have been in high strength concrete that is more relevant to stronger rock. Recent discussion in the climbing community has focussed on the strength of the various anchors in use in sandstone. This paper will examine the strength of various components and configurations of these anchors and determine their relative strengths when compared to each other in sandstone.

For descriptions of rock climbing terms used in this thesis. See glossary is located at the end of the thesis.

1.2 Testing Program

Testing was split into three sections, shaft treatment, adhesive comparison and sandstone anchor tests.

The shaft treatment section was designed to test a variety of shaft preparations used in rock climbing and compare their relative strengths. This was done by using a standard polyester adhesive across all the tests so comparisons could be made.

The adhesive comparison testing was included to make a comparison between a polyester and an epoxy adhesive. This involved testing some rods that were identical to ones that had been tested with the polyester adhesive

The main body of testing involved a series of anchors, used in rock climbing, to be installed into sandstone blocks. They were then subjected to tension or shear loads and the maximum strength was recorded. A standard adhesive was used between the anchors to allow comparisons to be made.

1.3 Scope of Thesis

This experimentally based thesis has a number of distinct components.

A review of literature identified the current understanding on the issues related to this thesis. This knowledge was used to refine the testing program.

The development of a testing program and apparatus was required to fulfil the thesis objectives. A number of test specimens were manufactured in order to test the desired variables in the experiments.

Tests were observed and documented to ensure that critical analysis was possible and comparisons could be made to previously documented results.

A discussion of results and the observed behaviour offers suggestions for the interpretation and use of the results.

Conclusions on the practical application of these results have been formed and recommendations to assist the direction of future research are provided.

Chapter Two

LITERATURE REVIEW

2.1 Introduction

This chapter is a literature review of the subjects relevant to chemically bonded anchors.

2.2 Factors Influencing Anchor Strength

There are several variables that influence the strength of chemically bonded anchors [Cook 1993]. These are outlined in the subsequent section.

2.2.1 Adhesives

A number of different adhesives are typically used for chemically bonded anchors and they are manufactured by a variety of companies. Although each manufacturer has unique products, the adhesives are either epoxy or ester based adhesives with sub sections within these chemical groups. The manufacturers produce information on the strengths of threaded bars installed with their products. These indicate that epoxy based adhesives are substantially stronger than polyester based adhesives [Powers 2003]. Cook [2001] found that epoxy resins had a uniform bond stress of more than twice that of the polyester adhesives.

Due to the porous nature of sandstone the bond strength can be even more important than in concrete. Epoxy glues appear to infiltrate sandstone more effectively than other adhesives [Jarvis &Hyman 2000].

The amount of adhesive used in a hole can effect the strength of the anchor. The shear strength of adhesives is greatest when there is a 1mm adhesive thickness surrounding the shaft [Çolak 2001]. This corresponds to the guidelines of manufacturers that indicate that hole diameters should be 2mm greater than the anchor shaft diameter [Powers 2003. Hilti 2002].

2.2.2 Hole Condition

There are a number of factors that effect the strength of an anchor that relate directly to the condition of the hole. When drilling into concrete or rock there is a lot of dust created. Manufacturers recommend that the hole be cleaned of loose particles using compressed air, then brushing the inside of the hole to loosen remaining particles attached to the side of the hole, and then removing these by using compressed air again [Powers 2003]. If the hole is not cleaned before installation of the anchors then the strength is considerably lower. Cook [2001] found that the tensile strength of anchors in concrete with uncleaned holes was only 71% of the strength of anchors with holes cleaned according to the correct procedure.

Another variable involved in anchor installation is the dampness of the hole. Manufacturers state that the hole may be dry or damp but should be free of standing water [Powers 2003]. Cook [2001] tested the effect of damp holes and holes filled with water on the tensile strength of anchors installed in concrete. The anchors installed into damp holes had 77% of the strength of dry hole anchors and anchors placed in submerged holes retained 43% of dry hole strength. Cook concluded that in damp holes water can get trapped in the pores of the concrete and impede the migration of the adhesive into the concrete surface, and in submerged holes this process is exaggerated.

Cook [2001] found that anchors installed in holes that were uncleaned, damp or submerged have a higher variability than anchors in dry cleaned holes.

2.2.3 Shaft Treatment

Manufacturers of construction anchors use fully threaded bars to maximise the area available for the adhesive to form a mechanical bond with the steel anchor [Powers 2003]. There is little information available, however, about how different shaft treatments affect the strength. Huyton [1997] tested a number of anchors with smooth shafts that had no treatment and found that the strength of an anchor depends, to a large extent, on the ability of the glue to ‘key into’ the anchor. This ensures that the shear strength of the adhesive is employed rather than its adhesive properties.

2.2.4 Anchor Embedment Length

Depending on the thickness of the shaft there are different recommended embedment depths. Çolak [2001] tested a variety of embedment lengths using 6mm steel rods and concluded that embedment depths of 100mm provide optimum strength and embedment lengths longer than this are unnecessary. These results are valid for 6mm shafts but generally the embedment depth is related to the shaft thickness to a certain maximum for each diameter of anchor [Hilti 2002]

2.2.5 Base Material

The material into which the anchor is installed has an influence on the anchor's performance. It is generally accepted that stronger materials will increase the strength of adhesive anchors [Cook 2001]. Cook [2001] tested a number of adhesive products in different strength concretes and, contrary to common belief, found no consistent trend. The same paper concludes that the bond strength of adhesive anchors in concrete appears to be inversely proportional to the porosity of the aggregate in the concrete.

Hilti [2002] has a formula for theoretical strength that accounts for different strength concretes. The higher the concrete's compressive strength, the higher the factor, and thus the theoretical anchor strength.

Anchors that are installed into rock are more variable than concrete. A straightforward correlation between compressive strength and anchor strength in rock is not possible due to the varied nature of the rock and failure mechanisms [Jarvis and Hyman 2000].

2.2.6 Anchor Spacing and Edge Distance

The distance between the legs on U-bolts has an effect on the overall strength of the anchor. As discussed below, tensile failures often occur with a cone of base material being removed. Two anchors closely spaced causes these cones to overlap and reduces the strength of each anchor [Jarvis and Hyman 2000] as seen in Figure 2.1.

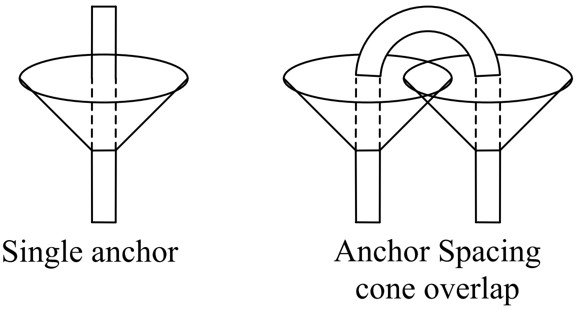

Figure 2.1

The effect of closely spaced anchors

The spacing between the anchors determines the size of the cones of influence. As the shaft spacing increases the amount of cone overlap decreases [Cook 1993]. Hilti [2002] have printed a chart that provides a strength reduction factor for a given anchor spacing and embedment depth. For instance, a U-bolt with 45mm leg spacings and embedded 75mm into the rock will have a strength reduction factor of 0.75 of the maximum strength of each shaft if they were individually tested. This would indicate that two shafts spaced 45mm apart and embedded 75mm would have a theoretical strength of 1.5 times that of a single shaft of the same embedment depth. The further apart the shaft spacing becomes the lower the influence on the other anchor and thus the higher the reduction factor. The minimum spacing of anchors to have no influence on each other is 2 x embedded depth [Hilti 2002]. This contrasts with Cook's [1993] finding that adhesive anchors spaced 1x embedment depth apart should achieve full strength capabilities.

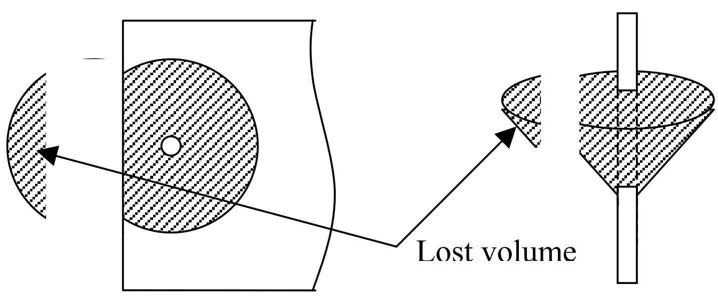

Figure 2.2

Minimised cone area due to small edge distance

The position of an anchor relative to one or more edges has an influence on the strength see Figure 2.2. A distance of 1.5 x embedment depth is required to ensure that the edge does not reduce the anchors strength [Hilti 2002].

2.3 Theoretical Strengths

There are a number of models that provide theoretical calculations for tension and shear strengths. Hilti [2002] have developed a formula that is used with their adhesive products and is as follows:

$$N_{rdc} = N^{o}{}_{rdc} \times f_t \times f_{bn} \times f_{an} \times f_{rn}$$

N_{rdc}	=	Design failure load
$N^{o}{}_{rdc}$	=	Shear or Tension load value from Hilti product information
f_t	=	Embedment depth
f_{bn}	=	Concrete strength factor
f_{an}	=	Anchor spacing factor
f_{rn}	=	Edge distance factor

This approach is useful if using Hilti products but for other adhesives it may not be as accurate due to different information that is provided by each manufacturer.

Cook [1993] developed a bond stress model that can be applied to any adhesive product but requires some test data. The elastic model is applicable for tensile strength only and assumes a concrete cone failure. The model requires testing of the adhesive being used to determine the maximum bond stress and an elastic property. The strength is derived from the following formula;

$$Tn = \frac{\Pi \times U\max \times d^{1.5}}{\lambda'} \times \tanh\left(\frac{\lambda'(\ell - \ell c)}{\sqrt{d}}\right)$$

Tn	=	Nominal tensile strength
$Umax$	=	Maximum bond stress for a given adhesive, determined from tests
d	=	Diameter of hole
λ'	=	Experimentally determined elastic property of the adhesive system
ℓ	=	Embedment length
ℓc	=	Depth of cone

Using an elastic behavioural model can effectively determine the tensile strength of adhesive anchors. Previous assumptions of uniform or linear bond stress distributions appear not to be conservative for longer embedment lengths. Testing revealed anchors of 100mm embedment were only 1.6 times stronger than anchors embedded 50mm [Cook et al 1993] if a linear trend was used 100mm embedment should be twice as strong as 50mm embedment.

Both these methods are based on a standard fully threaded anchor being installed into concrete. They are not particularly useful in determining anchor strength in sandstone with a not standard shaft treatment.

2.4 Tensile Failure Modes

The mechanism of a tensile failure largely depends on the embedment length of the anchor, the strength of the anchor, the strength of the base material and the type of adhesive used. Generally, when testing a threaded bar construction anchor, a cone of concrete or rock will be pulled from the surface of the material and the adhesive/shaft interface will fail. The depth of the cone decreases as the embedment depth increases [McVay et al 1996, Cook 1993].

Anchors used in rock climbing exhibit four different tensile failure modes [Pircher 2001, Jarvis & Hyman 2000]. These are:

- Anchor material failure- Failure due to the metal or weld.
- Adhesive bond/base material failure- Failure of the bond between the base material and the adhesive.
- Adhesive bond/anchor shaft failure- Failure of the bond between the adhesive and the anchor shaft.
- Splitting the base material- Cracks develop in the base material resulting in failure.

These failure modes have been observed in concrete and in rock tests. The type of failure is dependant on the anchor shape, adhesive used and strength of the base material.

2.5 Shear Failure Modes

The main body of research on shear failures is from tests undertaken on rock climbing anchors. A typical shear failure of an anchor starts elastically as the anchor is initially loaded. As the load increases the anchor starts to deform plastically in the direction of the applied force. This causes the shaft of the bolt to cut into the surrounding base material. This continues until only a fraction of the shaft remains embedded in adhesive and the shaft is effectively in tension. In the final stage of the mechanism, a tensile failure occurs in the remaining section of anchorage and it is completely removed from its placement [Pircher 2001].

2.6 Rock Climbing Anchors

Testing undertaken on specific rock climbing anchors has yielded mixed results. Pircher [2001] indicates that eight different types of chemically bonded anchors met the guidelines for European Standard EN 959 (discussed in Section 2.8). The tests were completed in accordance with EN 959 and used concrete blocks.

Tests carried out in sandstone boulders [Jarvis & Hyman 2000] in South Africa produced varied results. A number of 'U-Bolts' were tested and found to be inadequate for the European Standard EN 959. The maximum load recorded in these tests was 50kN. A variety of different glues and hole diameters were used which confused comparisons of the different anchors. The author's findings were that the U-bolts were inadequate and ideally should be removed.

The Victorian Climbing Club commissioned some tests on 10mm and 12mm diameter dynabolts and 10mm diameter glue in machine bolts [McIntosh 1999]. The findings were that none of the bolts tested passed the standards of EN:959. The Machine bolts failed due to the hangers failing, not the bolt. The dynabolt failures were a mixture of concrete cracking and bolt shear.

The Northern Caving Association (NCA) in Great Britain carried out a number of tests of ring bolts installed into limestone in various environmental conditions. The anchors exceeded guidelines for safety indicated in EN 959:1996.

In the 1960s some testing was undertaken by climbers in Australia. Machine bolts installed into undersized holes with a hammer were tested using a large lever arm until they were removed. The bolts were found to be able to withstand more than 10kN [Allen 2003].

These tests do not compare different anchor configurations in sandstone with a uniform adhesive.

2.7 Forces On Anchors

The force that a rock climbing anchor is required to withstand depends upon the type of rope, length of fall, amount of rope in the system and type of 'belay' device used to arrest the fall. The Union Internationale des Associations d'Alpinisme [UIAA 1998] stipulate that a dynamic climbing rope must limit the force exerted on a climber to a maximum of 12kN. This is achieved by the elastic properties of the rope. Equilibrium requires the force on an anchor to be twice that of the force in the rope minus friction [Law et al 1992, Pircher 2001]. This is illustrated in Figure 2.3 for the maximum possible loading with a nominal friction component.

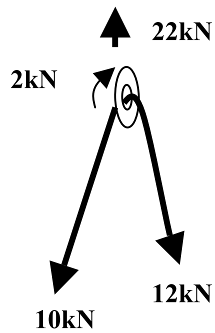

Figure 2.3

Maximum forces on an anchor during a rock climbing fall

The maximum loads possible are unlikely to occur as they generally involve a factor 1.78 fall or worse [Jarvis & Hyman 2000]. The fall factor is calculated by dividing the fall distance by the length of rope. A factor 2 fall requires a fall of twice the length of the rope holding the 'climber'. This can only occur when a fall goes passed a ledge on a ‘multipitch climb’. The 12kN maximum force is generated with an 80 Kg weight falling 5m with a fixed connection to the anchor [UIAA 1998].

Attaway [1996] developed the following equations to determine the impact load factor developed in a ‘climbing fall’:

Static Deflection of rope = δ_{st} = $\frac{W \times L}{M}$

W = Weight of ‘climber’, Kg

L = Length of rope, m

M = Rope modulus- Change in force for a given stretch, Kg m / m

Impact load factor

$$\frac{F}{W} = 1 + \sqrt{1 + \frac{2 \times h}{\delta . st}}$$

F = Force, N

h = length of fall, m.

These formulae allow a force to be determined for any fall distance and rope length. This method assumes a fixed rope and does not account for dynamic breaking forces that ‘belay devices’ provide. Slipping occurs in many types of ‘belay devices’ that will limit the impact load. These loads vary from 1.5kN to 9kN depending on the type of device used [Soles 2000].

2.8 Rock Climbing Anchor Standards

There is no relevant Australian standard for rock climbing anchors at present. Europe, however, has a standard that stipulates safety requirements and standards. EN 959:1996 requires anchors to withstand an axial (tensile) load of 15kN and a radial (shear) load of 25kN when tested in concrete blocks of a specific dimension. These standards are based upon rocks commonly found in Europe such as limestone and granite and cannot be compared to the sandstone properties commonly found in Australia.

The UIAA also produces guidelines for permanent Rockclimbing anchors. UIAA 123 1998 is based on EN 959 and requires top rope anchors (anchors placed at the top of a 'climb') to withstand 15kN of axial load and 15kN of radial load. The decreased standard of top rope anchors is due to the fact that top rope anchors are not subjected to the large dynamic loads created when a 'lead' climber falls. In top rope falls the fall factor is less than 0.5 due to the length of rope that is used to arrest a fall and the short fall distance.

Chapter Three

SANDSTONE ANCHOR TESTING RIG

3.1 Overview

The reaction frame test rig for the anchors in the sandstone blocks was fabricated specifically for this project. In addition to meeting the requirements of testing, the reaction frame needed to be easily usable by one person.

The testing rig was required to test anchors in shear and tension and be able to accommodate the sandstone blocks that would be positioned in various configurations.

The following chapter discusses the factors influencing the final design of the reaction frame and describes in detail the rig as fabricated.

3.2 Design Considerations

There were a number of considerations that needed to be accommodated in the design of the reaction frame. These included practical aspects governing the operation of the rig and possible forces generated by the testing.

The testing in this phase of the thesis involved applying tension and shear forces to a variety of anchors installed into sandstone blocks. The sandstone blocks had approximate dimensions of 300mm x 300mm x 400mm. Up to eight anchors were installed into each block in the configuration shown in Figure 3.1. Four anchors, one close to each corner, were placed in the top face for tensile tests and four anchors, one on each side, were placed for shear tests. To avoid damaging the adjoining anchors prior to testing, the attachment system for the block restraints needed to accommodate various alternatives depending on the anchor being tested.

The rig was required to test the anchors in shear and tension. This required the applied load to be vertical to ensure the tests were not undertaken with eccentric loading. To produce these loads a hydraulic jack was mounted above the blocks.

The forces that the testing would generate were an important factor of the design. The final rig was required to be robust enough so there were minimal deflections when undergoing the tests. The maximum load expected in the tests was determined to be in the shear tests and would be no greater than 50kN. Simple calculations were undertaken to ensure that the design would be adequate. These can be found in Appendix A.

Failure was expected to be quite variable and, in certain situations, to be sudden. In order to ensure that an accurate result could be obtained from a sudden failure a means of recording the maximum load reached was required. A load cell would be required to undergo forces of up to 50kN.

The above considerations were incorporated into the final design of the sandstone block reaction frame. Observations on the performance of the frame are recorded in chapter six.

3.3 General Description

The fabricated reaction frame was a very simple design. Figure 3.2 shows the final condition of the testing rig. The sandstone blocks sit on a platform built from reinforced compact rectangular hollow sections. At the front of the platform are two channel sections that are vertically fastened to the platform. At the top of these there is a reinforced rectangular hollow section cross bar that joins them together. This is the superstructure of the reaction frame.

On top of the cross bar a ten tonne hydraulic jack was mounted that had an 18mm steel bar passed through it. The load cell was attached to the base of the steel bar and in the bottom of the load cell was an hexagonal eye which allowed the anchors to be attached. Above the hydraulic jack the threaded bar could be adjusted with some hexagonal nuts to vary the length for different tests.

The sandstone block was restrained with two square hollow sections that were positioned with four threaded 18mm steel bars. The steel bars could be placed in a number of different holes below the platform and arranged to avoid the restraints damaging the remaining anchors in the block. The square hollow sections were placed over the threaded bars and the nuts were tightened to minimise the movement in the system.

The load cell was attached to a multimeter that was programmed with a high/low program. This allowed it to register the maximum load in the system before failure occurred.

The reaction frame was built robustly to avoid excessive deflections from the applied loads. The simplicity of the system allowed it to be used by one operator with ease.

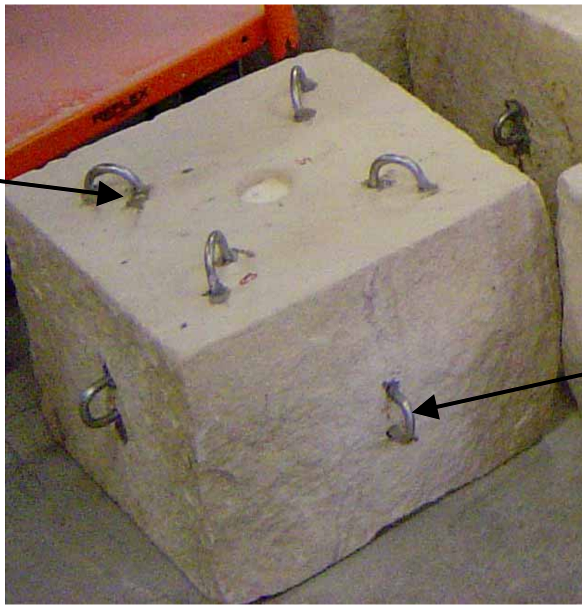

Figure 3.1

Anchor configuration in sandstone block

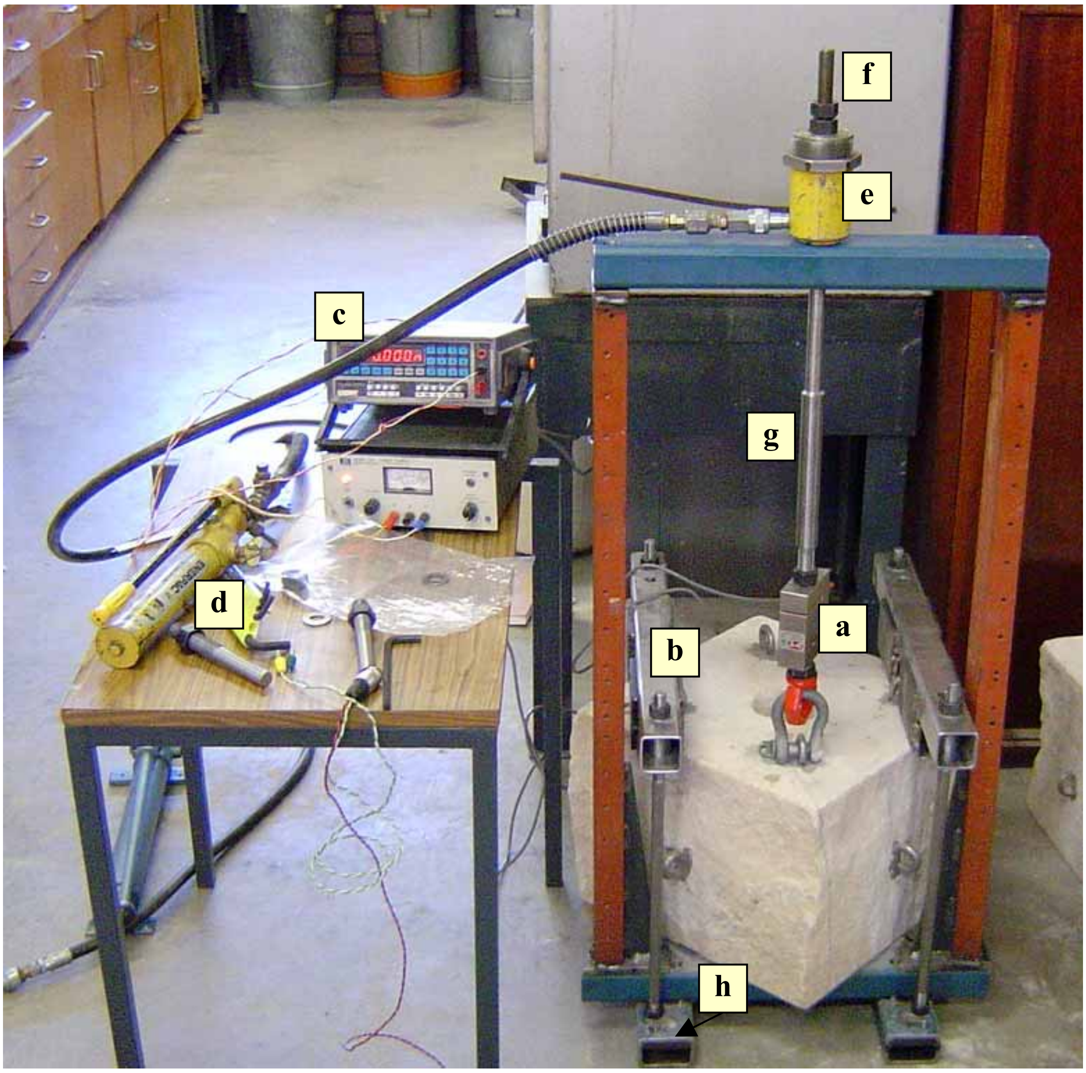

Figure 3.2

Components of the sandstone testing rig

a) *The 50kN load cell*

b) *Sandstone block restraints*

c) *Multimeter with readout displayed*

d) *Hydraulic pump*

e) *Ten tonne hydraulic jack*

f) *The hexagonal nuts used to adjust test rod length*

g) *Test rod*

h) *Holes to allow versatile restraint location*

Chapter Four

TEST SPECIMENS

4.1 Introduction

Specimens were manufactured and tested to produce the results required for this thesis. For statistical purposes, a minimum of five tests were planned for each series. There were three separate tests performed, the specimen manufacture and preparation is discussed below.

4.2 Test Specimens

The following section contains descriptions of the test specimens fabricated for each part of the testing program.

4.2.1 Shaft Treatment

In order to determine the significance of shaft treatment on the strength of an anchor, a series of preparations were manufactured. The shaft treatment extended for 80mm along one end of the rods. The following specimens were manufactured from 316 grade 10mm stainless steel bar:

- Clean untreated shaft- these rods were cleaned using methylated spirits but had no other change to the original surface condition.
- Notched shaft- these rods were notched using an angle grinder with a cutting blade. They have 14 notches 3mm wide and 5mm long and up to 1mm deep. This gives a total area of notching to be approximately 8.6% of total surface area in contact with the adhesive.
- Notched and Ground shaft- these rods had been notched with an angle grinder cutting blade and then ground using a coarse bench grinder to roughen the surface up between the notches. The notching pattern had the same dimensions as above with a surface area of approximately 8.6% of total surface area plus the grinding added a rough surface for the glue to bind on.

- Lightly (0.3mm) threaded shaft- these rods where constructed using a 0.3mm thread which was cut into the exterior of the rod. The depth being 0.3mm and spaced 1.5 mm apart and extended for 65mm along the shaft. The approximate area of the threading at the surface was 16% of total shaft surface area.
- Fully (1mm) threaded shaft- these rods were fabricated using a standard metric 10 x 1.25mm thread cut into the exterior of the rod. The thread depth was 0.7mm and at the surface the thread was approximately 1mm wide. The total area being 65% of total surface area exposed to the adhesive.

In order to test the bars in a tensile machine, ten 18mm steel bars were prepared to be used as holders for the adhesive and treated rods. They were fabricated by boring a 12mm diameter hole 80mm long into the centre of the bars, into which the rods were installed. The initial test specimens are shown in Figure 4.1.

4.2.2 Adhesive Comparison

An Acrylic Epoxy adhesive was tested using the notched and ground shafts that have been described above. These results were able to be compared to the notched and ground shaft tests that were undertaken with the polyester glue to gain a simple comparison.

4.2.3 Sandstone Anchors

A number of different anchor configurations commonly used in rock climbing were tested. They were manufactured by a variety of sources using 316 grade stainless steel bar. The samples used in these tests were:

- 8mm diameter ‘Ring Bolts’, lightly threaded. Embedded 85mm. Manufactured by an experienced rock climber.
- 10mm diameter ‘Ring Bolts’, notched and ground. Embedded 115mm. Manufactured commercially by a local business.
- 10mm diameter ‘U-bolts’ with 35mm leg spacing and kinked legs, notched and ground. Embedded 70mm. Manufactured by an experienced rock climber.
- 10mm diameter ‘U-bolts’ with 45mm leg spacing and straight legs, notched and ground. Embedded 80mm. Manufactured by the author.

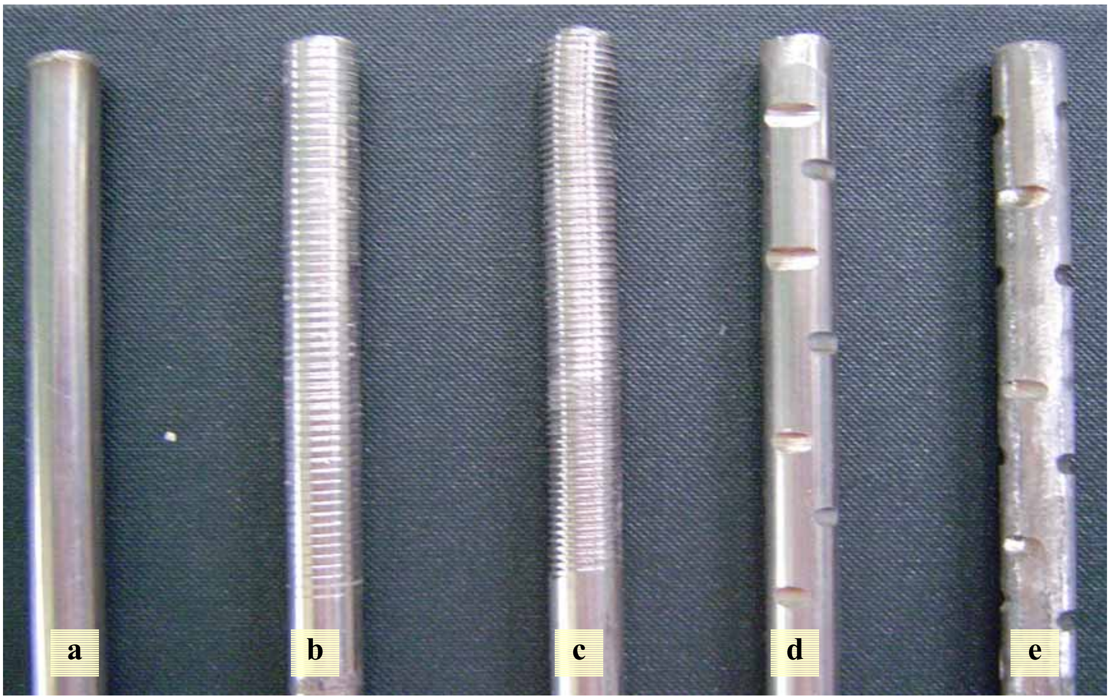

Figure 4.1

Shaft treatment specimens before testing

a) *Smooth, Clean shaft*

b) *Lightly threaded shaft*

c) *Deeply threaded shaft*

d) *Notched shaft*

e) *Notched and Ground shaft*

- 10mm diameter 'U-bolts' with 55mm leg spacing and kinked legs, notched and ground. Embedded 70mm. Manufactured by an experienced rock climber.
- 10mm Machine bolts, 30mm of threading then notched. Embedded 90mm. Purchased from a fastener supplier and modified by author.

Figure 4.2 shows the different anchors before testing and Table 4.1 contains a summary of the specimens and their parameters.

For a full description of the anchors mentioned in this and subsequent sections refer to the glossary located towards the end of this report.

4.3 Materials

The materials chosen for the specimens were representative of those currently used in rock climbing.

The majority of new anchors being placed in Australia are manufactured from 316 grade stainless steel. Anchors are also available in 304 grade stainless steel and various plated metals but these form the minority of placements at present. For this reason the anchors were manufactured from 316 grade stainless steel for these tests.

The sandstone blocks that were used as the base material were sourced from the local area. As the majority of the cliffs in the area surrounding Sydney are sandstone this was considered an appropriate test material.

The chemical adhesive used throughout the comparative shaft tests and sandstone anchor tests was a two part styrene based dibenzoyle peroxide. This product is popular throughout the climbing community to install anchors due to its ease of handling and low price. The strength of this adhesive is determined by the manufacturers to be at the lower end of the available products. By testing using this adhesive the findings will be relevant to many anchors being installed at this time.

Figure 4.2

Sandstone anchors before installation

a) *10mm Ring bolt*

b) *45mm U-bolt*

c) *55mm U-Bolt*

d) *35mm U-Bolt*

Anchor Type	Anchor Code	Shaft Diameter (mm)	Embedment Depth (mm)	Leg Spacing (mm)	Hole Diameter (mm)	Shaft Treatment
Ring	R10	10	115	N/A	12	Ground and notched
Ring	R 8	8	85	N/A	10	light threading
U-Bolt	U 35	10	70	35	12	Ground and notched
U-Bolt	U 45	10	80	45	12	Ground and notched
U-Bolt	U 55	10	70	55	12	Ground and notched
Machine Bolt	M10	10	90	N/A	12	40mm threading and notches

Table 4.1

Summary of rock climbing anchor specifications

4.4 Grouting Procedure

The subsequent procedures were followed to ensure that each test was prepared in the same manner.

4.4.1 Shaft Treatment Tests

Once the shafts had been fabricated they were installed into the bored steel bar. This was done following this procedure:

1. The 18mm bars were placed into the bottom of the jig, see Figure 4.3, that had been designed to ensure that the rods were centrally located in the 12m hole.
2. The adhesive was placed in the hole by using the caulking gun and static mixer attached to the glue cartridge. The static mixer ensures that the two parts of the glue are mixed at the appropriate ratio and come out the end of it correctly. The adhesive was placed to approximately half the depth of the hole.
3. Once the adhesive was in place, the rod was placed into the hole and twisted as it came in contact with the adhesive. This ensured that there was an even distribution of the glue around the shaft and in the threading or notching.
4. The top clamp was then tightened to ensure that the rod was centrally located. The rods were then left for 5 minutes for the adhesive to gel and then taken out of the jig.
5. The process was repeated for all of the specimens in the test series.

An example of the final grouted specimen is presented in Figure 4.4.

4.4.2 Adhesive Comparison Tests

The same grouting procedure for the shaft treatment tests was followed for the adhesive comparison test.

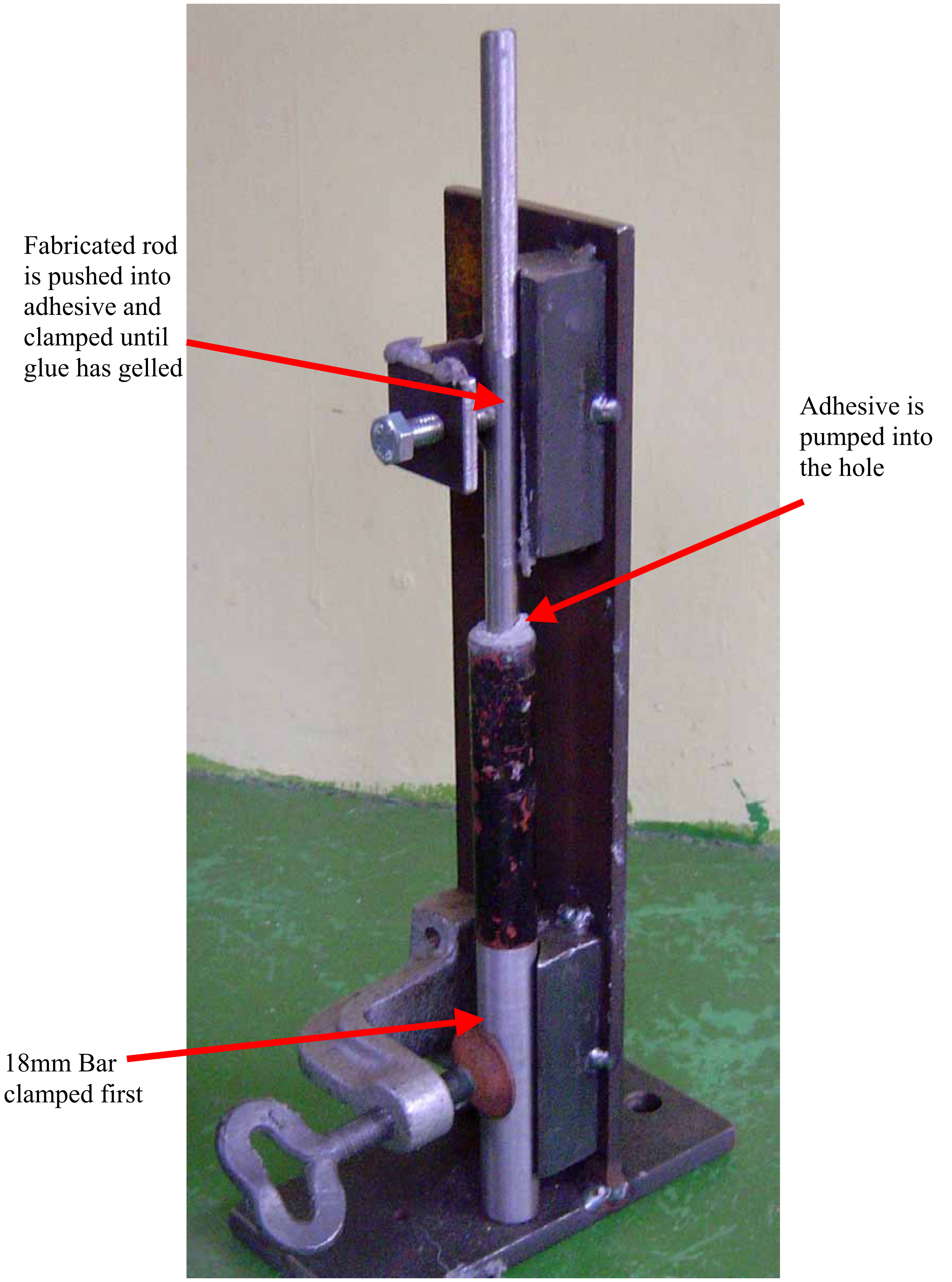

Figure 4.3

Jig for centring the rods during the grouting procedure

Figure 4.4

The grouted shaft treatment specimen before testing

4.4.3 Sandstone Anchor Tests

The grouting procedure undertaken for this series of tests followed a method commonly used in a rock climbing application. The procedure was as follows:

1. The hole for the anchor was drilled into the sandstone block using a cordless rotary hammer drill. A 12mm carbide tipped drill bit was used for 10mm shafts and 10mm carbide tipped drill bit was used for the 8mm shafts. For ring bolts, the shaft was drilled and a recess was cut into the rock surface to allow the ring to be indented into the rock. For ‘U-bolts’, two parallel holes were drilled at the appropriate distance for the shaft spacing. The depths of the holes were regulated by a depth gauge mounted onto the drill. This ensured that the holes for each anchor type were the correct depth.
2. The hole was then blown out using a small diameter plastic hose and using lung pressure.
3. Once the dust had been removed a plastic cylindrical brush was used to clean the sides of the hole and liberate any dust particles from the edge of the hole.
4. The hole was then blown again using the tube and lung pressure.
5. Once clean, the holes were filled to approximately half depth with adhesive mixed in the static mixer attached to the adhesive cartridge. This ensured that the adhesive was mixed to the same ratio each time it was used.
6. The bolts were then inserted into the holes. Ring bolts were rotated into the hole to spread the adhesive around the shaft evenly. U-bolts are not able to be rotated so they were pushed into the hole in one motion. The U-bolts with the kinked shafts were placed in the holes with a hammer to ensure they were fully seated in the hole to the correct depth.
7. Once in place the anchors were left to cure for a week or more.

Figure 4.5 shows the typical appearance of the various anchors placed in the sandstone.

4.4.4 Sandstone Compressive Strength

Samples of the blocks were used to determine the Unconfined Compressive Strength (UCS) of the sandstone. The specimens dimensions were 110mm long by 54mm wide. These dimensions were required to satisfy the ratio of 2D:L. Figure 4.6 indicates a typical sample used in the testing.

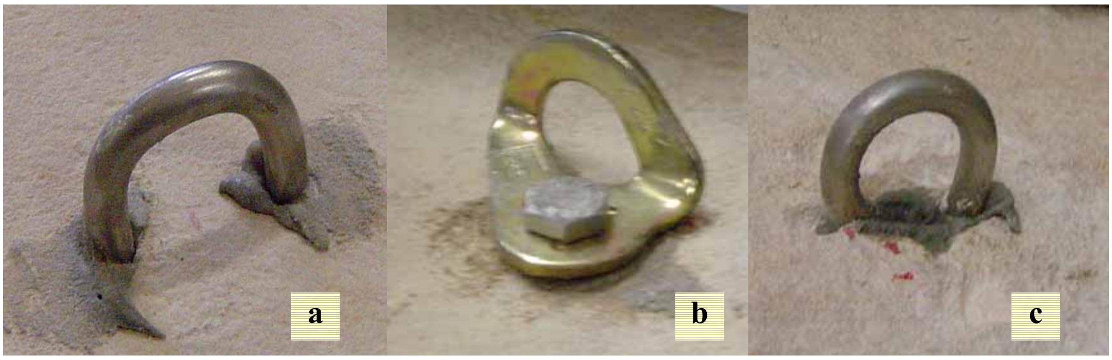

Figure 4.5

Typical installation detail of the different anchor types

a) *Typical U-bolt*

b) *Machine bolt with hanger*

c) *Typical ring bolt*

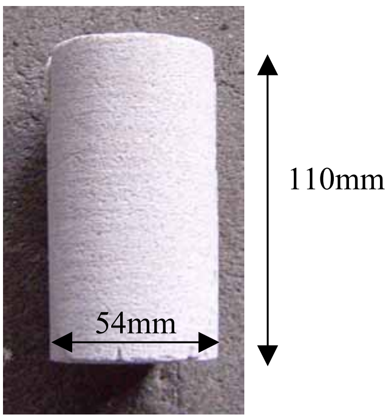

Figure 4.6

Unconfined Compressive Strength test specimen before testing

Chapter Five

EXPERIMENTAL EQUIPMENT AND PROCEDURE

5.1 Introduction

This chapter describes the items of experimental equipment used and the procedures implemented for testing the various specimens in this thesis.

5.2 Experimental Equipment

5.2.1 Shaft Treatment

The shaft treatment tests were tensile tests. The specimens were placed in an Amsler testing machine, with a capacity of 100kN as seen in Figure 5.1. The machine consisted of an operating console that was connected to the hydraulic ram that applied the tensile loading required. Depending on the expected load, the scale of the display and hydraulic ram could be changed between 100kN, 50kN, 20kN, 10kN, 5kN, and 2kN. This enabled a more accurate reading to be taken on lower results.

5.2.2 Adhesive Comparison

These tests were carried out in the same machine as the shaft treatment tests described above.

5.2.3 Sandstone Anchor Tests

To test the anchors installed in the sandstone blocks, a unique test rig was designed and built. This has been described in detail in Chapter Three.

5.2.4 Sandstone Compressive Strength

A diamond tipped rock core drill, shown in Figure 5.2, was used to core a sample of the sandstone blocks to be tested. These were then tested in an Avery testing machine as shown in Figure 5.3.

Figure 5.1

Amsler machine used for testing shaft treatment specimens

Figure 5.2

The diamond tipped rock core drill

Figure 5.3

The Avery machine used in the unconfined compressive strength tests

Figure 5.4

Shaft treatment specimen in machine prior to testing

5.3 Experimental Procedure

As there were a number of different tests undertaken in this thesis, there were different procedures implemented in each stage. These procedures are outlined in this section.

5.3.1 Shaft Treatment and Adhesive Comparison Tests

The test specimens were left for 15 hours to cure and then placed in the tensile machine. The following procedure was used to test the specimens:

1. The specimen was loaded so that the load was taken up by the shaft. Due to the stainless steel bar being smooth this was done slowly to minimise slippage
2. The loading was kept constant until a peak load was reached and the adhesive bond failed.
3. The shaft was extracted from the hole and the residual strength of the shaft was noted
4. The specimen was removed from the machine and the results were recorded.
5. The system was reset and the procedure repeated for the other experiments

Figure 5.4 shows a test specimen about to be tested.

5.3.2 Sandstone Anchor Tests

The anchors were left to cure in the sandstone for a number of weeks. This minimised the chance of erroneous results due to uncured glue. Before the tests were undertaken, the load cell in the test rig was calibrated using the following procedure:

1. The load cell was placed in an Amsler Tensile machine, attached to a multimeter and steadily loaded to 40kN and back to zero.
2. The millivolts readings were recorded at 5kN increments up to 40kN and 10kN increments as the load was decreased back to zero.

3. The readings were then plotted and a regression line formula was determined. This produced a constant that was programmed into the multimeter to calibrate the load cell and allowing the readout to display kilo newtons.

Once the load cell was calibrated the following procedure was used for both shear and tensile tests:

1. The block was placed on the reaction frame and secured using the restraints. The position of the block depended on whether shear or tensile testing was being undertaken.
2. The shackle was attached to the anchor being tested and all slack was taken out of the system by tightening the nut on top of the jack.
3. The hydraulic pump was then pumped at an even rate to increase the load until failure occurred.
4. Once the maximum load was reached and the initial failure had occurred, the anchor was pulled completely out of the hole to determine failure mechanisms.
5. Once the anchor was removed the pressure was released from the jack and the maximum reading was recorded. The multimeter had been programmed to record the maximum load.
6. The shackle and restraints were undone and the block was rotated to continue the testing.

Figure 5.5 shows the typical setup for a tensile test and Figure 5.6 shows the typical shear test setup.

5.3.3 Sandstone Compressive Strength

To test the compressive strength of the blocks used to house the anchors, a rock core was taken from four of the blocks. This was done by coring through the block with a diamond tipped drill piece. The core was retrieved and cut to the correct length. Since the core had a diameter of 54mm, the length of the samples was 110mm to ensure the ratio of L= 2D was maintained. The specimens were then placed in the testing machine and loaded in compression. The loads were recorded and the unconfined compressive strength of the sandstone was determined.

Figure 5.5

Test rig setup for tension testing

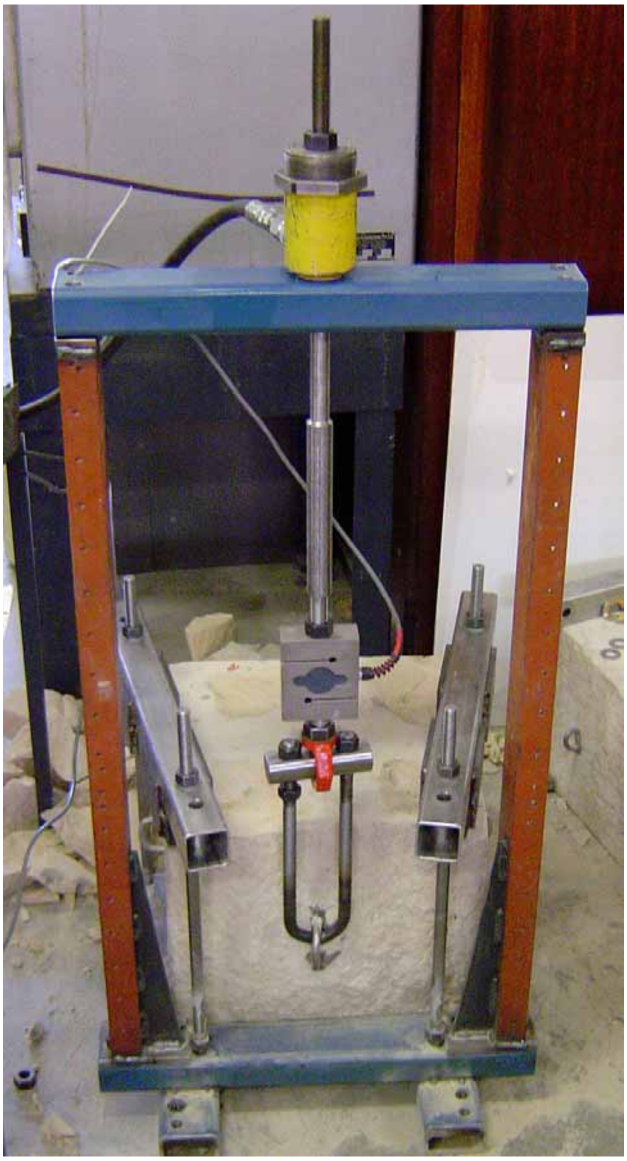

Figure 5.6

Test rig setup for shear testing

Chapter Six

EXPERIMENTAL RESULTS & OBSERVATIONS

6.1 Overview

The specimens were tested using the various procedures as outlined in Chapter Five. This chapter contains the results of those tests and additional observations made throughout the experiments. The results have been divided into three sections, shaft treatment, adhesive comparison and sandstone anchor testing. There were 81 tests completed throughout the duration of this research program. The statistics used to quantify the results were the mean of the test results, and the variance, which is the standard deviation divided by the mean. Variance was used as it provided an indication of the variability of the results.

6.2 Shaft Treatment

Tests were conducted on five different shaft preparation techniques. A total of 25 tests were conducted in the J W Roderick Materials and Structures laboratory at the University of Sydney. The results are presented in Table 6.1. A sample of each of the specimen types after testing can be seen in Figure 6.1 and Figure 6.2 contains a chart comparing the results of the tests.

6.2.1 Untreated Bar

The untreated bars were tested to get a baseline strength which was used to compare against the other results. The mean load observed was 0.185kN with a variance of 25%. Once the bond had broken on these tests there was no residual strength, the shafts could be pulled from the adhesive by hand. There was no glue residue left on the shaft.

6.2.2 Shallow Thread (0.3mm)

The first result in the shallow threading tests yielded at 21.4kN. The following four tests, however, had a mean of 5.05kN and a variance of 36%. The mean of the five tests was 8.32kN and the variance 89%. For this reason the first test was not included

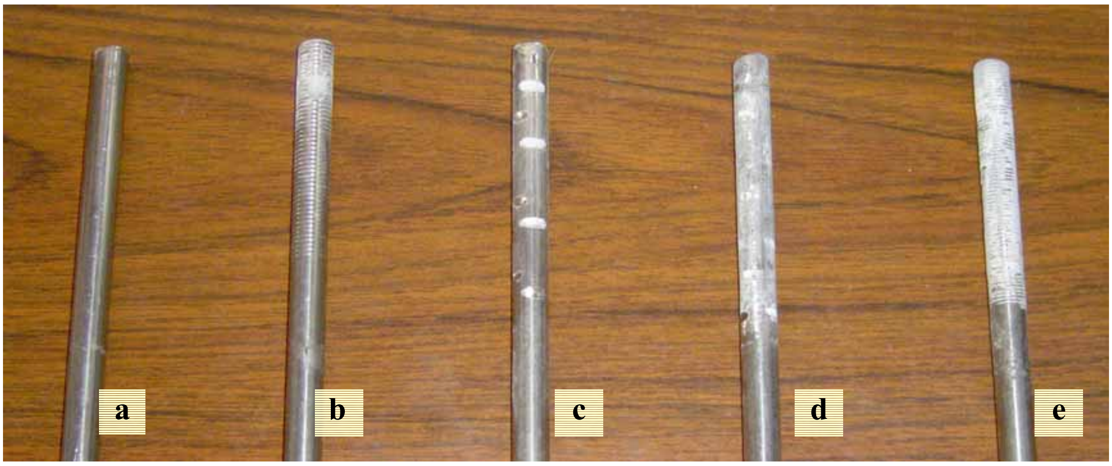

Figure 6.1

Shaft treatment specimens after testing

a) *clean untreated*

b) *Lightly threaded*

c) *Notched*

d) *Ground and notched*

e) *Heavily threaded*

in the results as it was determined to be an abnormality. The shallow thread tests, therefore, had a mean strength of 5.05kN and a variance of 36%.

The residual strength after failure was minimal. The shafts came out freely with a maximum force of 1.5kN after failure. There was a small amount of adhesive found to be in the threading when the shafts were examined after testing.

6.2.3 Notched

The notched shafts had a mean strength of 8kN and a variance of 13%. They had very little residual strength once the initial bond was broken. Glue was visible in the notches on the shafts.

The load required to pull the shaft from the hole once the bond was broken was minimal.

6.2.4 Notched and Ground

The notched and ground shafts produced an interesting result. The notching was the same as the notched shafts, the difference being the surface area of the shaft was ground with a bench grinder. The mean of these tests was 14.3kN and the variance was 19%.

There was a large amount of glue present on the shaft after it was extracted from the hole. The notches were filled with plugs of glue and the ground surface was covered with glue. The residual load required to remove the shaft from the hole was up to 13kN.

6.2.5 Deep Threading.

The deep threading was, by a large amount, the strongest of the tested shaft treatments. The mean for the five tests was 42.3kN and the variance was just 2%.

The threading was fully covered in glue when removed from the hole after testing. The residual load required to remove the shafts from the glue after the initial failure was up to 33kN.

Test Number	1	2	3	4	5	Mean	Standard Deviation	Variance
Type of treatment	kN	kN	kN	kN	kN	kN	kN	%
Untreated	0.2	0.17	0.23	0.21	0.11	0.18	0.05	0.26
Shallow Thread (0.25mm)	21.4	6.7	4.9	2.5	6.1	5.05	1.86	0.37
Notched	6.7	8.1	8.15	9.5	7.55	8.00	1.02	0.13
Ground and Notched	11.55	16.9	11.6	17.05	14.35	14.29	2.70	0.19
Deep Thread (1mm)	43	41.75	43.5	41.2	42.2	42.33	0.93	0.02

Table 6.1

Results from shaft treatment tests

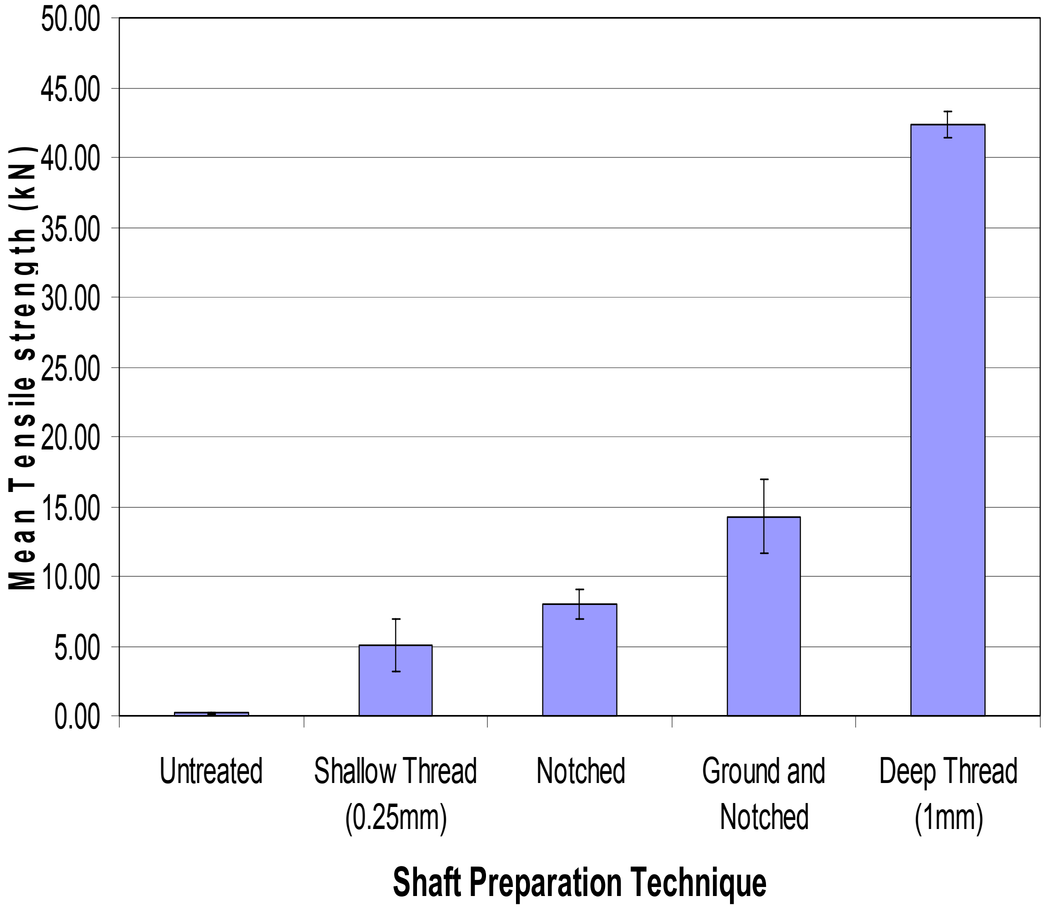

Figure 6.2

Comparison of shaft treatment results

6.3 Adhesive Type

The tests undertaken on the Acrylic Epoxy adhesive were highly variable. The results are tabulated in Table 6.2. Two of the tests had adhesive with a light cream colour, which is in contrast to the grey that is indicated by the manufacturer. These tests had strengths considerably lower than the other tests. The mean of all five tests was 22.7kN with a variance of 56%. The three grey, correctly mixed, adhesive tests had a mean of 31.6kN and variance of 12% and the two cream, poorly mixed, adhesive tests had a mean of 9.3kN and a variance on 35%.

Test Number	1	2	3	4	5	Mean	Std Deviation	Variance
Test results	kN	kN	kN	kN	kN	kN	kN	%
Epoxy- All Results	32.3	35.2	11.65	27.5	7	22.73	12.65	0.56
Epoxy- Correctly Mixed	32.3	35.2		27.5		31.67	3.89	0.12
Epoxy- Incorrectly Mixed			11.65		7	9.325	3.29	0.35

Table 6.2

Results from adhesive comparison tests

6.4 Sandstone Anchor Tension Tests

The sandstone tests were undertaken over a number of days in the soils laboratory at the University of Sydney. The results are presented for each of the anchor types tested. 8mm rings were not tested in tension. The results are summarised in Table 6.3 and a plotted graphically in Figure 6.19.

6.4.1 10mm Ring Bolts

The 10mm ring bolts produced a mean tensile strength of 20.6kN and a variance of 4.7%. All five of these tests failed by the adhesive/rock boundary failing. The failure was gradual. Once the maximum load was reached the anchor displaced vertically by approximately 5mm and then gradually continued, under decreasing load, to displace vertically. All five tests cracked the rock immediately around the shaft, see Figure 6.3, to a depth varying between 36mm and 55mm. Residual strengths of up to 8kN were registered before the anchor was removed from the sandstone. When fully extracted from the hole the glue remained predominantly intact around the anchor shaft as shown in Figure 6.4.

6.4.3 35mm U-Bolts

The 35mm U-Bolt tensile tests produced a mean tensile strength of 24.06kN and a variance of 6.4%. The failure displayed by these anchors was very sudden. The anchors failed by removing a large area of rock with a depth corresponding to the shaft length of the anchor. Three cracks formed during the failure. One ran through the axis of the shafts to the corner of the block. The other two radiated from the inner leg to the closest edge of block. This is clearly illustrated in Figure 6.5. Once failure had occurred there was no residual strength in the system. The bolts remained bonded to the rock and the failure was through the rock mass.

6.4.4 45mm U-Bolts

The 45mm U-bolt produced a mean tensile strength of 26.82kN and a variance of 6.2%. These anchors all failed by pulling out a relatively small cone of rock. The cone had a depth of between 20mm and 25mm and the failure below this point was a rock/glue boundary failure as shown in Figure 6.6. The adhesive was visibly intact around both shafts and had not sheared from the anchor.

6.4.5 55mm U-Bolt

These anchors behaved in a very similar manner to the 35mm U-Bolts. The mean tensile strength was 22.43kN with a variance of 11.5%. These results may have been affected by the proximity of the anchors to each other. The failure mode for four of the anchors was a sudden failure of a section of rock at a depth corresponding to the shaft length of the anchor as indicated in Figure 6.7. The area of rock removed by the anchor failure was significant as shown in Figure 6.8. The fifth anchor failed gradually with a rock/glue bond failure rather than a rock mass failure. Deformation of this anchor occurred during extraction which can be seen in Figure 6.9. One of the shafts remained in the rock while the other continued to be deformed. There was a reasonable residual strength in this anchor as it was slowly extracted.

Figure 6.3

Cracking around a ring bolt after failure in tension test

Figure 6.4

Ring bolt after being extracted from a tension test

Figure 6.5

35mm U-Bolt failure with cracks radiating from shafts

Figure 6.6

45mm U-Bolt tension failure displaying the shallow cone failure and sandstone/adhesive bond failure

Figure 6.7

55mm U- Bolt indicating the depth of sandstone removed relates to depth of the shaft embedment

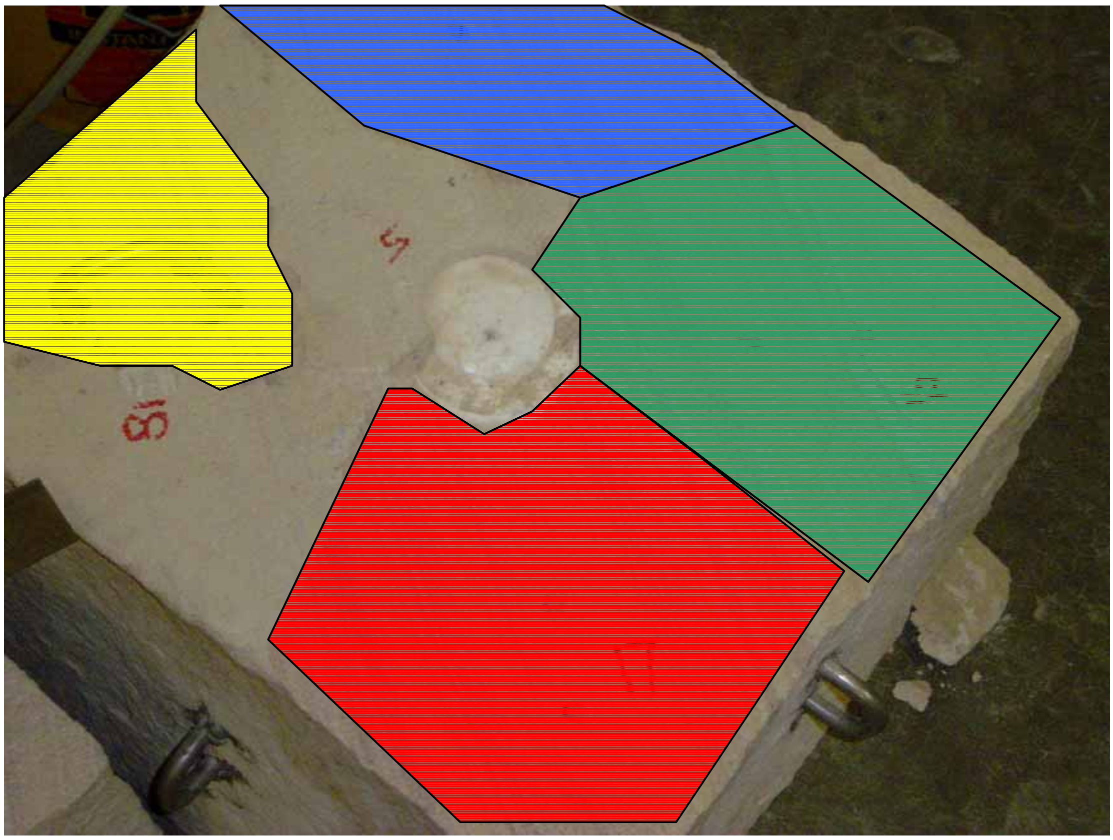

Figure 6.8

Area removed by 55mm U-Bolt tensile tests. The different colours represent the different areas affected by each anchor.

Figure 6.9

55mm U-bolt that failed by sandstone/adhesive failure and deformed

6.4.6 Machine Bolts

The hangers on the machine bolts failed in these tests. The machine bolts had started to bend but the hangers sheared before any displacement was observed in the anchor. The failures had a mean of 17.99kN and a variance of 18.4%. The hangers started to deform at 5kN and the head of the bolt started to rotate at 10-12kN. Failure occurred through the eye of the hanger and was a tensile failure of the metal. Figure 6.10 shows the failure mechanism.

Test Number	1	2	3	4	5	Failure Mode	Mean	Std Dev	Variance
M10	17.07	22.75	15.07	17.07		Hanger shear	17.990	3.310	0.184
R10	20.18	18.75	21.16	20.68	19.53	Glue/Rock bond	20.060	0.946	0.047
U35	24.35	22.66	25.95	25.00	22.36	Rock fracture	24.065	1.531	0.064
U45	25.22	28.88	27.90	25.03	27.07	Rock cone & bond	26.820	1.676	0.062
U55	24.66	24.78	21.56	18.54	22.64	Rock Fracture	22.436	2.570	0.115

Table 6.3

Sandstone anchor tension test result

6.5 Sandstone Anchor Shear Tests

Due to some of the anchors cracking the sandstone blocks three of the installed anchors were not tested as they were not surrounded by enough rock. These are indicated in the appropriate sections. The distance of the anchors to the top of the blocks was also variable due to the tensile failures of the anchors on top of the respective blocks. The average depths from the top of the blocks of the tests has been included in the observations for each anchor. The loads indicated here are the maximum loads reached by the anchors. The results are summarised in Table 6.4 and a plotted graphically in Figure 6.20.

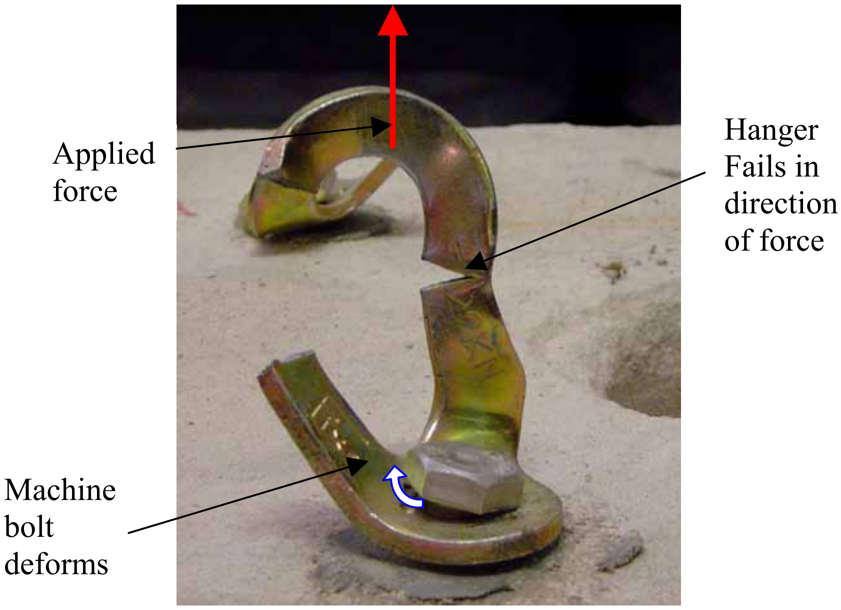

Figure 6.10

Tensile failure of hanger on machine bolt

6.5.1 10mm Ring Bolts

The ring bolts, with the exception of one which spilt the block down the centre, failed by the mechanism identified by Pircher [2001] and discussed in the literature review. The anchors crushed the rock vertically and deformed as the load increased to a maximum load. The eye of the bolt did not deform but the shaft was considerably bent by the shear tests. The anchor failure was gradual. As the load increased the anchor would gradually deform and crack the rock above it. Periodically the anchor would slip horizontally and the process would start again. As the deformation in the shaft increased the anchor was subjected to greater tensile loading on the shaft which eventually led to complete removal of the bolt. Figure 6.11 illustrates the shear failure mechanism. The shape of the failed ring before being removed from the block and the final shape of the anchor after removal can be seen in Figure 6.12. The maximum loads recorded had a mean of 30.66kN and a variance of 11.4%. The average distance of the anchors from the top of the block was 105mm.

6.5.2 8mm Ring Bolts

These anchors displayed much the same characteristics as the 10mm Ring bolts only at lower loads. Four of the five rings failed by the same mechanism as outlined in part 6.5.1. The fifth anchors failed as a result of the weld breaking as seen in Figure 6.13. The welds on the four other rings had significant cracks when inspected after removal. The mean load for the 8mm ring bolt was 24.65kN and they displayed a variance of 15%. The deformation in the eye of the all the 8mm rings was considerable and in the direction of the applied load as indicated in Figure 6.14. The anchors averaged a distance of 130mm from the top of the blocks.

6.5.3 35mm U-Bolt

Only three 35mm U-bolts were testable after cracks, from previous tests, had formed in the sandstone blocks very close to the anchors. The three anchors tested all failed in the same manner. As the load increased the rock above both shafts began to crumble. The top shaft formed a curve around the testing shackle and the lower shaft gradually displaced horizontally. Figure 6.15 shows the shear failure mechanism for the U-bolts.

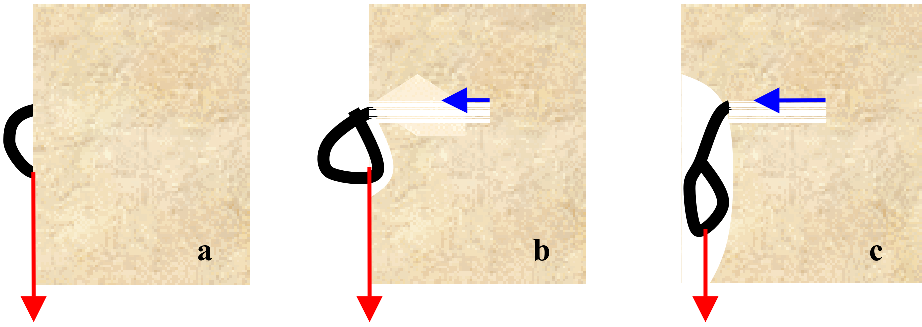

Figure 6.11

Ring bolt failure mechanism under shear loading

a) *The ring bolt in original position*

b) *Ring starts to crush rock below it as load increases. Deformation also starts to occur and the shaft moves horizontally as tension element of load increases*

c) *Ring continues to deform and crush rock until it is removed from the block*

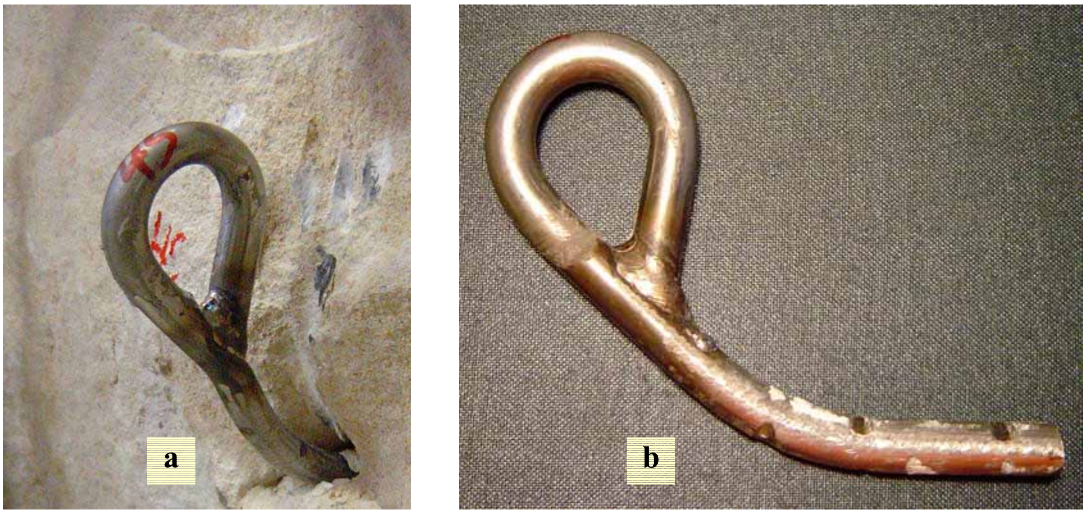

Figure 6.12

10mm Ring bolt failure shape

a) *10mm ring bolt in situ after testing*

b) *Shape and condition of 10mm ring bolt after shear testing*

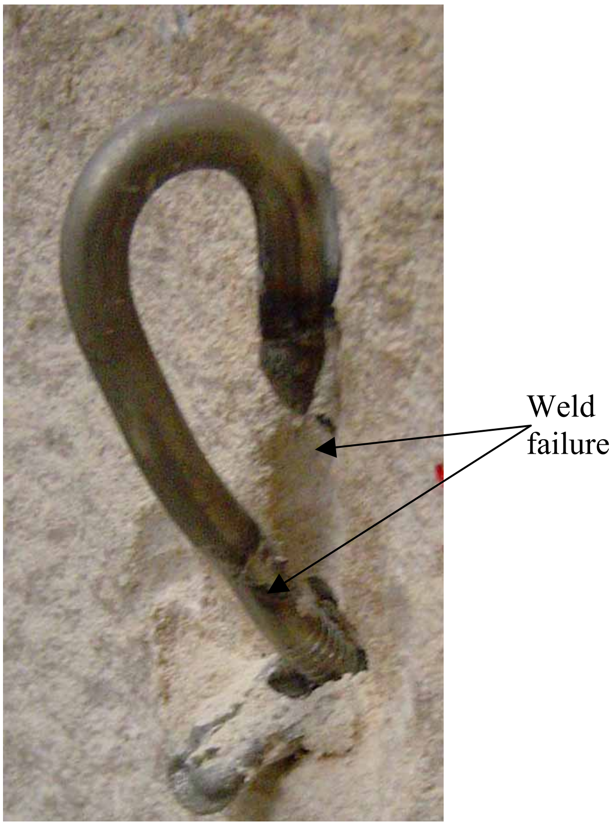

Figure 6.13

8 mm Ring bolt weld failure.

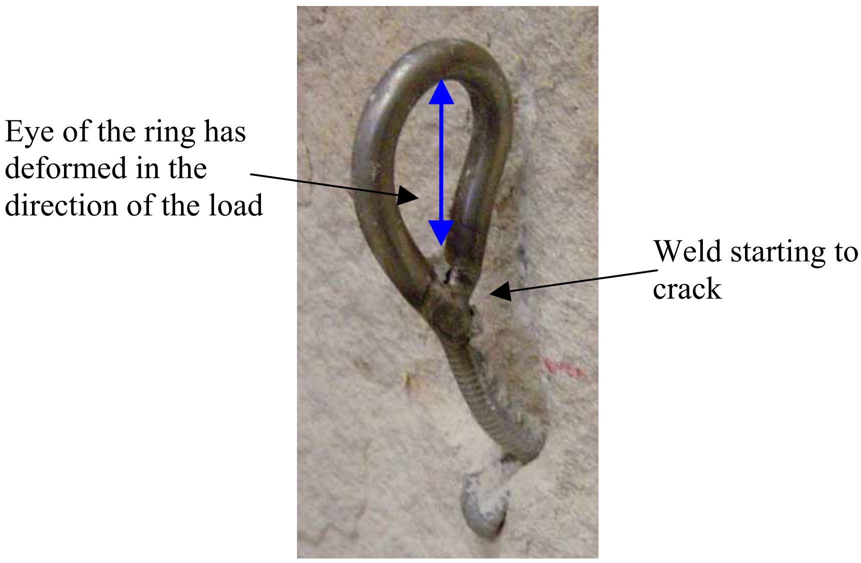

Figure 6.14

8mm Ring bolt plastic deformation failure

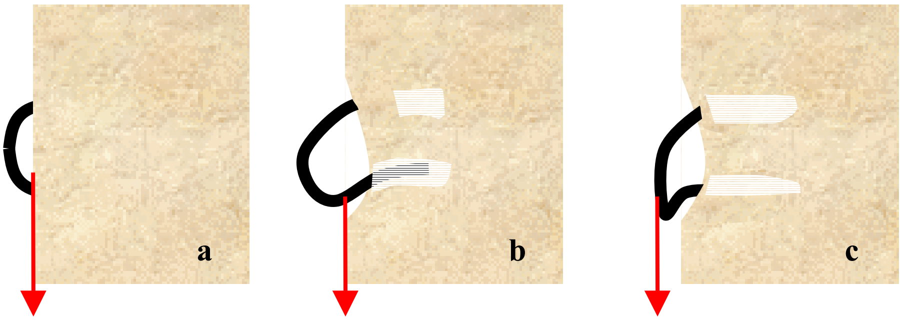

Figure 6.15

U-bolt failure mechanism under shear loading

a) *U-bolt in initial condition*

b) *As the load increases the U-bolt deforms around shackle and crushes rock*

c) *Deformation and rock crushing continues until block splits*

The anchor continued to deform in this manner until a crack suddenly formed in the sandstone block. There was no residual strength in the anchor after the maximum load was reached as the block had been split. Figure 6.16 show a typical U-bolt failure with the large crack evident in the block and Figure 6.17 shows a U-bolt after removal from the block completely. The mean failure load for 35mm U-bolts was the lowest at 23.35kN with a variance of 10.5%. The 35mm U-bolts were an average of 75mm from the top of the sandstone blocks.

6.5.4 45mm U-Bolts

Four 45mm U-bolts were tested. These anchors failed in the same manner as the 35mm U-bolts described in section 6.5.3. The mean failure load of these anchors was 25.9kN and they had a variance of 12.1%. The 45mm U-bolts were an average of 105mm from the surface of the blocks.

6.5.5 55mm U-Bolts

The four 55mm U-bolts that were tested displayed the same failure mechanism as the 45mm and 35mm U-bolts. The failure is the same as described in section 6.5.3. These anchors had a mean maximum load of 30kN and a variance of 11%. The average depth of the anchor from the surface of the block was 115mm.

6.5.6 Machine Bolts

The machine bolts tested remained largely intact and the maximum load was reached when the hangers failed due to the metal failing, see Figure 6.18. The bolts started to bend vertically and small amounts of rock spalling was observed around the bolts when the hangers failed. The mean failure load of the machine bolts was 27.41kN and the variance was 1.7%. The depth of these anchors from the surface of the block was 130mm.

6.6 Unconfined Compressive Strength Tests.

The results from the unconfined compressive tests undertaken on the sandstone blocks are found in Table 6.5. There were no abnormalities observed during the tests.

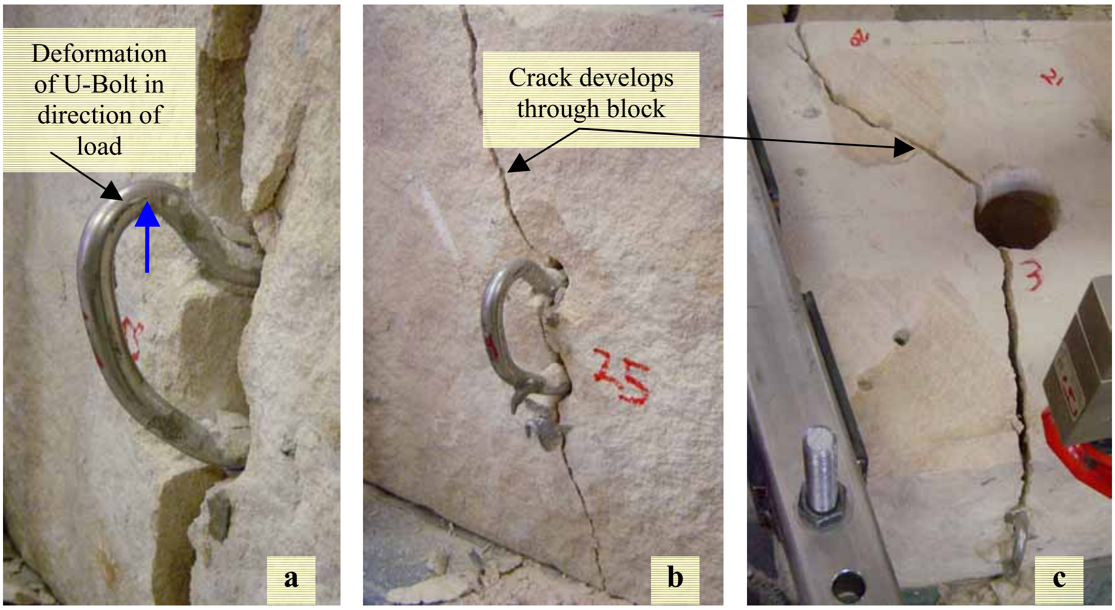

Figure 6.16

Typical U-Bolt deformation and failure during shear testing

a) *Side view of typical U-Bolt shear failure*

b) *U-bolt shear failure showing the crack propagation*

c) *Crack follows path of least resistance across block as a result of a U-Bolt shear test*

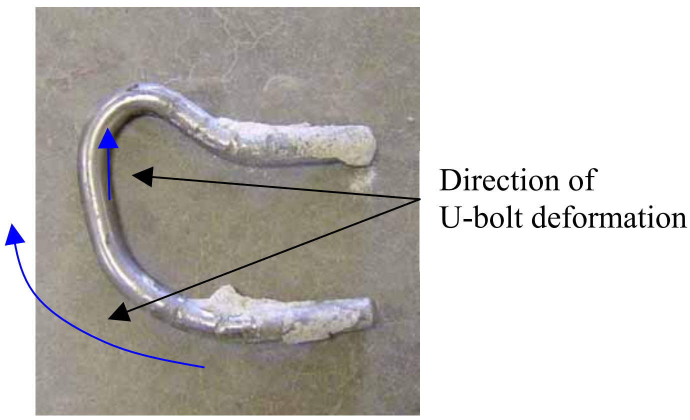

Figure 6.17

U-bolt after shear testing

Figure 6.18

Failure of the hanger on the machine bolts during the shear test

Test Number	1	2	3	4	5	Failure Mode	Mean	Standard Deviation	Variance
M10	27.15	27.92	27.30	27.86	26.83	Hanger shear	27.411	0.470	0.017
R8	27.50	25.60	19.51	22.28	28.37	Bending	24.652	3.703	0.150
R10	29.14	32.64	31.80	25.38	34.35	Bending	30.661	3.501	0.114
U35	25.10	24.40	20.55			Block	23.350	2.450	0.105
U45	24.81	28.43	21.95	28.37		Block	25.890	3.125	0.121
U55	25.65	29.30	32.92	32.38		Block	30.063	3.346	0.111

Table 6.4

Sandstone anchor shear test results

The Mean of the four tests indicate the sandstone strength was 27.8 MPa with a variance of 10%.

Test	Block	Test Result (kN)	Diameter (mm)	UCS (MPa)
1	2	67.8	54	29.60
2	1	70	54	30.56
3	4	58	54	25.33
4	3	59	54	25.76
		Mean		27.81
		Std Dev		2.66
		Variance		0.10

Table 6.5

Unconfined Compressive Strength results for sandstone blocks

6.7 The Reaction Frame

There were a number of modifications made to the connections of the test rig throughout the testing. The shear tests required a high strength steel shackle to be fabricated to allow the connection to the load cell to be secure. This followed a karabiner failure in an early test.

There were minimal displacement observed in the reaction frame throughout the testing program. The frame performed the tasks it was designed to undertake with no problems being encountered.

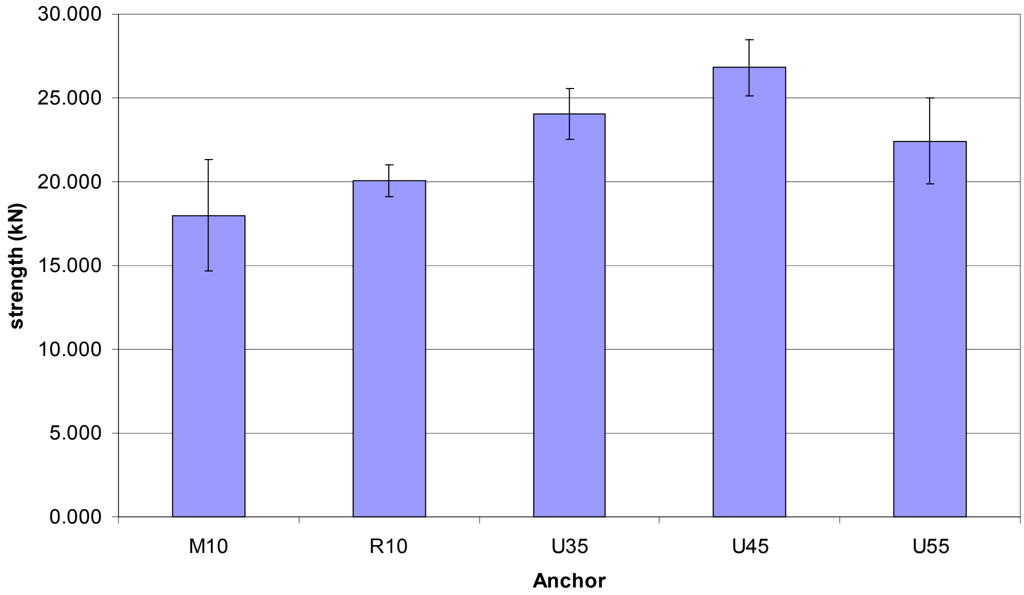

Figure 6.19

Graphical comparison of tensile test results

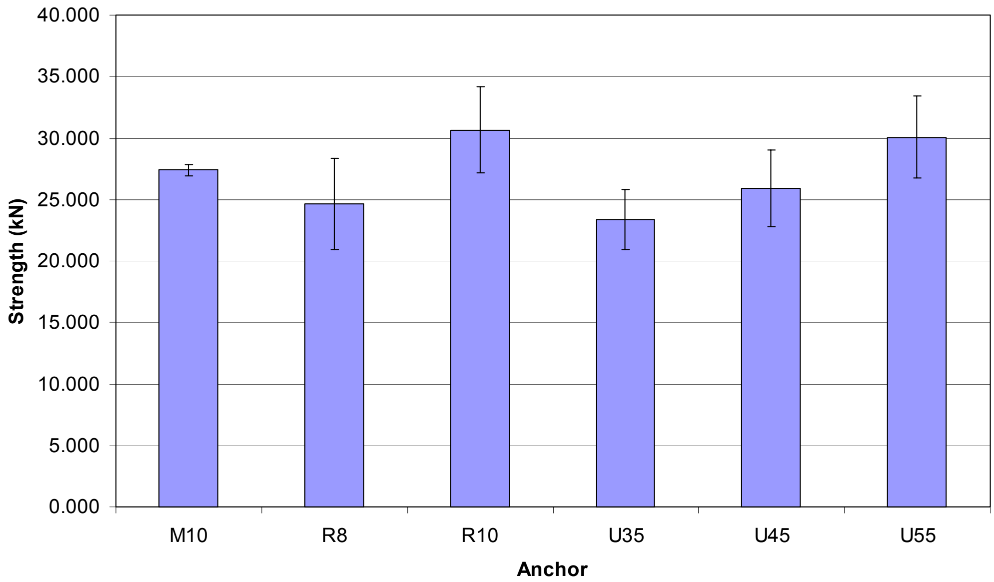

Figure 6.20 *Graphical comparison of shear test results*

Chapter Seven

ANALYSIS & DISCUSSION

7.1 Overview

This chapter analyses the results recorded from testing. The discussion proposes possible reasons for the observed behaviour and suggestions in the interpretation of the results.

7.2 Shaft Treatment

It is apparent from the test data that the preparation technique used on the shaft of the anchors can make a substantial impact on the strength of the anchor.

The tests indicate that the steel-adhesive interface bond strength is very low. An anchor with no shaft treatment will have a very low tensile strength. The more surface area of the shaft that is actively keyed into the adhesive the higher the strength. The notched specimens had a relatively low strength but considering only about 7.5% of the surface area was directly keyed into the adhesive the strength could be increased with a larger amount of notches. Similarly testing also revealed that grinding the surface of the shafts with a bench grinder increases the strength by approximately 6kN. This increases the friction between the bar and the adhesive. Since stainless steel is particularly smooth this is an important finding. The grinding creates a series of very small notches into which the glue can key. The increase in strength is a direct result of the increased surface area of adhesive that is utilised in shear. The shear strength of the adhesives is greater than its actual adhesive bonding strength.

The tests revealed that threading the shafts returned the highest tensile strength. The deeply threaded bars had a strength of 42kN yet the shallow threading had a strength of only 5kN. The area into which the glue could bond of the shallow threading was 16% and of the deep threading was 65% of the total shaft area. If it was only surface area that resulted in strength gain then shallow threading should have a strength of approximately ¼ that of deep threading or 10kN but it has only half that value. It is clear from these results that strength is not merely a function of surface area but also of the volume of the adhesive that is keyed into the shaft. Since the lightly threaded shaft had a very shallow thread there was insufficient depth for the adhesive to key into and the strength was lower as a result.

The viscosity of the adhesive may also have an effect on the strength. If the glue is able to work its way into the small surface features then strength would increase. This would have the greatest effect on shafts that had grinding over the entire surface as this produces a lot of small asperities for the glue to work into.

7.3 Glue Type

The results obtained from this series of tests are limited, since only 5 results were obtained. An interesting result to come out of this testing was the variability of the glue. When the specimens were being set it was noted that two of the samples had adhesive that had appeared not to mix properly. This was evident due to the cream colour of the adhesive, which should have been grey in accordance with the manufacturers guidelines. When testing took place these two specimens had strengths considerably lower than the other specimens. The highest of these being less than half of the lowest strength measured on correctly mixed test results. This indicates the need to check the glue as it is administered to the hole to ensure that the correct mixture ratio is being installed. If the two lower results are discounted the epoxy glue was more than twice the strength of the polyester glue, if they are included it was still one and one half times the mean strength of the polyester glue. These comparisons can be seen in Figure 7.1.

The epoxy adhesive displayed results that were consistent with manufactures specifications and Cooks' [2001] findings that indicate that epoxy has approximately twice the strength of polyester adhesives.

7.4 Sandstone Tests

The sandstone tests were undertaken with a polyester glue that was common for all anchors. The results that were gained for these tests are, therefore, relevant only for polyester adhesives similar to the one used in testing. As determined from the adhesive comparison tests and manufactures guidelines the epoxy adhesives have a

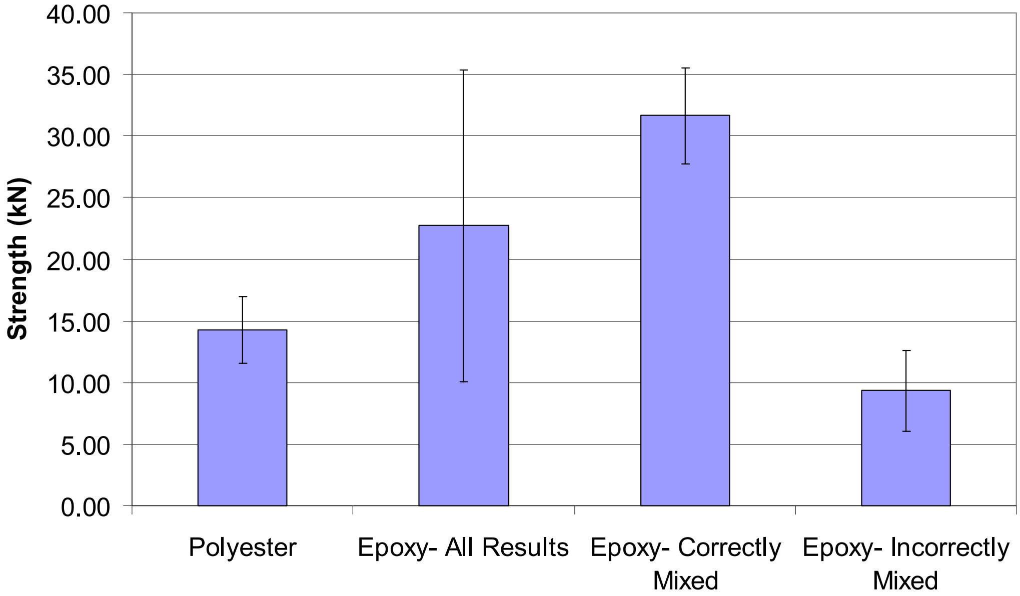

Figure 7.1

Comparison of polyester adhesive to the epoxy tests higher bond strength than polyester adhesives. This indicates that anchors installed with an epoxy adhesive could be stronger than the results gained in these tests.

7.4.1 Lost Tests

The sandstone blocks used in the testing produced some interesting results. It was evident that there may have been too many tests carried out in each block. This led to some of the results being lower than the might have been recorded if fewer tests were conducted in each block. This is apparent in both shear and tensile tests. In the tension tests the 35mm and 55mm U-bolts failed by removing a significant volume of rock. As there were up to four axial tests in each block the last anchors to be tested on a block appeared to suffer from the decreased rock mass surrounding the anchor.

This effect was noticeably larger in the shear tests. All the U-bolts failed by cracking the blocks down the axis of the anchor. This meant that anchors on the other side of the block from the first anchor tested would have much less rock surrounding them when they were subsequently tested. Figure 7.2 shows this effect on test number 26. It was tested after the block had been split and there was only 90mm of rock on one side of the anchor. This anchor failed at 21kN which is 9kN lower than the average of the other four tests. For this reason a number of anchors were not tested and the results for a few tests have not been included.

7.4.2 Tension Tests

All the anchors tested in tension passed the 15kN European standard. The mean strengths of the anchors ranged from the machine bolt with 17kN to the 45mm U-bolt with 26.82kN. The machine bolts may have been stronger but the hangers that were placed on them failed rather than the bolt. There was very little difference between the leg spacings of the U-bolts. Comparing the 35mm and 55mm U-bolts which bolt had kinked shafts. There mean strengths were 24kN and 22.4kN respectively. Ordinarily it would be expected that the 35mm leg spacing would be weaker as the effect of the close leg spacings would be larger.

An interesting finding from this testing was the failure mode of the U-bolts with kinked legs. As indicated in chapter 6 these anchors failed by removing a large portion of rock with a depth equal to the embedment length of the anchor. The anchors were installed between the rock layers which meant that the failure was not occurring along a bedding plane but through the bedding planes as indicated in Figure 7.3. This failure mode was very sudden. There was no indication that failure was imminent and once failure had occurred there was no residual strength remaining in the system. None of the straight shaft anchors failed in this manner. The ring bolts and 45mm U-bolt failed in a slow manner. There was no sudden failure. The anchors were gradually pulled out of their holes as the load increased to a maximum. Once the maximum load was reached there was still considerable residual strength that needed to be overcome to remove the anchors from the block. These anchors failed at the interface between the rock and the glue.

The kink in the shaft required the anchors to be hammered in to their placement. This may have induced some stress into the sandstone that may have weakened and caused the sandstone to fail before the glue bond. The kink in the shaft also induces an outward mechanical action on the side of the hole. This will strengthen the interface between the glue and the sandstone which may be sufficient to overcome that particular failure mode.

The embedment depth of the anchors were different between the different anchor types. It may be that longer kinked shaft U-bolts may not fail in the manner observed in these tests.

The strengths that were obtained from these anchors indicate that there is little or no disadvantage to using U-bolts in areas that will sustain tensile loading. The U-bolts had a higher strength than the ring bolts as their combined shaft embedment depth was greater than the ring bolts single shaft length.

7.4.3 Shear Tests

The shear tests indicate that the type of anchor has an effect on the failure mode. These tests were noticeably affected by the small size of the blocks that were used but would represent anchors placed on broken cliffs with 400mm joint spacings or those placed close to edges.

Figure 7.2

Test 26 failed due to the close edge distance

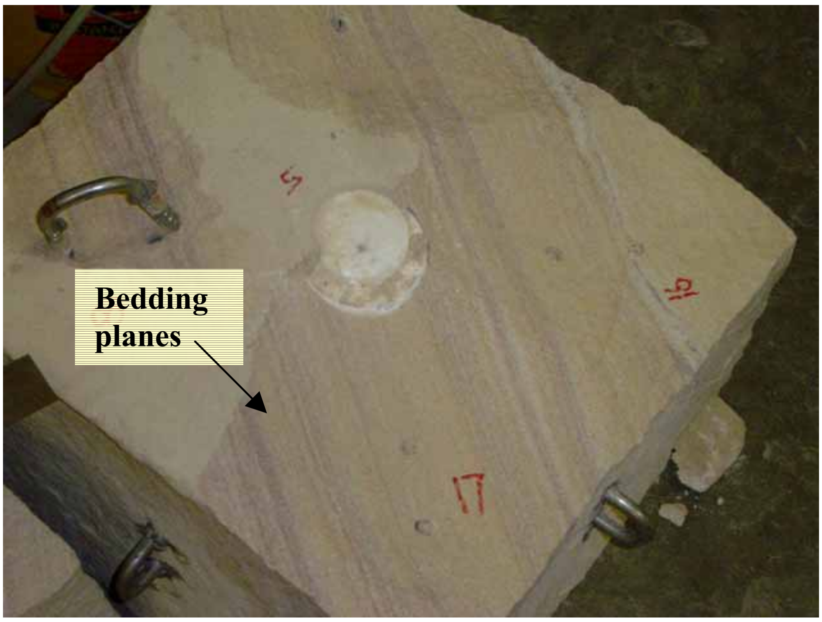

Figure 7.3

The U-bolts failures in the rock mass were perpendicular to the bedding

The single shaft anchors failed in the slow manner that was identified by Pircher [2001] and discussed in the literature review. It was evident when failure was occurring as the anchors would severely deform and crumble the rock as failure progressed. The U-bolts failure mode initially followed the Pircher mechanism as the anchors deformed, but the final failure of these anchors occurred when the block cracked down the axis of the anchor. The hole spacing appeared to have a marked effect on the strength under this form of loading. The mean failure loads for 35mm U-bolts was 24kN, for 45mm U-bolt was 25.9kN and for 55mm U-bolts it was 30kN. As the shaft spacing increased the anchor strength increased. Ideally large shaft spacings should be used in U-bolts but this causes aesthetic problems. The larger the bolt that is being placed the more visually intrusive it is. This issue is become increasingly important in regards to public perception of climbing and its environmental effect. Shaft spacings of 45mm or more would be an appropriate size.

The 8mm ring bolts were the weakest bolts tested in shear. In comparison to 10mm shaft anchors they suffer from reduced surface area and reduced stiffness. This means the adhesive will have less area to bond and 'key into' and the anchors will deform at lower loads. The eye of the 8mm rings deformed laterally, and the shafts deformed a considerably more than 10mm ring bolts. Figure 7.4 shows the deformations of each of the ring bolts the 8mm ring has clearly deformed more than the 10mm ring. The extra deformation requires the rock to take more of the load as the unit is deforming, rather than resisting the load. This may cause the rock to crack more and contributes to the lower strength of the anchors. The deformation in the eye of the ring places more load onto the welds, which are smaller than 10mm ring welds, which may have caused the cracking, and in one case failure, of the welds.

It is hard to ascertain whether the kink in the shafts had any effect on the shear strength of the anchors as there appeared to be no trend in regards to this variable.

The size of the block obviously affected the results. Had larger blocks been used the results for the U-bolts may have been higher and a true comparison could be made.

7.4.4 Adhesive Distribution

Once the anchors had been tested and removed from the block it was evident that the different anchor types had different glue distributions within the hole. The ring bolts, that were rotated as they were pushed into the hole, had glue evenly distributed around the shaft. The U-bolts, that cannot be rotated due to the two shafts, had a number of bubbles in the glue around the shaft as seen in Figure 7.5. This prevents the U-bolts from having optimum adhesive/hole surface area. This effect can be minimised by ‘buttering’ the shafts of the U-Bolts with glue before they are placed in the holes.

7.4.5 Mean and Variance

While the anchors had a mean strength that was quite high it is worth noting that the standard deviations of the anchors were high. An anchor that has a mean strength of 30kN but commonly has anchors that fail at 15kN is not as reliable as an anchor that has a mean of 25kN and the majority of its anchors fail above 20kN.

A method of comparing anchors using the mean and standard deviation is to subtract a multiple of standard deviations from the mean strength. The three sigma method, used by Black Diamond [2003] equipment manufacturer, subtracts three standard deviations from the mean which indicates that 99.87% of anchors will fail above the new calculated load. This is conservative but useful in comparing the influence of the variability of results. Figure 7.6 shows the tensile comparison of mean and mean minus three standard deviations and Figure 7.7 shows shear mean compared to the mean minus three standard deviations. The 55mm U-bolts had a high mean tensile strength but the variance of its results was high which brings down the three sigma strength. In shear the variance of a number of anchors was large although the machine bolt had a very low variance so had a greater reliability in shear.

This approach is conservative and is used to illustrate the variability of the anchors. If it was used in conjunction with the EN 959 standard then none of the anchors would pass the criteria for shear and tension.

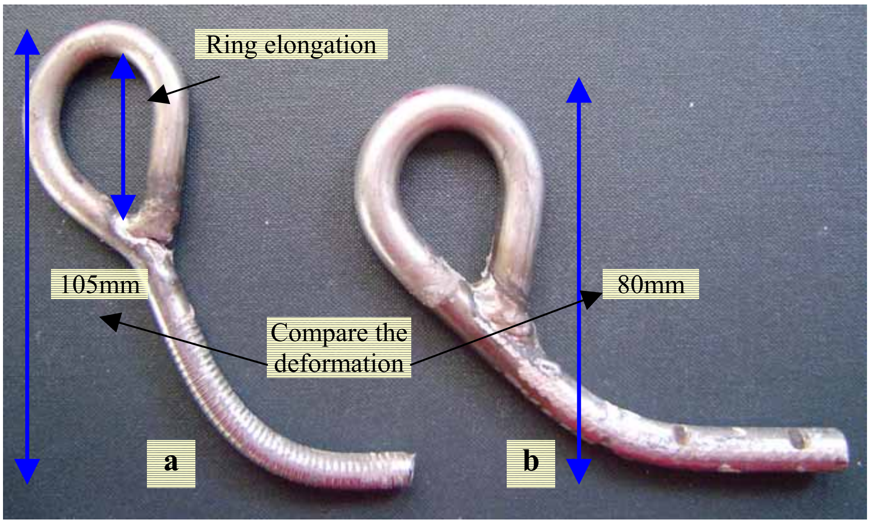

Figure 7.4

Deformation of ring bolts in shear tests

a) *8mm Ring bolt*

b) *10mm Ring bolt*

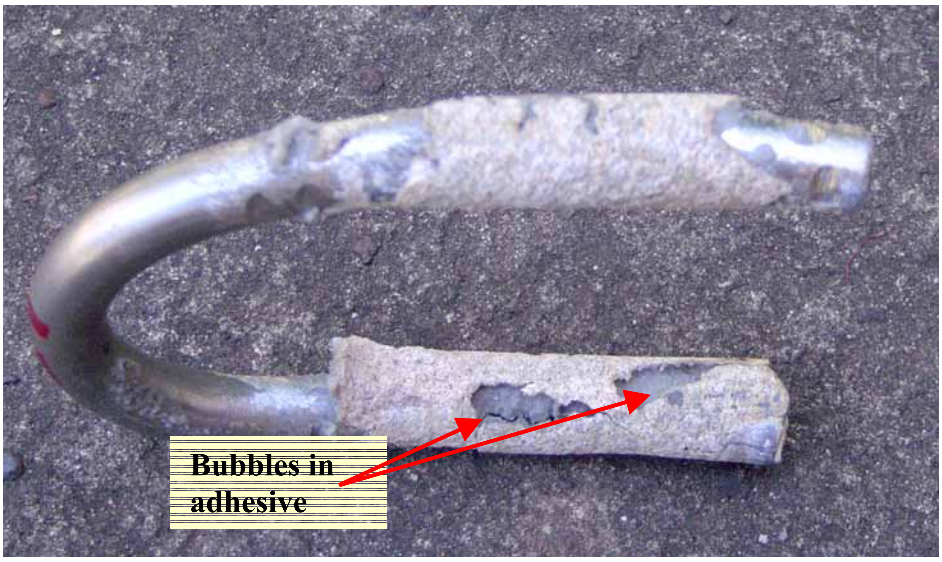

Figure 7.5

Bubbles in the adhesive resulting from the inability to spiral anchor into placement

The mean strength is not the only indication of how an anchor will perform and should be used in conjunction with the variance of the results to determine suitability of an anchor.

7.5 Rock Strength

The rock strength obtained from the UCS tests indicate that the sandstone can be classified as a medium strength rock with a strength range from 25-30MPa. The rock surrounding Sydney is highly variable in strength but is commonly found in the range that the blocks of this testing fall into.

7.6 Standards

The European standard stipulates that anchors should be able to withstand a 15kN axial load and 25kN radial load as discussed in the literature review in chapter two. Interpreting from the standard the criteria for an anchor passing the test is that none of the anchors in the tests are lower than the required levels. The only anchors that fully satisfy this criteria for tension and shear are the 10mm ring bolts, 55mm U-bolts (when the erroneous result is removed) and the 10mm Machine bolts with hangers. All the bolts tested in tension passed the 15kN requirement.

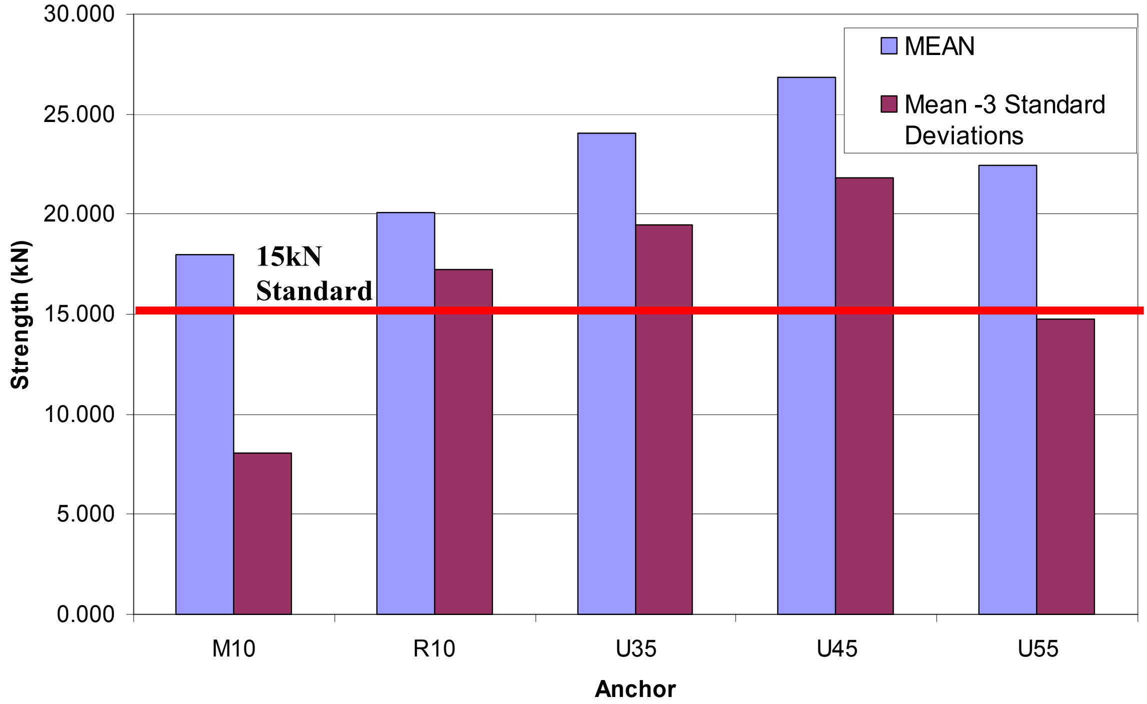

Figure 7.6

Comparison of tensile mean strength of anchors and the tensile mean strength minus three standard deviations

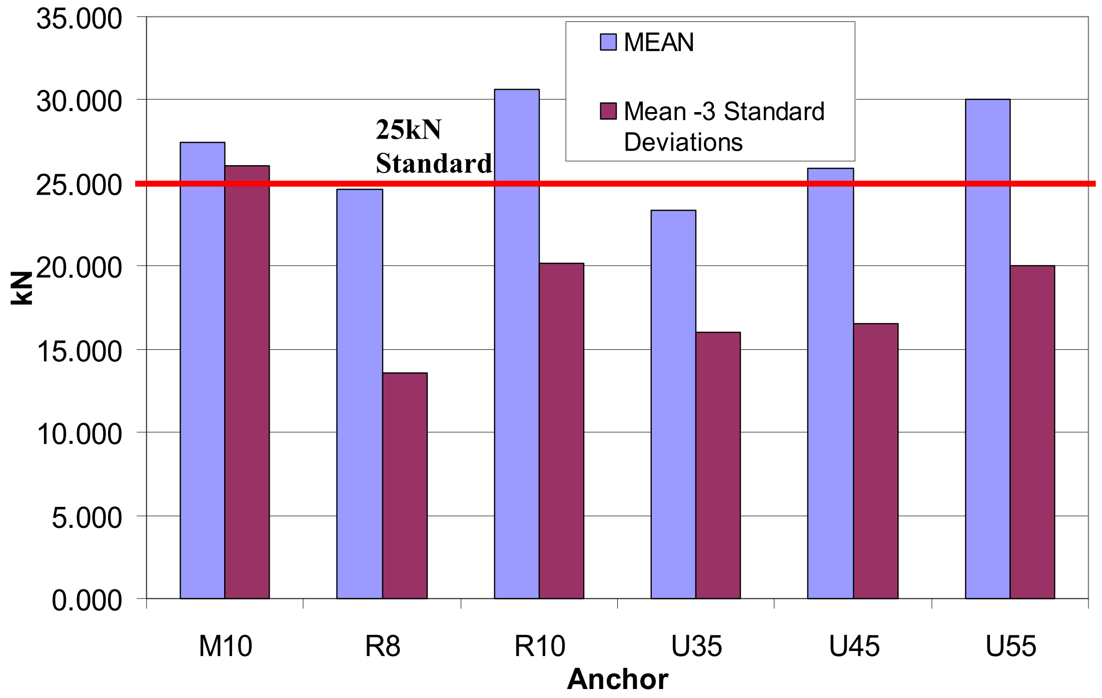

Figure 7.7

Comparison of mean shear strength of sandstone anchors with the mean shear strength minus three standard deviations

Chapter Eight

RECOMMENDATIONS AND CONCLUSION

8.1 Future Testing

This testing program has raised a number of issues that could form the basis of future testing. Possible future testing could include:

- Testing of anchors in sandstone cliff faces with a single adhesive to determine comparisons with sufficient surrounding rock mass.
- Testing of different adhesives in sandstone.
- Comparison of kinked shaft anchors to straight shaft anchors in sandstone.
- Testing a variety of shaft lengths within different anchor configurations.

8.2 Recommendations and Conclusion

From the testing program the following recommendations for chemically bonded rock climbing anchors in sandstone have been formulated

- Bolts should be fully threaded to ensure there is adequate area for the adhesive to infiltrate.
- Epoxy adhesives should be used to maximise the possible strength of an anchor.
- When installing anchors, observations of the glue colour and texture should be made to ensure the correct mix has been administered.
- Hangers, rated 22-25kN, are the weakest point in an machine bolt anchor system. They should not be placed in situations where large tensile forces will be applied to them.
- U-bolt shaft spacings should be no less than 45mm.
- U-bolts used close to each other as lower offs or belay anchors should be spaced approximately 200mm apart. This is due to the large amount of influence they have on the surrounding rock.

- 8mm anchors should not be used due to their ease of deformation and smaller surface area in contact with adhesive.
- Anchors should be tested before loading. A simple twisting force applied with a spanner should determine whether the adhesive has cured.

The purpose of this project was to determine the influence of shaft treatment and adhesive type on anchor strength and to compare the strength of various chemically bonded anchor configurations in sandstone. To accomplish these objectives a number of laboratory controlled experiments were undertaken. The results obtained indicate that the shaft treatment technique, adhesive type, and shape of the anchor have a large affect on the anchor strength. The results and recommendations from the sandstone tests are relevant to anchors installed within the range of the variables tested in this study.

GLOSSARY

The following is a list of rock climbing terms and their meanings that have been used in this thesis:

Belayer- Person responsible for arresting a climber when they fall.

Belay device- Device used to apply friction to rope to stop a fall without injuring the belayer.

Belay Anchors- anchors situated to allow a climber to attach themselves and remain safe at the top of a pitch.

Climb- A line up a cliff that is named and followed by subsequent climbers.

Climber- a person who is rock climbing

Lower off- a permanent anchor placed at the top of a climb to enable the climber to be lowered back to the ground by threading the rope through it.

Pitch- The length of a section of a climb. A long climb may be broken in lots of smaller climbs called a pitch. These are called multi-pitch climbs. Shorter cliffs may only have one pitch required. These are single pitch climbs.

Leading- - To climb from the bottom of a cliff to the top placing runners along the way. Also referred to as lead climbing

Lead Climbing- see leading

Machine Bolt- A common threaded bolt that is modified for use as a climbing anchor.

Multi-pitch climb- See Pitch

Ring Bolt- an anchor that has a single shaft and a welded eye or ring at one end and forms the shape of a P.

Runner- anchor positioned on a climb to stop a climber if they fall

Top Rope- A style of climbing where the rope runs from climber to top of climb, through an anchor system, and back down to belayer.

Top Belay- A person belaying from above the climber

U-Bolt- An anchor that has two shafts and is in the shape of a U.

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APPENDICES

Appendix A- Basic Testing Rig Calculations

Tension Members- Loading Bar and Restraints

Since the loading bar is the most critical tension member this is what dictates the material used in the tension members. For ease of construction all tension members will be constructed from the same material

Using Steel code HB 2.2 -2002

Clause 7.1 $N^* \leq \phi . N_t$

Table 3.4 $\phi = 0.8$

From literature review maximum load expected is 50kN

Therefore the loading bar must be able to withstand a 50kN force without being effected

$$\frac{50kN}{\phi} \leq N_t$$

Nt must be greater than 55.55 kN

Clause 7.2 *Nt* is the lesser of :

$$Nt = Agfy$$
or
$$Nt = 0.85ktAnfu$$

fy= 400MPa

fu= 440MPa

Therefore must find the minimum area which will be the larger of *Ag* and *An*

$$\frac{55.55}{400} \leq Ag$$
$$Ag \geq 138mm^2$$

Or

$$\frac{55.55}{440 \times 0.85 \times 1.0} \leq An$$
$$An \geq 148mm^2$$

Therefore the minimum Area is 148mm^2.

Using circular bar

$$148 = \Pi \times r^2$$
$$r = \sqrt{\frac{148}{\Pi}}$$
$$r = 6.86mm$$

Therefore a solid steel bar with a diameter of 14mm or greater is required for the restraints and the loading rod.

Compression members- Supports for jack

Two supports taking 25kN each

Clause 6.1

$$N^* \le \phi.N_s$$
$$N^* \le \phi.N_c$$

Clause 6.2 $N_s = kfAnfy$

Assuming $kf = 1.0$

$fy = 400\text{MPa}$

$$\frac{N_s}{\phi.\times kt \times fy} = An$$
$$An = 70mm^2$$

So area needs to be greater than 70mm^2

Nc requires info about the section being used to determine its appropriate strength. 25kN is a relatively small load. The channel sections used, have a cross sectional area that is well in excess of the required area.