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Design and testing of BA anchors for temporary support of reinforcement in cavern linings, Cross River Rail, Brisbane

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ABSTRACT: BA anchors were used extensively to provide temporary support for steel bar reinforcement in the Cross River Rail caverns and adits prior to pouring the permanent concrete linings. The load capacity of BA anchors is uncertain due to their short length and use of a plastic sleeve to transfer load between the threaded bar and founding stratum. The arched profile of the caverns and adits means that the anchor threaded rods are often subject to combined bending and axial loads. This introduces uncertainty in the design and application of BA anchors since threaded bars are not intended for use in bending.

A series of load tests were conducted to measure the axial tensile capacity of the anchors as well as confirm the combined bending and axial capacity of the threadbar. These tests enabled the validation of the design load capacity and adoption of a more efficient support design. This paper discusses failure mechanisms associated with BA anchors and proposes design methods which were validated by load testing. The maximum capacity of the BA anchors was found to be well in excess of values often assumed in design.

Thousands of BA anchors were installed across the project. Increasing the anchor spacing through robust design and testing achieved meaningful schedule and cost benefits.

1 INTRODUCTION

Cross River Rail (CRR) is a new 10.2 km long underground metro rail line in Brisbane extending from Dutton Park in the south and Bowen Hills in the north. It includes 5.9 km long twin tunnels below the Brisbane River and CBD. The Tunnel, Stations and Development (TSD) component of the project involves construction of twin Tunnel Boring Machine excavated and roadheader mined running tunnels; four new underground stations at Boggo Road, Woolloongabba, Albert Street and Roma Street; and dive structures at each end of the running tunnels.

The underground stations, running tunnels between Woolloongabba and Dutton Park, and all adits and cross passages were mined and utilised permanent cast-in-place concrete linings. Sheet waterproofing membrane was installed across the crown and sidewalls of the mined tunnels.

BA anchors were used in the crown and sidewalls of the tunnels where bar reinforcement was required (Figure 1). BA refers to “breakthrough anchor”, in which an anchorage point for steel fixing is provided with the anchor extending beyond the waterproof membrane and bonded within the external substrate, but without compromising the continuity or integrity of the waterproofing system. These anchors have a temporary function of supporting the reinforcement prior to placement of concrete to form the permanent tunnel linings.

Due to the highly manual nature of erecting reinforcing steel the consequences of anchor failure have the potential to result in injury to personnel.

The focus of this paper are the crown anchors in the station caverns as these are required to support the dead load of the reinforcement, whereas the sidewall reinforcement is typically self-supporting and only utilises anchors to prevent toppling of the reinforcing cage.

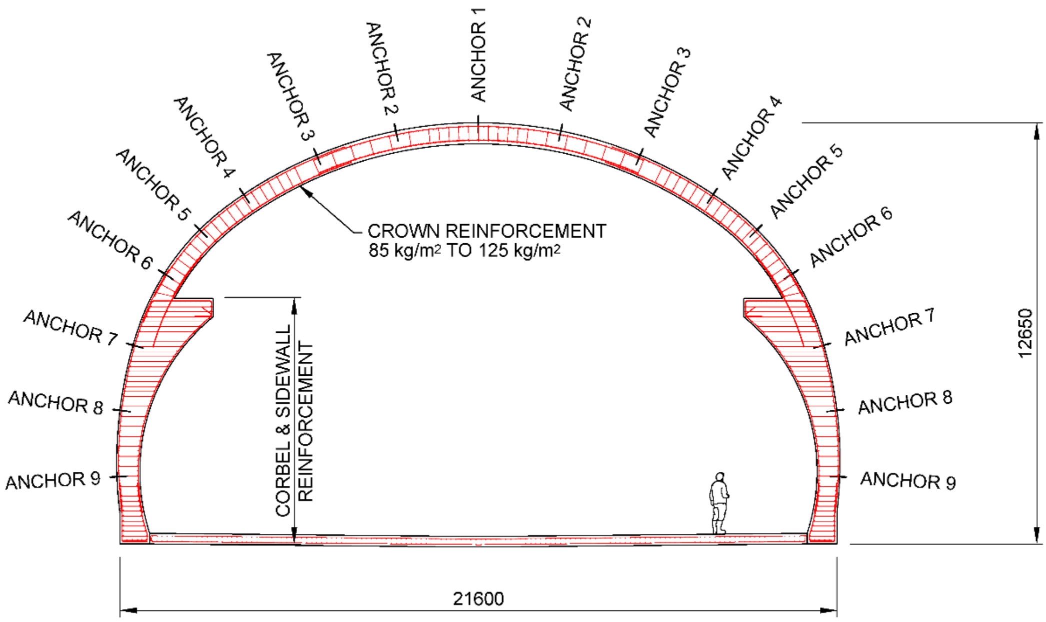


Figure 1. Boggo Road Station cavern lining reinforcement and adopted BA anchor layout.

BA anchors were used extensively across the project with thousands installed. Increasing the spacing of BA anchors through robust design and appropriate testing represented meaningful schedule and cost benefits to the project.

2 BA ANCHORS

2.1 *Description*

BA anchors are understood to have been first used in the Cohlfirst tunnels in Switzerland which was completed in 1996.

They consist of a rigid polyethylene (PE) or polyvinyl chloride (PVC) sleeve and flange, into which an M16 x 2.0 threaded steel rod is inserted (Figure 2). The embedment length of the anchors considered in this paper is less than 200 mm though the authors are aware that similar longer anchors are also available. The sleeve has an outer diameter of 28 mm and incorporates a coarse external thread to facilitate a high strength bond with the epoxy resin used to secure the anchor to the substrate.

A flexible membrane disc of approximately 300 mm diameter is factory-welded to the flange, which ensures a high quality weld and watertight seal. The membrane can be manufactured in either very low-density polyethylene (VLDPE) or PVC to achieve compatibility with the tunnel waterproofing membrane being installed.

2.2 *Applications*

Traditionally BA anchors are used to facilitate the installation of reinforcing steel bars without compromising the waterproofing membrane (Figure 3). Dummy bars are not part of the design reinforcement but are used to support the design reinforcing bars. The dummy bars are attached to the threadbar of the BA anchor via welding or use of a clamp. For CRR a simple clamp detail was developed which comprised two short lengths of unequal angle (UEA) held in place by nuts on either side. This detail can hold two dummy bars of up to N24 size.

Other common applications for these anchors are for anchoring scaffolding, and hanging of services such as ventilation bags, electrical cables and temporary lighting after the waterproofing membrane has been installed. The use of eye bolts threaded into the anchor is often employed in hanging services.

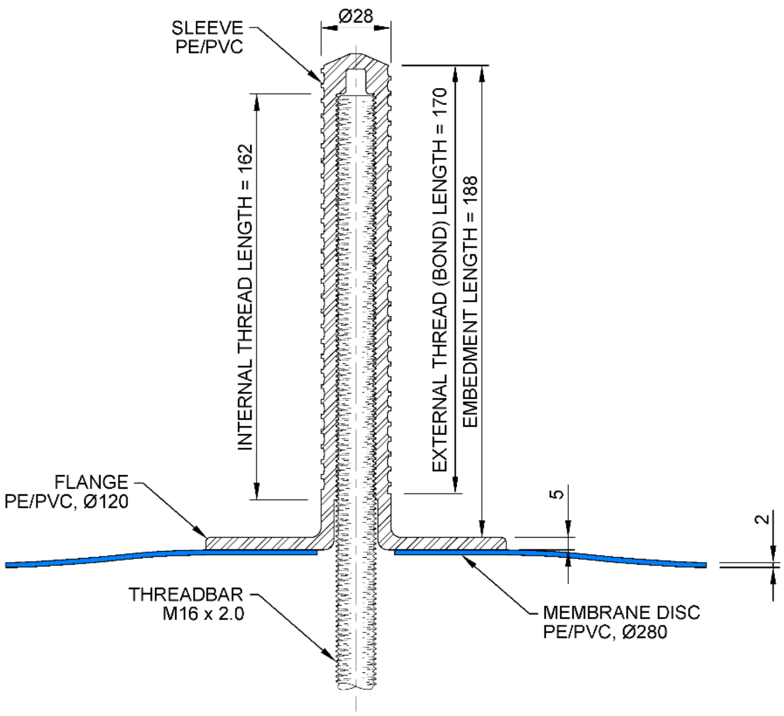


Figure 2. Sectional elevation of a BA anchor used on the CRR project.

2.3 *Load capacity*

There are many variables which can affect the load capacity of BA anchors. It is therefore difficult to determine a single reliable load capacity for a BA anchor. These variables include, but are not limited to:

- Thickness and strength of shotcrete substrate (where present).
- Rock substrate condition.
- Strength and extent of defects.
- Moisture condition in the drilled hole.
- Type of epoxy resin or grout.

As a conservative guide, an axial load capacity of 20 kN and shear load rating of 10 kN are often quoted by suppliers and manufacturers with the proviso that it is important to undertake pull-out tests of production anchors on site.

Section 3 and Section 5 of this paper discuss anchor failure mechanisms and production testing regimes as they apply to load capacity.

2.4 *Installation and QA procedures*

The typical installation procedure for BA anchors is as follows:

1. Mark out anchor installation locations, which may require surveyors for irregular or complex arrays.
2. Drill 32 mm diameter holes through the waterproofing membrane and into the substrate, to a depth of 200 mm, using a depth stop to ensure that the correct depth is achieved.
3. Blow out hole to remove debris and dust using a manual or powered blower until no more dust is produced.
4. Inject the specified epoxy resin from the back of the hole. The correct volume shall fill the hole once the anchor is installed, but not to the extent that excess epoxy is ejected. The epoxy must be suited to overhead application (i.e. sufficiently high viscosity that it remains in the drill hole).
5. Inspect each anchor prior to installation to ensure that there is no damage or manufacturing defects present.

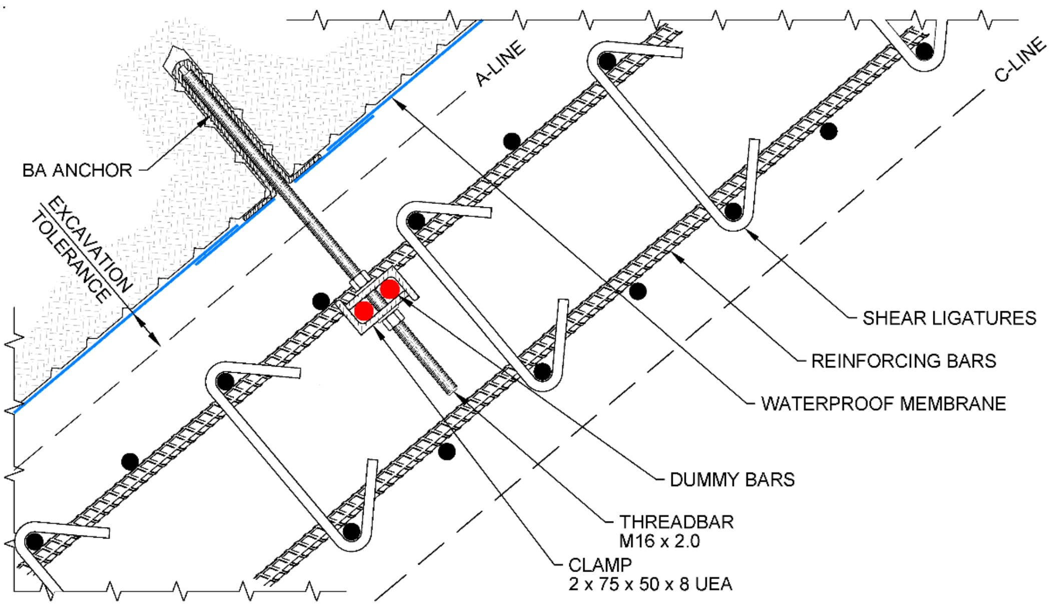


Figure 3. Typical BA anchor application used to support bar reinforcement prior to and during placement of concrete to form the permanent tunnel lining.

6. Install the anchor by pushing and twisting into the hole to ensure proper encapsulation of the external thread.
7. Screw threadbar of the required length and strength grade into the BA anchor sleeve using a depth mark to ensure that the bar reaches the base of the anchor but does not punch through the bottom and compromise the waterproofing function of the sleeve.
8. Weld the full circumference of the BA anchor membrane to the waterproofing membrane.
9. Test the weld using the needle or vacuum test methods.
10. Pull test anchors at the frequency and to the methodology required by the design.

3 FAILURE MECHANISMS

3.1 *Overview*

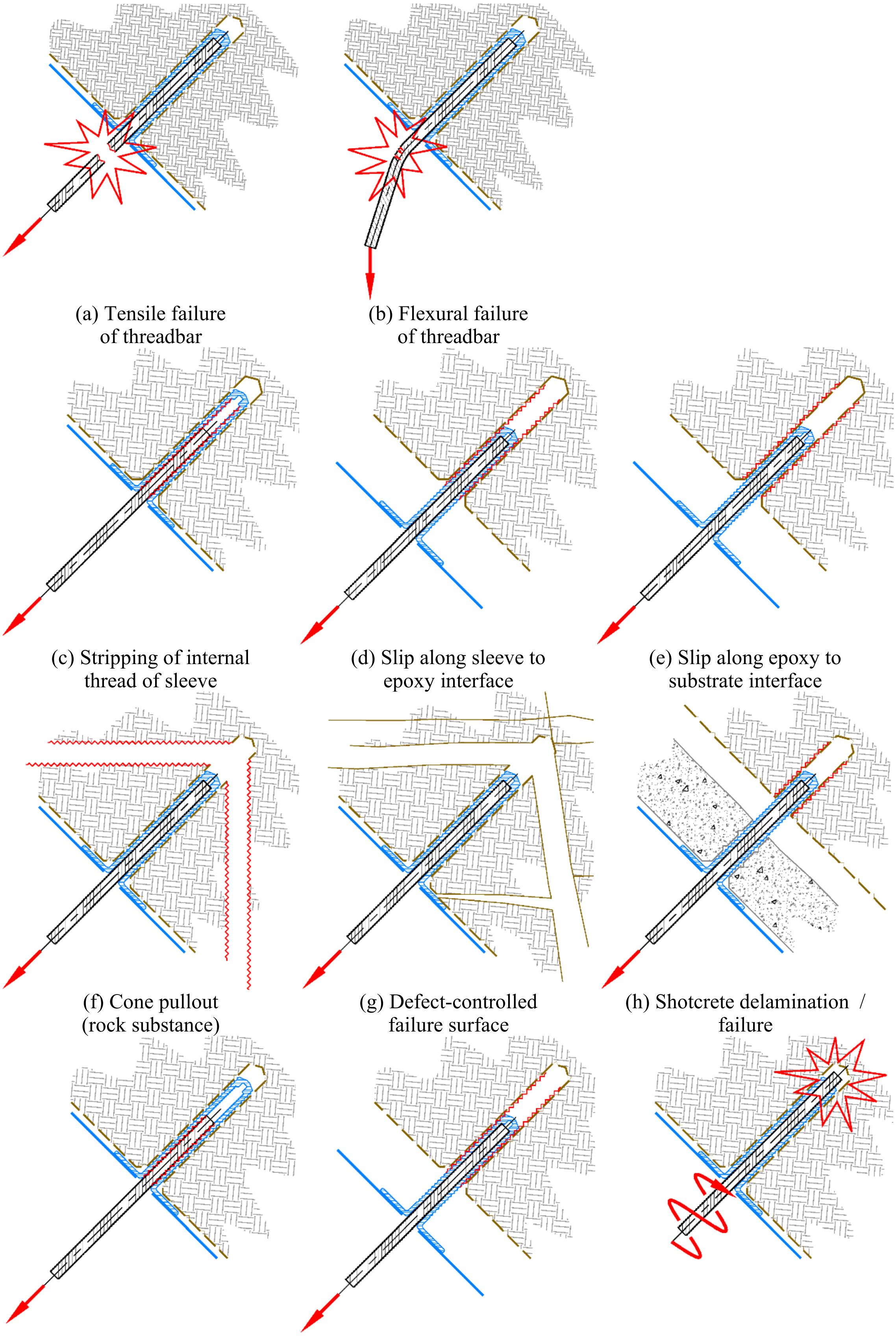
Figure 4 presents a graphic summary of failure mechanisms applicable to BA anchors. Since that since these anchors are very short and employ a plastic sleeve around the steel bar additional mechanisms are relevant in comparison to that of simple rock anchors. Figure 4 is arranged in four rows with each row addressing a different category of failure:

– Threadbar overload.
– Piston pullout.
– Substrate failure.
– Installation issues.

3.2 *Threadbar overload*

Axial loading of the anchor has the potential to rupture the threadbar in pure tension (Figure 4(a)). This failure mode is considered the least likely of those considered due to the relatively high axial tensile strength of threadbar (Table 1). It is noted that nuts and washers and other components need to be proportioned and specified such that they do not compromise the strength of the system.

Threaded bar is not an ideal structural member because the threads act as notches and, when subject to bending (Figure 4(b)), material failure can occur at a lower load than that for a smooth bar due to stress concentrations associated with the roots of the threads [Ref. 1]. To the authors' knowledge, the bending capacity of bolts or threaded bar is not addressed by structural standards, though BA anchors are commonly subject to this type of loading.



(a) Tensile failure of threadbar

(b) Flexural failure of threadbar

(c) Stripping of internal thread of sleeve

(d) Slip along sleeve to epoxy interface

(e) Slip along epoxy to substrate interface

(f) Cone pullout (rock substance)

(g) Defect-controlled failure surface

(h) Shotcrete delamination / failure

(i) Threadbar not fully inserted into sleeve

(j) Inadequate epoxy or hole cleanliness

(k) Threadbar screwed beyond end of anchor

Figure 4. Potential failure mechanisms for BA anchors.

Table 1. Design threadbar strengths

Bolt grade	Minimum tensile strength (1.)	Nominal yield strength (2.)	Design capacity (3.)		
			Shear (4.)	Tension (5.)	Bending (6.)
	f_{uf} (MPa)	f_y (MPa)	ϕV_f (kN)	ϕN_{tf} (kN)	ϕM_s (kNm)
4.6	400	240	27.0	50.2	0.08
8.8	800	640	54.0	100.5	0.21
10.9	1040	940	58.2	130.6	0.31

Notes:
1. Values given for M16 x 2.0 threadbar.
2. Nominal yield strength as per Table 1 of AS 4291-2015 (applied to calculation of design bending capacity only).
3. Capacity factor of 0.8 adopted as per Table 3.4 of AS 4100-2020.
4. Adopted minor diameter area 136 mm^2 as per Table 3.3 of AS 1275-1985.
5. Tensile stress area for M16 x 2.0 thread is 157 mm^2 as per Table 3.3 of AS 1275-1985.
6. Nominal section capacity moment calculated for a compact section as per Clause 5.2.3 of AS 4100-2020 with an effective section modulus calculated assuming a circular bar of diameter equivalent to the tensile stress area, i.e. d = 14.1 mm.

Table 1 presents calculated design bending capacities based on assumptions outlined in the table notes. Validating the veracity of these assumptions was the focus of the testing undertaken as described in subsequent sections.

Section 8 of AS 4100 provides approaches to assess the adequacy of members subject to combined actions. Where the design axial force is a small proportion of the design capacity (say, < 10%) then the bending capacity is reduced by no less than 90%.

3.3 *Piston pullout*

Figure 4(c) to Figure 4(e) illustrate failure mechanisms characterised by "piston pullout" which relates to failure along a cylindrical surface coinciding with the interface between different materials. These include:

- Stripping of the internal plastic thread inside the anchor sleeve as shown in (Figure 4(c)). This was originally considered a vulnerable failure mode and was a key reason for performing the axial load tests described in Section 4.1.
- Slip through the epoxy resin (or grout) as shown in Figure 4(d). This failure mode is primarily dependant on the strength of the epoxy employed, as well as the mechanical interlock provided by the external thread of the sleeve.
- Shear failure along the substrate to epoxy resin interface as shown in Figure 4(e). The strength of this interface is influenced by the characteristics of the substrate (e.g. shotcrete or rock), the roughness of the drilled hole, as well as the cleanliness and moisture condition of the hole upon application of the epoxy.

The above piston pullout failure mechanisms were investigated and strengths of the various interfaces quantified by the axial loading tests described in Section 4.1.

3.4 *Rock / substrate failure*

Figure 4(f) to Figure 4(h) illustrate mechanisms characterised by failure of the substrate, whether that be shotcrete or bedrock, or a combination of the two materials.

Failure through a homogenous material such as shotcrete or bedrock (without defects) is shown in Figure 4(f). This mechanism is typically associated with conical failure surfaces, with the failure load governed by the depth of anchor embedment and the strength of the substrate. The Hilti technical literature for chemical anchors can be used to provide an initial estimate of the likely failure load in concrete and shotcrete.

Figure 4(g) comprises a failure governed by pre-existing defects in the rock mass such as joints, bedding planes, shears etc. Depending on the frequency and orientation of the defects the failure load could be very low. The very short embedment length of BA anchors also means that any rock bolts installed nearby are unlikely to improve the load capacity of the anchor.

The final sketch in this series comprises thin shotcrete sprayed onto bedrock (Figure 4(h)). The failure mechanism is complicated by the interaction between the shotcrete and rock, and the relatively low strength of thin shotcrete to resist concentrated loads. The bond strength between shotcrete and rock is also a source of uncertainty, with adhesion rarely relied upon by tunnel designers. Unless the shotcrete has been specifically designed for the BA anchor loads, it is the authors' opinions that relying upon shotcrete without suitable testing is to be avoided.

3.5 Installation issues

Figure 4(i) to Figure 4(k) illustrate failure mechanisms associated with installation issues.

Where the threadbar is not fully screwed into the anchor sleeve the bond length is reduced and thus also the load capacity. This issue can be managed by marking bars prior to insertion to provide a visual check as to whether they have achieved full depth or not.

Inadequate placement of epoxy resin is addressed in Figure 4(j), and includes inadequate cleaning of the hole, excessive moisture or water present prior to injecting the epoxy, and incomplete filling of the hole with epoxy. Failure to apply epoxy at all is also possible and may not be detected until the anchor is first loaded.

Figure 4(k) involves screwing the threadbar too far into the sleeve, such that it punches through the base of the sleeve. This is unlikely to affect the strength of the anchor but rather results in compromising the continuity and thus integrity of the tunnel waterproofing system.

Additionally there other challenges associated with installation, such as those mentioned previously in Section 2.4. However, these are considered manageable by use of appropriately trained and motivated installers, and implementation of an effective QA system.

4 TESTING PROGRAM

4.1 *Axial capacity*

A series of three axial load tests were performed to investigate the piston pullout failure mechanisms (Figure 5). These tests were performed in ideal conditions and are considered to represent the maximum strengths which can be achieved for this type of anchor.

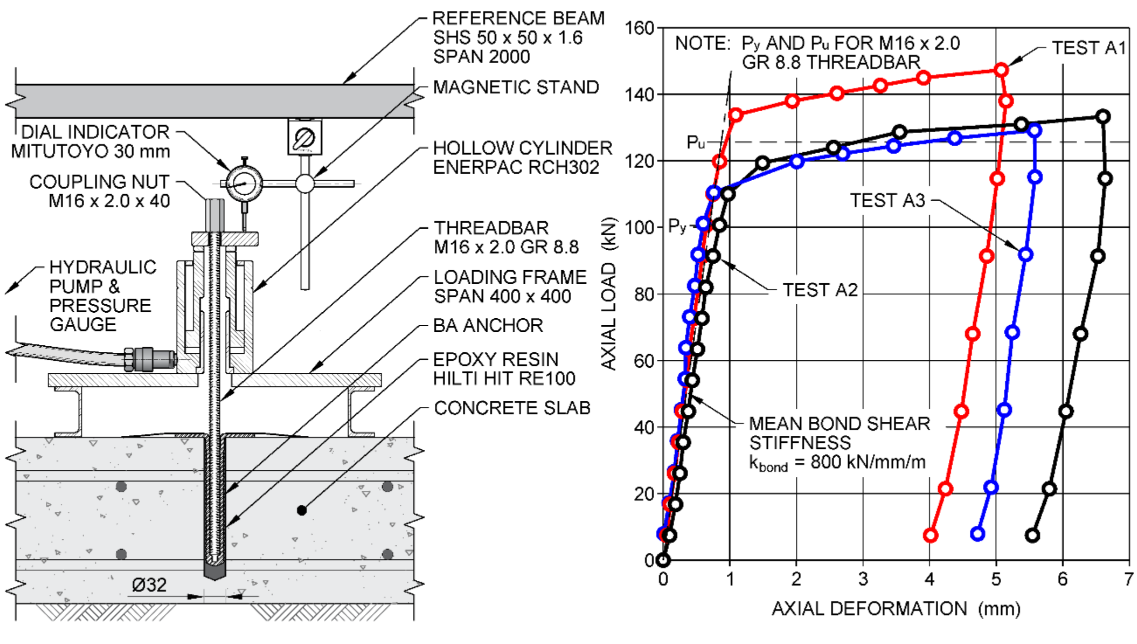


Figure 5. Axial pull test arrangement and summary results.

All three tests were governed by yielding of the steel threadbar rather than other failure mechanisms. It is noted that the yield load and ultimate loads measured were about 10% higher that the strength grade would suggest. This was borne out by the test reports and certificates obtained for the relevant manufacturing lots which indicated ultimate tensile strengths 113% to 115% of the requirement for Grade 8.8 threadbar, and 105% to 106% of the requirement for Grade 10.9 threadbar.

The minimum ultimate load from the three tests was 130 kN. Based on the lengths of the various interfaces indicated by Figure 2, the following interface strengths were calculated:

- Threadbar to sleeve, $f_s > 18.1$ MPa.
- Sleeve to epoxy, $f_s > 8.8$ MPa.
- Epoxy to concrete, $f_s > 6.9$ MPa.

For comparison, the Hilti technical datasheet (TDS) for HIT-RE 100 Injection Mortar gives a characteristic resistance of 183 kN for an M27 anchor installed in a 30 mm diameter hole with an embedment depth of 240 mm [Ref. 2]. This capacity corresponds to an interface strength, $f_s = 8.1$ MPa between the epoxy resin and concrete, which accords well with the above test results.

Bond shear stiffness was also calculated from these tests, as shown in Figure 5, noting that this parameter is not required for the design of BA anchors, and is provided purely for comparison with other rock bolt and anchor systems.

4.2 *Combined axial and bending capacity*

A further testing program was undertaken to investigate the load capacity of BA anchors when subject to combined bending and axial loading, such as occurs for most anchors installed to support bar reinforcement within the crown of a tunnel (Figure 1). A bespoke test configuration was designed in which a dead load was applied to the end of threadbar, with the angle of the threadbar able to be adjusted (Figure 6). The test regime was based on Section 17.4 of AS 4100, which relates to proof load testing of prototype specimens as a valid design approach, and includes the following key requirements:

- Applied test load is representative of limit state being assessed.
- Prototype shall be representative of production works.
- Period of loading no less than 15 minutes.
- Load factor of 1.2 applied where 10 prototype samples are tested (Table 17.5.2).

Four tests configurations were investigated, with proof loads applied to each of 10 samples for each configuration:

- Test B1, Grade 8.8 threadbar, applied load = 2.61 kN, anchor angle = 46°.
- Test B2, Grade 10.9 threadbar, applied load = 3.51 kN, anchor angle = 46°.
- Test B3, Grade 8.8 threadbar, applied load = 4.88 kN, anchor angle = 67°.
- Test B4, Grade 10.9 threadbar, applied load = 5.76 kN, anchor angle = 65°.

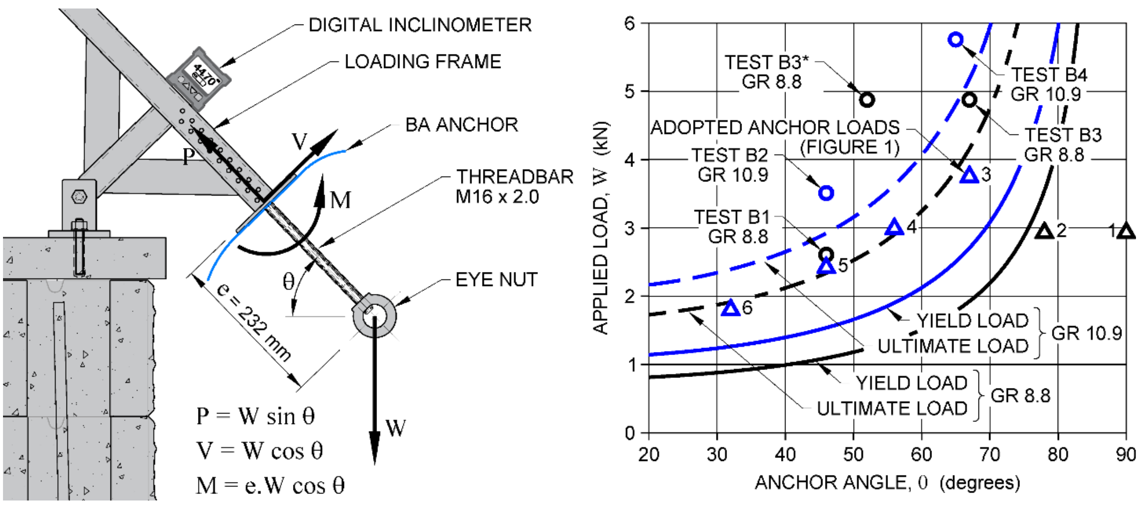


Figure 6. Bending proof load test configuration and summary results.

Table 2. Summary of pull test methods for production BA anchors

Failure mode		Capabilities of each test method		
		Simple pull test	Pull test with load frame	Proof load
Threadbar overload	Tensile failure of threadbar	✓	✓	✓
	Flexural failure of threadbar	×	×	✓
Piston pullout	Stripping of internal thread of sleeve	✓	✓	✓
	Slip along sleeve to epoxy interface	✓	✓	✓
	Slip along epoxy to substrate interface	✓	✓	✓
Substrate failure	Cone pullout (rock substance)	×	✓	✓
	Defect-controlled failure surface	×	✓	✓
	Shotcrete delamination / failure	×	✓	✓
Installation issues	Threadbar not fully inserted	✓	✓	✓
	Inadequate epoxy or hole cleanliness	✓	✓	✓
	Threadbar screwed beyond end of anchor	×	×	×

In addition, a single sample was the subject of Test B3*, in which the anchor angle was reduced to 52° to increase the bending moment applied to the bar.

All the tests satisfied the proof load testing requirements of AS 4100, with noticeable bending of the bars observed upon application of the proof load. Some of this deformation was recoverable and some permanent. Permanent deformation of all threadbars was observed, with the bars typically bent by 1° to 3.5°, and Test B3* recording over 7°.

The proof load tests show that the loads carried by the anchors exceeded the theoretical ultimate load capacity for each of the stress grades considered. This apparent inconsistency is attributable to two factors; the strength of the bars exceeded the requirements of the stress grades (refer to Section 4.1), and the significant bending of the bars during the test resulted in a reduction in the eccentricity of the applied load and thus the bending moment experienced by the bars.

Figure 6 also shows the anchor installation angles and calculated loads for each of the crown anchors indicated in Figure 1. Two strength grades were adopted as indicated by the colours of the symbols (i.e. black corresponds to Grade 8.8 and blue to Grade 10.9). The graph also demonstrates that the adopted anchor loads are consistent with the proof load test results.

5 DESIGN AND TESTING RECOMMENDATIONS

The use of higher stress grades provides a simple method to address bars which are required to resist flexural loading. Structural design checks for bending based on a plain circular bar of diameter consistent with the effective stress area were found to provide a reasonable assessment of capacity as verified by the test results. Because bending performance is sensitive to the adopted lever arm, over-excavation (see Figure 3 for excavation tolerances) can result in flexural overload and thus survey of the as-built membrane surface is recommended to allow calculation of the actual lever arm associated with the design loads.

Reliance on manufacturer’s lot certificates which indicate bar strengths greater than those required for the different stress grades is not recommended since these vary lot by lot.

Piston pullout modes of failure can be checked based on the results of the axial load tests reported in this paper.

Failure of the substrate is a key limitation of BA anchors due to their very short length. An exception to this generalisation is where the substrate comprises a thick passive shotcrete lining, or similar, where the material conditions and uniformity are known with a high degree of confidence. Pull testing of anchors is essential where the substrate comprises fractured bedrock or thin shotcrete.

A number of anchor pull test methods are available:

1. Simple pull test, where the anchor is pulled by a hydraulic cylinder, and the load frame bears against the substrate immediately adjacent to the anchor. This method does not permit the various substrate failure mechanisms to occur, nor apply flexural loads to the bar.
2. Pull test with a loading frame, similar to the simple test method but a loading frame is used such that the area within, say no less than 300 mm, of the anchor bar remains unloaded by the frame. This allows checking of the substrate failure mechanisms but does not apply flexural loads to the bar.
3. Proof load test, in which a dead load is suspended from the end of the anchor to properly simulate the vertical gravity load applied by the bar reinforcement.

The capabilities and limitations of each pull test method are summarised in Table 2.

Checking the adequacy of the installation may be addressed by specification of experienced and qualified contractors, adoption of effective quality assurance procedures, and adoption of an appropriate test method and test frequency.

Redundancy in design is an important consideration in the frequency of testing of production anchors. For an anchor layout which provides a significant degree of redundancy, testing of no less than 10% of anchors is recommended. Where failure of a single anchor could result in progressive failure and collapse of the entire reinforcing steel then testing of a very high proportion of anchors is appropriate. A higher rate would also apply where higher loads are applied, there is uncertainty in the substrate conditions or installation standard, or where inadequate performance is identified by initial test results.

6 CONCLUSIONS

BA anchors are widely used in the construction of bar reinforced concrete structures which employ a sheet waterproof membrane. Due to the unique features of this type of anchor they are susceptible to a larger range of potential failure mechanisms compared to simpler anchor types. This paper considers each of these failure mechanisms and proposes design approaches to address them. The test results presented in the paper reduce the uncertainty in the load capacity of the plastic sleeve employed in the anchor and demonstrate that much larger axial load capacity is possible compared to load capacities often quoted by manufacturers and suppliers. The bending capacity of the threadbar employed in the anchor is identified as a basic limitation of this type of anchor, and methods to perform structural checks are proposed and validated by full scale testing.

The design and testing approaches presented in this paper were applied in the Cross River Rail project and permitted optimisation of the spacing of BA anchors employed in the construction of the permanent tunnel linings and provided meaningful schedule and cost benefits to the project.

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