Effectiveness of different types of anti-burst reinforcements for achorage zones of post-tensioned concrete slabs

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ABSTRACT

A post-tensioned prestressed system basically consists of a high strength tendon or strand running through the length of the concrete structure. The strand is stressed using a hydraulic jack, the tensile stressing force of the strand is transferred into the concrete by the use of anchorages. One of the most critical aspects of post-tensioned construction, which is also necessary for the success of the system, is the "anchorage zone". The relatively large compressive forces generated from the strand are applied to the concrete over a small area. For this reason steel reinforcement known as anti-burst is used in the anchorage zone to control cracking caused by tensile forces as a result of the tensioning. Eight 150 mm thick 400mm x 1000mm post-tensioned concrete slabs with varying types of anti-burst reinforcements and two different concrete strengths were designed and tested to failure. Pull out tests were conducted at up to 95% of the tendon's tensile strength to find out the most effective type of anti-burst reinforcement and the effect of variation in concrete strengths. The rectangular helices type was found to be the best performer while the higher concrete strength was the better.

KEYWORDS

Anchorage zone. Anti-burst reinforcement. Post-tensioned. Prestressed concrete slabs.

INTRODUCTION

Post-tensioned concrete systems have been in use since the early 1900's in an attempt to overcome concrete's relatively low tensile strength and take advantage of its high compressive strength. The application of post-tensioning techniques in the design of bridges, buildings and other structures has become very common these days. Post-tensioning is now widely used in bridge piers, bridge decks, building slabs, and long-span girders where a substantial load carrying capacity is required.

A post-tensioned system basically consists of a high strength tendon or strand running through the length of the concrete structure. The strand is stressed using a hydraulic jack, the tensile stressing force of the strand is transferred into the concrete by the use of anchorages. The "anchorage zone" is possibly the most critical aspect in post-tension design because the failure of the anchorage zone would result in a loss in the stressing force of the strand, if not the failure of the entire structure; it is usually very difficult and expensive to rectify. The relatively large compressive forces generated from the strand are applied to the concrete over a small area. For this reason steel reinforcement known as anti-burst is used in the anchorage zone to control cracking caused by tensile forces as a result of the tensioning.

In order to determine the most effective type of anti-burst reinforcement and the effect of different concrete strengths, eight 150 mm thick 400mm x 1000mm post-tensioned concrete slabs with varying types of anti-burst reinforcements and two different concrete strengths were designed and tested to failure. Pull out tests were conducted at up to 95% of the tendon's tensile strength. The design of the specimens, the tests conducted and the results are presented in some detail in this paper. The rectangular helices type of ant-burst reinforcement was found to be the best performer while the higher concrete strength was the better.

Anchorage zone - design and background

One of the most critical aspects of post-tensioned construction, which is also necessary for the success of the system, is the anchorage zone. The anchorage or end zone of a post-tensioned concrete structure can typically be defined as the area of concrete that transfers the post-tensioning force from the tendons to the rest of the structure. Depending on which analysis method is used this distance is approximately equal to the depth of the section. The anchor itself can be seen in Fig. 1 and is best described as "a stiff steel bearing element which is embedded in the concrete, and connected to a cone-shaped former-tube or 'trumpet' which provides a transition to the relatively small duct used to house the cable in the beam" (Warner & Faulkes, 1988). Also shown in the figure, is the anti-burst reinforcement surrounding the anchor to provide resistance against tensile forces in the anchorage zone.

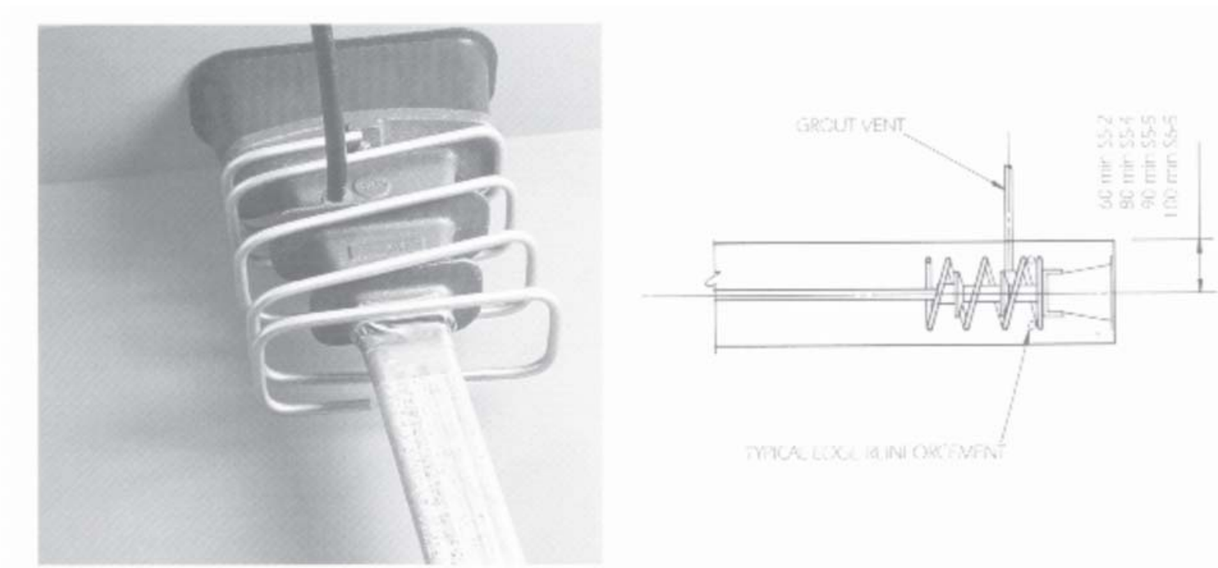

Figure 1 - Typical anchor and anti-burst reinforcement.

The first post-tensioned concrete system was patented in California, USA in 1886 but significant research did not begin until 1924 when an equilibrium-based model to visualise the load path on a concentrically loaded member was introduced from an investigation of the anchorage zone by Morsch (1924). Since then, many investigations on anchorage zones have been conducted using the theory of elasticity, finite element analyses and laboratory experiments. In 1950s and 1960s, extensive research was performed on anchorage zones utilising analyses based on the theory of elasticity and small anchor block tests (Komendant, 1952; Guyon, 1953; Zielinski & Rowe, 1960; Base et al., 1966; Gergley & Sozen, 1967; Yettram & Robbins, 1969). These studies helped generate a basic understanding of stress states in simple anchorage shapes. However, as anchorage configurations became more complicated, extrapolating from these basic results became more difficult. The situation improved somewhat as the use of finite element analyses became more common in the 1980s. This gave designers the option of conducting analyses on more complex anchorage zones (Adeghe & Collins, 1986; Yong et al., 1987).

Experimental research has been carried out to study post-cracking stress redistribution effects and the behaviour of anchorage zones according to the arrangements of ant-burst reinforcing bars (Burdet, 1990; Sanders, 1990). Also, design equations for anchorage zones, which divide a post-tensioned anchorage zone into general and local zones, were suggested by a NCHRP study (Breen et al., 1991). The analysis and design of post-tensioned anchorage zones can be carried out using the AASHTO (1998) approximate stress analysis/design method, the bearing strength equation (Roberts, 1990), the critical section concept (Sanders, 1990), or the nonlinear strut-tie model approach (Yun, 2000). A recent study (Yun, 2005) estimated the ultimate strengths of post-tensioned beams tested to failure (Wollmann, 1992) using the above four methods and found varied results. A survey conducted by the Comite Euro - International du Beton (CEB) found similar variations when different code methods were used (Sanders & Breen, 1995).

Among other findings, Oh et al. (1997) from their testing of 11 post-tensioned specimens of identical dimensions (1200mm x 400mm x 2430mm) using a 7 strand 12.7mm system, found that the spiral reinforcement was able to sustain a higher load (up to 10%) than the orthogonal reinforcement before the development of cracks due to transverse tensile stresses. Like the variations in the design methods there are various types of ant-burst reinforcements in use. The current study therefore attempts to look at the effectiveness of different types of ant-burst reinforcement in the anchorage zone of a post-tensioned member.

ANTI-BURST REINFORCEMENT

The objective of the anti-burst reinforcement is to control cracking by resisting against transverse tensile forces in the anchorage zone due to the transfer of the stressing force to the concrete section. Anti-burst reinforcement comes in a range of shapes and sizes from the use of everyday steel reinforcement such as individual bars and mats through to purpose designed and made helices and ligatures.

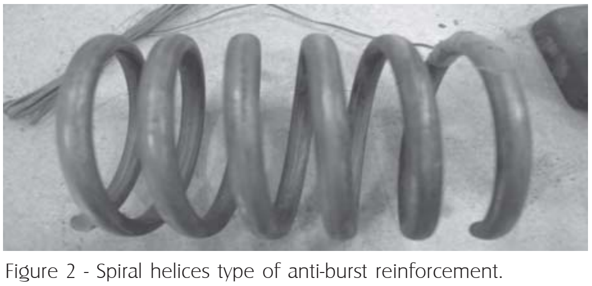

Figure 2 - Spiral helices type of anti-burst reinforcement.

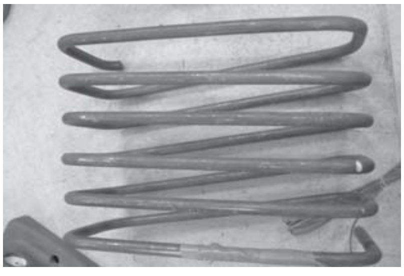

Figure 3 - Rectangular helices types of anti- burst reinforcement.

There are no set standards as to which type of reinforcement is used as long as the required area of steel is provided through out the anchorage zone. However previous research has shown that in some instances helices are less effective especially spiral when small diameters are used (CIA, 1996). In the current study, the post-tensioned specimens tested include 3 different types of anti-burst reinforcement namely; spiral helices, rectangular helices and U-bars.

Spiral helices are one of the most commonly used types of anti-burst reinforcement in the post-tension industry, due to a lot of post-tension equipment manufacturers supplying them as a kit form with their anchors, tendons and ducting, etc. They basically take the form of a spring as shown in Fig. 2. Rectangular helices, like the spiral ones, are a popular anti-burst reinforcement option often used as standard reinforcement distributed with other products as a package. The rectangular helices are very similar to the spirals except as the name suggest the helix takes the shape of a rectangle as can be seen in Fig. 3. The U-bar or hairpin anti-burst reinforcement basically consists of standard U-bars placed on either side of the anchor as can be seen in Fig. 4.

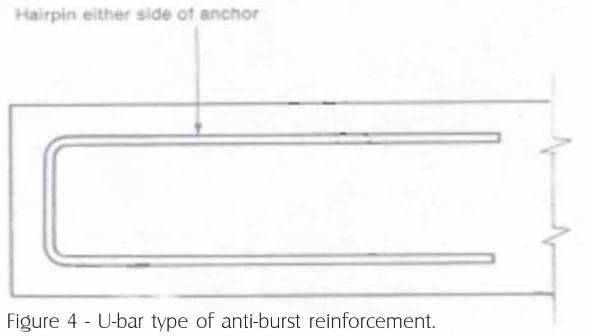

Figure 4 - U-bar type of anti-burst reinforcement.

EXPERIMENTAL PROGRAM

A total of eight 150 mm thick 400mm x 1000mm post-tensioned concrete slabs with 3 different types of anti-burst reinforcements and two different concrete strengths were designed and tested to failure. The two strengths of concrete used were 27 MPa and 32 MPa. For each concrete strength, 3 slabs with 3 different types of ant-burst reinforcement and 1 slab with no reinforcement were constructed. The slabs with no ant-burst reinforcement were used as control slabs to gauge the effectiveness of the three reinforcement types. The specimen designation and their typical details are given in Table 1, and the typical dimension of a specimen slab in Fig. 5.

Table 1. Details of test specimens

Specimens	Anti-burst reinforcement type	Concrete compressive strength, f_{cm} (MPa)
1A	Rectangular helix	27
2A	Spiral helix	27
3A	U-bars	27
4A	None	27
1B	Rectangular helix	32
2B	Spiral helix	32
3B	U-bars	32
4B	None	32

The post-tensioning for each slab was a 3 strand (12.7mm) single anchor system and each system comprised of the following items:

" 1 trumpet type anchor - bearing size dimensions 135mm x 75mm;

" 3 sets of 40mm barrels and wedges;

" 1 length of galvanized ducting 60mm x 20mm, 1000mm long; and

" 3 - 12.7mm diameter high tensile strands (184 kN), 2.2m long.

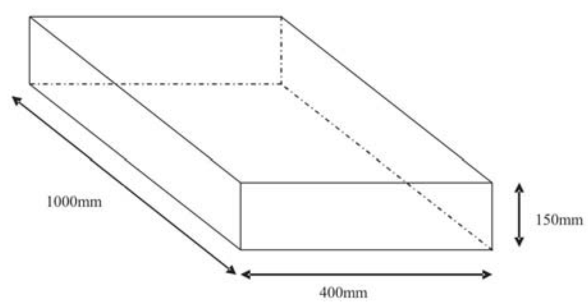

Figure 5 - Typical dimension of a test specimen.

Design of test specimens

The anti-burst reinforcement for the specimen slabs were designed in accordance with the Australian Standard AS 3600 - 2001 (SAI, 2001). The Australian Standard is based on the symmetrical prism theory which was first developed by Guyon (1953). Section 12.2 of the Standard covers the design of anchorage zones and Section 12.2.4 recommends using the following equation to calculate the transverse tensile stresses in the anchorage zone:

$$T = 0.25P(1-k_r) \tag{1}$$

where T = Transverse tensile stress, P = the maximum force occurring at the anchorage during jacking and kr = the ratio of the depth, or breadth, of an anchorage bearing plate to the corresponding depth, or breadth, of the symmetrical prism.

The symmetrical prism is defined as a notional prism with an anchorage at the centre of its end face and a depth or breadth, taken as twice the distance from the centre of an anchorage to the nearer concrete face.

The transverse tensile force (T) obtained using Eq. (1) is divided by 150 MPa in order to calculate the area of steel required for the anti-burst reinforcement. The reinforcement is to be distributed evenly through out the zone which spreads from 0.2D to D, where D is the slab depth (thickness). With the specimen slab thickness of D = 150mm, the reinforcement is to be distributed from 30mm from the loaded face to 150mm - a total of 120mm. To satisfy the area of reinforcement, distribution and cover requirements the arrangements presented in Table 2 were decided on.

Table 2. Anti-burst reinforcements for the test slabs

Specimens	Anti-burst reinforcement dimensions	f_{cm}
1A	110mm x 250mm @ 20mm centres for 120mm (N10 bar)	27
2A	110mm diameter @ 20mm centres for 120mm (N10 bar)	27
3A	4 x U-bars @ 100mm spacing 120mm long (N10 bar)	27
4A	None	27
1B	110mm x 250mm @ 20mm centres for 120mm (N10 bar)	32
2B	110mm diameter @ 20mm centres for 120mm (N10 bar)	32
3B	4 x U-bars @ 100mm spacing 120mm long (N10 bar)	32
4B	None	32

Test set up and procedures

Pull out tests at up to 95% of the tendon's tensile strength were conducted on all 8 test slabs according to the Australian Standard AS/NZS 1314: 2003 (SAI, 2003). This Standard sets the following criteria in order to determine the failure of a test sample:

" The anchor must be loaded to 95% of maximum breaking load of the tendons

" No cracks with a width of >0.2mm after 15 minutes at 90% of maximum load.

In the current test program the tendons were rated to 184 kN each, giving a maximum load of 3 x 184 kN (= 552 kN). In order for the specimens to pass the test they must withstand 525 kN (95% of 552 kN) with no cracking > 0.2mm.

The testing procedure and apparatus (see Fig. 6) is also based on the Australian Standards AS/NZS 1314: 2003. The Standard also gives other specifications such as the concrete strength must be between 22 MPa and 50 MPa and the ambient temperature between 10o C and 35o C.

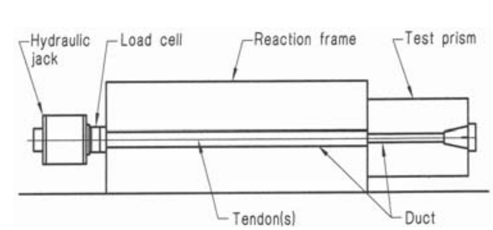

Figure 6 - Test apparatus as per AS/NZS 1314: 2003.

All 8 test slabs were cast at the same time using the same concrete but were tested at two different days to have the two different concrete strengths. To help measure the effectiveness of each individual reinforcement type a strain gauge was placed on the anti-burst reinforcement. A testing reaction frame similar to that shown in Fig. 6 was used for the tests. A 200 tonne (2000 kN) multi-strand jack was used to post-tension the tendons. The multi-strand jack had a pressure gauge attached so that the applied jacking force could be measured. In order for the gauge to be accurate the jacks and gauge were calibrated at a NATA (National Association of Testing Authorities Australia) accredited laboratory. In each test, the maximum load of 525 kN was applied in 6 steps - 100kN, 200 kN, 300kN, 400kN, 500kN and 525kN. Strain gauge reading at each load level was recorded.

Test results

Material strengths

All 8 test slabs were cast on the same day using the same concrete but 4 of them were tested 6 days after and the rest 10 days after casting. This was done for the test slabs to have two different strengths of concrete i.e. 27 MPa and 32 MPa. Twelve standard 100mm diameter and 200mm high concrete cylinders were cast at the same time as the slabs. These were tested to determine the compressive and tensile strength of concrete at the corresponding testing dates of the two groups of slabs. The cylinder test results at 6 days and 10 days are presented in Tables 3 and 4, respectively. Note that Slabs 1A to 4A were tested at 6 days and Slabs 1B to 4B at 10 days. The average concrete compressive strength for the first group of 4 slabs was 27 MPa and for the second group 32 MPa. The concrete tensile strengths for the corresponding groups were 2.8 MPa

Table 3. Cylinder test results for Slabs 1A to 4A

Age (Days)	Cylinder No.	Compressive strength, f_{cm} (MPa)	Average f_{cm} (MPa)	Cylinder No.	Tensile strength (MPa)	Average tensile strength (MPa)
6	1	28.30		1	3.24	
6	2	27.64	27	2	2.13	2.8
6	3	26.55		3	3.00	

Table 4. Cylinder test results for Slabs 1B to 4B

Age (Days)	Cylinder No.	Compressive strength, f_{cm} (MPa)	Average f_{cm} (MPa)	Cylinder No.	Tensile strength (MPa)	Average tensile strength (MPa)
10	1	31.61		1	3.78	
10	2	30.88	32	2	3.85	3.8
10	3	32.56		3	3.80	

and 3.8 MPa, respectively.

Ultimate loads

The pos-tensioned anchorage zones for the test slabs were designed according to the Australian Standard AS 3600-2001 (SAI, 2001) with enough anti-burst reinforcement to withstand an ultimate load of 552 kN which is the maximum working load of tendons. In accordance with the Australian Standard AS/NZS 1314: 2003 (SAI, 2003), the specimen slabs were tested to 95% of this load which is 525 kN. However, due to the use of different types of anti-burst reinforcement or no reinforcement different slabs failed at different loads. The ultimate load for each slab is presented in Table 5.

Table 5. Ultimate loads for the test specimens

Specimens	Ultimate loads (kN)	Observations
1A	525	Cracking started at 400 kN; tendons started to fail at 525 kN
2A	416	Sudden explosive type of failure at 416 kN
3A	317	Sudden explosive type of failure at 317 kN
4A	317	Sudden explosive type of failure at 317 kN
1B	525	Tendons started to fail at 525 kN
2B	448	Sudden explosive type of failure at 448 kN
3B	416	Sudden explosive type of failure at 416 kN
4B	416	Sudden explosive type of failure at 416 kN

It can be observed from Table 5 that the only specimens that were able to withstand the maximum load of 525 kN were the ones with rectangular helix type reinforcement (Slabs 1A and 1B). The lower concrete strength specimen had signs of some minor cracking but was able to hold the load for the required 15 minutes. All the remaining 6 specimens failed in the same manner of a crack appearing along the tendon path and increasing in size until a sudden explosive failure.

The most disappointing results were those of the U-bar type of anti-burst reinforcement which failed at the same load as those with no reinforcement, suggesting that they provided very little or no resistance against the transverse tensile forces. This is most likely due to the fact that the reinforcements were placed close to the bearing surface. Another possible reason is the fact that the U-bars were not tied together and therefore did not provide reinforcement in both directional axes.

Other poor but expected results were produced from the spiral helix type of anti-burst reinforcement. Previous research (CIA, 1996) has shown that the spiral helix with a small diameter can be less effective than other types of anti-burst reinforcement. This was the case in the current study as the spiral helix type was only able to sustain 416 kN (for 27 MPa concrete slab) and 448 kN (for 32 MPa concrete slab), respectively 79% and 85% of the maximum testing load of 525 kN, and 75% and 81% of the design load of 552 kN.

The other important finding is that as expected the higher concrete strength yielded higher ultimate loads for all specimens. All B-series slabs had higher ultimate loads compared to their corresponding A-series counterparts.

Strain in ant-burst reinforcement

The strain gauges placed on the anti-burst reinforcement were used to measure the strain applied to the reinforcement during the tensioning process. Note that for the two slabs with no anti-burst reinforcement, no strain was required to be measured. For the remaining 6 slabs, the strain is plotted against the tensioning load for the three 27 MPa concrete slabs in Fig. 7 and for the three 32 MPa concrete slabs in Fig.8.

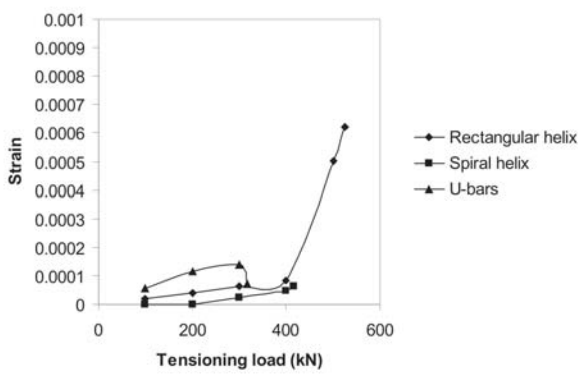

Figure 7 - Strain versus tensioning load for 27 MPa concrete slabs.

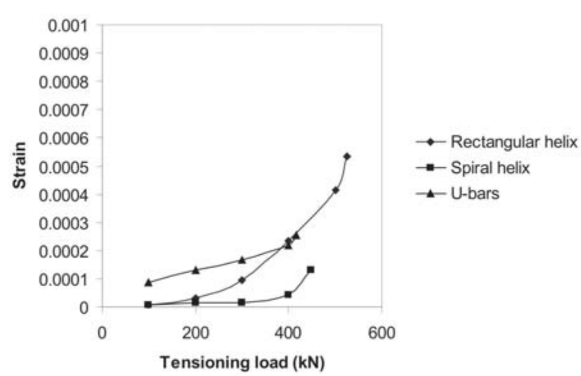

Figure 8 - Strain versus tensioning load for 32 MPa concrete slabs.

From Fig. 7, it is evident that for 27 MPa specimens the spiral helix had the least amount of strain for the same load when compared to other types. The strain in both the rectangular and spiral helix seemed to be increasing reasonably linearly up until 400 kN when it increases sharply for the rectangular helix and the spirals fails. The most strain was recorded in the U-bar reinforcement for the same amount of load, the graph shows the strain peaking and then falling. After failure it was noticed that the strain gauge had broken from the reinforcement which might be responsible for the sudden dip in the curve.

Figure 8 shows that the 32 MPa concrete specimens exhibited similar behaviour with the spiral helix reinforcement having the least amount of strain and the U-bars, the most. The main difference is that the rectangular helix was not as linear and showed a greater difference compared to the spiral helix.

Conclusions

In order to determine the most effective type of anti-burst reinforcement and the effect of different concrete strengths, eight 150 mm thick 400mm x 1000mm post-tensioned concrete slabs with three types of anti-burst reinforcements and two different concrete strengths were designed and tested to failure. Pull out tests were conducted at up to 95% of the tendon's tensile strength. The design of the specimens, the tests conducted and the results are presented herein in some detail. The rectangular helices type of ant-burst reinforcement was found to be the best performer while the higher concrete strength specimens exhibited better performance for all types of reinforcement.

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