Laboratory test methods and results for double shear performance of Australian CT bolts in simulated strata

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ABSTRACT: Australian CT Bolts are a strata support system used in major Australian tunnelling projects, engineered for a 100-year lifespan using the Double Corrosion Protection (DCP) system. Sandvik Ground Support (formerly DSI Underground Australia) has undertaken a series of comprehensive test programs on the Australian CT Bolts in collaboration with tunnel designers and construction companies. A major component of this work has been laboratory double shear tests, providing critical information on the deformation limits of the bolt for combined shear and tension. This paper discusses a program of laboratory double shear testing that was conducted on three types of Australian CT Bolts: the 310kN solid steel rebar, a 579kN solid steel rebar, and a 573kN steel strand cable bolt. The results from this test program provide evidence for a practical shear displacement limit for the Australian CT Bolt design.

1 INTRODUCTION

The Australian CT bolt product family is widely used within civil tunneling applications for permanent and primary ground support. During the construction and service life of the tunnel, the shear displacement of strata is a common geotechnical concern that impacts upon the lifespan of strata control elements (Bertuzzi 2004) and (Pells & Bertuzzi 1999). Due to the redistribution of rock stresses arising from tunnelling excavations, it is common for the strata to move with a shearing motion (Roper et al. 2021) – and this shear can cause installed rock bolts to bend and permanently deform. For sheathed bolts, the impact of shear deformation on the outer plastic sheathing is important to evaluate, as this sheath forms a primary protective layer against the ingress of water. If the sheathing is punctured, water ingress may initiate corrosion of the steel tendon, compromising the lifespan of the installed bolt. In addition to corrosion, mechanical shear damage to the internal steel tendon is also important to assess as this is the structural element of the bolt.

Three bolt types are discussed within this paper; the CT Corrosion Protected Mechanical Bolt (abbreviated hereafter as CT bolt), the CT High Strength Corrosion Protected Mechanical Bolt (abbreviated hereafter as CT26WR bolt) and the Double Corrosion Protected Cable Bolt (abbreviated hereafter as DCPCB) – the three bolt types are shown for comparison in Figure 1. For clarity, note that these bolt types are products of Sandvik Ground Support Australia. The internal steel tendon is the primary difference between each bolt type, each tendon having different mechanical properties; the CT bolt is a 310kN solid bar with a 21.7mm diameter high tensile steel rebar, the CT26WR bolt is a 579kN continuously threaded high tensile solid steel bar with 26.5mm diameter thread and the DCPCB contains a 573kN 21.8mm diameter nineteen wire steel strand cable bolt. The CT bolt uses a nominal 35mm diameter plastic sheath, while the CT26WR and DCPCB both use a nominal 45mm diameter plastic sheath.

Figure 1. From left to right - DCPCB, CT26WR, and CT bolt

Over the past decade, Sandvik Ground Support (DSI Underground Australia) has undertaken a total of nine in-house test programs for the shear testing of CT Bolts (product group), at the request of and in co-operation with tunnel designers and construction companies. The initial test method was developed with the direct input of clientele, as well as in reference to previously published techniques (Aziz & Jalalifar 2007). Prior to the first test program, only limited information existed concerning the shear performance of double corrosion protected bolts and specifically the outer plastic sheath. Given the complex and time-consuming nature of both sample preparation and the test technique, each program was typically limited to three tests in total, of the same bolt type and the same rock block type. Additional test programs were progressively requested by clientele, to investigate further test variables and different bolt types. The test method was subsequently refined and improved, evaluating different shear block types, test fixture modifications and improved post load analysis of the test samples.

Presented and discussed in this paper is the shear test method, results of the test programs, and results to provide evidence for a practical shear displacement limit for the Australian CT Bolt design.

2 DOUBLE SHEAR TEST METHOD

2.1 *Double shear test overview*

The shear strength of a material is determined by applying opposed forces between two parallel planes to induce shear stress within the test specimen. Although shear displacement within strata will typically occur between a single pair of shear planes, it is a common laboratory technique to simultaneously place load across two pairs of parallel shear planes within the same specimen. This technique is known as the double shear method, which permits the balance of overall forces within the test sample and the test equipment. The two shear planes are positioned well apart in the test jig design, so that there is negligible stress influence between the two shear planes during the test.

A double shear test method was used to apply a specific, pre-determined shear displacement across the rockbolt, as installed within the shear blocks. Full sized rockbolts were used for the testwork, along with shear blocks of strength and properties comparable to common strata conditions encountered within the relevant underground environment. A steel framework was used to house the shear block segments, allowing for accurate control and progressive measurement of shear displacement during each test. Shear forces were applied to the test samples using a calibrated universal test machine. After each test, the blocks were dissected and samples analysed to find the effects of shearing on the rockbolt. Figure 2 shows both a photo and graphic images of a test arrangement prior to shear loading.

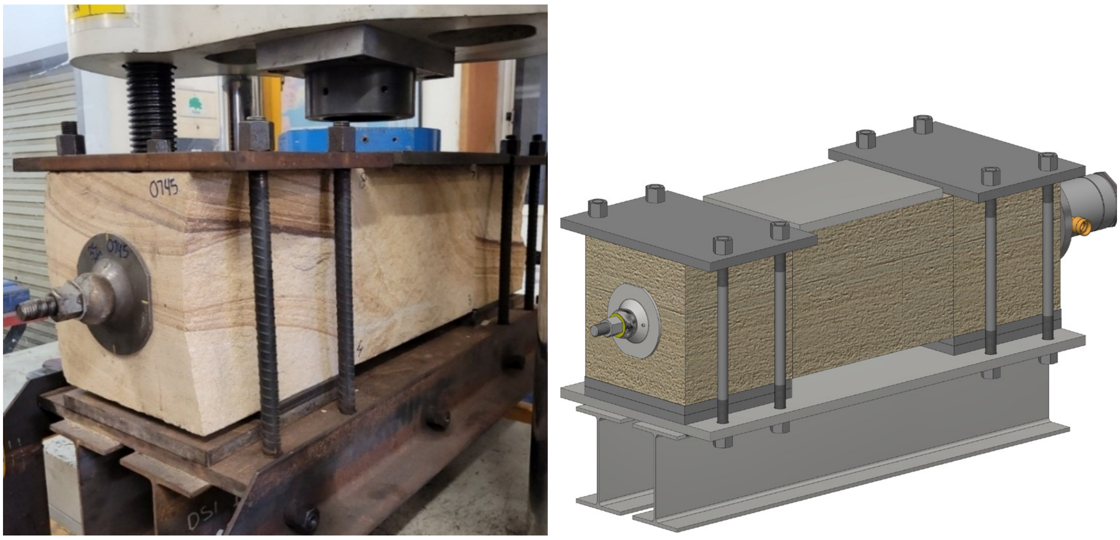

Figure 2. The left image shows test frame and machine prior to load testing, at the Sandvik ground support laboratory at Newcastle. The right image shows a graphic representation of the test sample and apparatus.

2.2 *Shear displacement measurement*

Across all test programs, the primary aim was to determine the durability limit of the plastic sheathing, given a specific shear displacement. The established test method permitted excellent control of the block shear displacement and could be directly correlated to sheathing durability, providing clear test outcomes. Displacement measurements were recorded from the change in crosshead position on the universal test machine. The zero point (or first measurement) for displacement initiates at a load of 2kN applied to the test sample.

Note that it is only possible to observe the sheathing condition following the completion of each test and after sectioning of the block sample. For this reason, a pre-determined shear displacement value was set for each test – and across the majority of the test programs, this targeted value was set by the tunnel designers, being the clientele of the test program. Due to the cost and complexity of testing, initial test programs only had a limited number of test samples available to determine the durability limits of the sheathing. Hence, the initial test programs targeted lower and more conservative shear displacements, with later test programs focusing on achieving higher displacement values.

A further focus area of the test work was to measure the performance of the steel tendon. During shear testing, the axial loads induced on the steel tendon were recorded using a load cell located at the distal end of the tendon and seated against the outer block face. This enabled measurement of the axial force induced onto the steel tendon during shear displacement of the centre test block. Following test completion, the permanent bend displacement and damage of the steel tendon was measured to provide a subjective indication of bolt strength.

2.3 *Exclusion of shear force measurements*

While the true shear strength of the installed bolt assembly (including grout, plastic sheath, and steel tendon) is of interest, it is problematic to measure with any degree of accuracy. The predominant influence is the frictional forces generated between the contact faces of the test block shear planes. Frictional forces are induced initially during axial bolt pre-tensioning and progressive increase of axial bolt loading during loading. Normal stresses induced through initial pre-tensioning and the continuous anchorage of the bolt within the surrounding rock mass are also known to have a significant effect on the shear forces during loading (Aziz & Jalalifar 2007). Subsequently the interaction of the forces between the bolt assembly and the rock blocks cannot be isolated.

The shear force results applied to the test samples were recorded, however they are not presented within this paper and were not used to determine sheathing durability. Instead, the shear displacement applied to the block was used as a far more reliable test measurement, reflecting the primary aim across the test programs.

2.4 *Test samples and apparatus*

The size, shape, and materials used for the test samples were selected to accurately replicate the mechanics of a full sized rockbolt. Each test sample and blocks were used only once and consisted of the following:

- 1500mm long rockbolt (plastic sheathing, steel tendon, bolt specific fasteners).
- Two 'end position' rock blocks, each with dimensions of 300 x 300 x 300mm long.
- One 'centre position' rock block, with dimensions of 300 x 300 x 450mm long.
- A bore hole drilled through the centre of the three blocks with diameter to suit each bolt type.
- 50kN of pre-tension applied with fasteners typical to each bolt type.
- Cementitious grout pumped into the rockbolt and bore hole. Typical grout strength of 40MPa UCS. Unconfined compression testing was conducted for each test sample to determine grout strength.
- Each sample contained either homogeneous sandstone or concrete blocks containing no reinforcing elements. Sandstone blocks were sourced pre-cut from a quarry and concrete blocks were cast in the laboratory.

A mechanical test frame was developed to house the three blocks (and installed test bolt) to permit the use of a universal test machine. The test frame consisted of a rigid solid steel frame, with packing plates and tensioning bolts to restrain the two end blocks while providing clearance for movement of centre block (see Figure 2).

Note that one set of tests for the CT26WR bolts, requiring displacements of 20 and 30mm, included further confinement of the centre block, using an additional four horizontal tensioning bolts and steel side plates. This additional support was required due to the high compressive strength and more brittle properties of the concrete blocks that were used for this specific test.

2.5 *Sample analysis*

Post-test sectioning of the test samples was required to determine the level of damage to the plastic sheathing. This was undertaken in a series of sequenced steps as the different layers of the test sample were progressively exposed. The stages of sample analysis included:

- The test blocks were cut using a concrete saw through to the centre grout and bolt element – see Figure 3. The conditions of the outer grout layer and the overall condition were subsequently documented.
- The bolt was then extracted from the blocks and the external sheath surface was inspected and photographed. Any suspected damage or perforations of the sheath were subsequently documented.
- Two 250mm long sections of the sheath were then removed from the bolt, one from each of the two shear plane regions. Removal of the sheath enabled visual inspection of grout coverage within the inner annulus and was photographed at each location (see Figure 4 as an example).
- The cut-away sheath sections were then cleaned and placed above a light source to enable clear visual inspection for any perforations, with photographed records being maintained. Where indicated by the backlighting, each individual perforation was measured using digital vernier calipres to calculate the area of that opening (in mm^2). Figure 5 shows an example of the sheath section before and after removal from the bolt. Typically, holes were irregular in shape and measurements for area were completed using a rectangular size estimation – for example, a 1mm by 0.2mm measurement yielding a 0.2mm^2 area.
- The final stage was to measure the steel tendon for bending. Measurements of the axial offset of the tendon centre portion were taken using a rule and square. An example of this axial offset is shown in Figure 6.

Figure 3. Initial sectioning of a CT26WR shear test sample after 20mm of shear. The centre block has been halved and opened, with the outer grout annulus remaining intact (lower left section), also revealing the bolt and sheathing (upper right section).

Figure 4. Sectioning of a tested CT26WR bolt sample at the shear plane, following 20mm of shear displacement. The inner annulus of cement grout has substantively held together during deformation of the bolt at the shear plane.

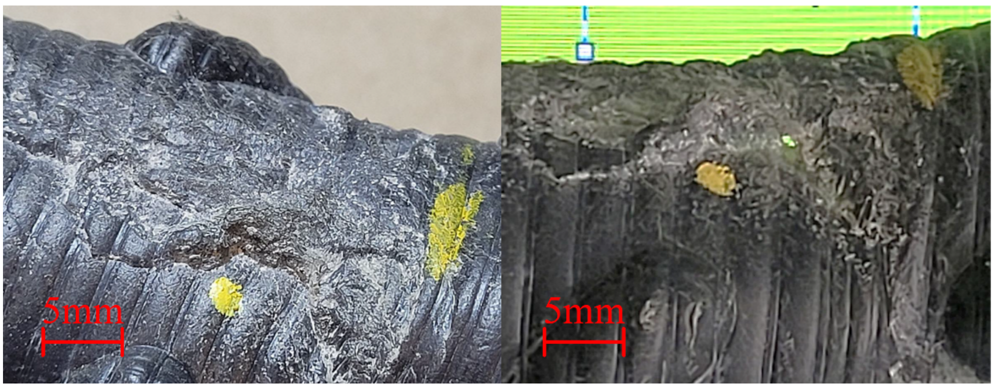

Figure 5. Example of a small perforation revealed under back-light inspection, the left image shows before the sheath was removed from the bolt and the right image shows the sheathing under back-light inspection.

Figure 6. An example of a bolt, taken at the shear plane, following loading to 20mm shear displacement test.

3 RESULTS

The results in this paper are drawn from nine different test programs that were conducted between 2016 and 2022. Acknowledging that minor improvements in methodology were made across the test programs, the overall procedure and technique offered consistency to provide a full set of aggregated data. In total there were 27 individual double shear tests completed. A summary of the results is provided in Figure 7 and Table 1.

Each test was completed at, or marginally above, a pre-determined shear displacement, with measurements of force and displacement recorded during the test. Visual analysis of the test sample after block sectioning consistently revealed compressive fracture of the block material and the outer grouted annulus (external to the sheathing) at each of the two shear planes. All samples consistently displayed full grout encapsulation of the inner and outer annulus. During inspection of the bolt, before the sheath was removed from the bolt, it was not possible to see perforations in the sheath smaller than the order of 5mm². Upon sectioning of the sheathing, the internal grout annulus typically displayed only minor compression fractures within each shear plane region, as exampled in Figure 4. Bolt bend measurements were taken for both the CT and CT26WR bolt types across the axial offset, as exampled in Figure 6. In all test samples, the internal steel tendon had no cracks or ruptures – only bending and minor elongation modes being witnessed. As indicated by the lack of change in the distance between the ribs of the steel tendon, there was no evidence of high levels of permanent tensile elongation. Deformation results could not be taken for the DCPCB bolt, as the internal steel cable would elastically return to its original shape after release from load testing.

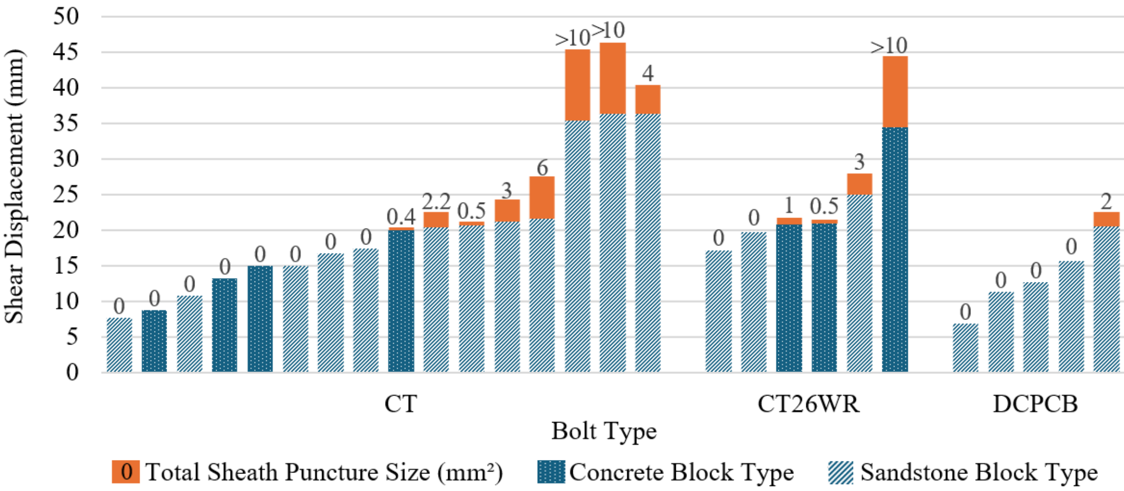

Figure 7. Shear displacement values for all test results, with bolt type, sheath puncture area and block type used.

Table 1. Summary table of individual test results across all test programs.

Bolt Type	Shear Displac-ment (mm)	Shear Block Material	Block Strength UCS (MPa)	Total Sheath Puncture Area (mm²)*	Bolt Bend Measurement (mm)**	Peak Load at Bolt End (kN)**
CT	7.8	Sandstone	35	0	-	18
CT	8.8	Concrete	26.5	0	1.5	0
CT	10.8	Sandstone	35	0	-	0
CT	13.3	Concrete	41.5	0	4	0
CT	15	Concrete	41.5	0	5	13
CT	15	Sandstone	35	0	-	6
CT	16.75	Sandstone	35	0	-	6
CT	17.5	Sandstone	35	0	-	6
CT	20	Concrete	41.5	0.4	7	18
CT	20.4	Sandstone	35	2.25	9.5	15
CT	20.7	Sandstone	35	0.5	10	5
CT	21.3	Sandstone	35	3	8	-
CT	21.6	Sandstone	35	6	8	5
CT	35.4	Sandstone	35	>10	22.5	25
CT	36.4	Sandstone	35	>10	23	25
CT	36.4	Sandstone	35	4	24	15
CT26WR	17.14	Sandstone	35	0	-	-
CT26WR	19.78	Sandstone	35	0	-	-
CT26WR	20.8	Concrete	60	1	9	3
CT26WR	21	Concrete	60	0.5	7.25	18
CT26WR	24.99	Sandstone	35	3	-	-
CT26WR	34.5	Concrete	60	>10	16.5	60
DCPCB	7	Sandstone	35	0	-	-
DCPCB	11.4	Sandstone	35	0	-	-
DCPCB	12.7	Sandstone	35	0	-	-
DCPCB	15.7	Sandstone	35	0	-	-
DCPCB	20.6	Sandstone	35	2	-	-

*Figures shown are the total sum of area for all holes in a test sample – and includes the two shear planes within this summation.
** Some test results for bolt bending and bolt end load were not recorded, indicated with a "-" symbol.

4 DISCUSSION

As each test program was completed over time, a clear understanding emerged regarding the performance and trends of CT bolt sheathing durability. At around 20mm shear displacement, any holes observed in the sheath were typically sub-millimeter in size. Above 20mm, the hole area increased in line with increasing displacement. A general observation across test samples is that the sheathing could withstand large amounts of plastic deformation damage before puncture.

Holes were rarely circular and would range in shape from thin slits to irregular polygonal shapes. Grout would typically be lodged within the area where holes occurred and careful effort was required to remove the grout before a hole could be seen. However, the possibility existed that the grout removal process may have initiated a hole, or caused further damage to an existing hole within the sheath sample – particularly given the fine nature of the required technique to measure hole area.

Damage to the steel tendon from shear testing was less severe than anticipated. The permanent bend within the steel tendon would increase proportionately with shear displacement, with the 35mm shear displacement tests showing the highest amount of bend. The amount of permanent elongation for all steel tendon types suggested the shear stress applied to the tendon was well below its ultimate strain and material strength. For both the CT and CT26WR bolt tests, the final displacement of the steel tendon sample did not match shear blocks test displacement. The strongest evidence for the difference in observations is due to the compressive fracture of the block and grout material at the shear planes. Compression of the block and grout caused shear forces to disperse across the steel tendon and resulted in the S-shaped bend within the tendon.

The lack of damage to both internal and external grout annulus in the regions near the shear planes are a match to the low axial loads witnessed at the bolt ends during shear loading. This is an indicator that the axial load placed on the steel tendon during the test were predominantly restrained by load transfer within the fully grouted bore hole.

There was minimal evidence arising from the overall test program to suggest that the durability performance of the sheath was affected by the shear block type and strength used. Beyond the block material type differences, the three tests with centre block confinement and higher UCS block material did not indicate a difference in sheathing durability. However, further test data would be required to explore these parameters more fully.

5 CONCLUSION

Double shear tests, conducted on the Australian CT Bolt product family across nine test programs and 27 individual tests, clearly show the durability limits of the plastic sheathing with a reasonable confidence level. A number of parameters were explored throughout these programs; shear block material, sheathing diameter and steel tendon type – with the durability limit of the plastic sheathing under shear returning similar values across these programs.

6 REFERENCES

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