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BEHAVIOUR OF CABLE BOLTS IN SHEAR; EXPERIMENTAL STUDY AND MATHEMATICAL MODELLING

Naj Aziz¹, Peter Craig², Ali Mirza¹, Haleh Rasekh¹, Jan Nemcik¹ and Xuwei Li¹

ABSTRACT: The application of cable bolts for ground support is on the increase in underground coal mines worldwide. Currently, two methods of evaluating the performance of the cable bolt are favoured; the short encapsulation pull test and shear test. The former method can be used both in the laboratory and the field, while the latter can be undertaken mainly in the laboratory. There are two methods of shear strength testing, single and double shear tests. This paper examines the double shear testing of several cable bolts currently marketed in Australia under various pre-tension stresses. Both plain and indented wire cable bolts were tested. It was found that, the shear strength of the cable bolt was a function of the wire geometry and initial pre-tension. Indented wire cable bolts were lower in shear strength than the plain wire cable bolts. A mathematical model was proposed to evaluate the shear strength of cable bolts using Fourier series and Mohr-Coulomb failure criterion. The model coefficients were determined based on the experimental results. The findings from the mathematical modelling tallied well with the experimental results.

INTRODUCTION

Cable bolts have been used for ground support in mines worldwide since the 1960s. Cable bolts have been mostly used as a secondary support in addition to conventional rebar type primary support. Longer cable bolts act to reinforce strata above the primary bolted beam, and also to suspend the primary bolted beam to the higher competent stratification layers. Shorter cable bolts have also been used as flexible primary roof support, known as FLEXIBOLT, replacing the ordinary rigid rebar (Fuller and O'Grady, 1993).

Traditionally the mechanical integrity of cable bolts and rebar is evaluated for tensile strength and axial load transfer assessed by the pull testing method. Various publications have reported on the subject, covering studies undertaken both in the laboratory and field; Hyett *et al.*, (1992), Hyett *et al.*, (1996), Clifford *et al.*, (2001); and Thomas (2012). Pull tests are generally carried out to evaluate the axial reinforcement behaviour of cable bolts as the necessary requirement for cable bolt application to strata support in underground coal mines. Cable bolts are typically installed vertically above a coal mine opening, perpendicular to the sedimentary rock bedding planes. Rock movement resulting from *in situ* and mining intensified horizontal stresses often occurs along these horizontal bedding planes, resulting in shearing loads across the cable bolts.

Recently in Australia's coal mining industry, there has been increasing interest on the evaluation of the cable bolt shear behaviour. Generally, there are two main methods of testing cable bolts in shear, single and double shear methods. Goris and Martin (1996) reported on single shear tests conducted in pairs of 0.025 m³ concrete blocks having joint surfaces ranging from smooth to rough. The failure of cable bolt strands in the field may not occur in shear alone, but could be a combination of tensile and shear due to the movement of bedded strata formations in various directions.

The understanding of cable bolt behaviour in shear is still in its infancy as there are various practical issues to be examined and many theories and mechanisms involved are yet to be fully explored, which could provide better understanding of any particular cable bolt's behaviour in shear. The double shear testing study reported by Aziz *et al.*, (2004) used a three piece concrete block double shear apparatus to simulate shear behaviour of rock bolts in rock at the University of Wollongong. Aziz, 2010, Craig and Aziz *et al.*, (2010a and b) used a similar but larger apparatus and examined the failure behaviour of 28 mm hollow strand "TG" cable bolts taken to complete failure. Their findings demonstrated the symmetric characteristics of the double shear equipment with the cable bolt being sheared to failure on each side of

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the sheared joints. Analysis of the failure mode and loads achieved indicated that the cable strand undergo bending and crush the concrete surrounding the borehole at the shear plane. This kind of behaviour of the cable will not occur when the cable bolt is grouted in steel pipes instead of rock, as the case of the single shear method as recommended by the British Standard BS 7861-part 2 (British Standards 2009). The equipment used in BS 7861 is a guillotine style tool, where the cable bolt is sheared fully in the steel frame (see Figure 1). Crushing of the rock will enable a cable bolt to bend and subsequently load in both shear and tension; hence, the British Standard methodology using steel pipe is inappropriate and may be misleading.

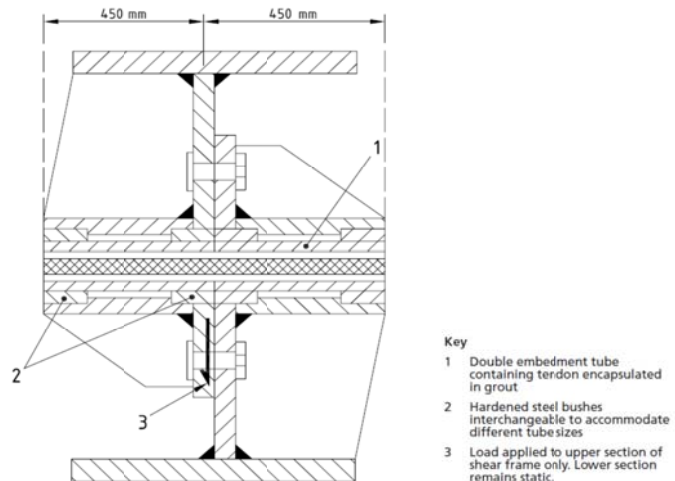


Figure 1: Sectional diagram of double embedment shear frame with the unit being tested (BS 7861-2: 2009)

With Australia having the largest variation of high capacity, pre-tensioned and post-grouted cable bolts in the world, there exist a minimum of literature on shear testing of these products using a recognised shear testing methodology. While pull testing of cable bolts can be practiced both in the field and in the laboratory, testing of cable bolts in shear is normally carried out in the laboratory. The difficulty of monitoring shearing process in holes drilled in the ground formation in remote location renders testing in the field an inconvenient approach.

Further, Aziz *et al.*, (2014) carried out a comparative study on 22 mm diameter plain and indented wire cable bolts, as the cable bolt surface indentation remains an issue of concern, particularly in shear. The study indicated that shear properties of indented wire cables were inferior to plain wire cables of the same type. The indentation appeared to cause a reduction in the cable strand cross section, leading to the loss of strength (see Figure 2), including the failure in shear initiated at the indent. The three types of cable tested to date included hollow plain wire, PC plain wire and PC indented wire. Thomas (2012) reported on laboratory axial pull tests of all the Australian cable bolts on the market including the design variables of bulbs, nutcages (birdcages), hollow, PC, multi-strand, indented and plain wires. It was requested of manufacturers to provide shear performance of cable bolts with these multiple variables, and Jennmar proceeded to test their cable bolts at the University of Wollongong. The University has since expanded upon the laboratory tests to include mathematical modelling of the cable bolt behaviour in shear.

EXPERIMENTAL STUDY

A total of six different cables were subjected to double shear testing in 40 MPa concrete. Figure 3 shows the schematic view of various cables as assembled in concrete blocks. Each double shear testing process requires three concrete blocks with two outer 300 mm side cubes and a central rectangular block 450 mm long. The casting of the concrete blocks can be carried out either in a specially prepared plywood mould or directly in the confining steel frame of the double shear apparatus. A plastic conduit 20 mm in diameter, set through the centre of the mould lengthways, will create a centralised hole for cable installation in the concrete blocks. Once the concrete blocks are allowed to set, and the plastic conduit is taken out, the hole in each block hole is reamed to the desired diameter. The concrete blocks are left immersed in a concrete curing solution to cure for a minimum period of 28 days.

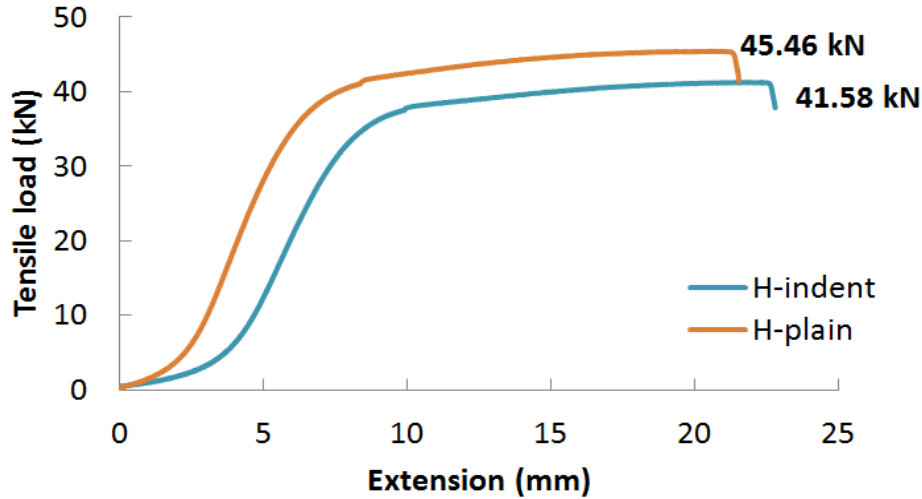


Figure 2: Tensile load / elongation profiles of both plain and indented 5.5 mm wire from cable bolts

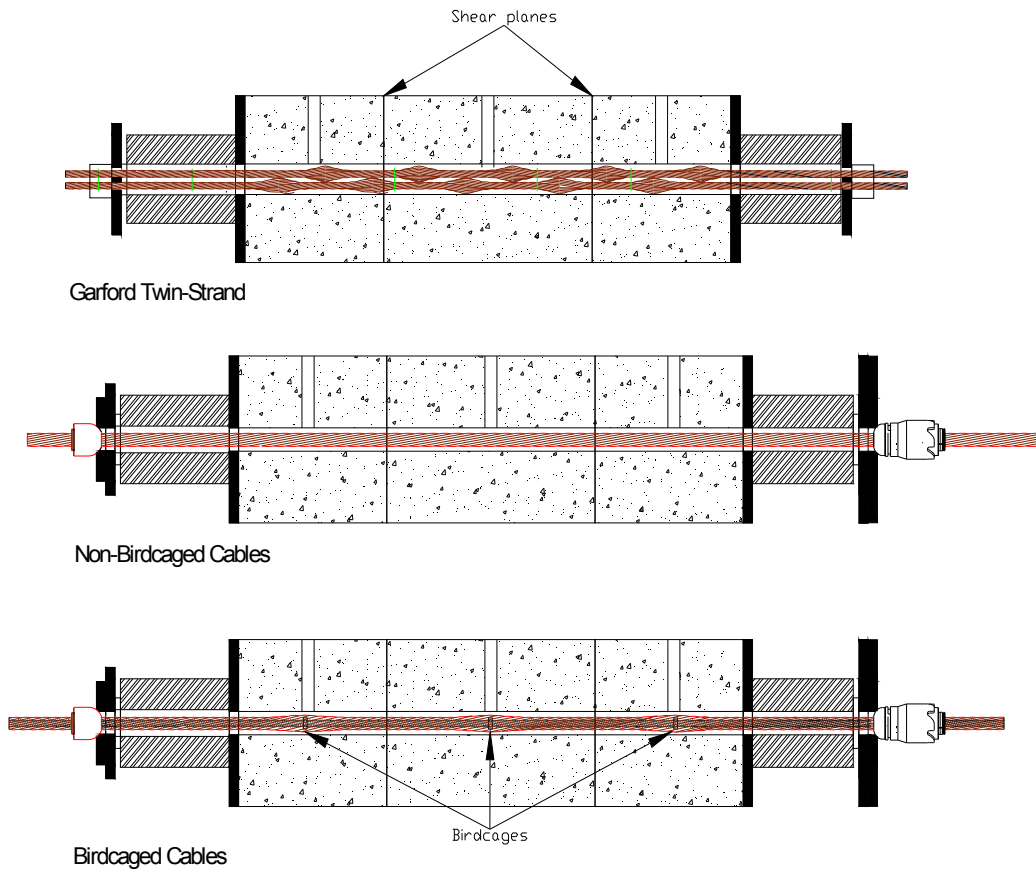


Figure 3: Cross section of double shear blocks and cables

The cured blocks are then mounted in the double shear confining steel frames and the cable bolt specimen placed into the borehole. Two 60 t load cells were inserted onto each end of the cable followed by the typical cable bolt end fitting. The load cells were connected to the data logger during tensioning. Once the cable is pretensioned, the grout is injected to the annulus between the cable and borehole through the intersecting small holes on top of the block. Cables with hollow central tubes were also filled with grout, and the grout or polyester resin left to cure for at least 7 days. The top of the concrete blocks are covered by the bolted steel plates and the whole assembly is then mounted on the carried base platform. The whole double shear assembly and the base frame is then mounted on to the 500 t compression testing machine for shearing process as shown in Figure 4.

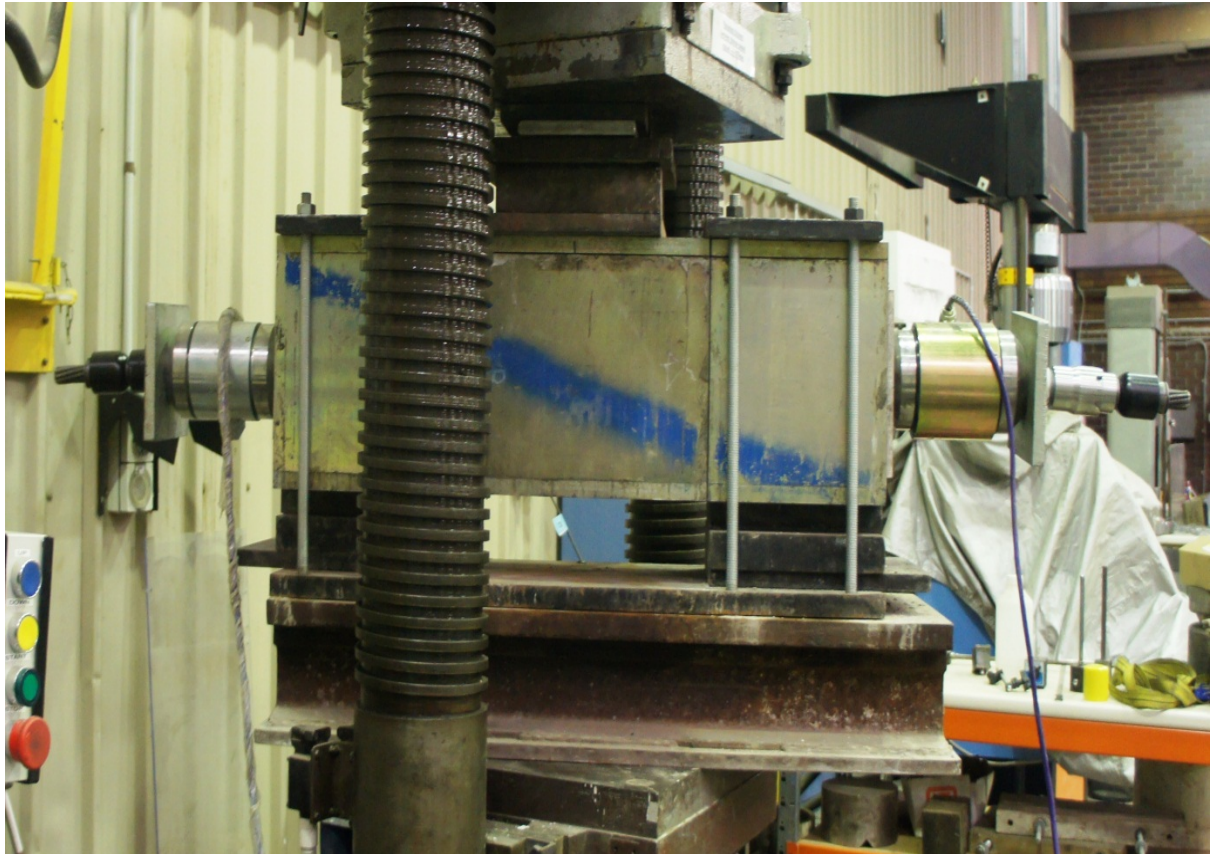


Figure 4: Arrangement of shearing apparatus on compression machine

The properties of the eight different cable bolts are described in Table 1. The study focussed on the main cables in the market as supplied by Jennmar, with indented wire hollow cable included for additional research. Cables were subjected to three different values of initial axial load ranging from 0 to 25 t. Three types of bonding agent were used in this particular study; Jennmar bottom-up grout (BU100), Jennmar top-down grout (TD80) and J-Lok standard oil based resin. The values of shear and axial loads versus shear displacement were monitored and recorded. The shear and axial stresses were calculated using following equations:

$$\sigma_n = \frac{N}{CA} \quad (1)$$

$$\tau = \frac{0.9 \times S}{2 \times CA} \quad (2)$$

where, σ_n is the normal stress, N is the normal load, CA is cable area, τ is the shear stress and S is the shear load.

It is noted that 10% of the shear load was ascribed to the rubbing of concrete surfaces and therefore 90% of the measured shear load incorporated as shown in Equation (2) in calculating the value of shear stress. The rubbing of concrete surface was evaluated by painting the concrete surfaces in checkered pattern before shearing. The damaged pattern on concrete surfaces was then carefully examined after dismantling the double shear apparatus. Figure 5 shows a typical checkered sheared face, which clearly shows approximately the percentage part of the surface damage during the shear process. Due to the significant stiffness of the cable, it is therefore rational to postulate that the shear load almost concentrates on the cable cross sectional area rather than on the concrete surfaces.

The process of double shear testing consists of loading the central block vertically in the 500 t compression testing machine (Figure 4). The 450 mm long middle section of the double shear apparatus is then vertically shear loaded at the rate of 1 mm/min for the maximum 100 mm vertical displacement.

The rate of loading and displacement are monitored and simultaneously displayed visually on a PC monitor.

Table 2: list of tested cables and the test environment

Test No.	Cable Bolt Properties					Drill bit (mm)	Bonding agent	Pre-tension load (t)	Peak shear load (kN) [½ double shear]
	Product name	Cable ϕ (mm)	Wire geometry	Cable cross-section	Cable geometry				
1	Twin-strand	15.2	Plain	2 x 7 wire, PC strand	25mm Bulbs	55	BU100 Grout	0	501
2	Indented TG	28	Indented	9 wires, hollow centre	Non-birdcaged	42	TD80 Grout	25	604
3	SUMO	28	Plain	9 wires, hollow centre	35mm birdcage	42	TD80 Grout	10	659
4	SUMO	28	Plain	9 wires, hollow centre	35mm birdcage	42	TD80 Grout	25	711
5	Indented SUMO	28	Indented	9 wires, hollow centre	35mm birdcage	42	TD80 Grout	10	488
6	Indented SUMO	28	Indented	9 wires, hollow centre	35mm birdcage	42	TD80 Grout	25	414
7	Superstrand	21.8	Plain	19 wire, PC strand	Non-birdcaged	28	Oil based resin	25	628
8	Indented Superstrand	21.8	Indented	19 wire, PC strand	Non-birdcaged	28	Oil based resin	25	558



Figure 5: A typical concrete block surface after shearing

MATHEMATICAL MODELING

The mathematical model was developed by assuming the linear Mohr-Coulomb relationship between the shear and normal stresses as (in below equation, surface roughness has been omitted):

$$\tau - \sigma_n \tan(\varphi) - c = 0 \quad (3)$$

where, φ is the friction angle and c is the cohesion.

The Fourier series concept as described below is applied to replicate the variation of normal stress against shear displacement. Fourier series is a mathematical technique incorporated to solve a large variety of engineering problems mainly adopting the principle of superposition:

$$\sigma_n = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[a_n \cos\left(\frac{2n\pi u}{T}\right) + b_n \sin\left(\frac{2n\pi u}{T}\right) \right] \quad (4a)$$

$$a_n = \frac{2}{T} \int_0^T \sigma_n \cos\left(\frac{2n\pi u}{T}\right) du \quad (4b)$$

$$b_n = \frac{2}{T} \int_0^T \sigma_n \sin\left(\frac{2n\pi u}{T}\right) du \quad (4c)$$

where, a_n and b_n are Fourier coefficients, n is the number of Fourier coefficient, u is the shear displacement and T is the shearing length.

Introducing Equations (4a, b, and c) in equation (3) by considering a_0 to a_3 , the shear strength is obtained as:

$$\tau = \left(\frac{a_0}{2} + \sum_{n=1}^3 \left[a_n \cos\left(\frac{2n\pi u}{T}\right) \right] \right) \tan(\varphi) + c \quad (5)$$

The shear displacement at peak shear strength is determined by taking derivation of the above relationship respect to the shear displacement and equating to zero as:

$$\frac{d \left\langle \frac{a_0}{2} + \sum_{n=1}^3 \left[a_n \cos\left(\frac{2n\pi u}{T}\right) \right] \right\rangle \tan(\varphi) + c}{du} = 0 \quad (6)$$

Thus, the peak shear displacement at peak shear strength (u_p) is obtained as:

$$u_p = \frac{T}{2\pi} \cos^{-1} \left[\frac{-4a_2 + \sqrt{16a_2^2 - 48a_1a_3 + 432a_3^2}}{24a_3} \right] \quad (7)$$

Introducing equation (7) in equation (5), the peak shear strength (τ_p) is proposed as:

$$\tau_p = \left(\frac{a_0}{2} + \sum_{n=1}^3 \left[a_n \cos\left(\frac{2n\pi \frac{T}{2\pi} \cos^{-1} \left[\frac{-4a_2 + \sqrt{16a_2^2 - 48a_1a_3 + 432a_3^2}}{24a_3} \right]}{T} \right) \right] \right) \tan(\varphi) + c \quad (8)$$

The model coefficients including Fourier coefficients (a_n), cohesion (C) and angle of friction (φ) were determined according to the measured data for various conditions of cable type and pre-tension as listed in Table 2. Generally, the values of Fourier coefficients showed a decreasing trend with the increasing the number of Fourier coefficients.

RESULTS AND ANALYSIS

Figures 6 to 13 show the shear stress and axial stress profiles against shear displacement for the tests conducted in this study. The initial changes in some of the shear stress graphs after the elastic state may be related to the barrel/wedge settlement as the cable ends begins to take axial load due to cable bending at the shear planes. Various shear drops beyond the peak value are attributed to individual cable strand failures. The larger shear drop corresponds to the higher diameter strand failure while the smaller ones are due to the small strand failures. It is of interest to note that the number of visible sudden drops in stress upon shear displacement is equal or slightly less than the number of failed strand, which might be due to two strands snapping near the same time. The strand failure in the cable at the shear plane was also observed as load drop at the load cells measuring axial load near the end fittings. Figure 14 shows snapped strands of the tested cables. It is obvious that the failures of strands in the cable is a mix of tensile and shear, depending on the location of the strand in the cable cross-section, the direction of the shearing and cable construction. For multiple mixed wire diameter cables of the superstrand cable, it was observed that smaller diameter strands of the inner layer appears to fail in tension with con and cup pattern (Aziz *et al.*, 2014 a, b).

Table 2: Model coefficients for different types

Test number	a_0	a_1	a_2	a_3	C (GPa)	φ (°)
1	0.63	-0.42	0.11	-0.012	0.32	44.72
2	2.51	-0.266	-0.06	0.07	0.03	51.59
3	1.56	-0.47	0.06	-0.01	0.22	53.47
4	2.06	0.01	-0.29	0.21	0.26	56.83
5	1.36	-0.11	-0.26	0.16	0.18	55.23
6	2.09	0.45	-0.19	-0.02	0.37	44.71
7	2.15	-0.05	-0.25	0.23	0.36	47.21
8	2.63	-0.24	-0.13	0.09	0.21	47.21

Table 3 summarises the peak shear strength of the different cable bolt and testing configurations. It is obvious from the results that the plain wire birdcaged cables had higher shear strength when compared to the indented wire birdcaged cables. The shear performance of non-birdcaged superstrand and hollow TG cable was lower when wires were indented, but the shear strength was still close to the UTS (Uniaxial Tensile Strength) of the cable bolts.

The lower shear behavior of the indented wire of the same cable type was likely attributed to the fact that the indented wires have a small cross section and the indent geometry forms a stress raiser to initiate failure. The indented wire cable bolts display lower deflection (stiffer) than the plain wire equivalent type. No cable rotation was observed in either the plain or indented strand cable bolts during the double shearing tests. As can be seen from Figure 15, the shear strength of cable bolted concrete block subjected to shearing can be represented reasonably by the proposed model for different initial pretension stresses, bonding agents and cable bolts.

In order to compare the method of double shearing used in this study with single shear test of British Standard, Superstrand cables both indented and plane ones were also sheared as suggested by British Standards (2009). Figure 16 shows the comparison between the shear load against shear displacement using double shear and single shear test methods. It is inferred that the single shear testing method significantly underestimates the shear strength of Super strand cable bolts. The conspicuous difference between the value of shear load in single shear and double shear tests can be related to the fact that the single shear test is only a metal to metal shearing and does not carry any pretension or axial load during shearing. Thus, all the strands only experience shear failure without having any tension failure as

observed in double shearing and shown in Figure 14. Nevertheless, in the process of double shearing, the initial pretension value is subjected to the cable before shearing and increases upon shearing due to the cable deformation. This profoundly increases the strength at which cables can resist against shearing and simulate properly the field conditions.

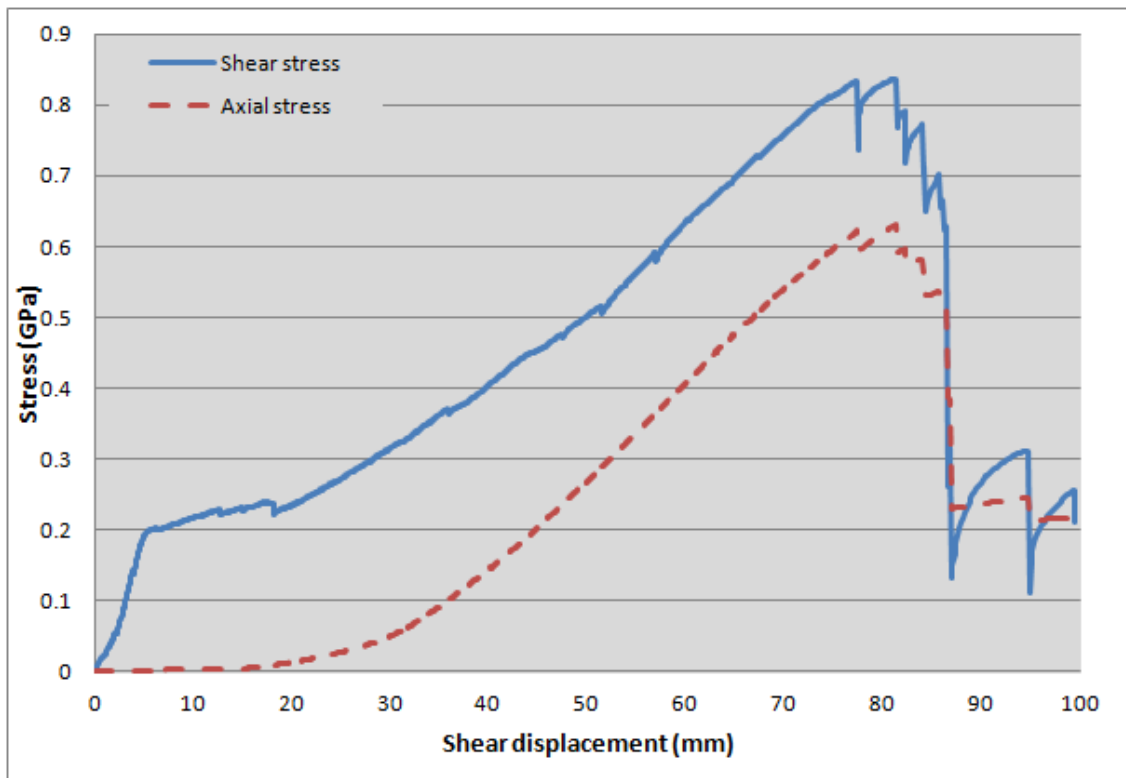


Figure 6: Shear behaviour of cabled concrete [test 1]

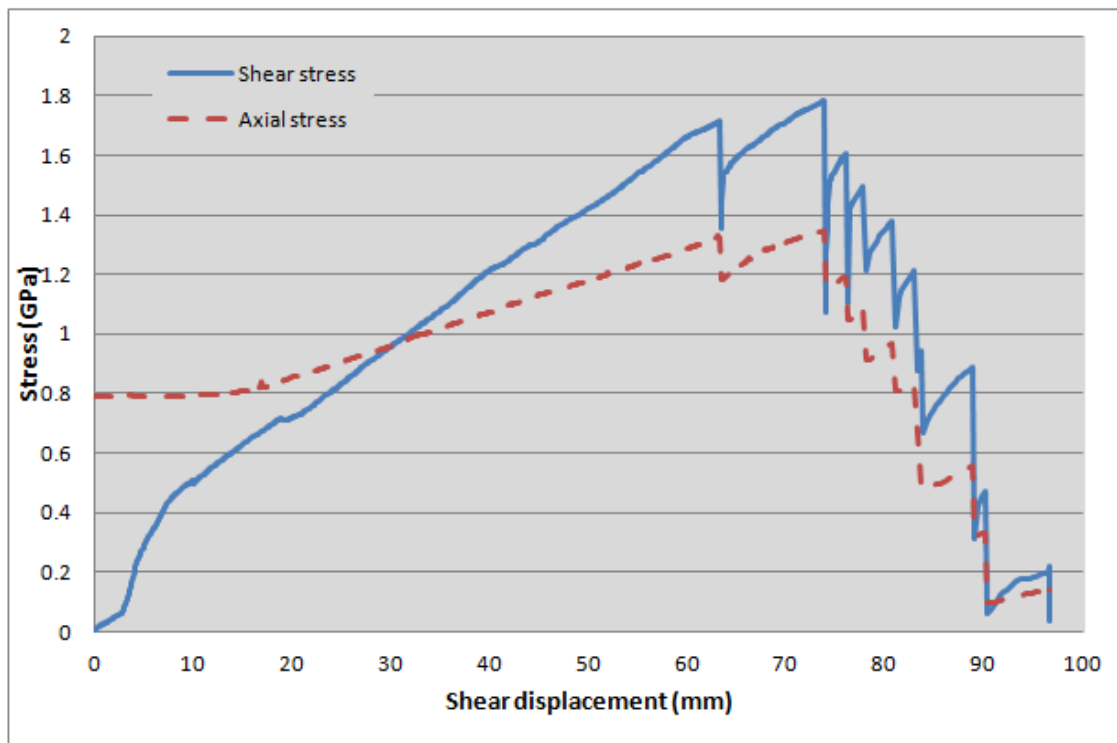


Figure 7: Shear behaviour of cabled concrete [test 2]

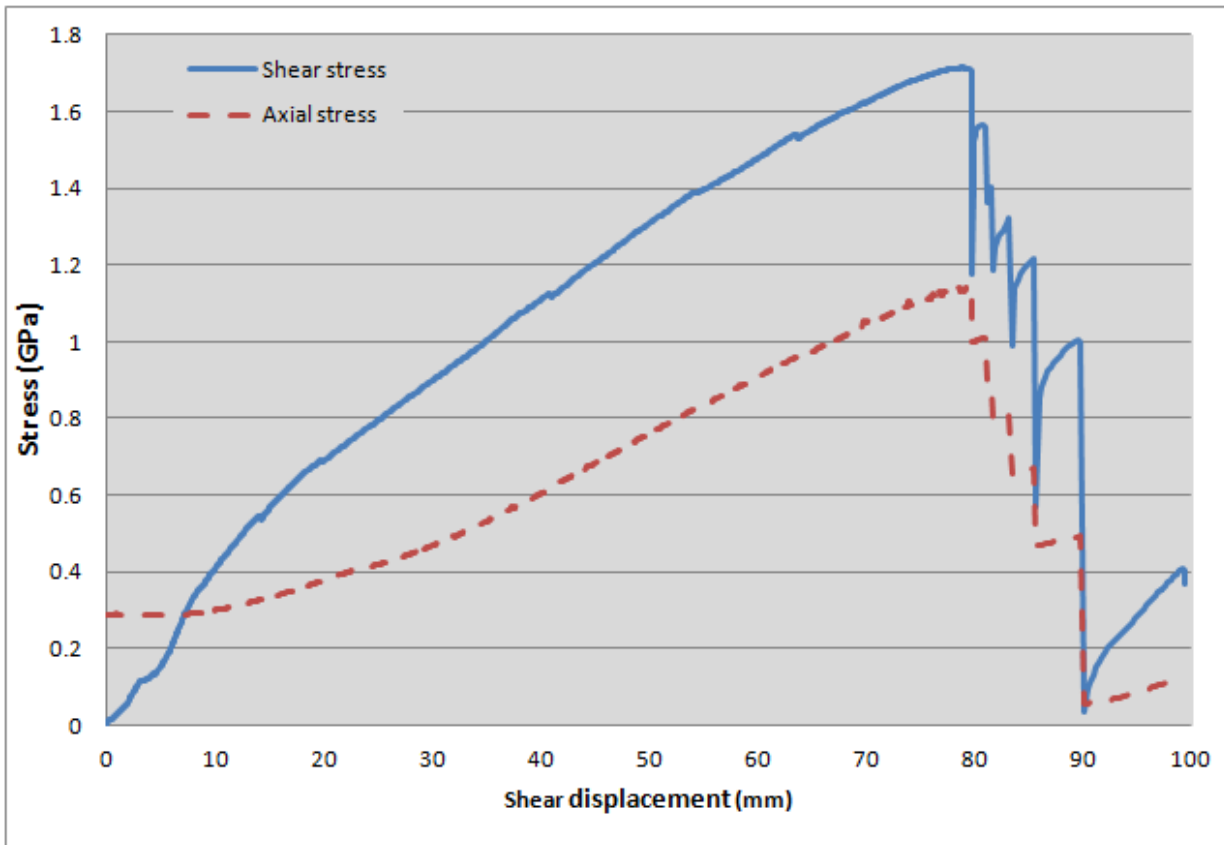


Figure 8: Shear behaviour of cabled concrete [test 3]

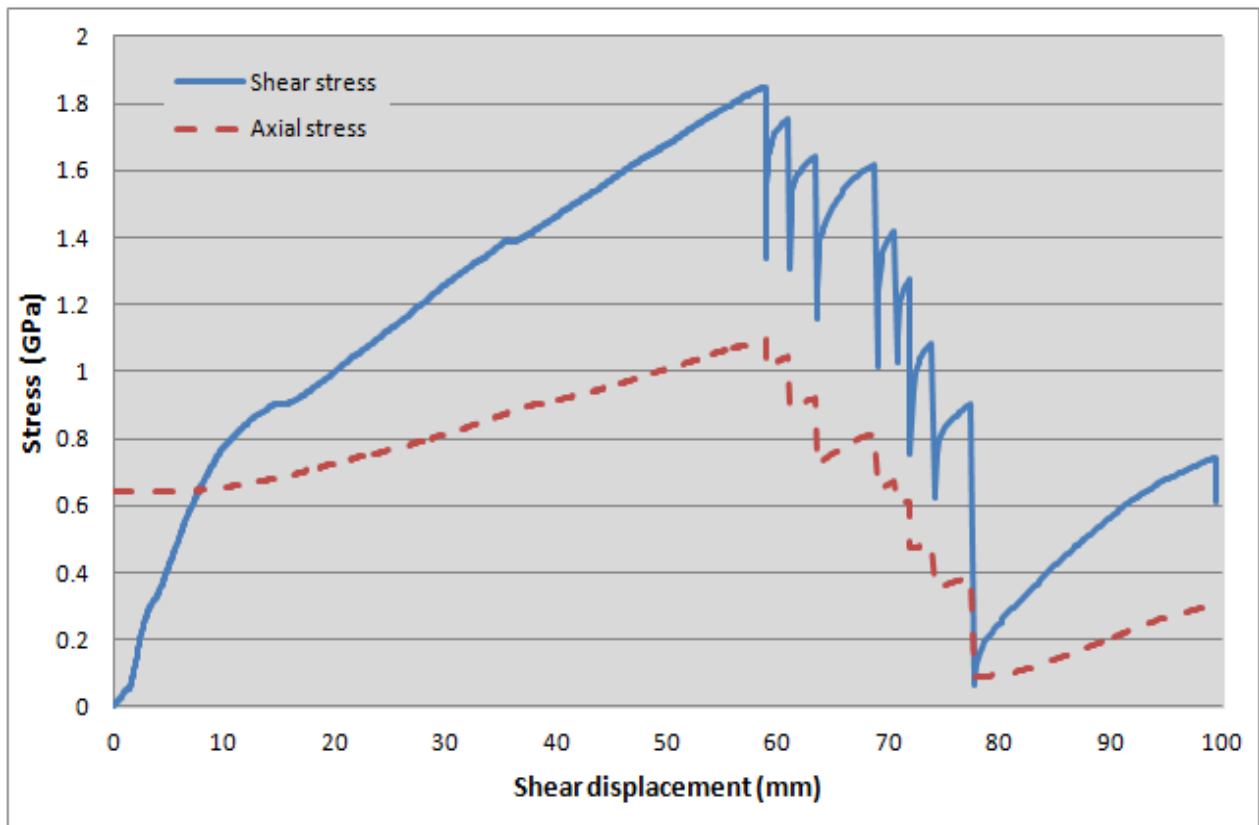


Figure 9: Shear behaviour of cabled concrete [test 4]

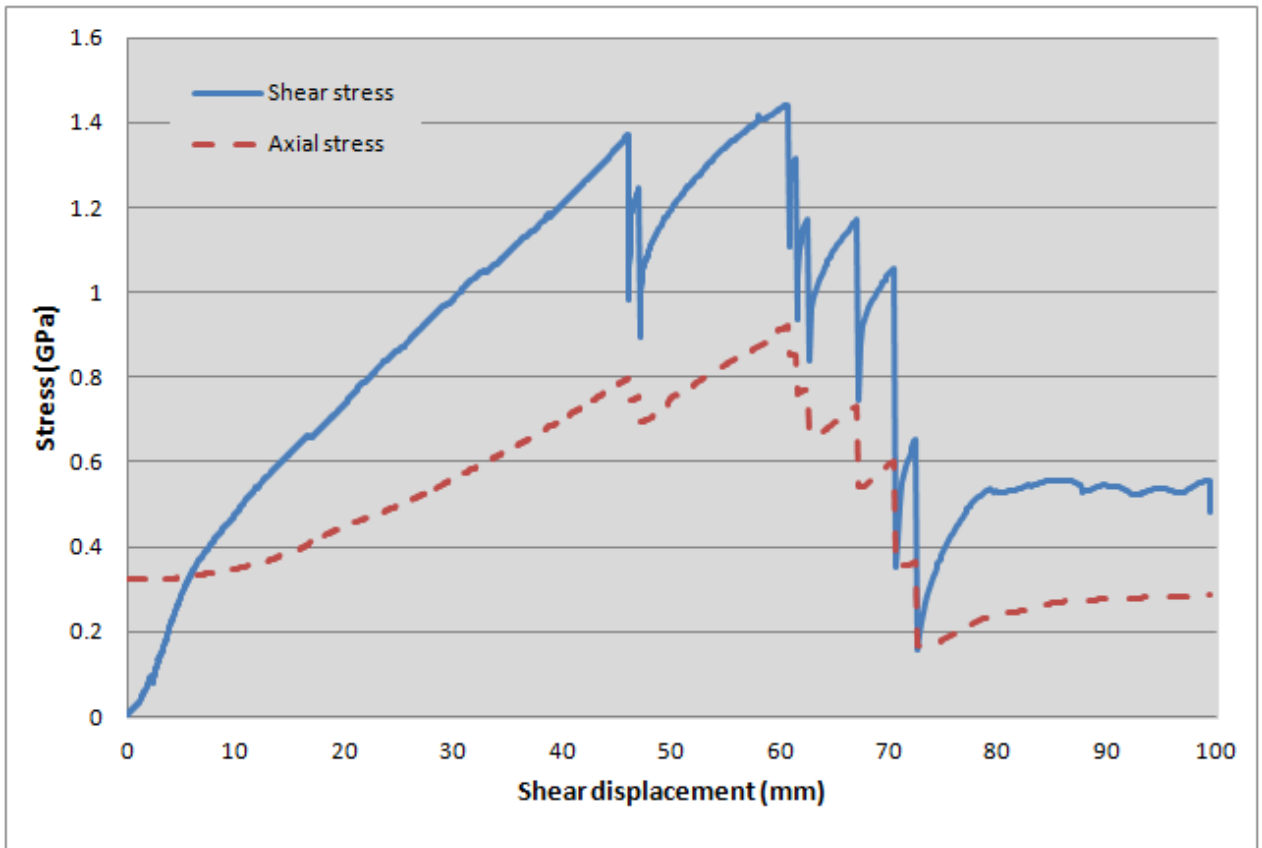


Figure 10: Shear behaviour of cabled concrete [test 5]

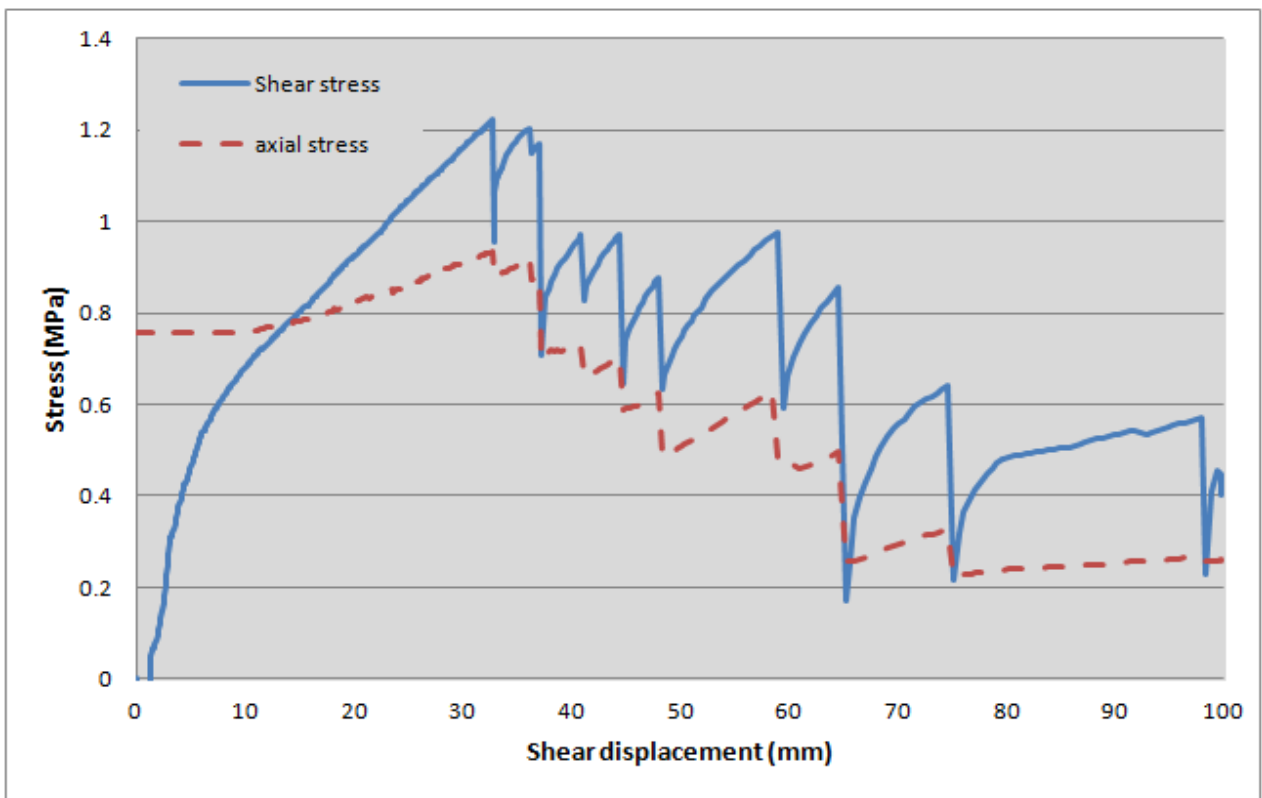


Figure 11: Shear behaviour of cabled concrete [test 6]

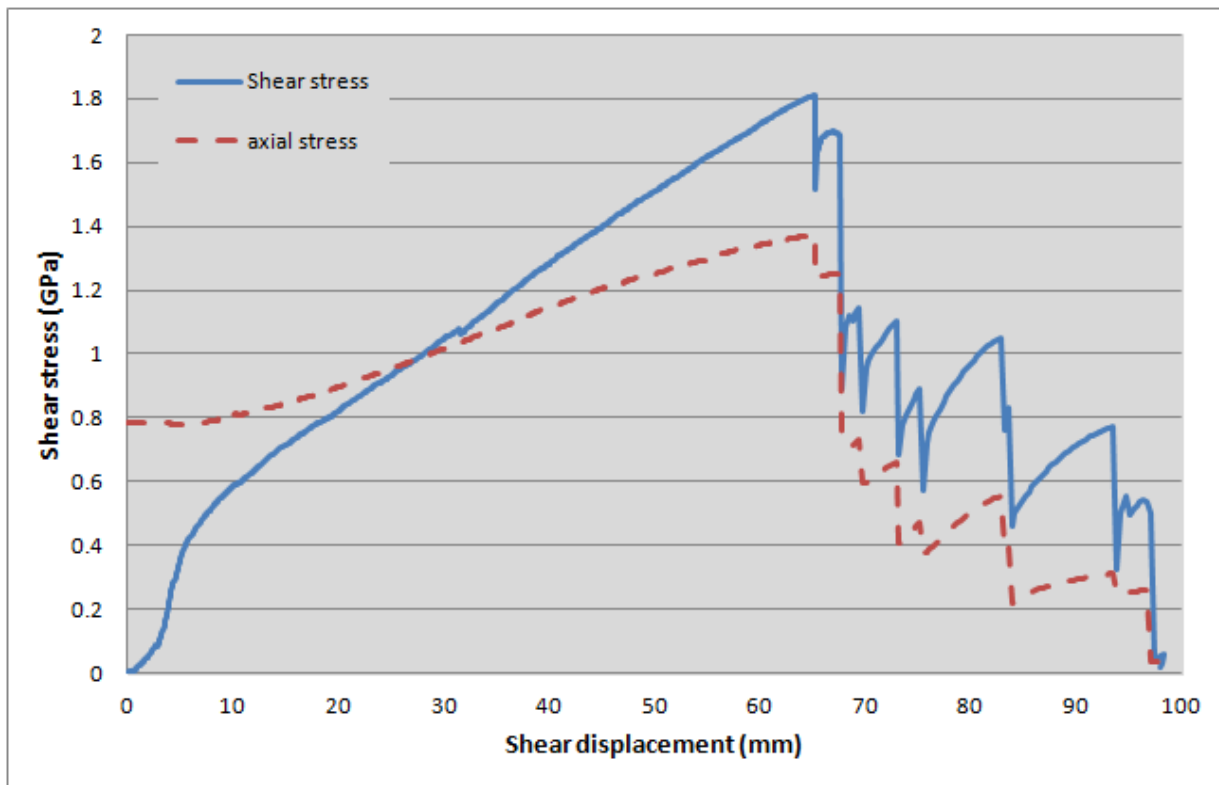


Figure 12: Shear behaviour of cabled concrete [test 7]

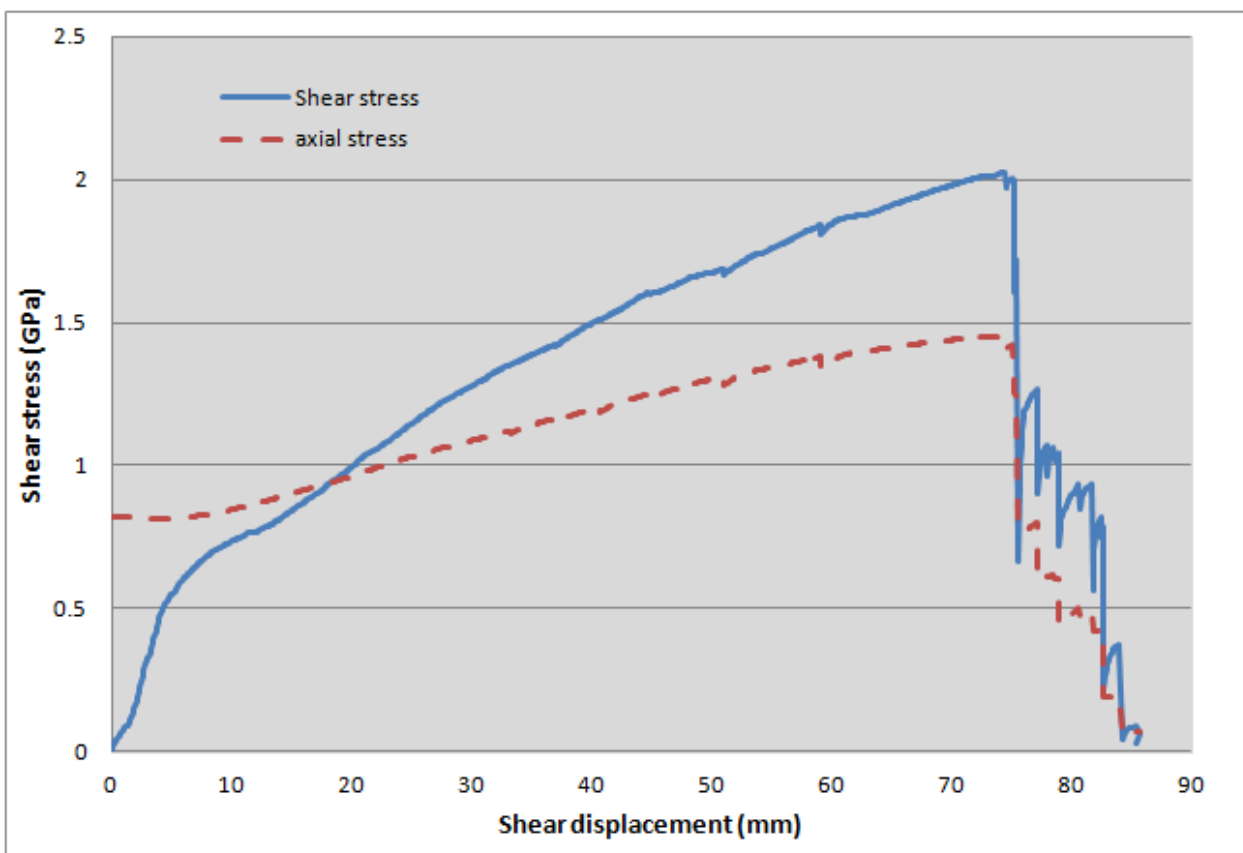


Figure 13: Shear behaviour of cabled concrete [test 8]

Table 3: Peak shear stress for different cabled concrete blocks

Test number	Peak shear stress per surface (GPa)
1	0.84
2	1.79
3	1.71
4	1.85
5	1.44
6	1.22
7	1.81
8	2.02



Figure 14: strands snapped of the tested cables

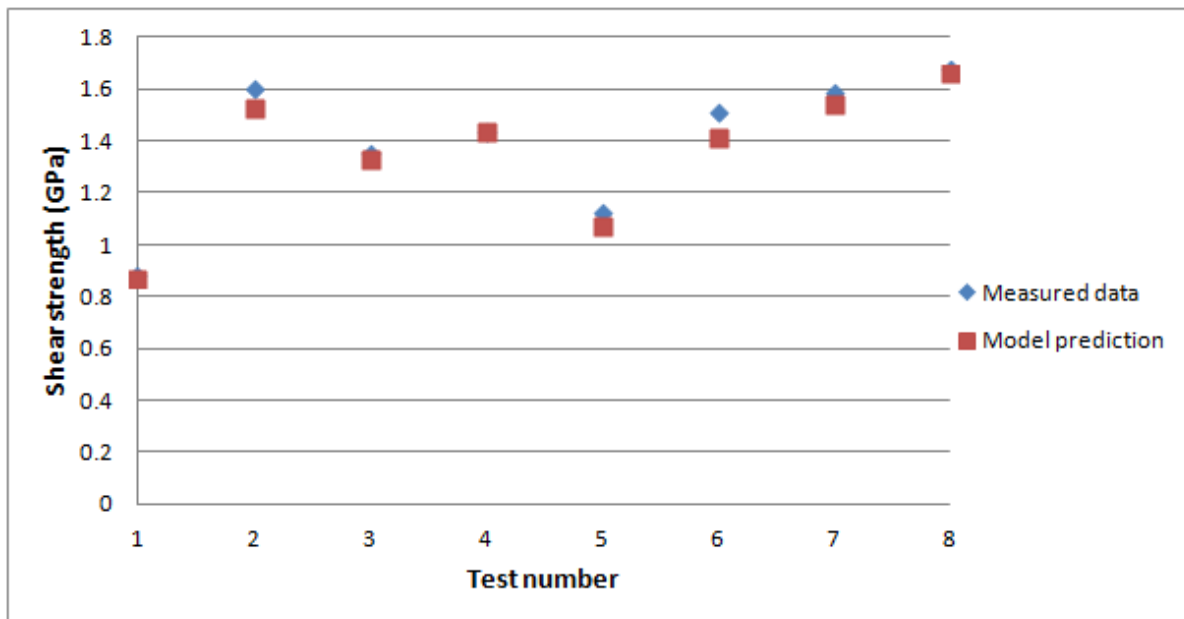


Figure 15: Comparison between the model results and measured data

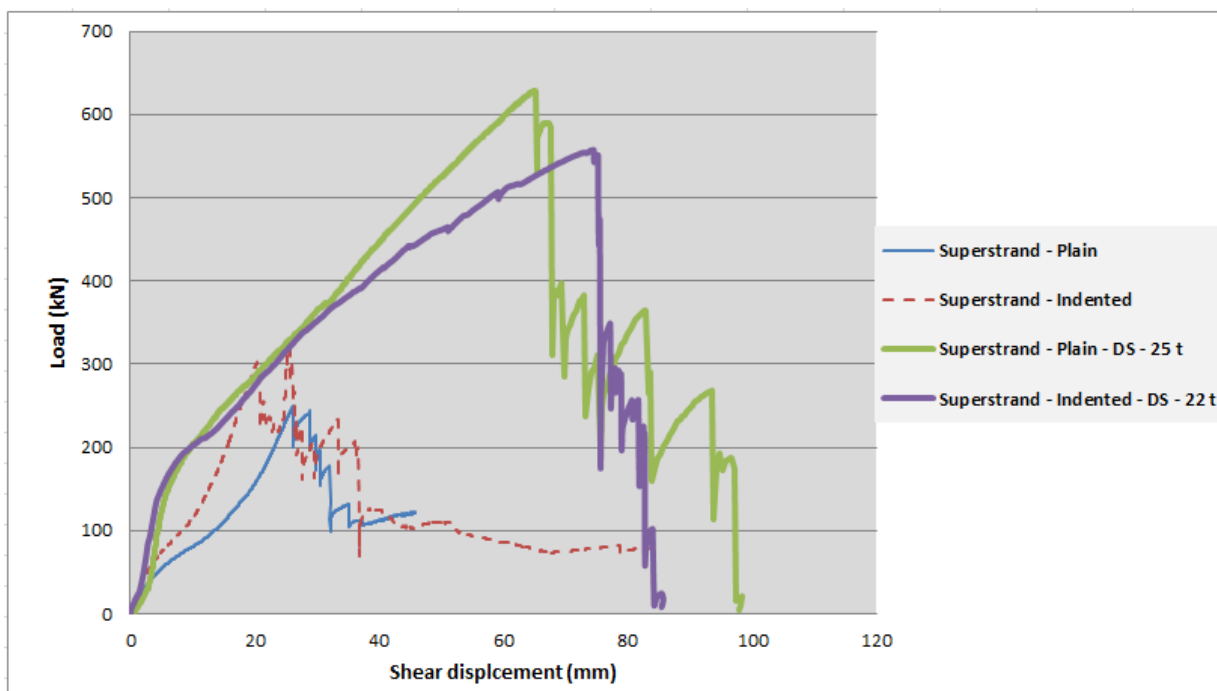


Figure 16: Comparison between the double and single shear methods

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn from this investigation:

- Indented wire combined with birdcaging of cable bolts is detrimental to the cable shear performance.
- Shear strength of non-birdcaged cables bolts are less affected by indentation of the wire.
- It is likely that the reduced cross-section reduces tensile strength and the geometry forms a stress raiser to initiate failure.
- A mathematical model was proposed incorporating Mohr-Coulomb failure criterion and Fourier series concept to simulate the shear strength of cabled concrete blocks.
- The values of Fourier coefficients decreased as the number of Fourier coefficients increased.

Recommendations include:

- a) Due attention must be given to the study of the cable shear across closed and interlocking sheared beds as well as across separated beds with no contacts between sheared faces.
- b) More experiments are suggested to calibrate the model for practical purposes.
- c) The double shear method in simulated rock has proven to provide valuable insight into in-situ performance. The British Standard BS 7861 (part 2)* cannot be applied to the study of shear behaviour of the cable bolt in rock. The equipment used in the BS 7861 (part 2) is a guillotine style tool, where the cable bolt is sheared fully in the steel frame. Shearing of the cable bolt in rock normally undergoes both shear and tension; hence, the British standard methodology is inappropriate and may be misleading.

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