Enlightening Bolts: Using Distributed Optical Sensing to Measure the Strain Profile along Fully Grouted Rock Bolts

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INTRODUCTION

Over the last 30 years, a transition away from end-anchored bolts to fully grouted rock bolt systems has occurred in many underground mines. It seems geomechanically intuitive that the success of such bolts, which interfere with rock movements around underground excavations through a variety of complex interactions, is precisely why they remain challenging to instrument and monitor. Whereas measuring the load profile for an end-anchored mechanical bolt is trivial, for a fully grouted system, the load may vary dramatically due to discrete rock movement at cracks and joints.

Despite the challenges, measuring the strain (i.e., load) along fully grouted rock bolts remains very appealing, and a lot of valuable research has been conducted using foil resistance strain gauges, particularly in US coal mines (Signer and Jones, 1990). Despite good intentions, more widespread adoption of this instrumentation remains unlikely for the following reasons:

(i) The technology is expensive, partly because Intrinsically Safe (IS) requirements limit the number of suppliers and solutions.
(ii) The technology is perceived as challenging to successfully implement except by those who are skilled in the art.
(iii) The reliability of the technology is questionable in harsh environments.
(iv) The technology relies on discrete pairs of strain gauges that may not capture the complete strain distribution along the bolt.

No existing alternative technology can offer a solution to all of these limitations. However, in this paper, we introduce results from a new Distributed Optical Sensing technology that promises significant potential. Since the technology is capable of distributed sensing, our results suggest that this new technology can, for the first time, reveal the detailed strain profile along fully grouted rock bolts.

SOURCES OF STRAIN IN FULLY GROUTED ROCK BOLTS

The strain developed in a rock bolt results from a superposition of the torque applied to the bolt during installation (Active Load) and the load induced by ground movements during the life cycle of the bolt (Passive Load). It is important that the new technology be able to monitor the complete range of loading modes.

Active Bolt Loading

Almost all rock bolts are installed by a rock drill that secures the bolt into the hole by applying torsion to the bolt. This torque may be used to (i) simply mix a single speed resin cartridge, in which case it may be dissipated, (ii) tighten an expansion shell to provide tension while the resin sets (Double Lock), or (iii) mix a fast resin cartridge at the toe and then torque the bolt to apply tension to the remainder of the bolt (Torque Lock). For (ii) and (iii), a proportion of the applied torque will reside in the bolt and may remain throughout the bolt lifecycle. The corresponding axial load associated with the applied torque during installation is a function of the tension-torque ratio, which depends on factors such as the specifications and properties of the bolt, the plate and the nut assembly, and whether or not they are properly lubricated (Osen and Parsons, 1966).

Due to their high length/diameter ratio, rock bolts are prone to bending during installation. Whereas end anchored rock bolts can bend throughout the life-cycle of the bolt, for fully grouted bolts, it is restricted after the resin has set. However, bending during installation is common for all bolts; in fact, even when appropriate hardware is used, it is almost ubiquitous for bolts that are installed in holes obliquely oriented to the excavation surface.

Passive Bolt Loading Caused by Rock Movement

After installation, the increases in rock bolt loads result from movements in the rock mass that are transferred to the rock bolt through the grout annulus. Windsor (2004) recognized that load transfer involves the following three mechanisms:

(i) rock movement, which induces load transfer from the unstable rock to the reinforcing element

(ii) transfer of load through the reinforcing element from the unstable zone to a stable zone
(iii) transfer of the reinforcing element load to the stable rock mass

Depending on the rock mass characteristics and the stress state around the excavation, rock movements may be either distributed or discrete. It is well documented in the literature (Freeman, 1978; Aydan, 1989; Hyett, Moosavi, and Bawden, 1994; Li and Stillborg, 1998) that each induces radically different strain profiles along a fully grouted bolt.

If these rock movements are coaxial with the bolt, axial loading results. For each increment of rock movement, the corresponding amount of load transferred to the bolt depends primarily on the stiffness of the grout annulus, which, in turn, depends on the material properties of the grout and the mechanical interlock between the grout and the profile of the deformed rebar. If the rock movements are transverse to the rock bolt, shear loading results. In blocky or stratified rock masses, shear deformations localized at joints and bedding planes induce a “dowel” response from the rock bolt (Ferrero, 1995). Numerical simulations (Jalalifar, 2006) suggest that the resultant strain profile may be highly variable.

Most commonly, rock bolts will be subjected to a combination of axial and shear loading, and, during the life cycle of the excavation, rock movements may transition from distributed to discrete as cracks and shear zones localize. Consequently, accurately monitoring the strain profile of fully grouted rock bolts could reveal as much about rock mass behavior around an excavation as about the rock bolts themselves.

DISTRIBUTED OPTICAL SENSING

Several methods are currently available for distributed strain sensing using optical fiber. These include techniques based on Raman, Brillouin, and Rayleigh scattering, as well as those involving multiplexed fiber Bragg gratings (FBGs). Techniques based on Brillouin scattering typically employ optical time domain reflectometry and are, thus, limited in spatial resolution to 0.1 to 1 m. FBG methods (optically analogous to strain gauges) are often limited by the number of gratings that can be multiplexed in a single fiber. Both FBG-based and scatter-based techniques also often require specialty optical fiber.

This paper introduces an emerging optical technology based on Rayleigh backscattering. This solution is attractive for monitoring fully grouted rock-bolts because of the following:

(i) The instruments are inherently IS certifiable and the readout unit can be set back 50m in fresh air.
(ii) The distributed strain profile using the Rayleigh technique is measured with a spatial resolution in the order of 5mm.
(iii) Its operational accuracy is perfectly acceptable (better than +/- 10 microstrain).
(iv) It is based on low-cost standard telecom fiber. The cost of the analyzer has dropped significantly in recent years.

Test Results

The test data presented below is designed to demonstrate the capabilities of the new technology with respect to the three modes of bolt deformation: bending, axial loading, and shear loading. It represents a due-diligence evaluation prior to underground field trials. The tests were conducted using a #6 grade 60 rebar supplied by Jennmar Canada Ltd. A pair of diametrically opposed grooves, 3mm wide x 3mm deep, was machined into the rebar (Figure 1). The strength of the modified bar was 116.1kN (yield) and 185.3kN (tensile). The fiber is only 100 microns in diameter so the possibility of smaller grooves exists. A 3.2m long optical fiber was positioned within the groove and encapsulated with a high strength epoxy resin. At the toe of the bolt (2.1m), the fiber was looped to enable monitoring of both grooves.

Figure 1. The diametrically opposed groves cut in the rebar samples.

Bending Tests

In view of the very low loads (<1kN) required, bending represents the most controlled method for establishing the baseline accuracy of the new distributed optical sensing technique. Two types of test were conducted: (i) Symmetric Simply Supported Beam bending test, and (ii) Cantilever Beam bending test.

The setup and results are shown in Figures 2 and 3. A single length of optical fiber was looped around so that both sides of the rebar are monitored; one side exhibits contraction(-ve) and the other extension(+ve). The lower graphs in Figures 2 and 3 are the corresponding theoretical simulations based on Euler–Bernoulli beam theory. The comparison is within +/- 5%, but, more remarkably, the shape of the two plots is essentially identical. This is important because, for fully grouted rebar, the shape of the strain profile could be more informative than the absolute strain magnitudes.

Axial Pull Tests

The setup, shown in Figure 4, was used to assess the capabilities of the technology to monitor axial deformation. The instrumented bolt was resin grouted into a 31mm reamed hole created in a concrete (40MPa mix) block. The embedment length was 200mm. Axial load was applied to the rebar at a distance of 900mm from the embedded section.

One general observation, when applying axial load to instrumented bolts, is that it was almost impossible to obtain perfect axial loading without some component of bending. At low axial loads, bending is associated with initial straightening of the rebar, which is, without exception, imperfectly straight. Slight realignments of the sample within the test frame resulted in quite different patterns of bending. In Figure 4, the effect of bending can

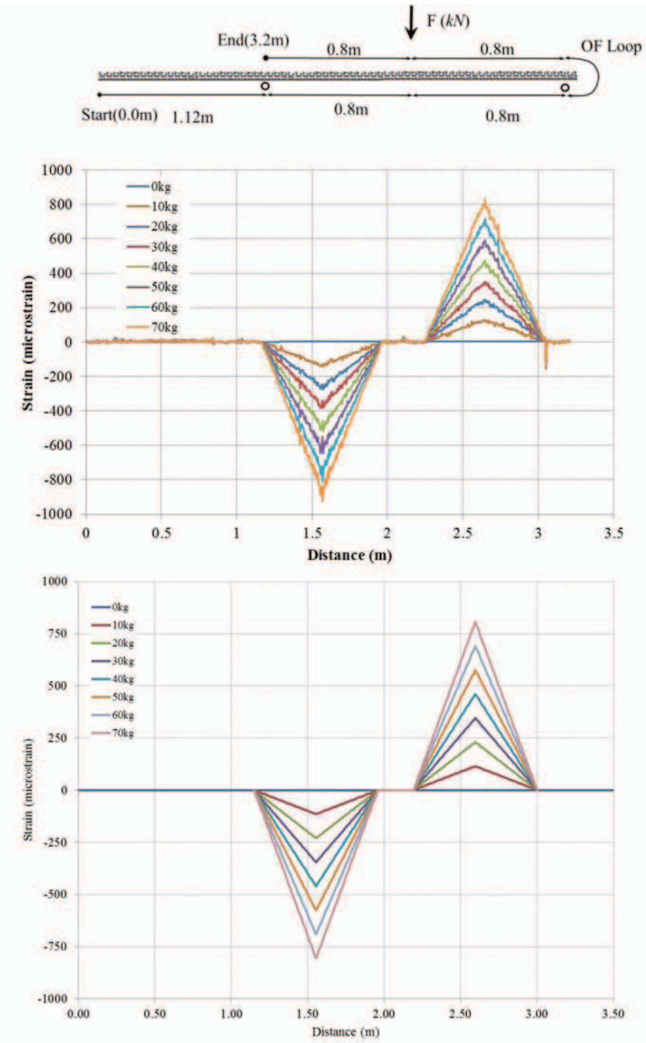

Figure 2. Simply supported beam test. Upper: Test configuration. Middle: Experimental resutls. Lower: Theoretical results (extension is +ve). 20 kg corresponds to a force of 196N.

clearly be seen by comparing the response of the fiber along the free lengths on opposing sides of the rebar (mirror image between 0.9-1.8m and 2.4-3.3m). These variations derive from limitations with the test setup rather than errors in the instrumentation technology. Our experimental experience strongly suggests that calibration of instrumented rebar may be more accurately accomplished under bending rather than axial load.

Figure 5 shows the detailed strain profile along the section grouted within the concrete block. As expected, the strain decays according to an exponential form predicted by theory (Farmer, 1975; Serbousek and Signer, 1987; Aydan, 1989). However, periodic disturbances in the profile are exhibited that seem to correspond with the spacing of the rebar ribs. Such an effect was simulated by Jalalifar (2006) using Finite Element modeling (Figure 6).

Figure 7 shows the displacement profile corresponding to the upper plot in Figure 5. At a given point (x=l) along the bar, this

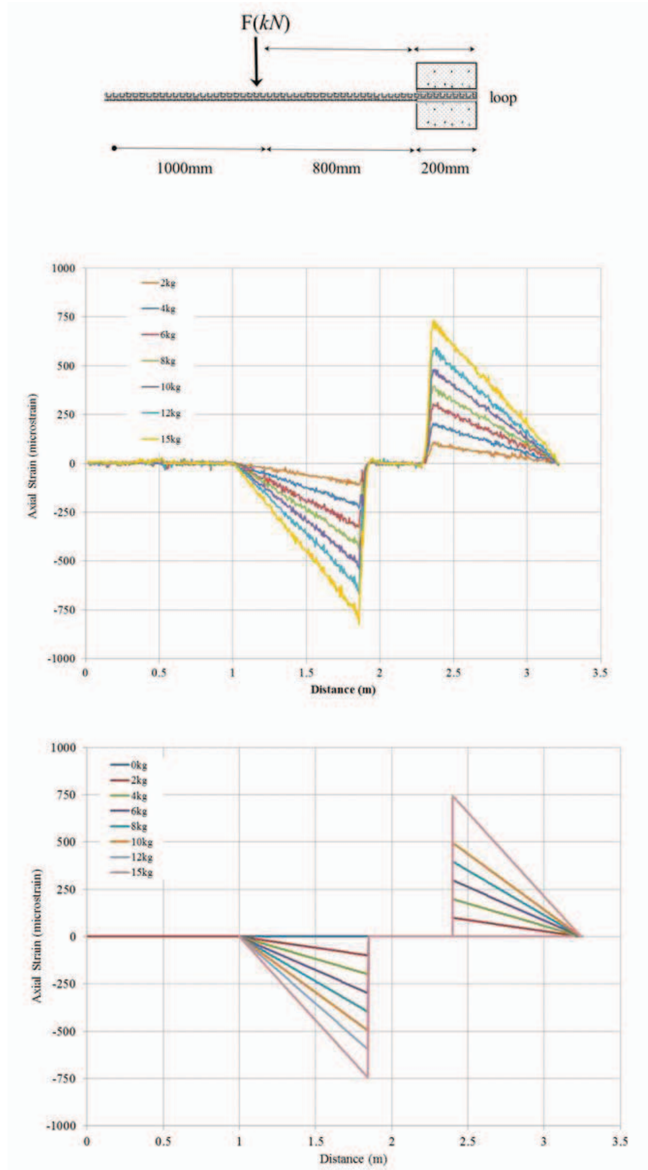

Figure 3. Cantilever beam test. Upper: Configuration. Experimental results. Lower: Theoretical results.

is calculated from the summation of the product of strain and measurement spacing (L_e):

$$U_{x=l} = \sum_{x=0}^{x=l} \varepsilon_x \ . L_e$$

The displacement distribution is exponential in form as predicted by the literature

Shear Tests—Double Shear Configuration

Shear behavior of the bolt was assessed using double shear tests in which an instrumented rebar was grouted into 3 blocks with pre-formed and reamed boreholes (31mm in diameter). The end of

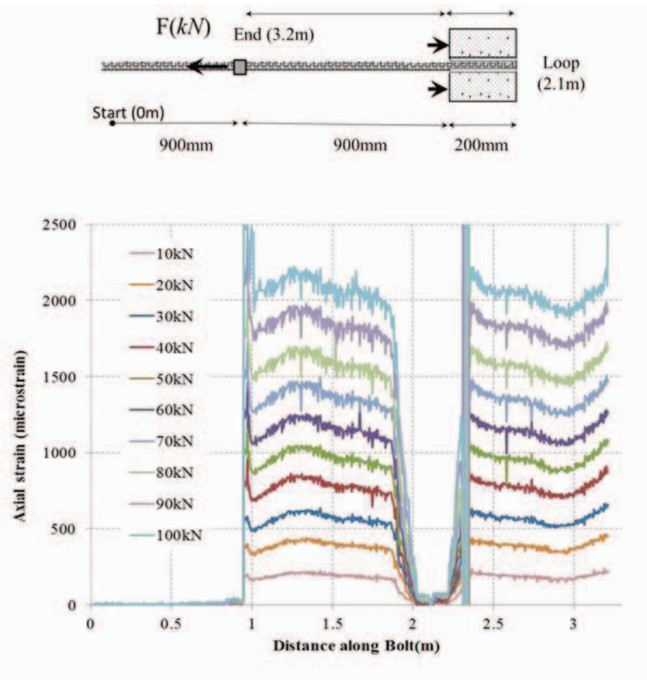

Figure 4. Axial pull test results. Upper: Configuration. Lower: strain profile along whole fiber length.

the rebar was un-tensioned. The configuration is shown in Figure 8 (upper). Dimensions relate to the position along the optical fiber. Load was applied to the sample using a test frame, and the displacement of the central block relative to the end blocks was monitored (Figure 9). The corresponding strain profiles along the rebar are shown in Figure 8 (middle and lower). A distinctive shear couplet across the discontinuity is measured, similar to that which was predicted by Finite Element modeling (Figure 10), conducted by Jalalifar (2006).

DISCUSSION

The laboratory results presented in this paper reveal, for the first time, the complexity related to load transfer along fully grouted rebar subjected to bending, axial loading, and shear deformation. Due to the high stiffness of resin grouted rebar, the loads can vary rapidly along the bolt length.

Perhaps the most "enlightening" application of the results is to provide a rationale for interpreting the results from previously used discrete monitoring solutions based on strain gauges.

Foil resistance strain gauges

As indicated by the results shown in Figures 4 and 8, a typical array of 10mm-long strain gauges with a 200mm gauge spacing may completely miss the initial strain development at a discrete fracture. Furthermore, it may be completely impossible to relate the measured strain profile along the bolt to the rock-mass structure around an excavation. It is entirely possible that what is often measured, as highly variable strain profile might well be reliable data, which is often dismissed as instrumentation scatter. The best chance of gaining acceptable results using standard strain

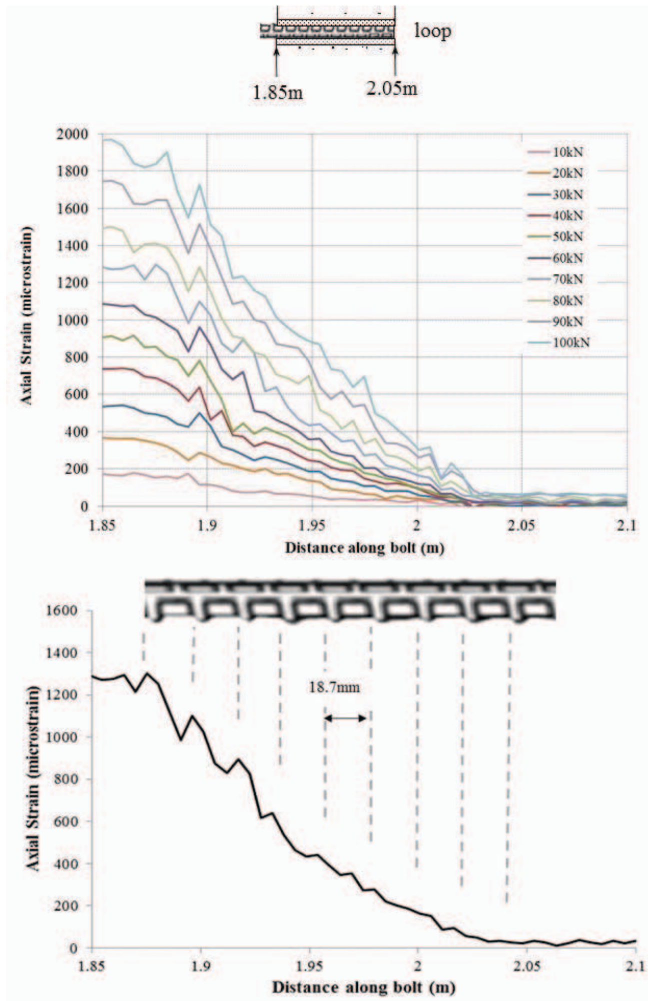

Figure 5. Detailed axial strain profile for the bonded section of the bolt (1.85m to 2.05m along the fiber. Upper: Change in strain profiles with the applied axial load. Lower: Detailed variation pf axial strain (at 70kN) related to rib geometry.

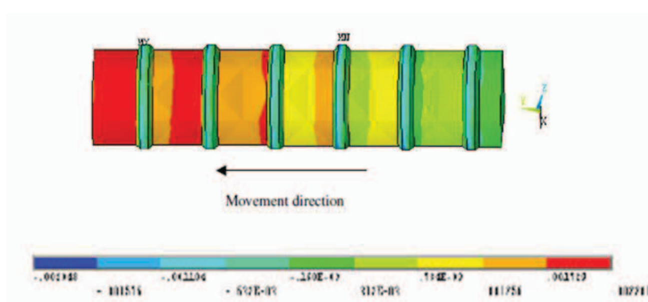

Figure 6. Simulation of the strain profile cause by ribbing using ANSYS FE program by Jalalifar(2006).

technology is when the rock mass behaves as a continuum: This is hardly surprising since the technology was originally designed for such problems.

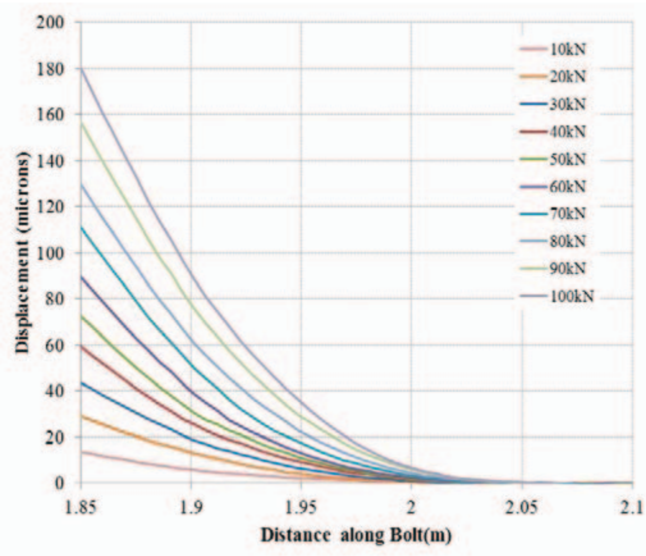

Figure 7. Experimental displacement profile based on integration of the strain profile in Figure 5(upper). Note: These are experimental results.

Long base-length strain gauges

The long base strain gauge monitoring system introduced by Spearing *et al.* (2012) represents an admission that the detailed strain distribution cannot be reliably or cost-effectively measured using electrical methods, and that, from an operational perspective, an average assessment of the bolt behavior will often be more informative. The results in Figure 8 confirm that long base-length strain gauges will effectively cancel out the shear couplet caused due to shear, and, therefore, these instruments can only provide insight into the axial response of the bolt.

If mines can be encouraged to embrace rock bolt monitoring as a means to improving excavation design, we suggest that measuring the strain profile should be the priority rather than accurately monitoring localized strains. Furthermore, since excavation geometries are 3-dimensional, the variation of the strain profile within a cluster of bolts will usually be more informative than the result for any single bolt. Consequently, the cost per instrumented bolt needs to be minimized, which is a feature of the technology introduced above, which is based on plain fiber.

As a final point, since the rock structure and deformation mechanisms are unknown a priori, distributed optical sensing technologies represent a perfect solution for geomechanical monitoring. However, if this technology is to be successfully applied, then protecting the optical fiber by embedding it with support elements undoubtedly provides the most promising deployment option. Thus, instrumented steel elements (i.e., rock bolts and cables) that are capable of distributed optical sensing should be regarded as an enhanced tool for the rock mass, as well as monitoring rock bolts themselves.

CONCLUSIONS

Embedment of fiber optic sensors with steel elements such as rock bolts represent the best opportunity to deploy distributed

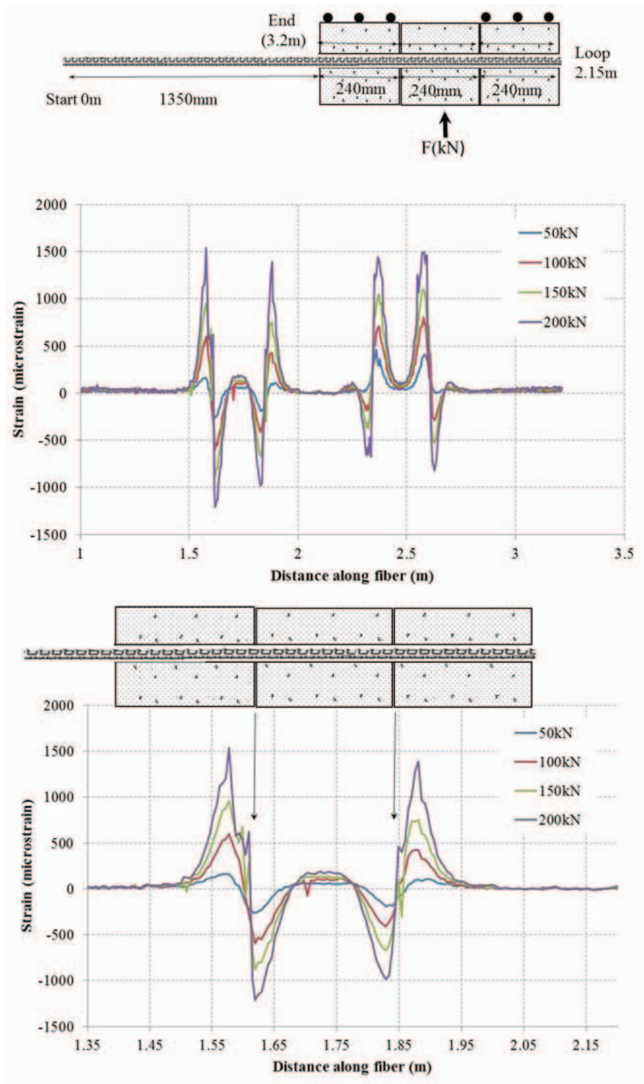

Figure 8. Results from the double shear test. The applied load in KN corresponds to the load-displacement profile in Figure 9. Upper: configuration. Middle: Strain profile along whole fiber. Lower: detailed Strain profile along a detailed section of fiber.

sensing in geomechanics. This paper has evaluated technology based on Rayleigh backscattering that has a spatial resolution of approximately 5mm. For both 3 point bending tests and cantilever bending tests, the measured strain profiles deviated by no more than 10% and were typically within 5% of the results predicted by theory. For short embedment length, axial pull tests the results agreed well with theoretical predictions from the literature and even the effect of the deformed ribs on the rebar could be discerned. Likewise, the strain profiles measured for a simple three block shear test were qualitatively similar to those predicted by theory and numerical modeling.

This test program highlights the potential of the technology for future field trials.

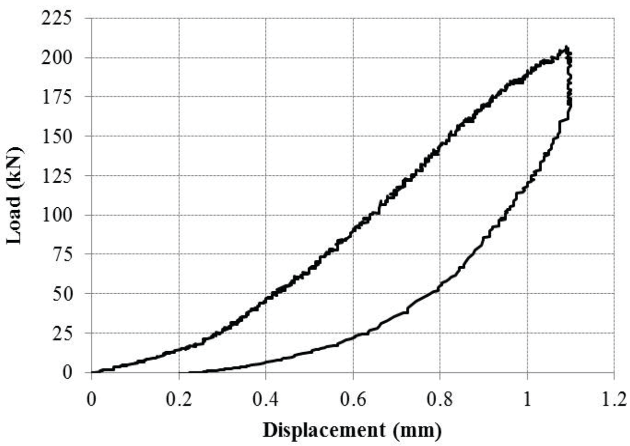

Figure 9. The load-deformation response of the Double Shear specimen. The load(kN) was applied to lower surface of the central block. Displacement(mm) is the relative movement between the central block and the outer blocks.

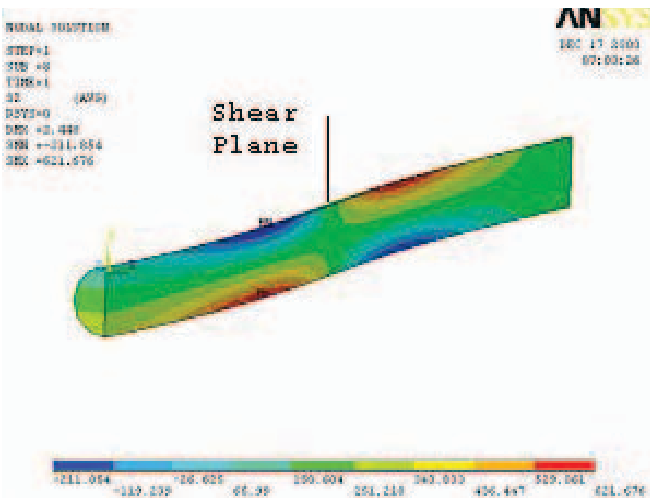

Figure 10. Simulation of shear using Finite Element modeling (Jalalifar, 2006).

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