

# Full scale testing of rebar and SFRC segmental lining using independent and wireless instrumentation systems.

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**ABSTRACT:** Development and acceptance of steel fibre reinforced concrete (SFRC) segmental tunnel lining requires an accurate understanding of the performance of the SFRC segments under real load conditions. An innovative instrumentation scheme has been implemented during the construction of the Liantang Lung Shan highway tunnels in Hong Kong to evaluate the distribution of the loads in the segments during erection and tunnelling and for comparison with the design assumptions obtained by numerical simulations. The monitoring system used embedded micro-electronic technology and was designed to be independent and wireless allowing data to be collected throughout the full lining erection process. The instrumentation program included 10 segments, both conventionally and steel-fibre reinforced. This paper will present the development of the instrumentation, the installation methods and initial data obtained.

## 1 INTRODUCTION

### 1.1 *Main objective*

An R&D project was implemented by Dragages Hong Kong and Bouygues Travaux Publics at the Liantang Lung Shan highway tunnels project in Hong Kong to study the structural behaviour of the steel fibre reinforced concrete segmental lining and to evaluate the distribution of loads in the segments in order to confirm design assumptions used in numerical simulations.

A comparison between numerical and experimental results will be carried out to assess the effectiveness of the adopted numerical model in predicting the behaviour of segmental lining under a thrust load simulating the effect of the TBM machine during excavation. Monitoring data enabling a comparison to be made between conventionally reinforced concrete and steel fibre reinforced concrete

(SFRC) segments was also obtained for similar analysis.

The monitoring instrumentation was developed to record strain developed in the segment due to the segment handling, TBM thrust and the annular void grouting/ground loads.

Segment reinforcement ratio is generally defined during design by the grout/ground/TBM thrust loads hence, the strain gauges were positioned where it was predicted that the maximum strain would be developed due to these loads.

### 1.2 *Specific development requirements*

Prior to the development of the monitoring system several important criteria were defined which needed to be considered by the system developer; one of the most important development criteria considered was to be able to obtain data as soon as the TBM thrust pads

are in contact with the segment and before the vacuum erector is removed. Literature studies indicated that previous segment monitoring schemes have not been able to capture this window of data. Due to access restriction during segment erection, the difficulty to plug cables to segments when the erector pad is still on the segment and also the inconvenience of having cables running in the tunnel that can be damaged by the traffic (TBM, MSV, cable bracket installation...), a wireless monitoring seemed the most appropriate technology to pursue.

Other factors to be taken into consideration during the development were the positioning of the instrument components, so as not to adversely affect the data obtained (i.e. affecting stress distribution within the concrete or introducing artificial lines of weakness within the segment), together with the frequency of monitoring and the duration of monitoring.

## 2 INSTRUMENTATION

### 2.1 Instrumentation development

Instrumentation using conventional vibrating wire strain gauges, multiplexer, datalogger and battery would be impossible to embed in the concrete due to the size of the elements. The power consumption of vibrating wire strain gauges would require big batteries which are also not convenient to embed within the segments. Collecting data through a multiplexer would also prevent synchronous data reading at the frequency required.



Figure 1. Foil strain gauges and strain gauge module (SGM)

Foil strain gauges (Figure 1) were considered as they are resistive and can be recorded at a higher frequency than vibrating wire gauges. Such gauges are commonly used for concrete testing and to monitor the performance of structures. However, these gauges are susceptible to variable signal loss in cabling and this is why measuring vibrating wire instruments in the frequency domain is often preferred. A new method which samples a resistor / capacitor time constant rather than simple voltage allows conversion of analogue sensor direct to microstrain without being affected by line losses. This new electronic arrangement requires much less power and therefore a smaller logging unit and power supply. As a result the system works on regular batteries (8.5Ah battery C cell size, Figure 2).

An application was developed to communicate with the datalogger via Bluetooth and to download data. The application also enabled the data sampling rates to be configured on site and to manually read temperature, battery condition and strain gauge conditions.



Figure 2. Data logging module (DLM)

The key points of the custom development were as follows:

1. The design used a very low-power strain gauge coupled with an RS485 transceiver.
2. The sensor nodes comprised 3 x ¼ bridge strain gauges.
3. The strain gauges were temperature compensated.
4. The strain gauges were wired directly to a nearby module containing signal conditioning circuitry and microprocessor.
5. The wiring configuration was designed such that there would be independent channels providing redundant paths to all strain gauge modules. The system was designed so that there would be no single point of failure. In the event that one of the digital strain gauges failed it would not impact the ability to obtain data from the remaining. One additional channel was

available to access the crackmeter data (Figure 3).

6. Power to the sensor nodes is controlled by the data logger component and are only powered while readings are being taken.

7. The data-logger batteries should last 180 days (D-Cell battery with 8.5Ah rating) with the logging schedule envisaged.

8. The 2Gb memory card can store nearly 4 years of data at a sample rate of 1sample/10s.

9. Integrated Bluetooth wireless module with range up to 30 metres (line of sight).

10. Data can also be retrieved via a USB cable if necessary.

11. All equipment is sealed against moisture and corrosion.

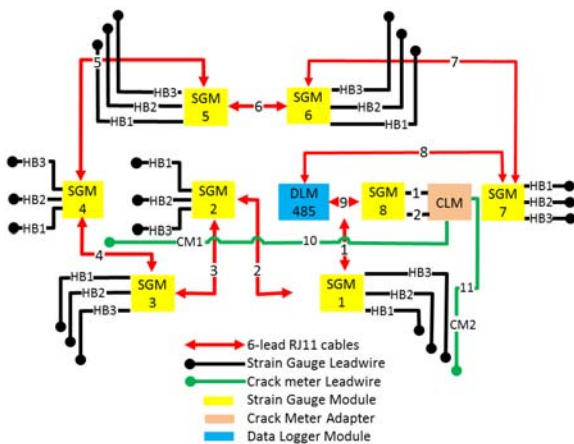


Figure 3. Segment cabling schematic

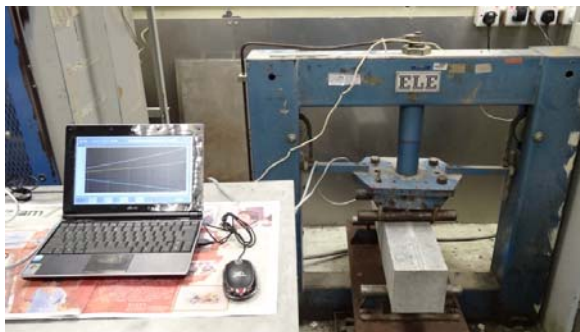


Figure 4. SFRC beam flexural testing

During the development stage a flexural test on a steel fibre reinforced concrete beam was performed to confirm that the proposed strain gauge solution would provide reliable results. The strain gauge module and three strain gauges were embedded inside the concrete beam and worked satisfactorily for the duration of the test (Figure 4).

## 2.2 Instrument location

The strain gauges (21no. per segment) were located in the areas where the highest tension loads were anticipated (Figure 5) and two crack-metres were installed per segment on the intrados surface at location where cracks could develop.

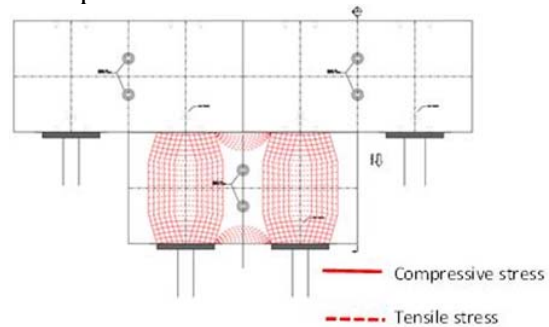


Figure 5. Principle stress trajectories

Initially four segments of two SFRC lining rings and four segments of one conventionally reinforced lining ring were instrumented. However, two instrumented segments did not function when they arrived on site so ten instrumented segments were used for field testing and data collection.

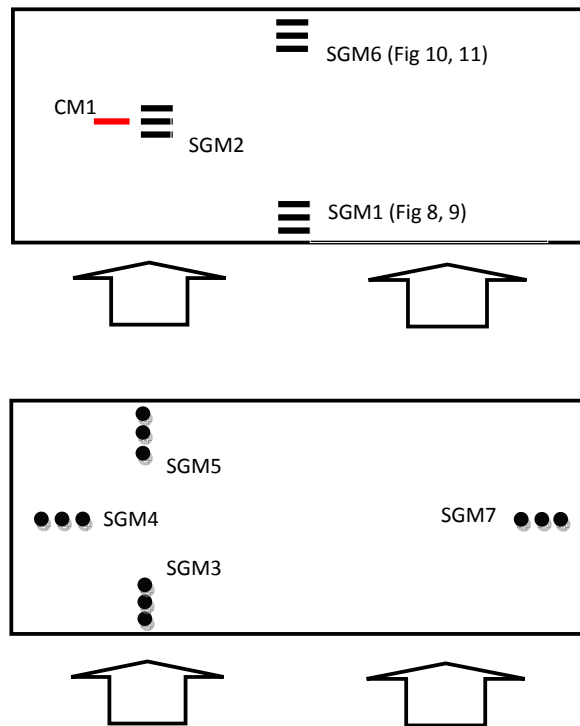


Figure 6a. and b Typical strain gauge arrangement a. Circumferential strains b. Radial strains.

The monitored segments were located on the upper half of the lining ring to allow easier access (Figure 8) and at locations where the rock was foreseen to be good so allowing more rigorous testing.

Figure 6 a. and b. show the arrangement of the gauges relative to the thrust ram contact points on the ring. Three sets of three gauges were positioned to measure the circumferential strains in the ring. Two sets (SGM1 and SGM6) were arranged between the rams and one (SGM2) and a surface crack meter were arranged at segment midpoint directly in front of the thrust rams. These gauges were positioned at the middle of the segment thickness to avoid circumferential bending moments.

Four sets of three gauges SGM3, SGM4, SGM5 and SGM7 were positioned radially perpendicular to the circumference and in the centre of the ring.

### 3 INSTRUMENT INSTALLATION

#### 3.1 Installation first stage

A first stage of installation was done at the segment precast yard, where all the strain gauges and strain gauge modules were embedded in concrete. The datalogger and the crackmeters were installed at the site in order to avoid damage during storage and transportation.

As the SFRC segments only contain a small amount of conventional reinforcement a frame was required to position and secure the strain gauges correctly and to train the wires to the position of the box out (for the data logger). The frames were constructed from 6mm diameter fibre glass bars which were tied with steel wires to the existing rebar (Figure 7).

The strain gauges were attached to the fibreglass GFRP rods with steel wires and plastic ties. The fibreglass bars have benefits over a steel frame as fibreglass has a similar elastic modulus to that of the concrete and so will not affect the behaviour of the SFRC around the strain gauges.

#### 3.2 Instrument devices

The monitoring instrumentation comprised:

- Seven groups of three strain gauges.
- Seven Strain Gauge Modules.

- Two cables to connect the crackmeters at the external surface and 2 cables to connect the equipment to the datalogger cast within the concrete.
- One box embedded into the concrete to create the recess where the datalogger will be installed (on site Liantang).

#### 3.3 Installation sequence

The installation procedure was as follows:

a. Crackmeter lead-wires were inserted within plastic pipes connected to the rebars with cable ties to protect them during concreting. Both ends were filled with silicone sealant. The part against the mould was protected with a sponge.



Figure 7. Instruments mounted in-situ

- b. Strain gauges were attached to the GFRP bars at the accurate locations using a spacer measuring tool. The position of each strain gauge was checked and adjusted to the theoretical position with a tolerance of  $\pm 5\text{mm}$ .
- c. The instrumentation was tested using a PC to check that all the components function correctly prior to concreting.
- d. The two cables from SGMs and the two crackmeter lead-wires were inserted into the plastic box-out which was filled with foam and wrapped with bubble wrap before concreting to allow easy extraction later.
- e. Concreting of the segment was performed with care in order to avoid direct dropping of concrete onto the strain gauges.
- f. Demoulding of the segment. Recovery of the crackmeter cables and cables in the plastic box-out.
- g. The instrumentation was again tested to check that all the components functioned correctly.

h. The instrumented segments were marked on the leading and trailing edges and on the intrados for identification.

### *3.4 Lesson learned during installation at the Precast Yard*

The environment in which tunnel lining segments are fabricated is harsh for electronics hence, all electronic components need to be designed for physical and thermal robustness and protected against water ingress.

The strain gauges need to be installed to a high degree of accuracy if the data is to be meaningful; less than  $\pm 5$ mm which is less than tolerance usually achieved in a precast yard (for rebar placing for example). The strain gauges were eventually attached to the GFRP bars when the cage was inside the mould.

Placing concrete needs to be performed with care to avoid forceful dropping or flowing of concrete directly onto the instruments.

All cabling and electronic components need to be designed to resist vibration in a wet environment. The very strong vibration of the segment mould will affect cabling and electronic components if these are not effectively fixed in place.

Some leakage into the strain gauge module (SGM) occurred during the first trial due to a lack of sufficient waterproofing.

In order to mitigate this risk posed, the intensity of the vibration for these temporary segments was reduced. SGMs were suspended between rebar by wires instead of directly attaching them to the steel rebar to avoid excessive shaking during the vibration of the mould. The SGMs were filled with foam to make them completely waterproof.

### *3.5 Installation second stage*

A second stage of installation was undertaken on site before segment erection. Here the crack meters were installed on the segment intrados surface, the instruments plugged to the data logger and data logger sealed in the recess in the segment. A Plexiglas plate was bolted on top of the data logger module in order to protect it from the erector vacuum pressure (around 1bar). The crackmeter, adapter and crackmeter wires were covered with duct tape on the intrados surface to protect them from damage that could be caused by workers or the vacuum pad. A

plastic cover plate was used in order to not impact the Bluetooth communication signal.

### *3.6 DLM installation details*

Prior to DLM installation, the box-out for the DLM was removed. Care was taken to avoid damaging the cables which protruded from the concrete segment into the box and were required to remain intact for connection to the DLM. The data cables were then fed into the DLM through a hole with a rubber grommet located on the bottom of the DLM box.

Once all the data and crackmeter cables have been inserted and connected in the DLM, foam has been applied to the cable entry area and the lid screwed on top. The foam expanded in the confined space to form a protective barrier against the environment.

The unit was powered by 2x8.5Ah “C Cell sized” batteries. Once switched on, the DLM reads the internal configuration and starts operation. The DLM was tested to ensure that it was “reading” all available SGMs and data could be downloaded to the tablet.

Once the testing was completed the DLM lid was fixed and silicon applied around the edges to provide a water resistant barrier.

The last step of installation was to screw the Plexiglas plate on top of the DLM box. A foam gasket and silicone sealant was provided between the Plexiglas plate and concrete in order to provide an airtight and watertight system.

## **4 APPLICATION**

The original firmware allowed for 10-second reading cycle. A tablet device with bespoke application was used to access and download files from the DLMs. The application included the ability to:

- Find all available DLMs,
- Check the DLM status,
- Change the DLM configuration settings,
- Download data files from the DLM,
- Modify the DLM polling schedule,
- Commission the DLM.

The ability to communicate with the data logger wirelessly was very useful to check that the DLMs were functioning properly and to change the configuration as necessary. Unfortunately, at Bluetooth baud rates data



download times were lengthy which impacted on the efficiency of this system. It is recommended that future systems use real time data transfer over wireless mesh networks.

## 5 TEST PROTOCOL

The test protocol was predefined and included several parties: construction, survey and technical teams.

The load test itself consisted of increasing the jack pressure and maintaining the pressure at different steps. In order to more precisely control the pressure in the jacks the test was done in static mode i.e. not in excavation mode and with the cutterhead not turning and to avoid damaging the cutterhead and disc cutters, due to high contact pressures with the ground, the cutterhead was retracted. The confinement pressure was increased in order to be able to reach high jack pressure values, up to 7.5MN per pad.

TBM data records including thrust loads and jacks elongation were obtained by the machines data logging system.

Eccentricities and stepping between segments within an instrumented ring and between segments of the instrumented ring with the adjacent rings, were surveyed and recorded.

Another important parameter to monitor was the development of cracks at the surface of the segments. After each step the instrumented segments were visually checked and cracks, if any, recorded and mapped.

The segment instrumentation logging schedule was set to the following;

- 1) First 2 days after erection: one reading every 10 seconds.
- 2) From day 3 to 15: one reading per minute.
- 3) From day 16 to 30: two readings per day.

## 6 OBSERVATIONS/CONCLUSIONS

### 6.1 Overview

Sensors were installed on four rings within the top hemisphere of the ring. One ring was conventionally reinforced and the other rings were built with steel fibre reinforcement. In this paper we shall consider one segment at the 10 o'clock position (Figure 7) and look at the circumferential strains between the rams; a location of tensile strains.

The monitoring device was designed to record the first thrust of the jack on the segment and avoid cable obstructing the working area.

The global analysis of the results shows the expected behaviour of the concrete at the location of the strain gauges (tension between and behind jacking pads both circumferentially and radially). This tension decreases rapidly towards the trailing edges which are predominantly in compression. Gauges at the trailing edge responded most to the grouting pressures.

In term of cracks, segments with conventional reinforcement displayed more cracking (Figure 9) than the SFRC segments with the same magnitude of load. This is reflected in the results where the peak tension strains recorded in the RC segment were four times those in the SFRC segment. The variation of strain with depth within the RC segment was 1.5  $\mu\text{strain/mm}$  whereas in the SFRC segment the strain was more evenly distributed at only 0.33  $\mu\text{strain/mm}$  and with lower tensile strain.

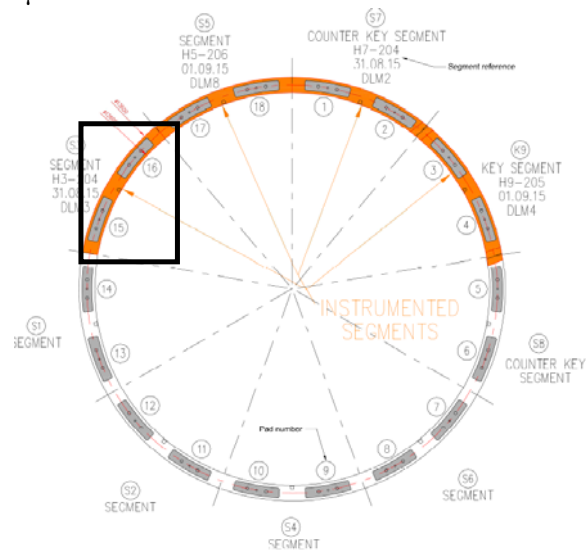


Figure 8. Locations of instrumented segments with analysed segment shown



Figure 9. Cracks on segment (TTR1172)

## 6.2 Circumferential Strains

The profile in Figure 10 below shows that in the early part of the thrust the tensile strain in the conventionally reinforced segment tracks that of the SFRC segment with tensile strain over applied stress (bar) at about 0.5 to 0.6. The lower values correspond to the conventional reinforcement. At peak thrust pressure there is a rapid increase in strain in the conventionally reinforced segment which reduces as load is removed but not down to levels expected for the thrust pressures being applied. The stress strain behaviour is indicative of concrete cracking. The data further shows the extent of the cracking with each gauge showing the same pre and post failure characteristics to different extents. The gauges were installed up to 300mm into the concrete and even the deepest sensor shows the behaviour. This suggests that cracks during installation may have propagated well into the reinforced area of the concrete. The cracks appear very sensitive to differential pressure between the two applied jacks with clear spikes in tensile strains when one or other jack was unloaded. This may have stimulated deeper propagation of the cracks.

The SFRC concrete (Figure 11) was subjected to stresses 40% higher than the conventional concrete (240bars) yet shows no such propagation of cracks.

Figures 12 and 13 show the distribution of circumferential strains near the trailing edge of the rings. At this location there is no tensile expression of the thrust loads in either the RC or SFRC segments only a small compression. Increased transient compression due to grout pressure can also be seen and dissipation of this pressure as grout penetrates into the surrounding ground is observed as soon as the grout pressures are removed. A slowly increasing trend can be seen over one day of observation which may be indicative of ground load transferring onto the ring.

## 6.3 Radial Strains

Radial strains in both RC and FRC segments are similar and track closely the application of ram thrust pressures (Fig. 14 and 15). Generally radial strain is between 0.3 and 0.45 of the applied ram pressure in bars.

## 7 FUTURE CONSIDERATIONS

The data has provided valuable information on the dynamic behaviour of RC and SFRC segments during the installation processes. Future projects may benefit from attention to the following:

- Finding mounting solutions to avoid the use of additional GFRP bars to attach the strain gauges.
- Minimise as much as possible work to be done on site (i.e. install at the precast factory) and the interaction between workers and monitoring devices.
- Increase robustness of devices and cabling to avoid damage during installation and concreting.
- Increase the long term water resistance of all the monitoring devices.
- Employ remote wireless systems rather than local Bluetooth to check the status of the monitoring from a computer at the office.

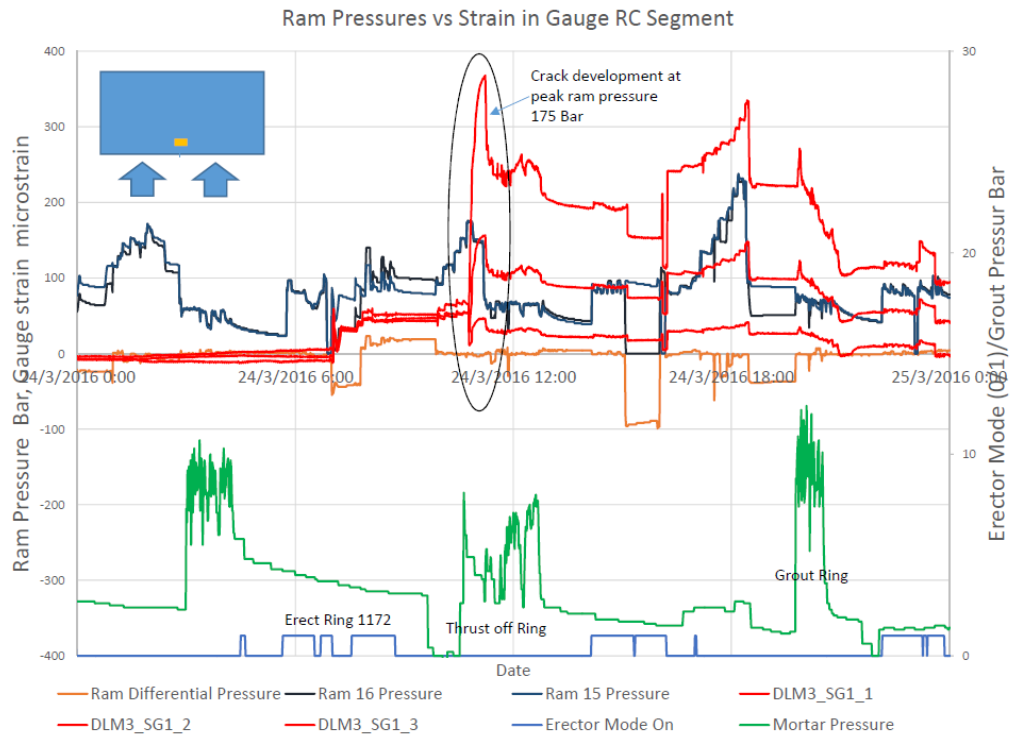


Figure 10. Conventional reinforcement Ring 1172 – Leading Edge Circumferential Tensile Strain (red) against rams thrust pressure (blue) and grouting pressure (green) - (+ve tension)

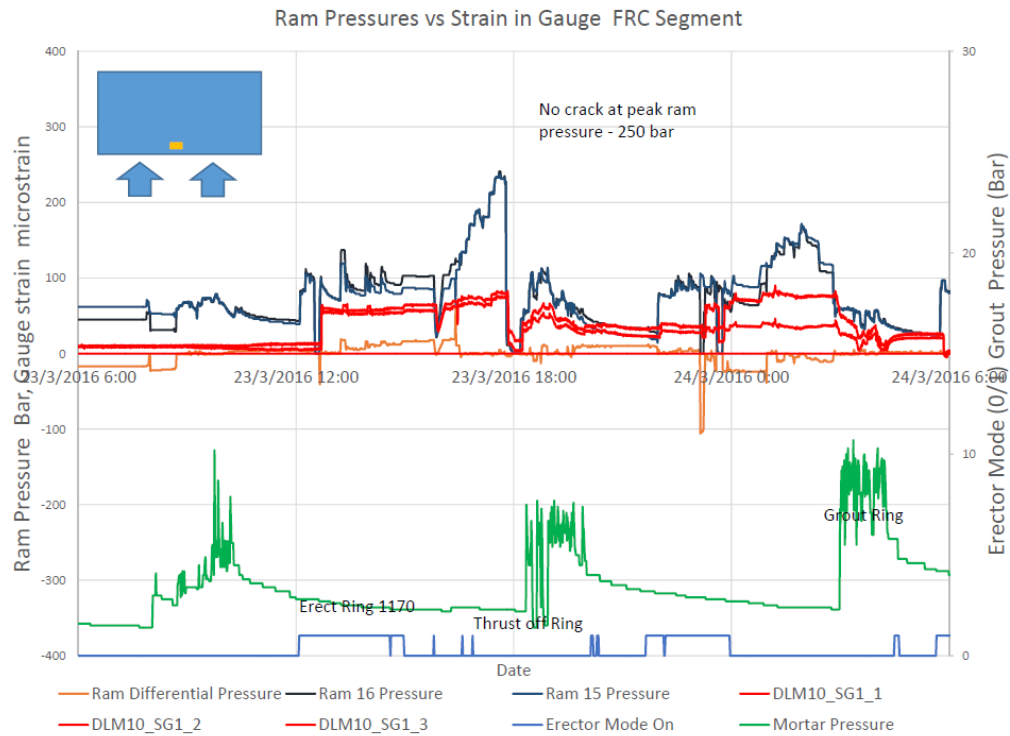


Figure 11. Fibre Reinforced concrete re-inforcement 1170 – Leading Edge Circumferential Tensile Strain (red) against rams thrust pressure (blue) and grouting pressure (green) - (+ve tension)



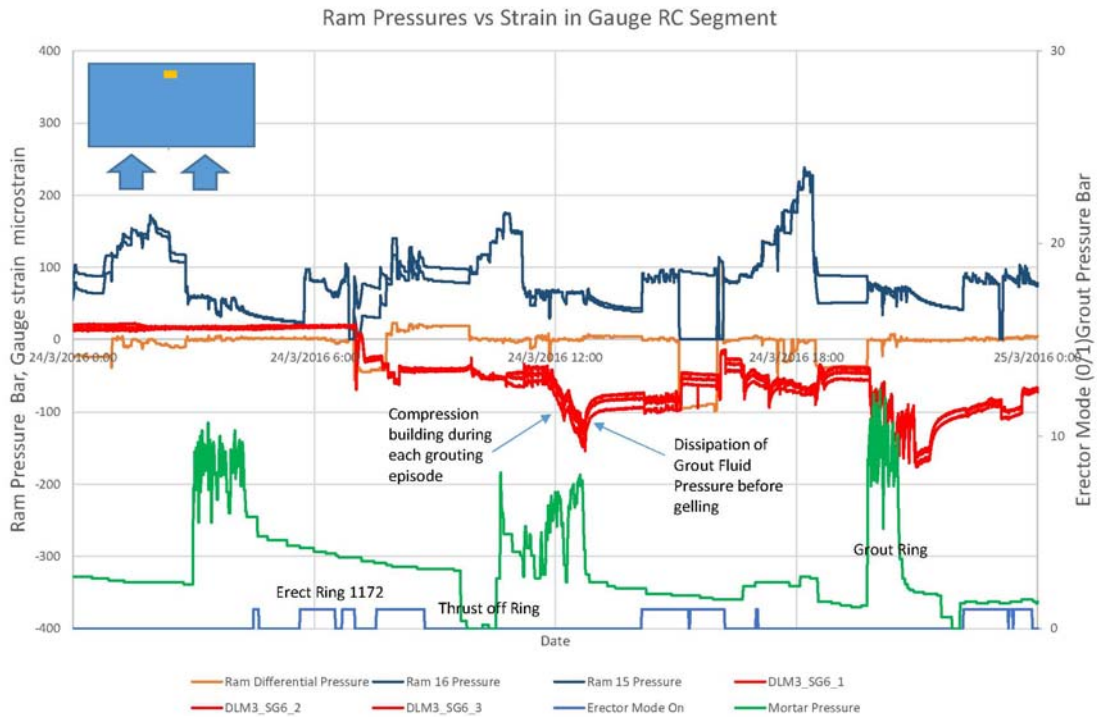


Figure 12. Conventional reinforcement Ring 1172 – Trailing Edge Circumferential Tensile Strain (red) against rams thrust pressure (blue) and grouting pressure (green) - (+ve tension)

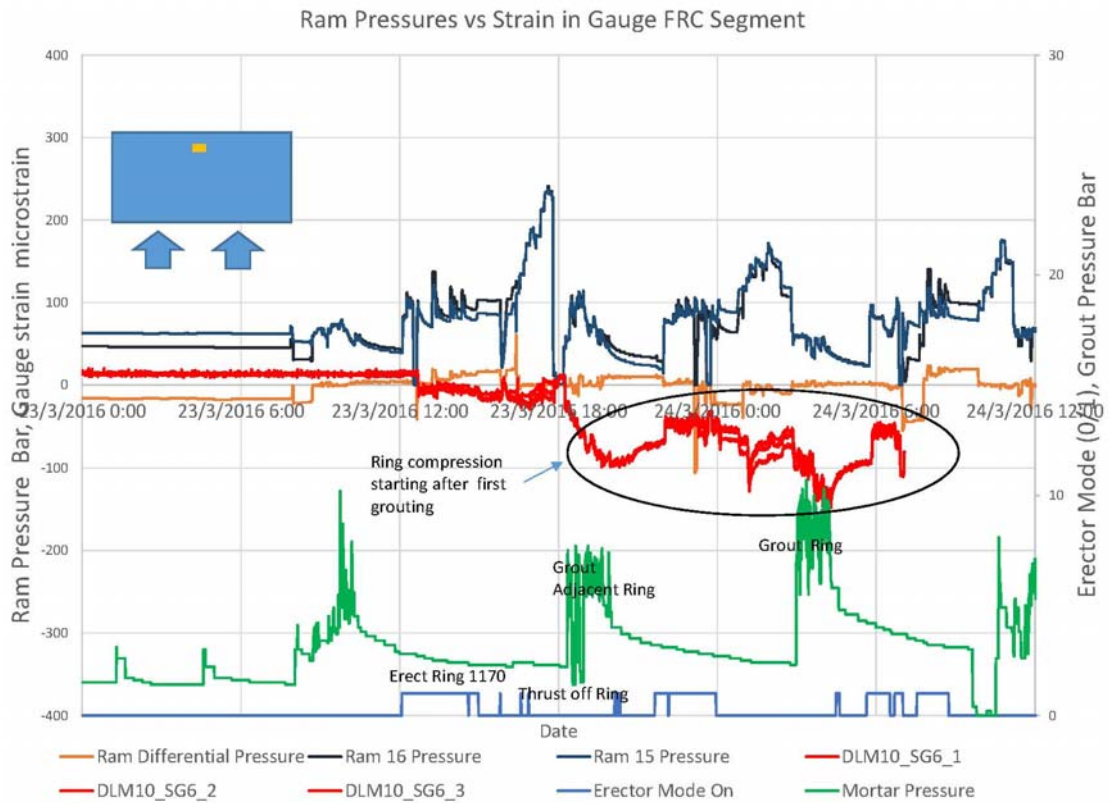


Figure 13. Fibre reinforcement Ring 1170 – Leading Edge Circumferential Tensile Strain (red) against rams thrust pressure (blue) and grouting pressure (green) - (+ve tension)

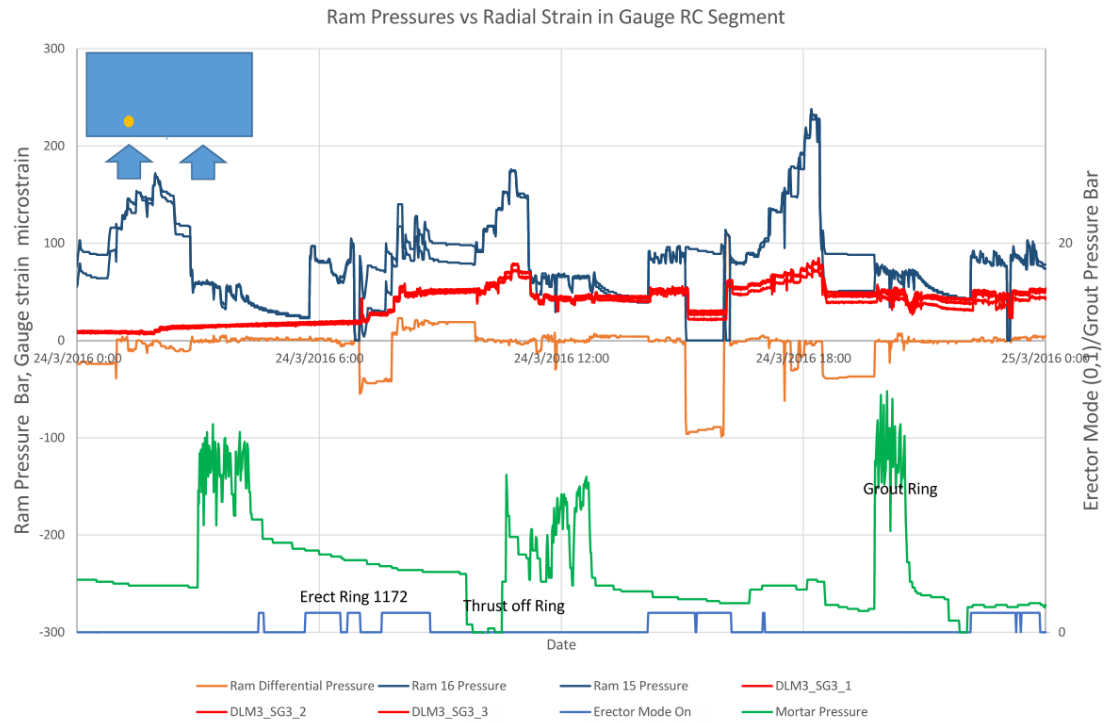


Figure 14. Conventional reinforcement Ring 1172 – Leading Edge Radial Tensile Strain (red) against rams thrust pressure (blue) and grouting pressure (green) - (+ve tension)

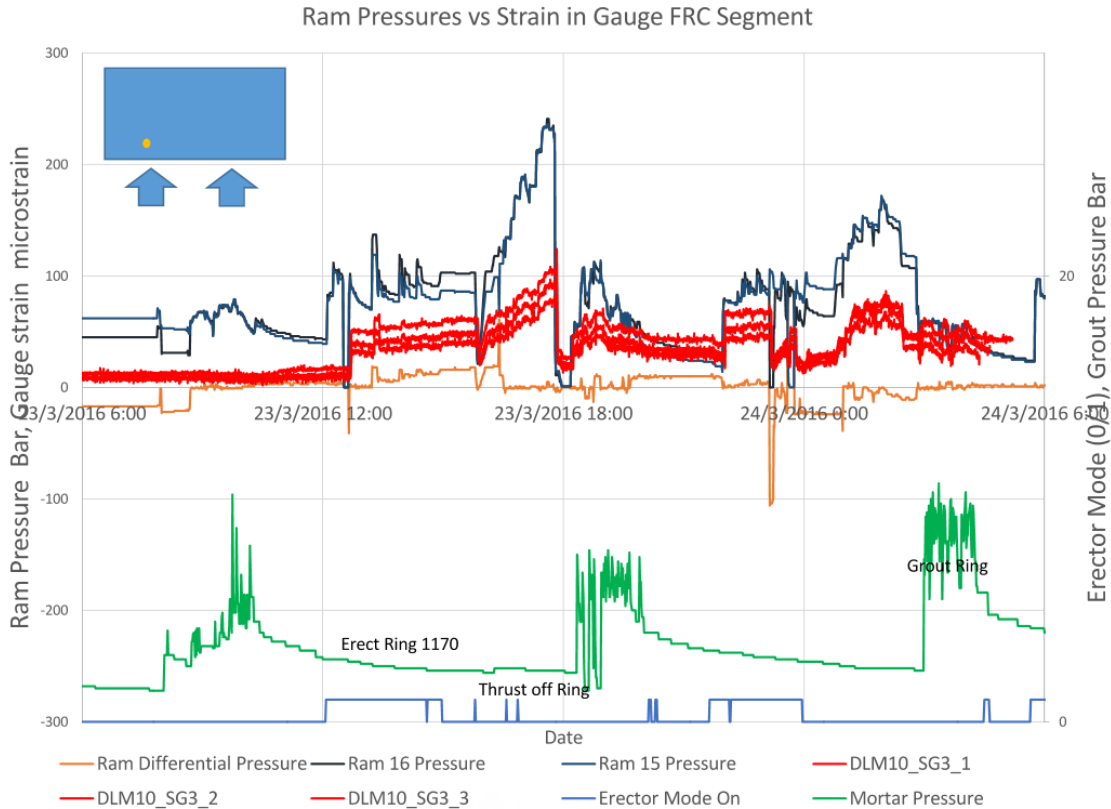


Figure 15. Fibre reinforced Ring 1170 – Leading Edge Radial Tensile Strain (red) against rams thrust pressure (blue) and grouting pressure (green) - (+ve tension)