Full Scale Test of a SSP 34m boxgirder 2

Data report

Jensen, Find Mølholt; Branner, Kim; Nielsen, Per Hørlyk; Berring, Peter; Antvorskov, Troels Skieller; Nielsen, Magda; Lindahl, Morten Michael; Reffs, Joan Højsholm Humble Ascanius; Jensen, Peter Hjuler; McGugan, Malcolm; Skamris, Carsten; Sørensen, Flemming; Schytt-Nielsen, Rune; Laursen, Jeppe H.; Klein, Marcus; Stang, Henrik; Morris, Andy; Dear, John P.; Puri, Amit; Fergusson, Alexander; Wedel-Heinen, Jakob

Publication date:
2008

Document Version
Publisher's PDF, also known as Version of record

Risø-R-Report

RISØ

Full Scale Test of a SSP 34m box girder 2. Data report

Find M. Jensen, Kim Branner, Per H. Nielsen, Peter Berring, Troels S. Antvorskov, Magda Nielsen, Morten Lindahl, Joan H. Reffs, Peter H. Jensen.
Risø - Wind Energy Department

Malcolm McGugan,
Risø - Materials Research Department

Carsten Skamris
Blaest Test Center

Flemming Sørensen, Rune Schytt-Nielsen
SSP-Technology A/S

Jeppe H. Laursen, Marcus Klein
Zebicon – GOM

Henrik Stang
DTU – Department of Civil Engineering

Andy Morris,
E.ON-UK

John P. Dear, Amit Puri, Alexander Fergusson
Imperial College London

Jakob Wedel-Heinen
DNV

Risø-R-1588(EN)

Risø National Laboratory for Sustainable Energy
Technical University of Denmark
Roskilde, Denmark
Publication date: May 2008

DTU

Author: Find M. Jensen, Kim Branner, Per H. Nielsen, Peter Berring, Troels S. Antvorskov, Magda Nielsen, Morten Lindahl, Joan H. Reffs, Peter H. Jensen, Malcolm McGugan[1], Carsten Skamris[2], Flemming Sørensen[3], Rune Schytt-Nielsen[3], Jeppe H. Laursen[4], Markus Klein[4], Andy Morris[5], Henrik Stang[6], Jakob Wedel-Heinen[7], John P. Dear[8], Amit Puri[8], Alexander Fergusson[8]

Risø-R-1588(EN)
May 2008

Title: Full Scale Test of a SSP 34m box girder 2. Data report

Department: Wind Energy Department

1 Risø – Materials Research Department
2 Blaest Test Center
3 SSP-Technology A/S
4 Zebicon – GOM
5 E.ON – UK
6 DTU – Department of Civil Engineering
7 DNV
8 Imperial College London, Department of Mechanical Engineering - UK

ISSN 0106-2840
ISBN 978-87550-3574-4

Abstract (max. 2000 char.):

This report presents the setup and result from three static full-scale tests of the reinforced glass fiber/epoxy box girder used in a 34m wind turbine blade. One test was without reinforcement one with cap reinforcement and the final test was with rib reinforcement. The cap reinforcement test was part of a proof of concept investigation for a patent.
The tests were performed at the Blaest test facility in August 2007.

The tests are an important part of a research project established in cooperation between Risø National Laboratory for sustainable energy – Technical university of Denmark, SSP-Technology A/S and Blaest (Blade test centre A/S) and it has been performed as a part of Find Mølholt Jensen's PhD thesis.

This report is the second data report containing the complete test data for the three full-scale tests. This report deals only with the test methods and the obtained results, no conclusions are drawn. These can be found in papers and patent referenced in the data report

Various kinds of measuring equipment have been used during these tests: acoustic emission, force transducers, strain gauges and optical deformation measuring system (DIC).

The experimental investigation consisted of the following tests:

1) Flapwise bending with no reinforcement

2) Flapwise bending with wire reinforcements

3) Flapwise bending with rib reinforcements

Contract no.:

Group's own reg. no.:
(Føniks PSP-element)

Sponsorship:

Cover :

Pages:
Tables:
References:

Information Service Department
Risø National Laboratory for sustainable energy
Technical University of Denmark
P.O.Box 49
DK-4000 Roskilde
Denmark
Telephone +45 46774004
bibl@risoe.dk
Fax +45 46774013
www.risoe.dk

Table of Contents

1 Introduction

Risø National Laboratory for sustainable energy - Technical University of Denmark (DTU) has initiated full-scale tests of two 34m glass fiber/epoxy box girders manufactured by SSP-Technology A/S. The research project is performed in cooperation with SSP-Technology A/S, Blaest (Blade test centre A/S) and Risø DTU. The full scale test is a part of Find Mølholt Jensen PhD-project, see ref. [1]. This report deals with the test of the second box girder. The test setup for box girder 2 is identical with the test performed on box girder no 1. The test setup is described in details in data report 1, see ref.[2]

Comparisons between experimental and numerical results can be found in [1] and smaller test specimens from the same type of blade in [9] to [13]. A comprehensive description of structural behaviour of the box girder and failure mechanisms can be found in Find Mølholt Jensen's PhD-thesis, ref. [1]. This thesis also contains the background information for testing the reinforcement. The first reinforcement which was tested was a reinforcement of the load carrying cap. This reinforcement prevents out of plane deflection of the load carrying cap e.g. buckling capacity is increased.
In the full-scale test wires were used as reinforcement, but other embodiments/design are suggested in the patent application [8]. In the third and final full-scale test ribs were inserted in the critical region. The ribs and longitudinal bulkheads shown in Figure 1 were inserted before the final destructive test. The longitudinal bulkheads are inserted to prevent unwanted buckling failure in this region. Some of the ribs and one of the bulkheads were also present in the first two tests (with and without wire). Explanations of the reinforcements are given in the following chapters.

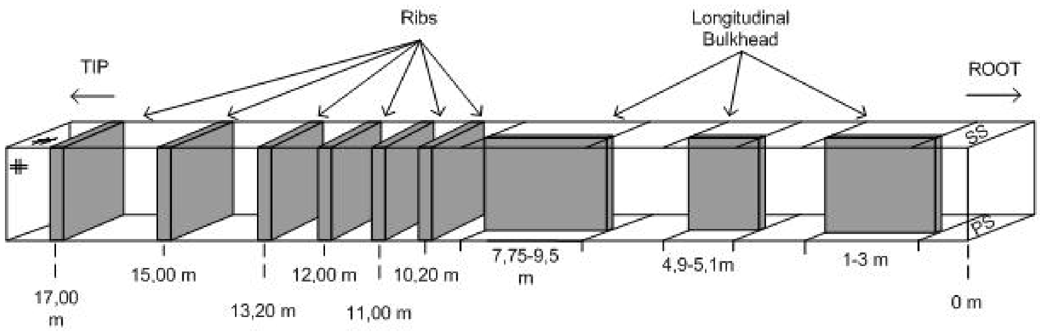


Figure 1. Rib and bulkhead reinforcements were inserted before the final destructive test.

Three static tests were performed and are presented in this data report. The three tests were:

1) Flapwise bending with no reinforcement
2) Flapwise bending with wire reinforcement
3) Flapwise bending with rib reinforcement.

The wire reinforcement is presented in chapter 3 and the rib reinforcement is described in chapter 4.

2 Test specification

This chapter will give a brief explanation of the test setup and the preparation of the box girder before the full-scale tests.

2.1. Strain gauges used in the full-scale test

Strain gauges in the section 11.5m are presented in Figure 2. The box girder failed in this section, see chapter 4. Positions of strain gauges in other sections can be found in appendix B. Results from the strain gauge measurements can be found in appendices C to E.

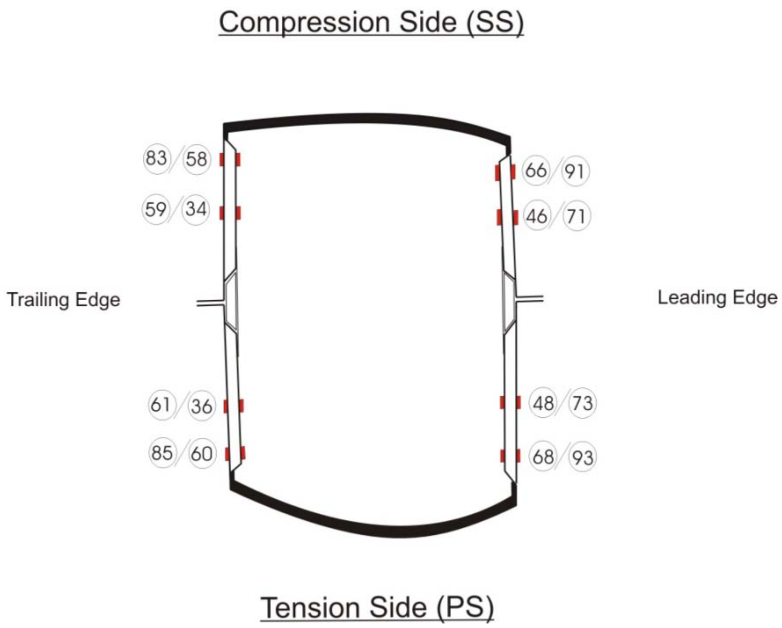


Figure 2. Strain gauge positions at section 11.5m from the root. The strain gauges were numbered with odd numbers on the outside, and even number on the inner side.

2.2. General information

The box girder is an essential part of a 34m blade designed for a 1.5MW wind turbine and is manufactured by SSP Technology A/S. The box girder is made of prepreg glass fiber/epoxy and most of the fibers are oriented in the longitudinal direction in order to carry the flapwise loads. The test setup for the box girder was identical with the test of box girder 1, see ref [2]. Due to handling and the load configuration the box girder was shortened to 25.4m, see Figure 3.

Figure 3. Box girder no 2 ready to be tested in flapwise bending. The box girder was shortened to 25.4m.

Figure 4. Box girder 2 mounted in test rig. Note there is no tophat reinforcement as in the first box girder test, see reference [2]

The tophat reinforcement which was included in the first box girder test was substituted by a longitudinal bulkhead in box girder 2. This was done in two steps. First a bulkhead in 1m to 3m region and in the final test, additional longitudinal bulkhead was added.

2.3. Longitudinal bulkhead reinforcement in the first two test

To avoid unwanted buckling behaviour in the root section the box girder was reinforced with a longitudinal bulkhead from 1m to 3m, see Figure 5. The bulkhead is shown in Figure 5 where the box girder is illustrated by a square box beam.

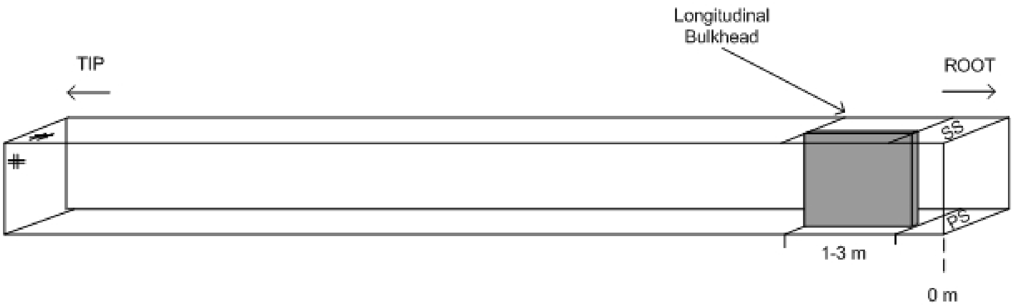


Figure 5. Position of longitudinal bulkhead reinforcement from 1-3m used in the first two full-scale tests. – this test were the wire reinforcement tested.

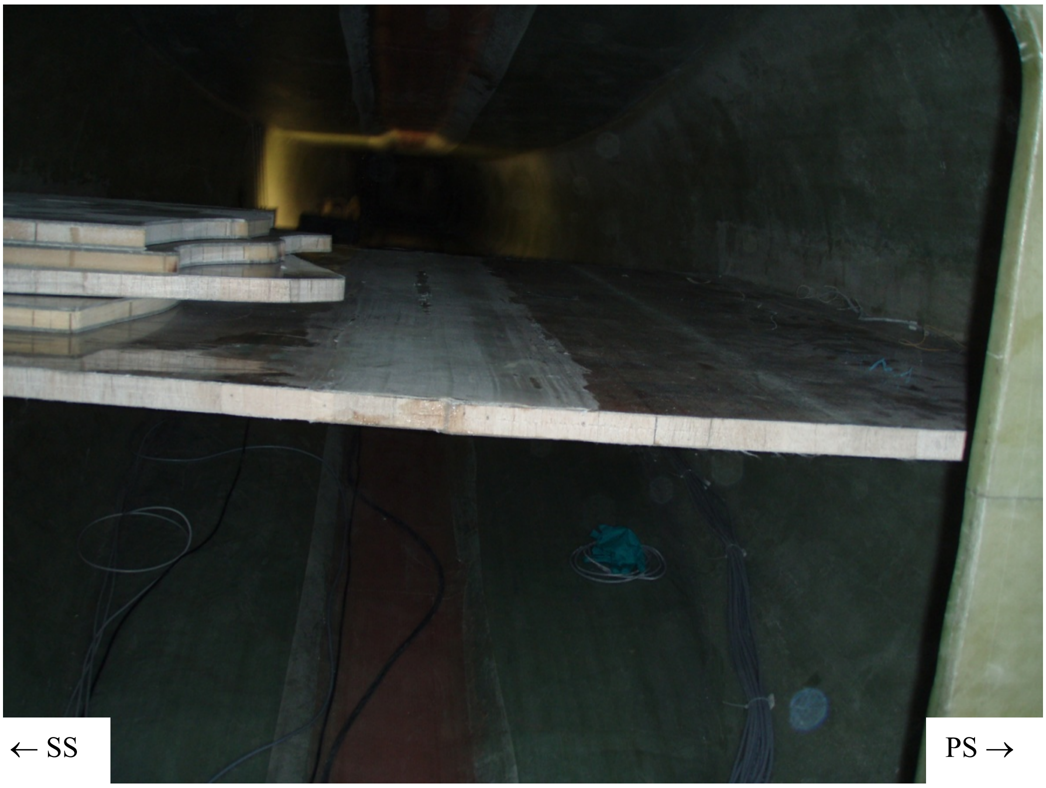


Figure 6. Longitudinal bulkhead from 1-3m manufactured and bounded by SSP Technology A/S. The bulkhead is seen from the root towards the tip rotated 90° counter-clockwise compared the sketch in Figure 5.

2.4. Transverse rib reinforcement in outer section 13-17m

The box girder was reinforced with transverse ribs in two regions, 9-12m and 13-17m.The ribs in the 9-12m region were first placed in the box girder after the second full-scale test, see chapter 4. The purpose of the reinforcement in 15m and 17m was to prevent collapse due to the crushing pressure explained in ref. [1]. The rib in 13.20m was introduced to transfer the force from the loading clamp into the box structure. Figure 7 illustrate the transverse ribs inserted in all the three tests.

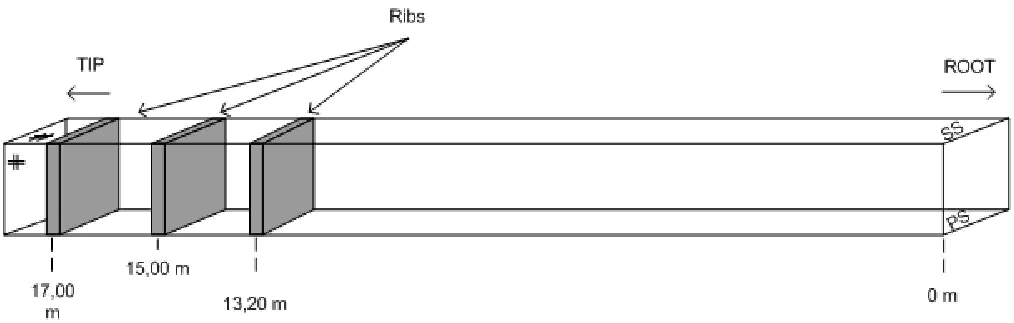


Figure 7. Positions of transverse ribs in the outer section 13 to 17m.

Figure 8. Rib in 13.20m manufactured and bounded by SSP Technology A/S.

3 Full-scale test 1 + 2 (with and without wire reinforcement)

As described in the introduction, two full-scale tests were performed for box girder no 2 in order to prove the value of the cap reinforcements. Before the wires were mounted the box girder had ribs and bulkhead inserted, see Figure 9.

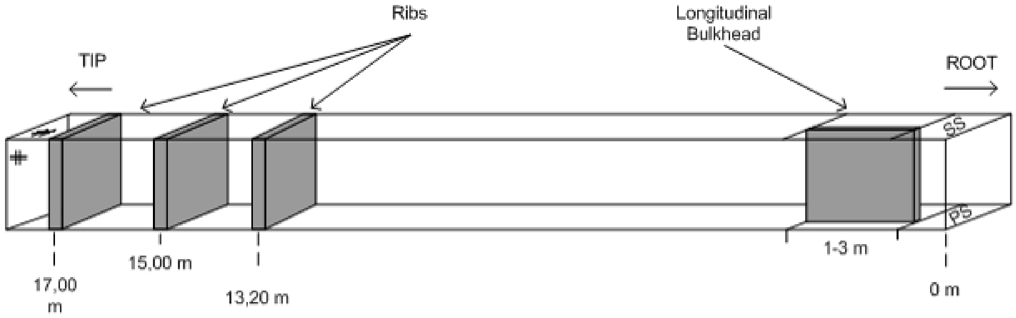


Figure 9. Ribs and longitudinal bulkhead in box girder before the test with and without wire reinforcement.

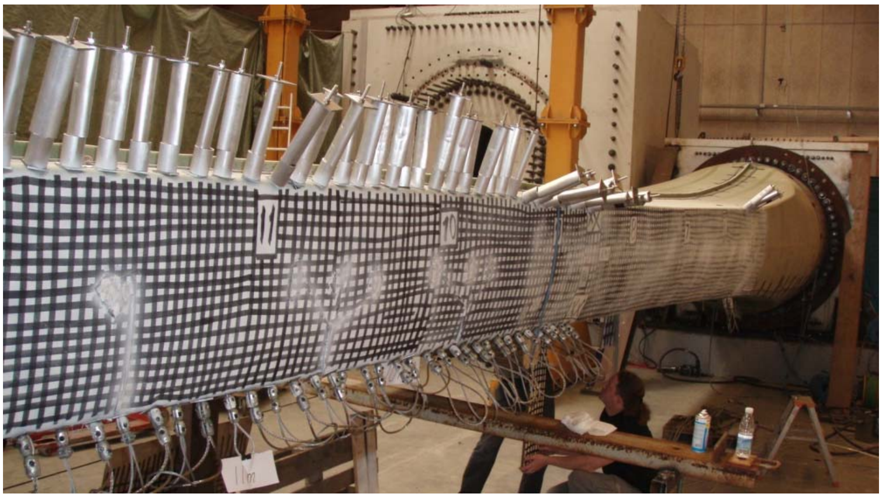


Figure 10. Full-scale test of box girder 2 with wire reinforcement as part of a "proof of concept" for the cap reinforcement patent.

Based on a FE-study in ref. [1], two areas were found critical to buckling and cap wire reinforcement was placed in these two regions. One critical region was the 5m section, where three wires were placed to prevent buckling, see Figure 11.

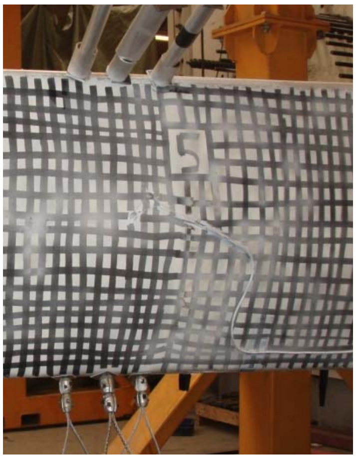


Fig. 11a

Fig. 11b

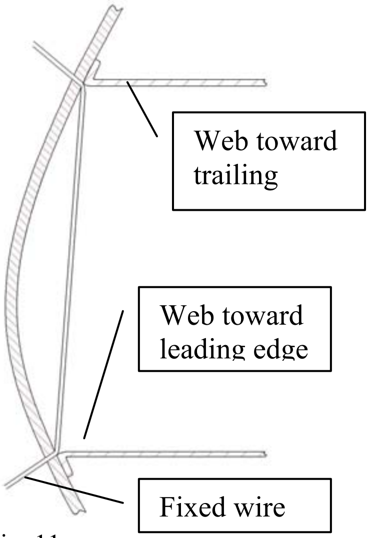


Fig. 11c

Figure 11. Wire reinforcement in 5m region. a) The box girder seen from outside b) Box girder seen from inside with tensioned wires c) Sketch of wire reinforcement

In Figure 12 the second section in 10-12m are shown to illustrate the big difference between the two transverse curvatures in the two regions, see Figure 11b and Figure 12b.

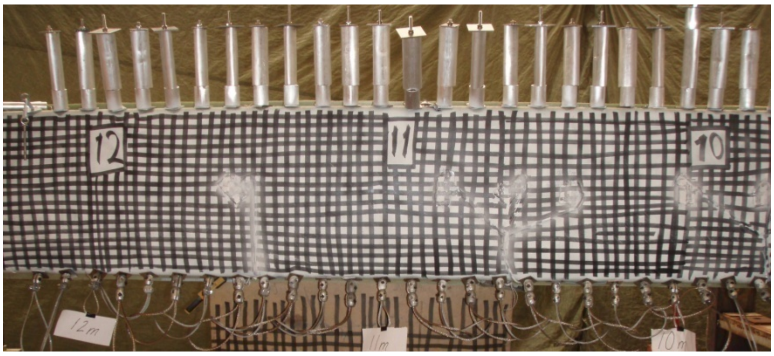


Fig. 12a

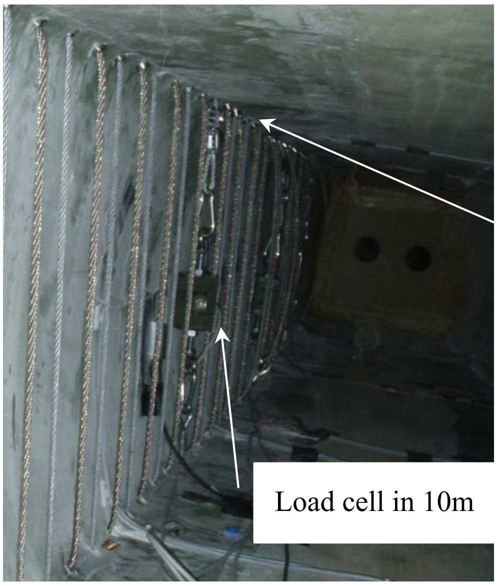
Fig. 12b

Figure 12. Wire reinforcement in 8.5-12m region (10-12m shown) **a)** Photo outside the box girder **b)** Photo inside the box girder with tensioned wires

The FE-studies showed that the reinforcement also would have an effect in regions with small curvatures.

3.1. Reaction forces measured in wires with load cells in three locations

In the wire reinforcement (test 2) three load cells were placed at 10m, 11m and 12m in order to measure the reaction forces in the wires, see Figure 13.



Detail:
wire and sleeve

Fig. 13a Fig. 13b

Figure 13. a) Load cells inside the box girder. b) Wire and sleeve enlarged

3.2. Measured reaction forces

The wires were tightened before the measurement started. Before the box girder was loaded the load cell was reset. The box girder was then loaded, unloaded, reloaded, and finally unloaded. This is seen in Figure 14. Note the load size in 12m.

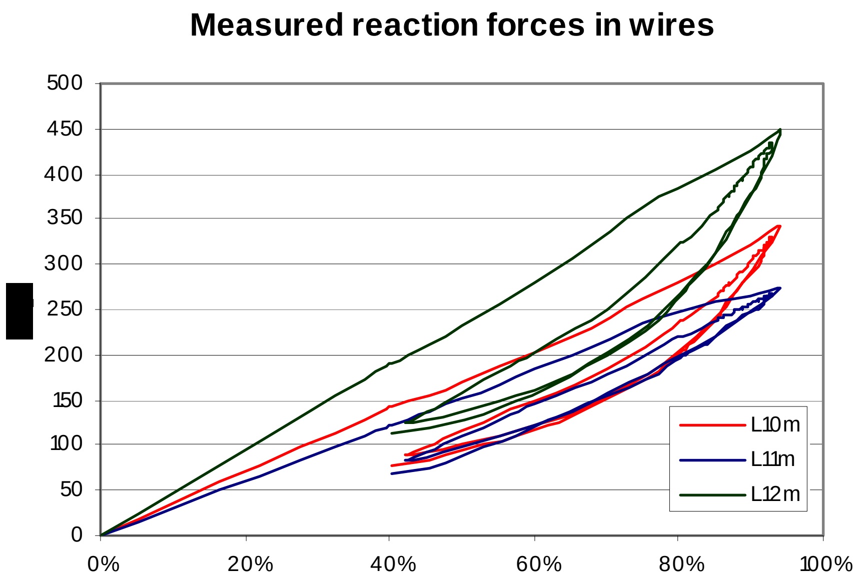


Figure 14. Load cell measurements inside the box girder.

The box girder was loaded and reloaded twice. What is the reason for the hysteresis? Notice that the wire loads in the second loading were less loaded in the first 2/3 of the loading. This was probably because the wires were too flexible.

Optical measurement - Digital Image Coloration

Aramis measuring system was used during the first two full-scale tests (with and without wires). Aramis is an advanced 3D digital optical deformation measuring system capable of measuring deflection on a surface. The Aramis system is described in data report 1, ref. [2]. The companies GOM/ Zebicon who have developed and produced the Aramis system, have performed the measurements.
The Aramis measurements were performed from 5m to 8.5m and in 9.5 to 12 meters from the root, which is presented in Figure 15b and c. For further information, see ref [2].

3.3. Results from test 1 + 2 and comparison

To verify the effect of the wire reinforcement test one and test two were compared. The deflection of the cap centreline was measured using the Aramis system. Figure 15a compares the test with and without wire reinforcement. The blue curve is the result from test no 2 and the red curve from test no 1.

In the two regions 5-8.5m and 8.5-12m where the wires were placed, the out of plane deformation of the cap is reduced. In the region 6.5-8.5m, with no wires, there was no significant difference between the two loadings. The region 5.2-6.5m, the difference is noticeable even though there are no wires. This is caused by the wires in 5-5.2m region which is affecting this region due to the strong reinforcement following the large transverse curvature. It is also interesting, that mainly the waves which bend inwards have been reduced. This is seen in 10m and 11.5m where the deformations have been reduced.

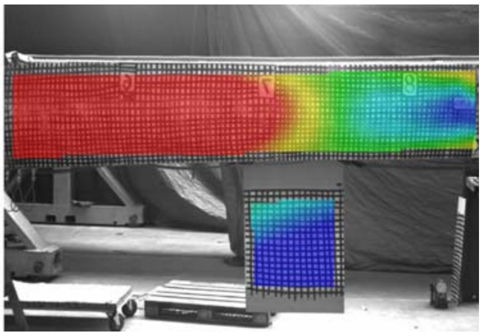


Fig. 15a

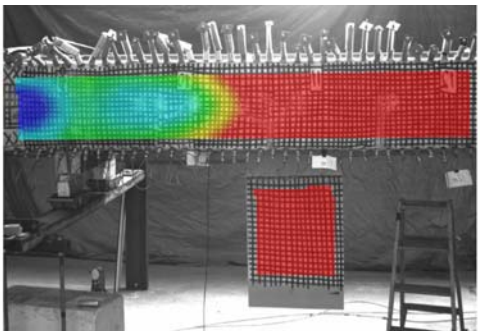


Fig. 15b

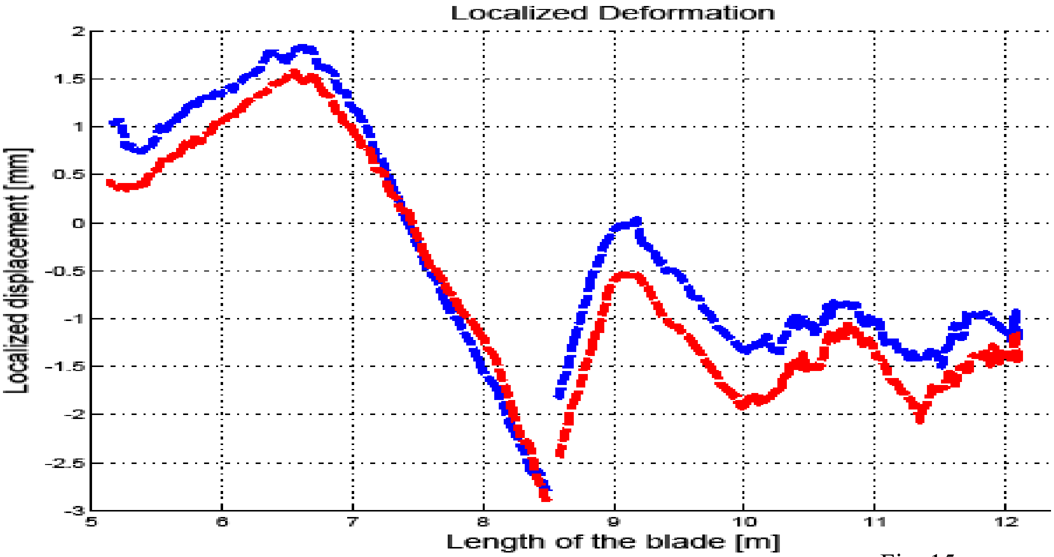


Fig. 15a

Figure 15. Cap deformations measured using Aramis DIC system. **a**) Two graphs show the cap deformations in the centerline. Red line is without wires and blue line is with wires. **b)** + **c**) Photos with an overlaid fringe measurement from the Aramis system. The photos are mirrored so it fits the graphs above in the length direction

Not only the displacements have changed due to the cap reinforcement, but also the measured strain level has increased. In Figure 16 the measured strain results in the transverse direction are plotted for section 10.8m and 11.5m.

Strain measurements

All strain results can be found in appendix B to E, here only two positions are presented

In 10.8m a small difference in the strain level between the reinforced and non-reinforced is observed see Figure 16a. In 11.5m the test without wires (blue curve) shows buckling behaviour after 70% load, see Figure 16b. The wire reinforced box girder (pink curve) did not show any tendency to buckle even though the box girder was loaded up to 95%. If these observations can be generalized it can be concluded that the buckling resistance has been increased significantly.

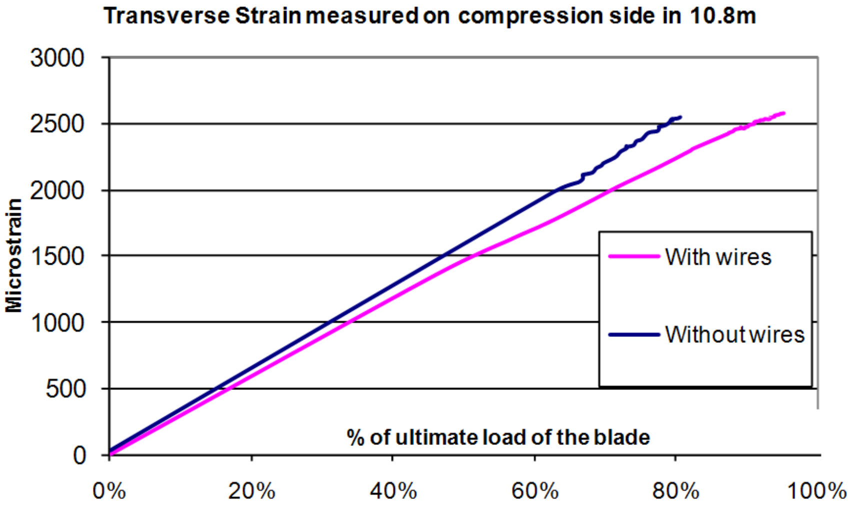


Fig. 16a

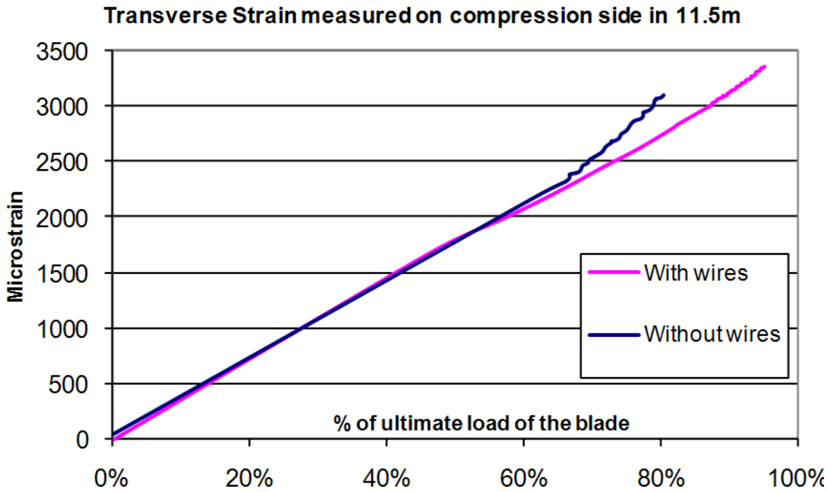


Fig. 16b

Figure 16. Strain gauges measurements with and without cap reinforcement. Transverse strains for section 10.8m (**a**) and 11.5m (**b**) are showed.

4 Test 3 with additional transverse ribs in the critical region and additional longitudinal bulkheads

For the final test longitudinal and transverse reinforcement was mounted. Figure 17 shows the positions of these reinforcements.

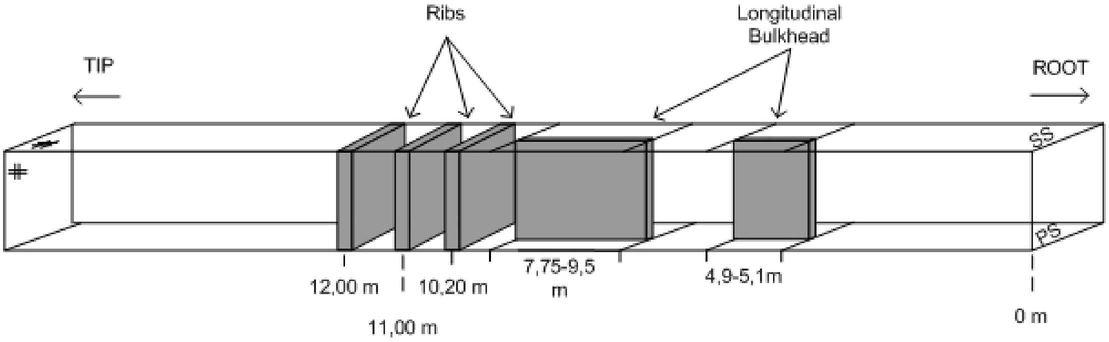


Figure 17. Additional transverse rib reinforcements including additional longitudinal bulkheads.

Photos of the additional rib in the box girder are shown in Figure 18, whereas the additional longitudinal bulkheads are shown in Figure 19.

Fig. 18a

Fig. 18b

Figure 18. a) Rib in 10.2m **b)** Rib in 11m.

Additional ribs were inserted after the cap reinforcement. (test 1 + 2)

Figure 19. Additional longitudinal bulkheads, to prevent buckling failure at height load. The legs under the plates were used to secure the plate position.

The additional longitudinal bulkheads were made of wood plates which have shown to be satisfactory. The failure happened in the predicted region.

4.1. Results from test 3 with additional ribs

This chapter contains photos taken after the final test. Strain gauge results are placed in appendix D. More photos can be found in appendix B1.

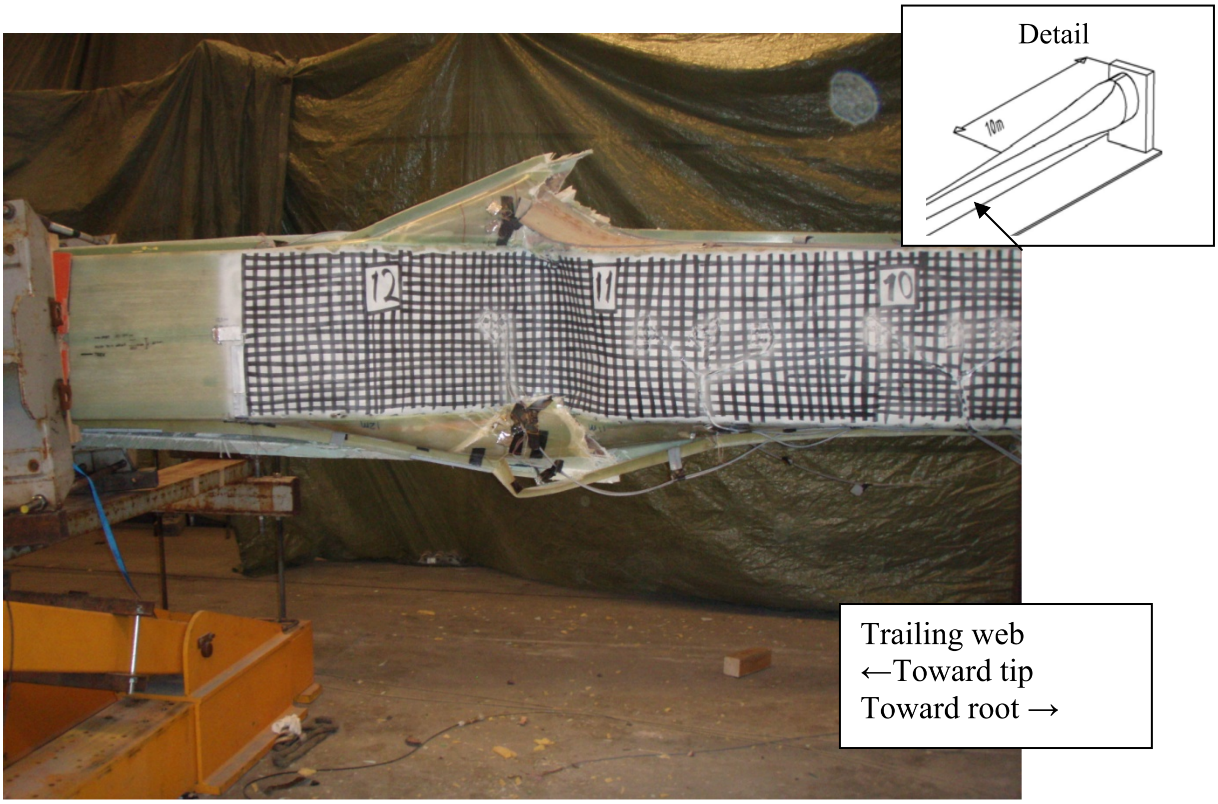


Figure 20. Photo of box girder after the destructive test. The box girder failed in 11.5m between two ribs.

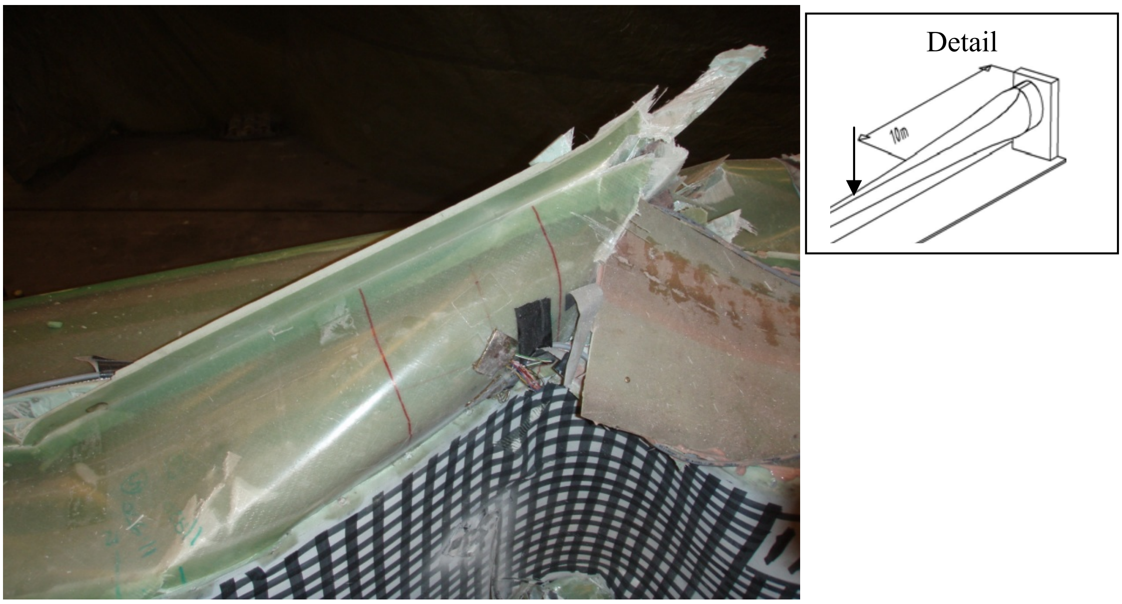


Figure 21. Photos of the shear web in the area where the box girder failed.

In Figure 21 a photo of the shear web towards trailing edge, where the box girder failed. The plate seen on the photo was a repair of damage, this is explained in the following section.

4.2. Damage of the box girder before test

Before the full-scale tests started there was found a damage on the shear web towards trailing edge 11m from the root. The sandwich skin laminate layer had been accidentally polished away in approximately Ø50mm diameter, see Figure 22

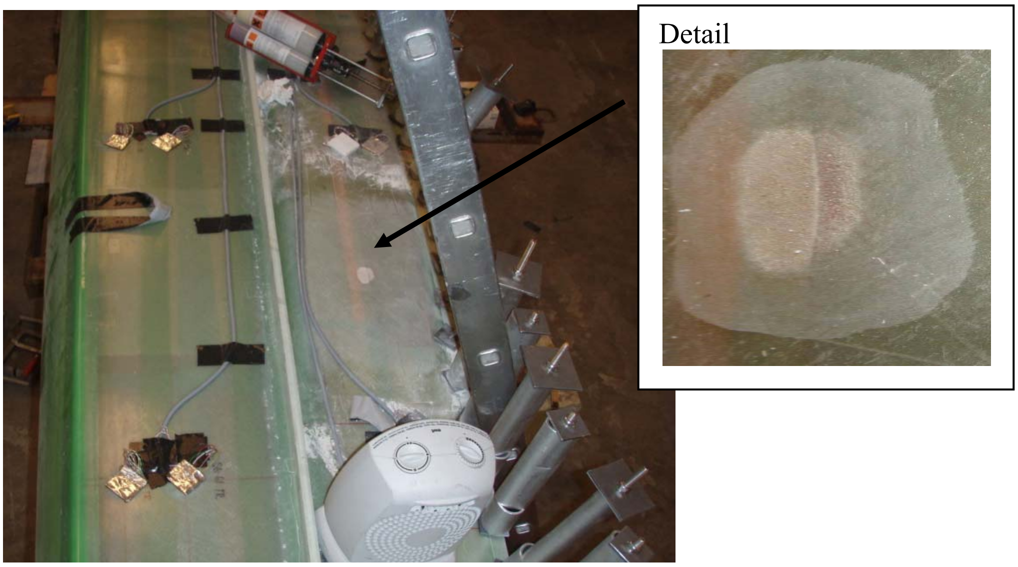


Figure 22. Repair of damage on box girder 2. Right: The repaired damage on the box girder.

The damage was repaired on site with a plate of same material as the original laminate. After preparing the surfaces, the plate was bounded to the web with epoxy adhesive, see Figure 23.

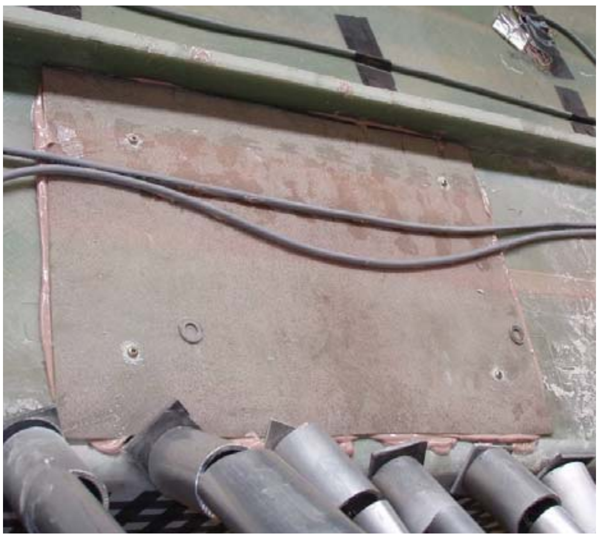


Figure 23. Repair damage on the shear web in the area 10.7m - 11.5m

5 Summary

The DIC investigation of the cap area made it possible to verify the effect of the wire reinforcement. The test without wire was compared with the test with wire reinforcement. It was found that the wire reinforcement increased the buckling strength significantly. The wires were strained with almost 450kg in the section 12m.

In the third and final test with ribs inserted in the expected critical regions, the box girder failed in the area where the numerical analysis had shown low buckling strength. The rib reinforcement improved the ultimate strength with 25% compared to the ultimate test of box girder 1 see reference [1], [2]. The failure of the box girder was close to the repaired area, it is possible that a higher load could have been reached if the web had not been damaged.
The additional longitudinal bulkheads made of wood proved to have sufficient strength to avoid failure in this region. The box girder failed in the expected critical region

6 Acoustic Emission

The load was applied to the spar in a stepwise manner. Meaning that once a target load was achieved there was a pause while the structure accommodated the strain and AE activity could stabilise before the load was increased again. This static loading profile assists the use of AE measurement in controlling the test structure and reducing the risk of premature spar collapse or development of unexpected failure types.

The AE system used was a "handheld" PAC Pocket AE2. This system is easy to transport and quick to apply; it was sufficient for assisting with the test loading of this spar. If any problems had arisen regarding the load application, the reinforcement strategies, unwanted damage types, etc., then a more extensive AE system could have been used to help overcome these difficulties.

For more detailed information on the AE measurements see Appendix A.

As expected, the testing generated most activity at the AE sensor placed on the Suction Side at 10m. A second sensor placed on the reinforcing internal platform near the root of the spar was far less active during loading and confirmed that this reinforcement was stable. Later this second sensor was also moved to the suction side of the spar at 7.5m. Once here the sensor was active during load applications, but to a far lesser degree than the primary sensor at 10m.

In most cases there is also some activity measured during unloading, this is due to movement of the loading yokes against the spar.

In test4 the spar is loaded up to 70% (the highest loading at that point) while the wire reinforcements are in place. The sensor at 10m on the suction side (Ch1) returns a burst of activity with an "energy" rating of 2000. In test05 the spar is loaded in exactly the same way but Ch1 returns only a burst of 350, this drop in activity on subsequent loading is very typical and suggests that no significant damage is present here at this time.

Test06 is the first loading where the wire reinforcement of the spar is removed. For a third time the spar is loaded up to 70%, but this time Ch1 is more active returning an "energy" rating of 700. This increase is most likely due to the redistribution of stress/strain into the spar material caused by the removal of the wire reinforcement.

AE measurement of the spar test has:-

- Assisted in controlling the load application and reducing risk of unwanted damage/failure
- Given early confirmation of activity at the predicted "failure" section of the spar

- Increased confidence in the stability of the internal platform support under load application
- Confirmed that the wire reinforcement has had an effect on the stress/strain distribution in the spar

Further the different AE measurements taken during the spar test are summarised.

Time	AE .data file name	Test title	MAX Load %	Note
Thurs 1540	Test01	Test1, Træk1	57%	
Thurs 1737	Test02	Test1, Træk2	55%	
Thurs 1810	Test03	Test1, Træk3	65%	
Fri 1010	Test04	Test1, Træk4	30%	Part A
			70%	Part B
Fri 1057	Test05	Test1, Træk5	30%	Part A
			70%	Part B
Fri 1230	Test06	Test2, Træk1	72%	
	MISSED TEST!	Test2, Træk2	70%	
Fri 1350	Test07	Test2, Træk3	79%	New sensor positions
Fri 1550	Test08	Test1, Træk6	87%	
Fri 1630	Test09	Test1, Træk7	87%	
Fri 2155	Test10	Test3. Træk1	95%	And fail

Table 1. Table summarising the load history

Test 1 – With tensioned wires

Test 2 – Without tensioned wires

Test 3 – With internal platform supports

AE System information

For this test the AE measurement system used was a Physical Acoustics (PAC) Pocket AE-2 with 20m cabling, in-line amplifier and R15alpha sensors. This is a hand-held system that is very quick and convenient to transport and apply. There are only two channels available so it is important to choose the structural area that is of most interest for AE monitoring. If there had proven to be difficulties during the load application or with any of the reinforcement strategies then a more extensive AE system could have been used to help negotiate them.

The system specifications used throughout the testing are given here.

Spar test .lay file

Time driven data set:
RMS, Abs.Energy, and ASL
RMS/ASL time constant 500ms
Time Drive Data Rate 10.000ms

Both channels enabled and separate
Threshold 40dB
26dB pre-amp, in-line (no internal pre-amplification)
Sample rate 5MSPS   Lower 20kHz   Upper 400kHz

Max allowed duration 6 us
PDT 50us   HDT 200us   HLT 300us

Hit Data set
Amplitude   Energy   Counts   Duration   RMS   ASL   Risetime   Counts TP
Avg.Freq.
Energy reference gain 20dB

Timeline

Thursday April 26th 2007

0700 Arrive at Risø. Pack the AE system (PAC-Pocket), laptop and other equipment
0800 Depart Risø DTU.
1200 Arrive at Sparkær test center.
The PAC system is set up very quickly, with the sensors inside and the cabling running out to a table placed behind the control room blast shell.

The first sensor (Channel 1, Ch1) is positioned on the suction side at approximately 10m. This is a critical area and will be the control sensor for the test loading. This internal section is a busy structural area with many tensioned wires, load cell transducers, strain gauges, etc.
The second sensor (Channel 2, Ch2) is positioned on the horizontal internal platform near the root, towards the suction side. This sensor will provide an early warning for any potential instability in the internal stiffening.

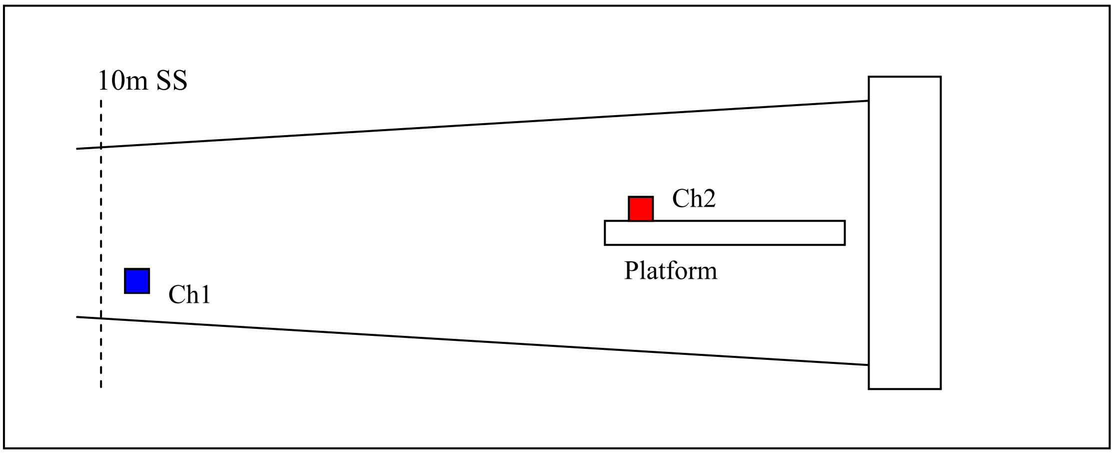


Figure 24. Scheme presenting the general position of the PAC sensors inside the spar

The text in this timeline gives only a quick summary of the AE output; refer to the test load activity trace later in this appendix for more detail. Full txt files for each test are also available.

For the initial series of tests (Test1) the use of tensioned wires inside the spar was investigated.

1540 Test01 (Test1, Træk1)
Max. Load 57%
All AE activity recorded on Ch1

1737 Test02 (Test1, Træk2)
Max. Load 55%
In this test there is a long load hold at 55% (showing no significant AE activity) before unloading. It was necessary to unload due to problems with the load application.
All AE activity recorded on Ch1

1810 Test03 (Test1, Træk3)
Max. Load 65%
The vast majority of AE activity from this test is at Ch1, however there is a single energetic hit detected on the reinforcing platform (Ch2) during load hold at 65%. This is also the first time there is an audible response from the spar during loading.

1830 Testing completed for today

Friday April 27th 2008

0800 Sensor check. Ch1 sensor appears loose and is refastened.

1010 Test04 (Test1, Træk4)
Max. Load 70%
For this test the spar was loaded up to 30% maximum load and then held while a change was made to the loading configuration to allow application of higher loads.

There is no significant AE activity until the load reaches 70%. Although the vast majority of activity from this test is at Ch1, there is a limited amount of AE activity on the reinforcing panel (Ch2) during load hold at 70%.

1057 Test05 (Test1, Træk5)
Max. Load 70%
For this test the spar was loaded up to 30% maximum load and then held while a change was made to the loading configuration to allow application of higher loads.
As this is the second time the spar is loaded to 70% there is significantly less AE activity.

LUNCH During this time the tension in the wires was released so that a load could be applied to the spar allowing a comparison of the structural response without this reinforcement type.

1230 Test 06 (Test2, Træk1)
Max. Load 72%
The AE measurements for this (and all subsequent tests) start from 30% load.
No significant AE activity is detected until 45% applied load.
All AE activity is recorded on Ch1

1300 It is decided to move the AE sensors from inside the spar to the outside, in order to minimise the likelihood of any hardware damage when the spar fails. Ch1 is again placed at roughly the same location; Suction side 10m. Ch2 is now placed at Suction side 7.5m. See the schematic below.

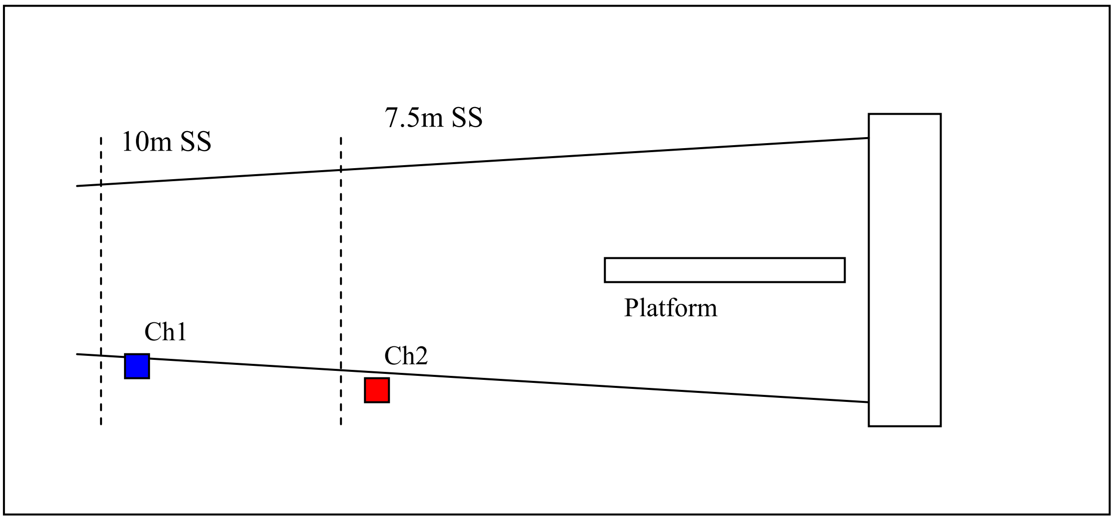


Figure 25. Scheme of the general position of the PAC sensors outside the spar

1315 MISSED TEST (Test2, Træk2)
Max. Load 70%
While this position change of the AE system took place the spar was loaded again.

1350 Test07 (Test2, Træk3)
Max. Load 79%

The new sensor positions give a slightly different activity profile. Ch1 (SS 10m) is still most active, however there is now also activity at Ch2 (SS 7.5m) during load application. There is no significant AE activity from either sensor until the applied load exceeds 70%.

1400 The tension in the wire reinforcements is now reapplied.

1550 Test08 (Test1, Træk6)

Max. Load 87%

With the wire reinforcement now reapplied, the test configuration is back to the original (Test1) condition.

There are low intensity bursts of AE activity from both sensors during load increases to 60% and 70%. There are higher intensity bursts of AE activity from both sensors during load increases to 79%, 83% and 87%.

The activity at Ch1 is generally of a higher energy content than the activity at Ch2.

1630 Test09 (Test1, Træk7)

Max. Load 87%

In this second loading up to 87% there is far less activity. At each load increase above 70% there is a slight AE activity during load application, but nothing significant.

1700 It was then necessary to significantly reinforce the spar with internal platforms. This configuration (Test3) would then be loaded to spar collapse.

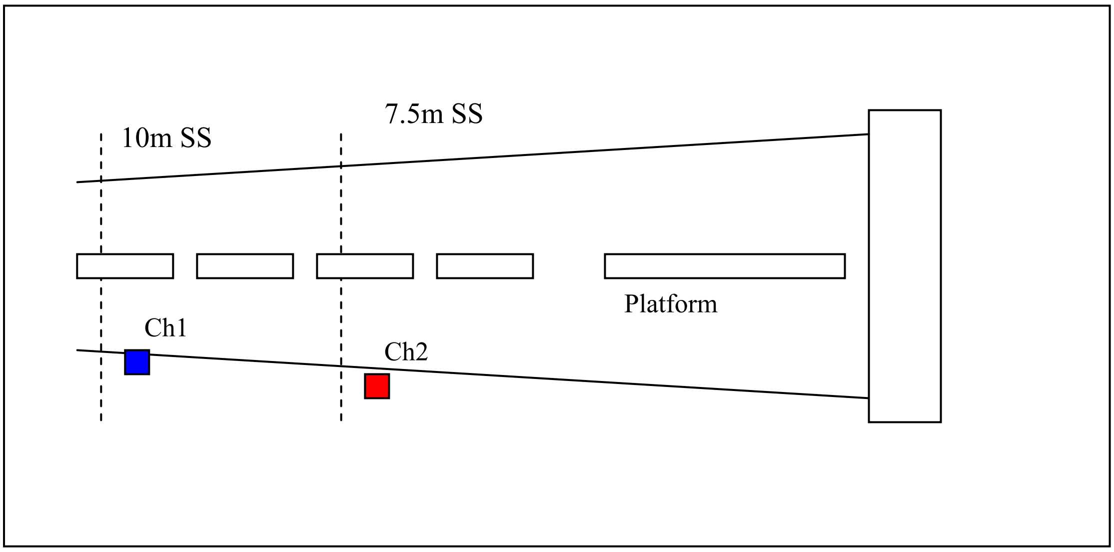


Figure 26. Scheme of the general position of the PAC sensors outside the spar after reinforcement by internal platforms

2155 Test10 (Test3, Træk1)

Max. Load 95%

There is significant AE activity once the load exceeds 87%. This activity is hugely dominated by the output from Ch1 at SS 10m. However, AE activity dies down during a 60 second load hold at 90%, before spar failure during load increase to 95%.

Summary of AE measurements on Spar test

The load was applied to the spar in a stepwise manner. Meaning that once a target load was achieved there was a pause while the structure accommodated the strain and AE activity could stabilise before the load was increased again. This static loading profile assists the use of AE measurement in controlling the test structure and reducing the risk of premature spar collapse or development of unexpected failure types.

The AE system used was a "handheld" PAC Pocket AE2. This system is easy to transport and quick to apply; it was sufficient for assisting with the test loading of this spar. If any problems had arisen regarding the load application, the reinforcement strategies, unwanted damage types, etc., then a more extensive AE system could have been used to help overcome these difficulties.

As expected, the testing generated most activity at the AE sensor placed on the Suction Side at 10m. A second sensor placed on the reinforcing internal platform near the root of the spar was far less active during loading and confirmed that this reinforcement was stable. Later this second sensor was also moved to the suction side of the spar at 7.5m. Once here the sensor was active during load applications, but to a far lesser degree than the primary sensor at 10m.

In most cases there is also some activity measured during unloading, this is due to movement of the loading yokes against the spar.

In test04 the spar is loaded up to 70% (the highest loading at that point) while the wire reinforcements are in place. The sensor at 10m on the suction side (Ch1) returns a burst of activity with an "energy" rating of 2000. In test05 the spar is loaded in exactly the same way but Ch1 returns only a burst of 350, this drop in activity on subsequent loading is very typical and suggests that no significant damage is present here at this time.

Test06 is the first loading where the wire reinforcement of the spar is removed. Once again the spar is loaded up to 70%, but this time Ch1 is more active returning and "energy" rating of 700. This increase is most likely due to the redistribution of stress/strain into the spar material caused by the removal of the wire reinforcement.

AE measurement of the spar test has:-

- Assisted in controlling the load application and reducing risk of unwanted damage/failure
- Given early confirmation of activity at the predicted "failure" section of the spar
- Increased confidence in the stability of the internal platform support under load application
- Suggested that the wire reinforcement has had an effect on the stress/strain distribution in the spar

AE activity traces for each test load

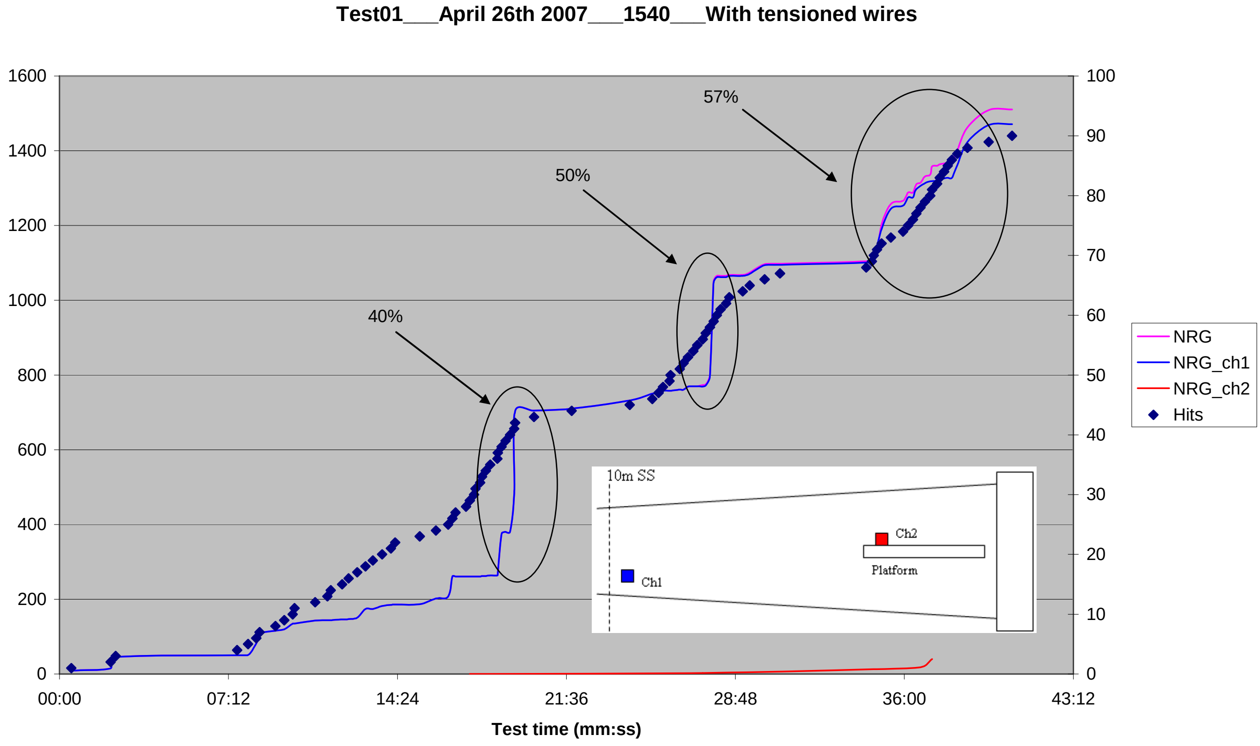


Figure 27. Activity trace for test 1, loading with tensioned wires.

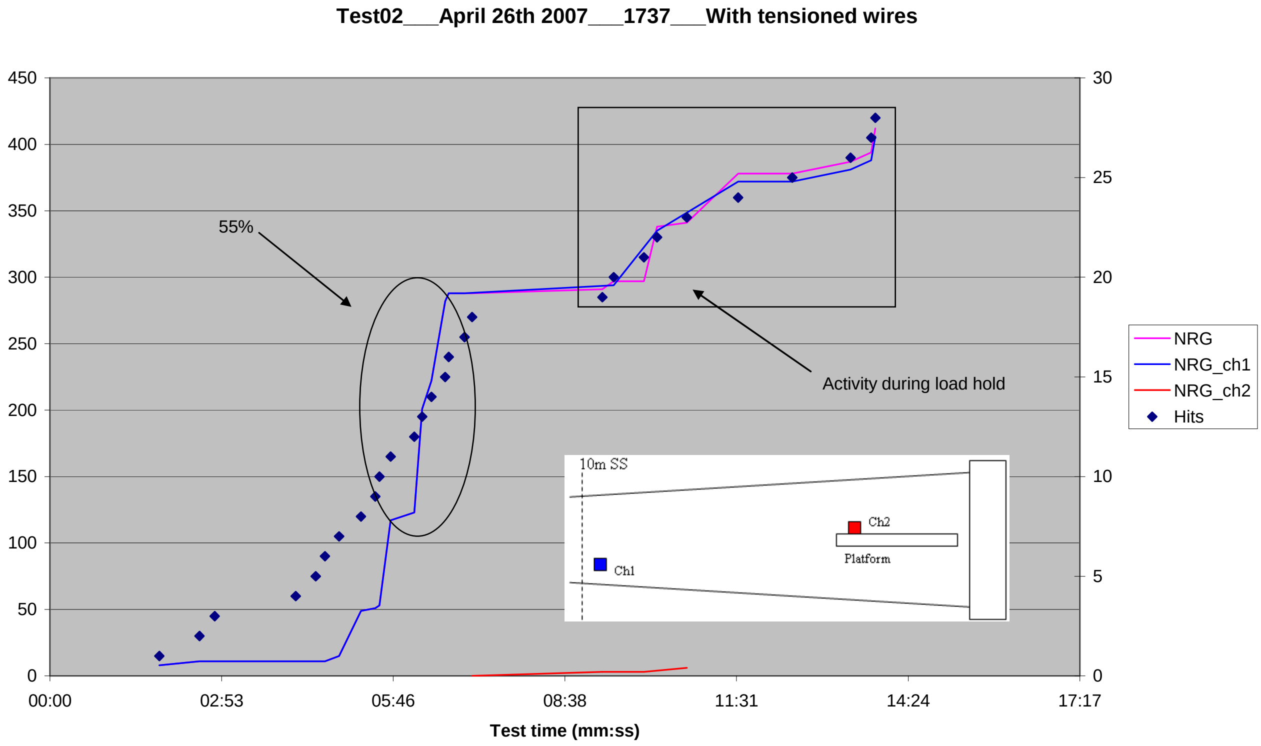


Figure 28. Activity trace for test 2, loading with tensioned wires.

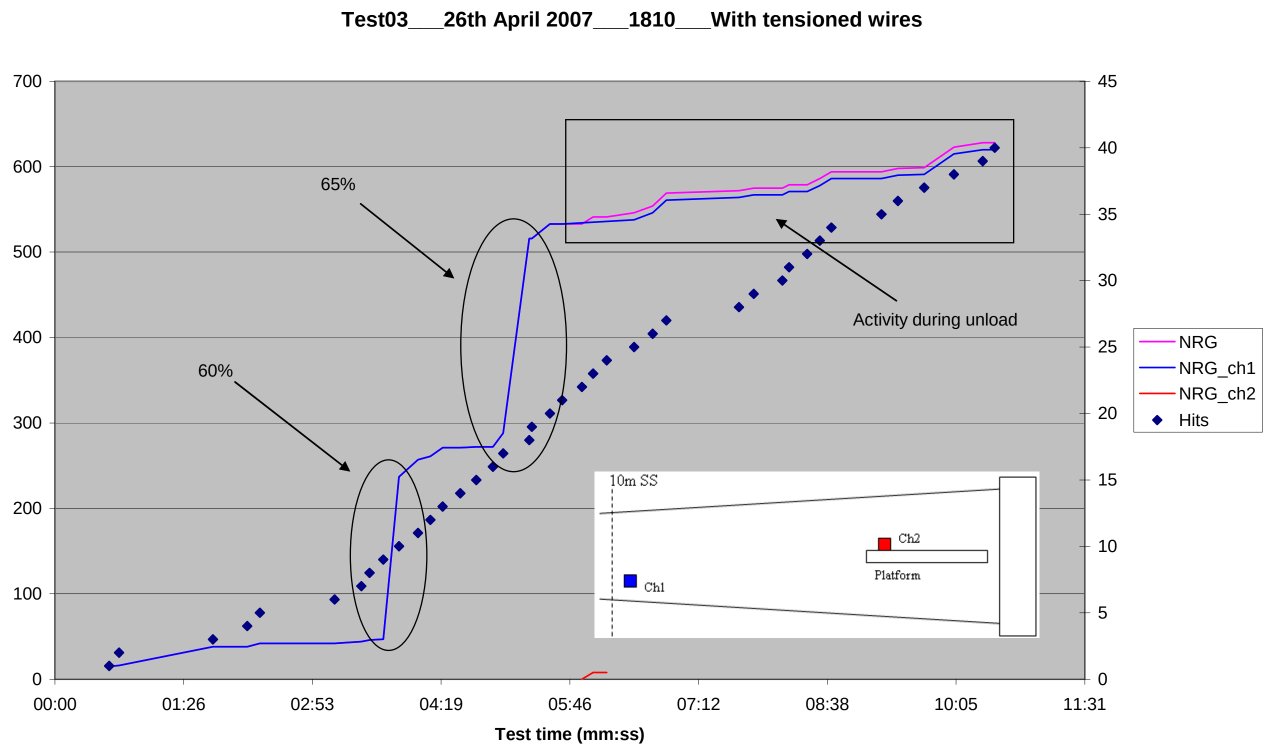


Figure 29. Activity trace for test 3, loading with tensioned wires.

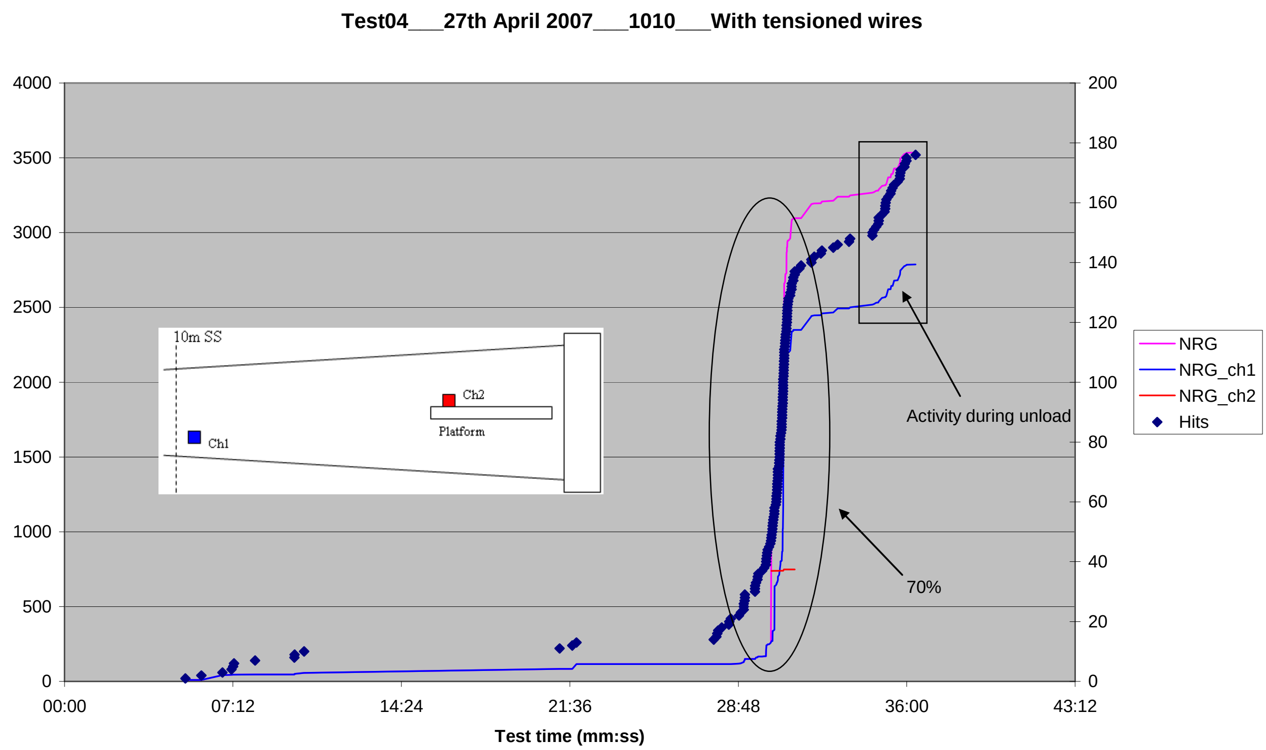


Figure 30. Activity trace for test 4, loading with tensioned wires.

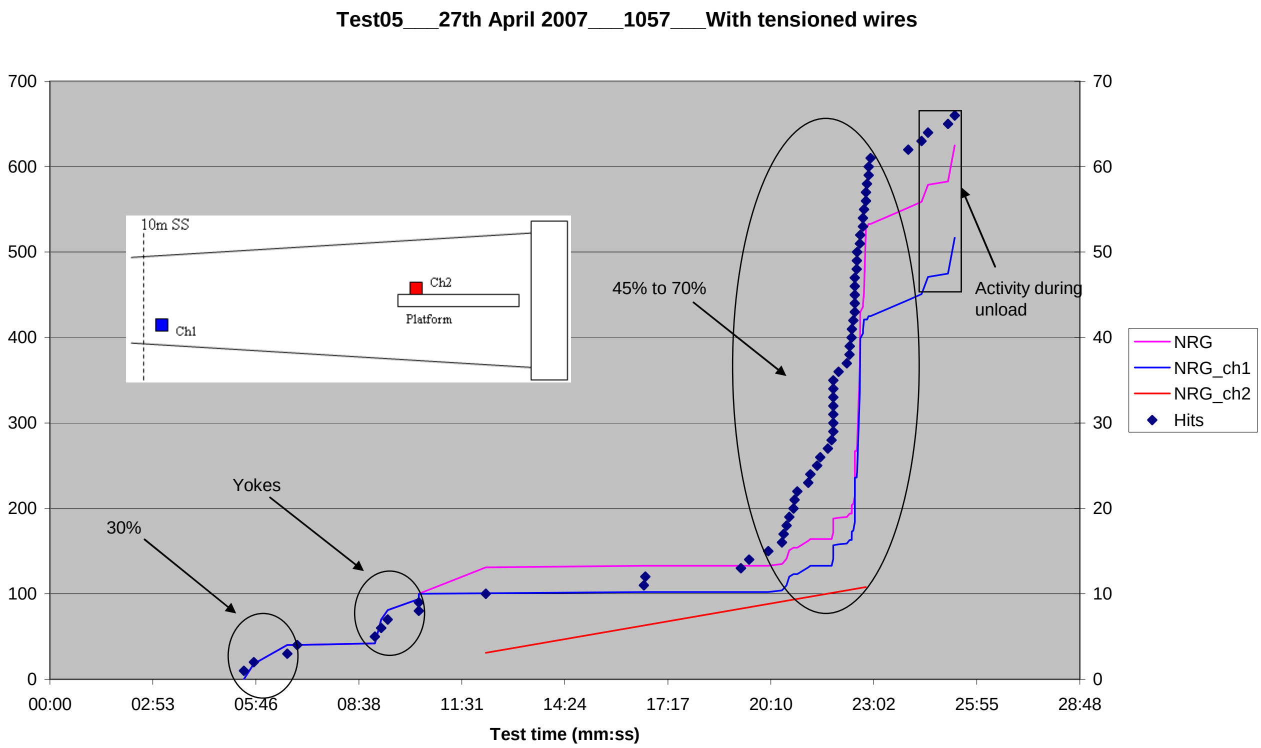


Figure 31. Activity trace for test 5, loading with tensioned wires.

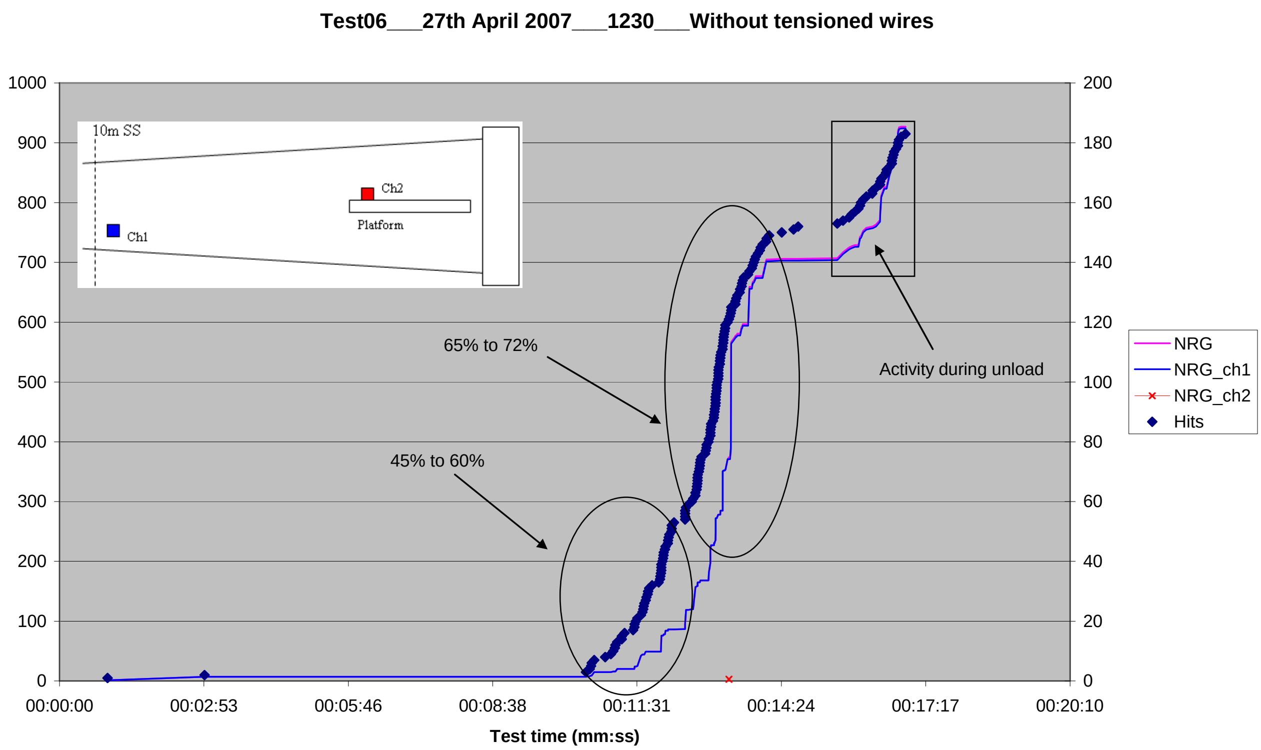


Figure 32. Activity trace for test 6, loading with tensioned wires.

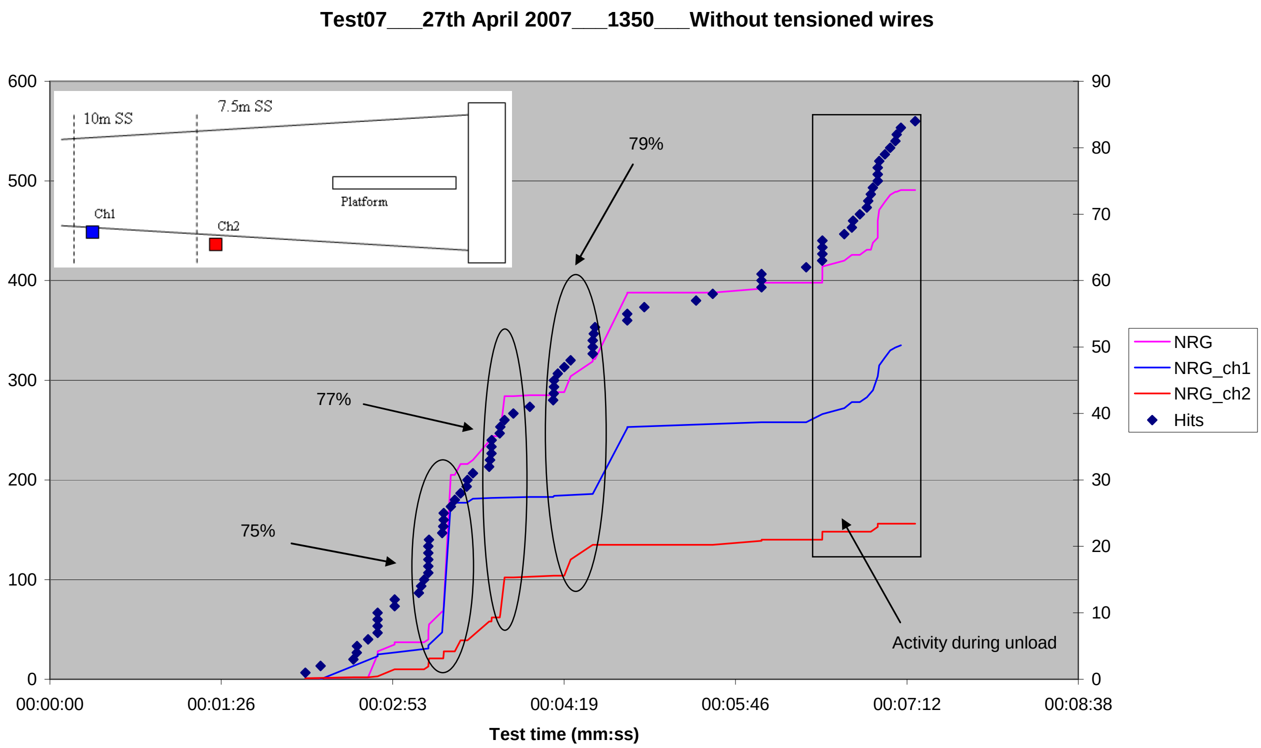


Figure 33. Activity trace for test 7, loading with tensioned wires.

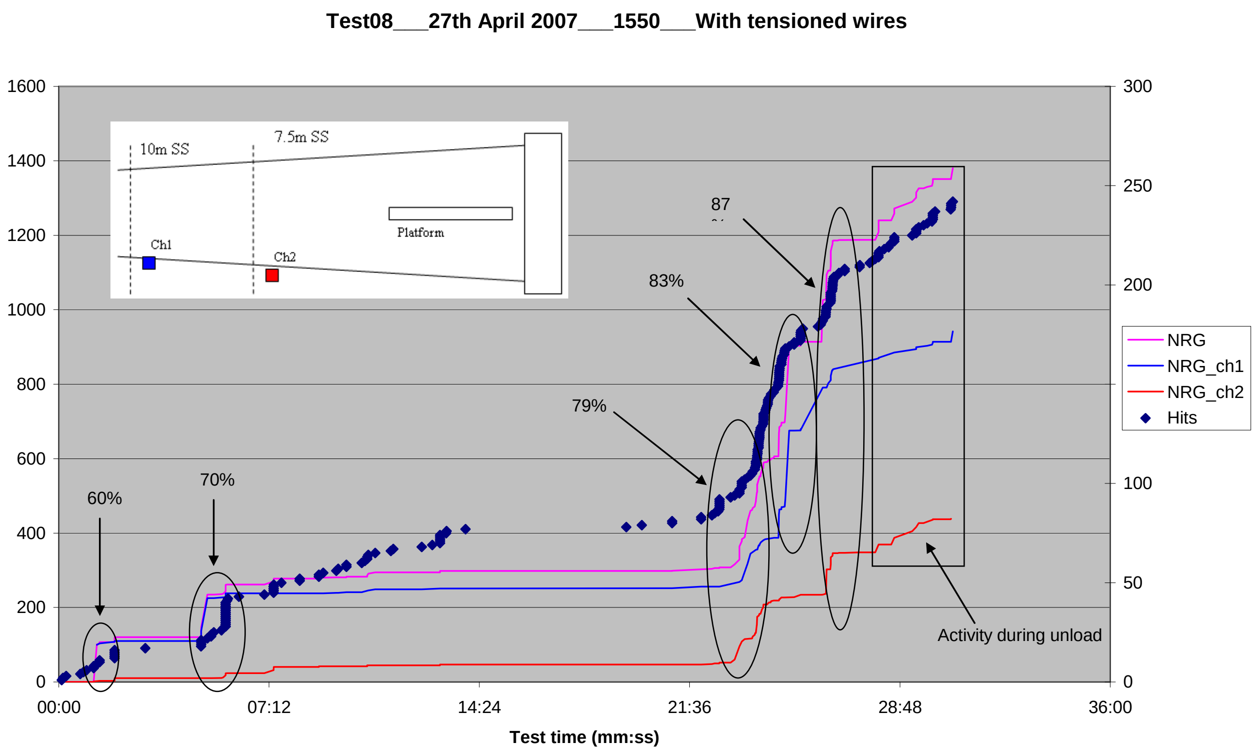


Figure 34. Activity trace for test 8, loading with tensioned wires.

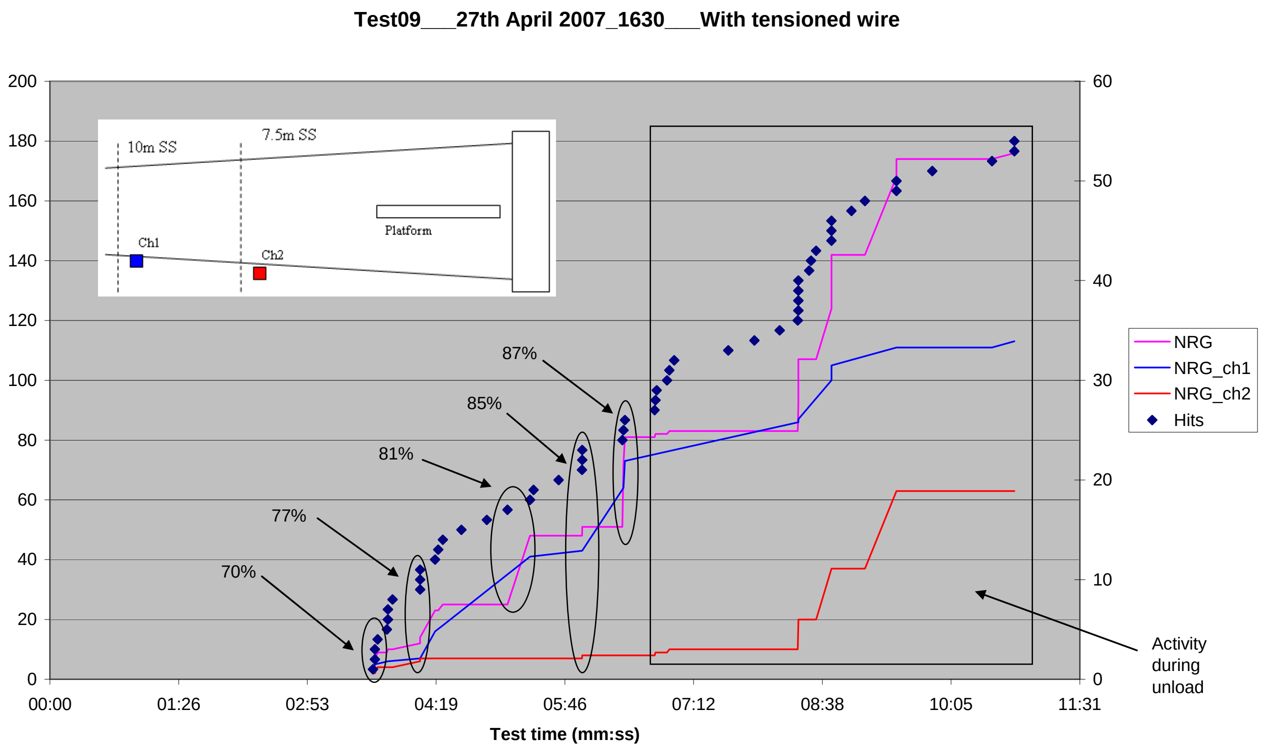


Figure 35. Activity trace for test 9, loading with tensioned wires.

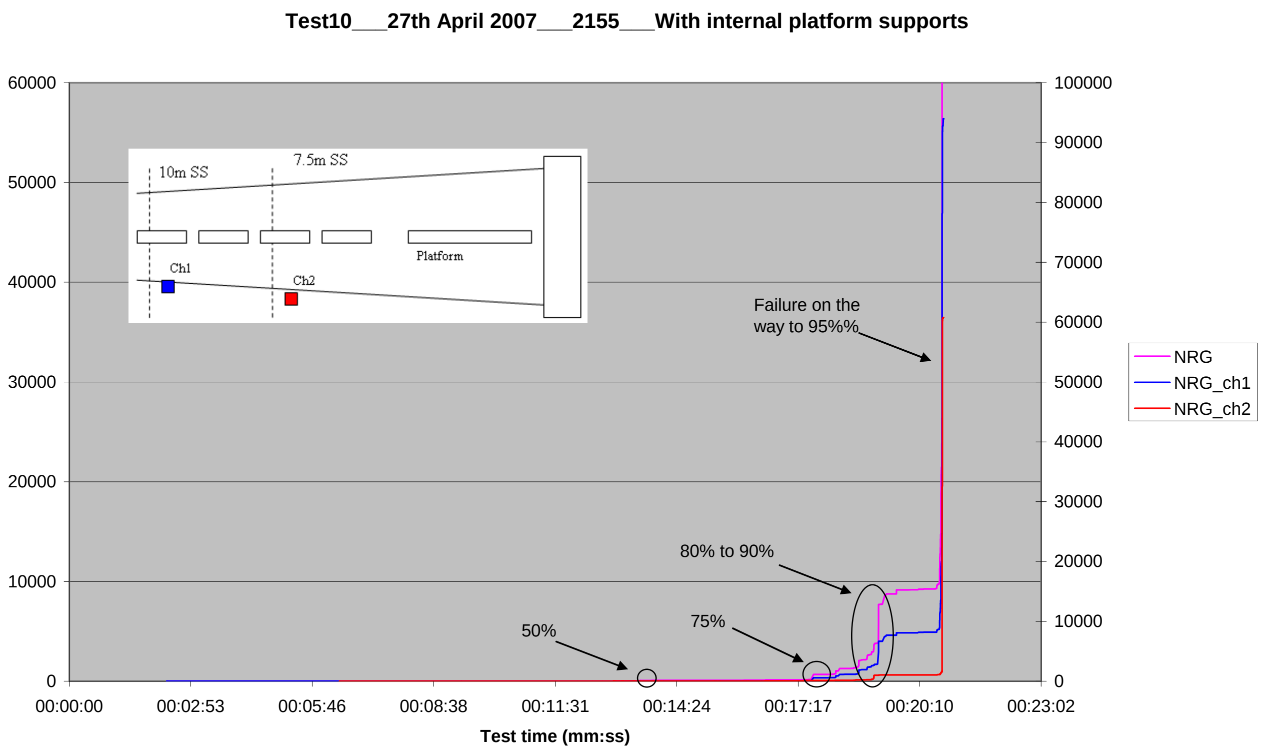


Figure 36. Activity trace for test 10, loading with internal platform supports.

7 References

[1] "*Ultimate strength of a large wind turbine blade*" Find M. Jensen. PhD Thesis. Risø National Laboratory, Technical University of Denmark. Submitted May 2008

[2] "*Full-scale Test of a SSP34m box girder 1 – Data Report*" F. M. Jensen, K. Branner, P. H. Nielsen, P. Berring, T. S. Antvorskov, M. Nielsen, B. Lund; C. Jensen, J. H. Reffs, R. F. Nielsen; P. H. Jensen, M. McGugan, K. Borum, R. S. Hansen, C. Skamris, F. Sørensen, R. S. Nielsen, J. H. Laursen, M. Klein, A. Morris, A. Gwayne, H. Stang, J. Wedel-Heinen, J. P. Dear, A. Puri, A. Fergusson. Risø-R-RIS88(EN) (Marts 2008)

[3] *"Full-scale testing and finite element simulation of a 34 metre long wind turbine blade"* Find M. Jensen, Andy Morris. NAFEMS World Congress – Vancouver (April 2007)

[4] *"Structural testing and numerical simulation of a 34m. composite wind turbine blade"* Find M. Jensen, B.G. Falzon, J. Ankersen, H. Stang Composite Structures 76 (August 2005)

[5] *"The Brazier effect in Wind-Turbine Blades and its Influence on Design"* F.M. Jensen, P.M. Weaver, L.S. Cecchini, H. Stang, R.F. Nielsen, Department of Wind Energy – Risoe National Laboratory, Technical University of Denmark. Department of Aerospace Engineering – University of Bristol – Bristol, UK DeepSea. Department of Civil Engineering – Technical University of Denmark – (submitted May 2008)

[6] *"Optics measurement and numerical simulation of a wind turbine blade"* Weitao Ma. Risø National Laboratory, Roskilde, and Technical University of Denmark, Lyngby, Denmark, (30th July 2007)

[7] *"Guidelines for Design of Wind Turbines"* – DNV/ Risø 2nd Edition

[8] *"WO 2008-071195 Reinforced aerodynamic profile (cap reinforcement-patent A)"* Jensen. F.M. (Submitted Dec. 2006) PTC/WO 2008/071195

[9] "*Effect of sandwich core properties on ultimate strength of a wind turbine blade*" 8thedition. Branner, K., Jensen, F.M., Berring, P., Puri, A., Morris, A., and Dear, J. International Conference on sandwich Structures. (April 2008)

[10] *"Analysis of Wind Turbine Material using Digital Image Correlation"* Amit Puri, Jon P. Dear, Andrew Morris & Find M. Jensen. EWEC Conference (2008)

[11] *"Experimental techniques for improving life assessment and qualification of wind turbine blades"* A. Puri, A. Fergusson, J. Dear, A. Morris, Find. M. Jensen. T12 Structural Design and Materials EWEC (2008).

[12] "*Digital image correlation and finite element analysis of wind turbine blade structural components*" A. Puri, A. Fergusson, J. Dear, A. Morris, F. M. Jensen 2007 European Offshore Wind Energy Association conference. Germany, (December 2007)

[13] "*Development of wind turbine rotor blade structural health monitoring techniques using digital image correlation"* Amit Puri, Alexander Fergusson, John

Dear, Andrew Morris, Find M. Jensen 2007 British Wind Energy Association Conference. Scotland. Abstract (October, 2007). Abstract only

8 Nomenclature

The tested box girder has the following terms:

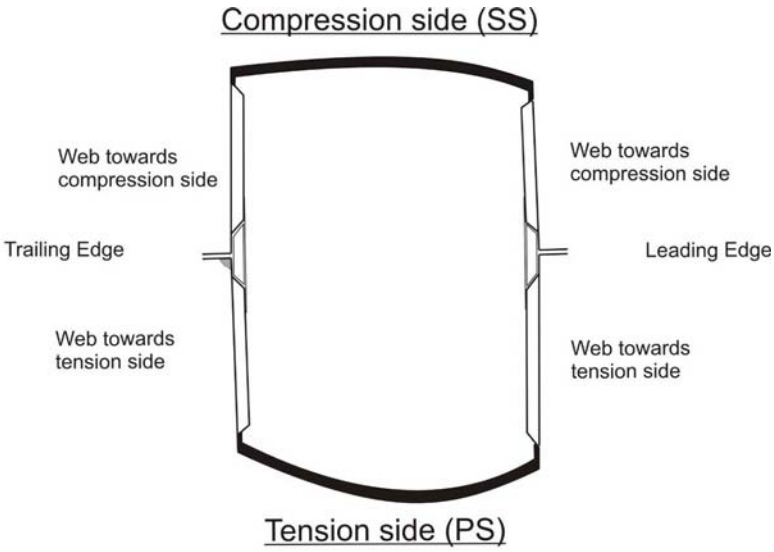


Figure 37. Box girder seen from the tip toward the root

Strain gauges definition

(UD)	Unidirectional (0° in longitudinal direction)
(Bx)	Biax (0°/90°)
(Tx)	Triax-Rosette (0°/45°/90°)

Blade root:	Part of the wind turbine blade that is closest to the hub
Box girder:	Primary lengthwise structural member of a wind turbine blade
Design loads:	Loads that the turbine is designed to withstand. They are obtained by applying the appropriate partial load factors to the characteristic values.
Edgewise:	Direction that is parallel to the local chord of the blade
Flapwise:	Direction that is perpendicular to the surface swept by the non-deformed rotor blade axis
Strain:	Ratio of the elongation (in shear displacement of a material subjected to stress) to the original length of the material.
Trailing edge:	Edge of blade pointing opposite travelling direction.
Ultimate strength:	Measure of the maximum (static) load-bearing capacity of a material or structural element

9 Appendices.

A: More photos of the box girder after failure

B: Strain Gauge plan

C: Wire placement and sizes

D: Measured strain gauge results flapwise bending with no reinforcement

Strain gauge longitudinal 0°
Strain gauge transverse 90°
Strain gauge transverse 45°

E: Measured strain gauge results flapwise bending with wire reinforcement.

Strain gauge longitudinal 0°
Strain gauge transverse 90°
Strain gauge transverse 45°

F: Measured strain gauge results flapwise bending with rib reinforcement.

Strain gauge longitudinal 0°
Strain gauge transverse 90°
Strain gauge transverse 45°

Appendix A: More photos of the box girder after failure

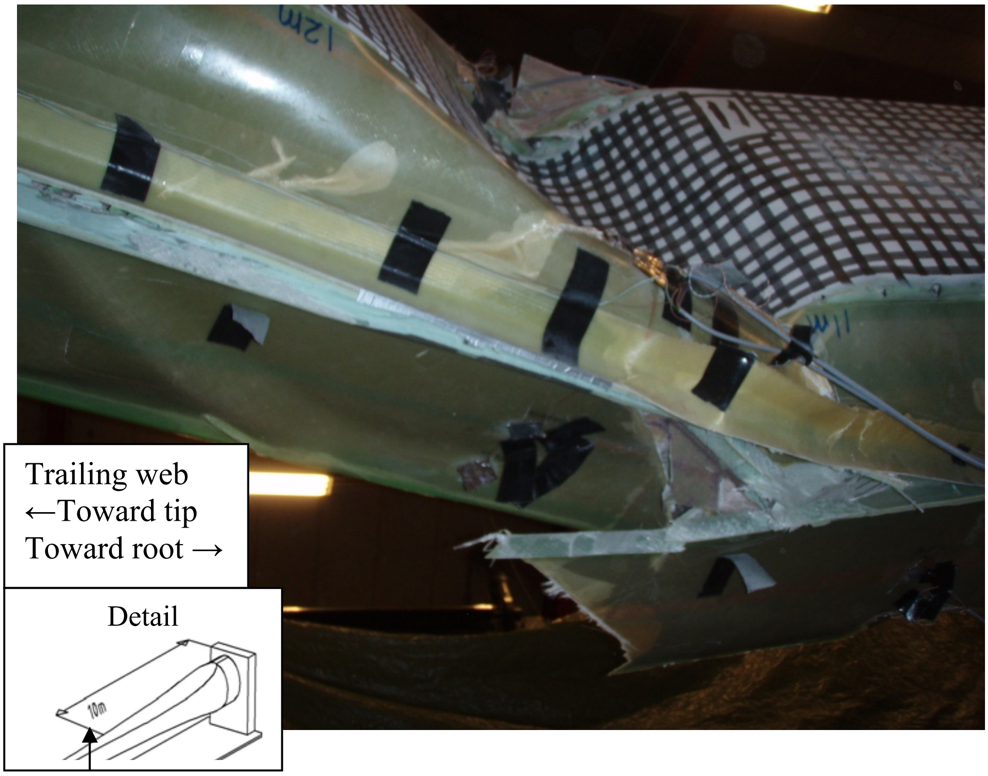


Figure 38. 10.1m Leading web of the box girder.

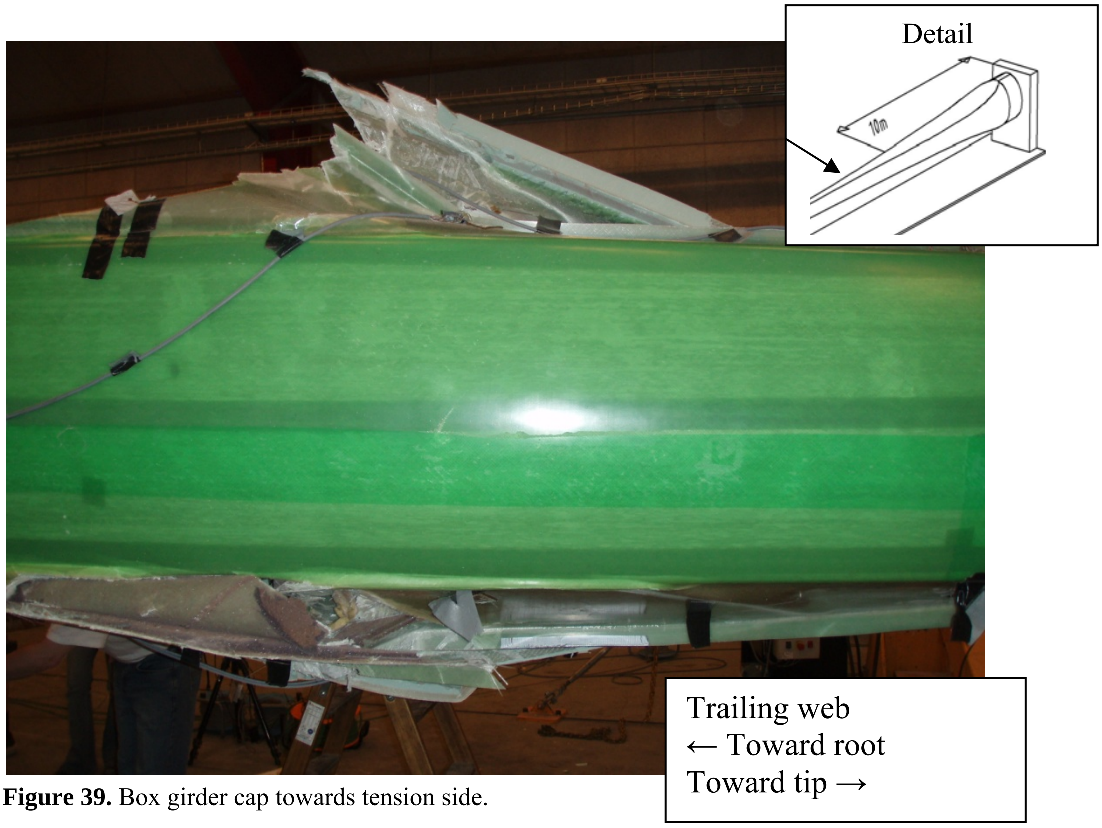


Figure 39. Box girder cap towards tension side.

Appendix B: Strain gauge plan

This chapter present the strain gauge plan including sketch over the 10.60;11.5 and 12.5

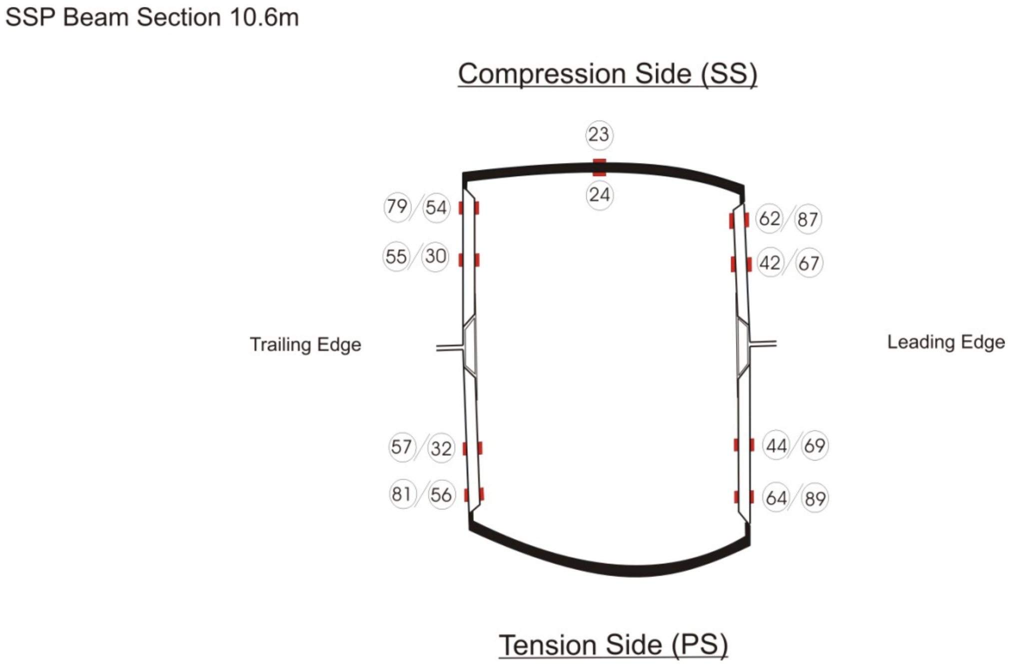


Figure 40. Sketch of the strain gauge placement at the 10.6m section.

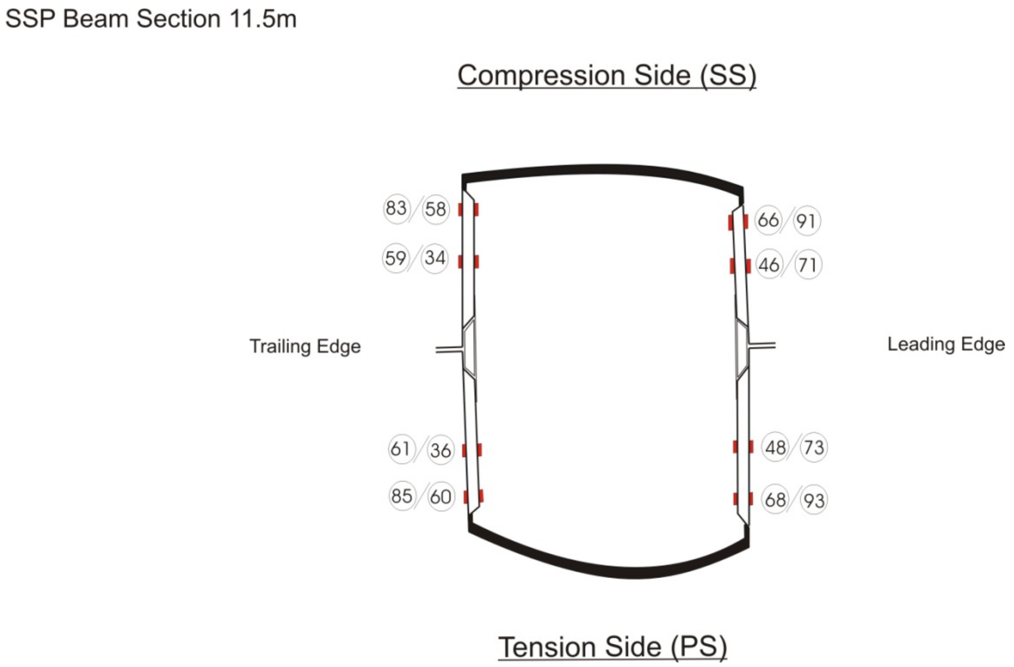


Figure 41. Sketch of the strain gauge placement at the 11.5m section.

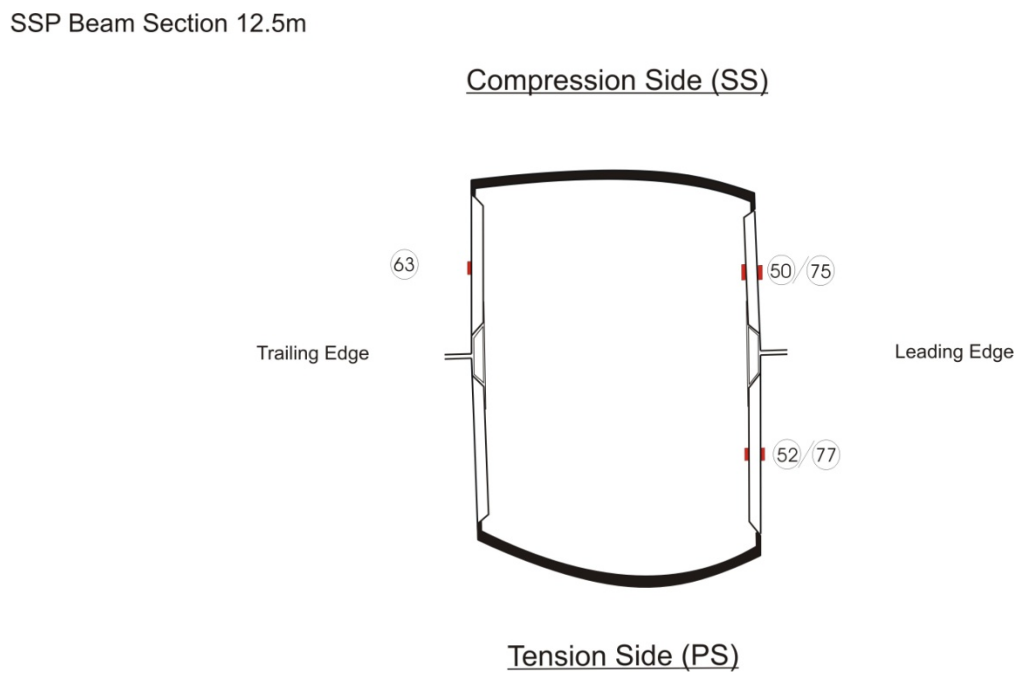


Figure 42. Sketch of the strain gauge placement at the 12.5m section.

Strain Gauge plan Cap

Numbering of strain gauge from 13-2-07

Unix gauge

Distance from start	Longitudinal compression			
[m]	Outer surface 0°	Outer surface 90°	Inner surface 0°	Inner surface 90°
9.60	1	13	2	14
9.75	3	15	4	16
10.00	5	17	6	18
Skot 10.2				
10.40	7	19	8	20
10.60				
10.80	9	21	10	22
Skot 11				
11.50				
Skot 12				
12.50	11		12	
Skot 13				

Triax gauge

Distance from start [m]	Longitudinal compression Outer surface 0° .1	Outer surface 90° .2	Outer surface 45° .3	Inner surface 0° .1	Inner surface 90° .2	Inner surface 45° .3
9.60						
9.75						
10.00						
Rib 10.2						
10.40						
10.60	23	23.2	23.3	24.1	24.2	24
10.80						
Rib 11						
11.50	25	25.2	25.3	26.1	26.2	26
Rib 12						
12.50						
Rib 13						

Triax gauge

Distance from start [m]	Longitudinal compression Outer surface 0° .1	Outer surface 90° .2	Outer surface 45° .3	Inner surface 0° .1	Inner surface 90° .2	Inner surface 45° .3
9.60						
9.75						
10.00						
Rib 10.2						
10.40						
10.60	2	23.2	23.3	24.1	24.2	2
10.80						
Rib 11						
11.50	4	25.2	25.3	26.1	26.2	4
Rib 12						
12.50						
Rib 13						
12.00	27					
13.00	29					

Strain Gauge plan Web

Triax

Distance from root [m]	Web	Trailing Edge: Outer surface 0° .1	Outer surface 90° .2	Outer surface 45° .3	Inner surface 0° .1	Inner surface 90° .2	Inner surface 45° .3
10.60	Toward SS	2	55.2	55.3	2	30.2	30.3
	Toward PS	4	57.2	57.3	4	32.2	32.3
11.50	Toward SS	6	59.2	59.3	6	34.2	34.3
	Toward PS	8	61.2	61.3	8	36.2	36.3
12.50	Toward SS	10	63.2	63.3	10	38.2	38.3
	Toward PS	12	65.2	65.3	12	40.2	40.3
13.00	-	-	-	-	-	-	-

Distance from root [m]	Web	Leading Edge: Outer surface 0° .1	Outer surface 90° .2	Outer surface 45° .3	Inner surface 0° .1	Inner surface 90° .2	Inner surface 45° .3
10.60	Toward SS	14	67.2	67.3	14	42.2	42.3
	Toward PS	16	69.2	69.3	16	44.2	44.3
11.50	Toward SS	18	71.2	71.3	18	46.2	46.3
	Toward PS	20	73.2	73.3	20	48.2	48.3
12.50	Toward SS	22	75.2	75.3	22	50.2	50.3
	Toward PS	24	77.2	77.3	24	52.2	52.3
13.00	-	-	-	-	-	-	-

Triax

Distance from root [m]	Web	Trailing Edge Outer surface 0° .1	Outer surface 90° .2	Outer surface 45° .3	Inner surface 0° .1	Inner surface 90° .2	Inner surface 45° .3
10.60	Toward SS	26	79.2	79.3	26	54.2	54.3
	Toward PS	28	81.2	81.3	28	56.2	56.3
11.50	Toward SS	30	83.2	83.3	30	58.2	58.3
	Toward PS	32	85.2	85.3	32	60.2	60.3
12.00	-	-			-		
13.00	-	-			-		

Triax

Distance from root [m]	Web	Leading Edge Outer surface 0° .1	Outer surface 90° .2	Outer surface 45° .3	Inner surface 0° .1	Inner surface 90° .2	Inner surface 45° .3
10.60	Toward SS	34	87.2	87.3	34	62.2	62.3
	Toward PS	36	89.2	89.3	36	64.2	64.3
11.50	Toward SS	38	91.2	91.3	38	66.2	66.3
	Toward PS	40	93.2	93.3	40	68.2	68.3
12.00	-	-			-		
13.00	-	-			-		

Appendix C: Wire placement and sizes

The wires had two diameters, 6mm and 8mm, see Table 2.

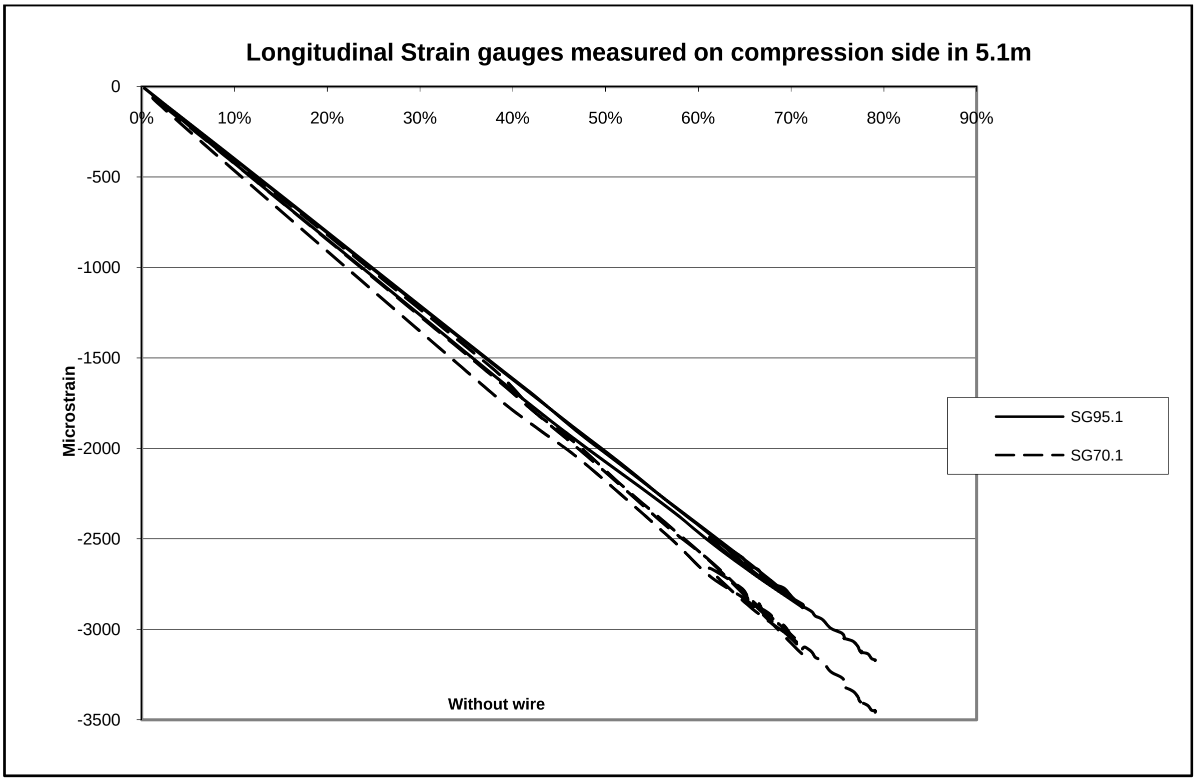
Distance [m] from root	Wire size [mm]
8.5	8
8.6	8
8.7	8
8.8	8
8.9	8
9	6
9.1	8
9.2	6
9.3	8
9.4	6
9.5	8
9.6	8
9.7	8
9.8	8
9.9	8
10	**6**
10.1	8
10.2	8
10.3	8
10.4	8

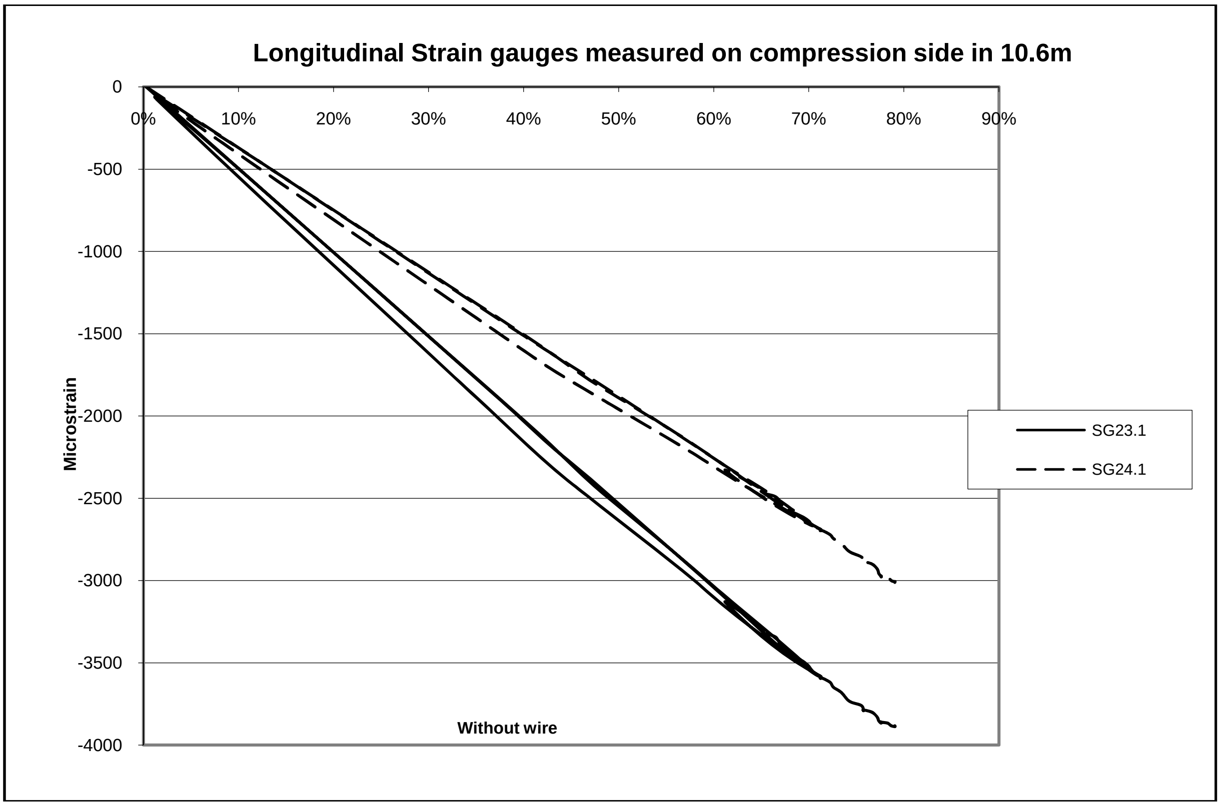
Distance [m] from root	Wire size [mm]
10.5	8
10.6	6
10.7	8
10.8	6
10.9	8
11	**6**
11.1	8
11.2	6
11.3	8
11.4	6
11.5	8
11.6	8
11.7	8
11.8	8
11.9	8
12	**6**
12.1	8
12.2	8
12.3	8
12.4	8
12.5	8

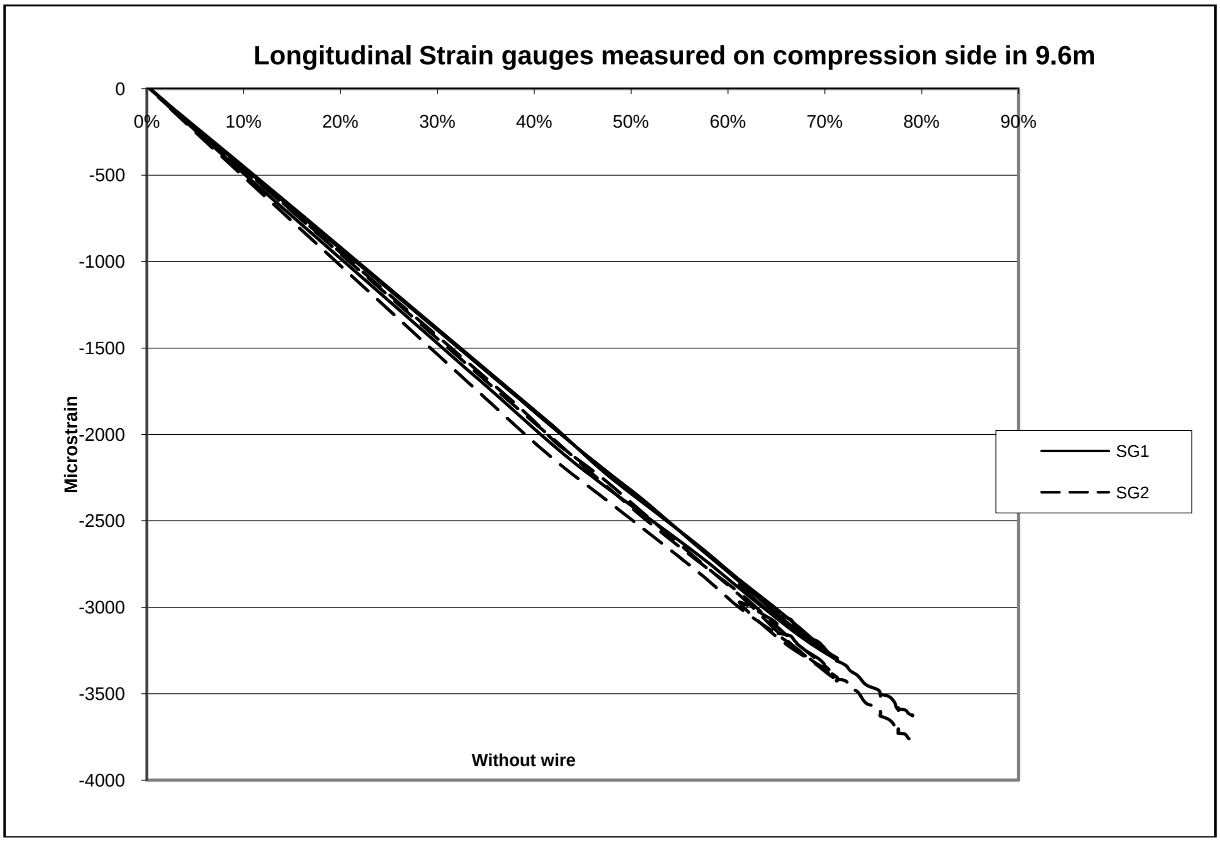
Table 2. Wire diameter and positions in the box girder.

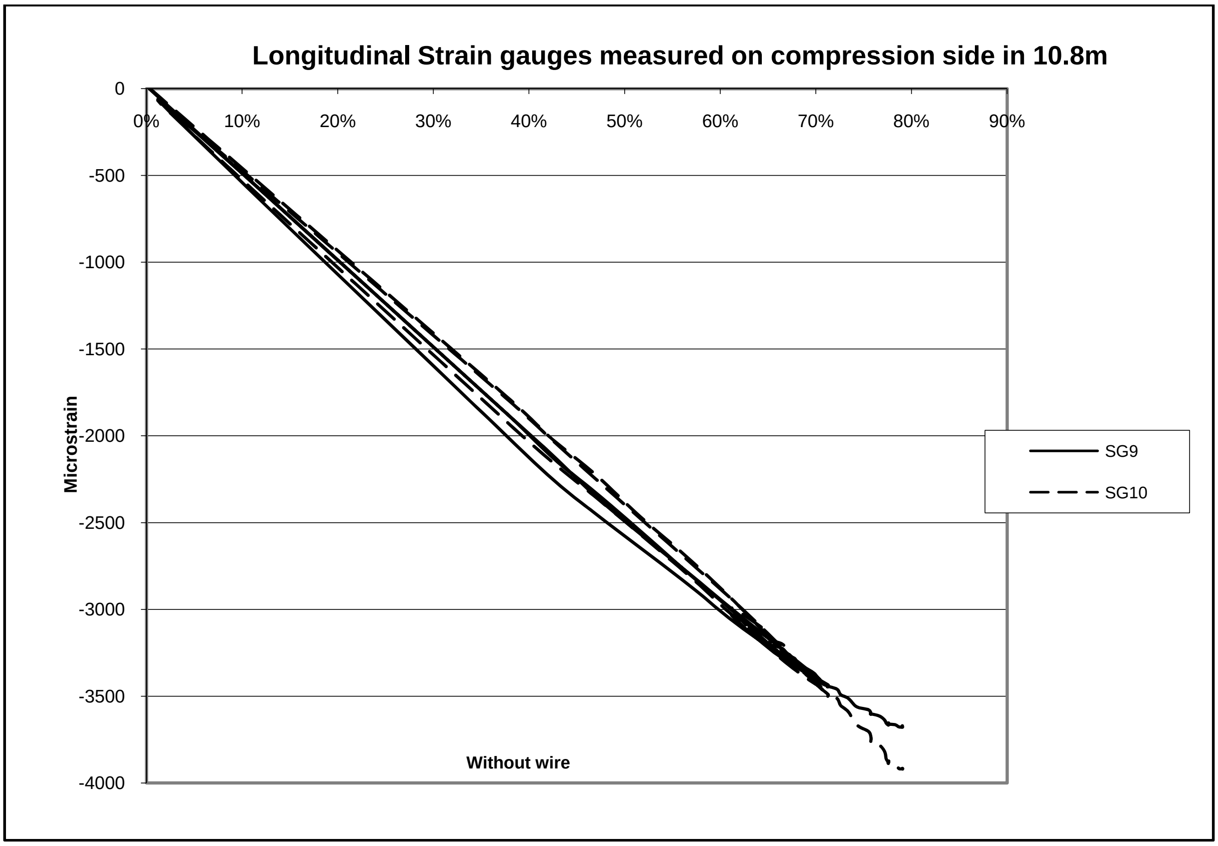
Appendix D: Measured strain gauge results flapwise bending with no reinforcement

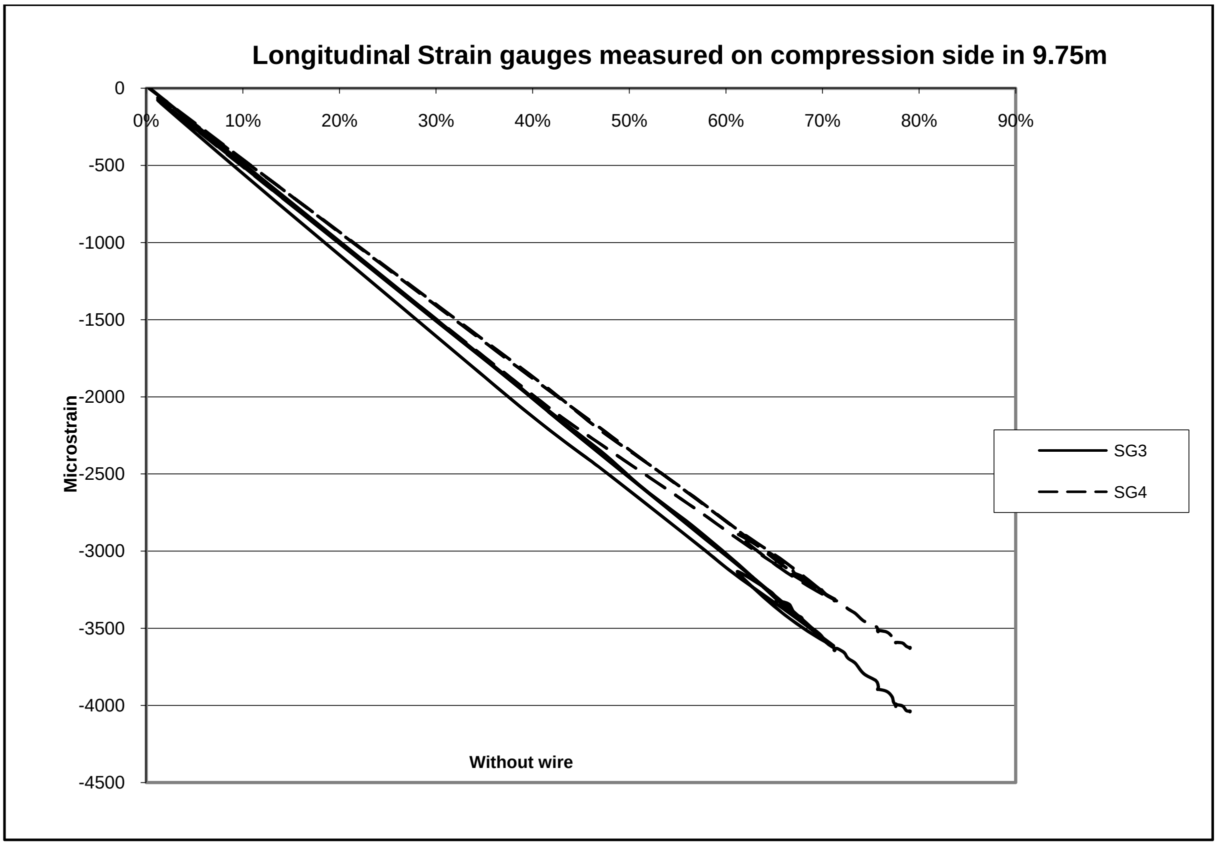
Graphs of Longitudinal measurements without wire

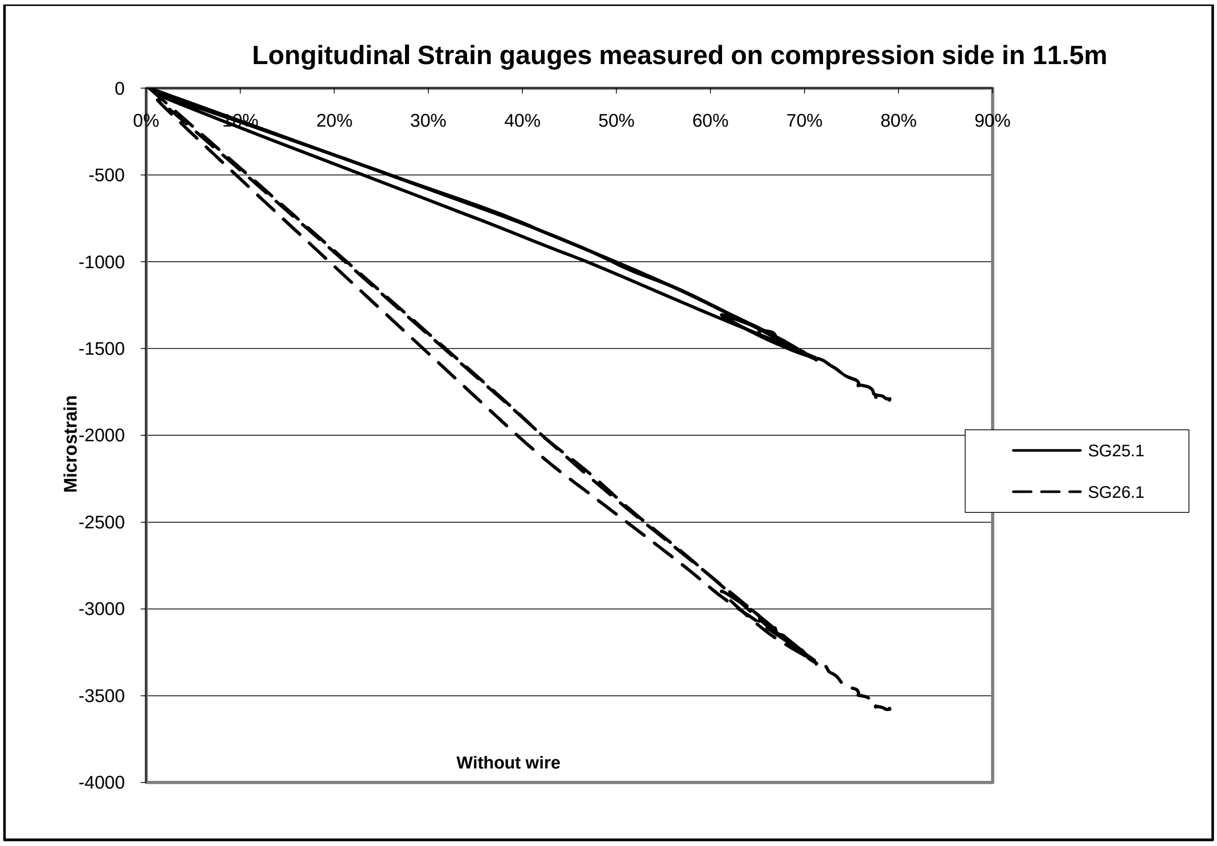


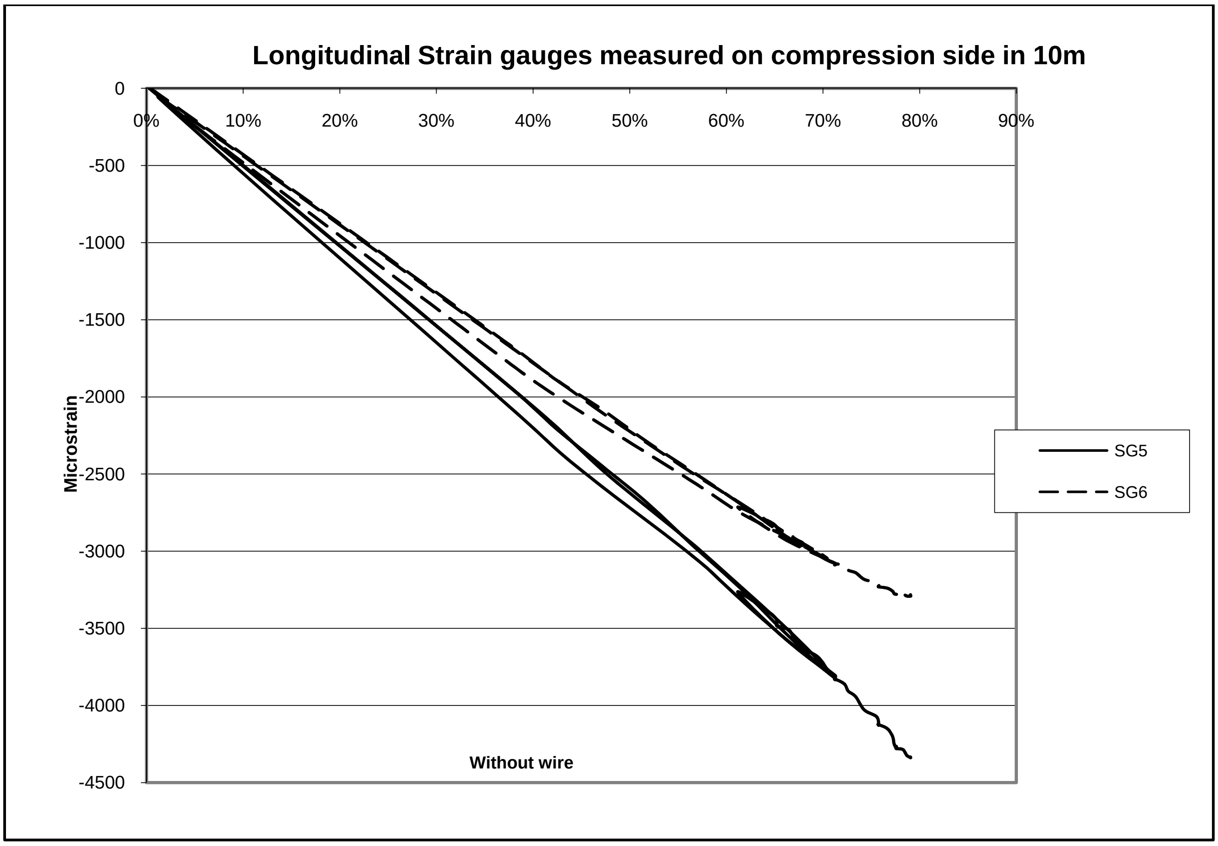



Longitudinal Strain gauges measured on compression side in 9.6m
Microstrain
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG1
SG2

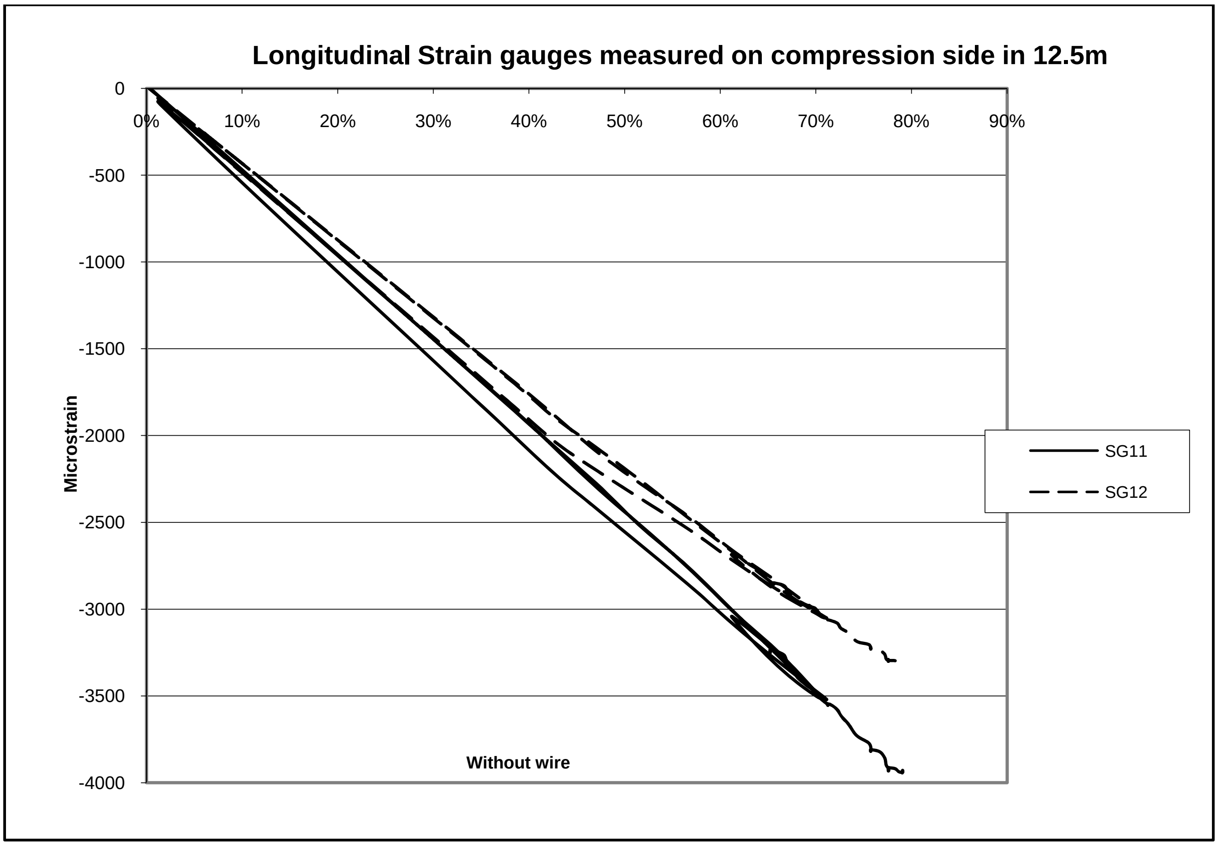

Longitudinal Strain gauges measured on compression side in 10.8m
Microstrain
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG9
SG10


Longitudinal Strain gauges measured on compression side in 9.75m
Microstrain
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG3
SG4

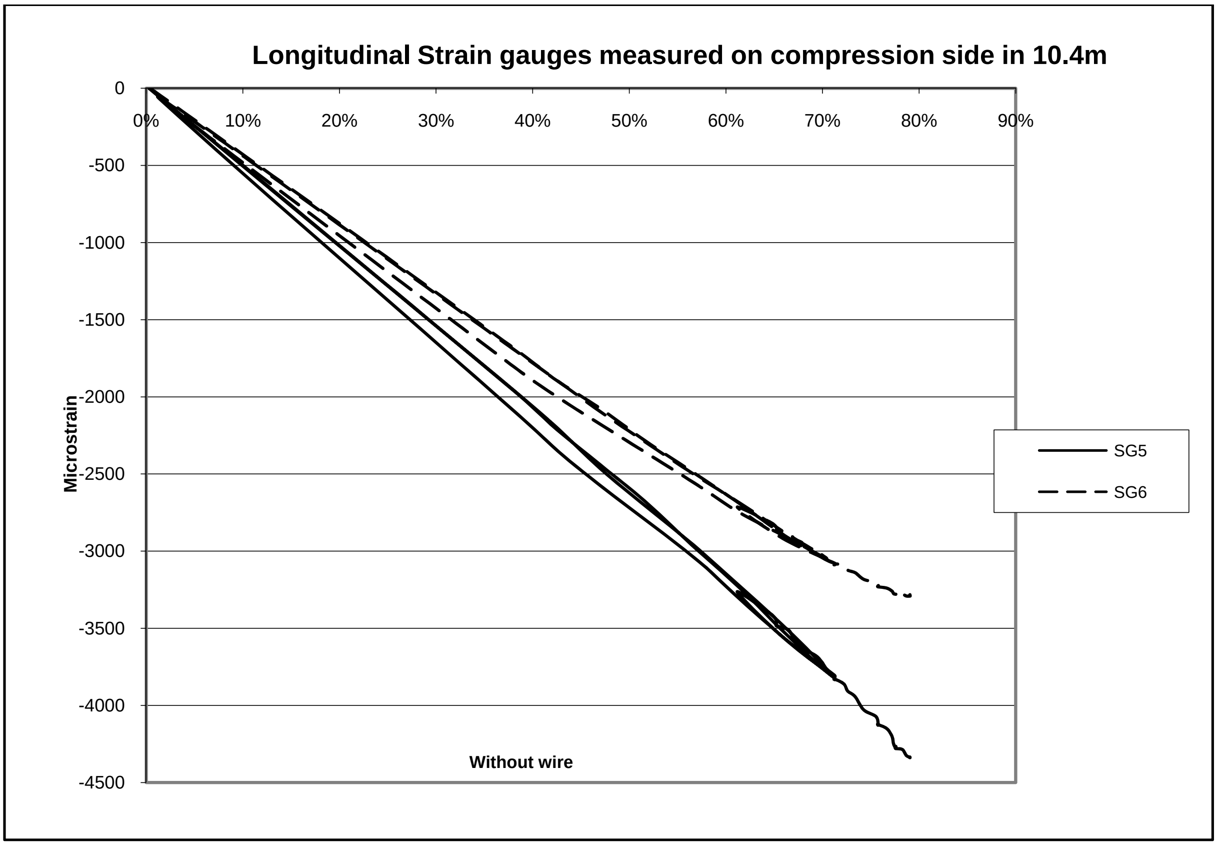

Longitudinal Strain gauges measured on compression side in 11.5m
Microstrain
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG25.1
SG26.1



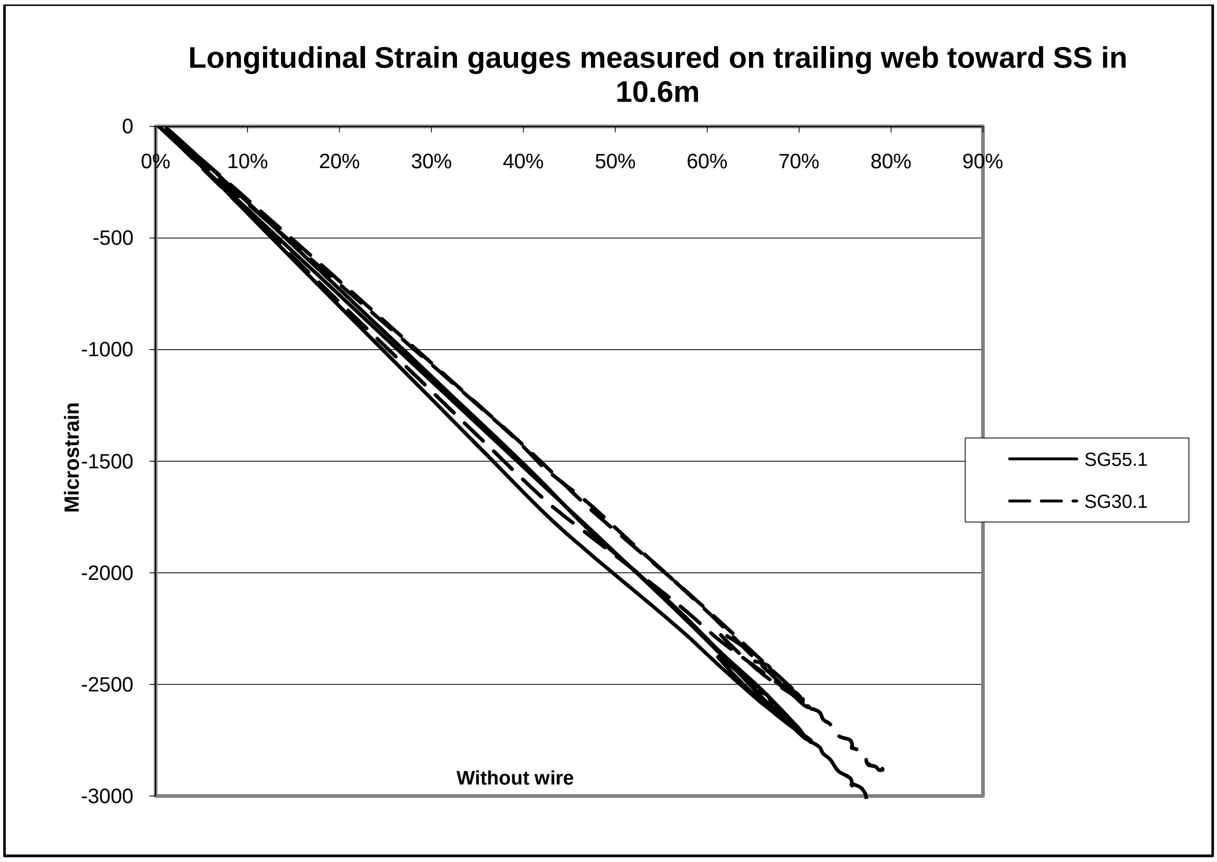
Longitudinal Strain gauges measured on compression side in 10m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Microstrain
Without wire
SG5
SG6



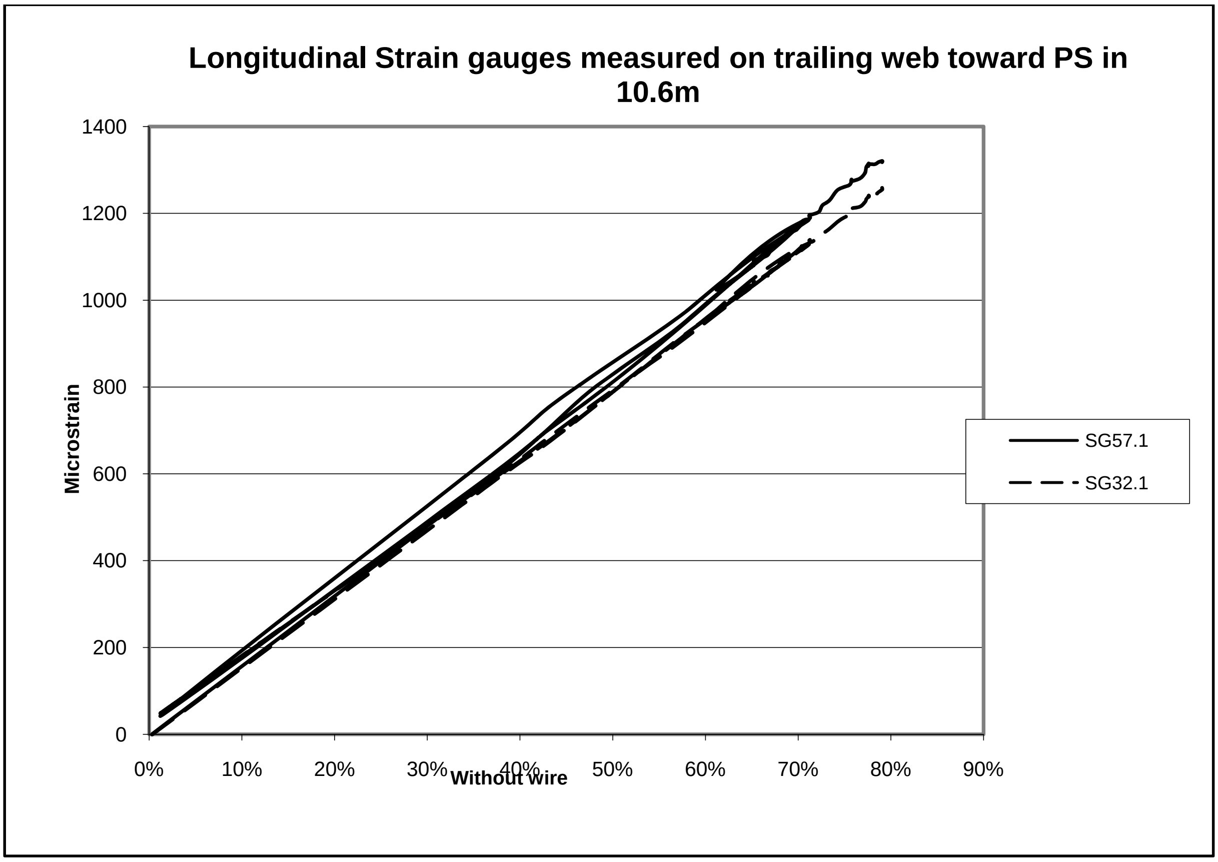
Longitudinal Strain gauges measured on compression side in 12.5m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Microstrain
Without wire
SG11
SG12

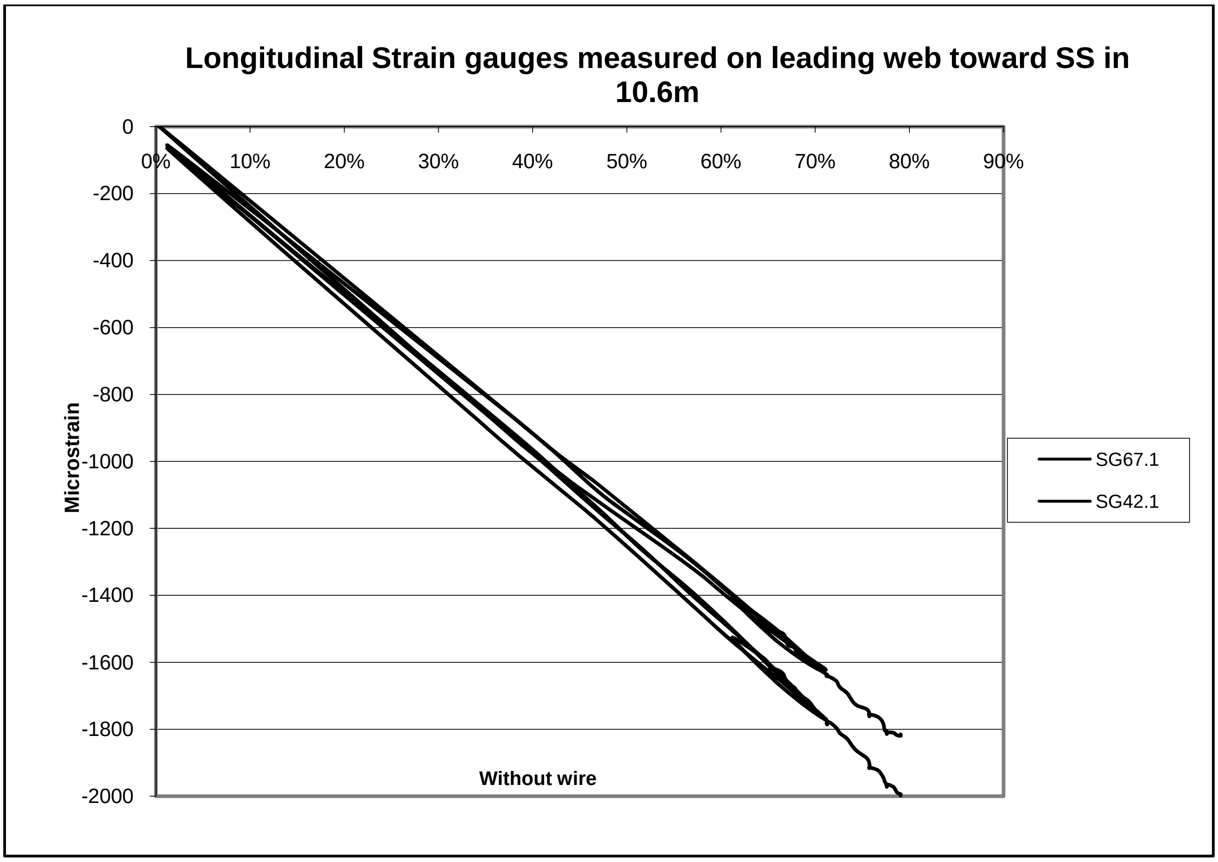


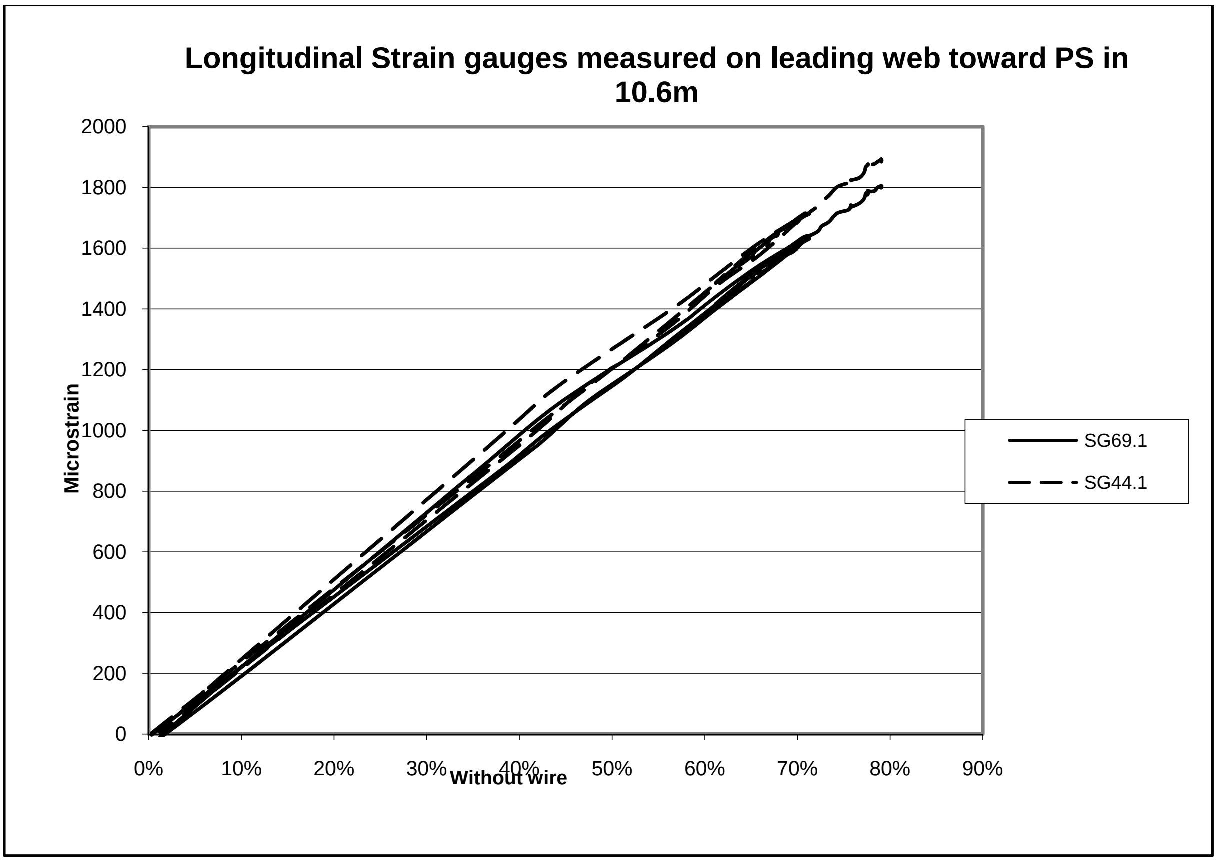
Longitudinal Strain gauges measured on compression side in 10.4m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Microstrain
Without wire
SG5
SG6

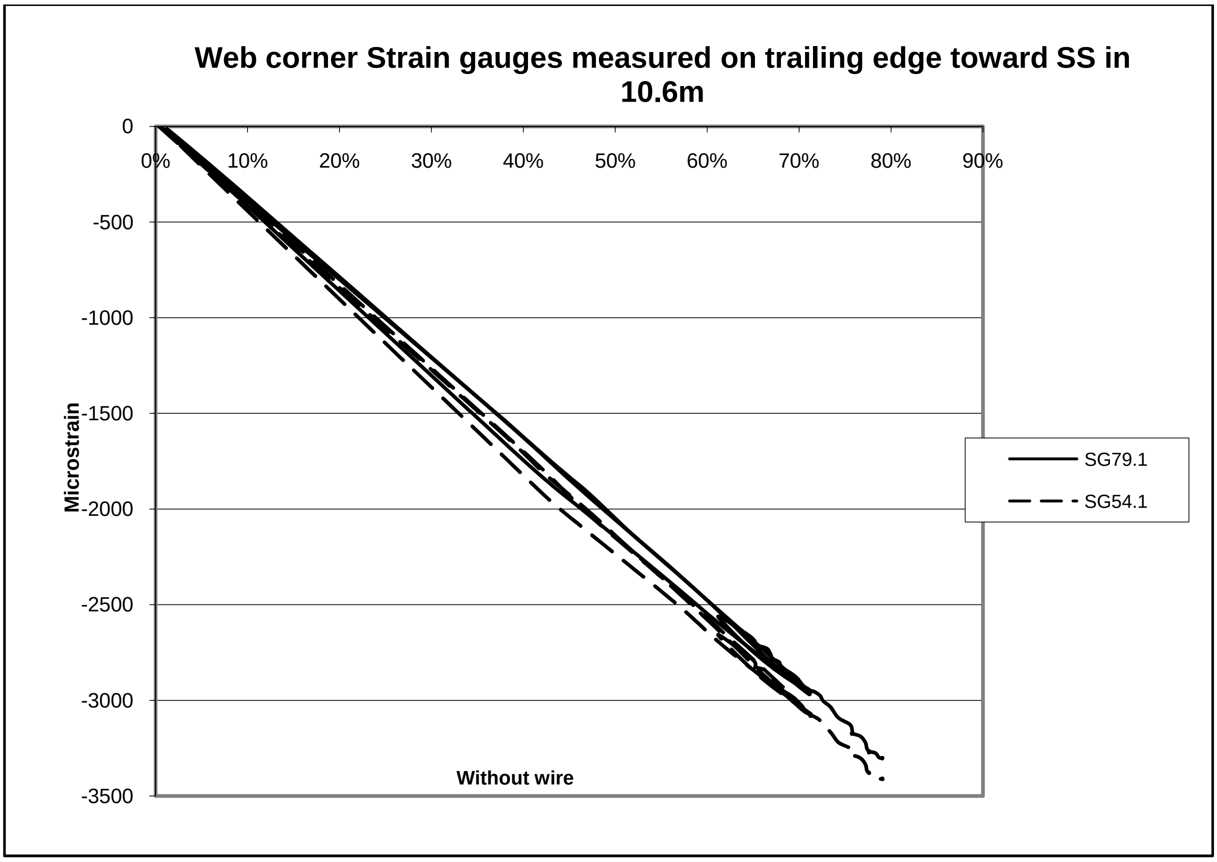


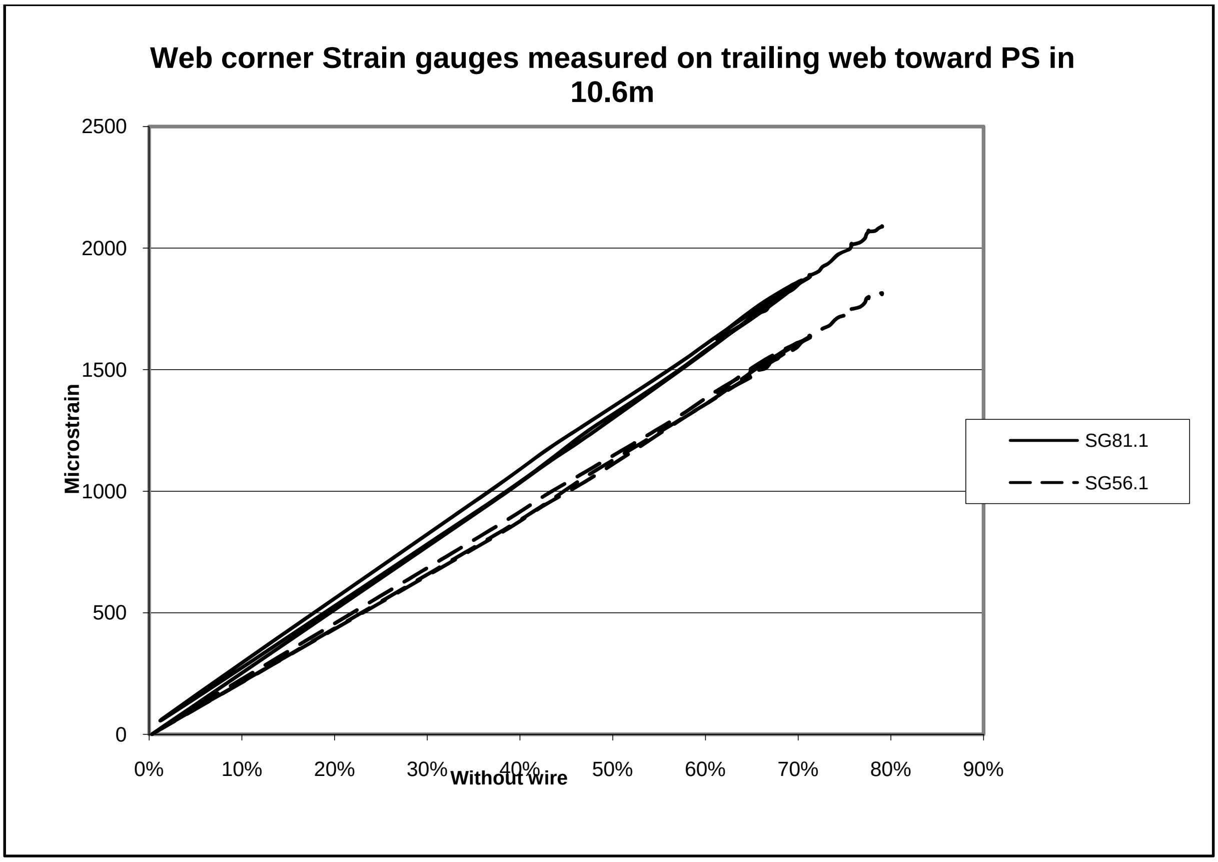
Longitudinal Strain gauges measured on trailing web toward SS in 10.6m
0
-500
-1000
-1500
-2000
-2500
-3000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Microstrain
Without wire
SG55.1
SG30.1


Longitudinal Strain gauges measured on trailing web toward PS in 10.6m
1400
1200
1000
800
600
400
200
0
Microstrain
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG57.1
SG32.1

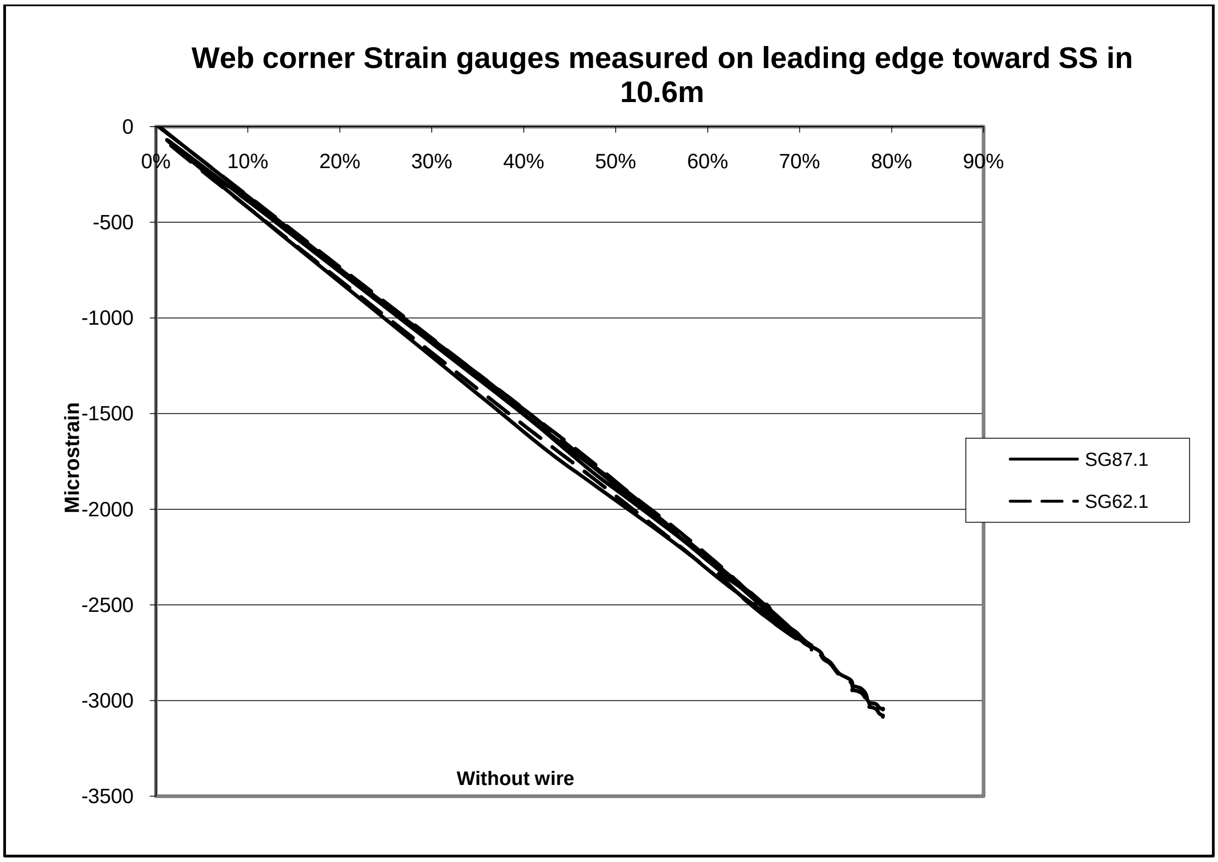

Longitudinal Strain gauges measured on leading web toward SS in 10.6m
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-2000
Microstrain
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG67.1
SG42.1


Longitudinal Strain gauges measured on leading web toward PS in 10.6m
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Microstrain
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG69.1
SG44.1

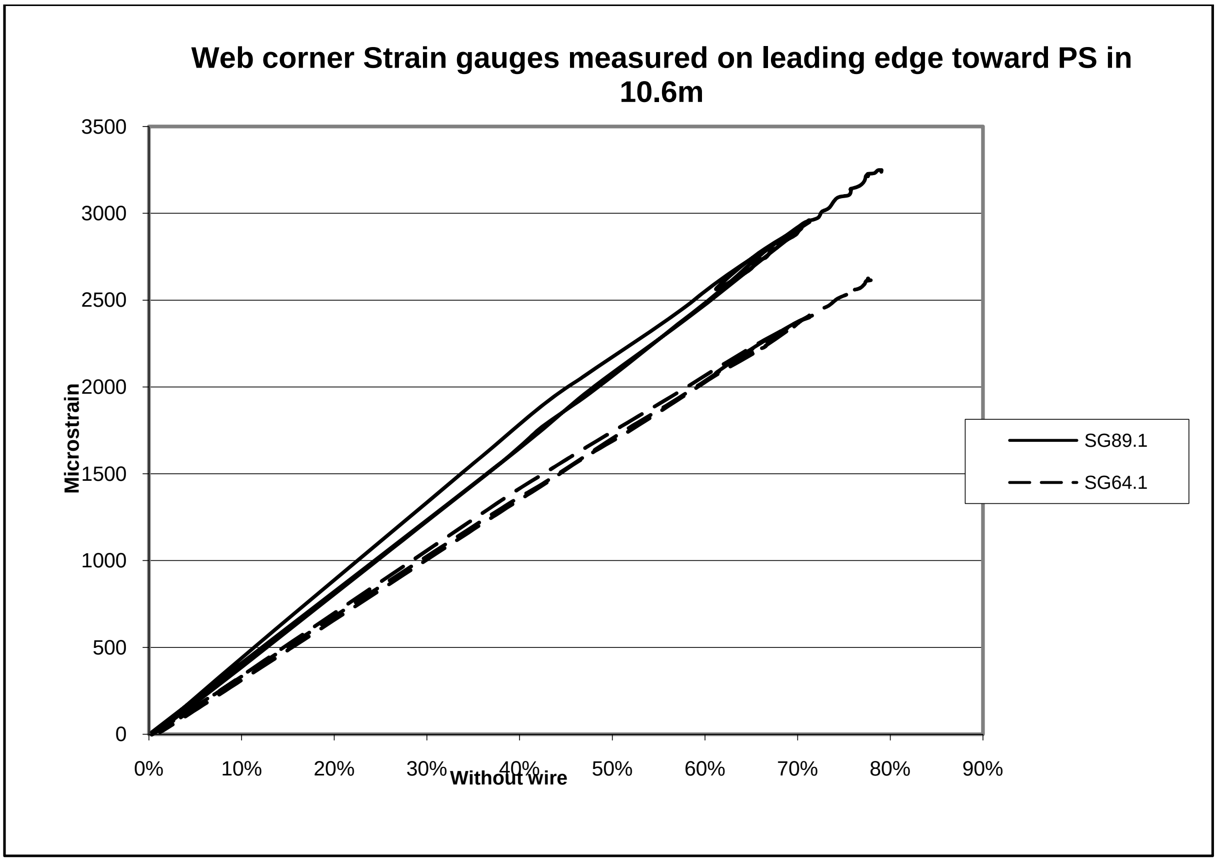

Web corner Strain gauges measured on trailing edge toward SS in 10.6m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
Microstrain
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG79.1
SG54.1

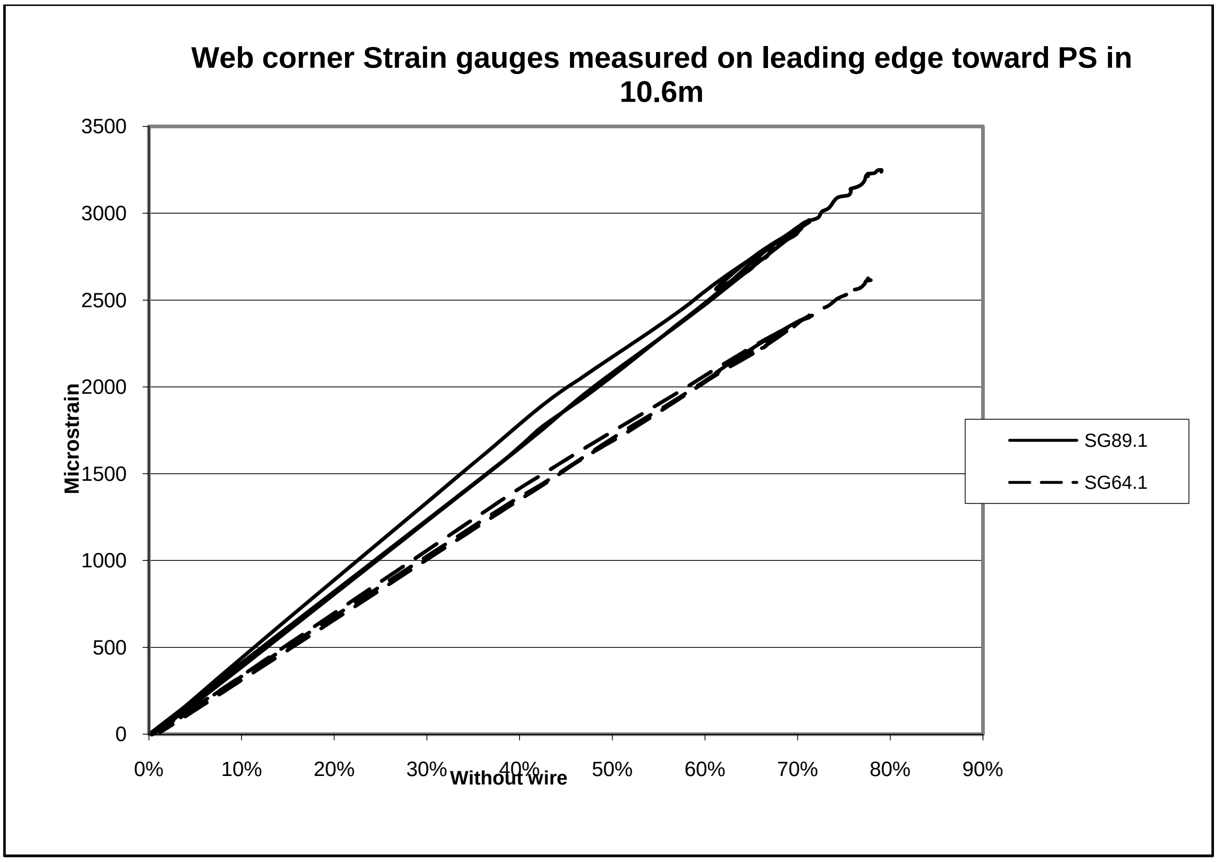


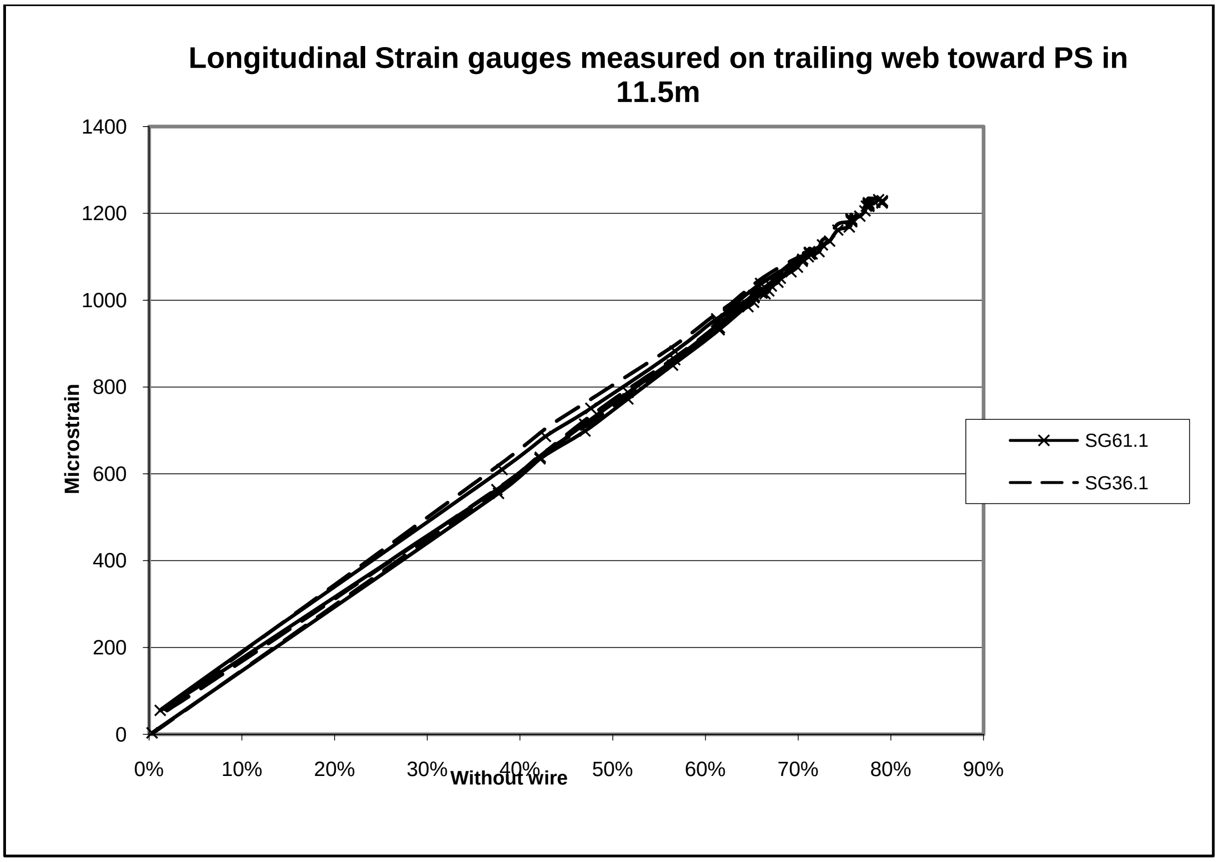
Web corner Strain gauges measured on trailing web toward PS in 10.6m
Microstrain
2500
2000
1500
1000
500
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG81.1
SG56.1

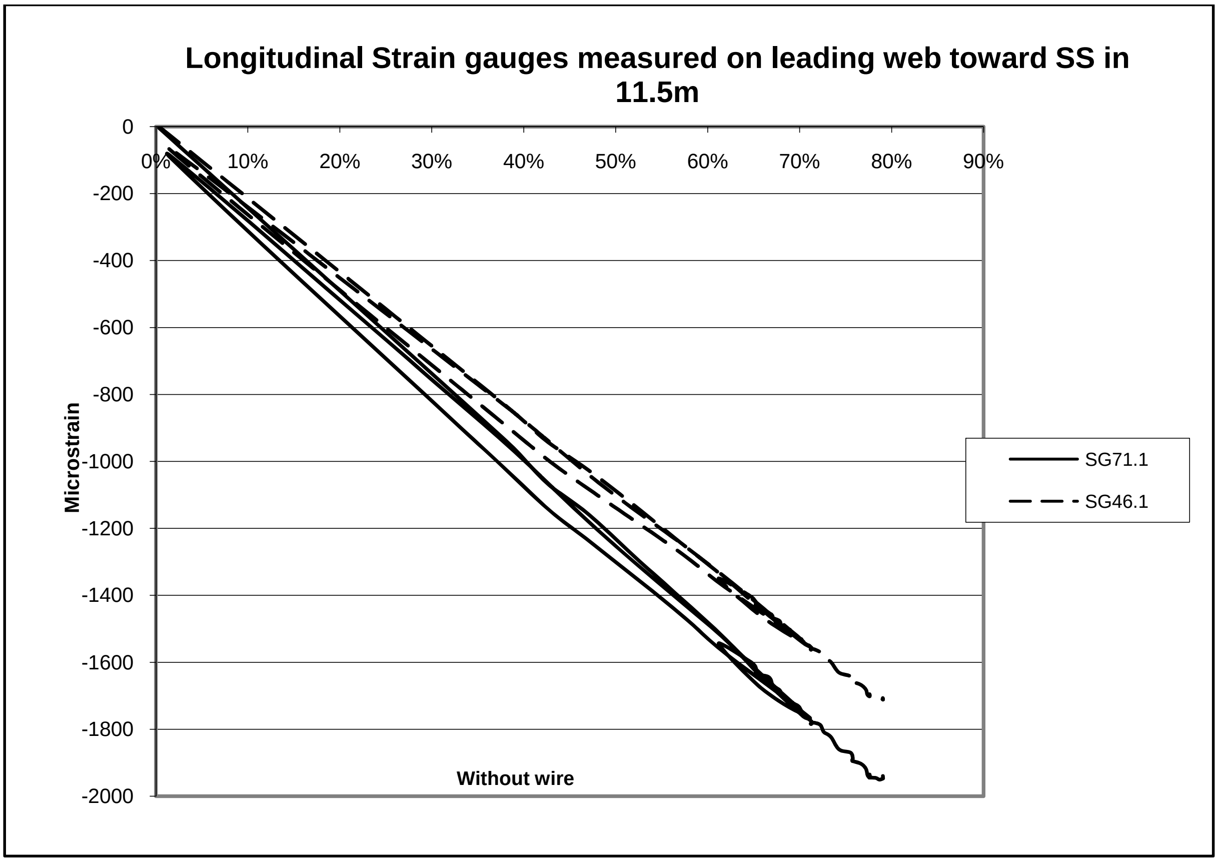


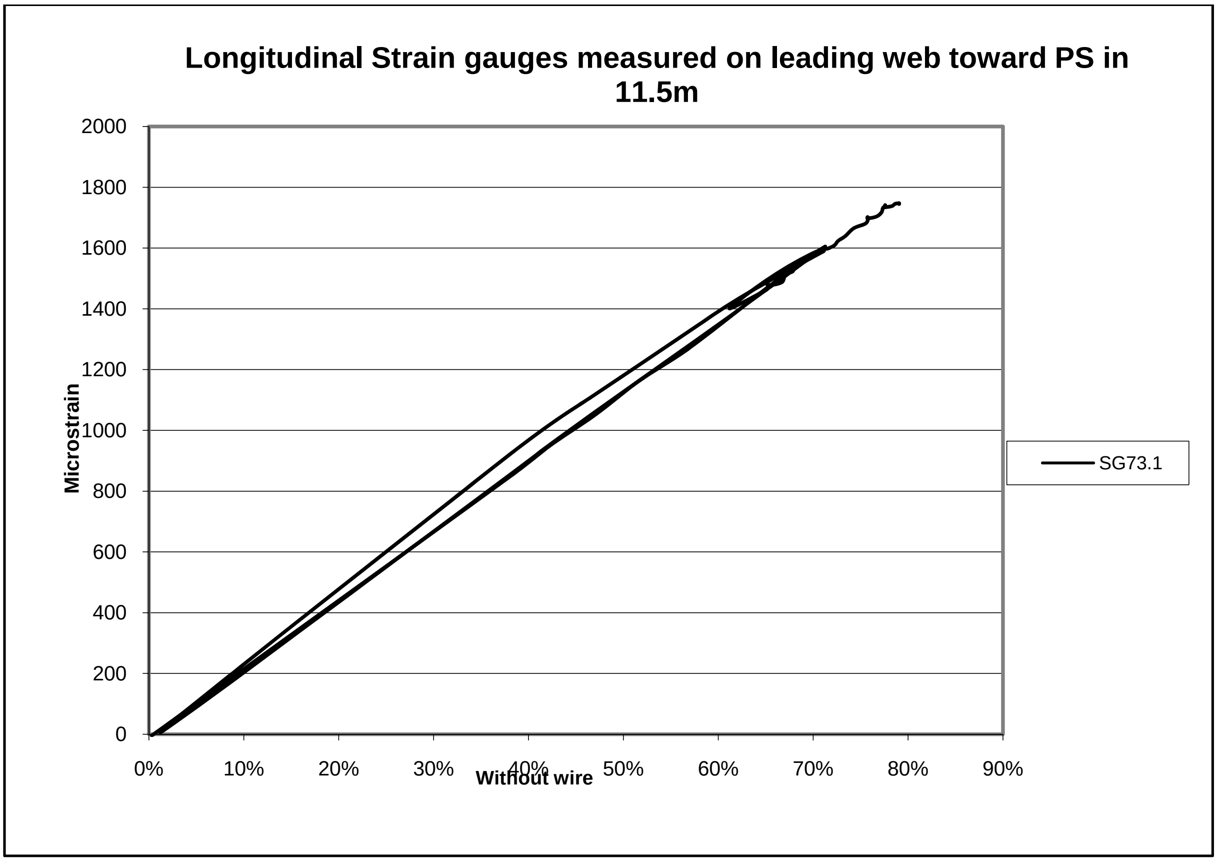
Web corner Strain gauges measured on leading edge toward SS in 10.6m
Microstrain
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG87.1
SG62.1


Web corner Strain gauges measured on leading edge toward PS in 10.6m
3500
3000
2500
2000
1500
1000
500
0
Microstrain
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG89.1
SG64.1

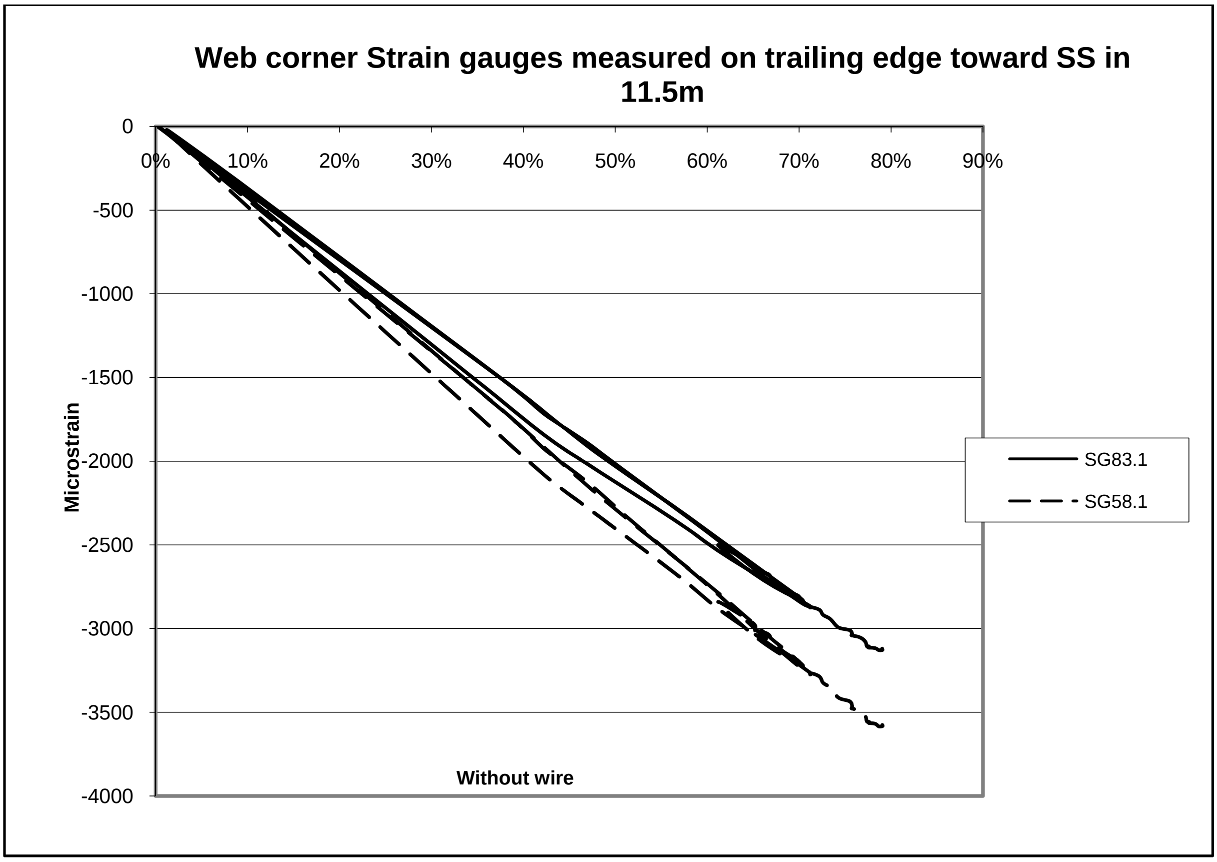

Web corner Strain gauges measured on leading edge toward PS in 10.6m
3500
3000
2500
2000
1500
1000
500
0
Microstrain
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG89.1
SG64.1


Longitudinal Strain gauges measured on trailing web toward PS in 11.5m
Microstrain
1400
1200
1000
800
600
400
200
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG61.1
SG36.1

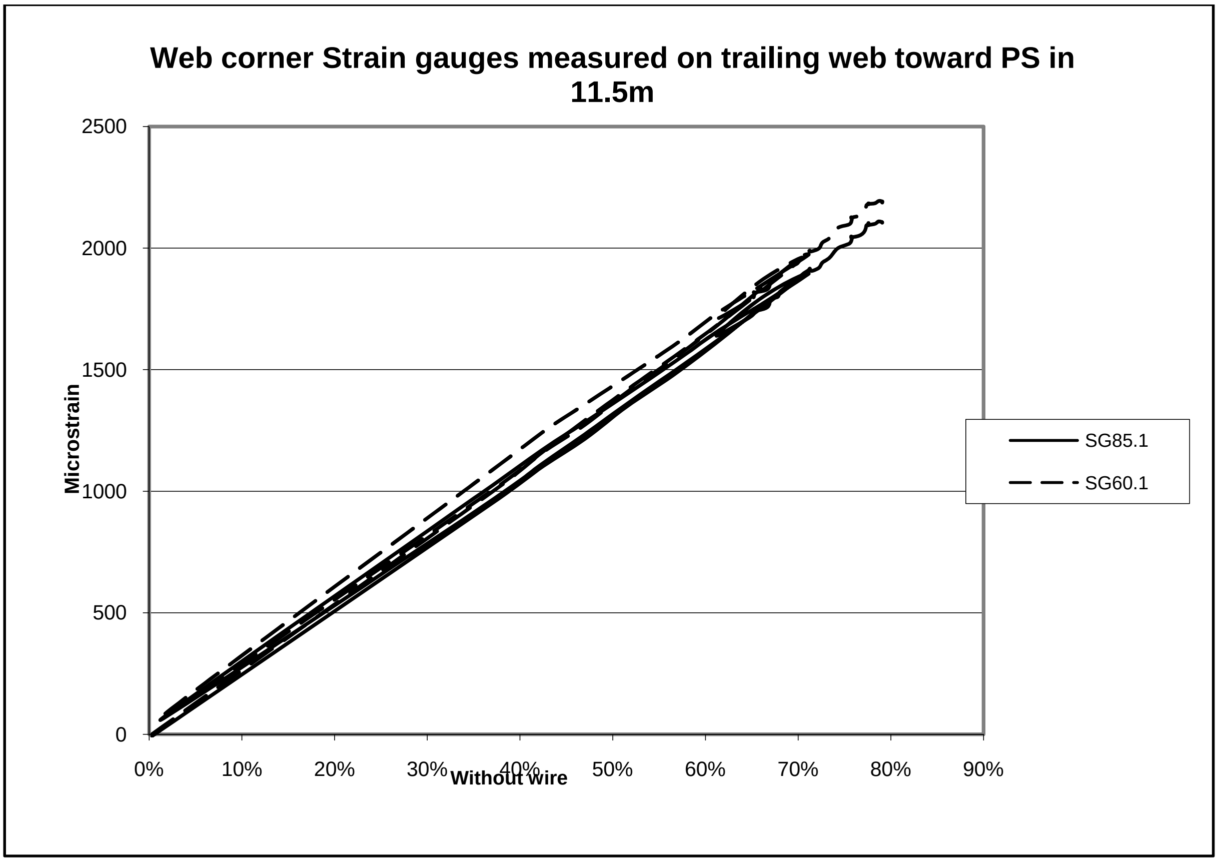

Longitudinal Strain gauges measured on leading web toward SS in 11.5m
Microstrain
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-2000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG71.1
SG46.1

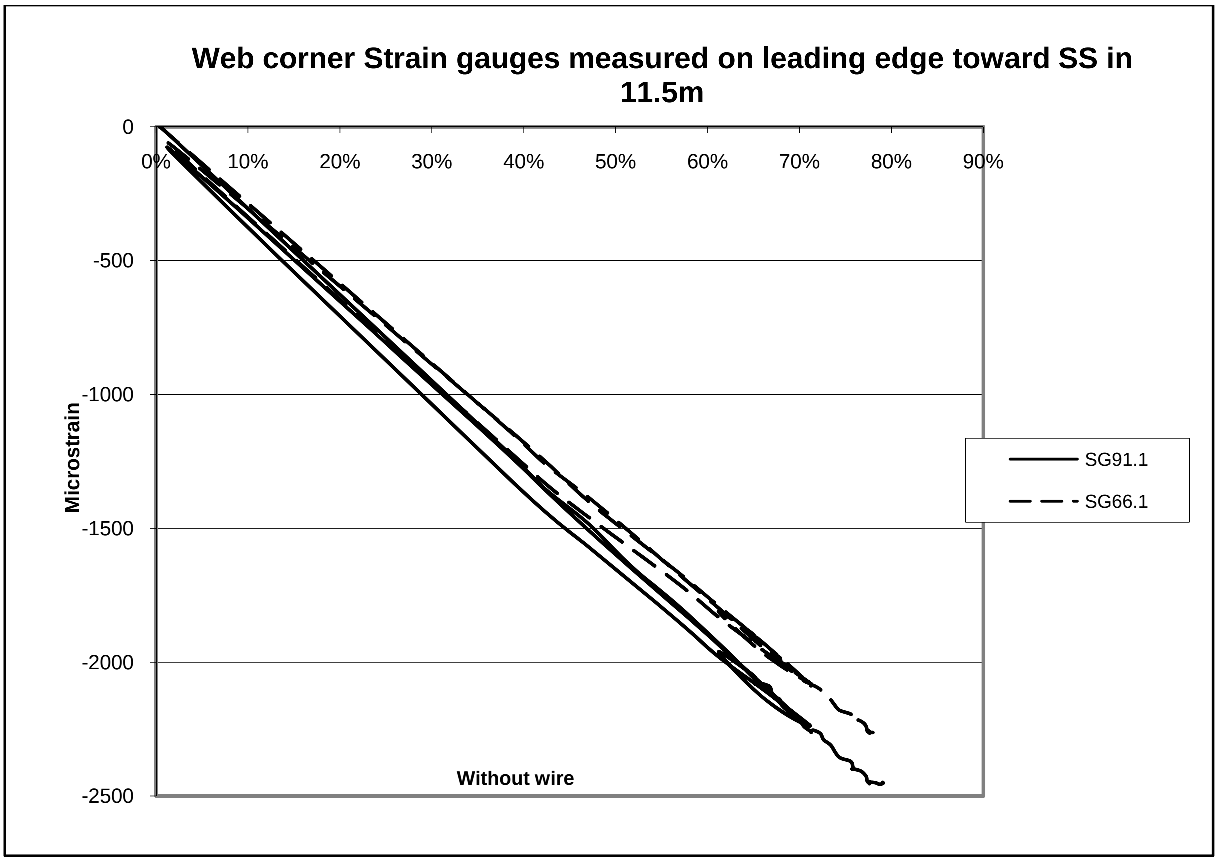


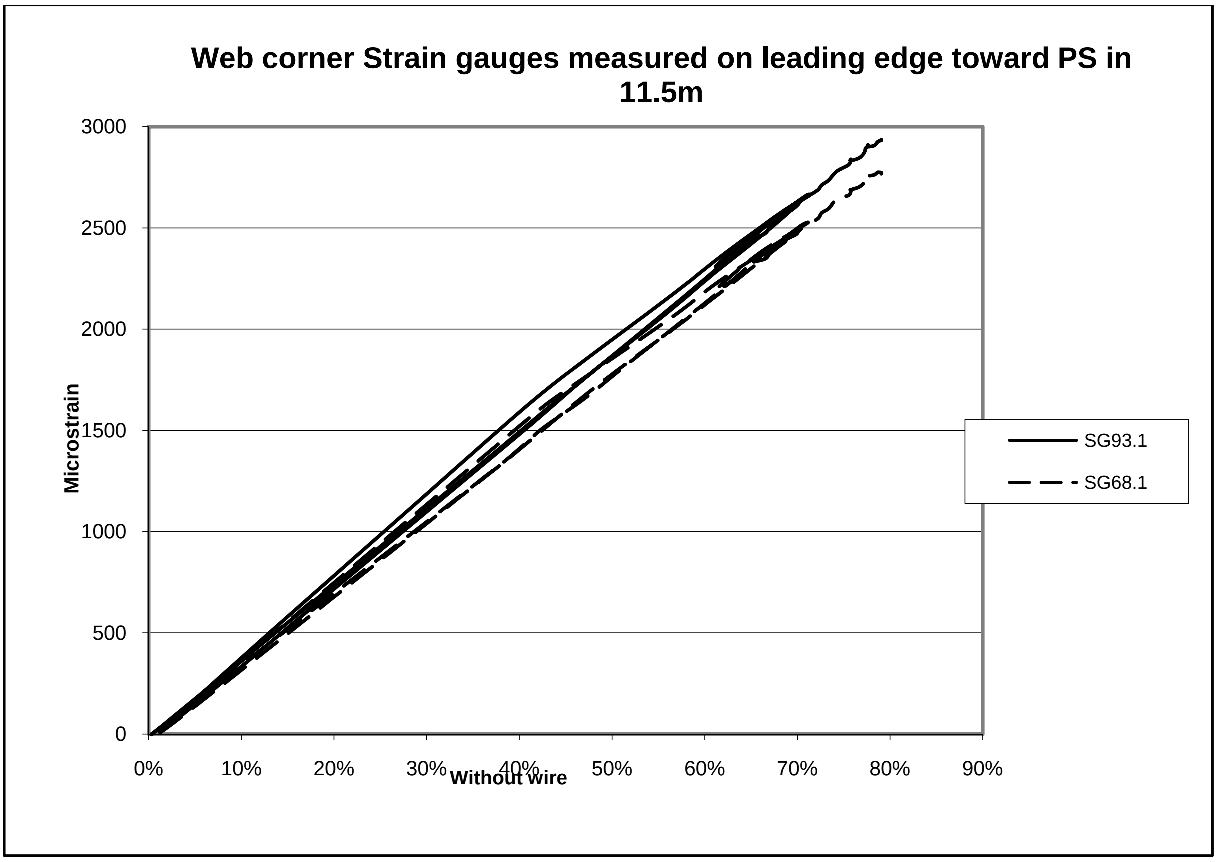
Longitudinal Strain gauges measured on leading web toward PS in 11.5m
Microstrain
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG73.1

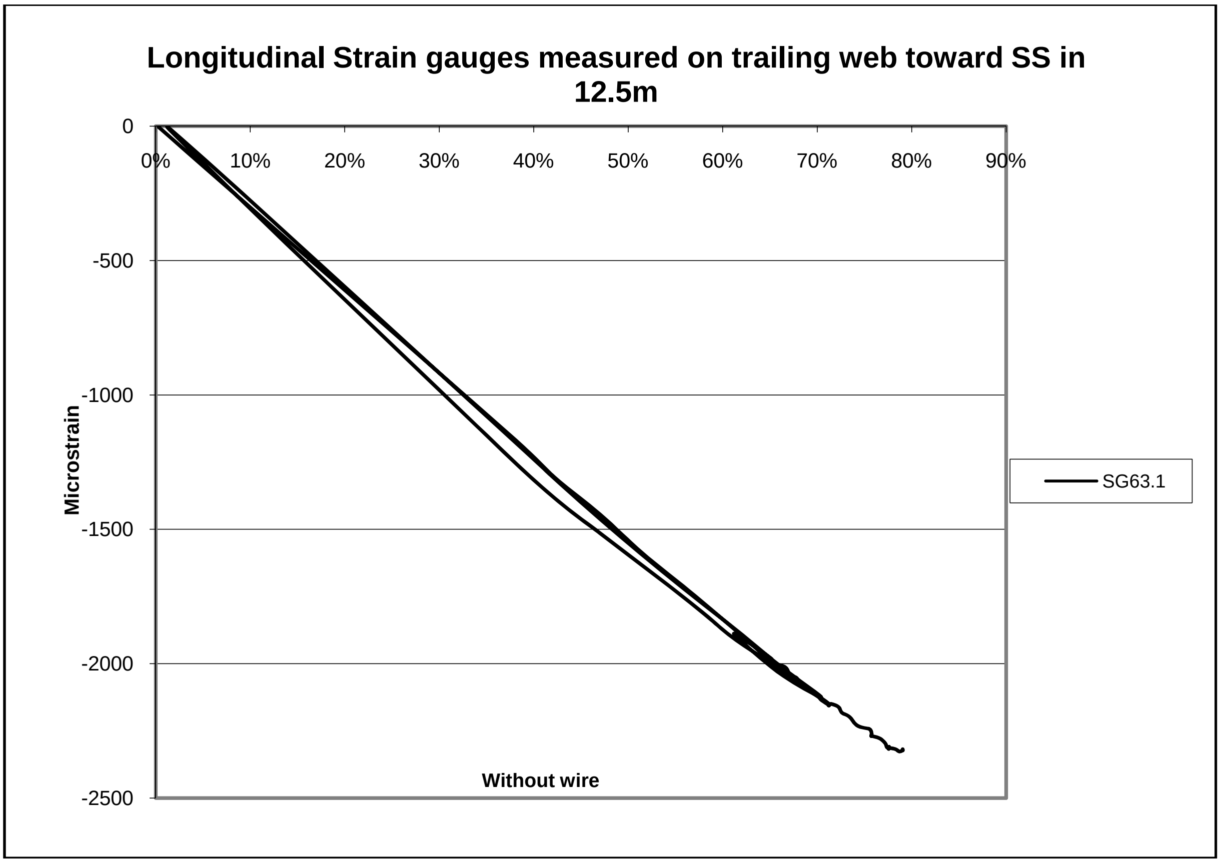


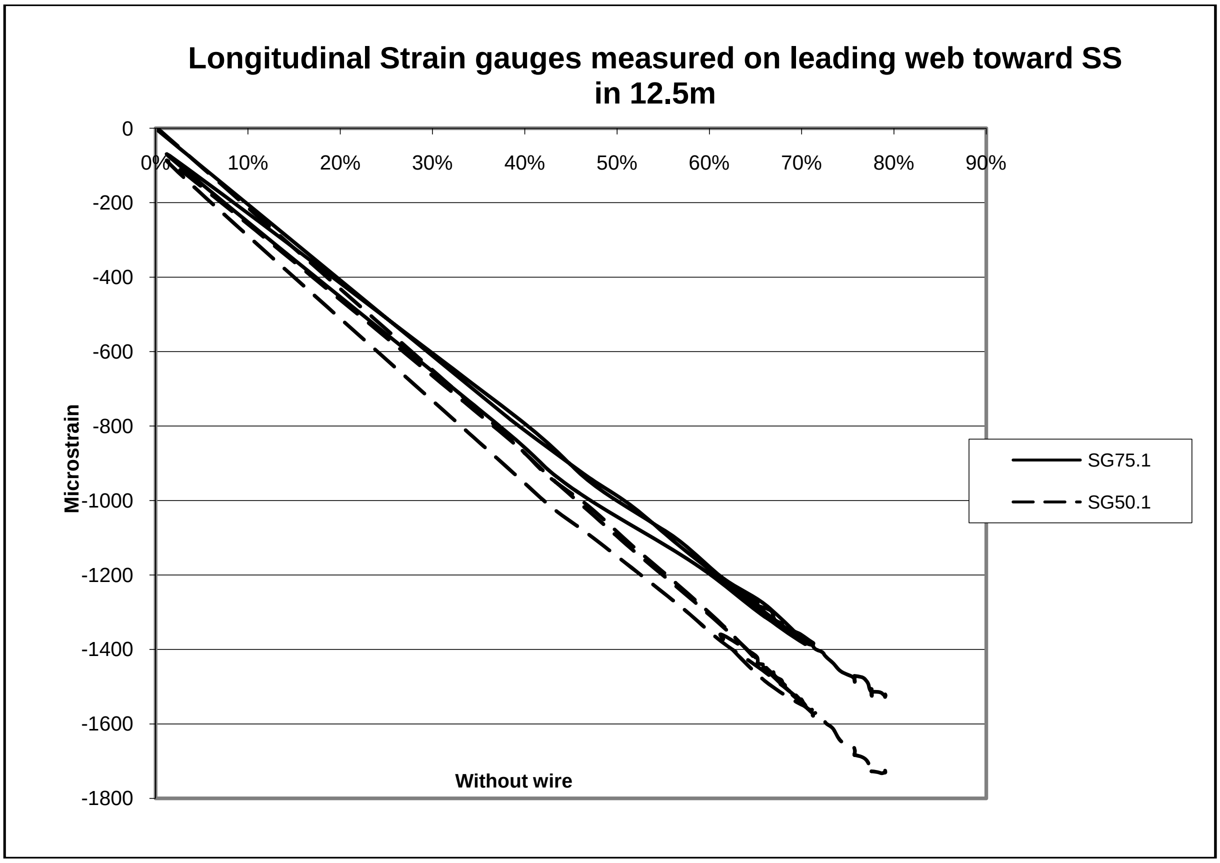
Web corner Strain gauges measured on trailing edge toward SS in 11.5m
Microstrain
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG83.1
SG58.1


Web corner Strain gauges measured on trailing web toward PS in 11.5m
Microstrain
2500
2000
1500
1000
500
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG85.1
SG60.1

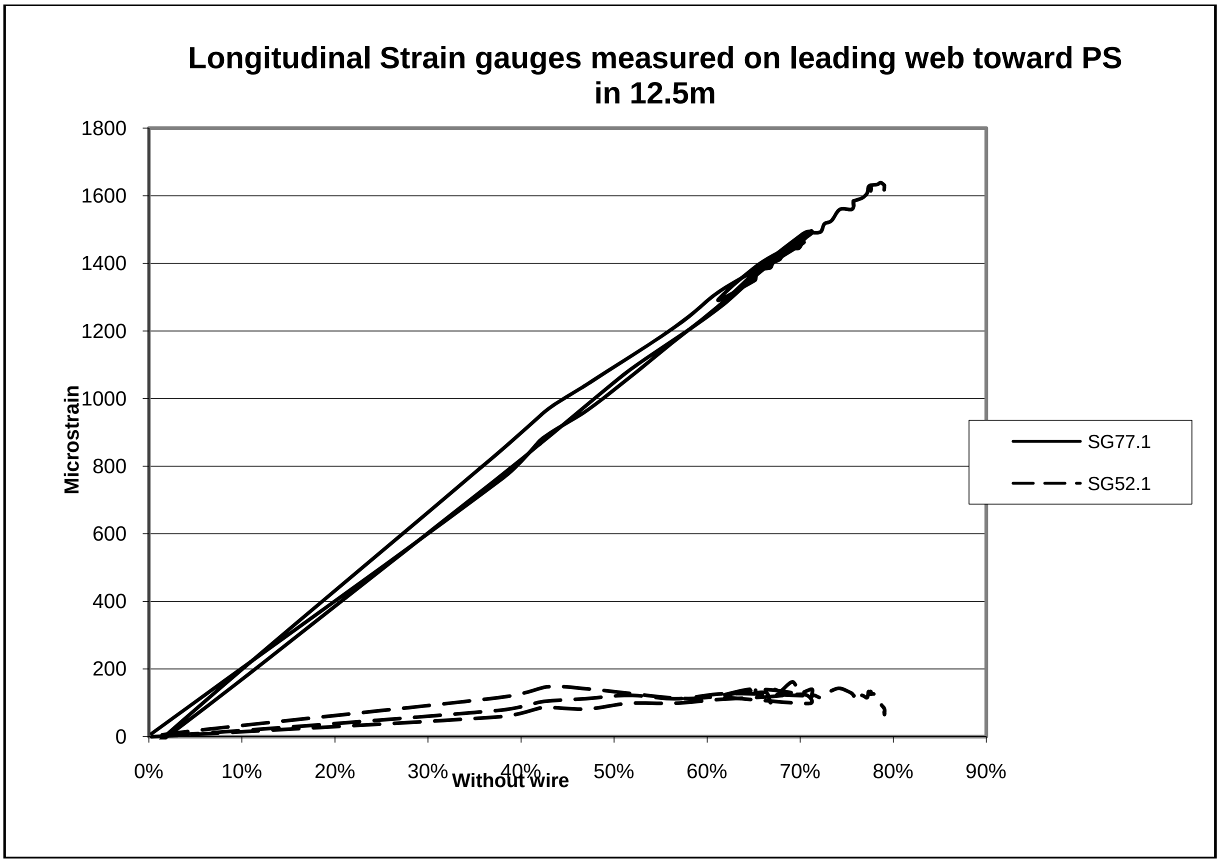

Web corner Strain gauges measured on leading edge toward SS in 11.5m
Microstrain
0
-500
-1000
-1500
-2000
-2500
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG91.1
SG66.1


Web corner Strain gauges measured on leading edge toward PS in 11.5m
Microstrain
3000
2500
2000
1500
1000
500
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG93.1
SG68.1


Longitudinal Strain gauges measured on trailing web toward SS in 12.5m
Microstrain
0
-500
-1000
-1500
-2000
-2500
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG63.1

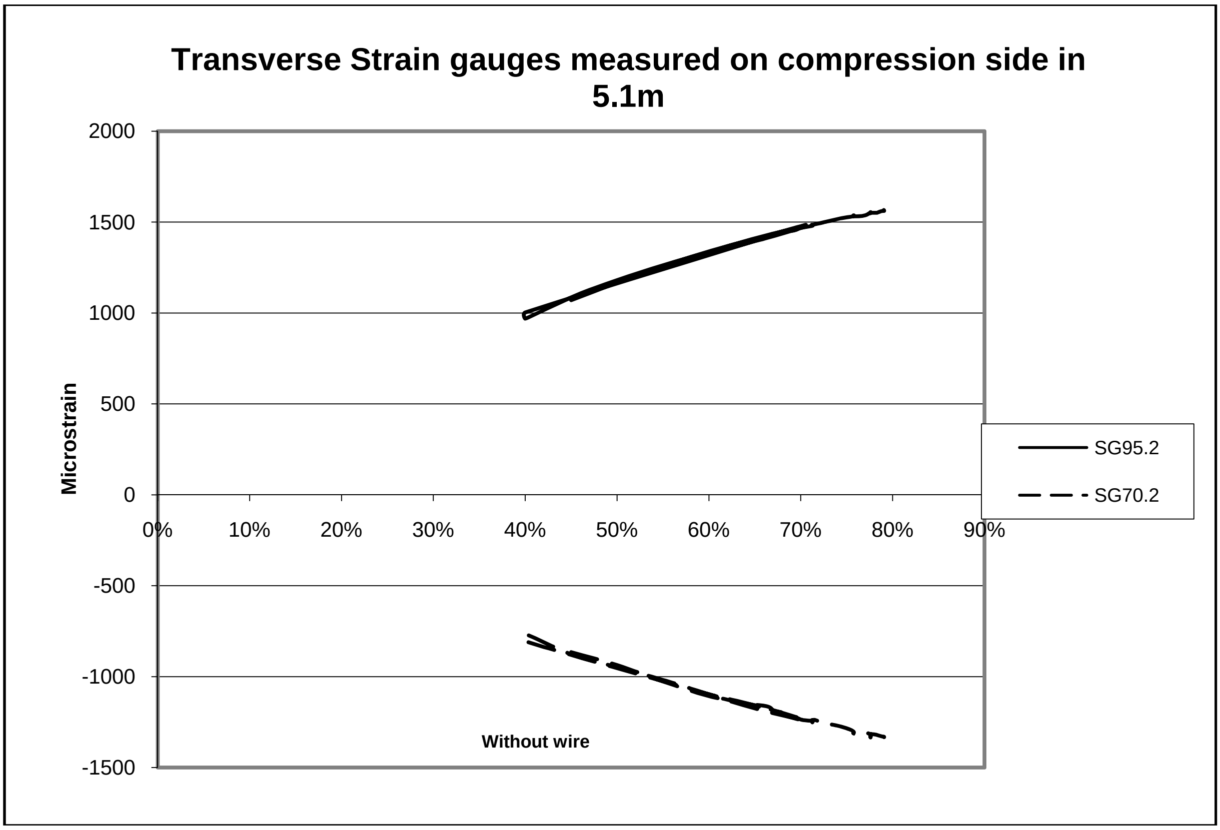


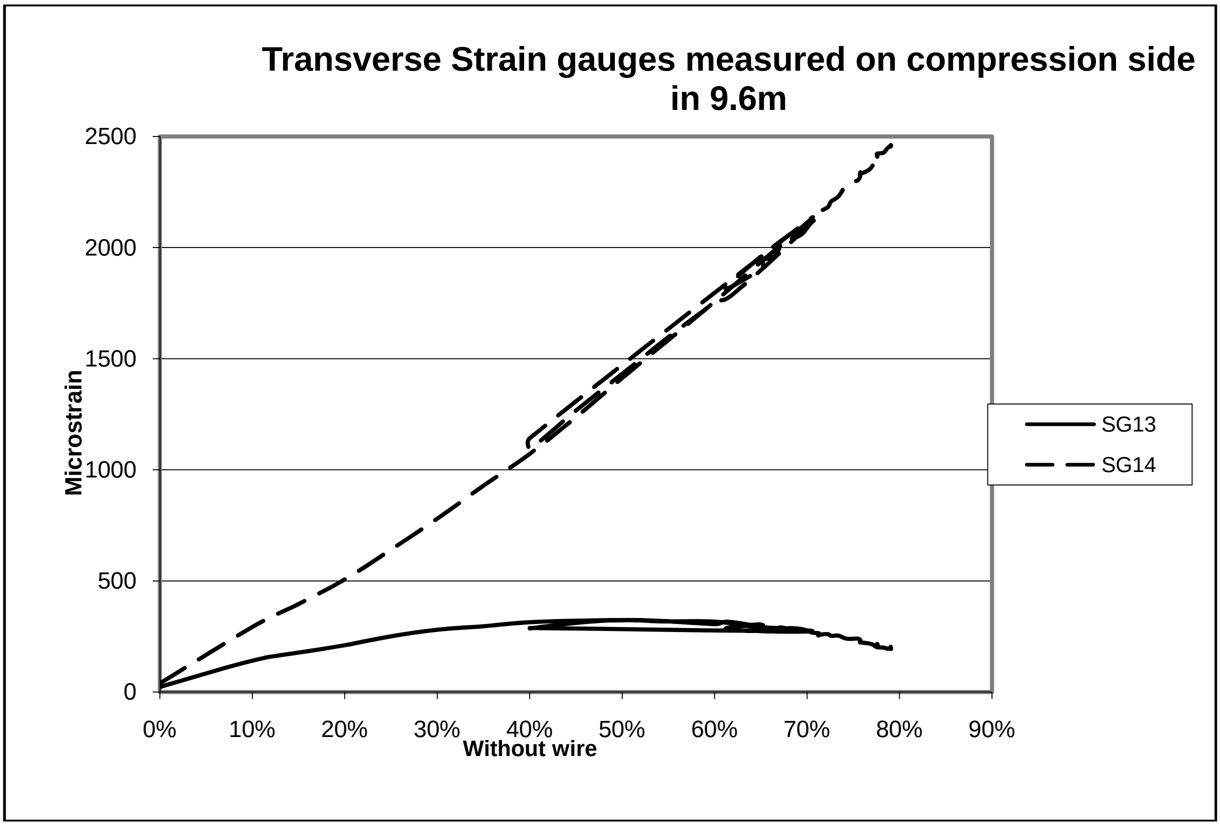
Longitudinal Strain gauges measured on leading web toward SS
in 12.5m
Microstrain
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG75.1
SG50.1

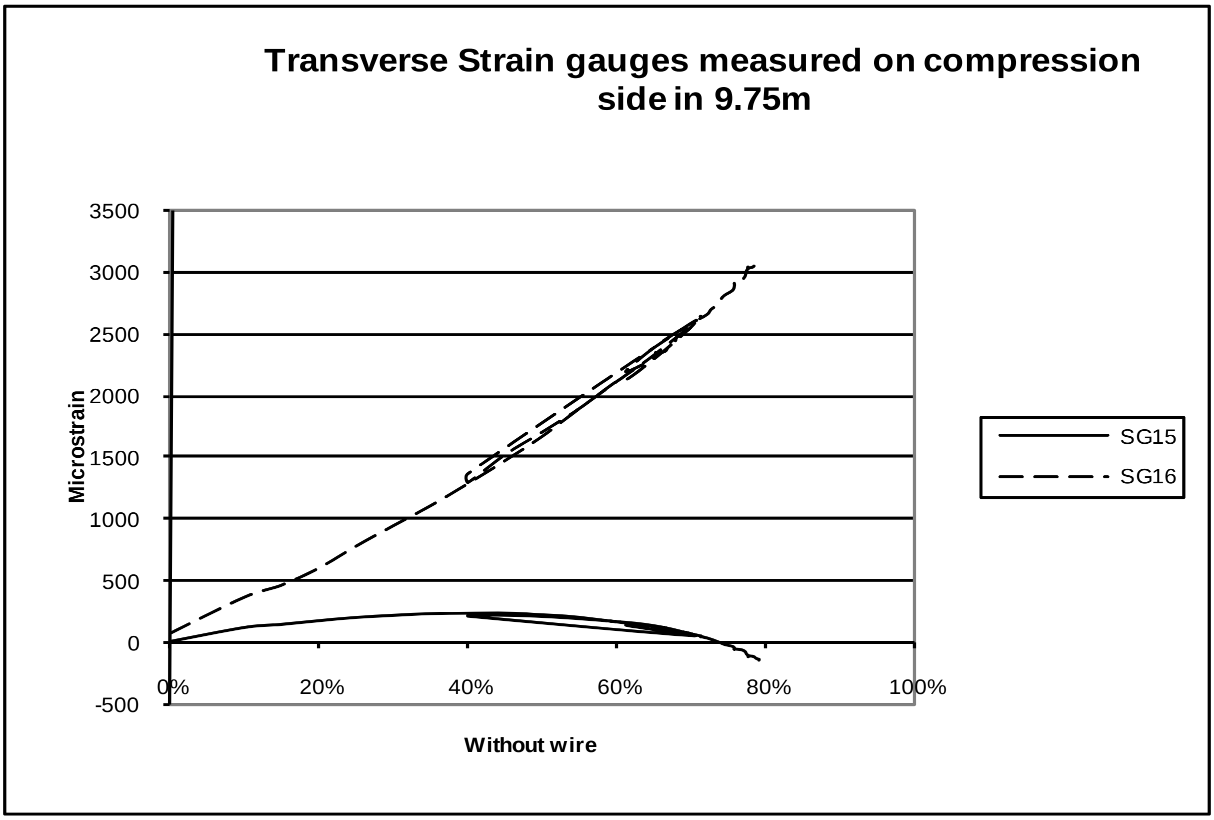


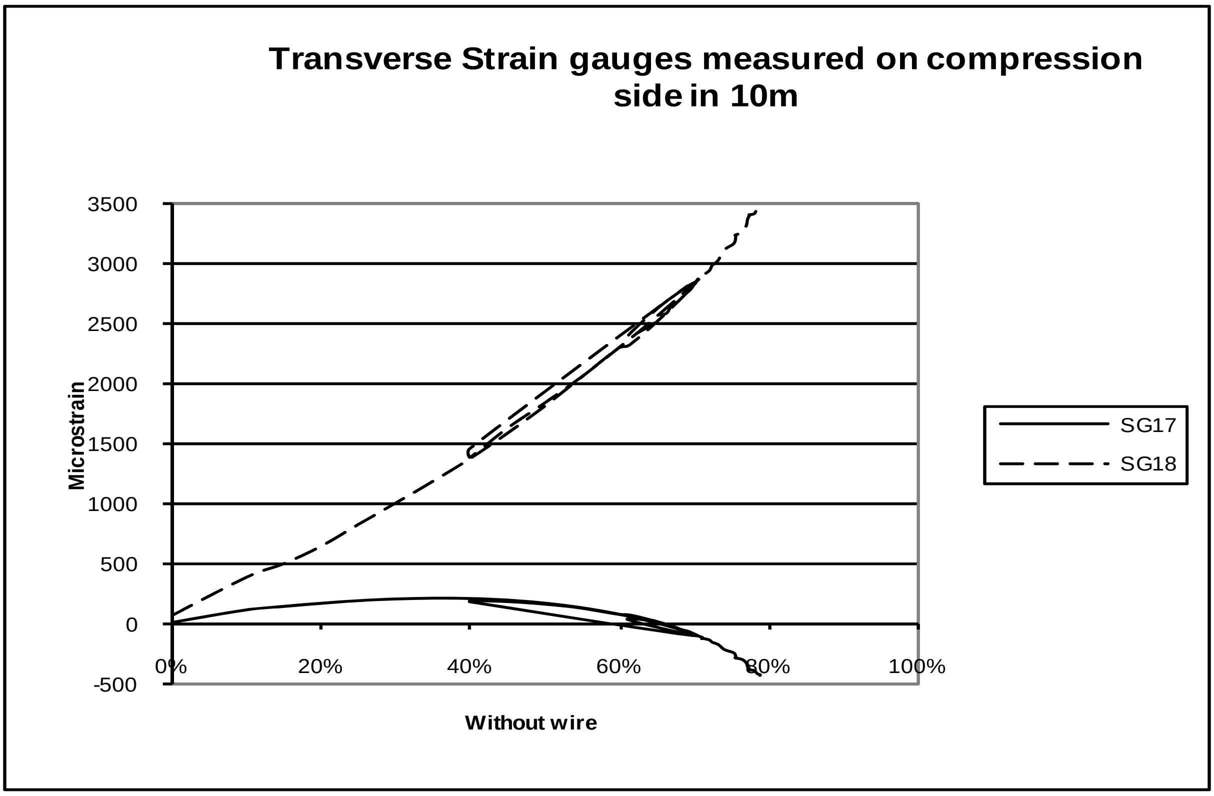
Longitudinal Strain gauges measured on leading web toward PS
in 12.5m
Microstrain
1800
1600
1400
1200
1000
800
600
400
200
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG77.1
SG52.1

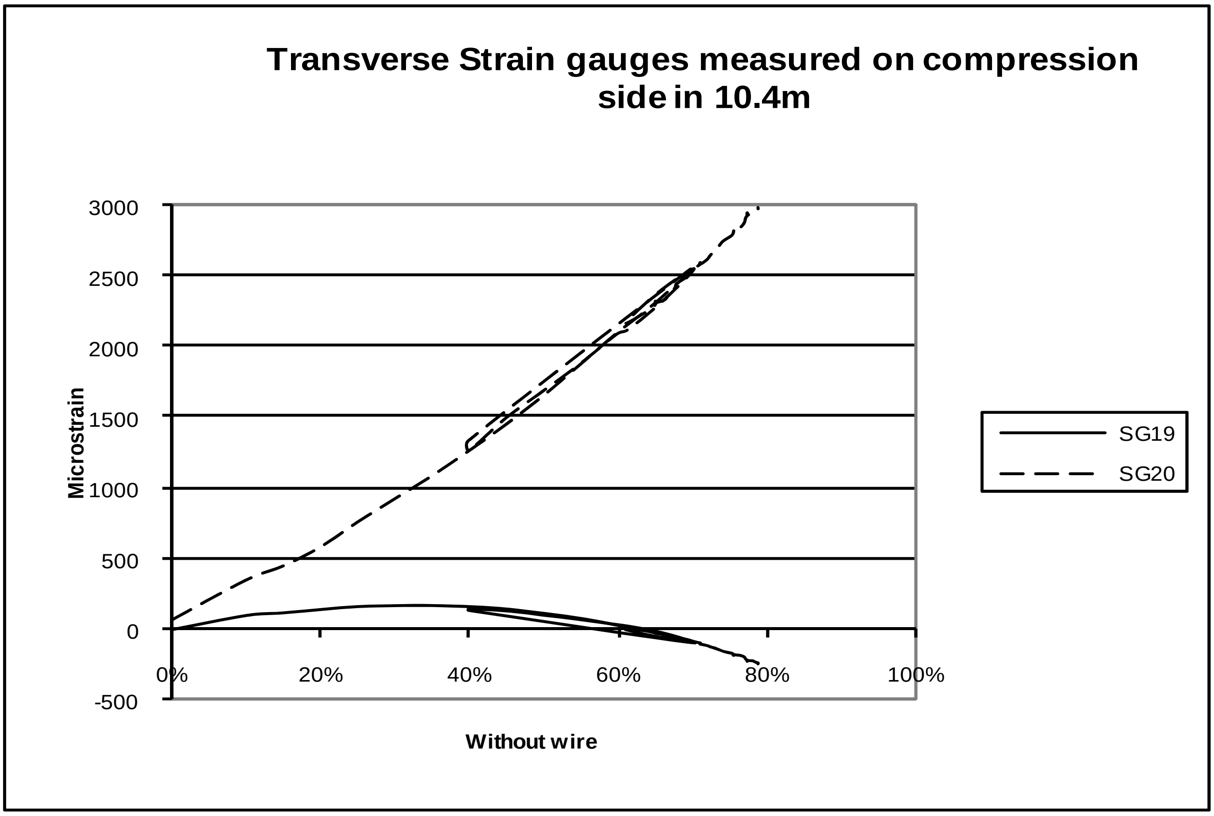
Graphs of Transverse measurements without wire

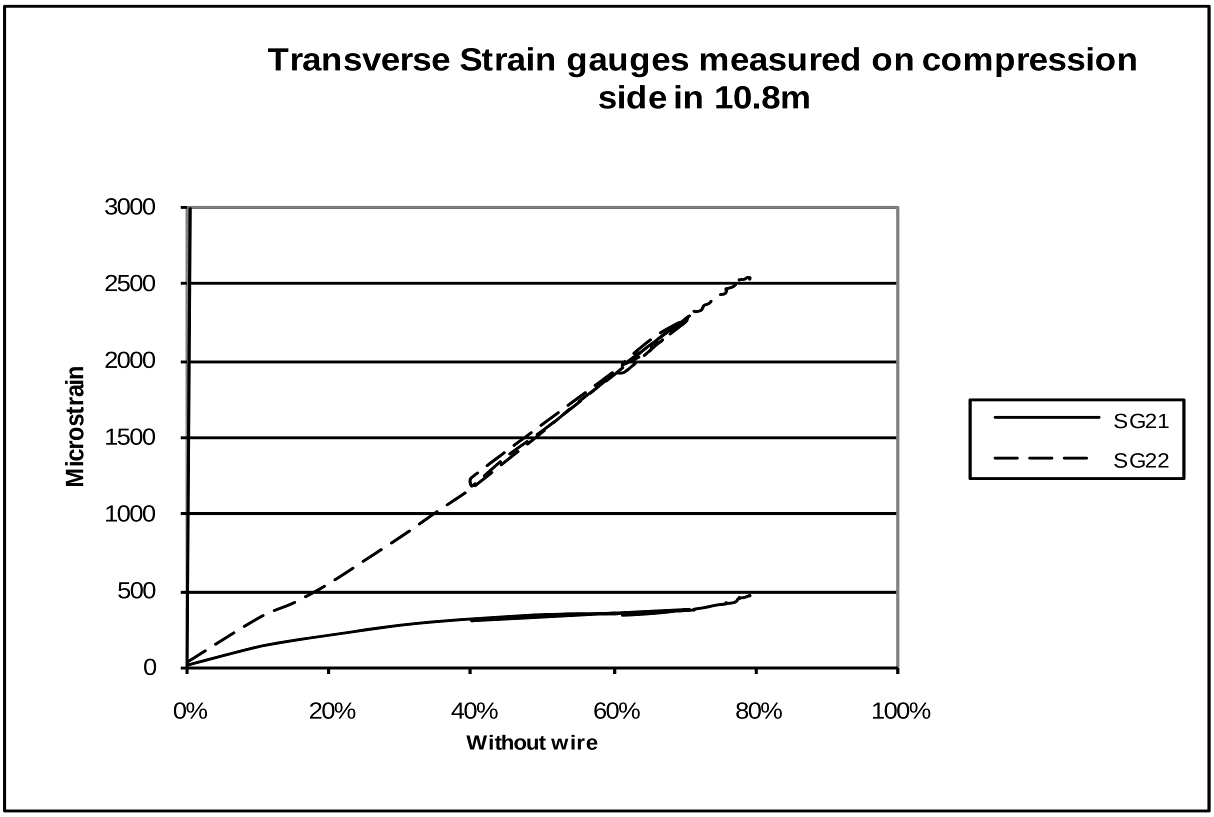


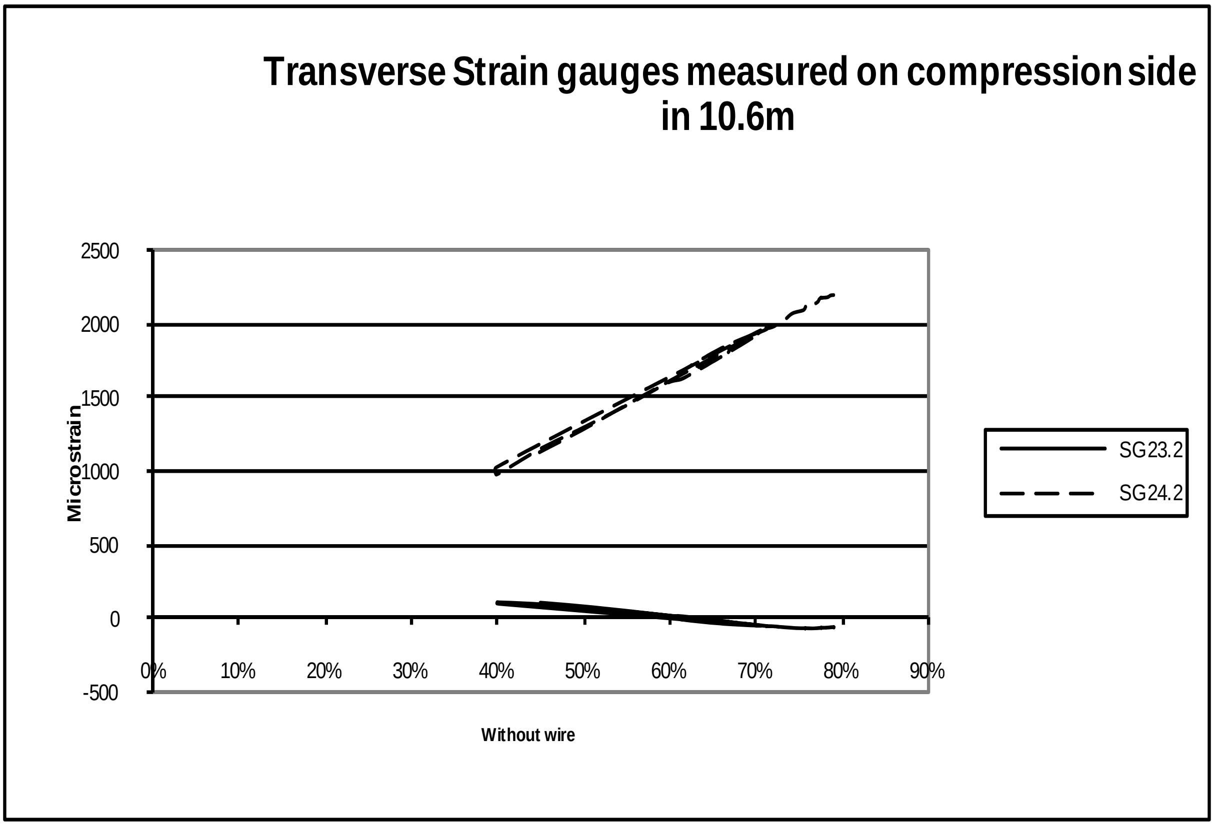


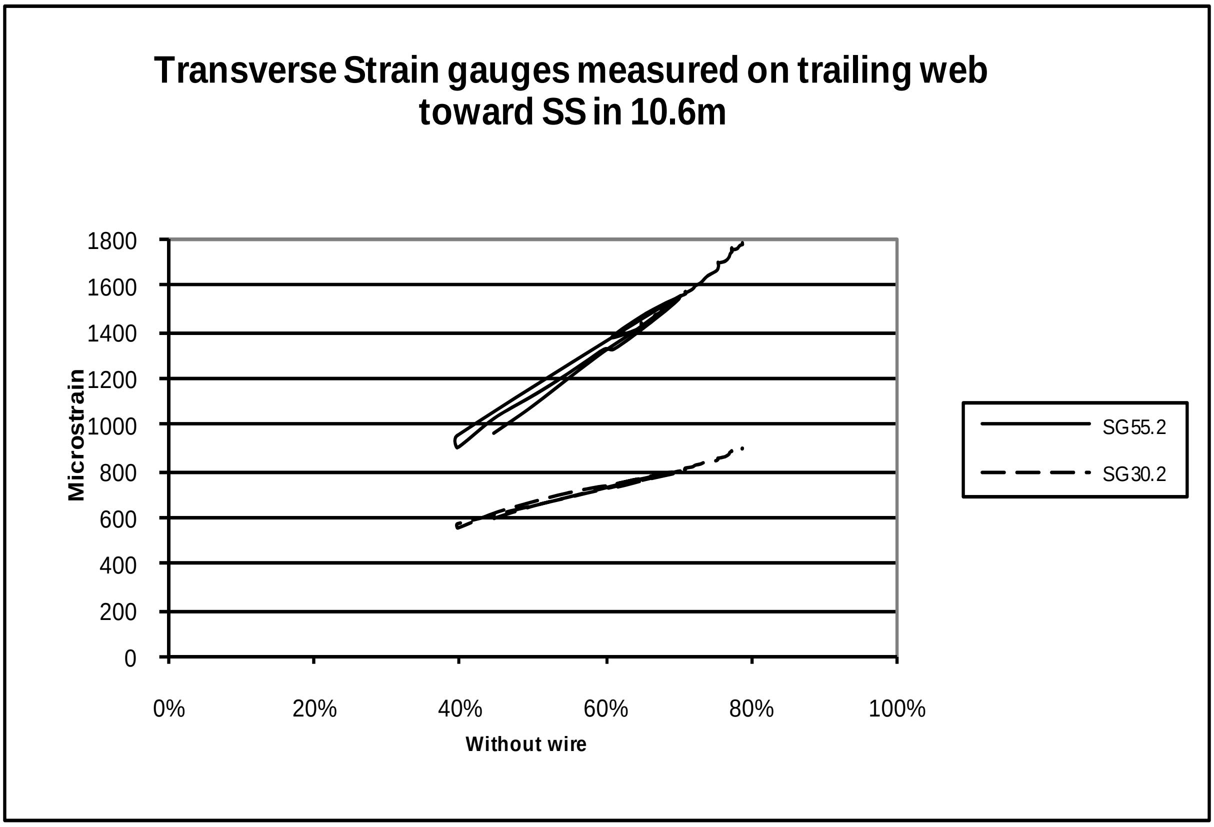

Transverse Strain gauges measured on compression side in 9.75m
Microstrain
3500
3000
2500
2000
1500
1000
500
0
-500
0%
20%
40%
60%
80%
100%
Without wire
SG15
SG16

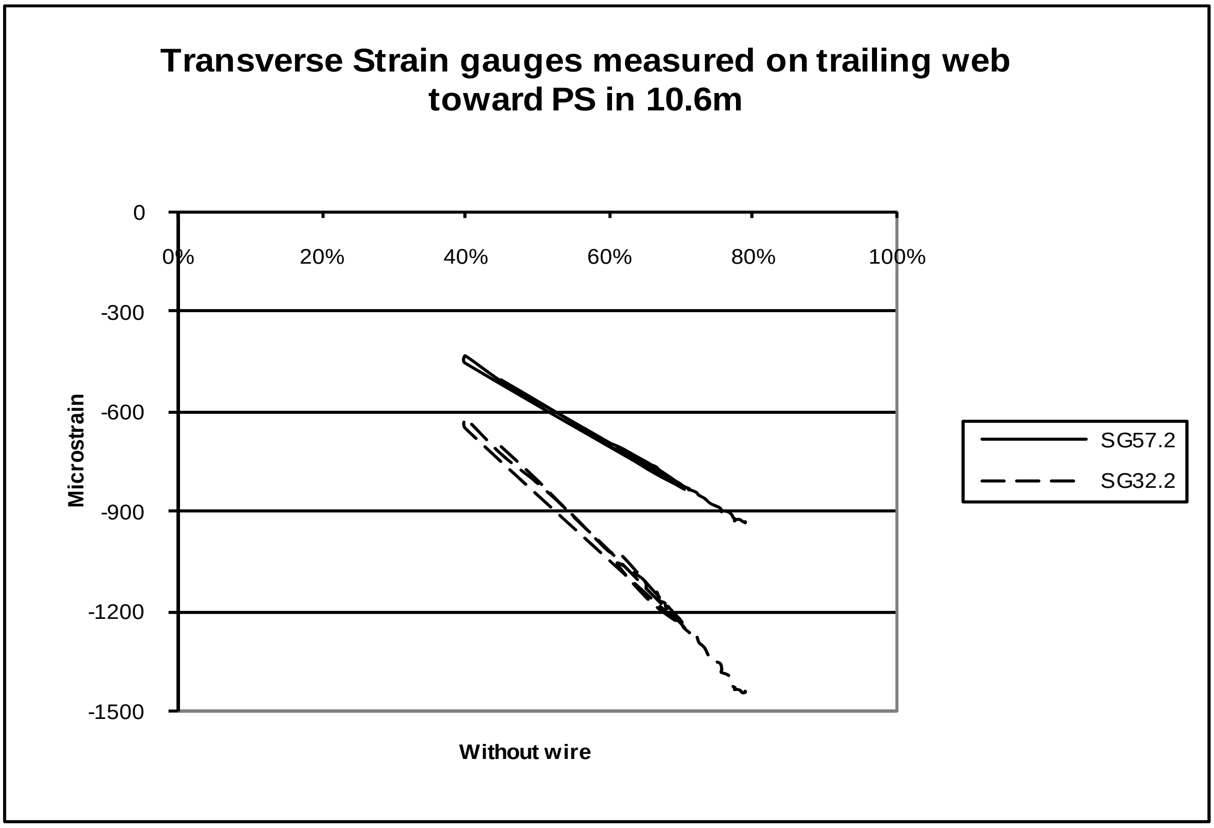

Transverse Strain gauges measured on compression side in 10m
Microstrain
3500
3000
2500
2000
1500
1000
500
0
-500
0%
20%
40%
60%
80%
100%
Without wire
SG17
SG18

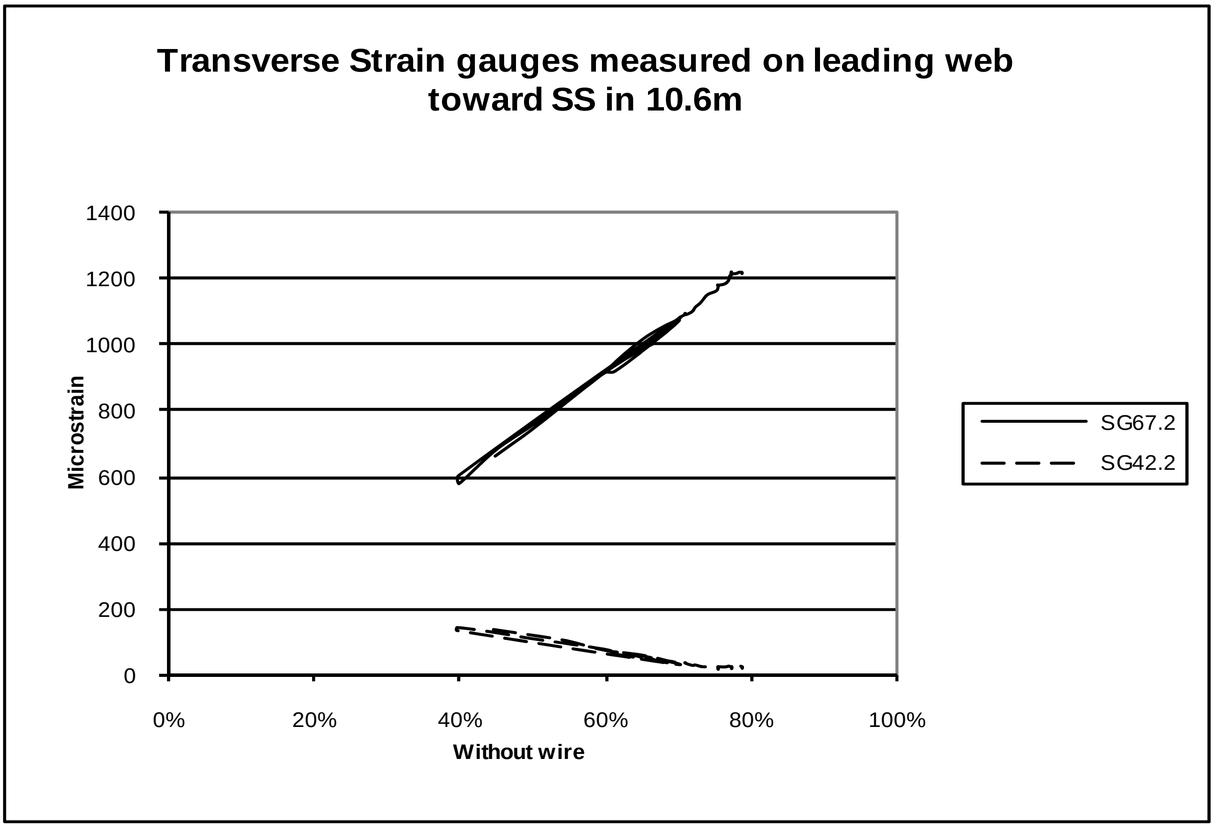

Transverse Strain gauges measured on compression side in 10.4m
3000
2500
2000
1500
1000
500
0
-500
Microstrain
0%
20%
40%
60%
80%
100%
Without wire
SG19
SG20

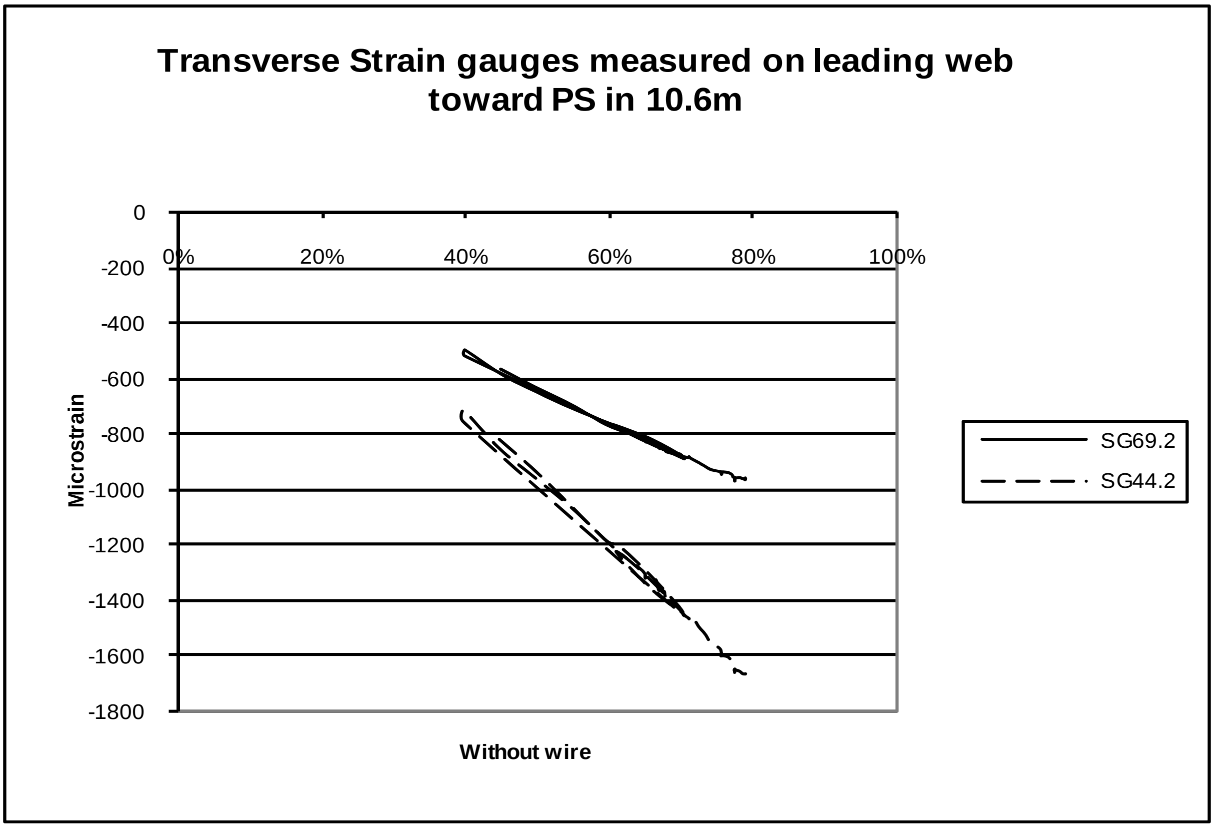

Transverse Strain gauges measured on compression side in 10.8m
3000
2500
2000
1500
1000
500
0
Microstrain
0%
20%
40%
60%
80%
100%
Without wire
SG21
SG22


Transverse Strain gauges measured on compression side in 10.6m
2500
2000
1500
1000
500
0
-500
Microstrain
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG23.2
SG24.2

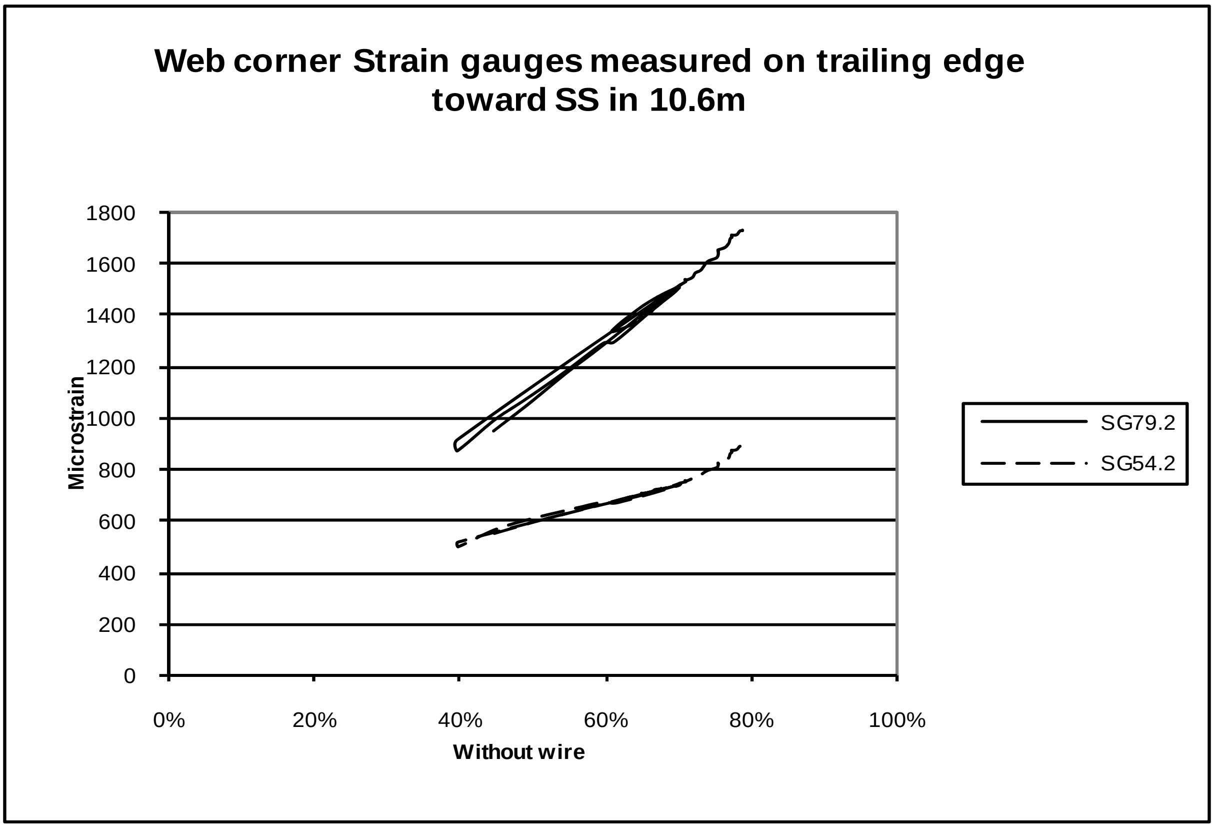

Transverse Strain gauges measured on trailing web toward SS in 10.6m
1800
1600
1400
1200
1000
800
600
400
200
0
Microstrain
0%
20%
40%
60%
80%
100%
Without wire
SG55.2
SG30.2


Transverse Strain gauges measured on trailing web toward PS in 10.6m
0
-300
-600
-900
-1200
-1500
0%
20%
40%
60%
80%
100%
Microstrain
Without wire
SG57.2
SG32.2

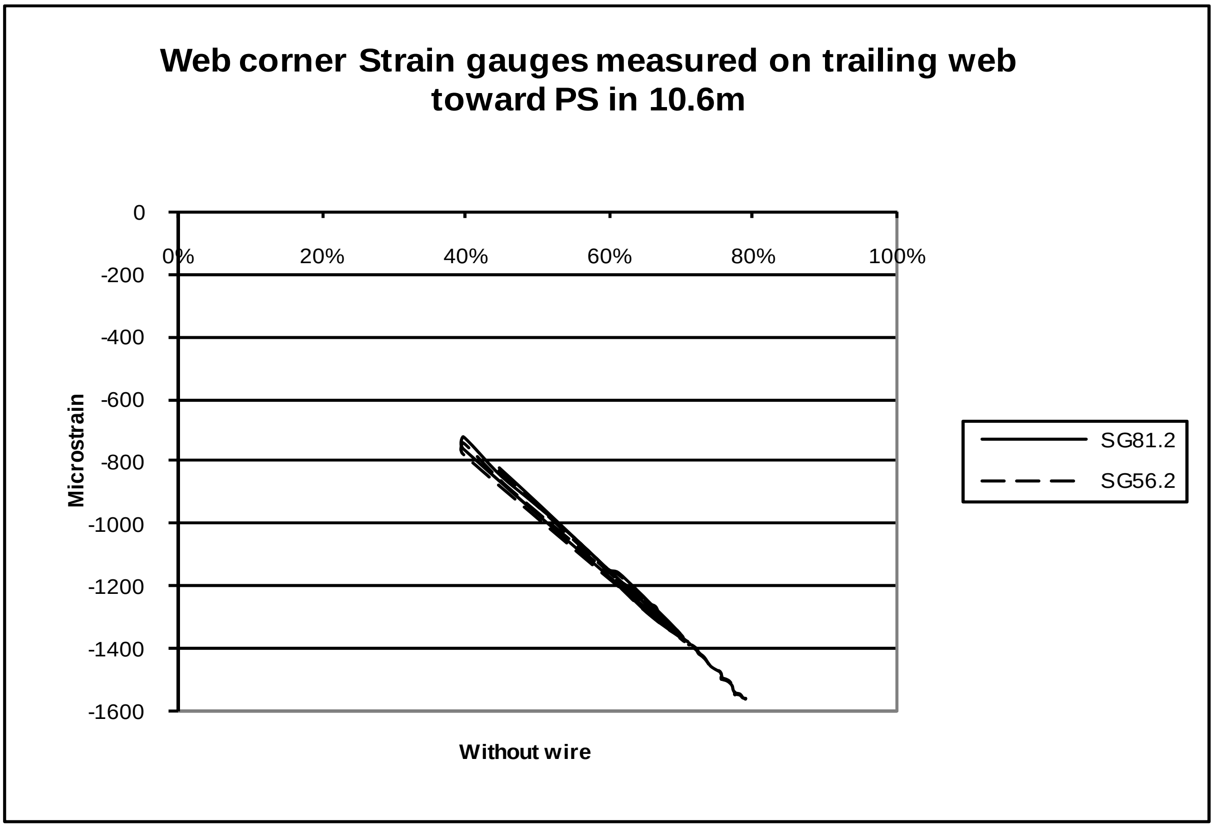

Transverse Strain gauges measured on leading web toward SS in 10.6m
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
Microstrain
Without wire
SG67.2
SG42.2



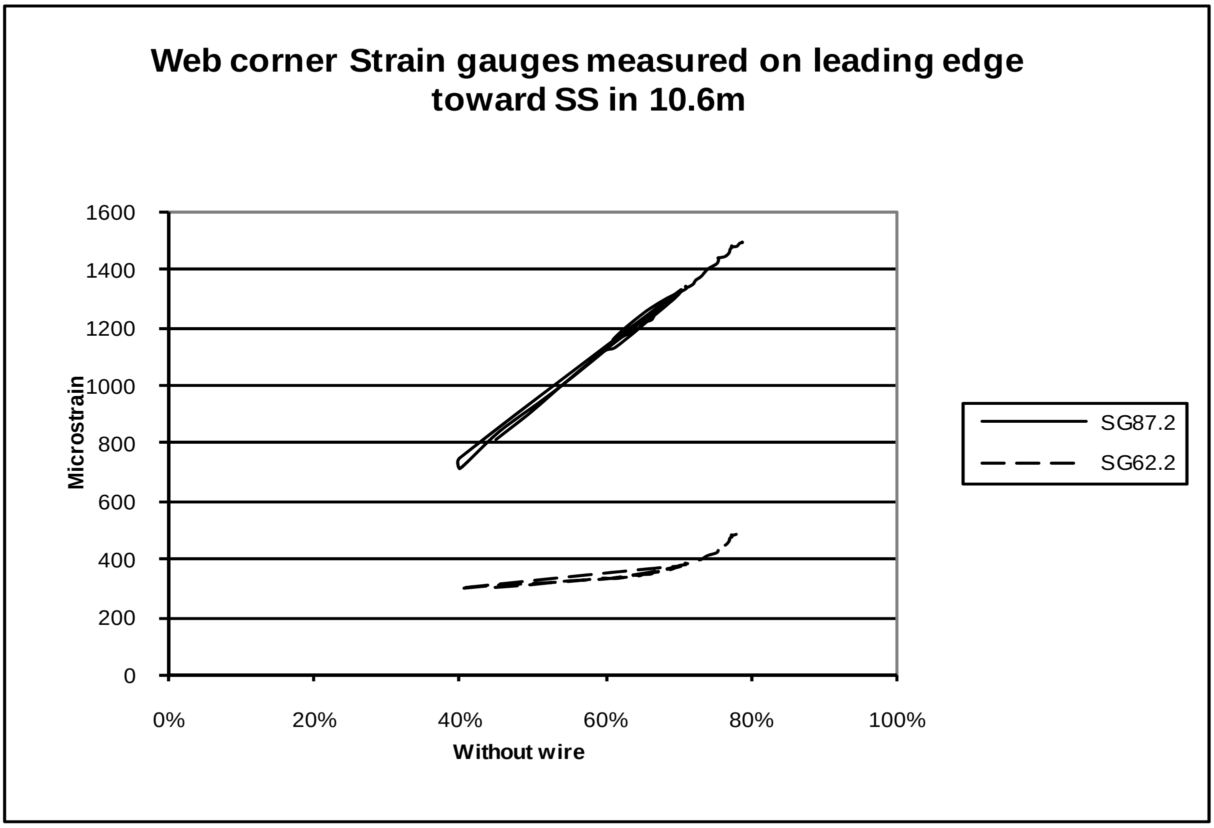
Transverse Strain gauges measured on leading web toward PS in 10.6m
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
0%
20%
40%
60%
80%
100%
Microstrain
Without wire
SG69.2
SG44.2



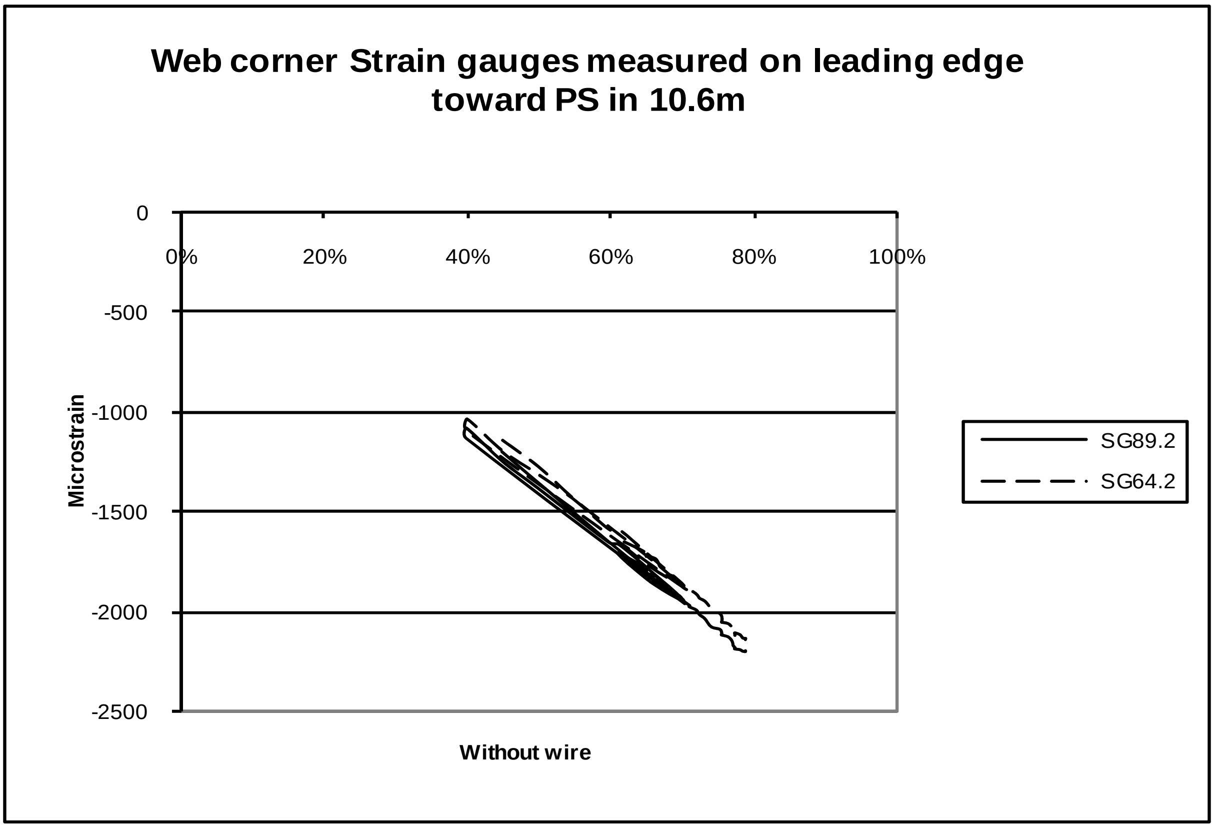
Web corner Strain gauges measured on trailing edge toward SS in 10.6m
1800
1600
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
Microstrain
Without wire
SG79.2
SG54.2

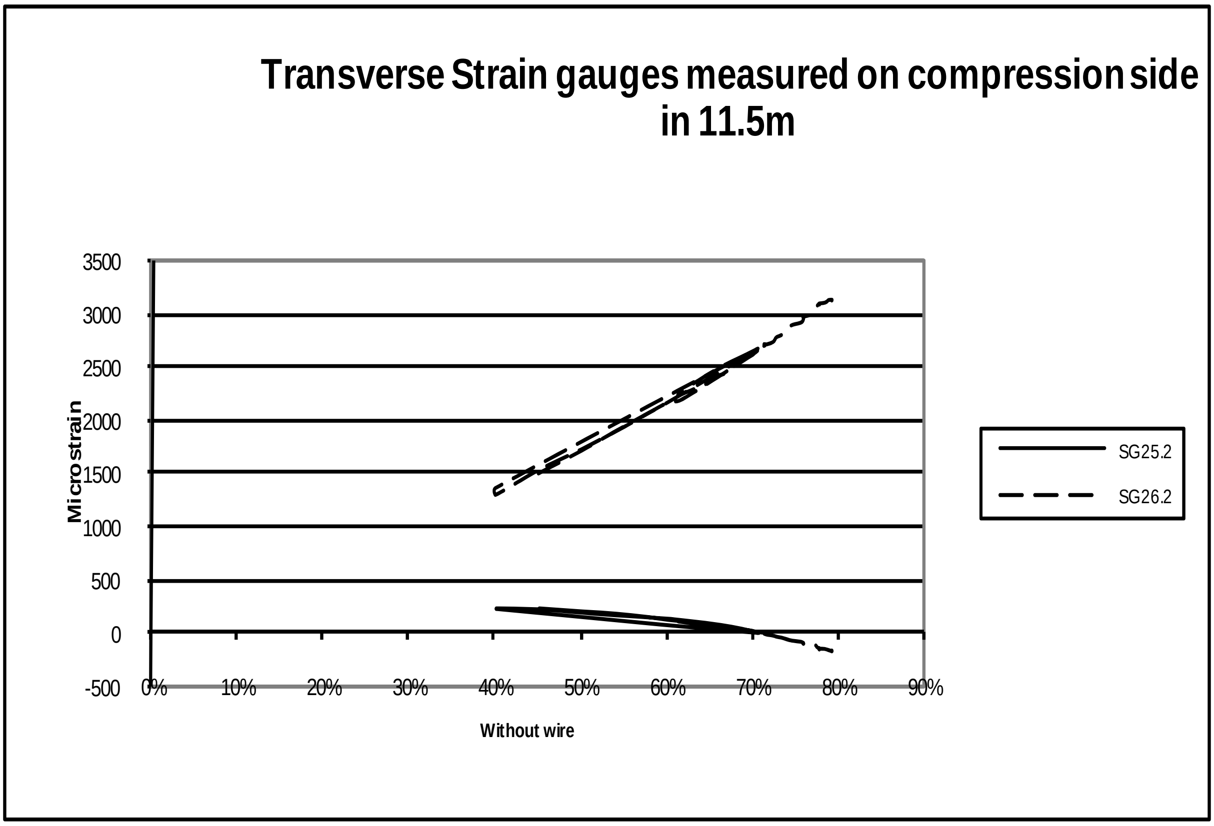


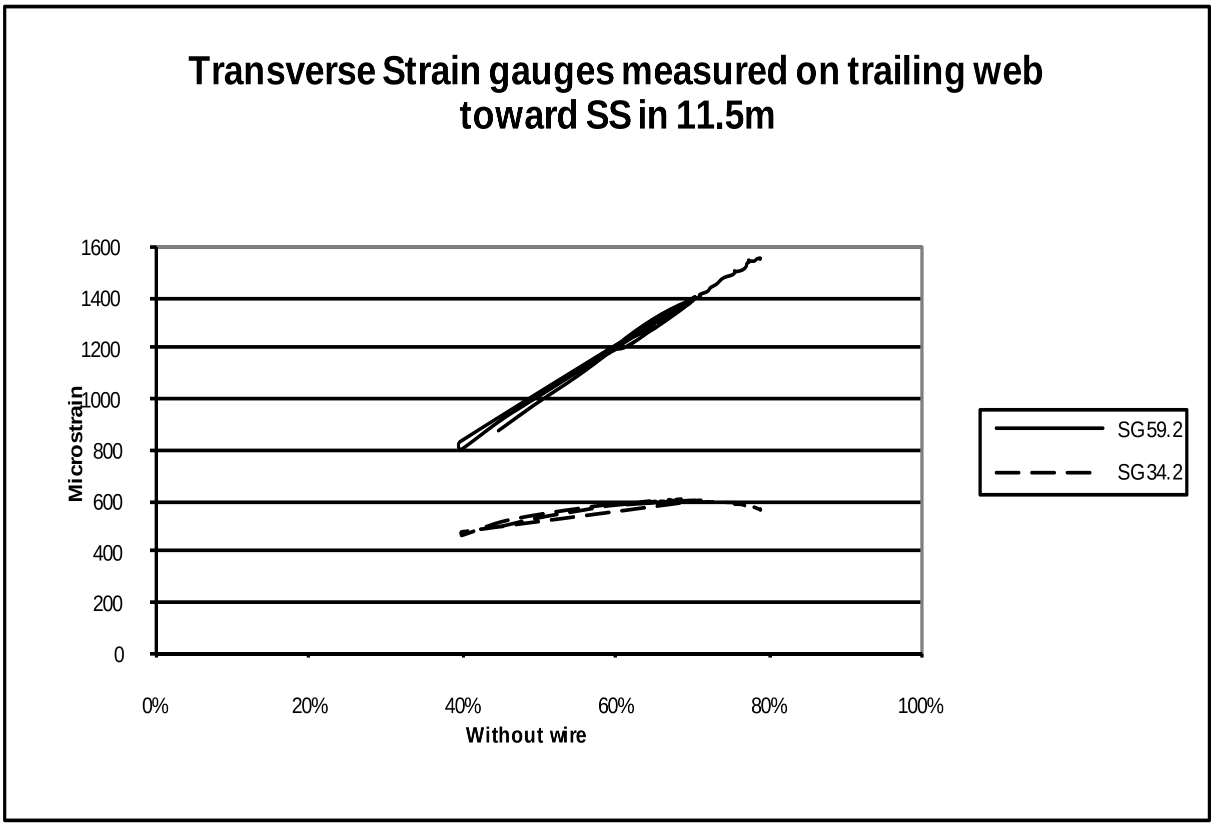
Web corner Strain gauges measured on trailing web toward PS in 10.6m
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
0%
20%
40%
60%
80%
100%
Microstrain
Without wire
SG81.2
SG56.2

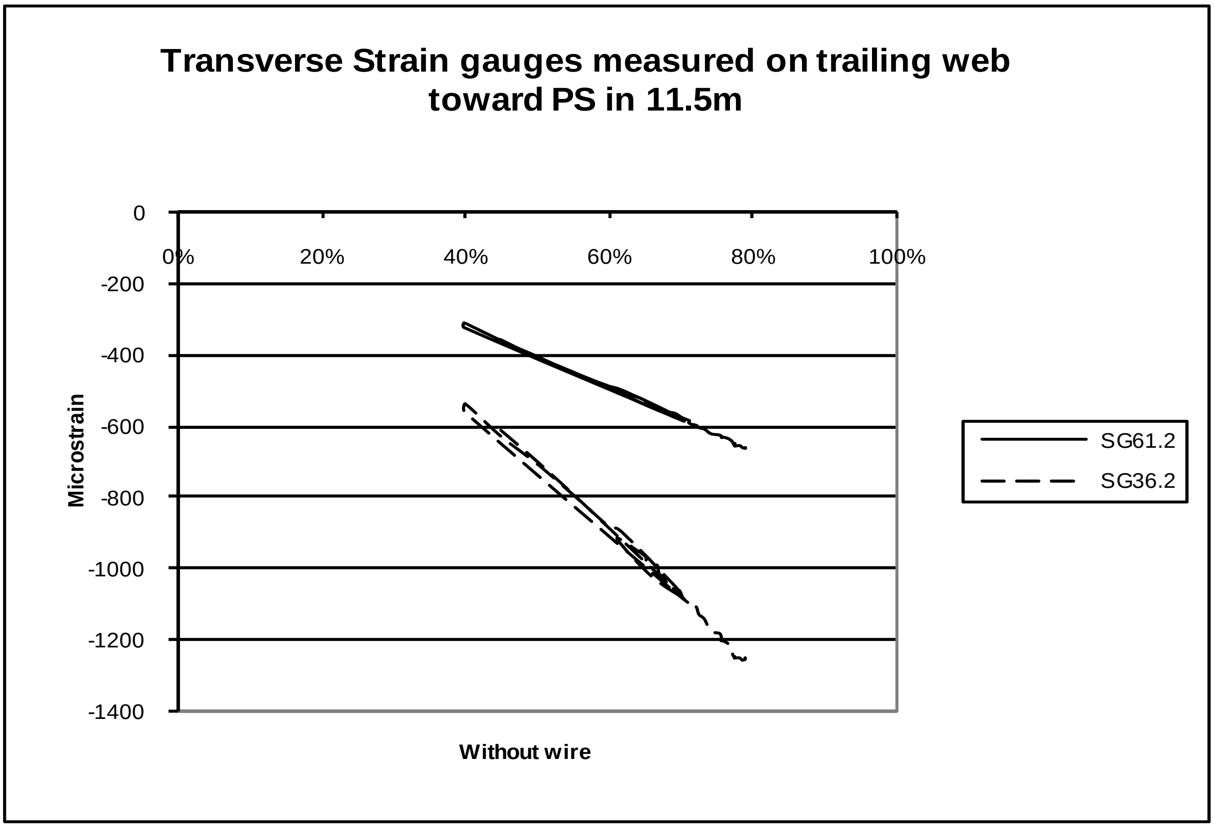


Web corner Strain gauges measured on leading edge toward SS in 10.6m
1600
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
Microstrain
Without wire
SG87.2
SG62.2

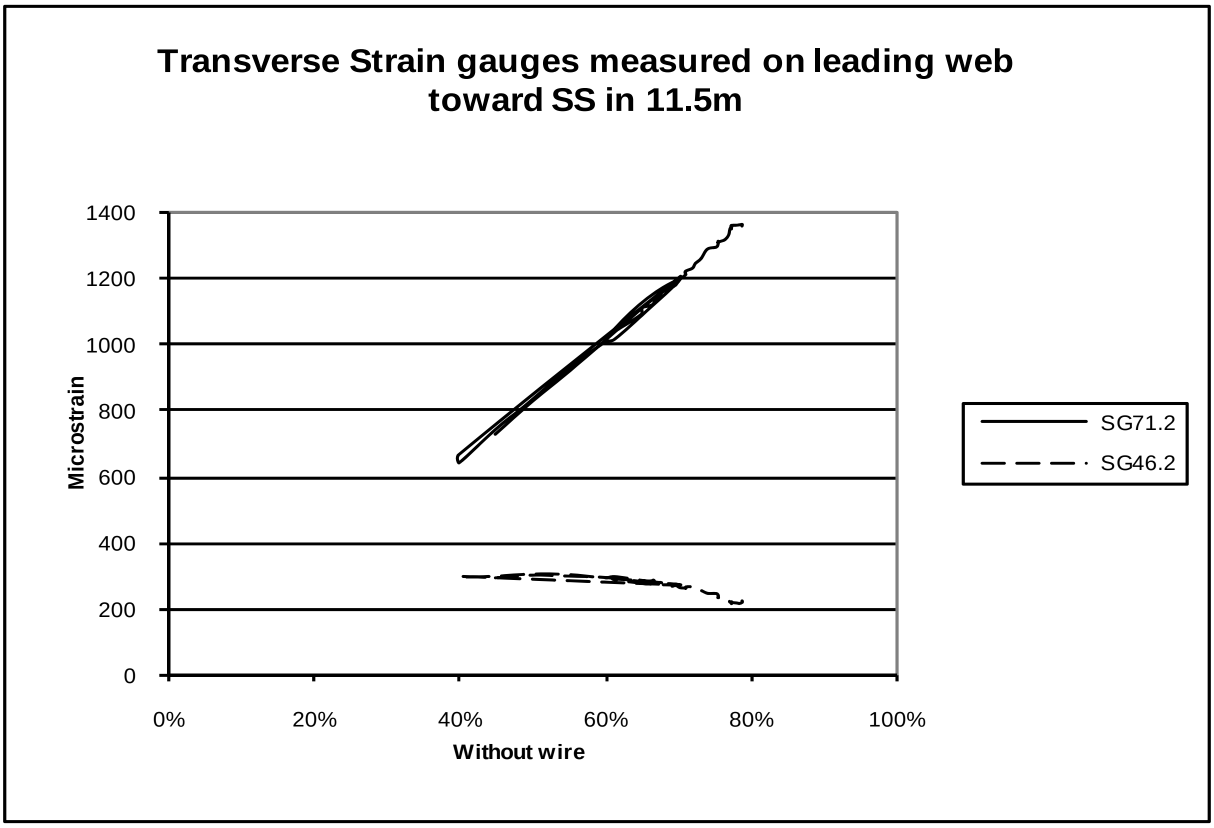

Web corner Strain gauges measured on leading edge toward PS in 10.6m
0
-500
-1000
-1500
-2000
-2500
0%
20%
40%
60%
80%
100%
Microstrain
Without wire
SG89.2
SG64.2

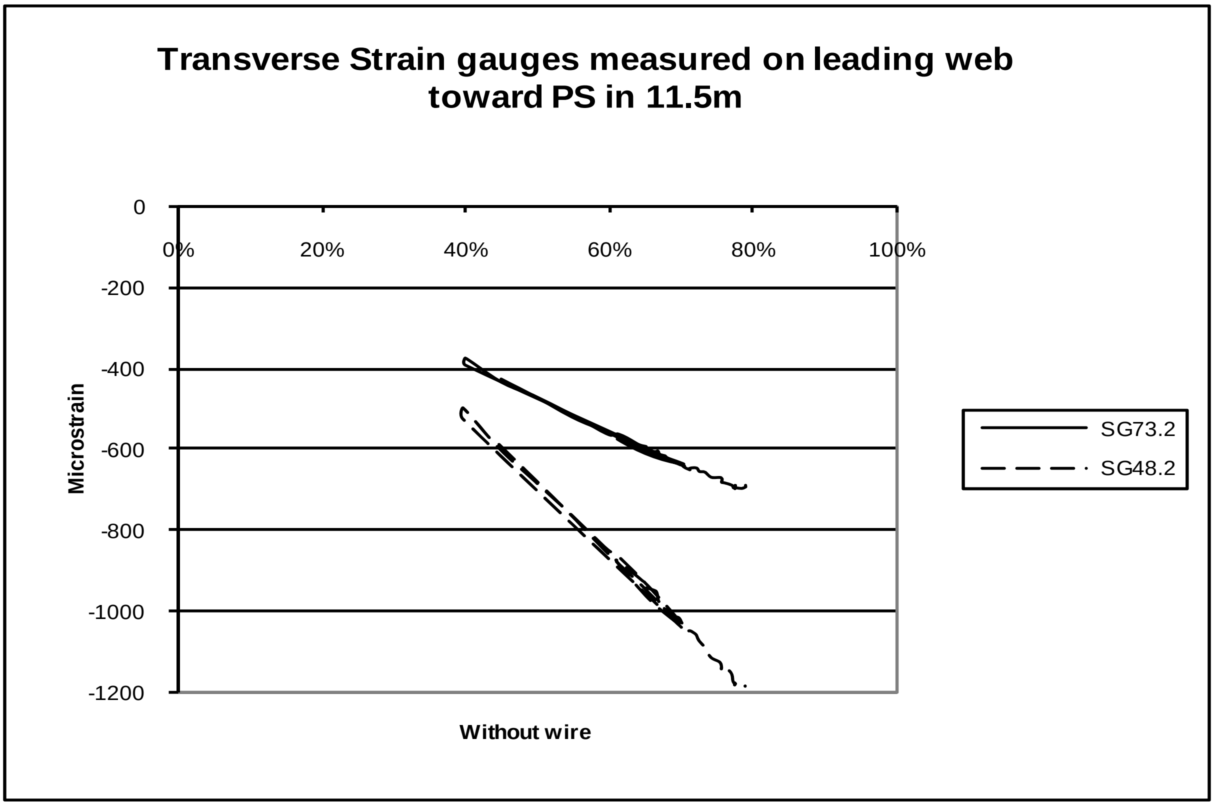

Transverse Strain gauges measured on compression side in 11.5m
3500
3000
2500
2000
1500
1000
500
0
-500
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Microstrain
Without wire
SG25.2
SG26.2

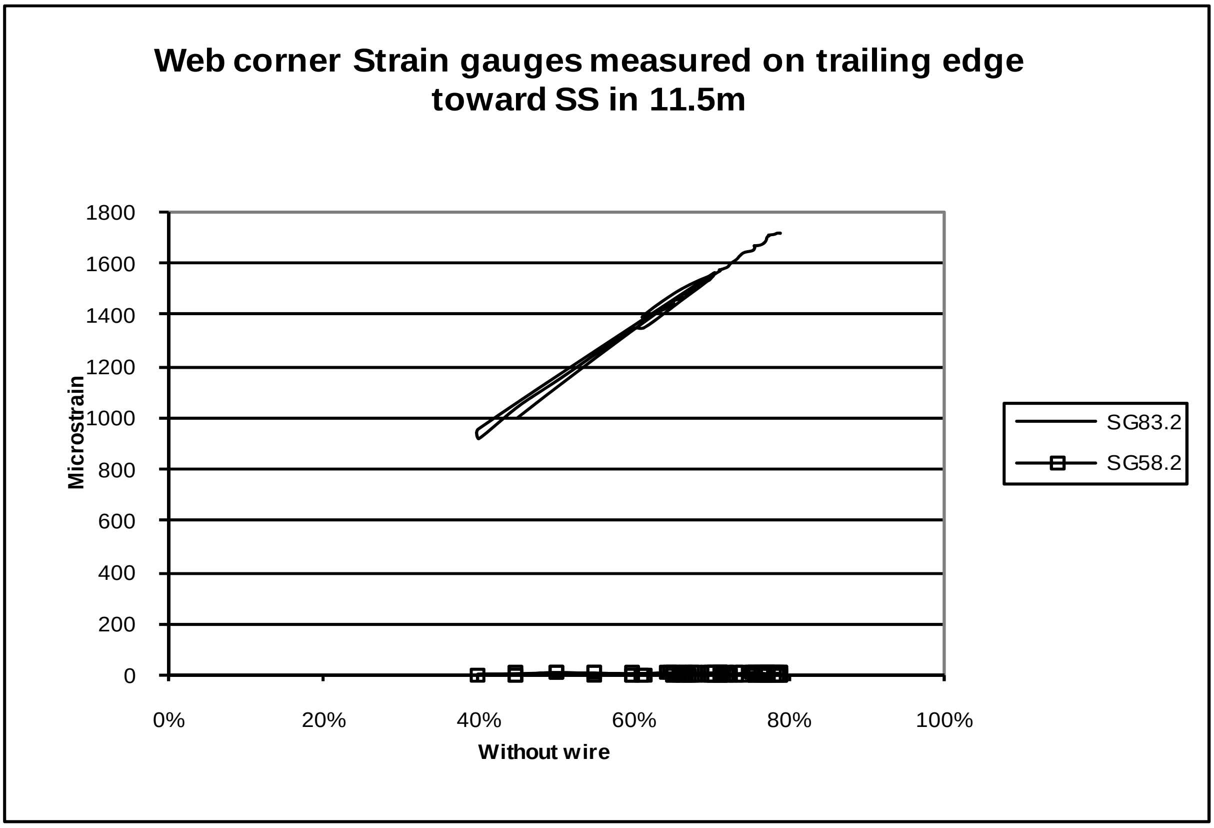


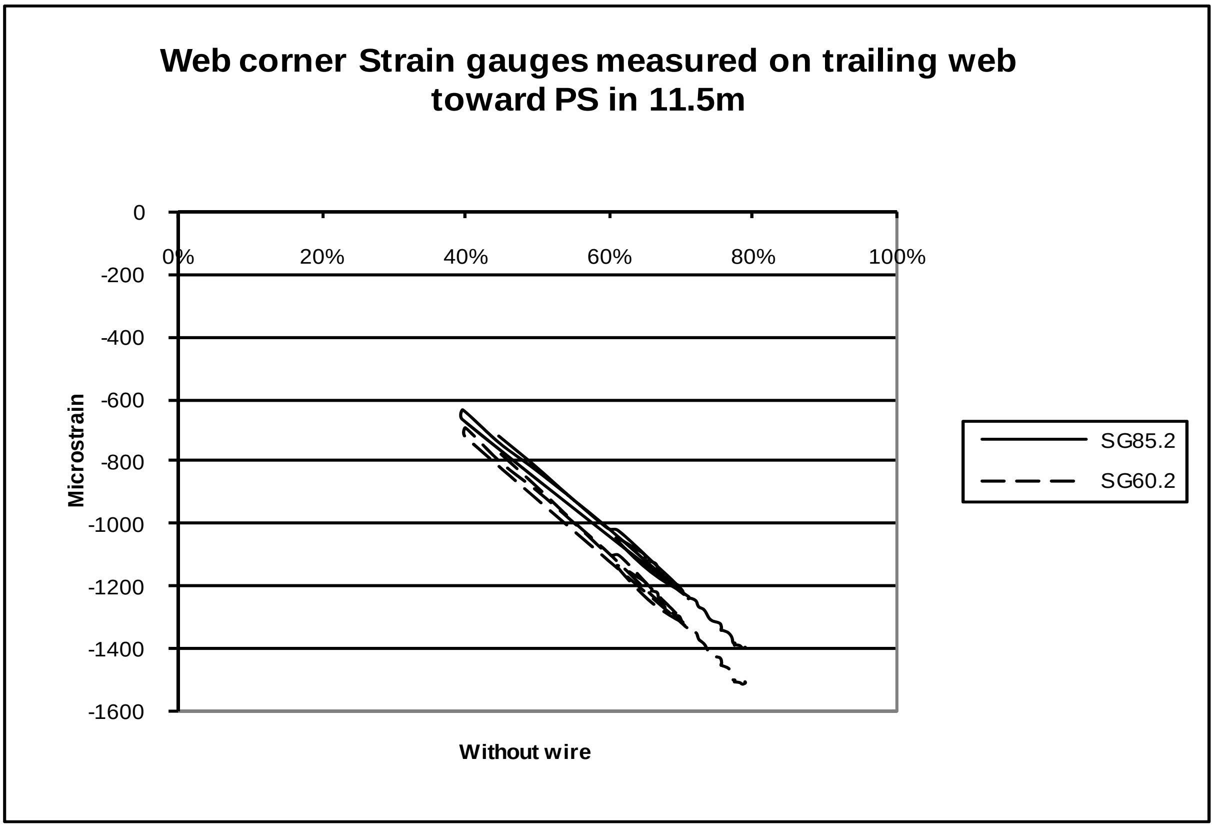


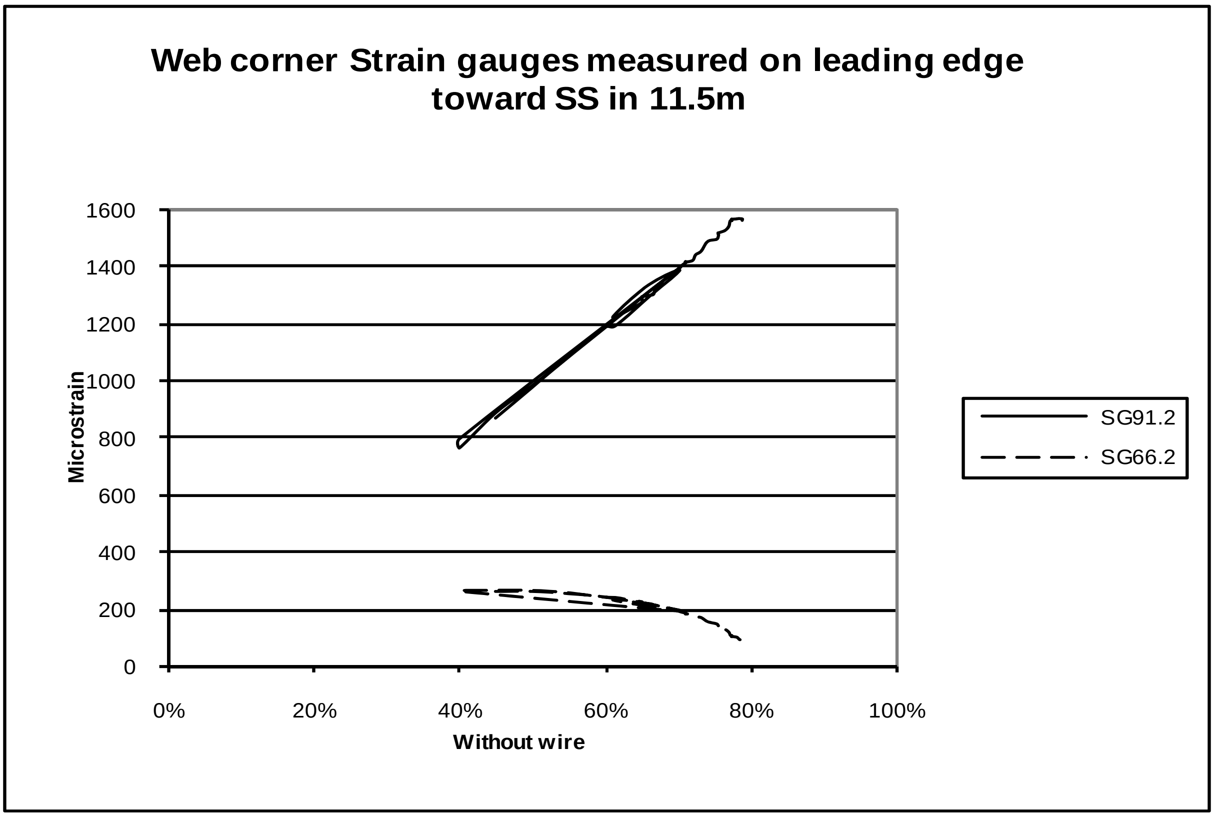
www.risoe.dtu.dk

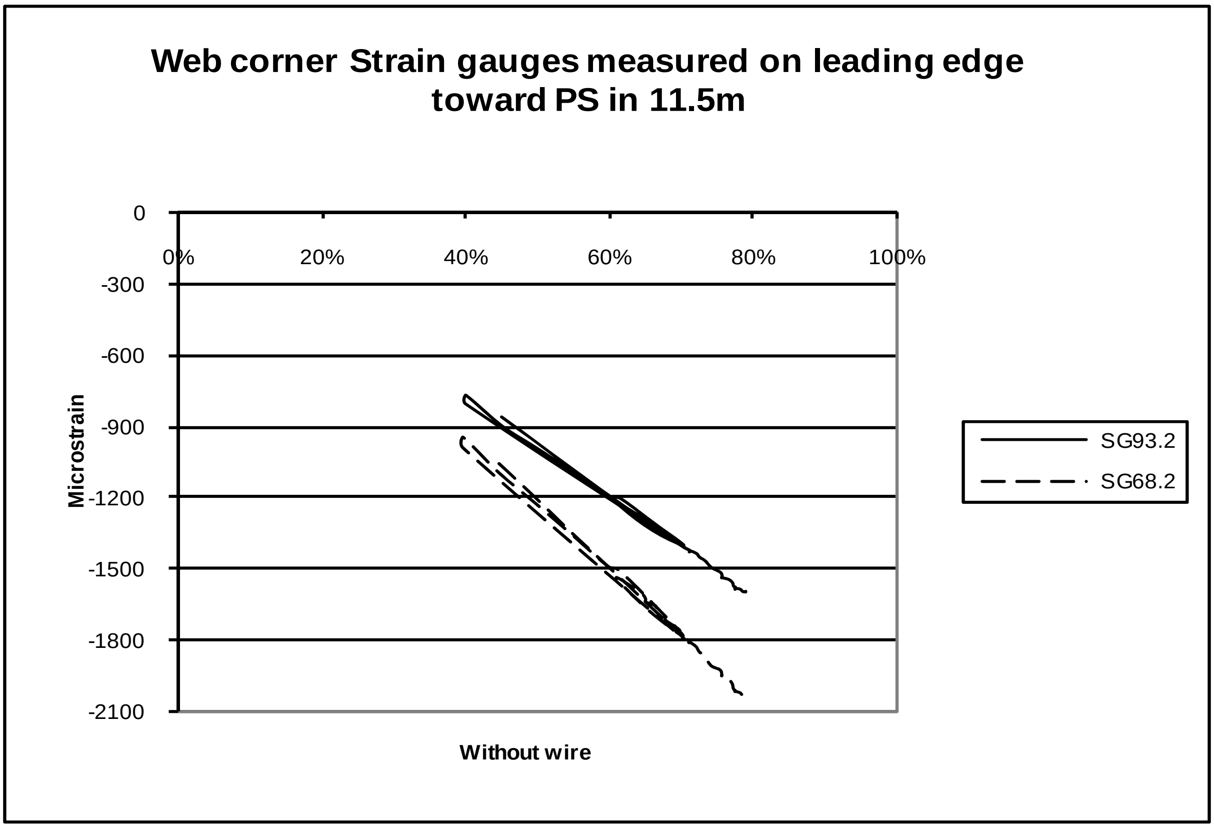

Transverse Strain gauges measured on leading web toward SS in 11.5m
1400
1200
1000
800
600
400
200
0
Microstrain
0%
20%
40%
60%
80%
100%
Without wire
SG71.2
SG46.2

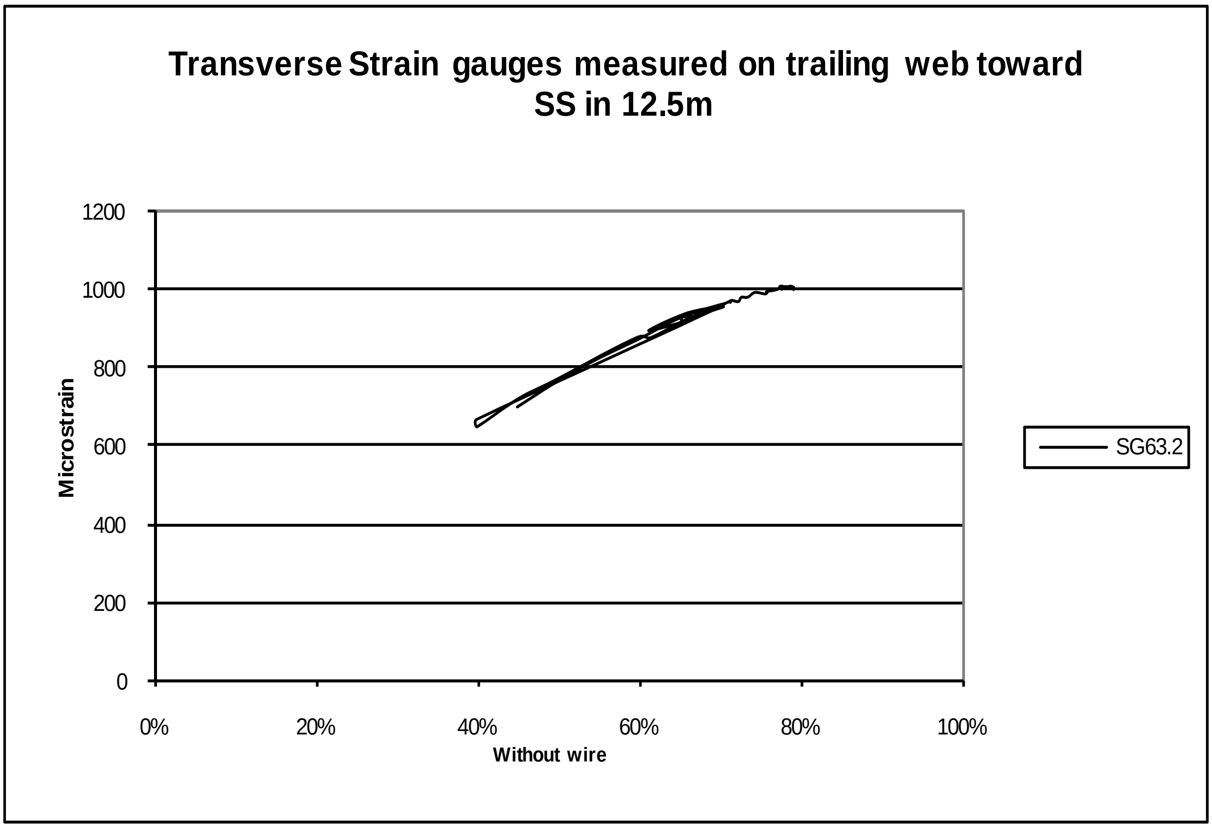

Transverse Strain gauges measured on leading web toward PS in 11.5m
0
-200
-400
-600
-800
-1000
-1200
Microstrain
0%
20%
40%
60%
80%
100%
Without wire
SG73.2
SG48.2

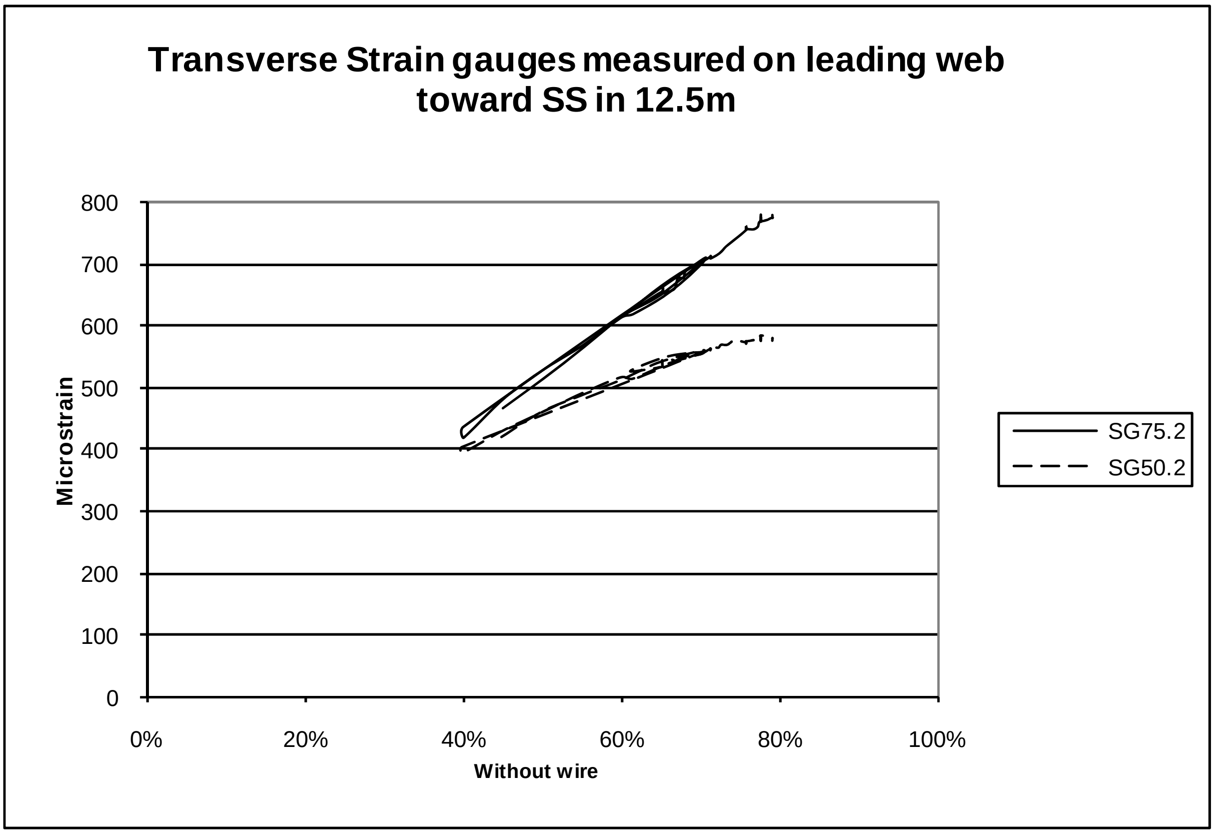

Web corner Strain gauges measured on trailing edge toward SS in 11.5m
Microstrain
1800
1600
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
Without wire
SG83.2
SG58.2

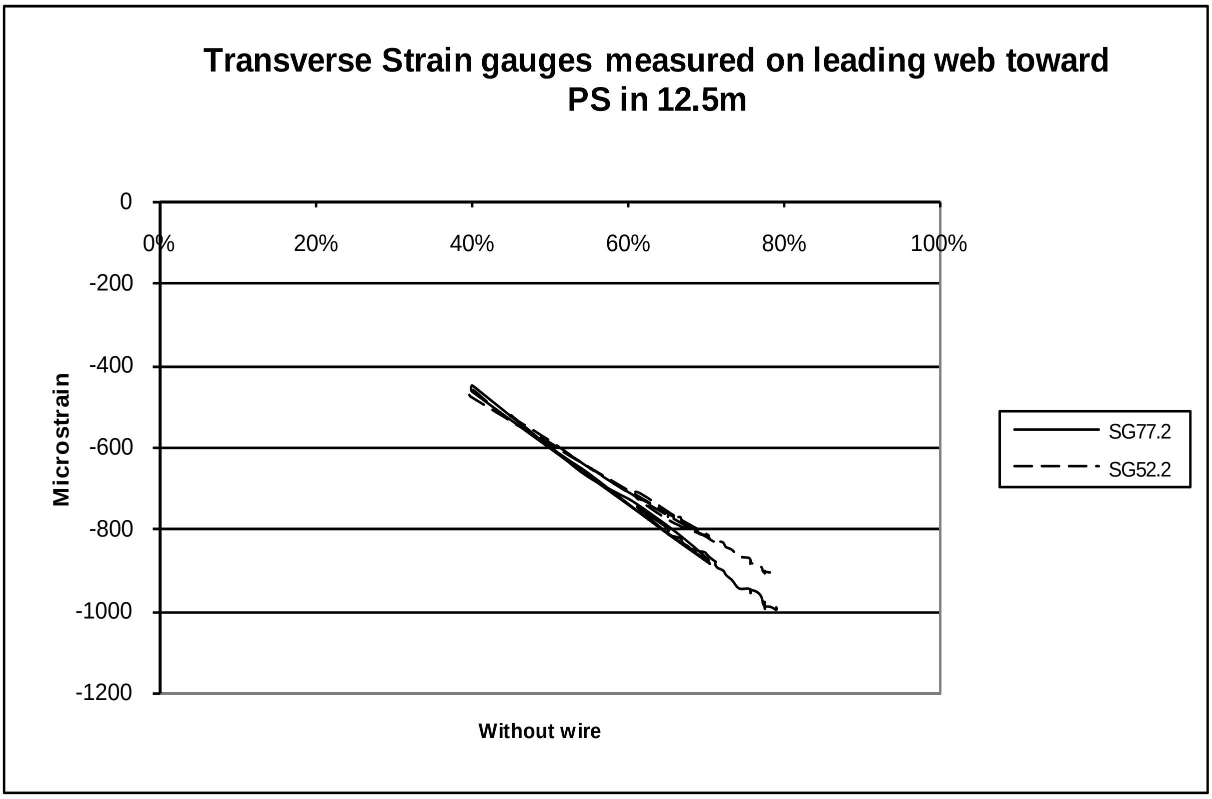

Web corner Strain gauges measured on trailing web toward PS in 11.5m
Microstrain
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
0%
20%
40%
60%
80%
100%
Without wire
SG85.2
SG60.2


Web corner Strain gauges measured on leading edge toward SS in 11.5m
1600
1400
1200
1000
800
600
400
200
0
Microstrain
0%
20%
40%
60%
80%
100%
Without wire
SG91.2
SG66.2

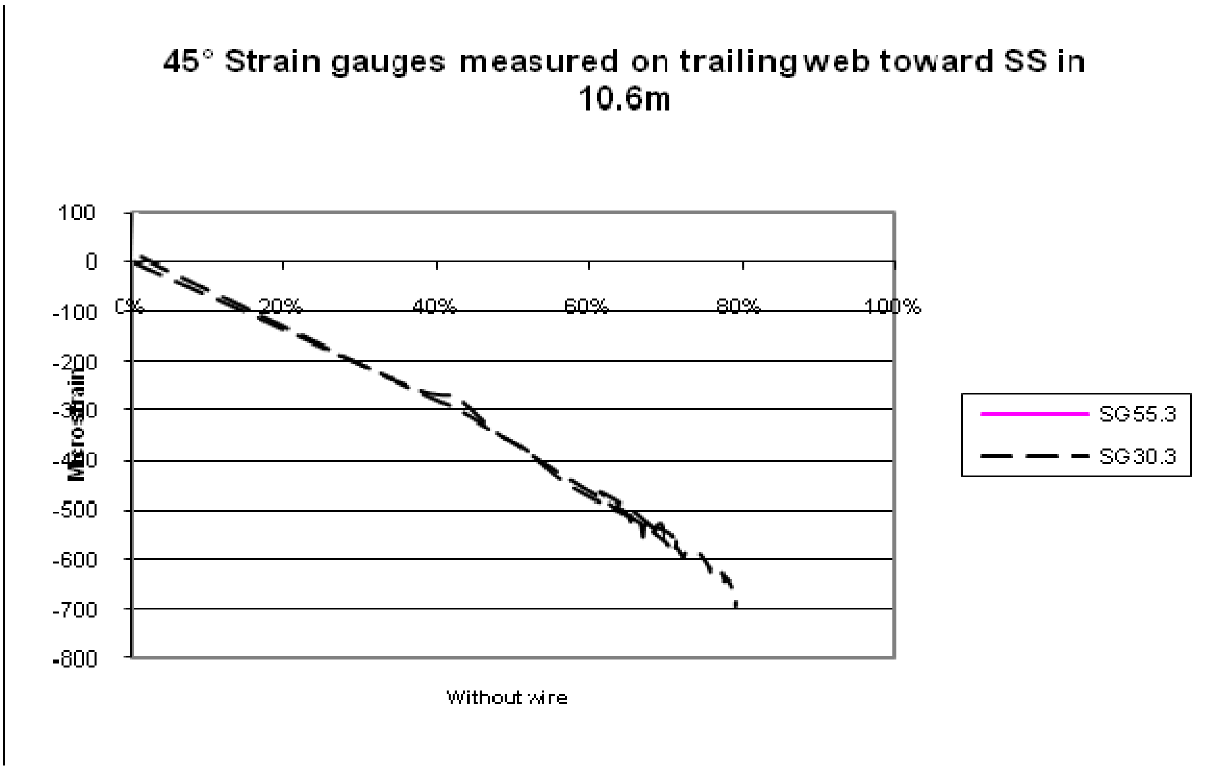

Web corner Strain gauges measured on leading edge toward PS in 11.5m
0
-300
-600
-900
-1200
-1500
-1800
-2100
Microstrain
0%
20%
40%
60%
80%
100%
Without wire
SG93.2
SG68.2

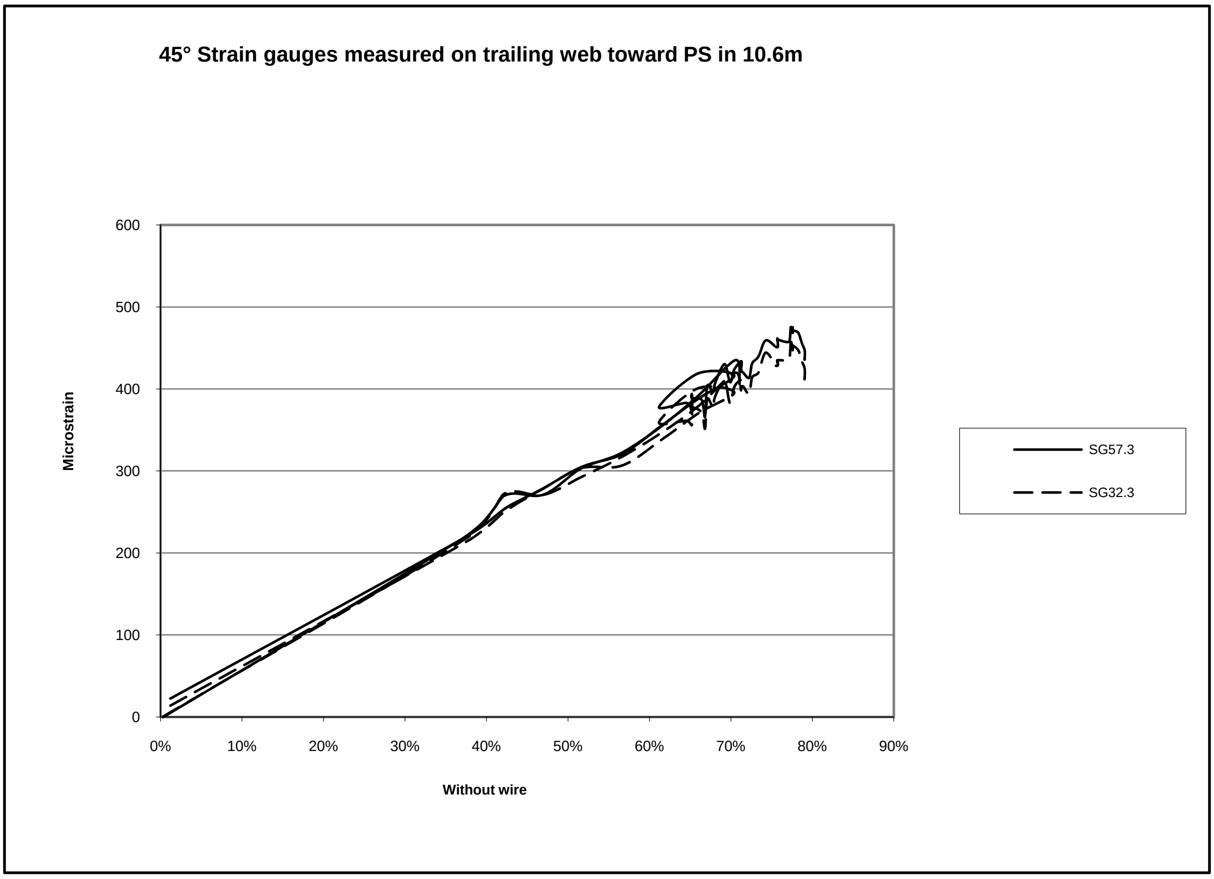

Transverse Strain gauges measured on trailing web toward SS in 12.5m
1200
1000
800
600
400
200
0
Microstrain
0%
20%
40%
60%
80%
100%
Without wire
SG63.2

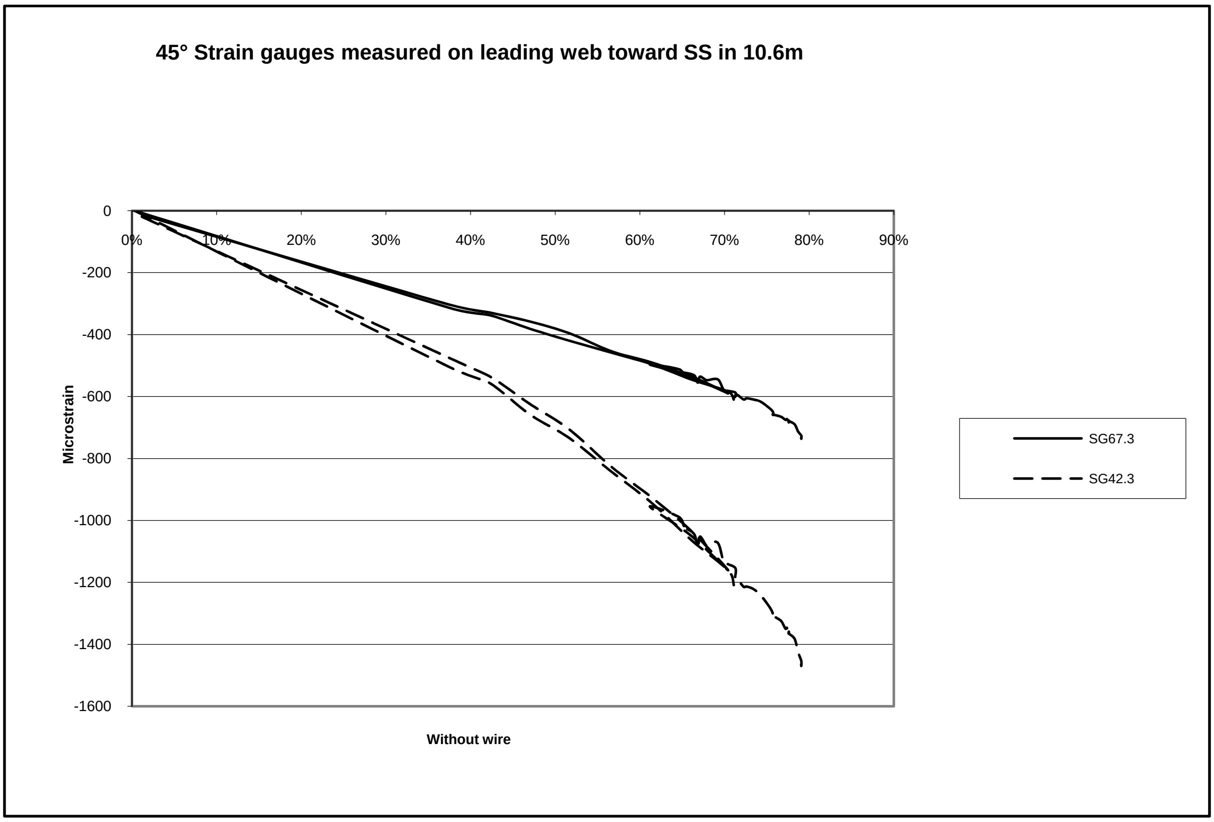

Transverse Strain gauges measured on leading web toward SS in 12.5m
800
700
600
500
400
300
200
100
0
Microstrain
0%
20%
40%
60%
80%
100%
Without wire
SG75.2
SG50.2

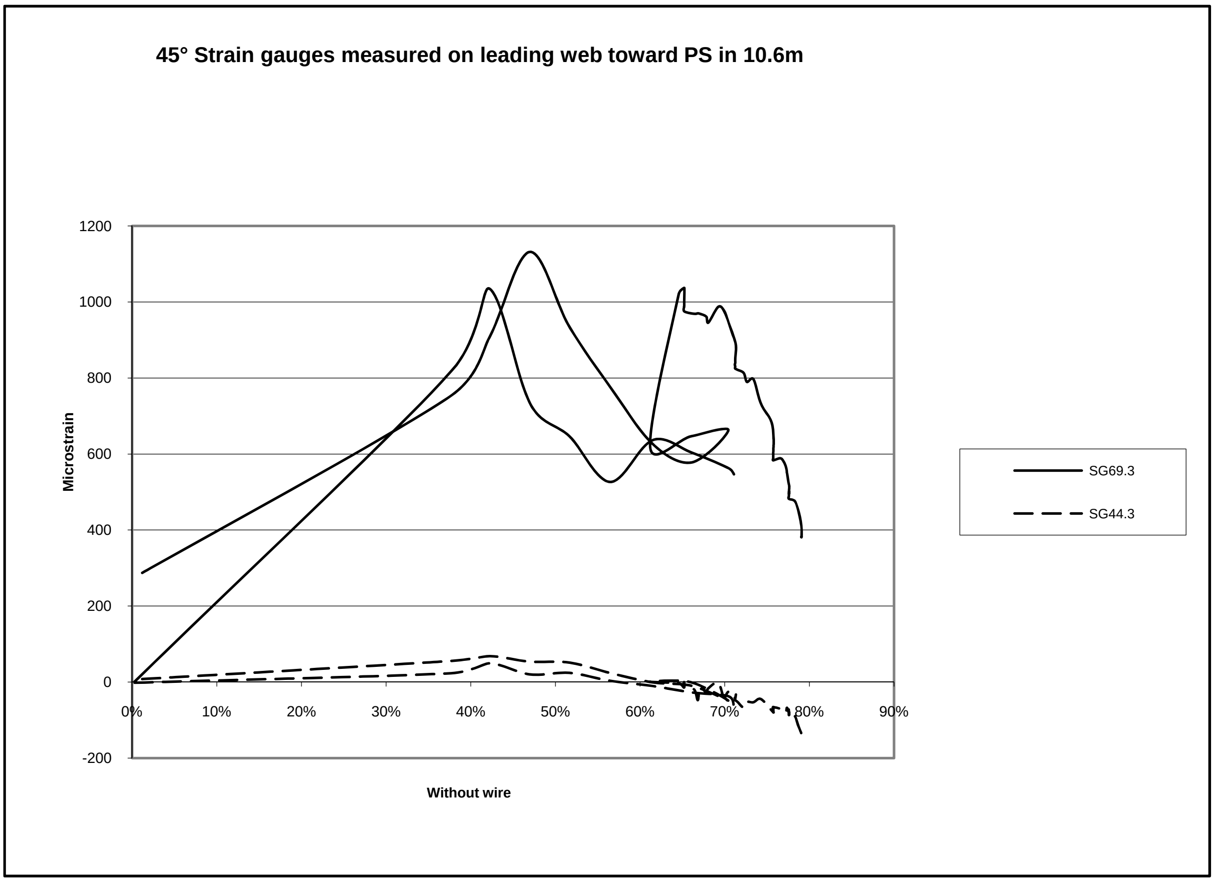


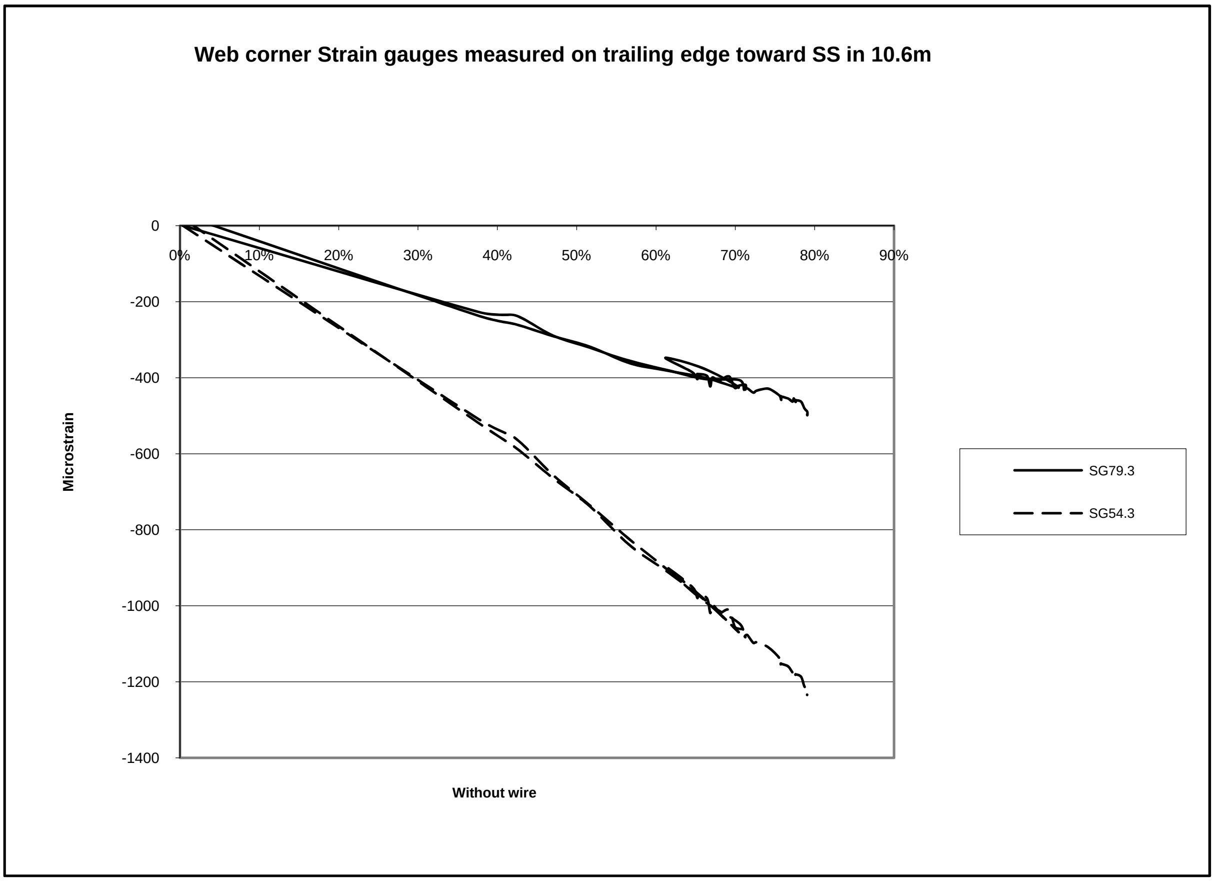
Graphs of the 45° measurements without wire

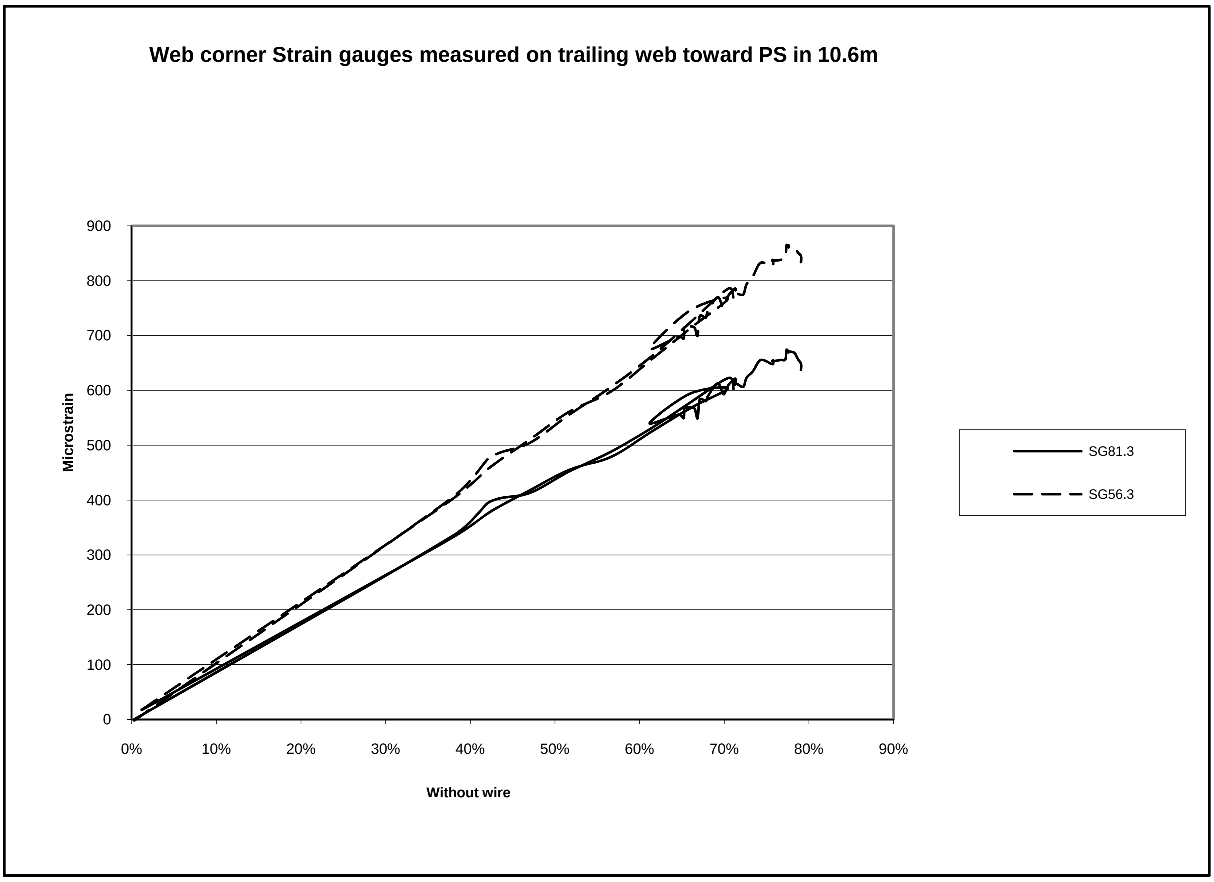


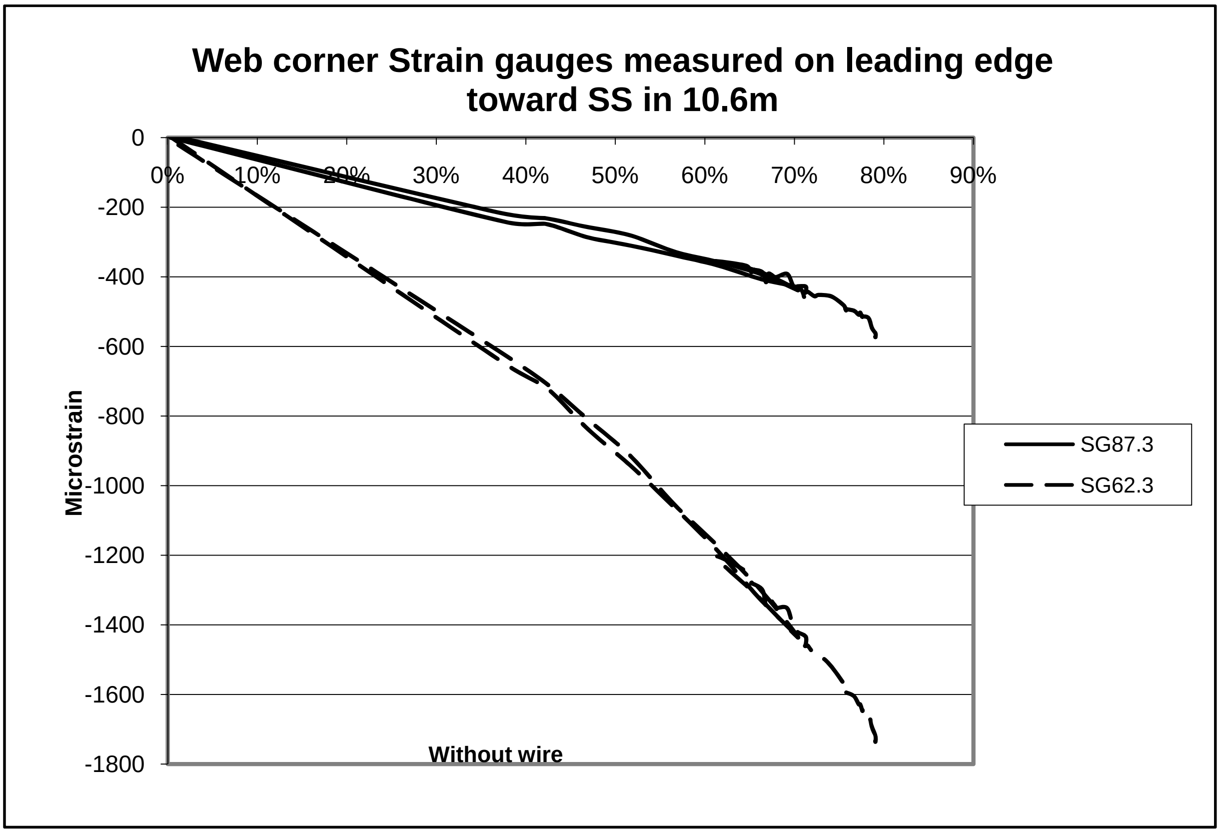

45° Strain gauges measured on trailing web toward PS in 10.6m
Microstrain
600
500
400
300
200
100
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG57.3
SG32.3

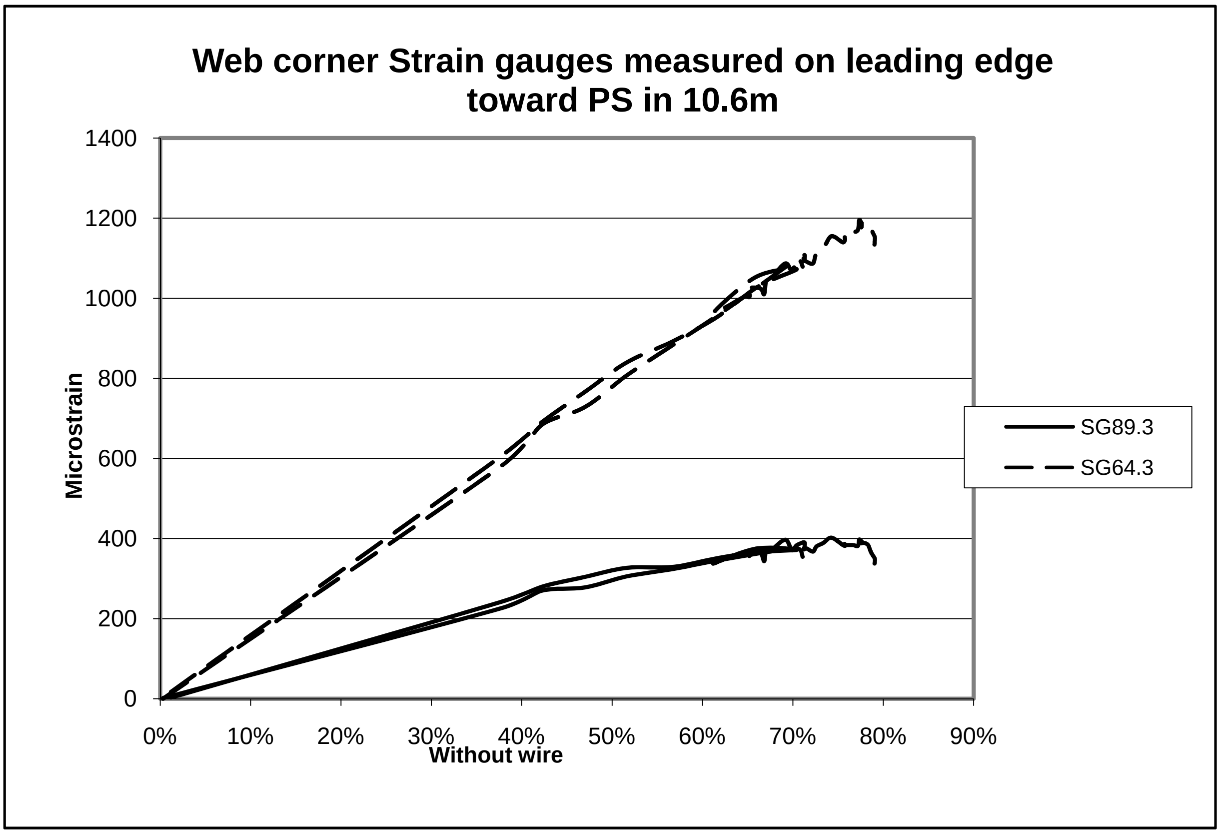

45° Strain gauges measured on leading web toward SS in 10.6m
Microstrain
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG67.3
SG42.3

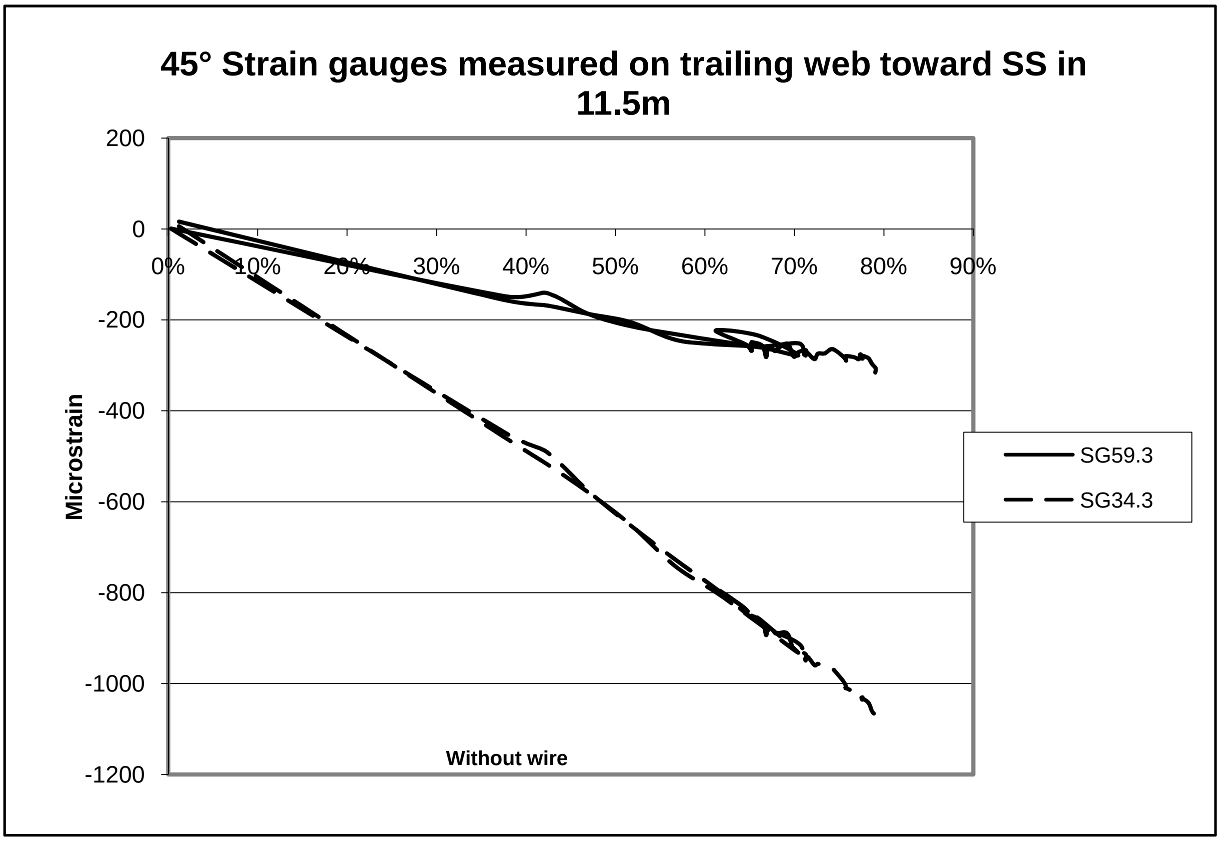

45° Strain gauges measured on leading web toward PS in 10.6m
Microstrain
1200
1000
800
600
400
200
0
-200
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG69.3
SG44.3

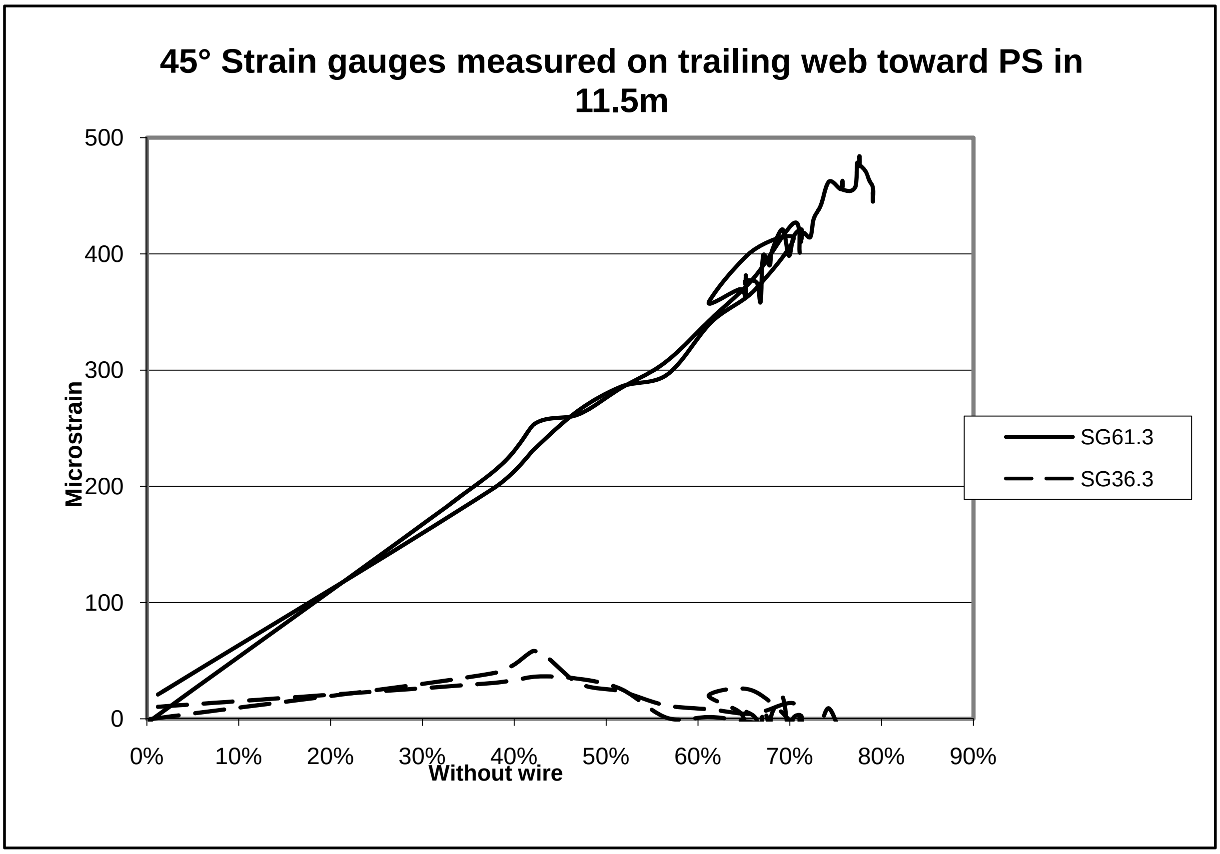

Web corner Strain gauges measured on trailing edge toward SS in 10.6m
Microstrain
0
-200
-400
-600
-800
-1000
-1200
-1400
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG79.3
SG54.3


Web corner Strain gauges measured on trailing web toward PS in 10.6m
Microstrain
900
800
700
600
500
400
300
200
100
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG81.3
SG56.3

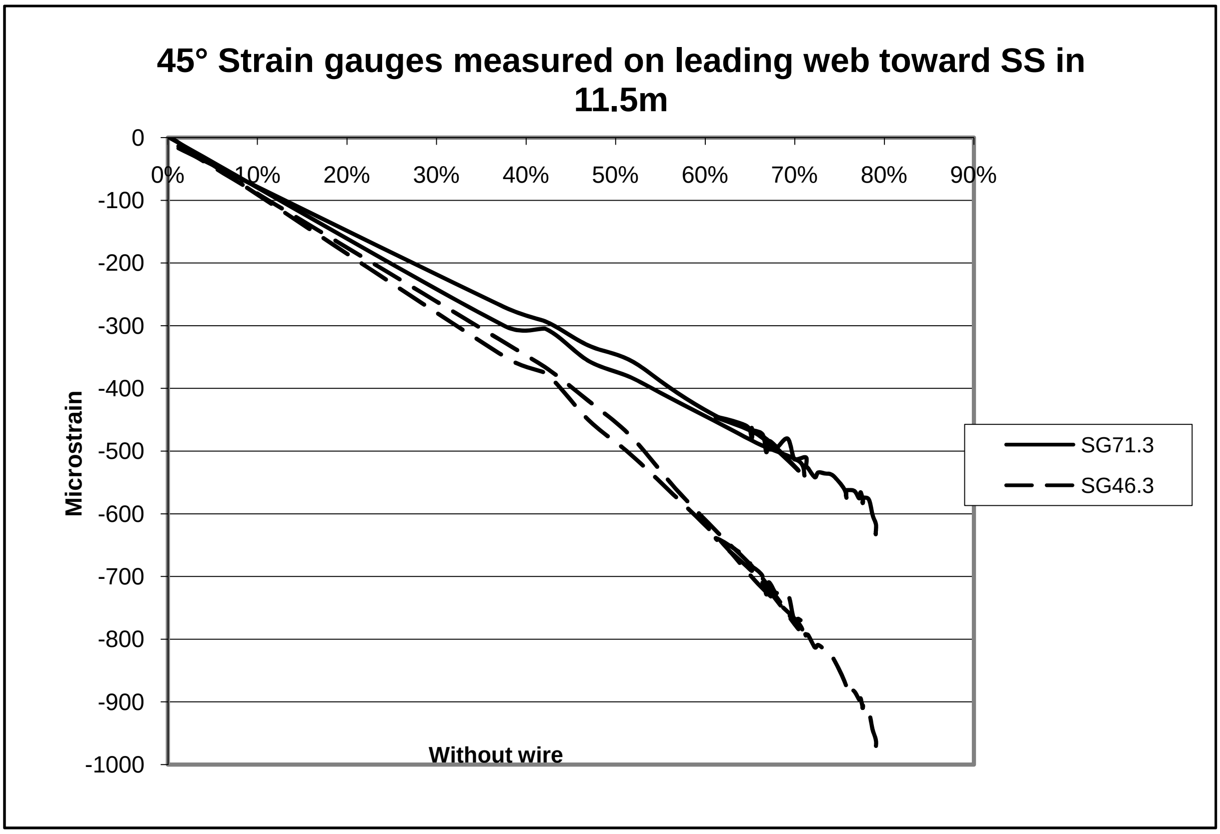

Web corner Strain gauges measured on leading edge toward SS in 10.6m
Microstrain
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG87.3
SG62.3


Web corner Strain gauges measured on leading edge toward PS in 10.6m
1400
1200
1000
800
600
400
200
0
Microstrain
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG89.3
SG64.3

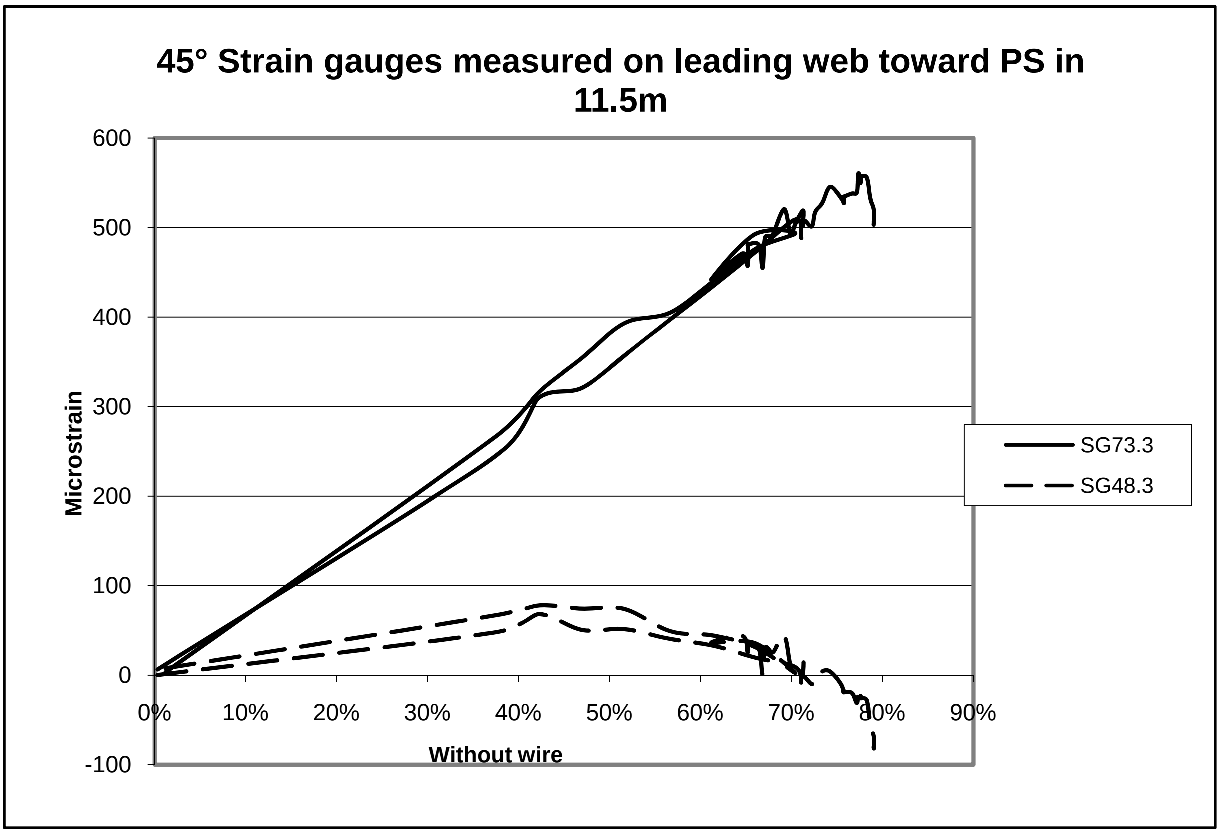

45° Strain gauges measured on trailing web toward SS in 11.5m
200
0
-200
-400
-600
-800
-1000
-1200
Microstrain
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG59.3
SG34.3

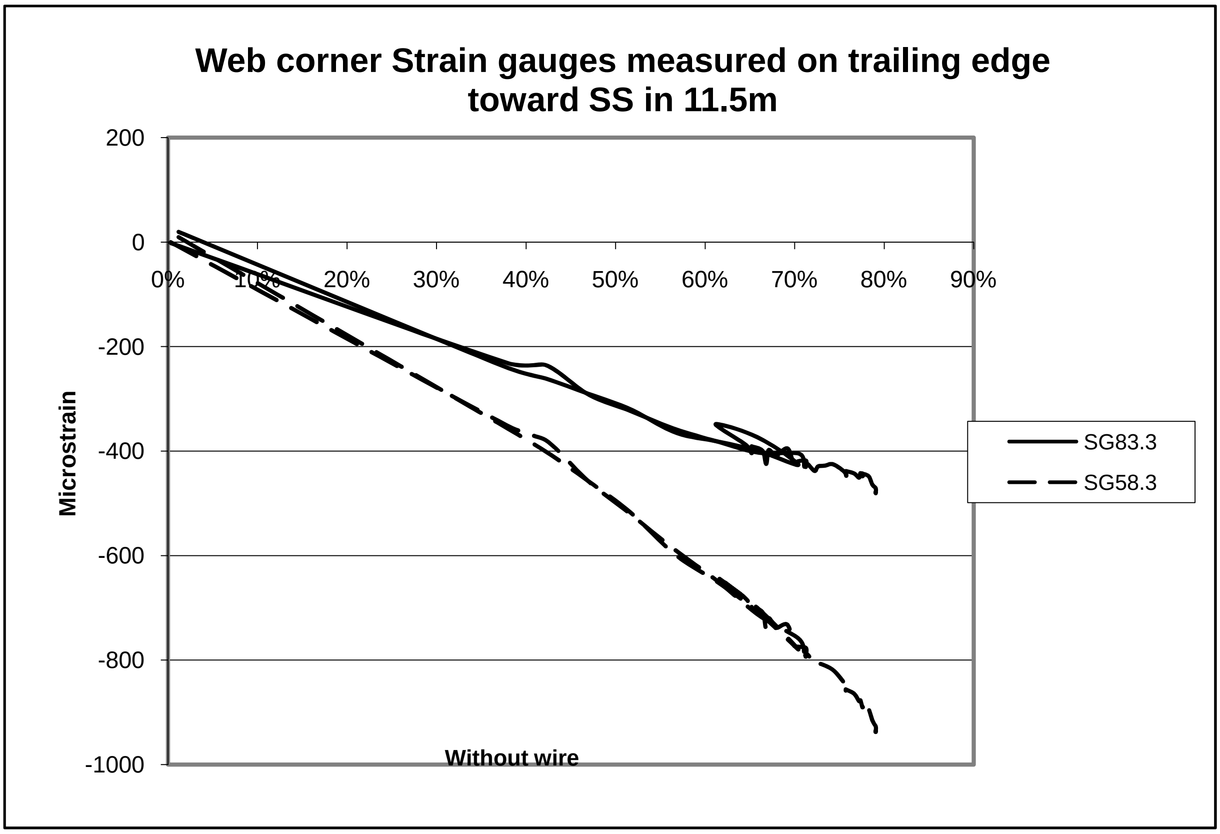


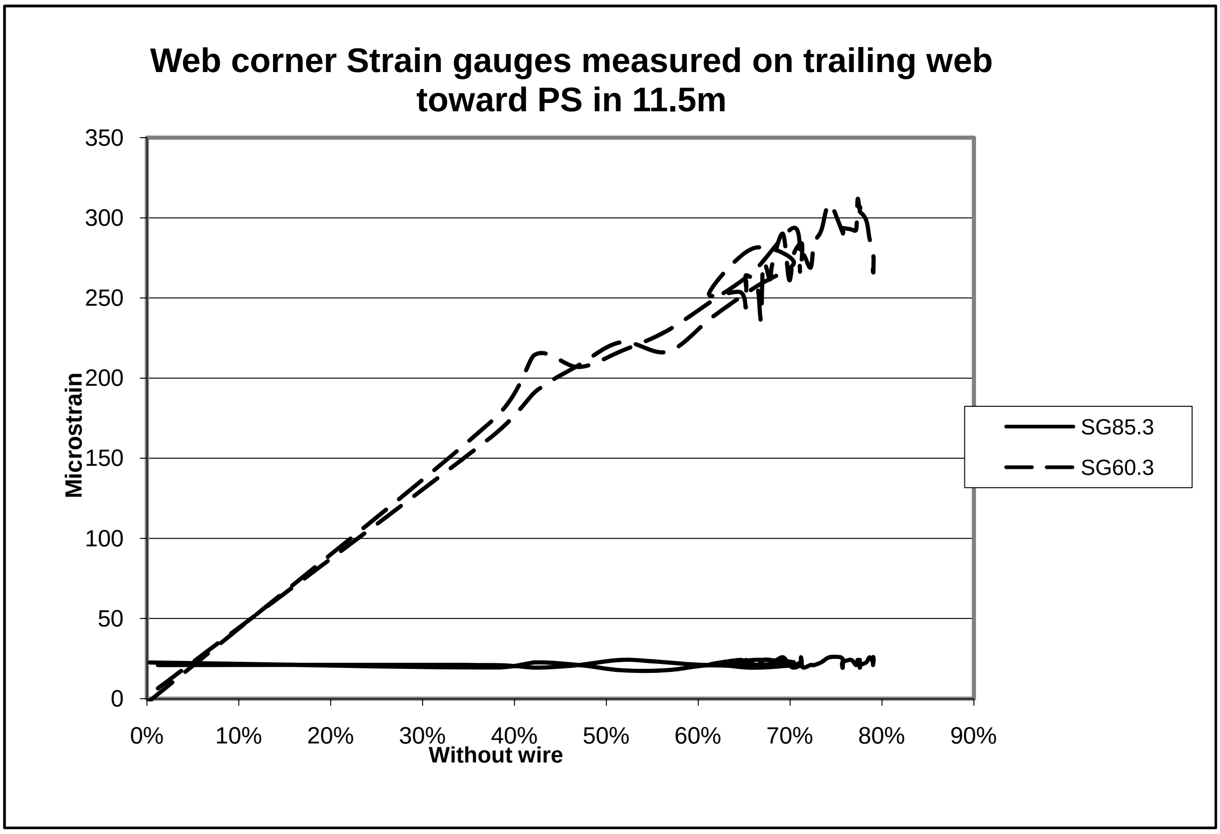
45° Strain gauges measured on trailing web toward PS in 11.5m
Microstrain
500
400
300
200
100
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG61.3
SG36.3

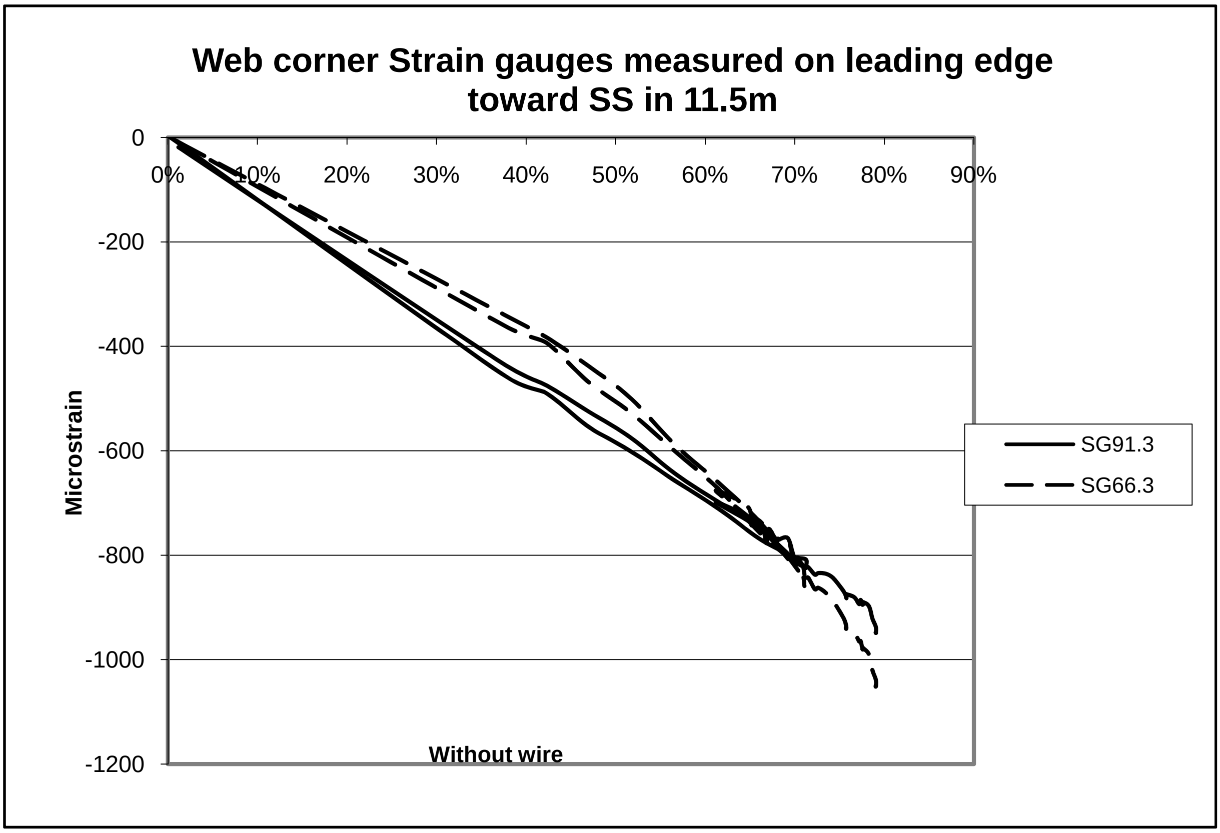


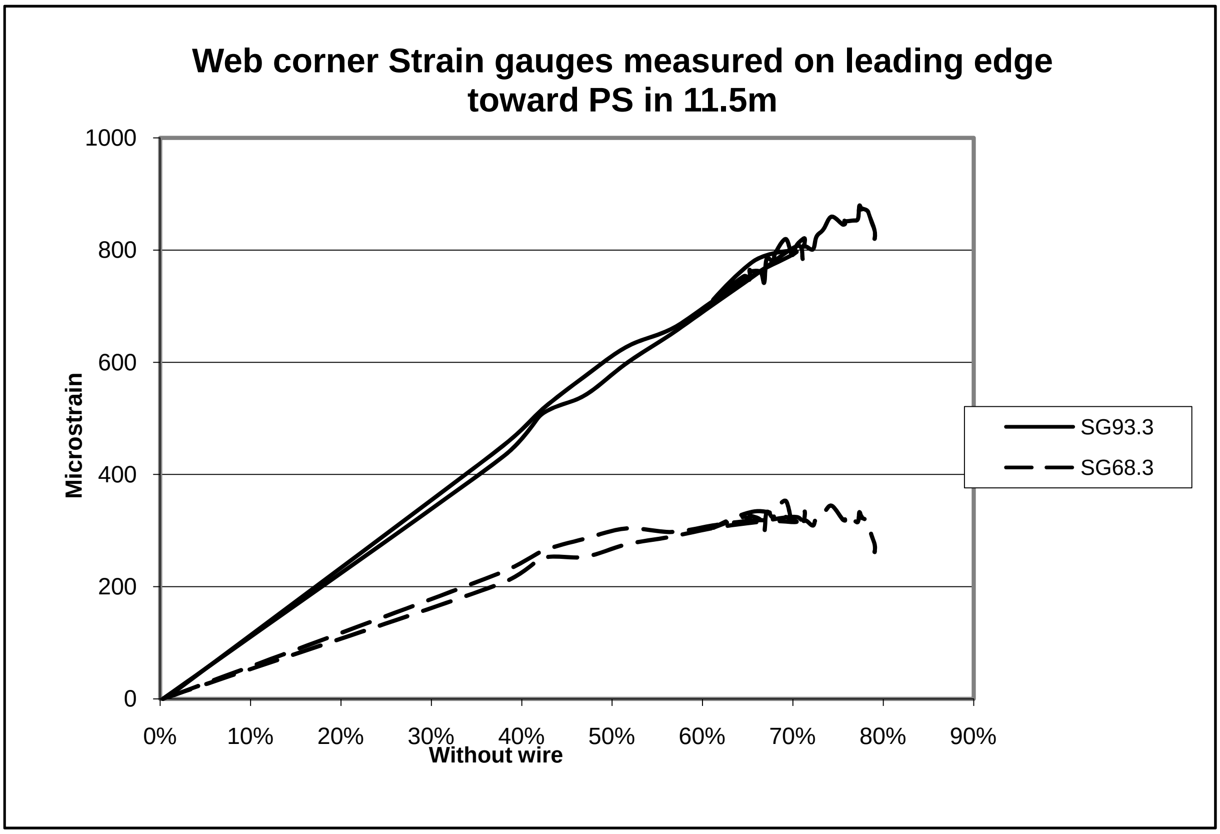
45° Strain gauges measured on leading web toward SS in 11.5m
Microstrain
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG71.3
SG46.3

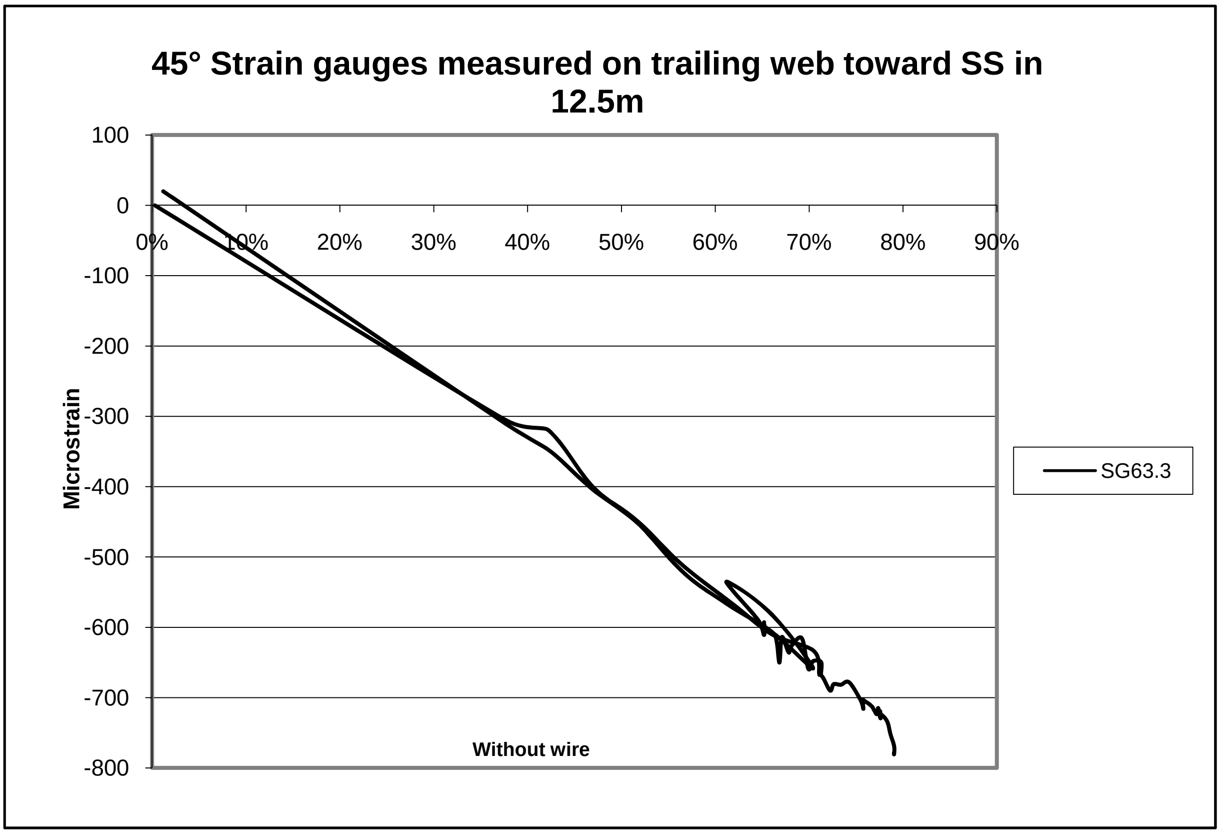

45° Strain gauges measured on leading web toward PS in 11.5m
Microstrain
600
500
400
300
200
100
0
-100
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG73.3
SG48.3

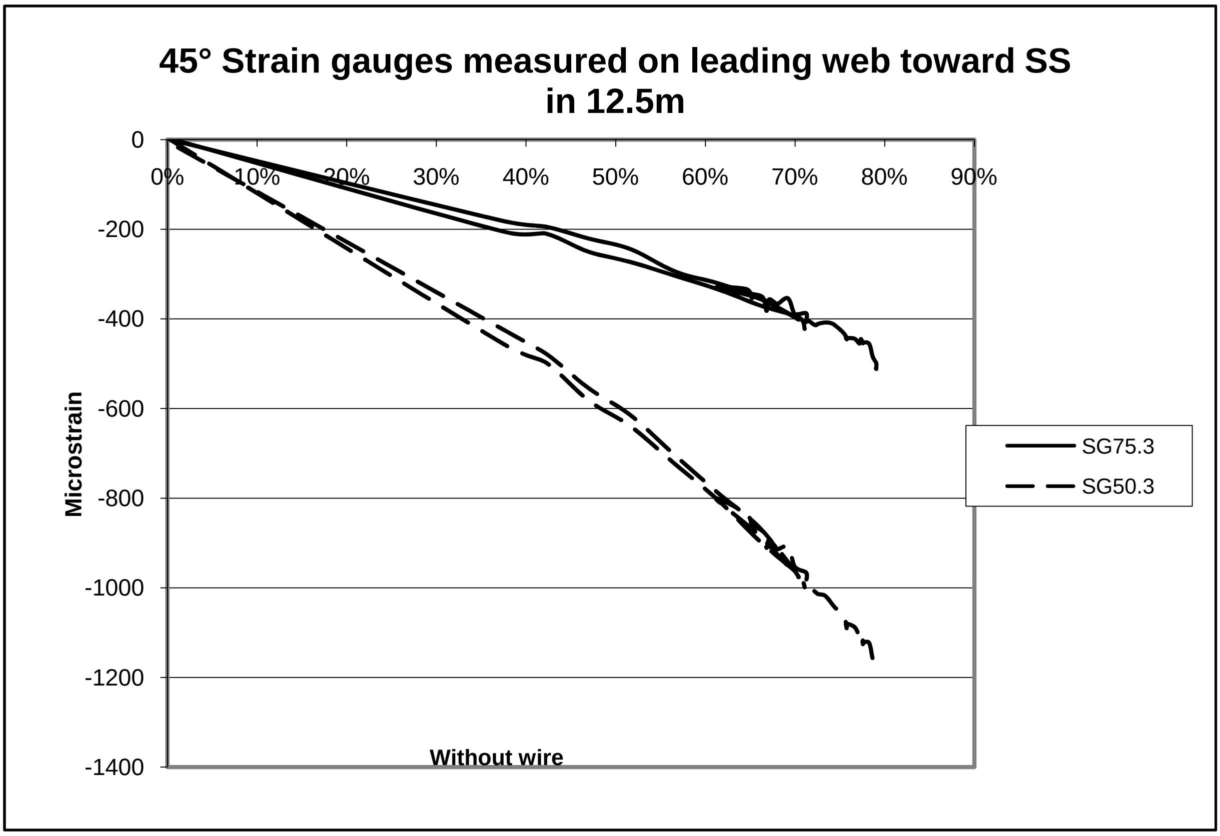

Web corner Strain gauges measured on trailing edge toward SS in 11.5m
Microstrain
200
0
-200
-400
-600
-800
-1000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG83.3
SG58.3

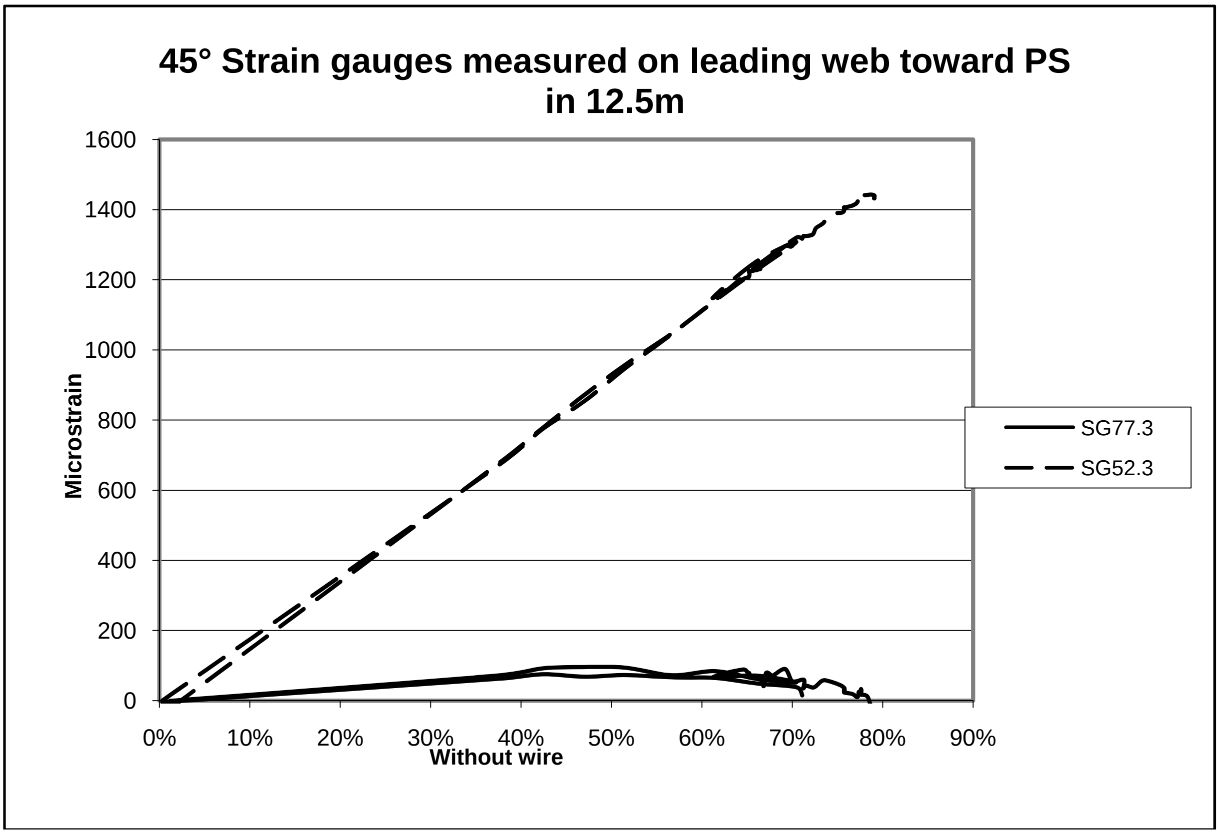

Web corner Strain gauges measured on trailing web toward PS in 11.5m
Microstrain
350
300
250
200
150
100
50
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG85.3
SG60.3


Web corner Strain gauges measured on leading edge toward SS in 11.5m
Microstrain
0
-200
-400
-600
-800
-1000
-1200
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG91.3
SG66.3


Web corner Strain gauges measured on leading edge toward PS in 11.5m
1000
800
600
400
200
0
Microstrain
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG93.3
SG68.3

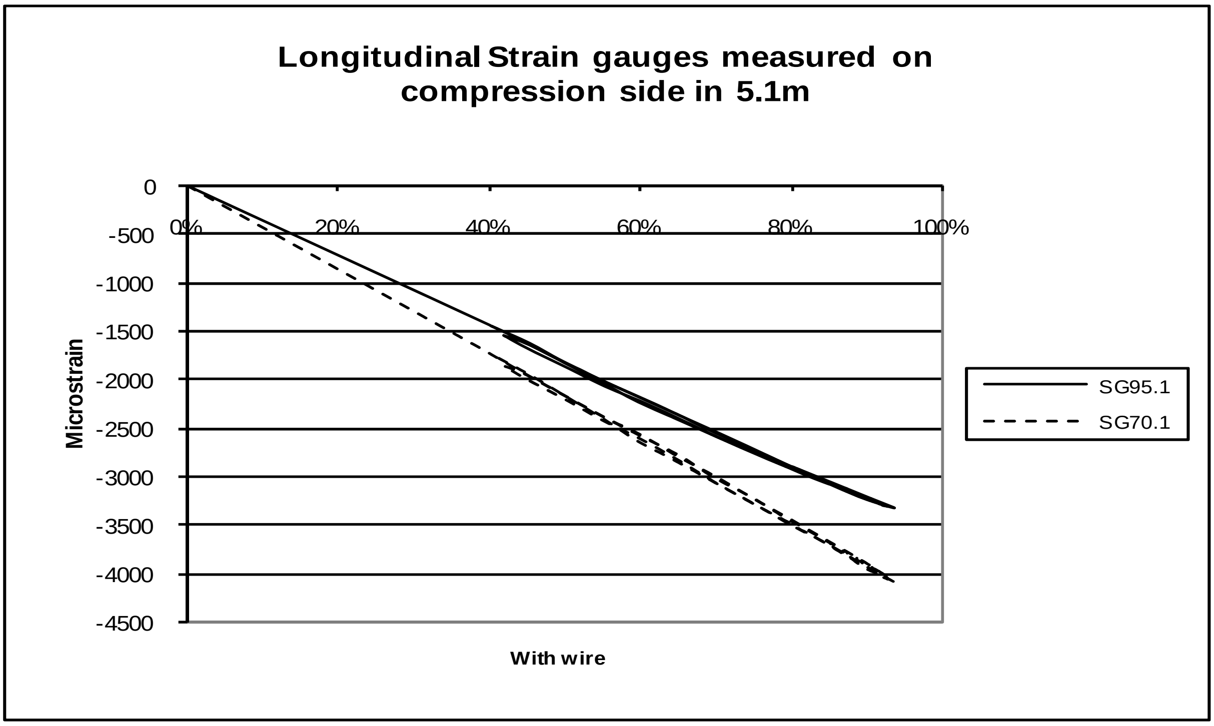

45° Strain gauges measured on trailing web toward SS in 12.5m
100
0
-100
-200
-300
-400
-500
-600
-700
-800
Microstrain
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Without wire
SG63.3

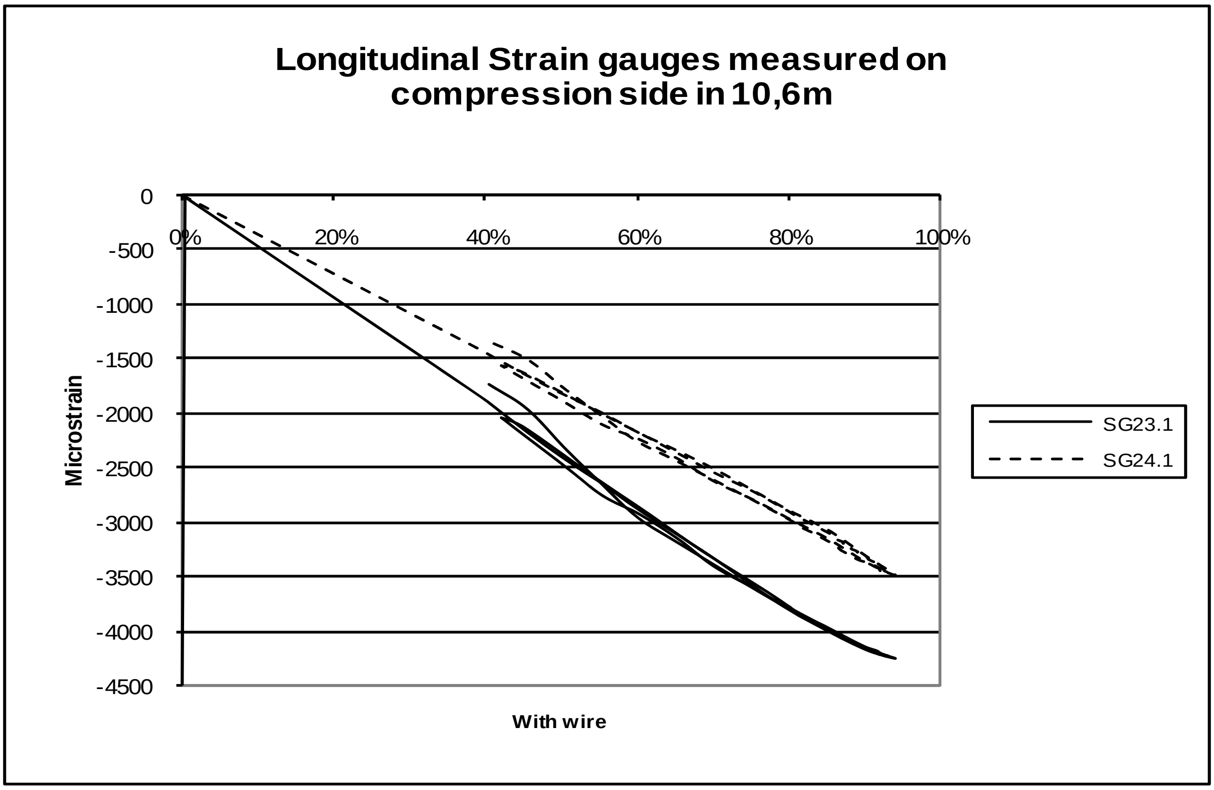

45° Strain gauges measured on leading web toward SS in 12.5m
0
-200
-400
-600
-800
-1000
-1200
-1400
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Microstrain
Without wire
SG75.3
SG50.3

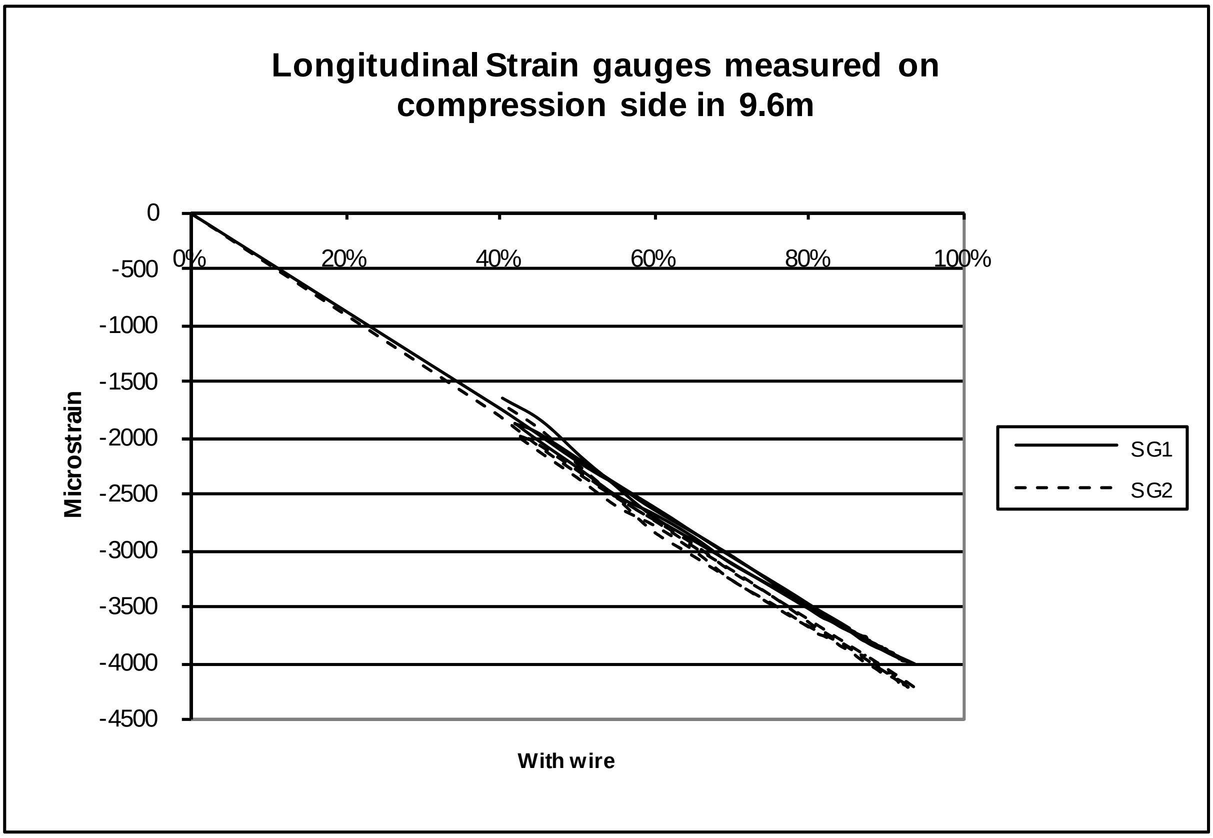

45° Strain gauges measured on leading web toward PS in 12.5m
1600
1400
1200
1000
800
600
400
200
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Microstrain
Without wire
SG77.3
SG52.3

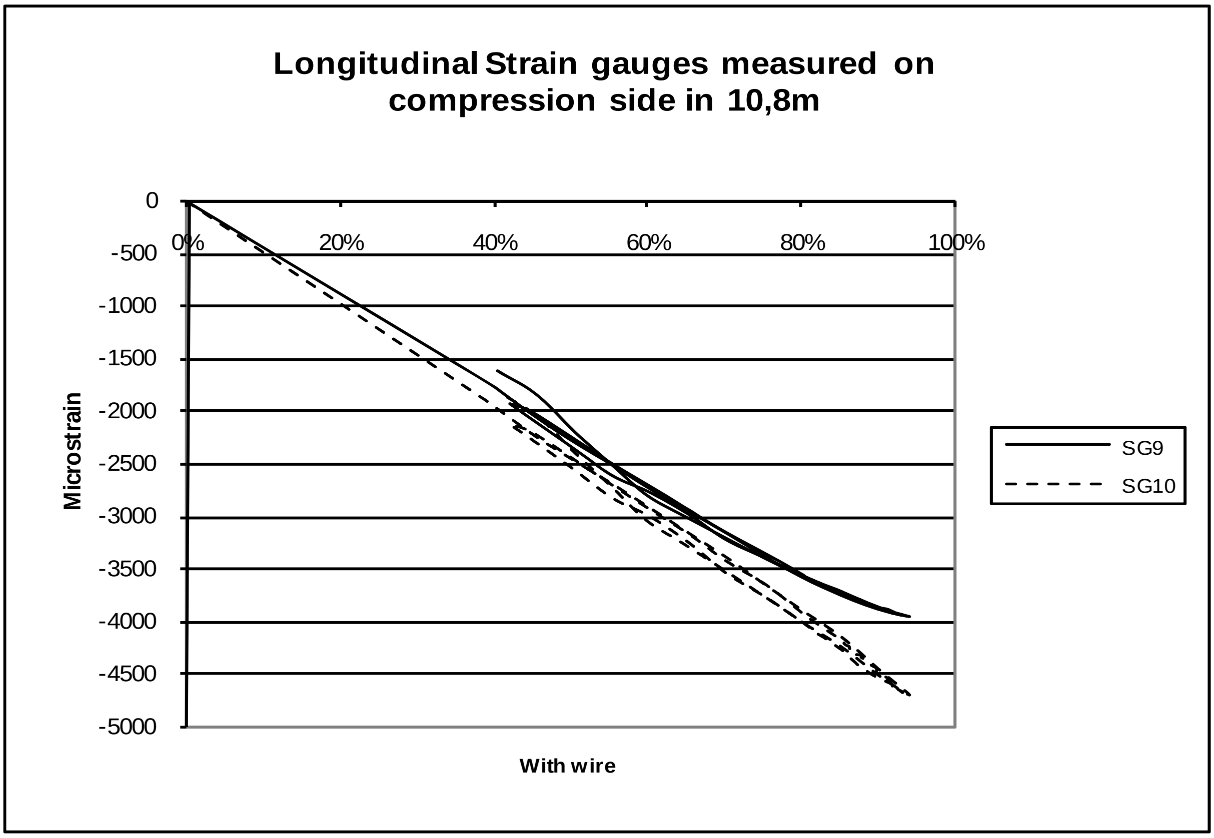
Appendix E: Measured strain gauge results flapwise bending with wire reinforcement

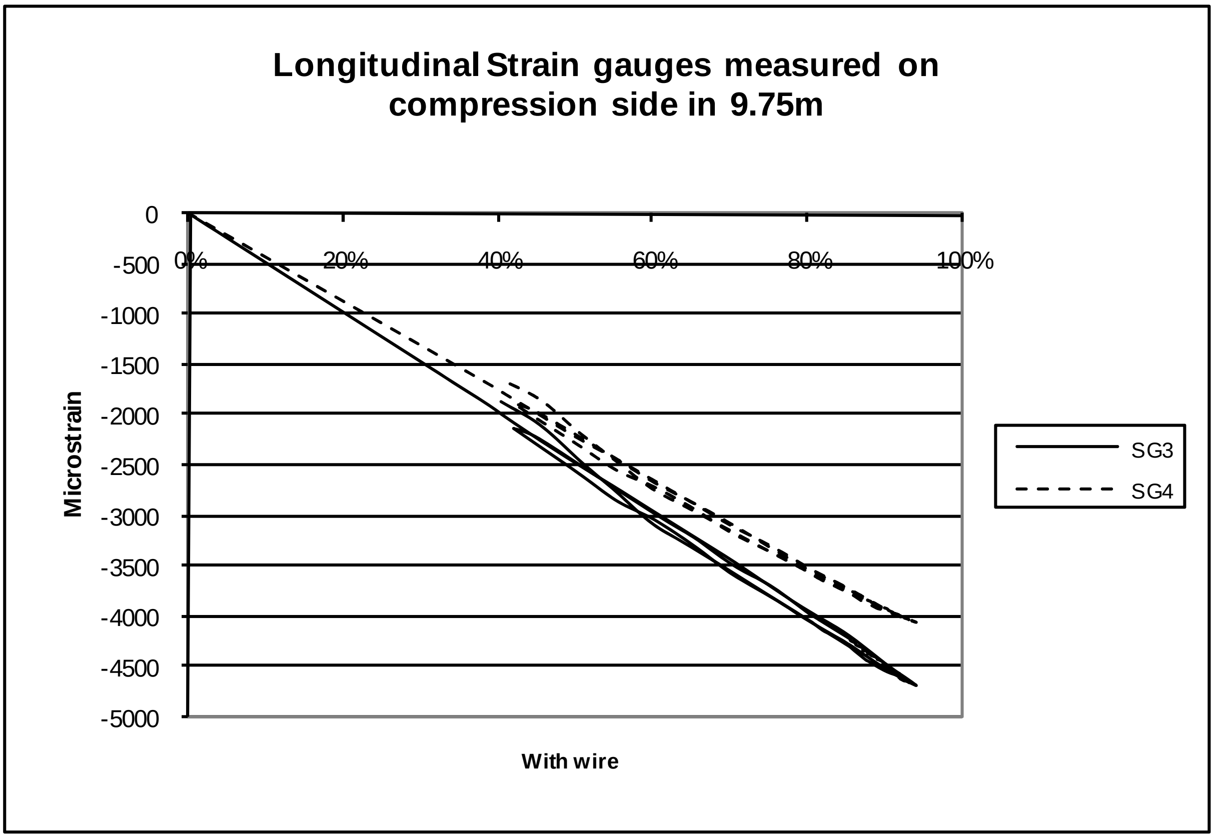
Graphs of Longitudinal measurements with wire



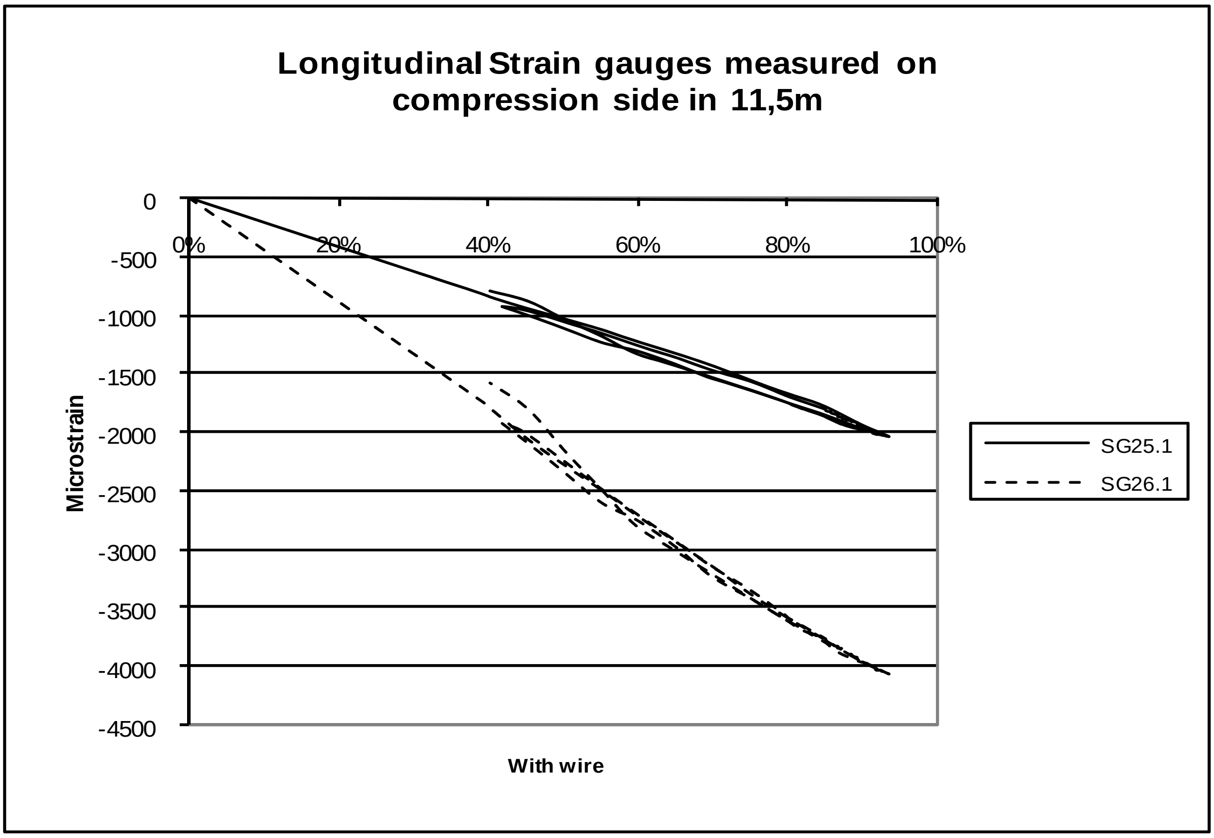



Longitudinal Strain gauges measured on compression side in 9.6m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG1
SG2

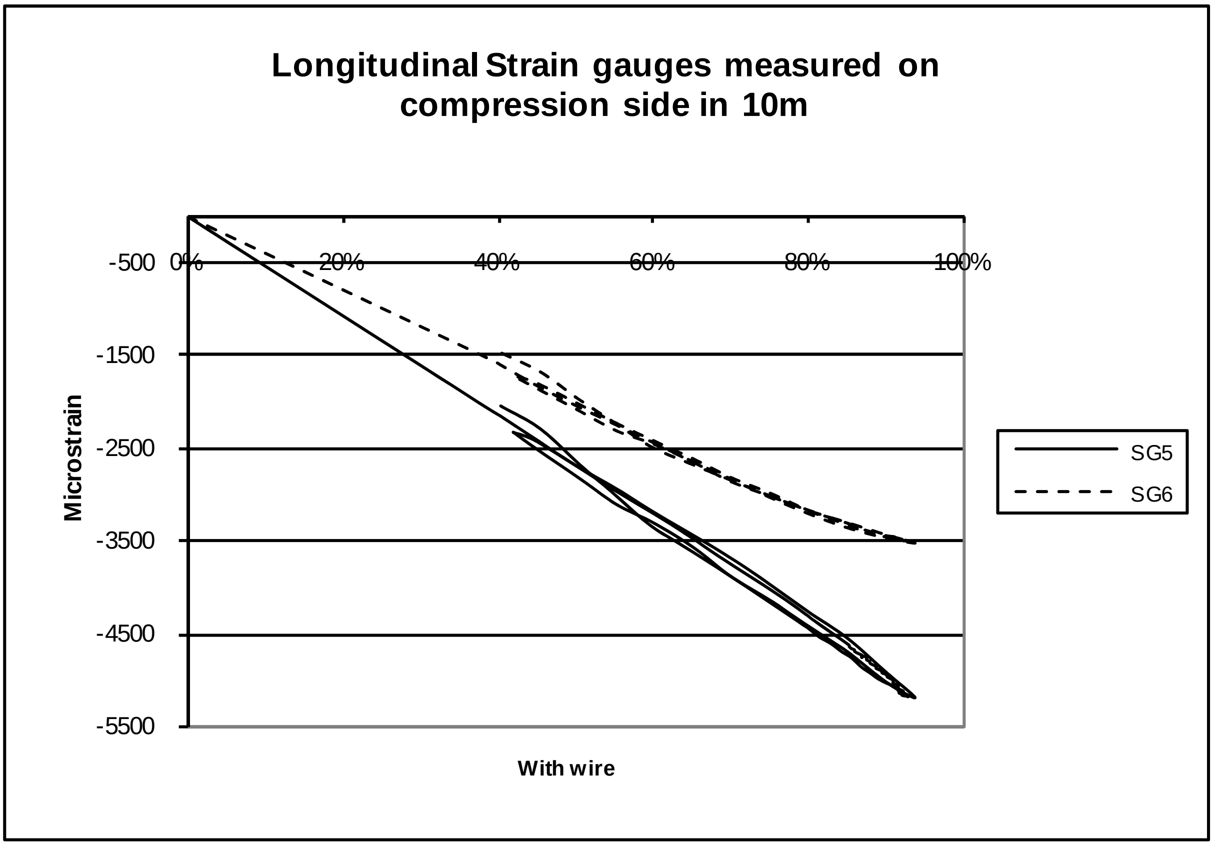

Longitudinal Strain gauges measured on compression side in 10,8m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG9
SG10

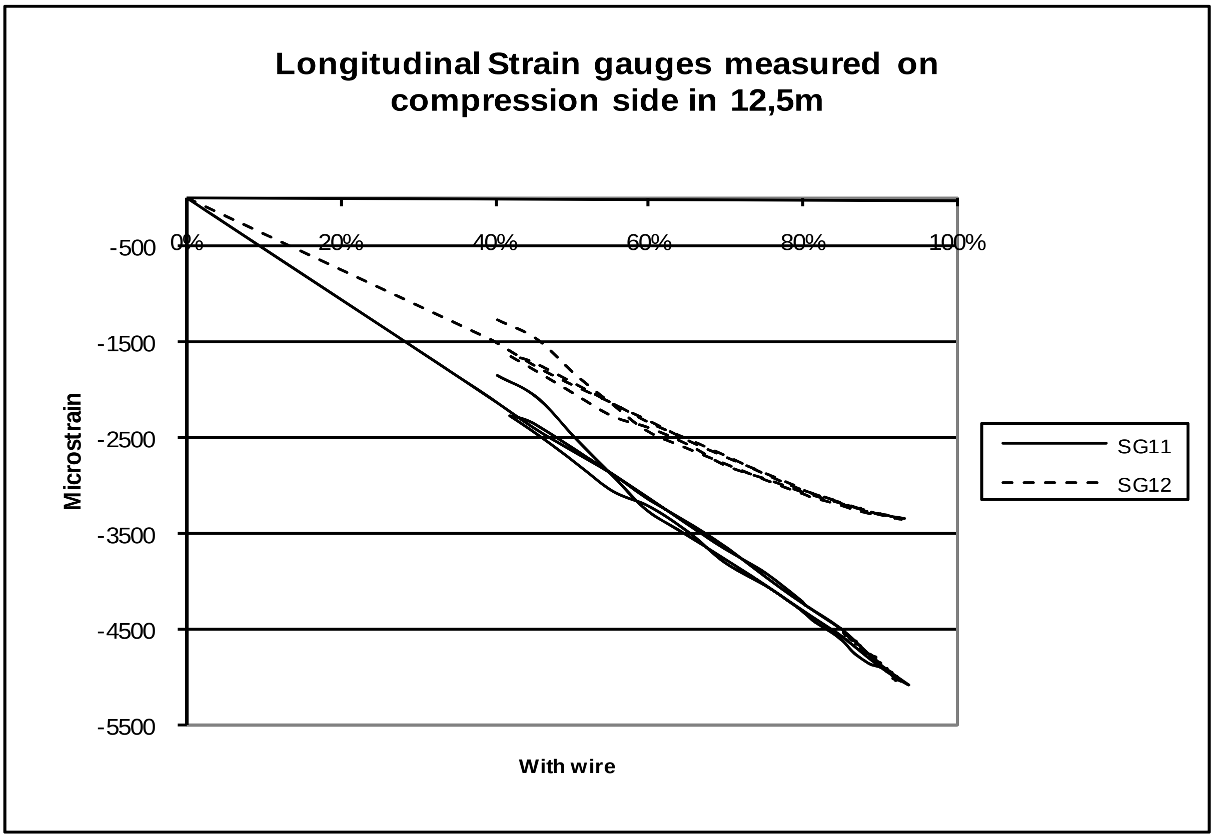


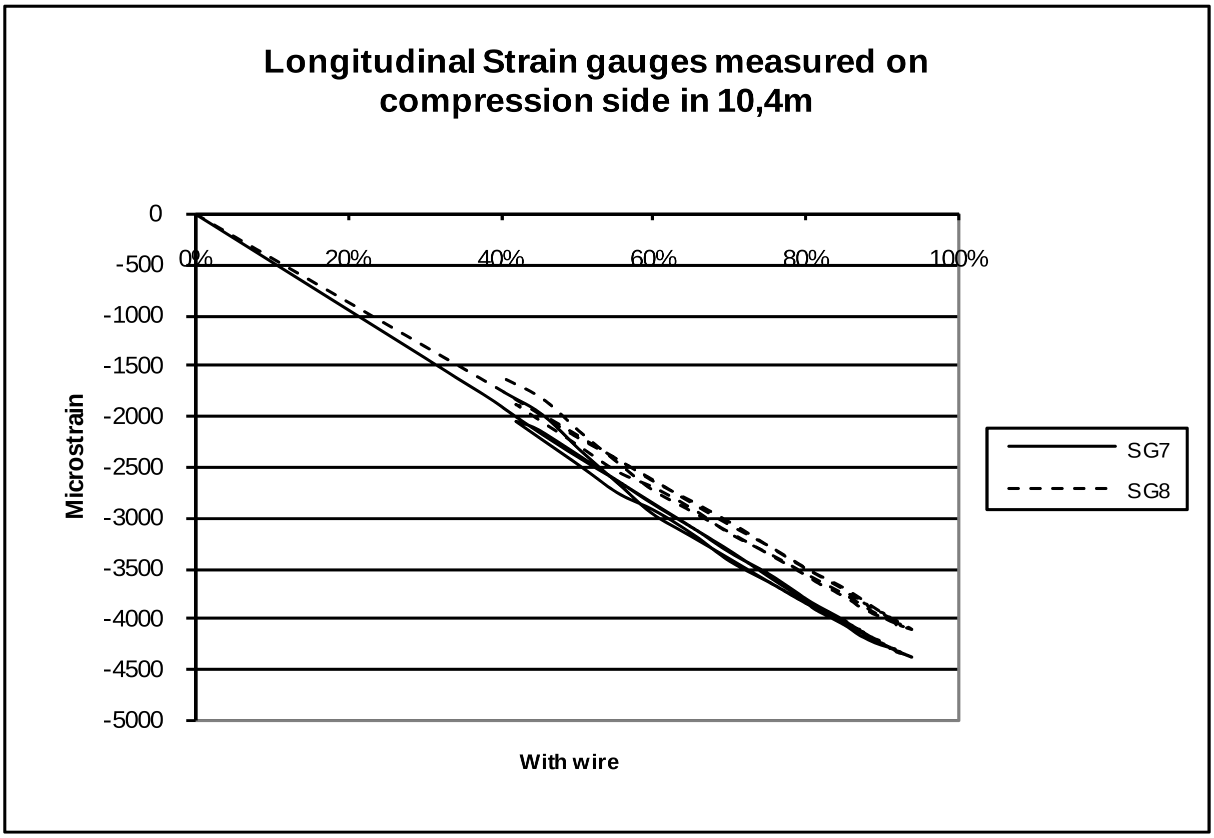
Longitudinal Strain gauges measured on compression side in 9.75m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG3
SG4

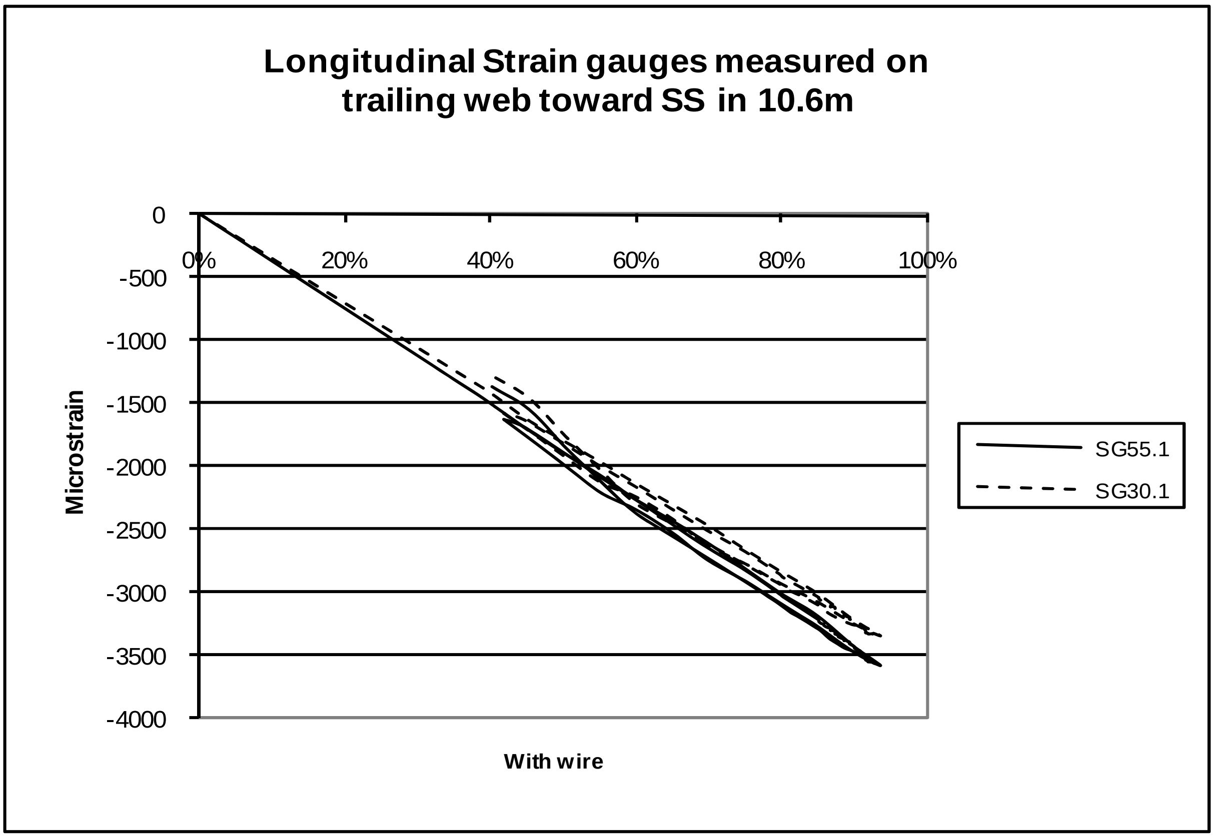


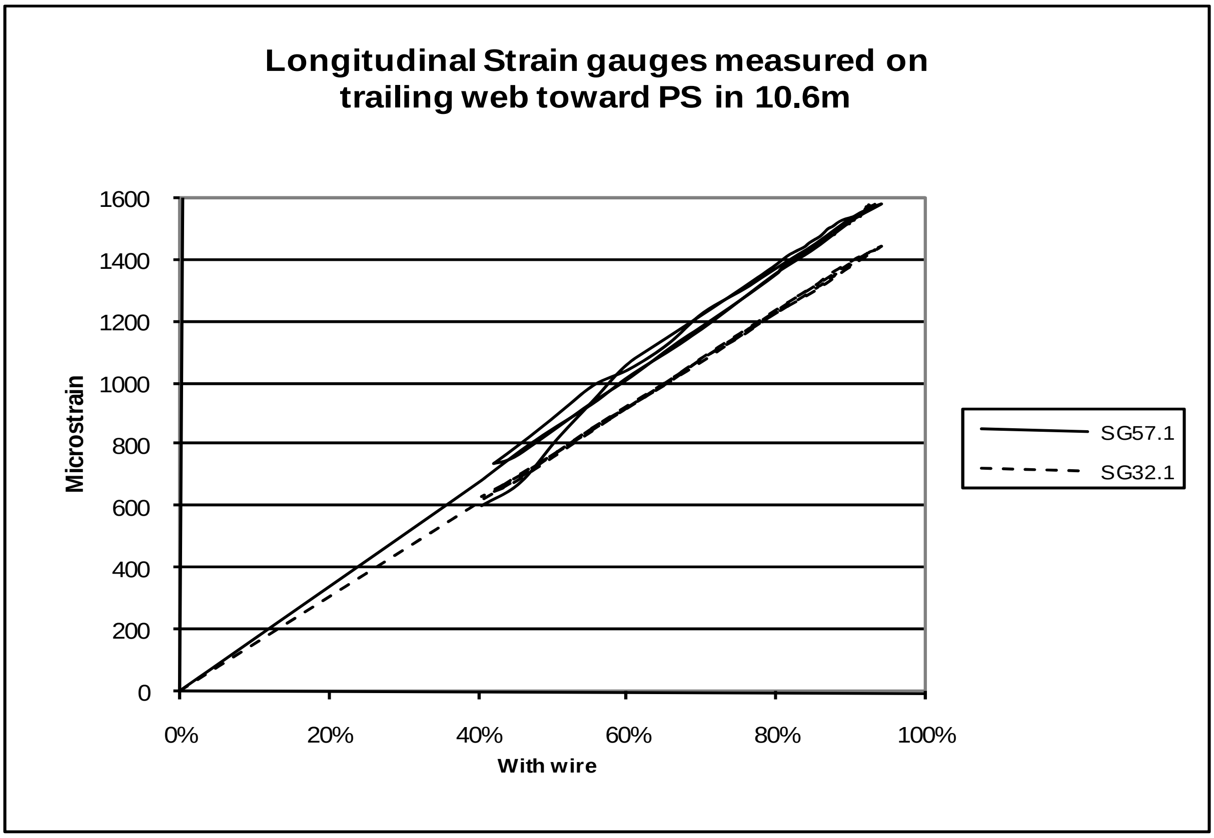
Longitudinal Strain gauges measured on compression side in 11,5m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG25.1
SG26.1

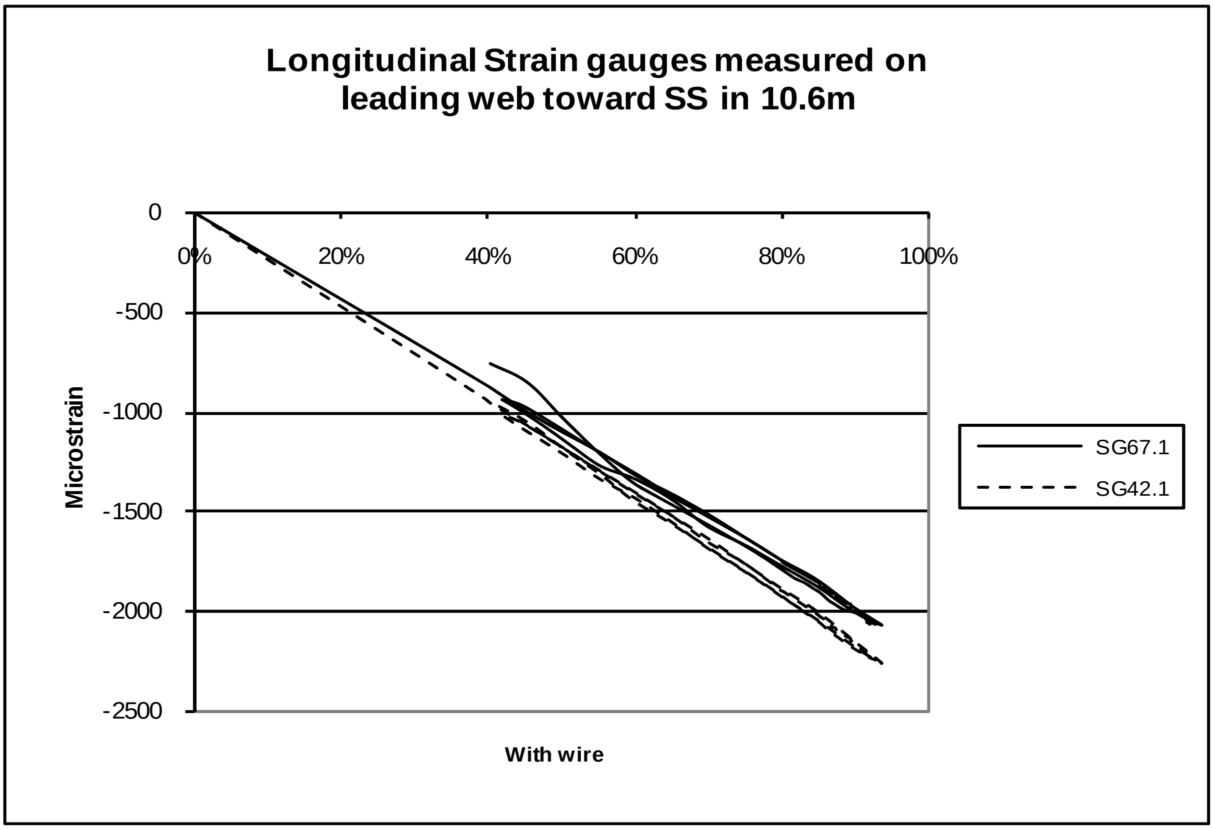

Longitudinal Strain gauges measured on compression side in 10m
-500
-1500
-2500
-3500
-4500
-5500
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG5
SG6

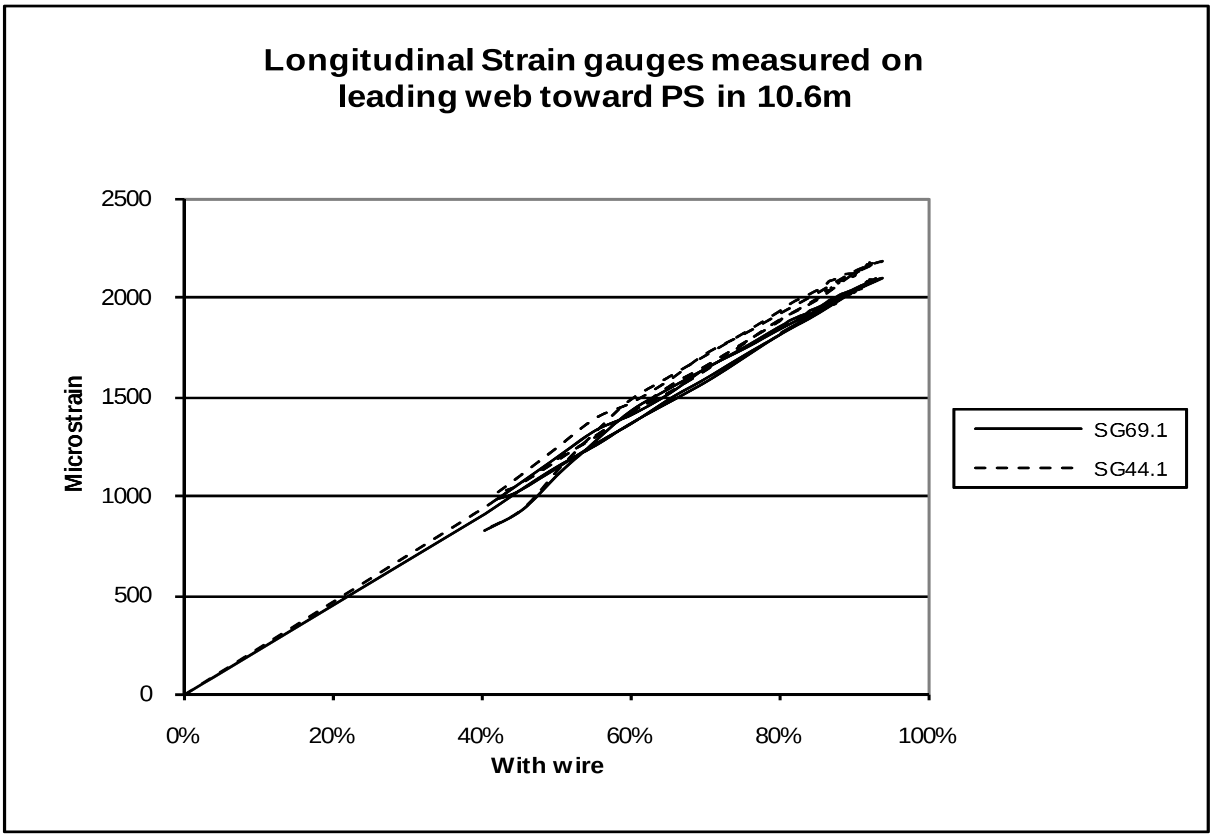

Longitudinal Strain gauges measured on compression side in 12,5m
-500
-1500
-2500
-3500
-4500
-5500
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG11
SG12

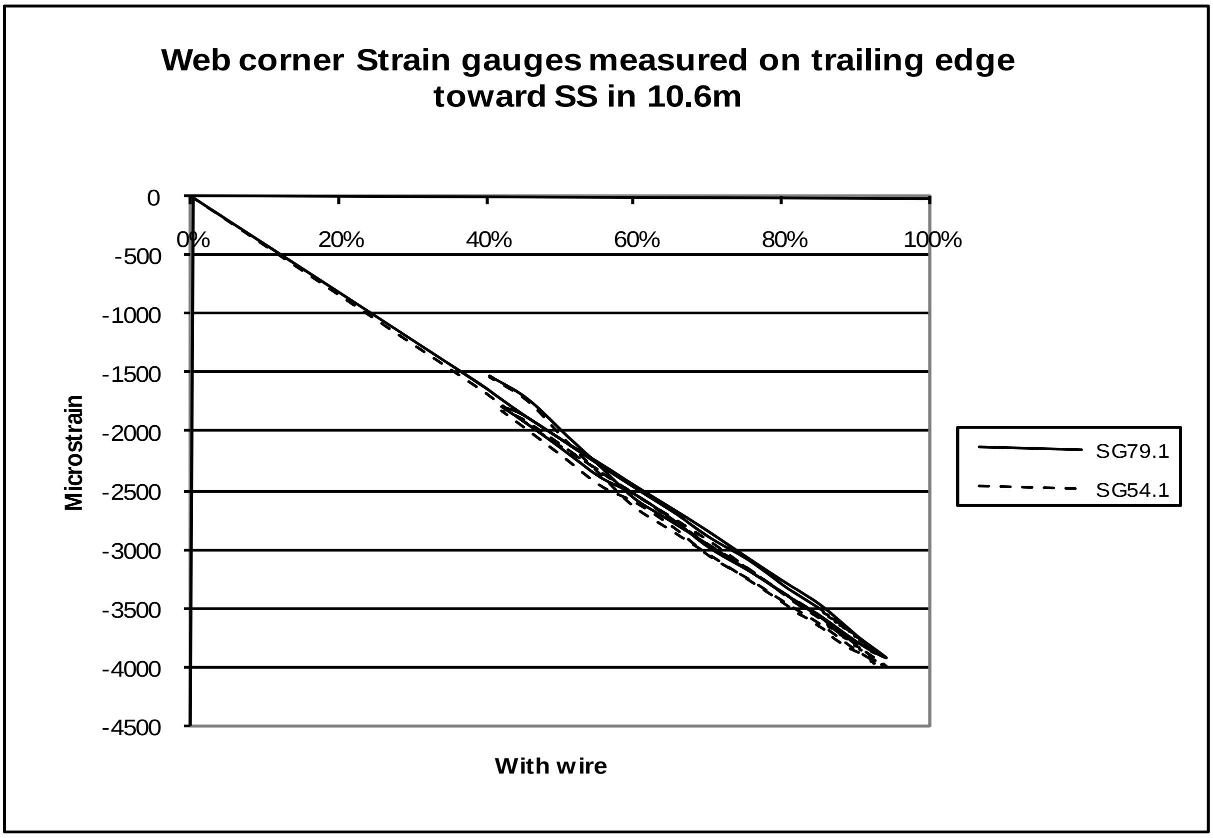

Longitudinal Strain gauges measured on compression side in 10,4m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG7
SG8

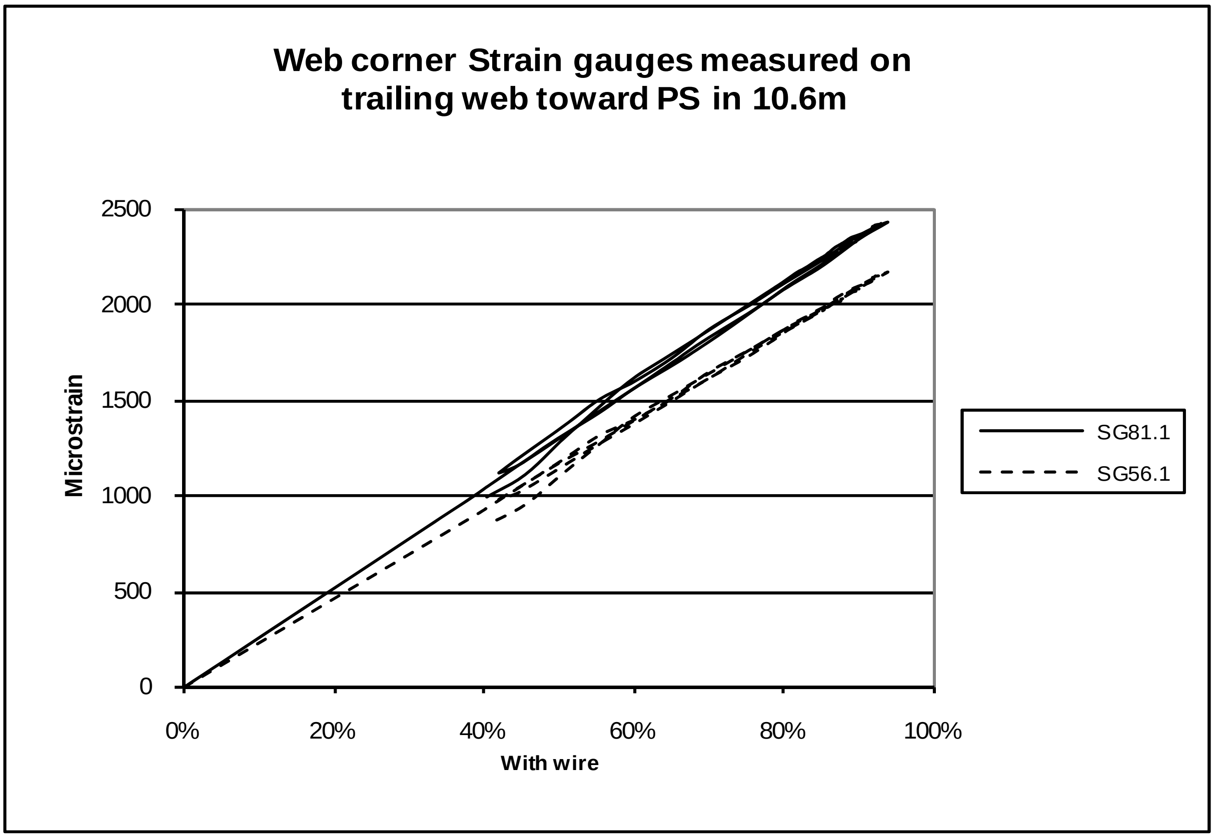

Longitudinal Strain gauges measured on trailing web toward SS in 10.6m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG55.1
SG30.1


Longitudinal Strain gauges measured on trailing web toward PS in 10.6m
Microstrain
1600
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
With wire
SG57.1
SG32.1

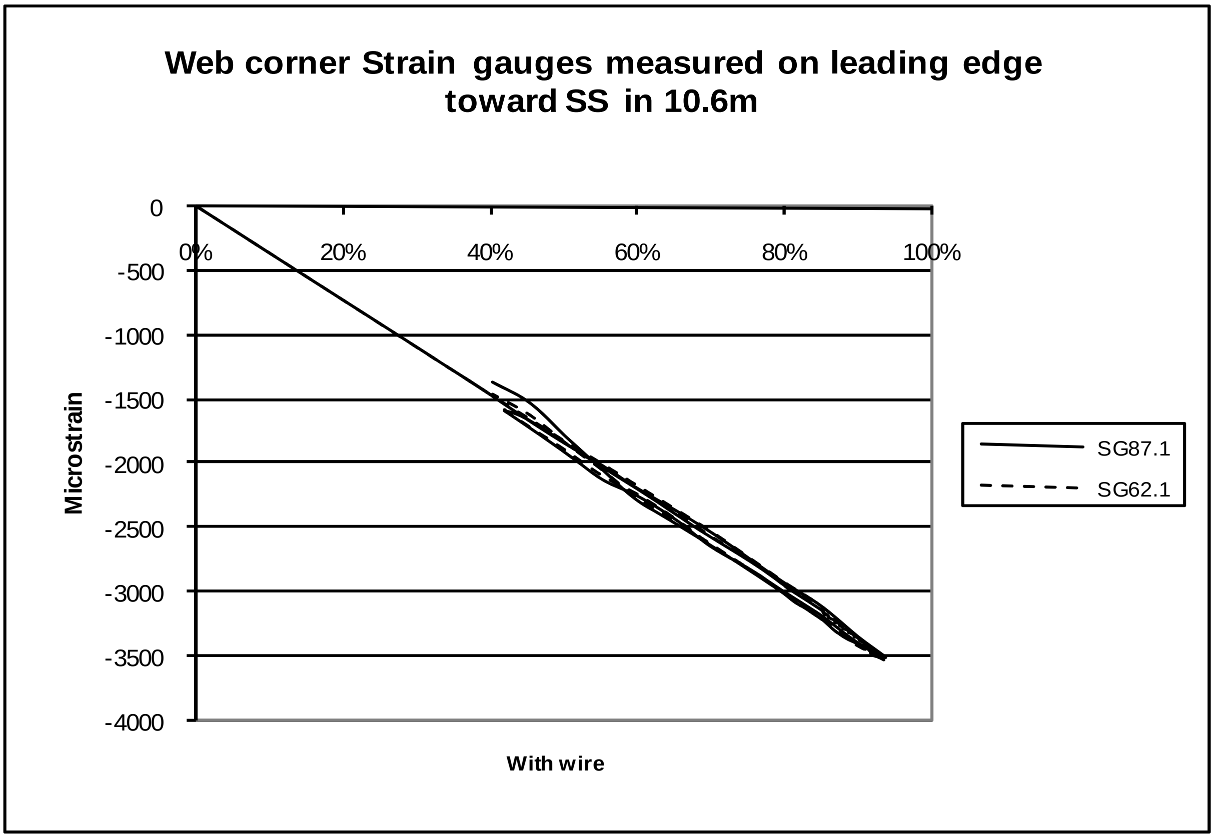

Longitudinal Strain gauges measured on leading web toward SS in 10.6m
Microstrain
0
-500
-1000
-1500
-2000
-2500
0%
20%
40%
60%
80%
100%
With wire
SG67.1
SG42.1


Longitudinal Strain gauges measured on leading web toward PS in 10.6m
2500
2000
1500
1000
500
0
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG69.1
SG44.1

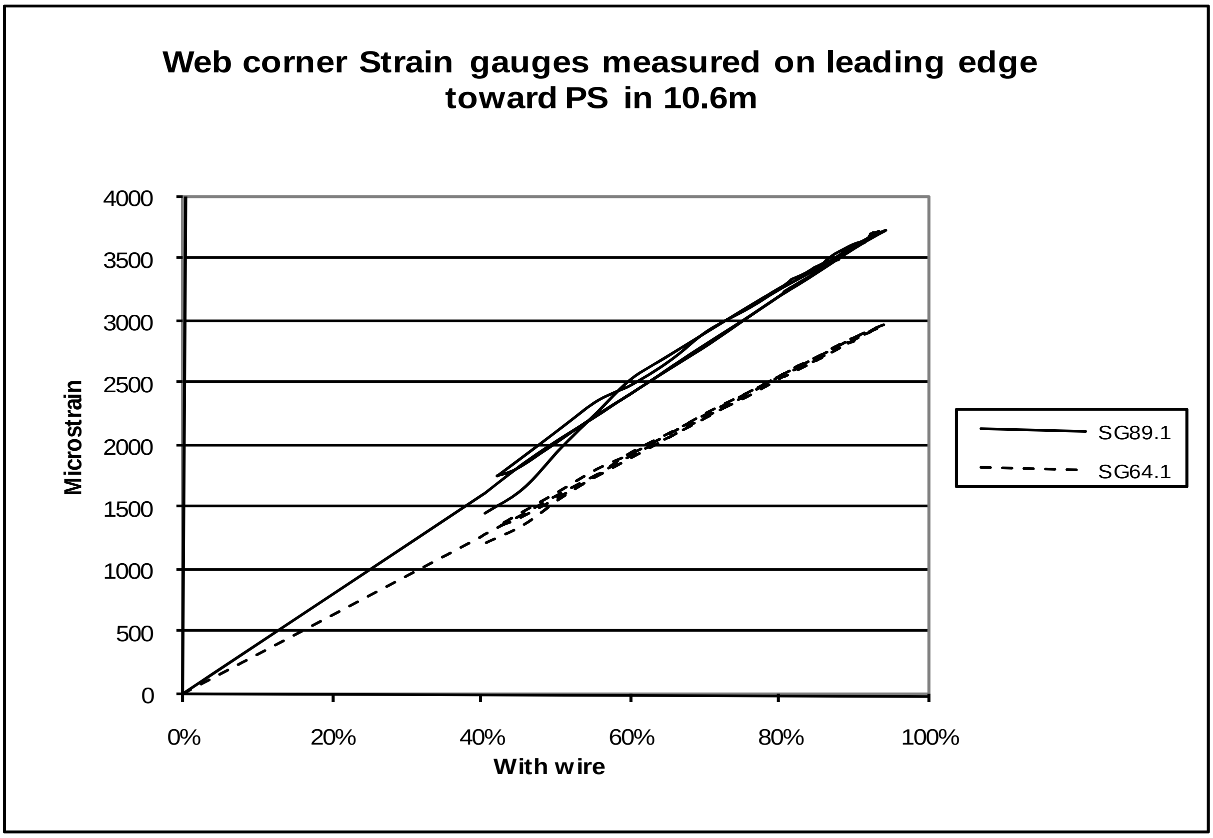

Web corner Strain gauges measured on trailing edge toward SS in 10.6m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG79.1
SG54.1

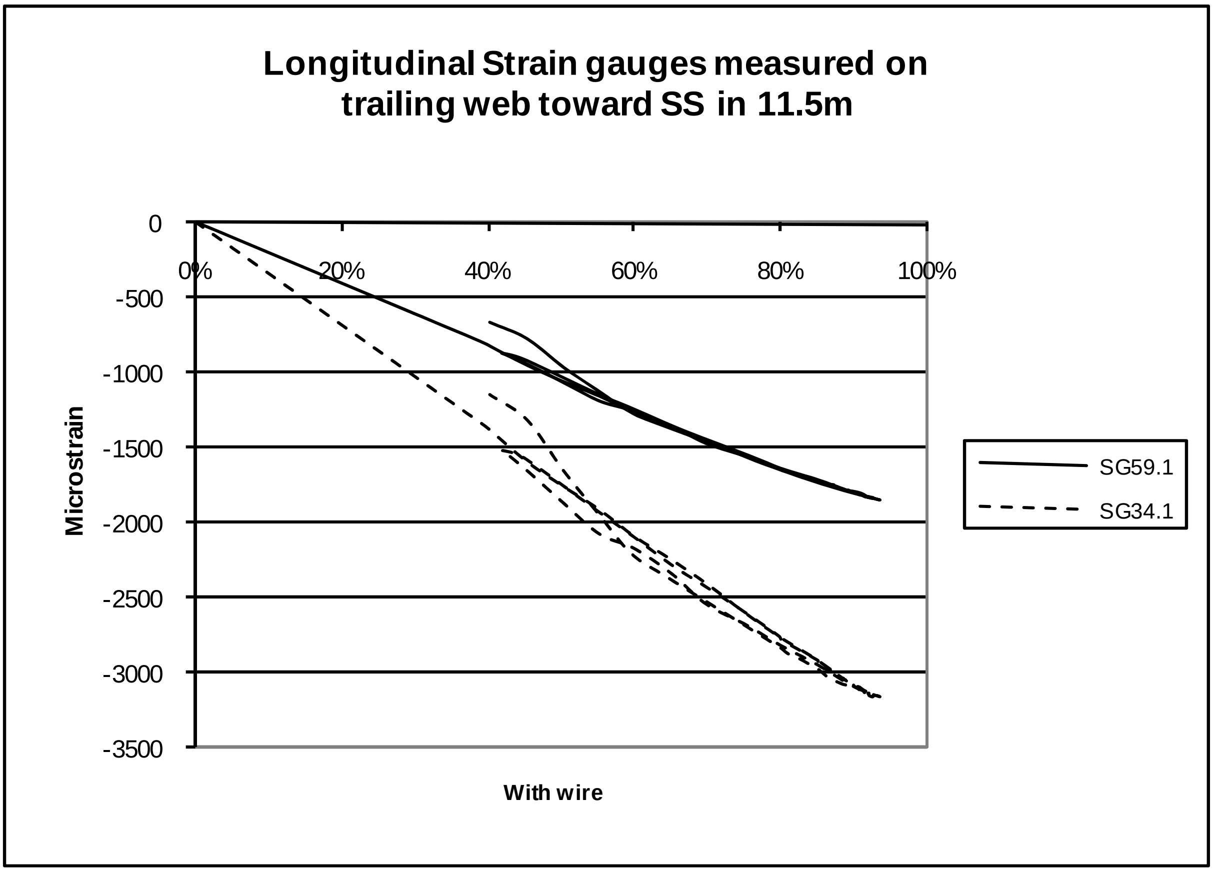


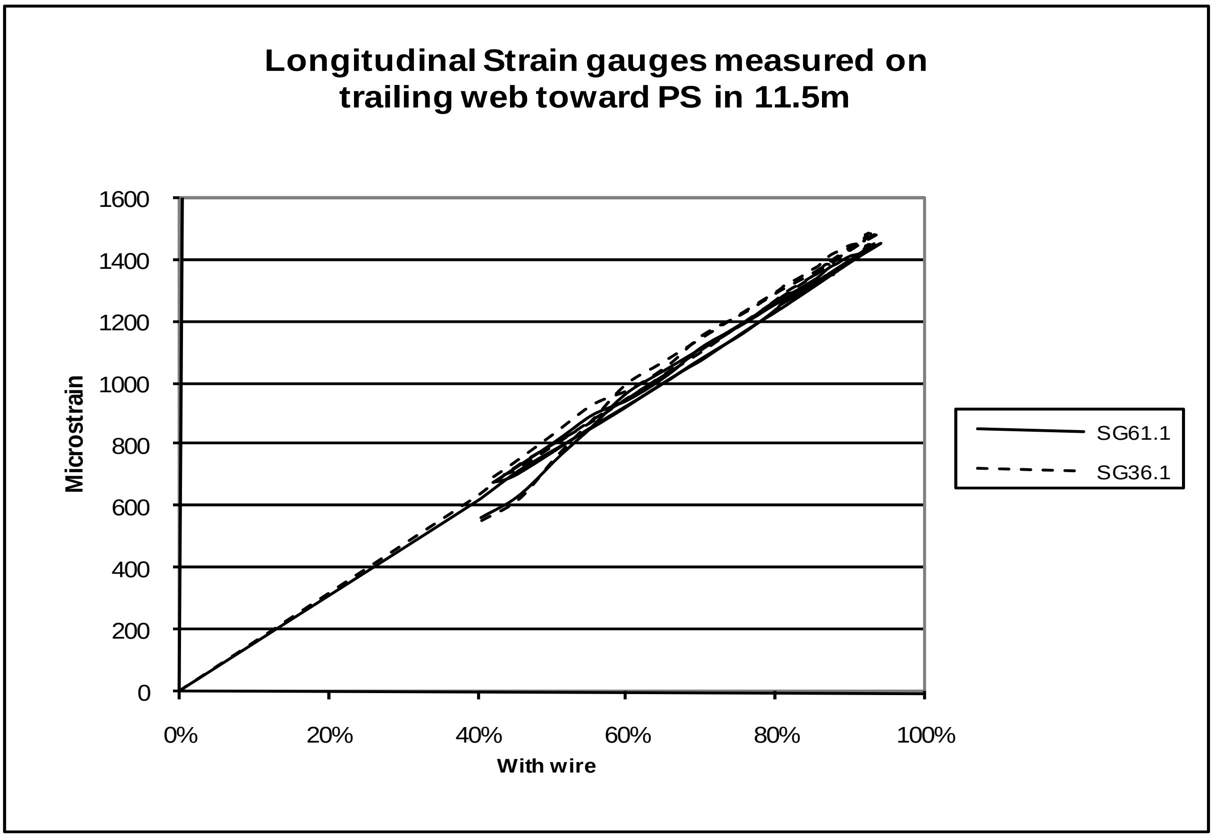
Web corner Strain gauges measured on trailing web toward PS in 10.6m
2500
2000
1500
1000
500
0
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG81.1
SG56.1

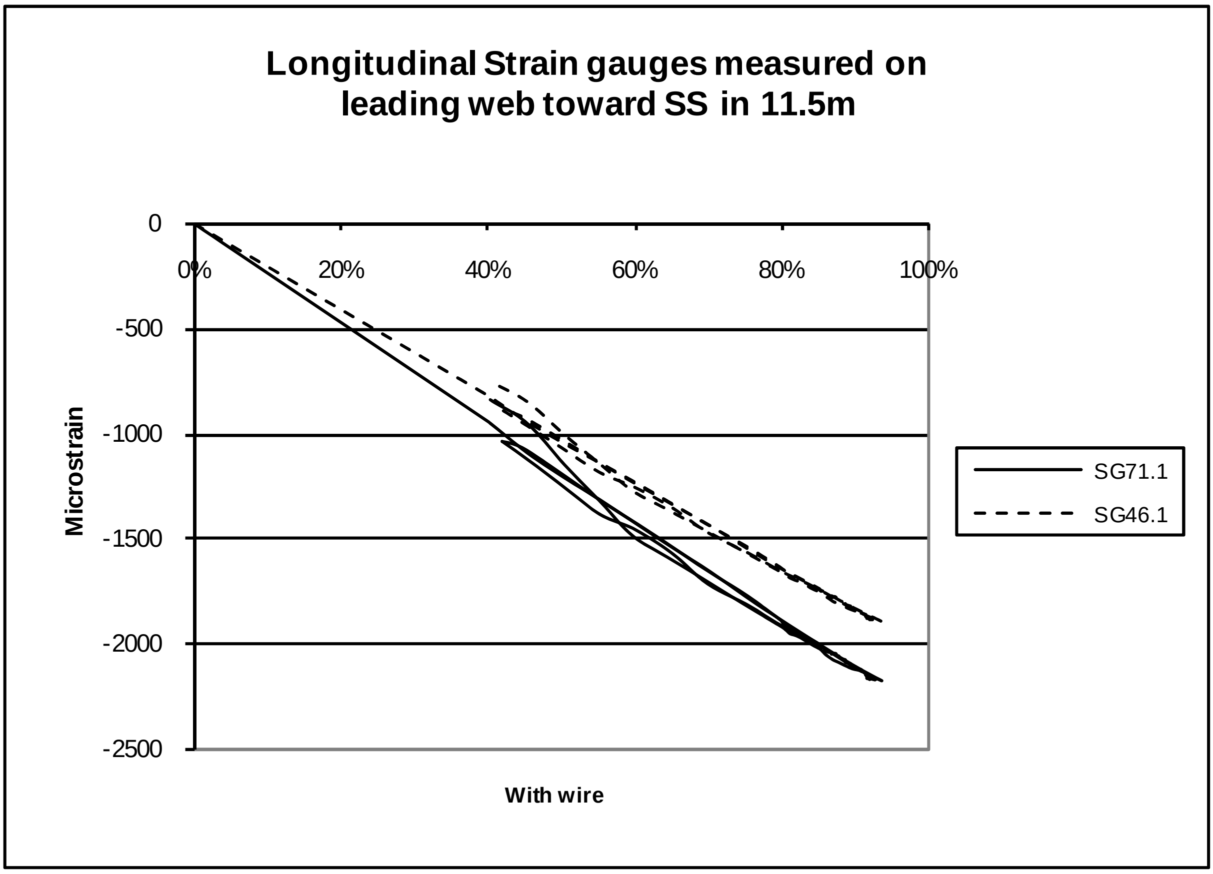


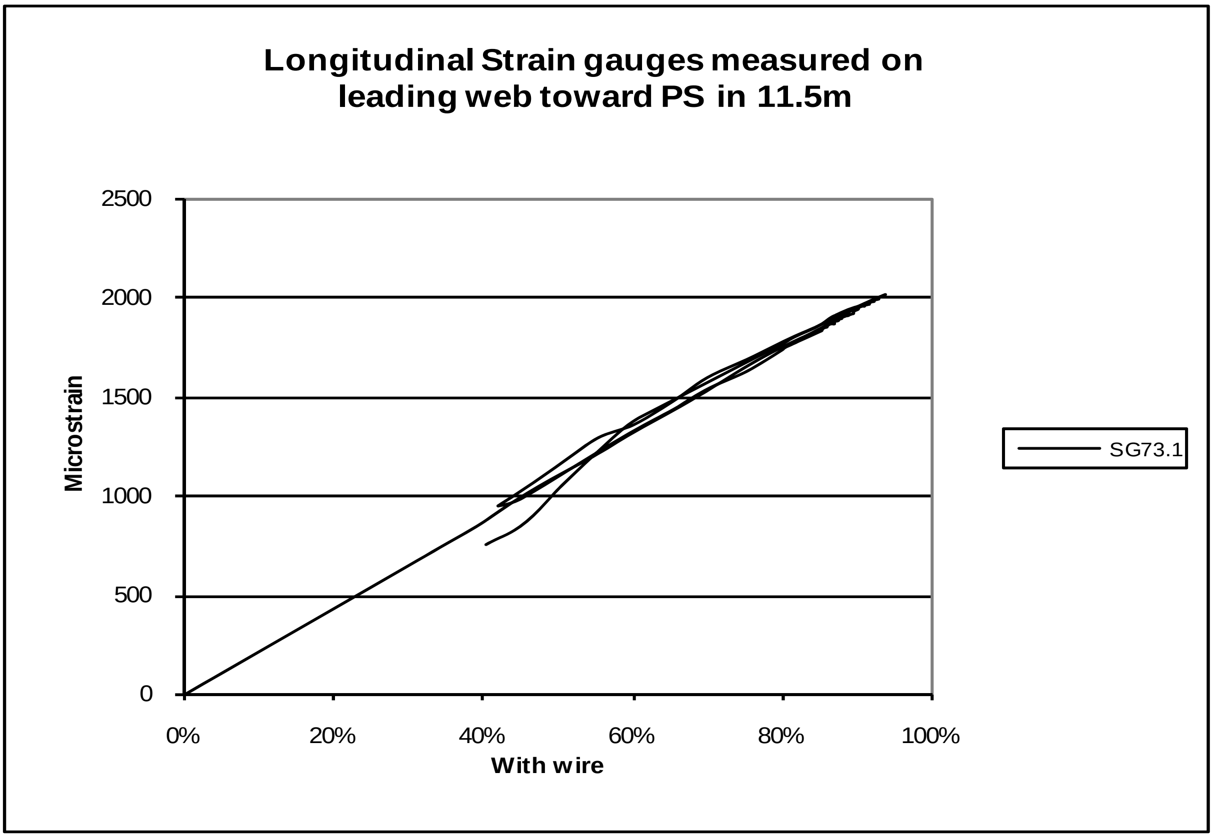
Web corner Strain gauges measured on leading edge toward SS in 10.6m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG87.1
SG62.1


Web corner Strain gauges measured on leading edge toward PS in 10.6m
Microstrain
4000
3500
3000
2500
2000
1500
1000
500
0
0%
20%
40%
60%
80%
100%
With wire
SG89.1
SG64.1

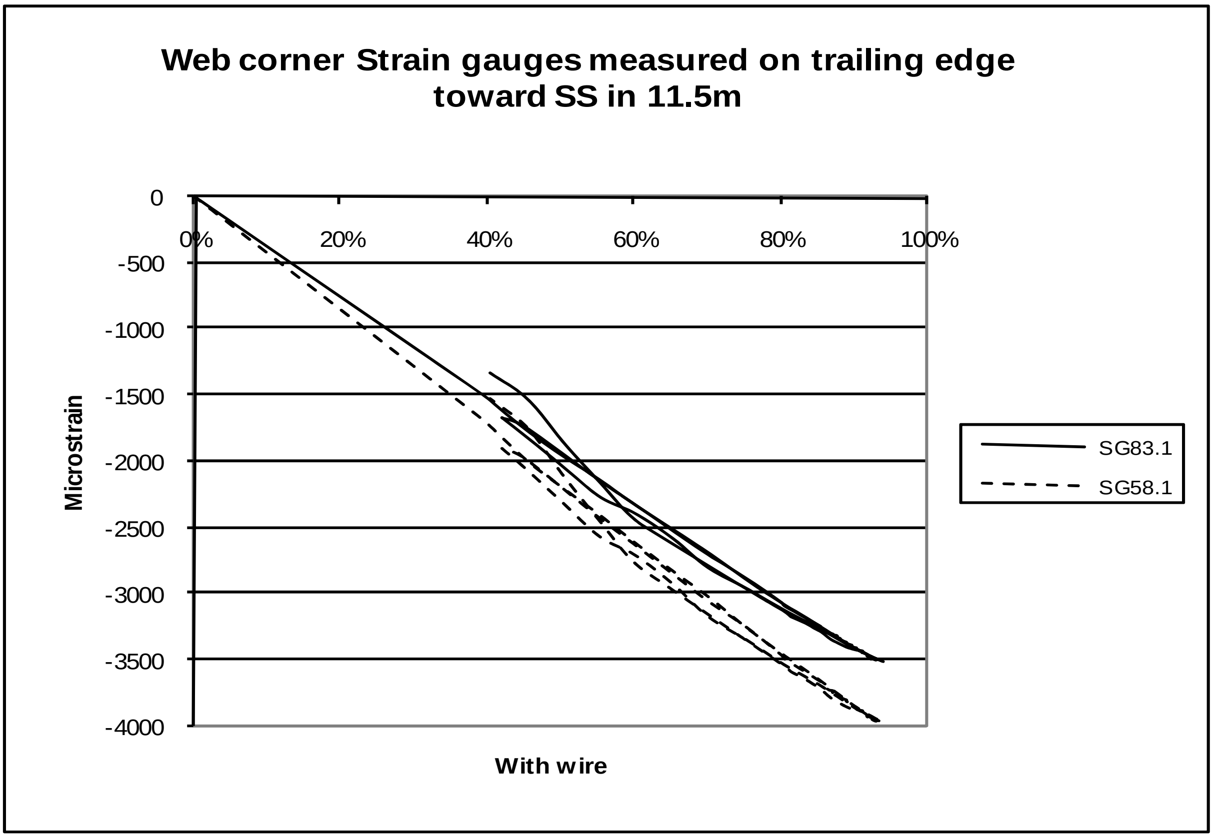

Longitudinal Strain gauges measured on trailing web toward SS in 11.5m
Microstrain
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
0%
20%
40%
60%
80%
100%
With wire
SG59.1
SG34.1


Longitudinal Strain gauges measured on trailing web toward PS in 11.5m
Microstrain
1600
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
With wire
SG61.1
SG36.1

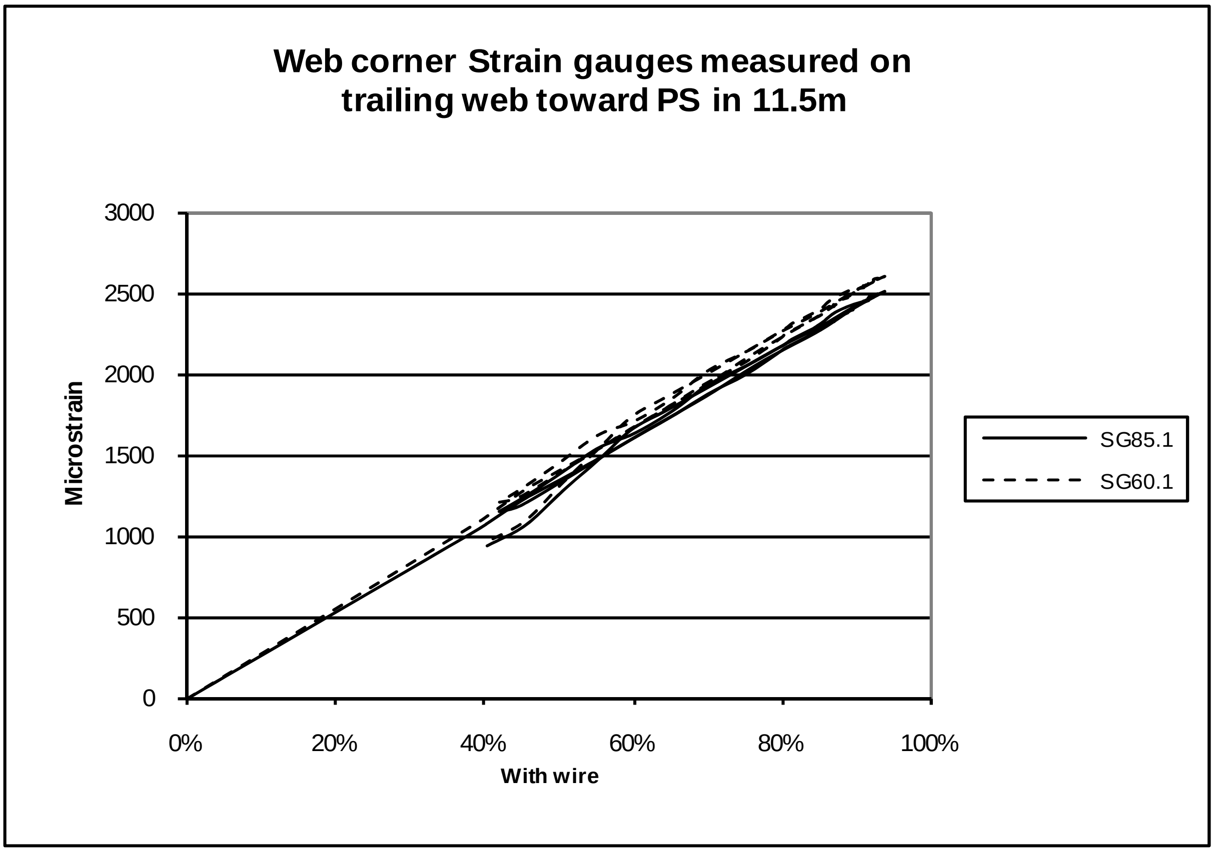

Longitudinal Strain gauges measured on leading web toward SS in 11.5m
Microstrain
0
-500
-1000
-1500
-2000
-2500
0%
20%
40%
60%
80%
100%
With wire
SG71.1
SG46.1

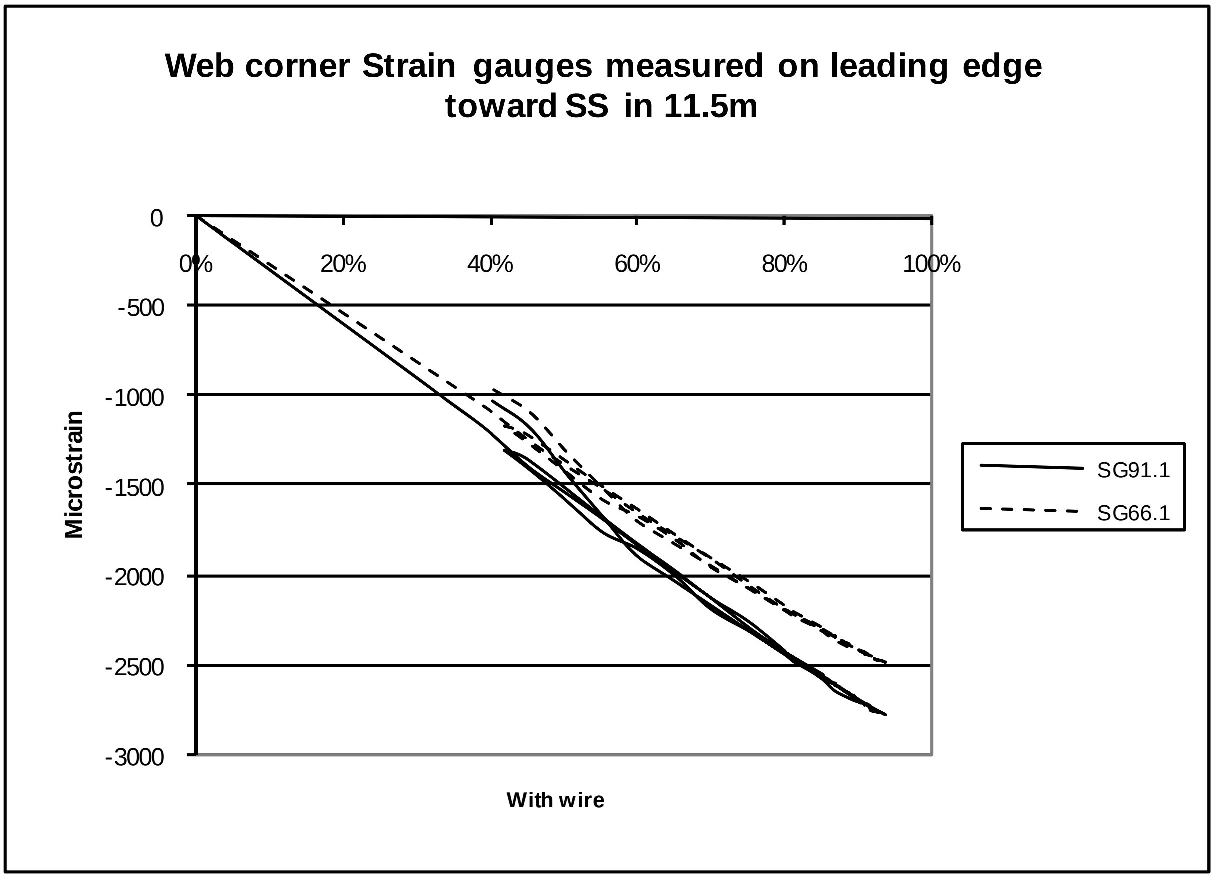


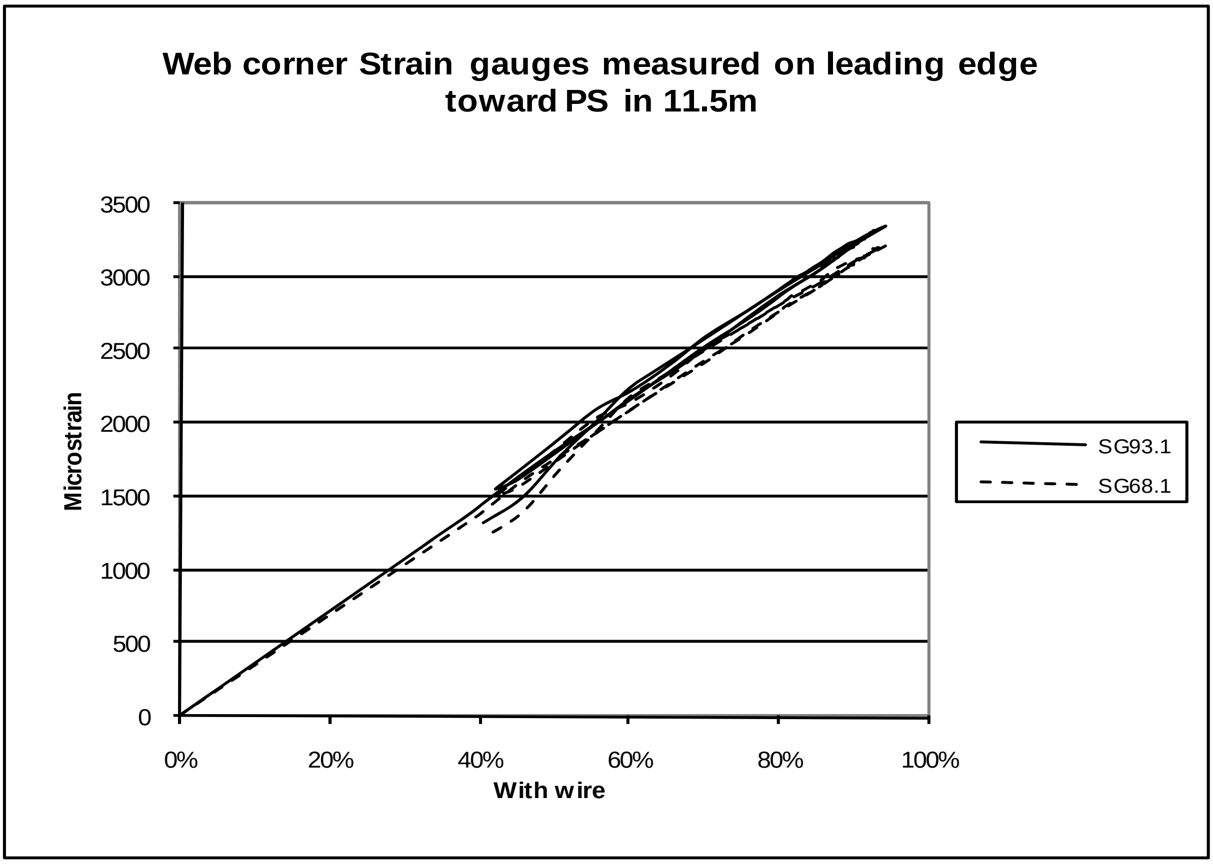
Longitudinal Strain gauges measured on leading web toward PS in 11.5m
2500
2000
1500
1000
500
0
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG73.1

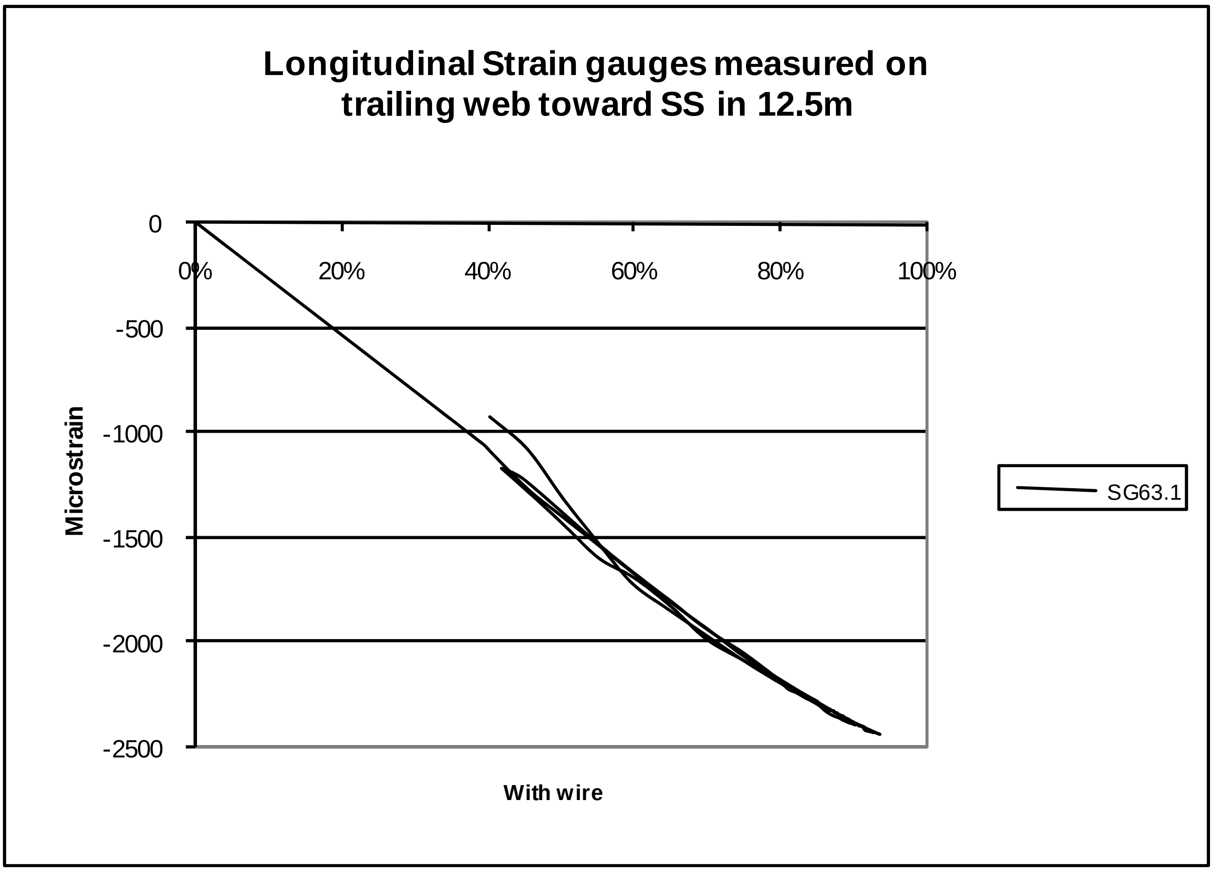


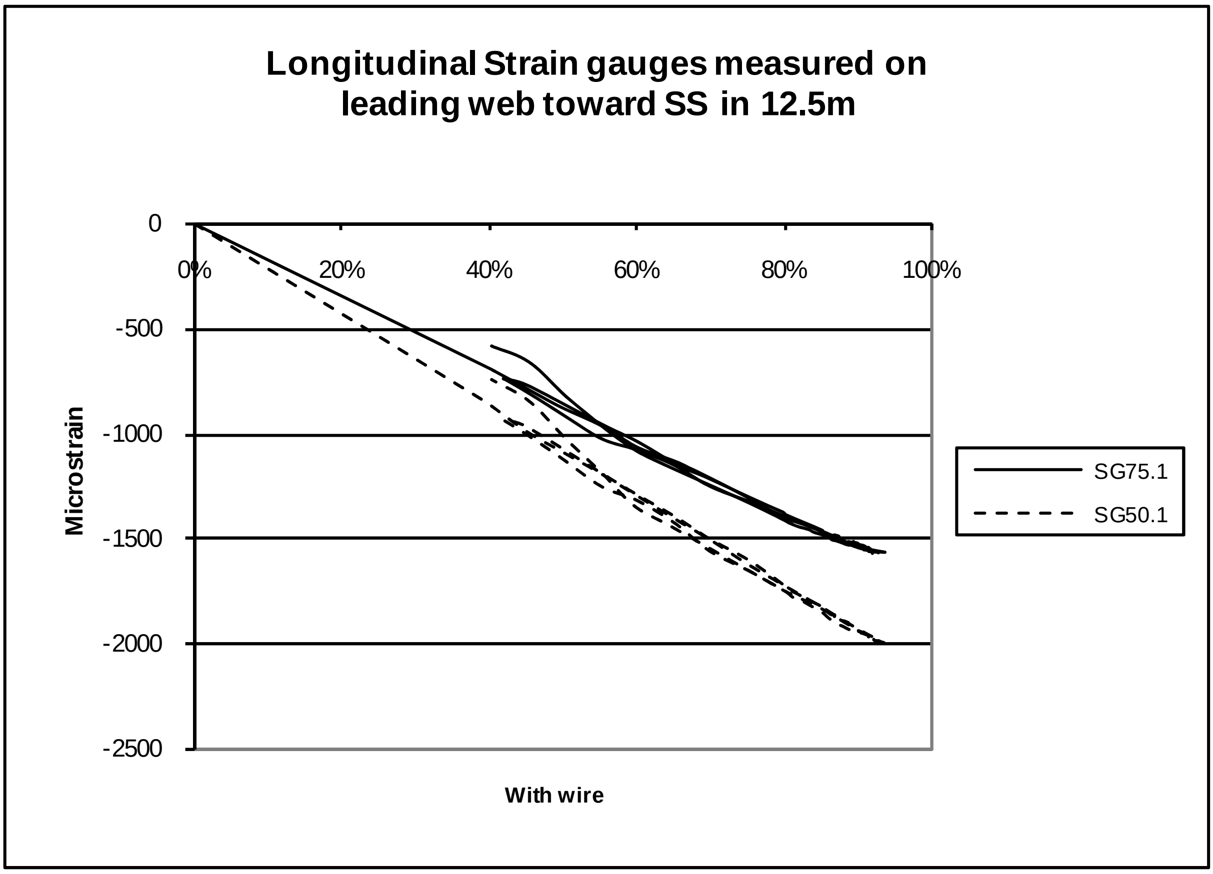
Web corner Strain gauges measured on trailing edge toward SS in 11.5m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG83.1
SG58.1

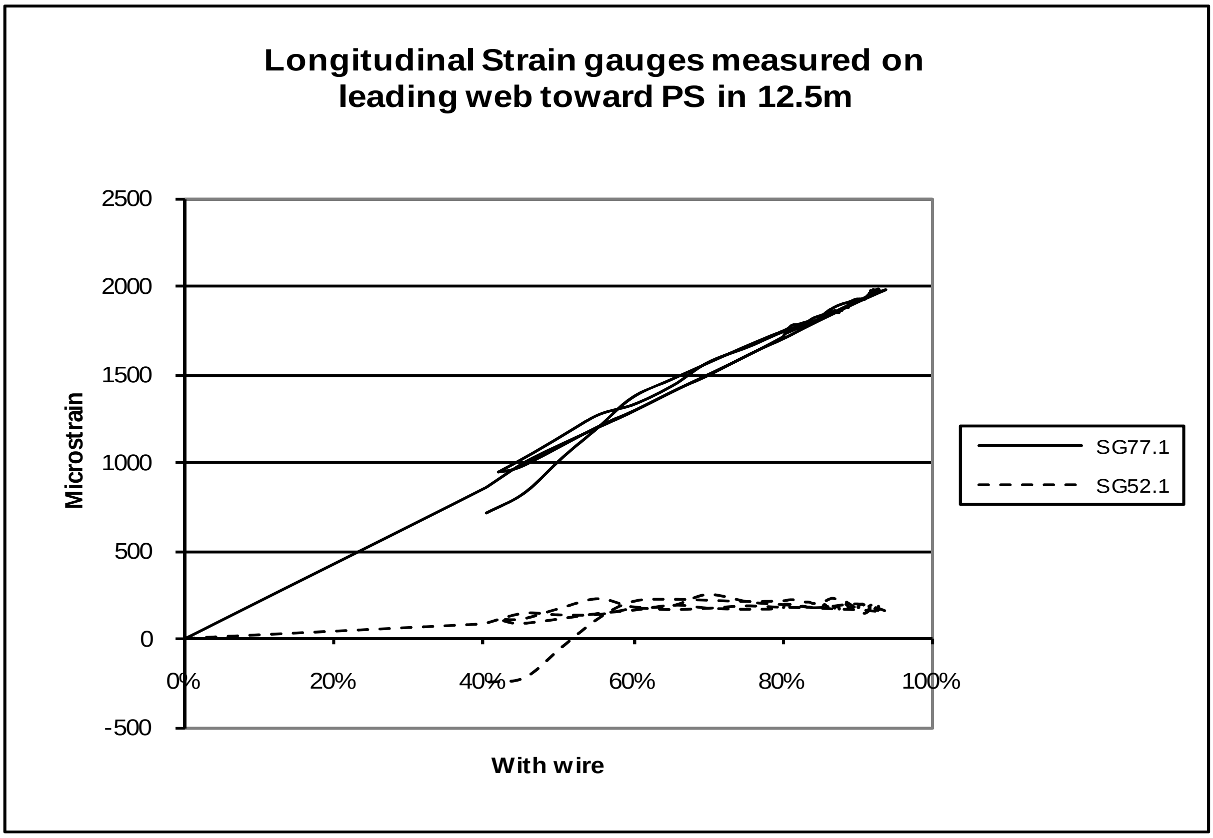

Web corner Strain gauges measured on trailing web toward PS in 11.5m
3000
2500
2000
1500
1000
500
0
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG85.1
SG60.1


Web corner Strain gauges measured on leading edge toward SS in 11.5m
0
-500
-1000
-1500
-2000
-2500
-3000
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG91.1
SG66.1

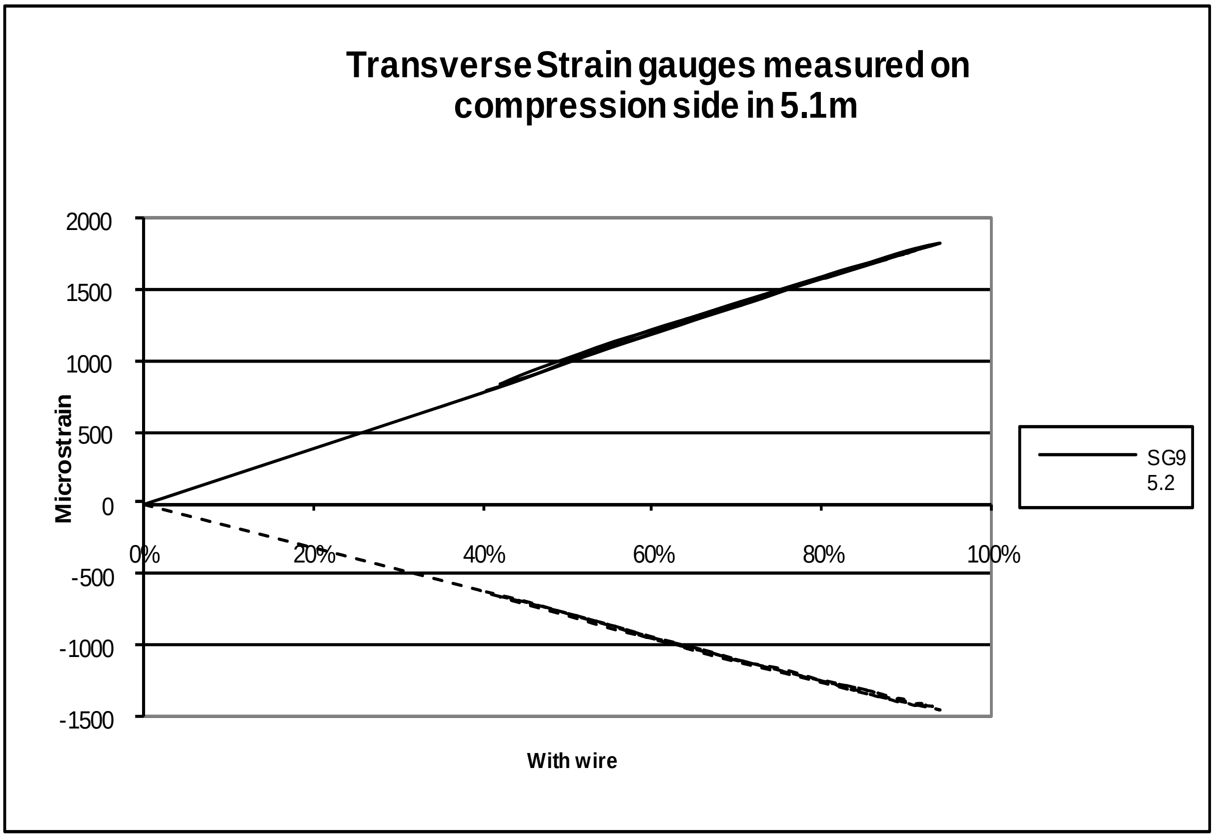

Web corner Strain gauges measured on leading edge toward PS in 11.5m
3500
3000
2500
2000
1500
1000
500
0
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG93.1
SG68.1

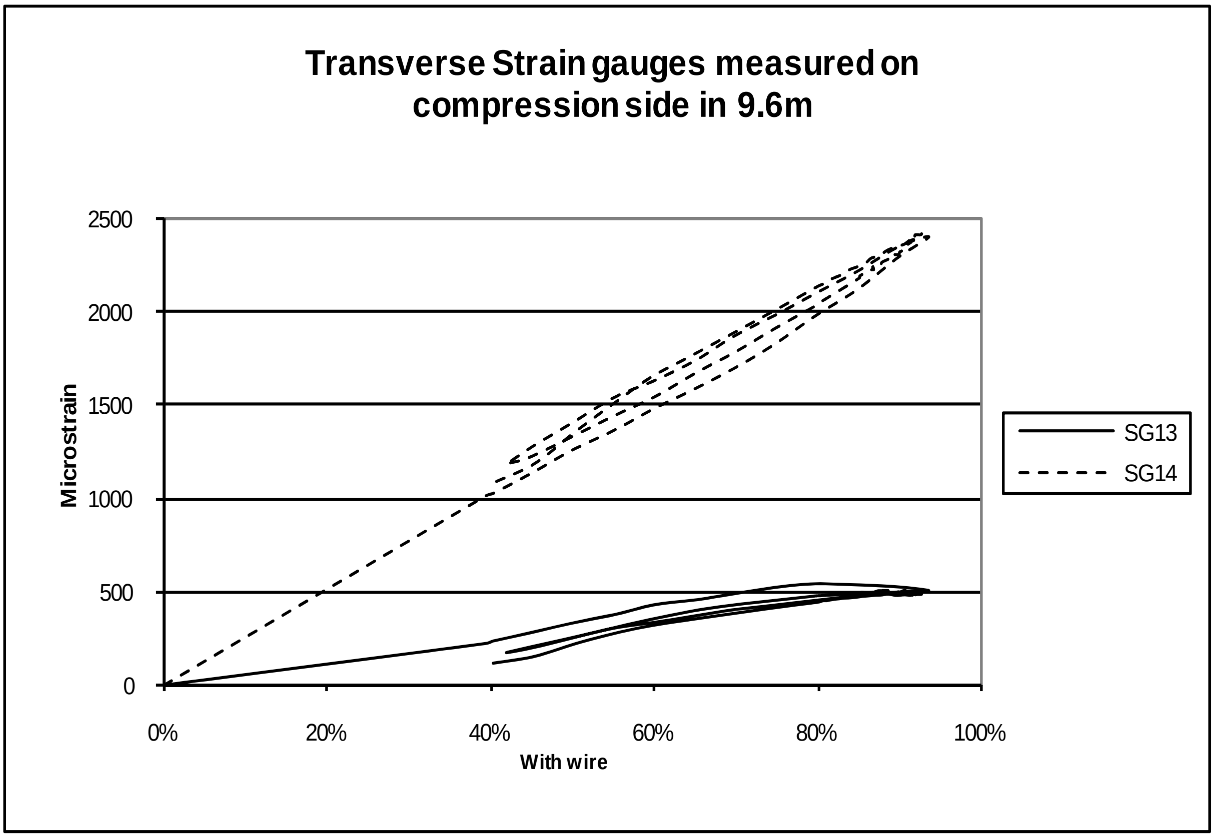

Longitudinal Strain gauges measured on trailing web toward SS in 12.5m
0
-500
-1000
-1500
-2000
-2500
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG63.1

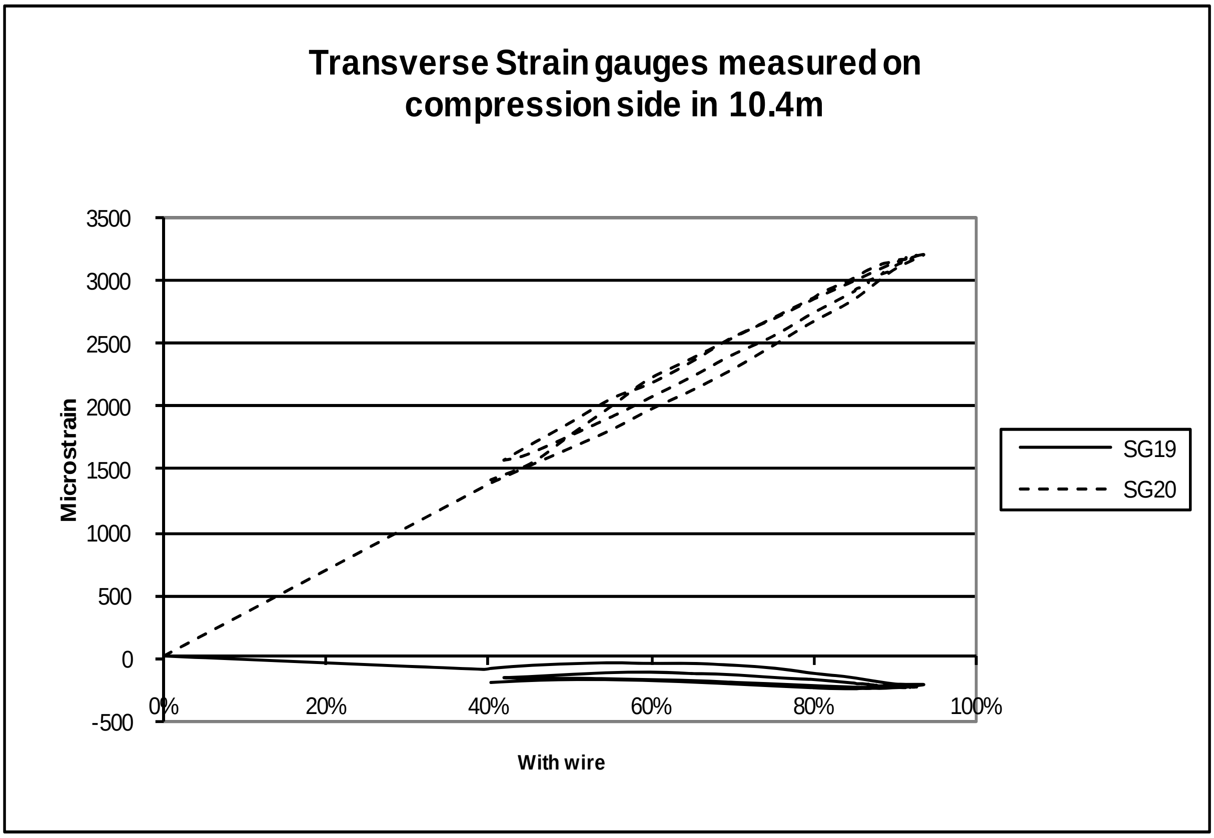

Longitudinal Strain gauges measured on leading web toward SS in 12.5m
0
-500
-1000
-1500
-2000
-2500
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG75.1
SG50.1

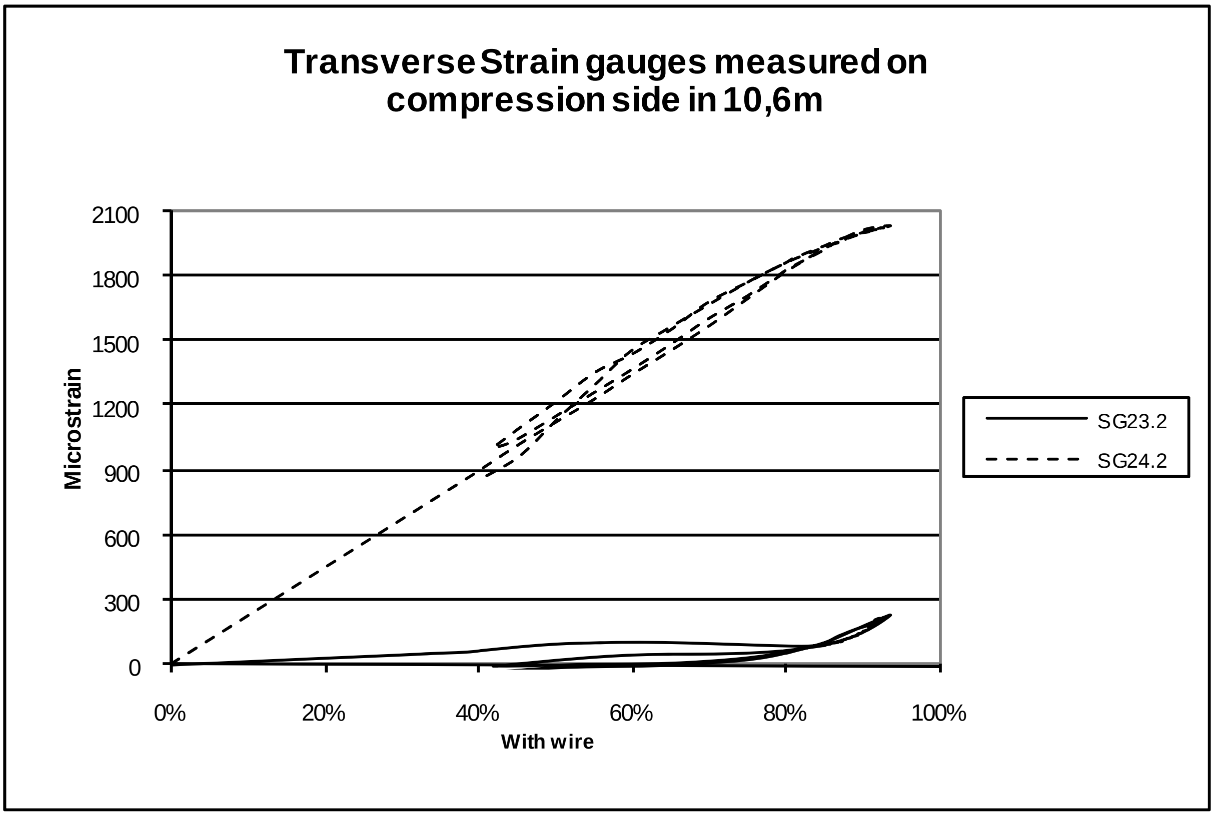

Longitudinal Strain gauges measured on leading web toward PS in 12.5m
2500
2000
1500
1000
500
0
-500
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG77.1
SG52.1

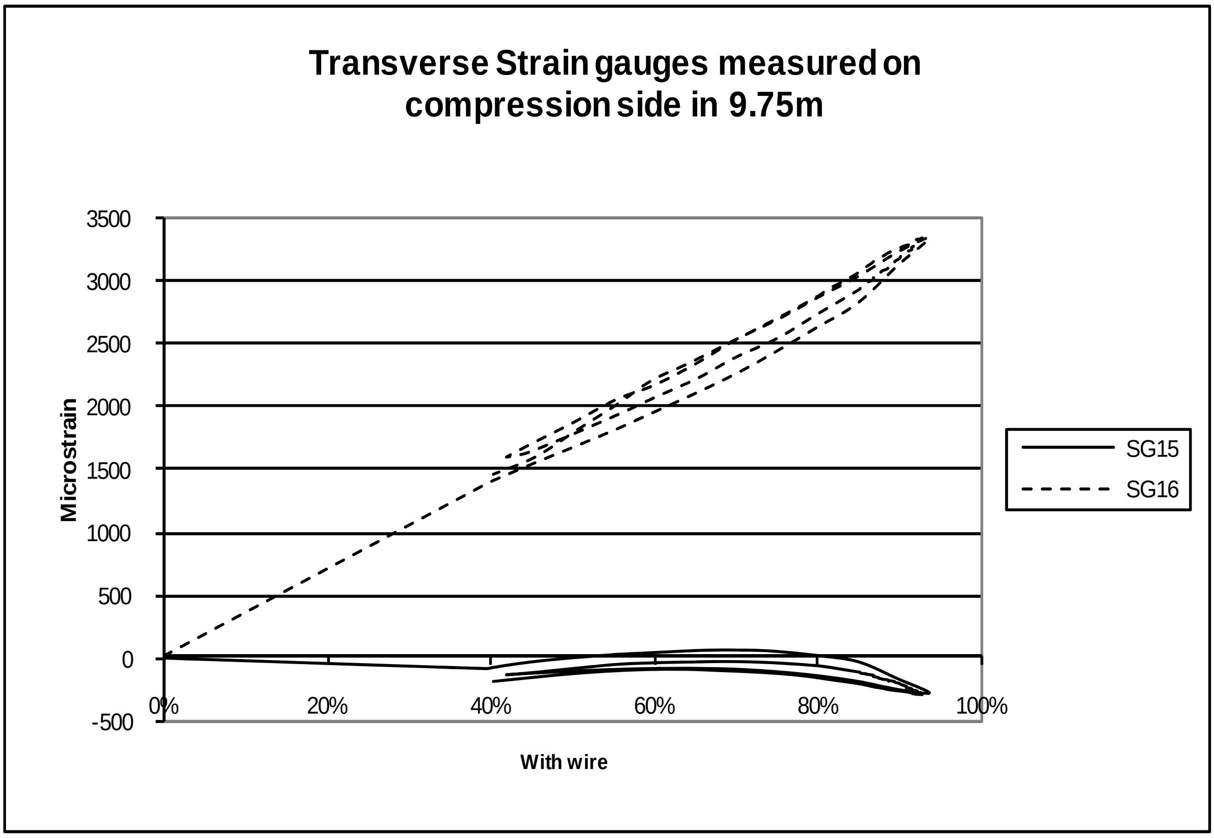
Graphs of Transverse measurements with wire

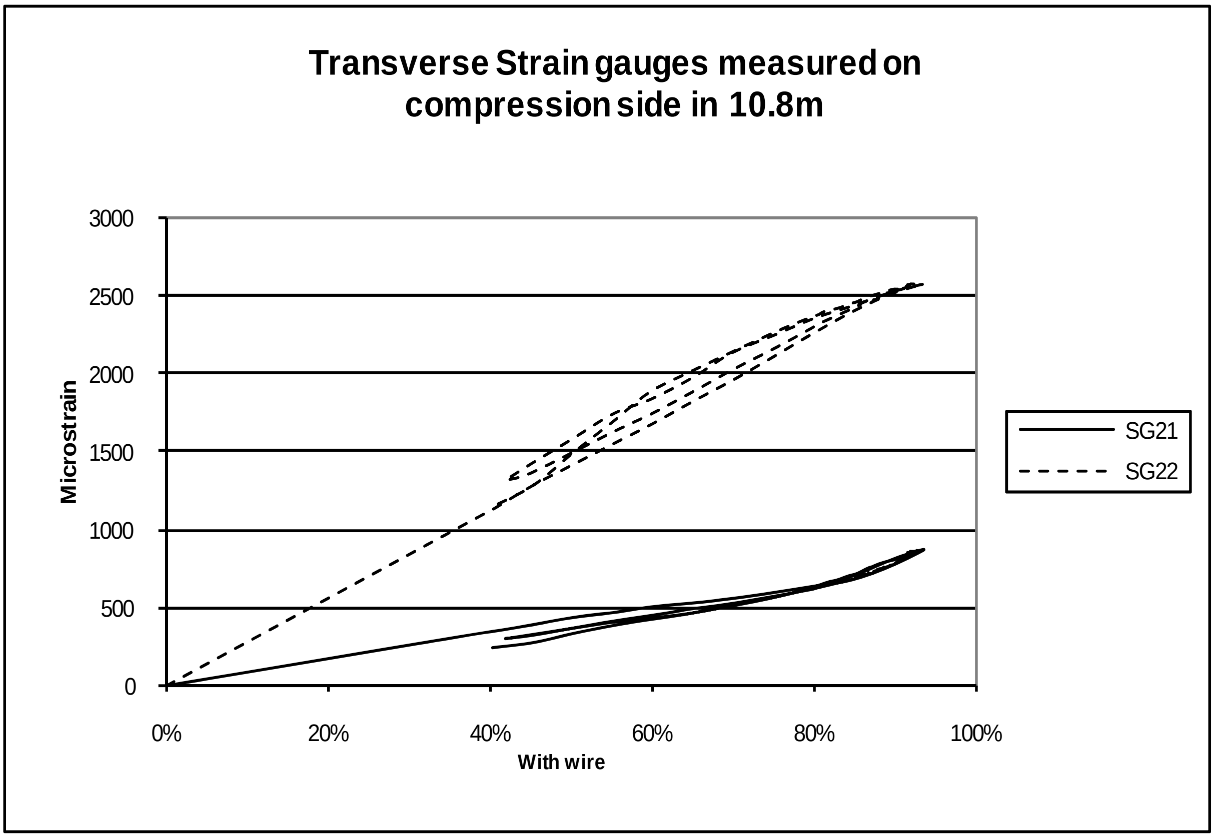


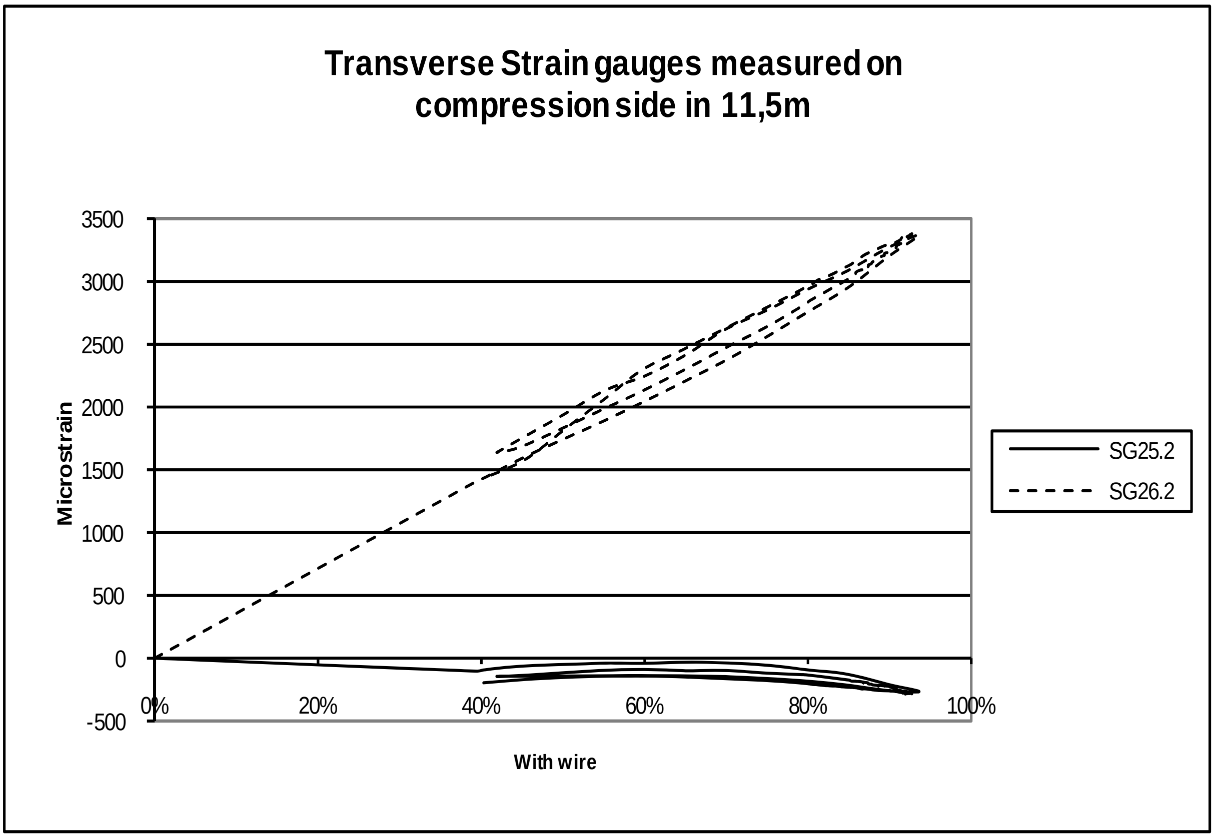


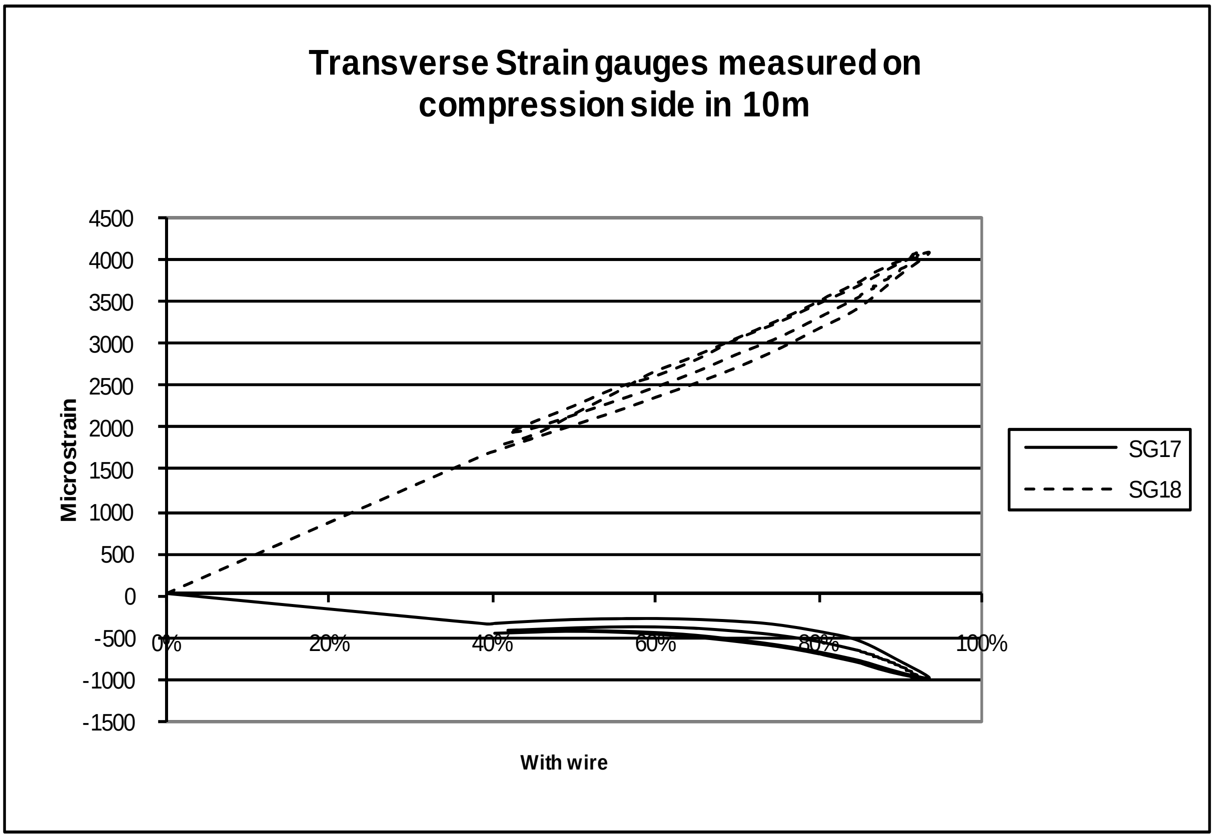

Transverse Strain gauges measured on compression side in 10.4m
Microstrain
3500
3000
2500
2000
1500
1000
500
0
-500
0%
20%
40%
60%
80%
100%
With wire
SG19
SG20

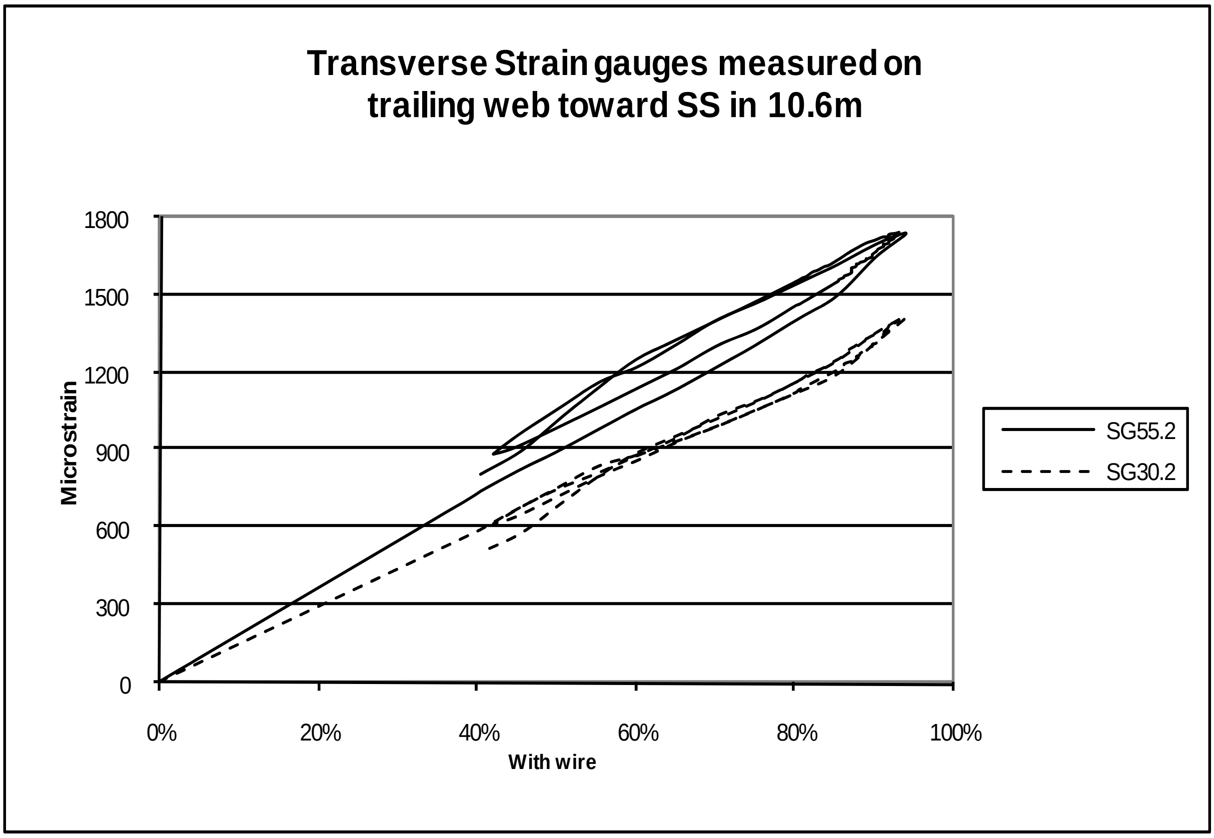

Transverse Strain gauges measured on compression side in 10,6m
Microstrain
2100
1800
1500
1200
900
600
300
0
0%
20%
40%
60%
80%
100%
With wire
SG23.2
SG24.2

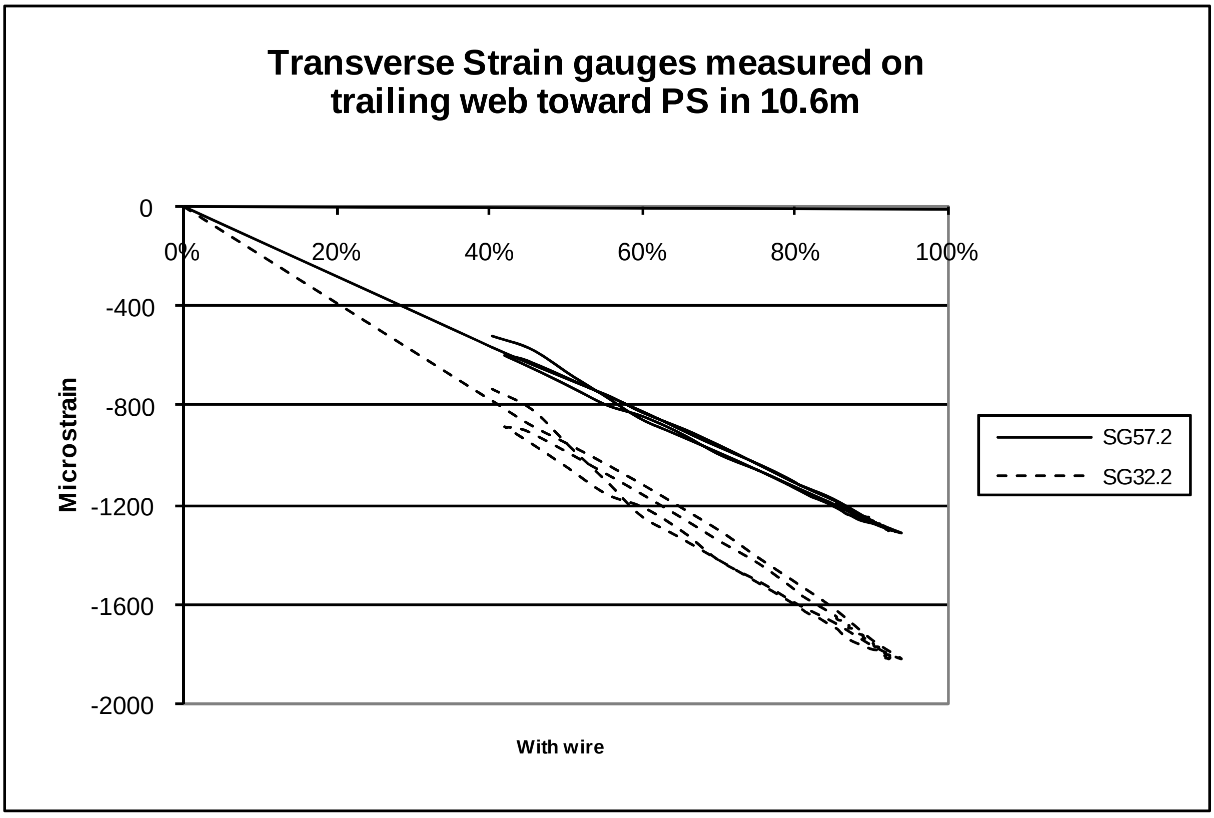

Transverse Strain gauges measured on compression side in 9.75m
Microstrain
3500
3000
2500
2000
1500
1000
500
0
-500
0%
20%
40%
60%
80%
100%
With wire
SG15
SG16

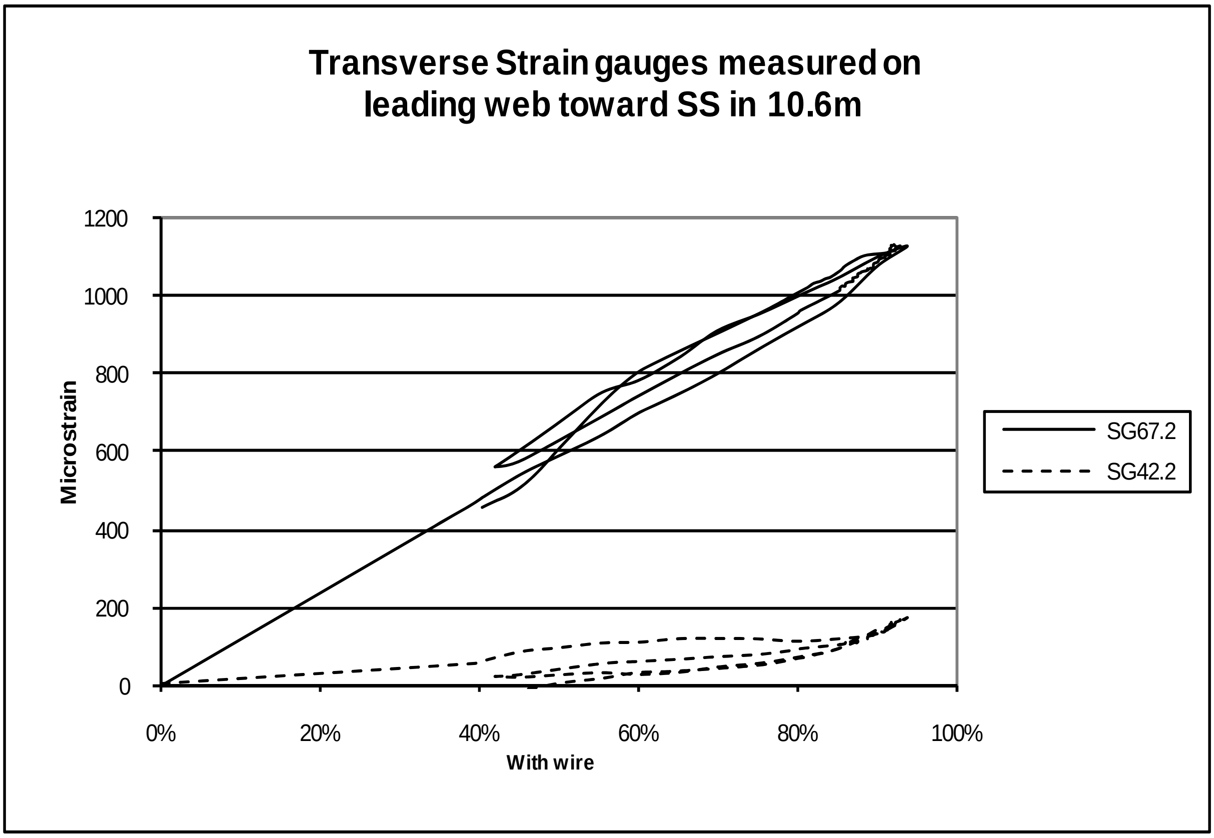

Transverse Strain gauges measured on compression side in 10.8m
Microstrain
3000
2500
2000
1500
1000
500
0
0%
20%
40%
60%
80%
100%
With wire
SG21
SG22

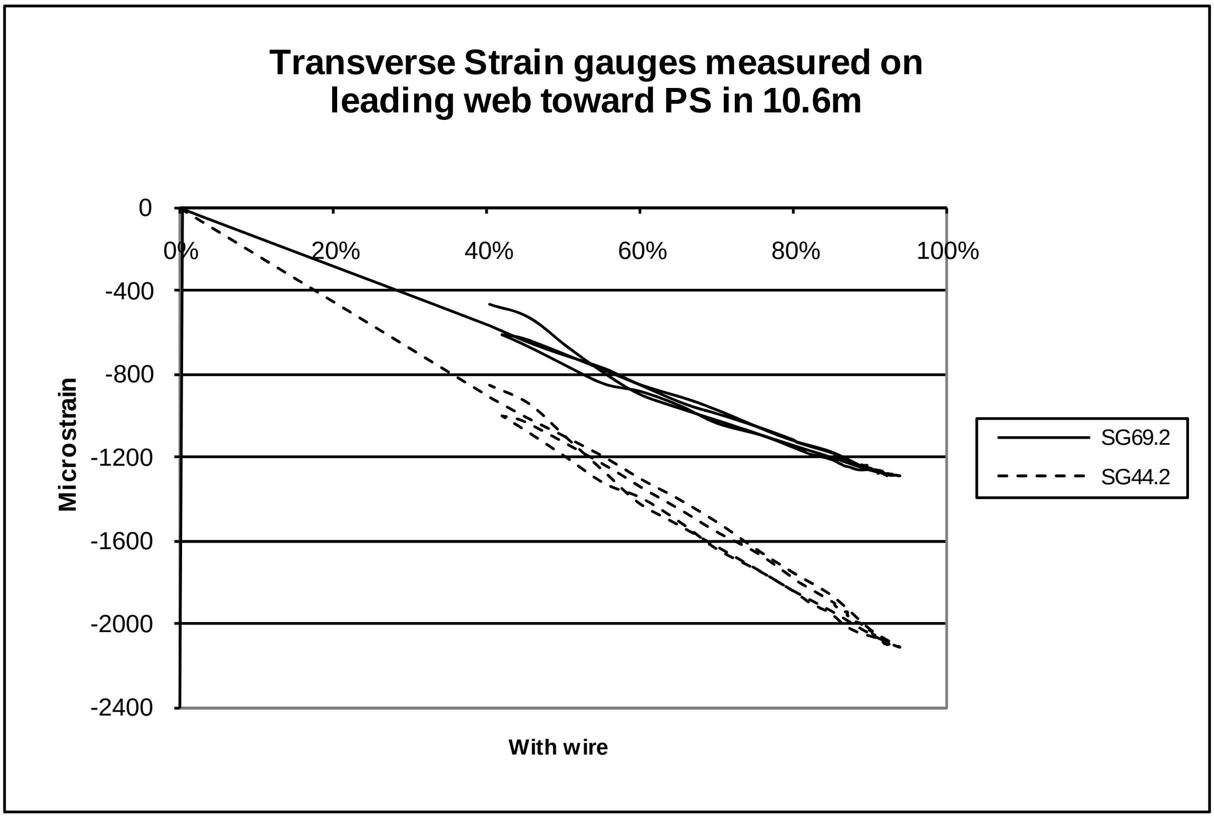

Transverse Strain gauges measured on compression side in 11,5m
3500
3000
2500
2000
1500
1000
500
0
-500
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG25.2
SG26.2

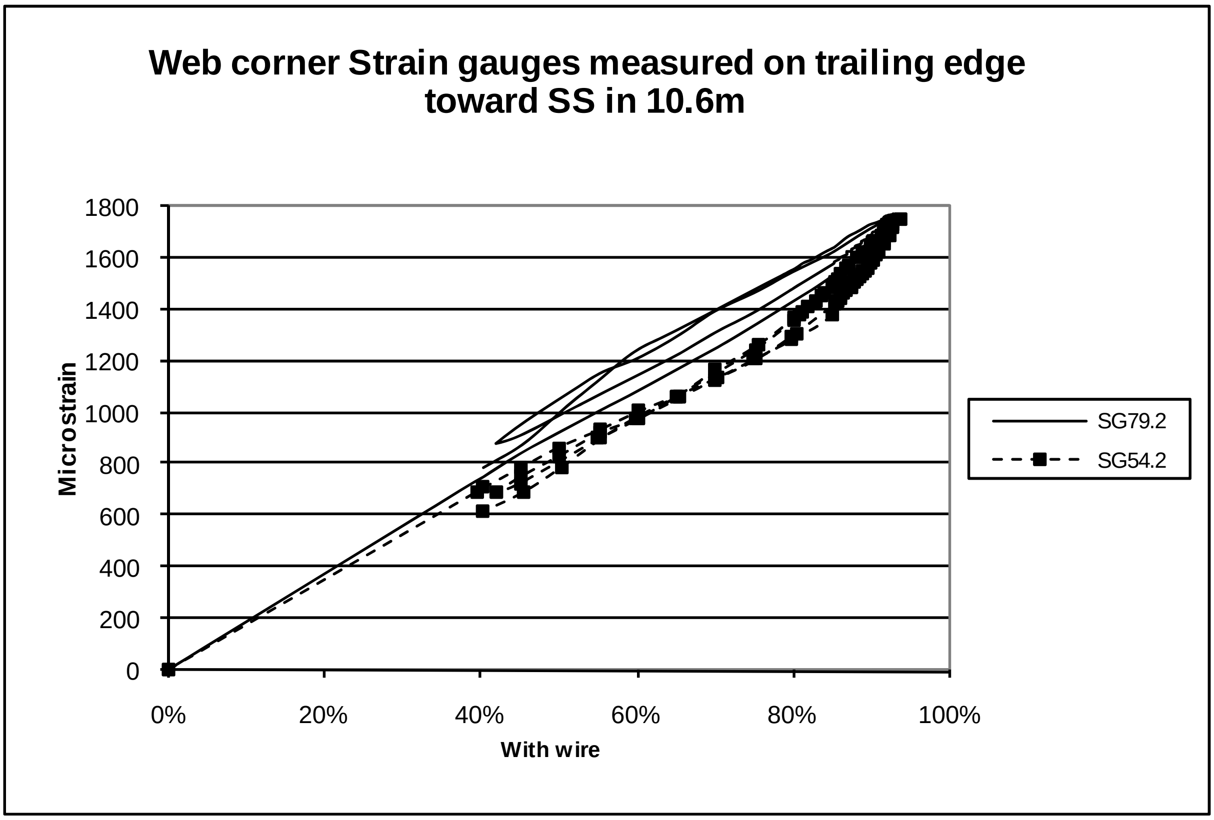

Transverse Strain gauges measured on compression side in 10m
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
-1500
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG17
SG18


Transverse Strain gauges measured on trailing web toward SS in 10.6m
1800
1500
1200
900
600
300
0
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG55.2
SG30.2

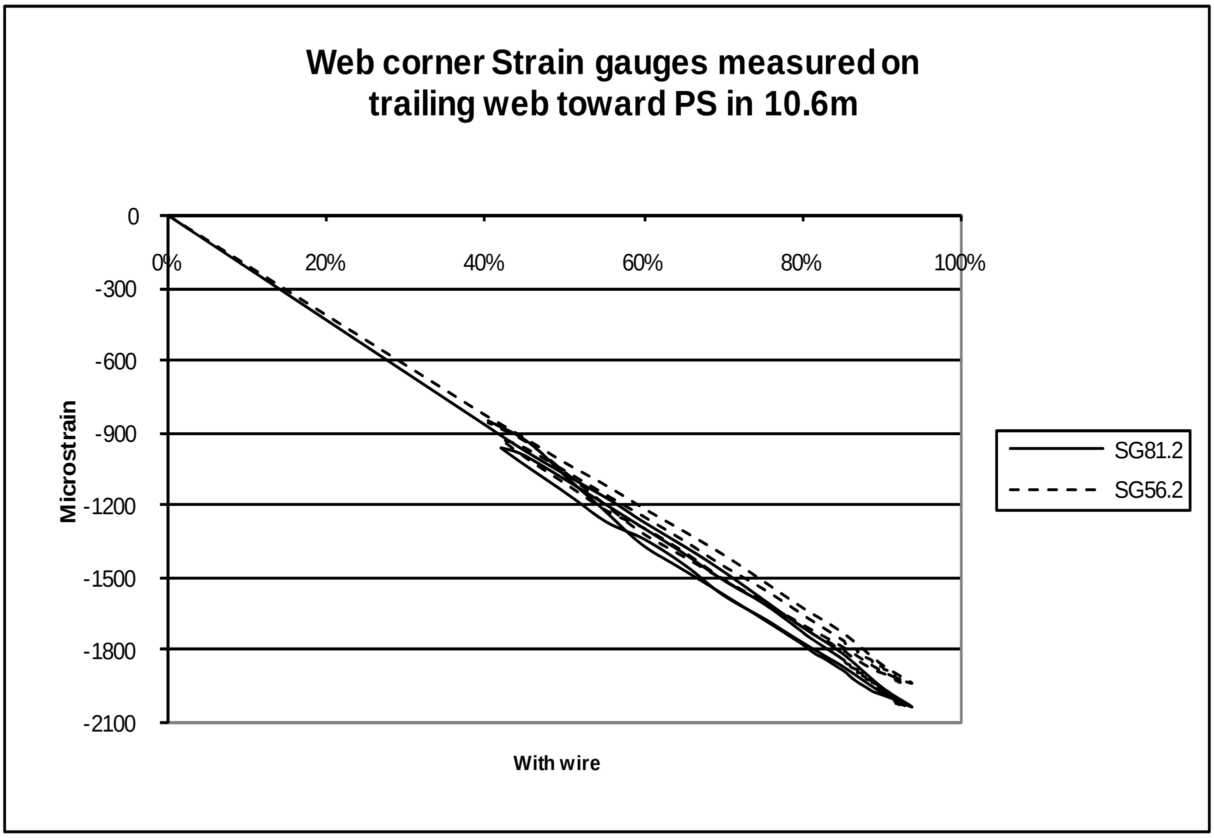

Transverse Strain gauges measured on trailing web toward PS in 10.6m
0
-400
-800
-1200
-1600
-2000
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG57.2
SG32.2


Transverse Strain gauges measured on leading web toward SS in 10.6m
Microstrain
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
With wire
SG67.2
SG42.2

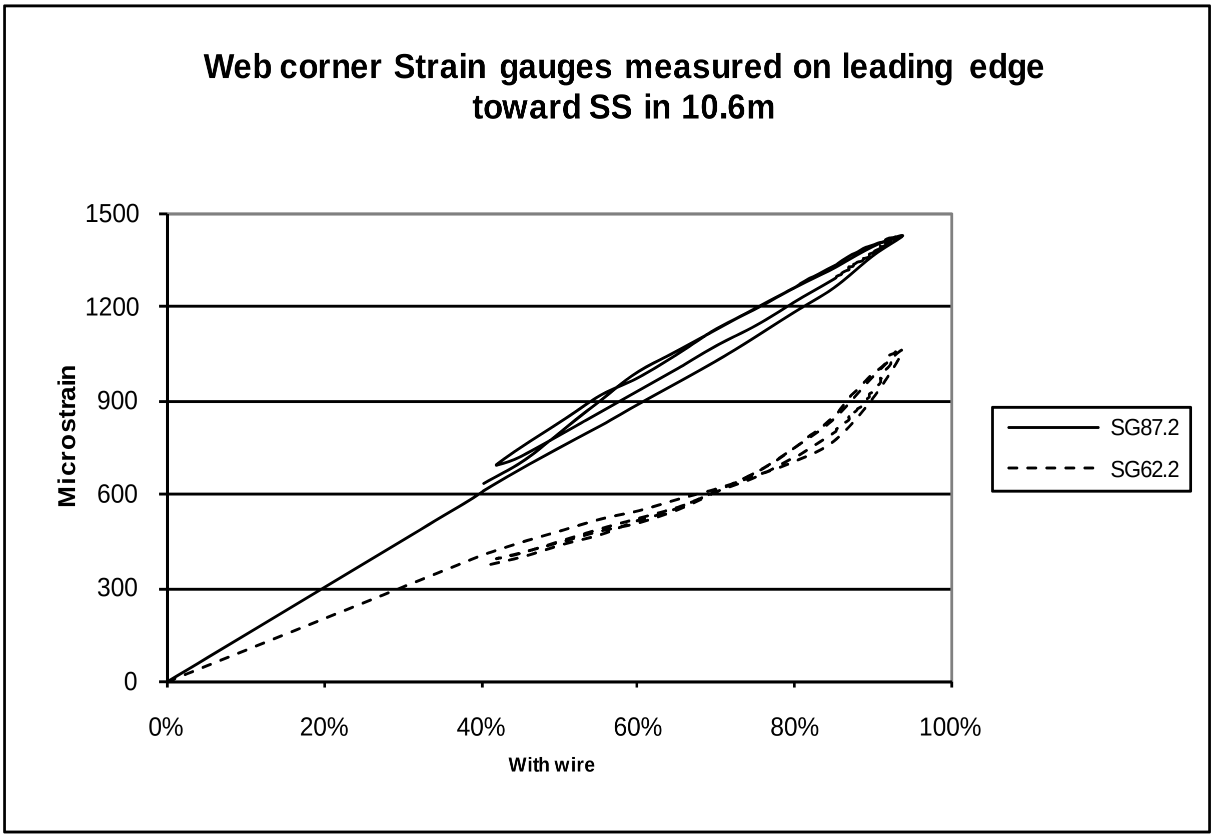

Transverse Strain gauges measured on leading web toward PS in 10.6m
Microstrain
0
-400
-800
-1200
-1600
-2000
-2400
0%
20%
40%
60%
80%
100%
With wire
SG69.2
SG44.2

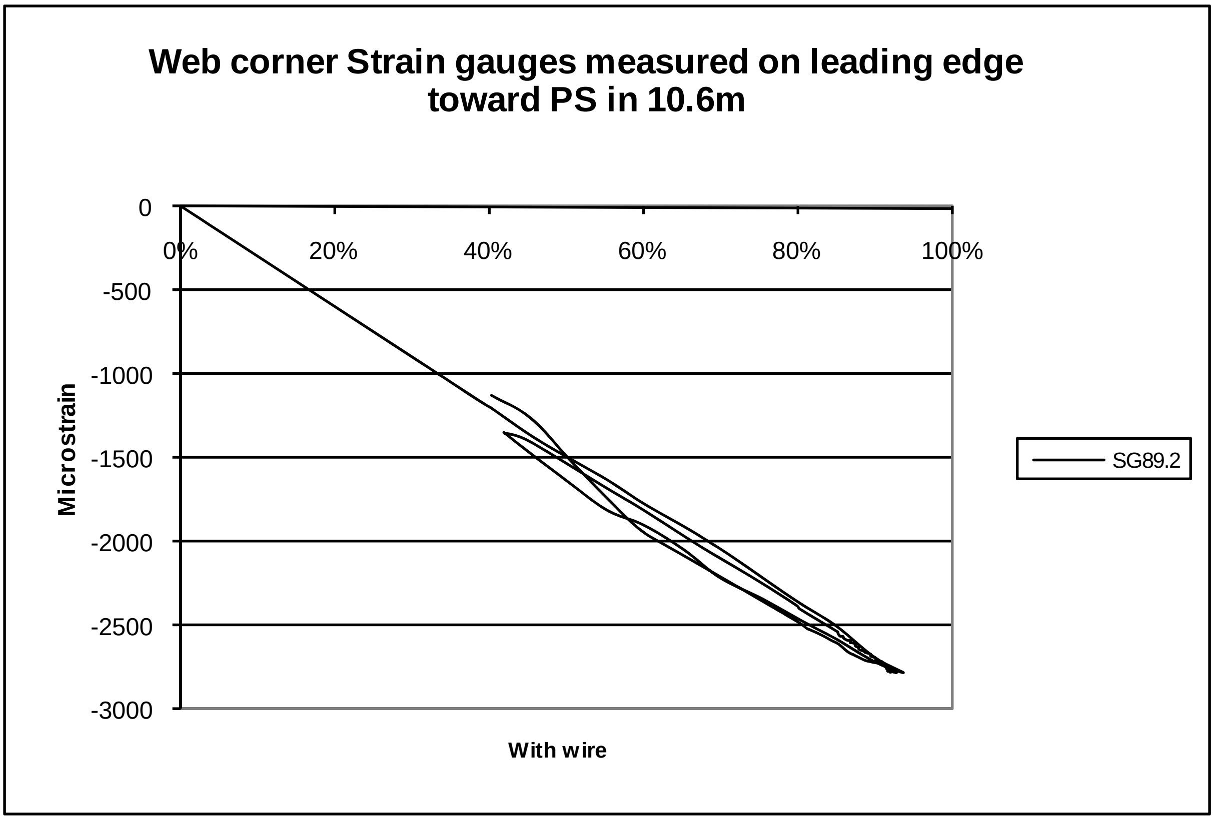


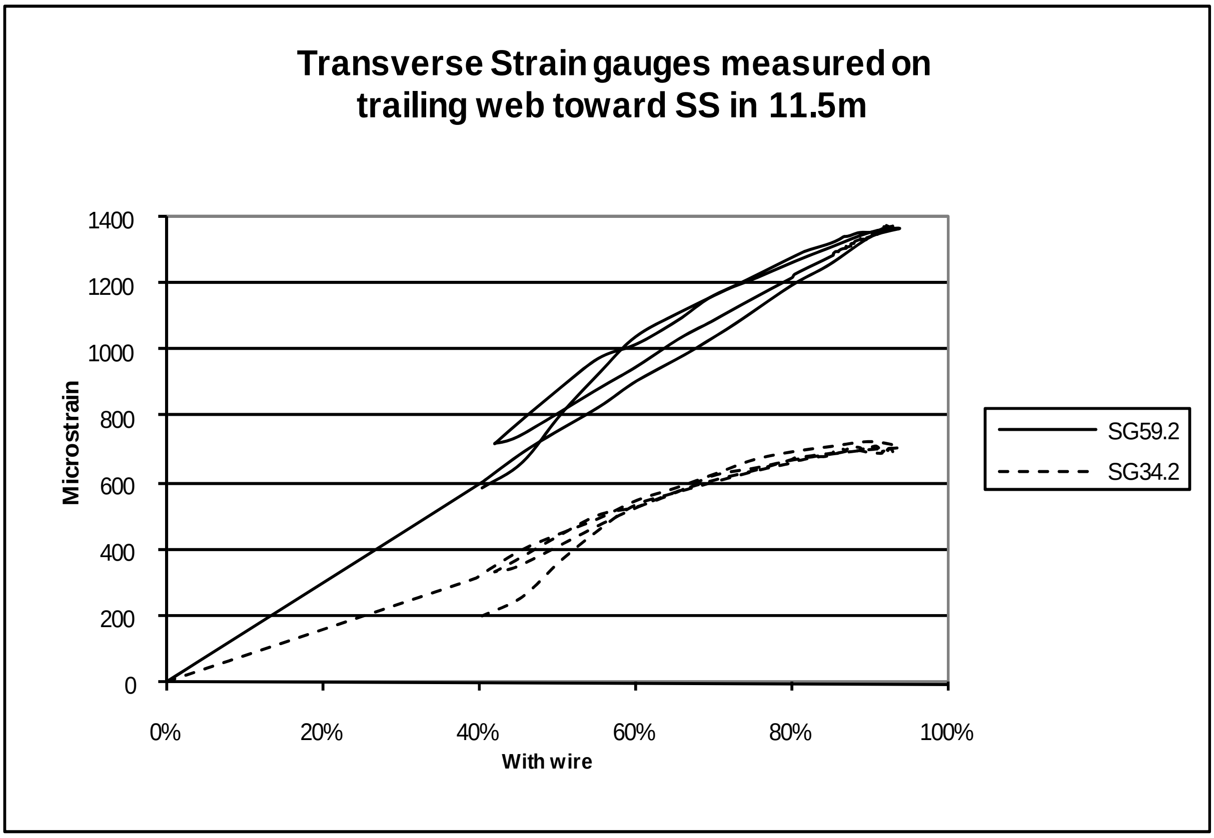
Web corner Strain gauges measured on trailing edge toward SS in 10.6m
Microstrain
1800
1600
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
With wire
SG79.2
SG54.2



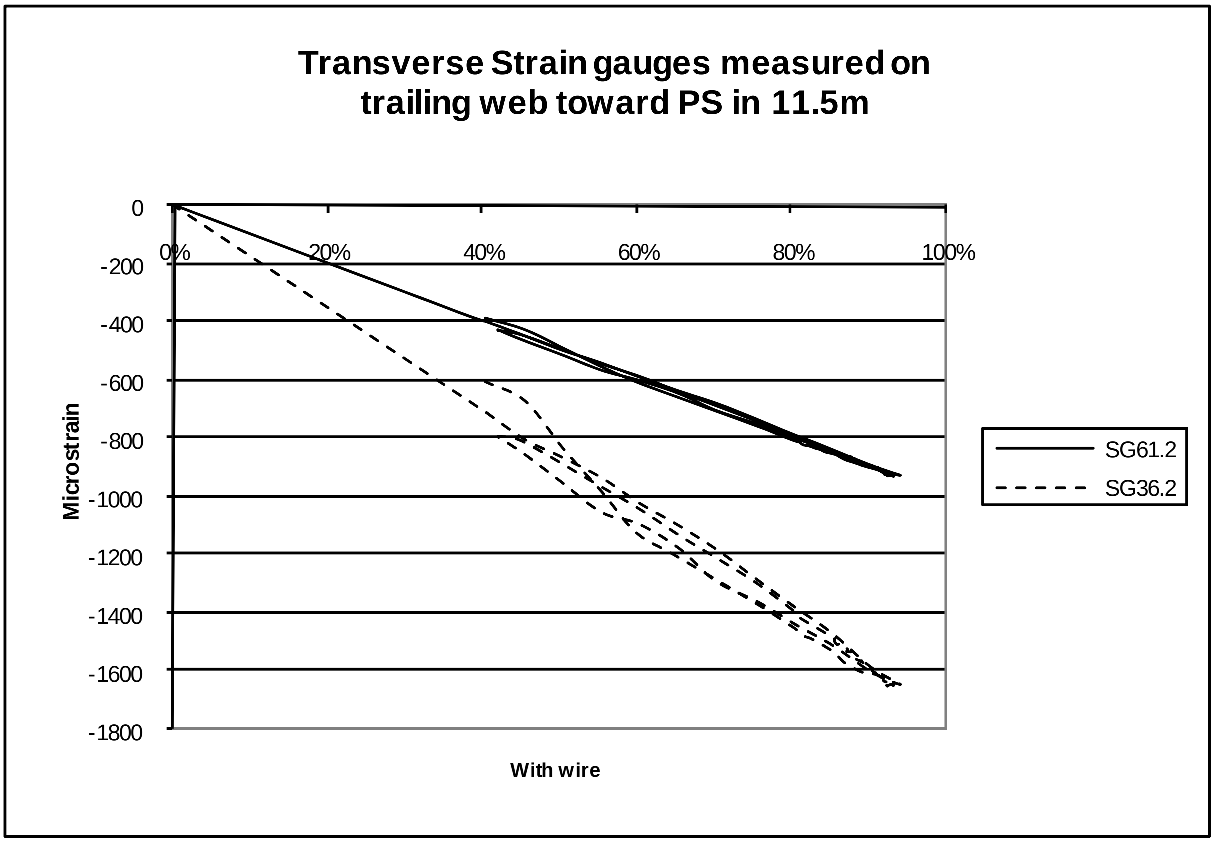
Web corner Strain gauges measured on trailing web toward PS in 10.6m
Microstrain
0
-300
-600
-900
-1200
-1500
-1800
-2100
0%
20%
40%
60%
80%
100%
With wire
SG81.2
SG56.2


Web corner Strain gauges measured on leading edge toward SS in 10.6m
1500
1200
900
600
300
0
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG87.2
SG62.2

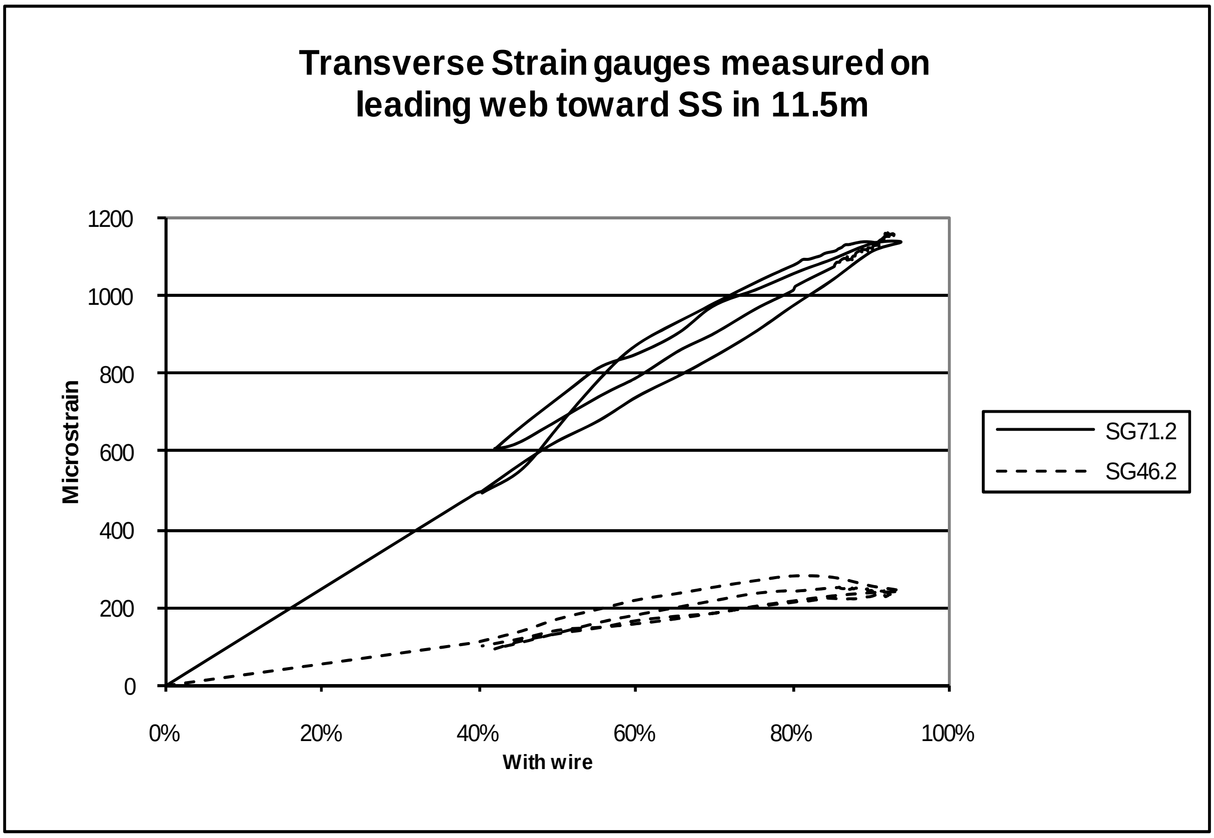

Web corner Strain gauges measured on leading edge toward PS in 10.6m
0
-500
-1000
-1500
-2000
-2500
-3000
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG89.2

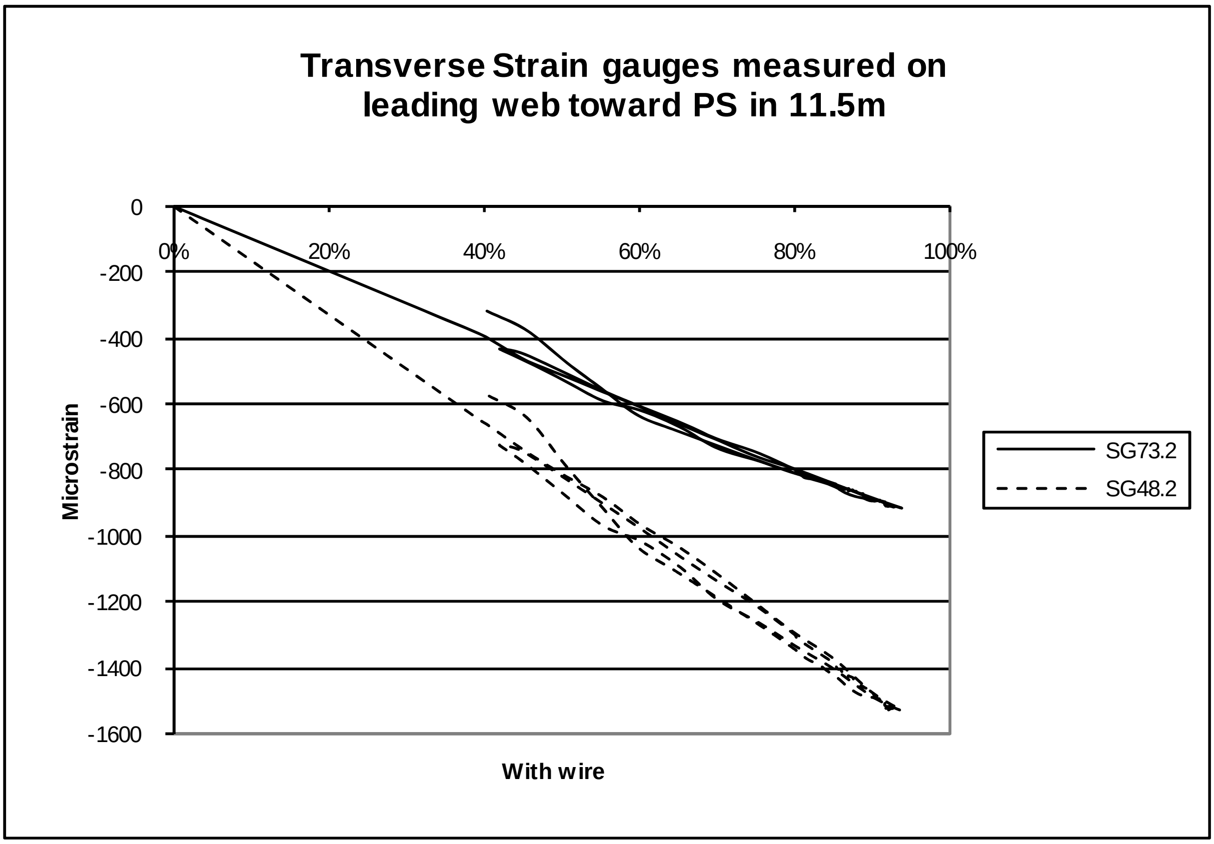


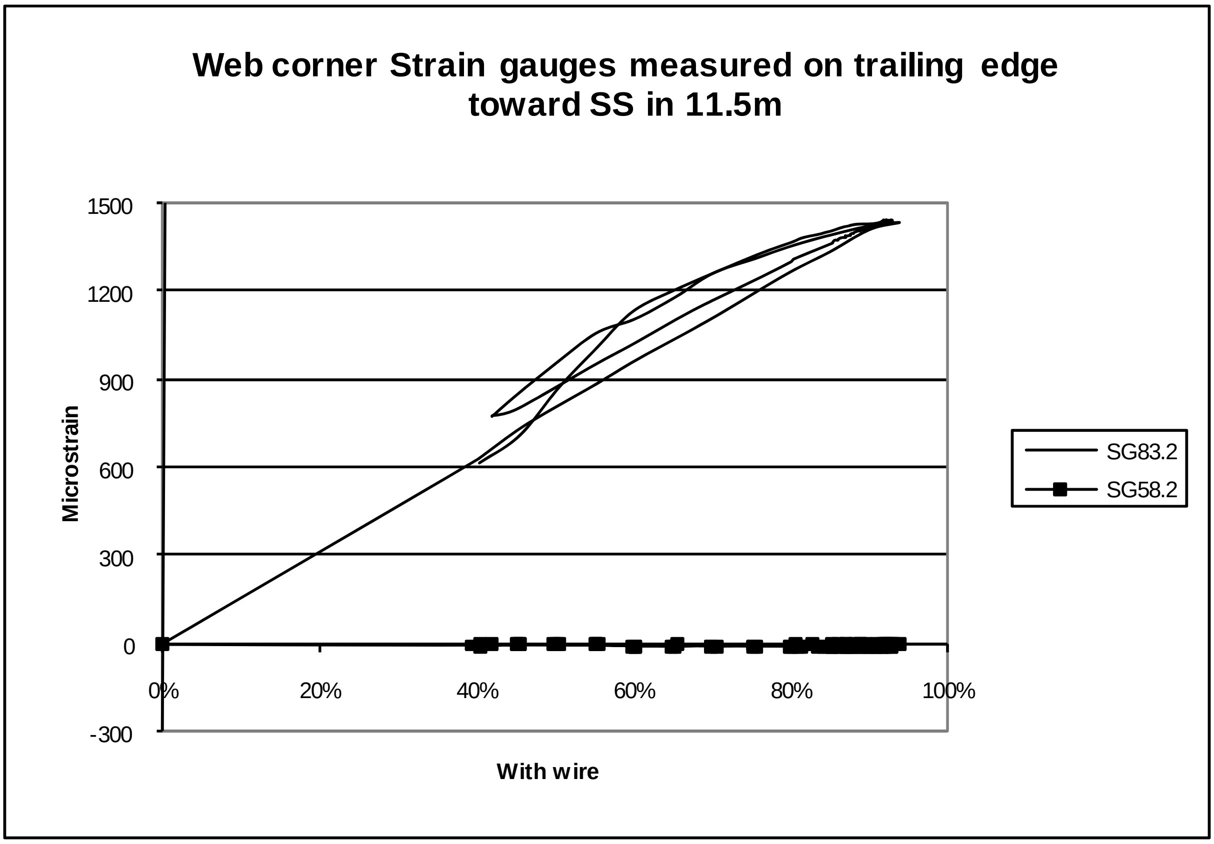
Transverse Strain gauges measured on trailing web toward SS in 11.5m
1400
1200
1000
800
600
400
200
0
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG59.2
SG34.2

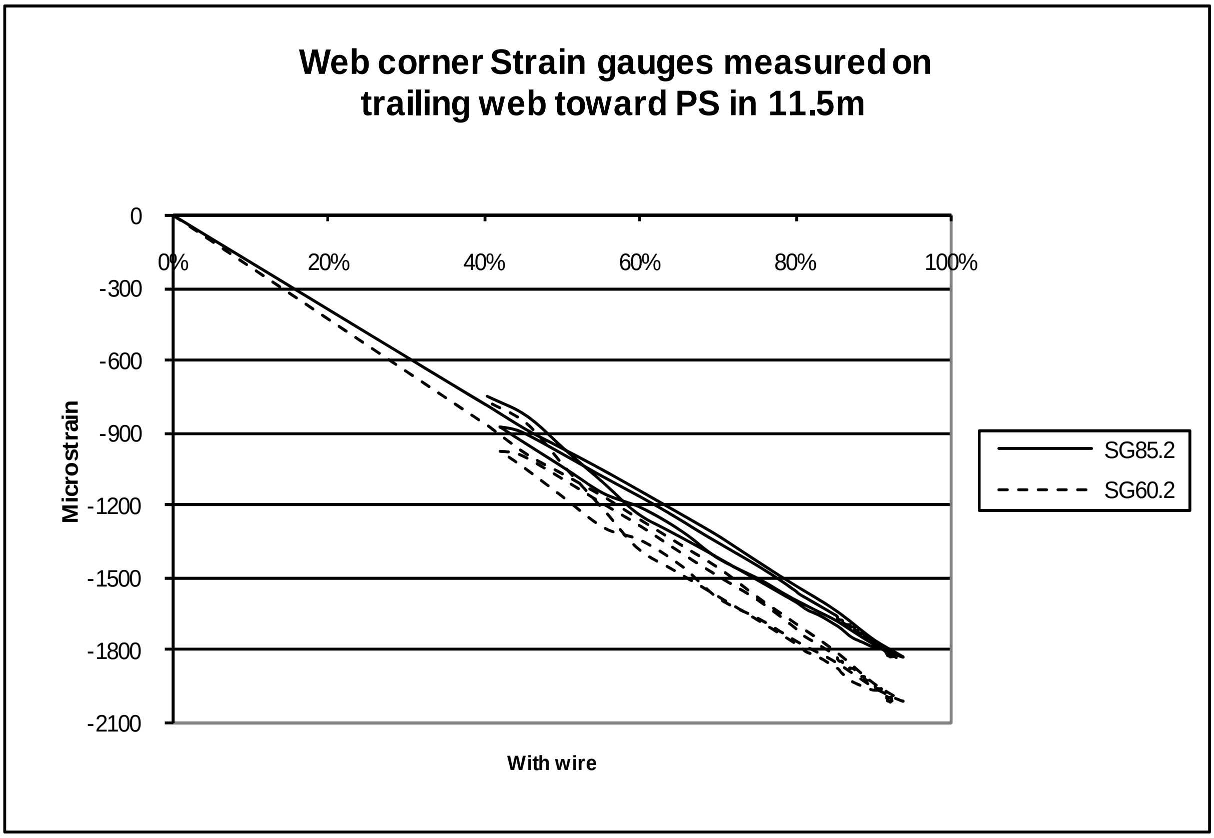


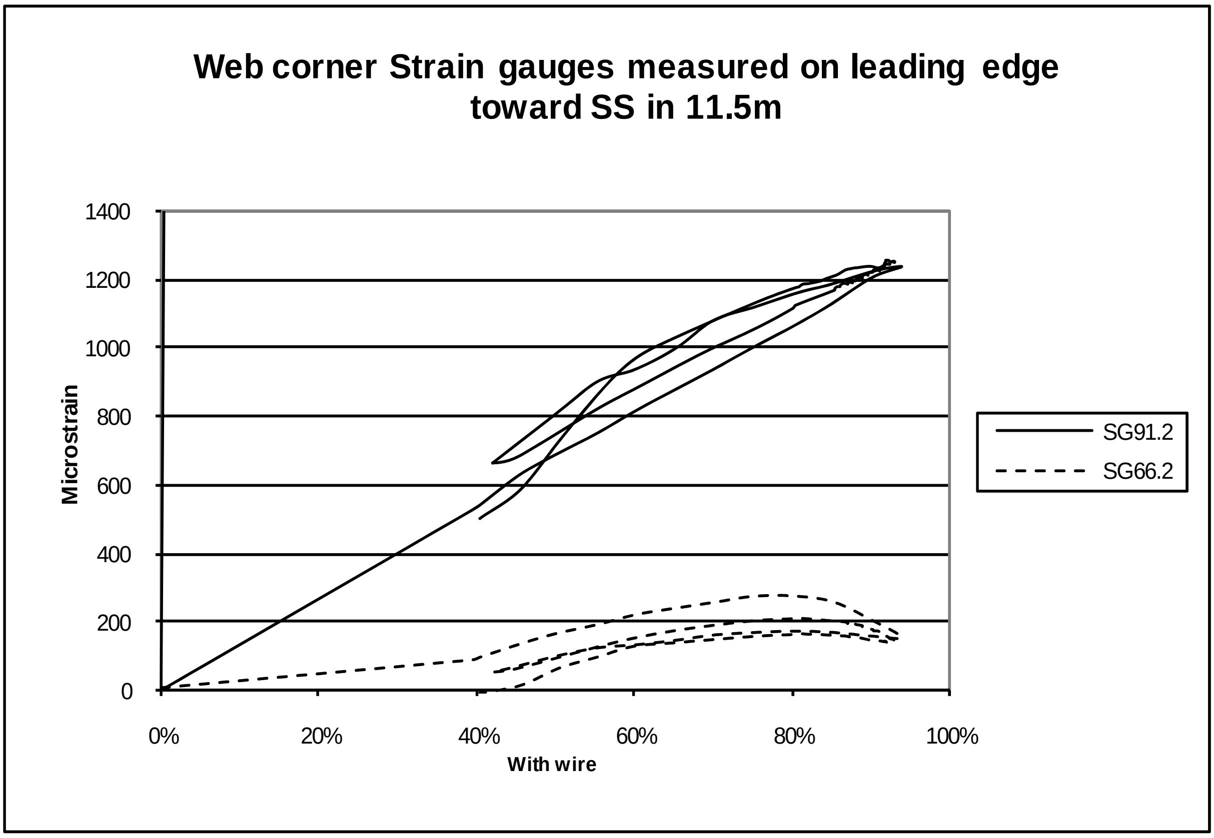
Transverse Strain gauges measured on trailing web toward PS in 11.5m
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG61.2
SG36.2

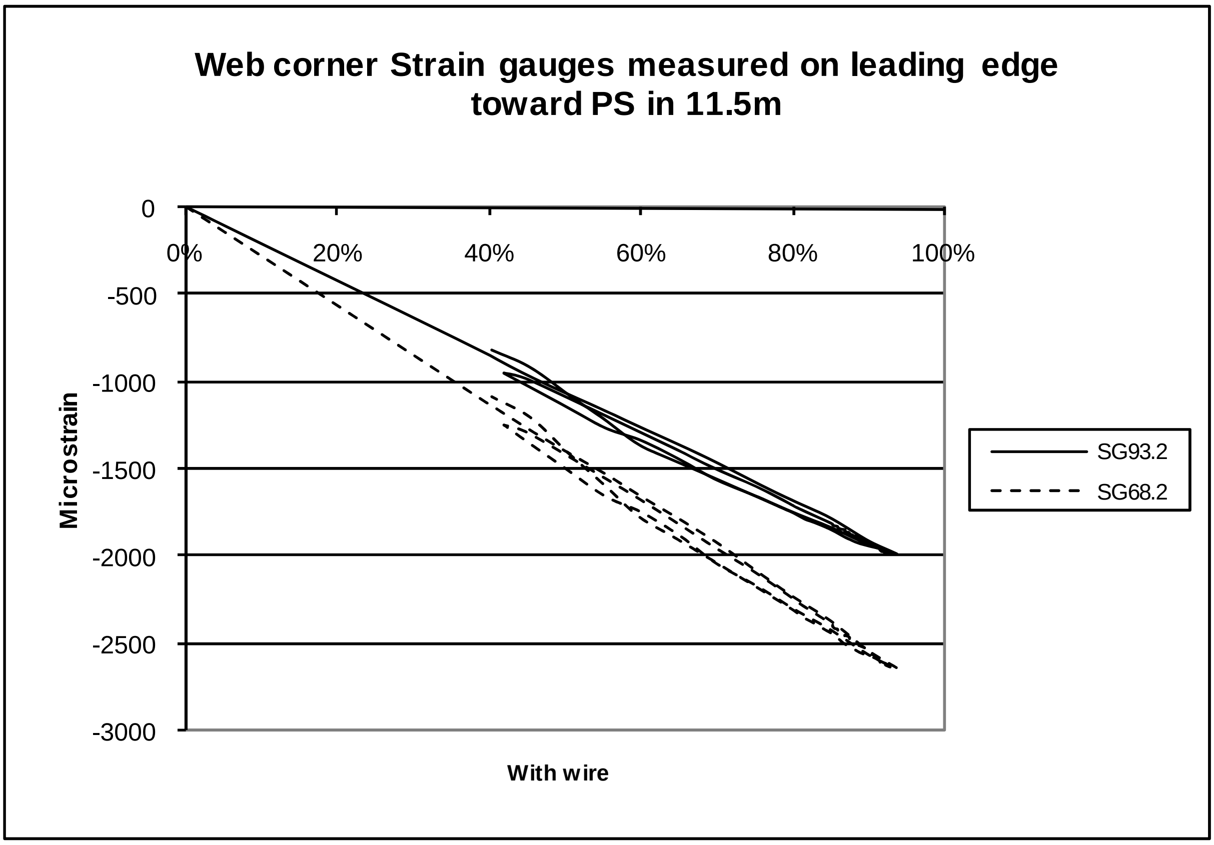

Transverse Strain gauges measured on leading web toward SS in 11.5m
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
With wire
Microstrain
SG71.2
SG46.2

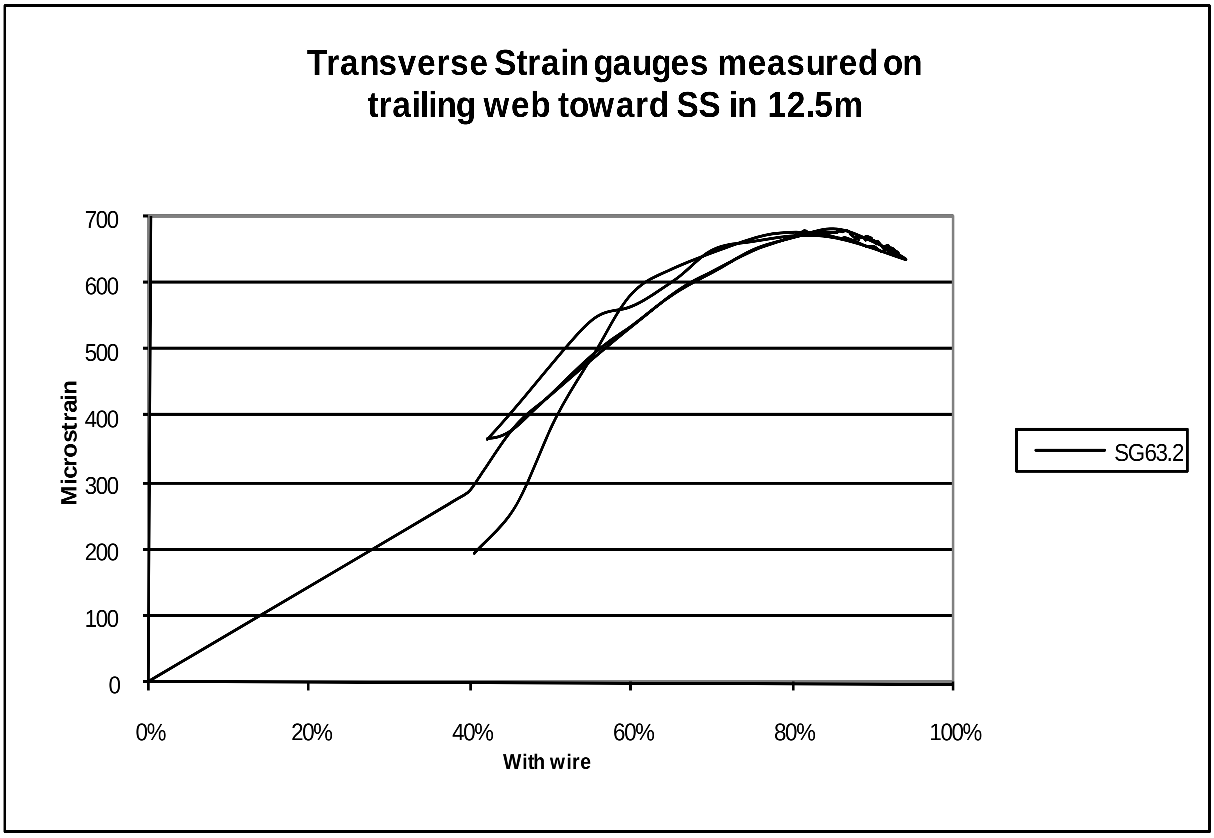

Transverse Strain gauges measured on leading web toward PS in 11.5m
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
0%
20%
40%
60%
80%
100%
With wire
Microstrain
SG73.2
SG48.2

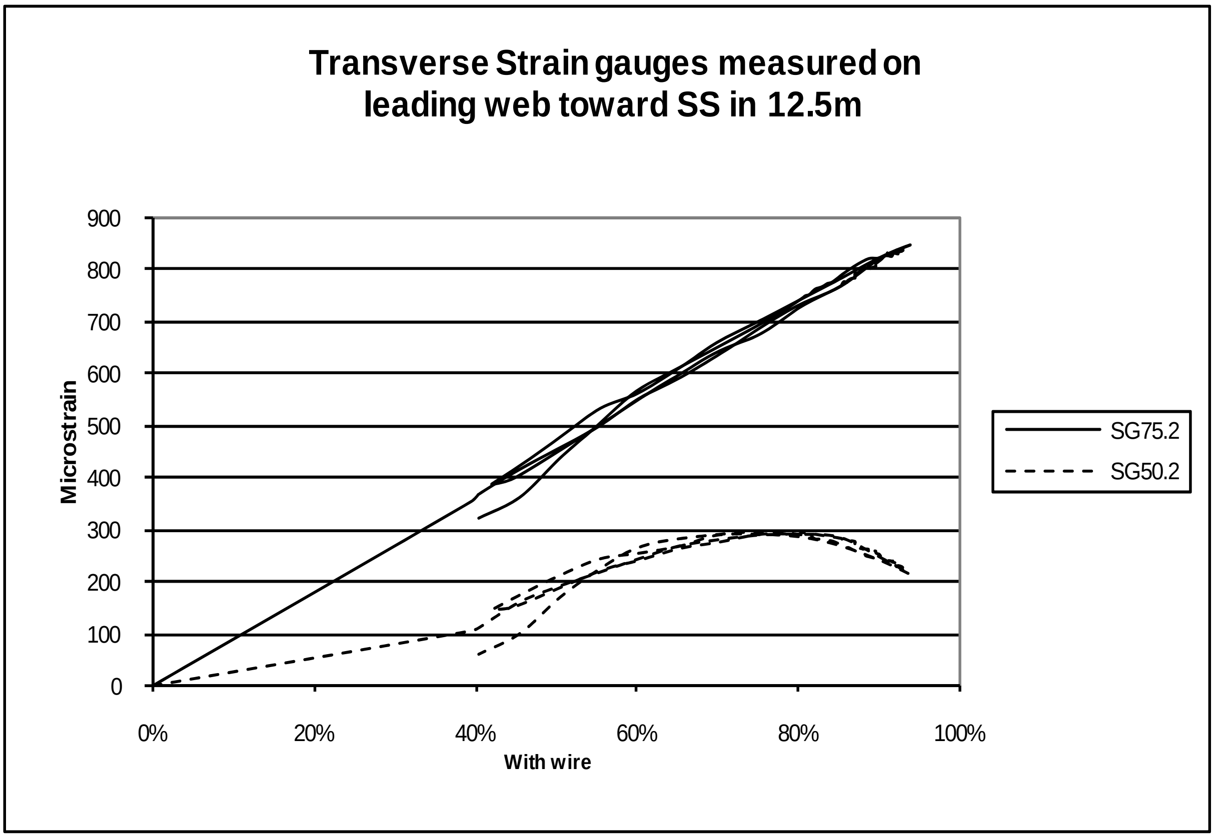

Web corner Strain gauges measured on trailing edge toward SS in 11.5m
Microstrain
1500
1200
900
600
300
0
-300
0%
20%
40%
60%
80%
100%
With wire
SG83.2
SG58.2

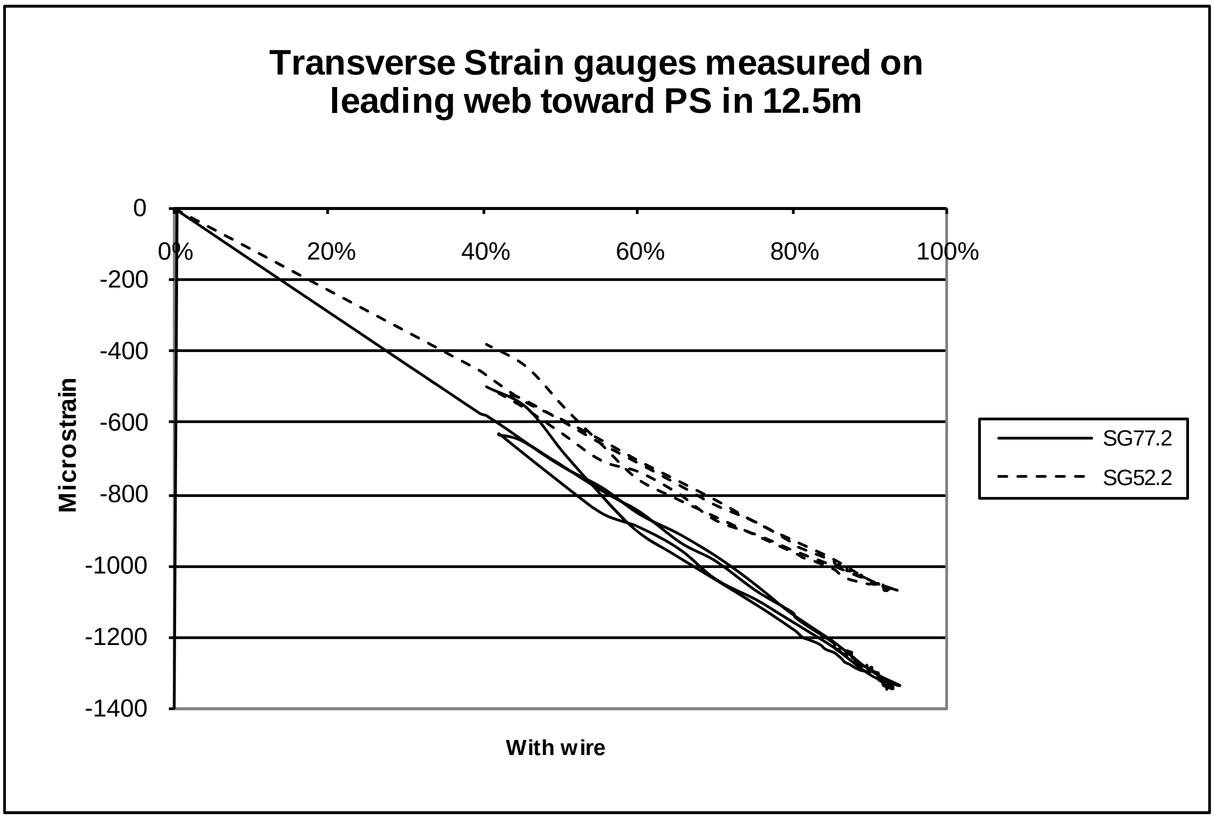

Web corner Strain gauges measured on trailing web toward PS in 11.5m
Microstrain
0
-300
-600
-900
-1200
-1500
-1800
-2100
0%
20%
40%
60%
80%
100%
With wire
SG85.2
SG60.2


Web corner Strain gauges measured on leading edge toward SS in 11.5m
Microstrain
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
With wire
SG91.2
SG66.2

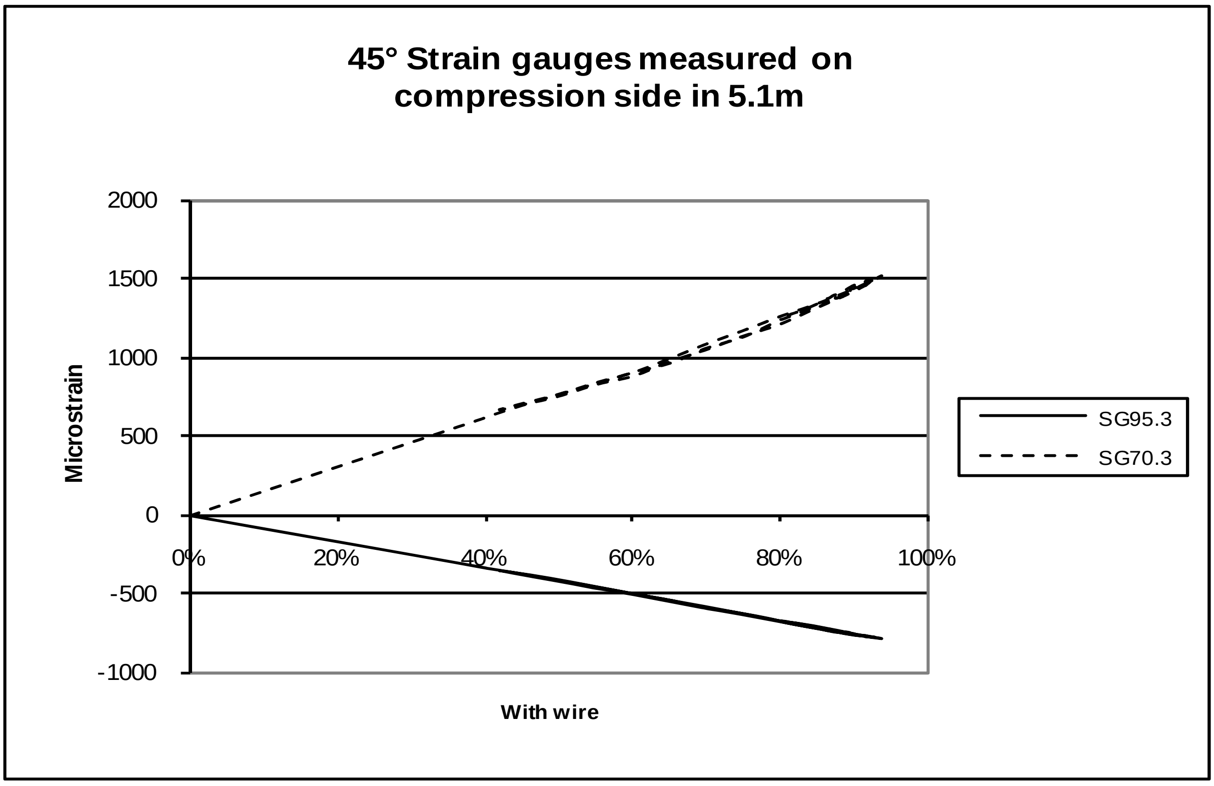

Web corner Strain gauges measured on leading edge toward PS in 11.5m
Microstrain
0
-500
-1000
-1500
-2000
-2500
-3000
0%
20%
40%
60%
80%
100%
With wire
SG93.2
SG68.2

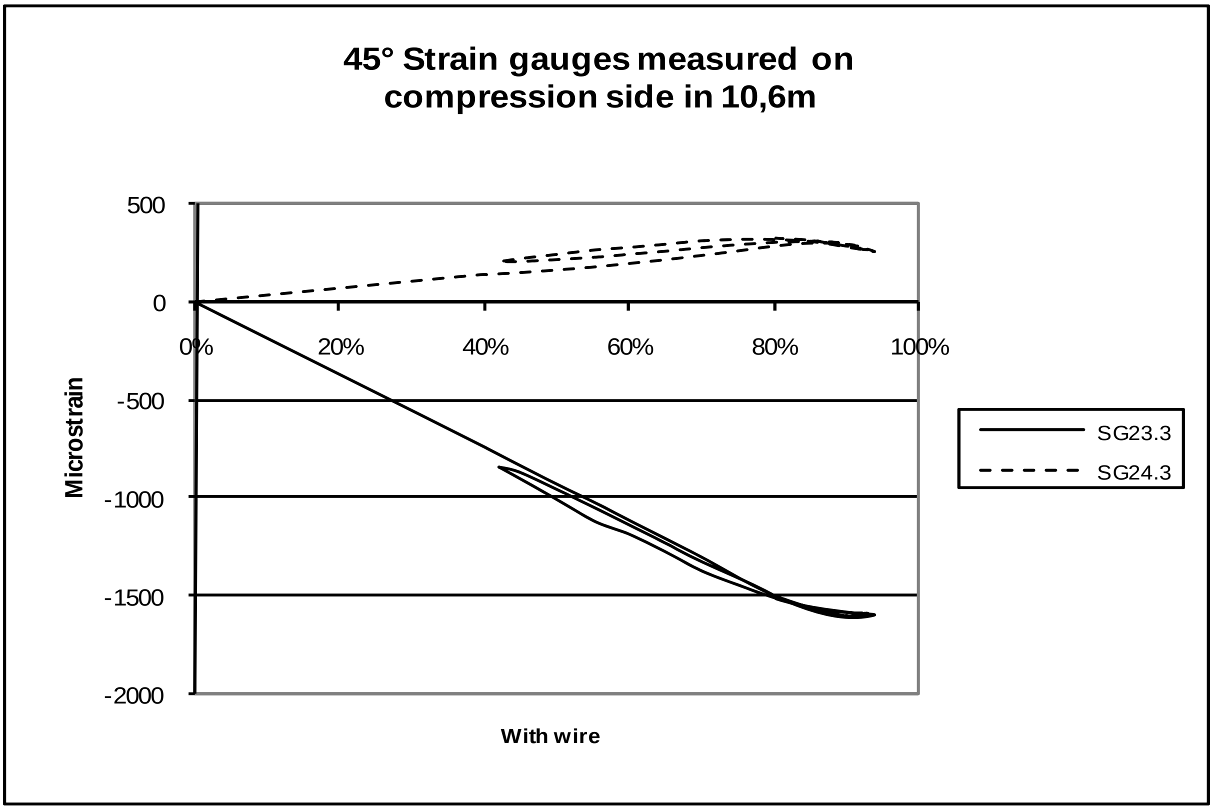

Transverse Strain gauges measured on trailing web toward SS in 12.5m
Microstrain
700
600
500
400
300
200
100
0
0%
20%
40%
60%
80%
100%
With wire
SG63.2

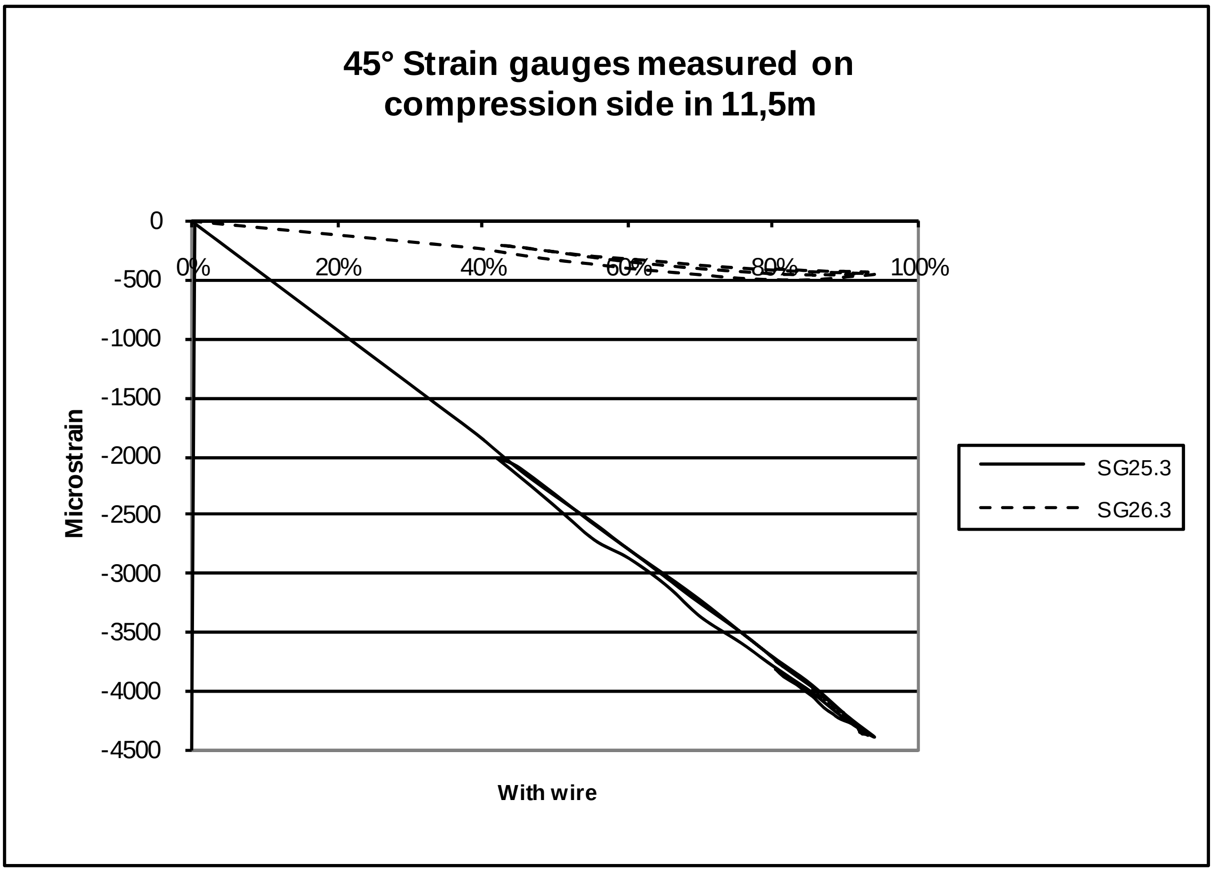

Transverse Strain gauges measured on leading web toward SS in 12.5m
Microstrain
900
800
700
600
500
400
300
200
100
0
0%
20%
40%
60%
80%
100%
With wire
SG75.2
SG50.2

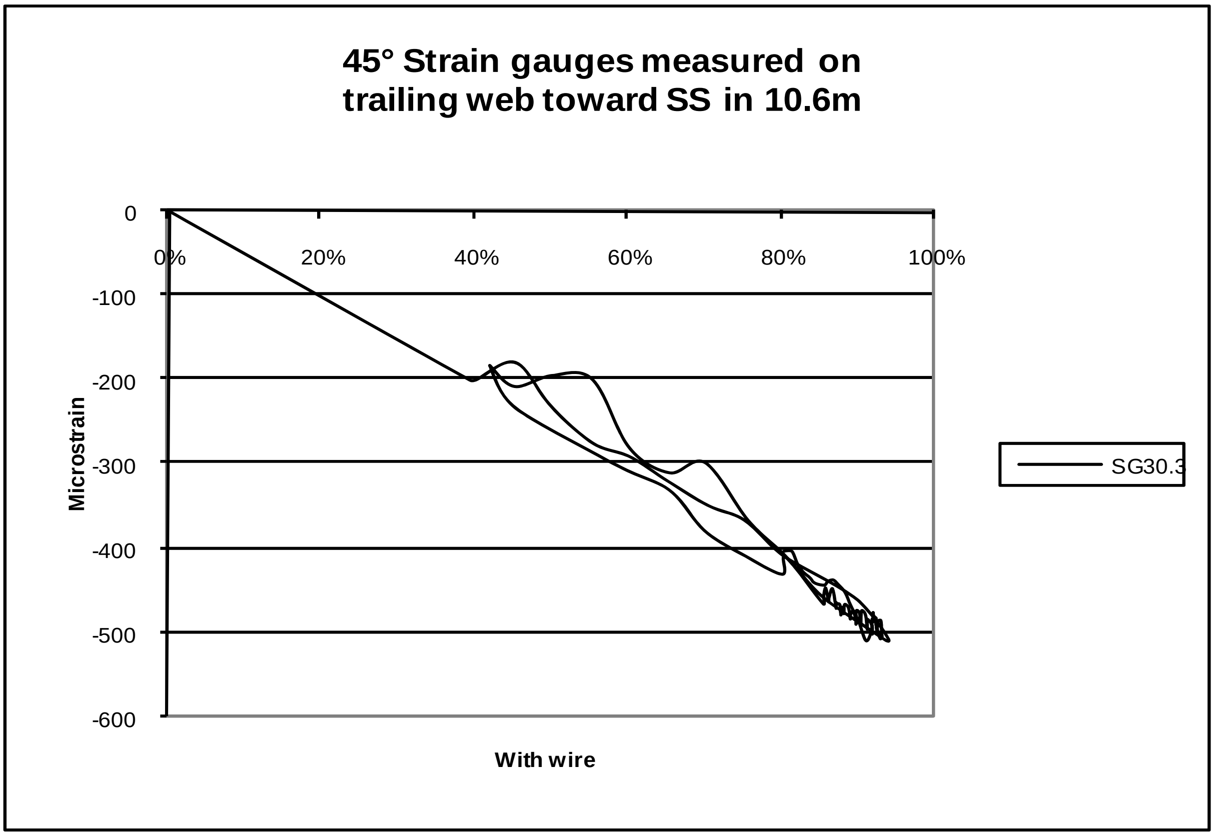


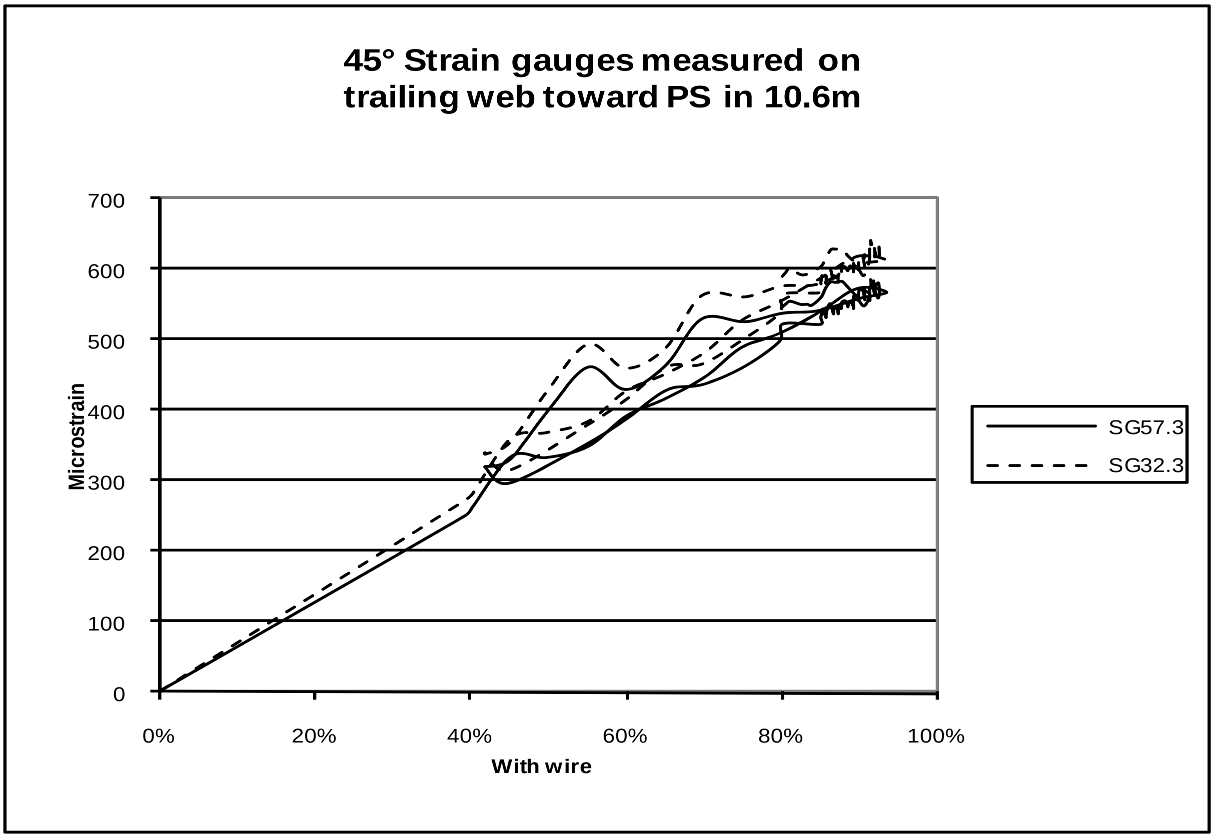
Graphs of 45° measurements with wire



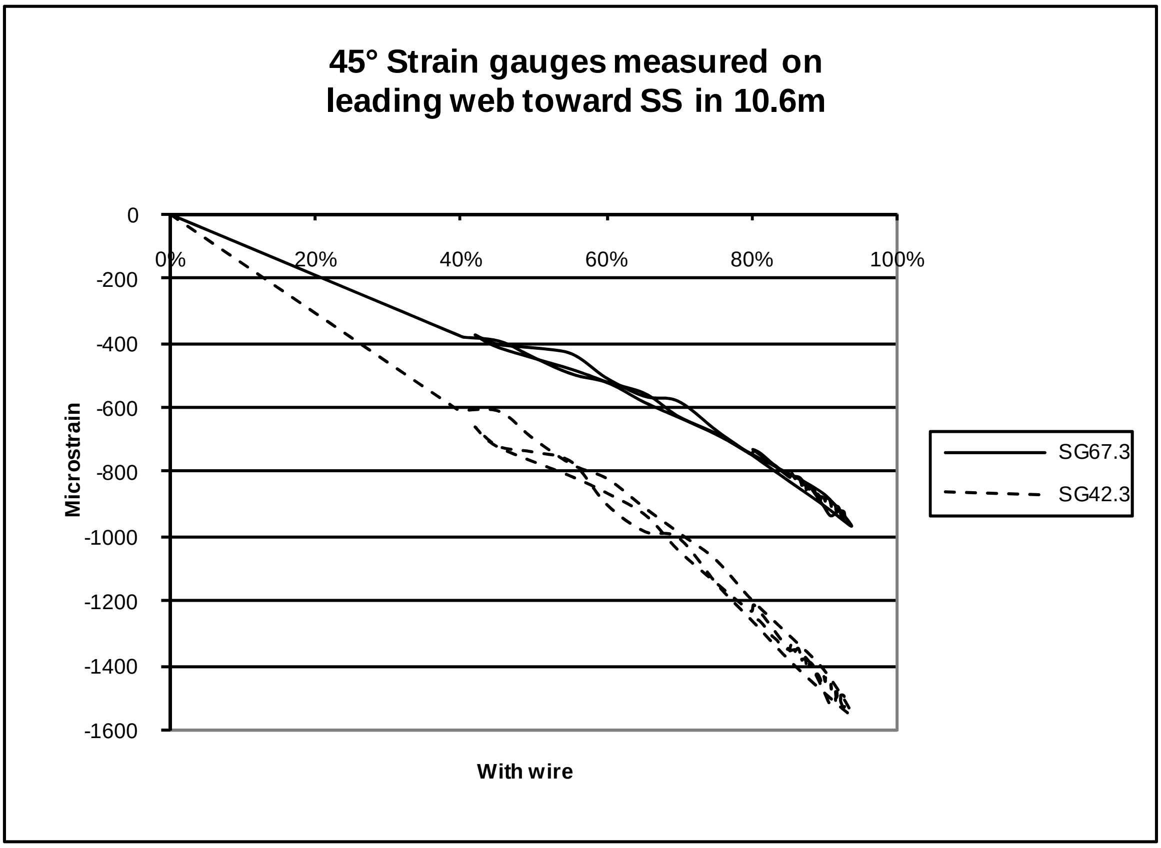

45° Strain gauges measured on compression side in 10,6m
500
0
-500
-1000
-1500
-2000
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG23.3
SG24.3


45° Strain gauges measured on compression side in 11,5m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG25.3
SG26.3

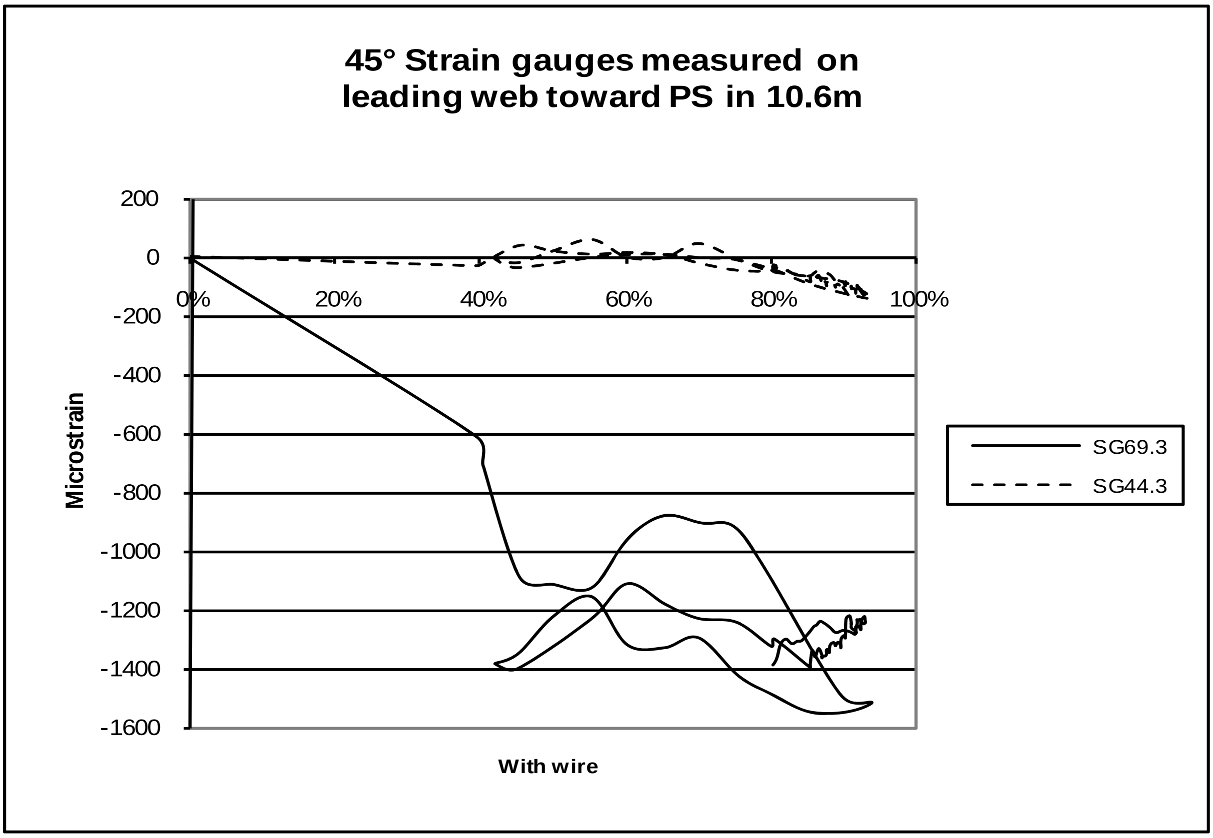




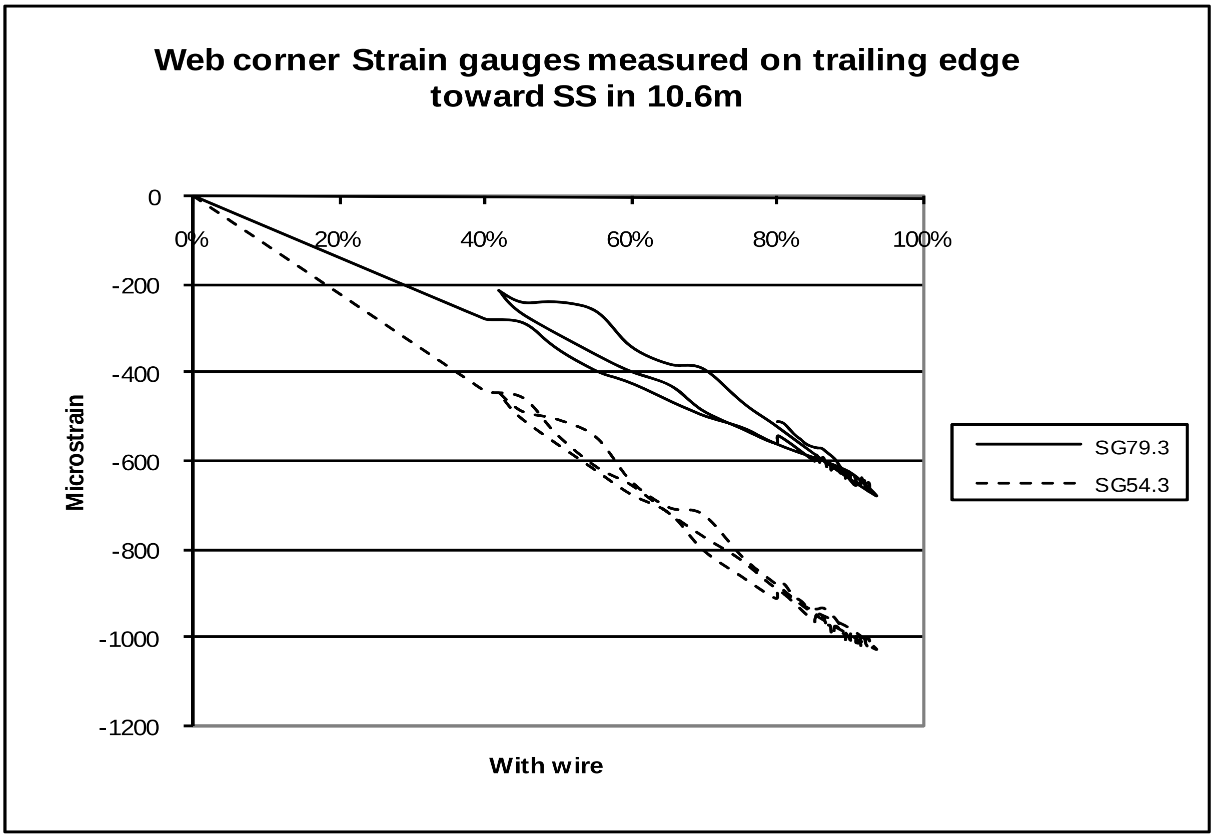
www.risoe.dtu.dk

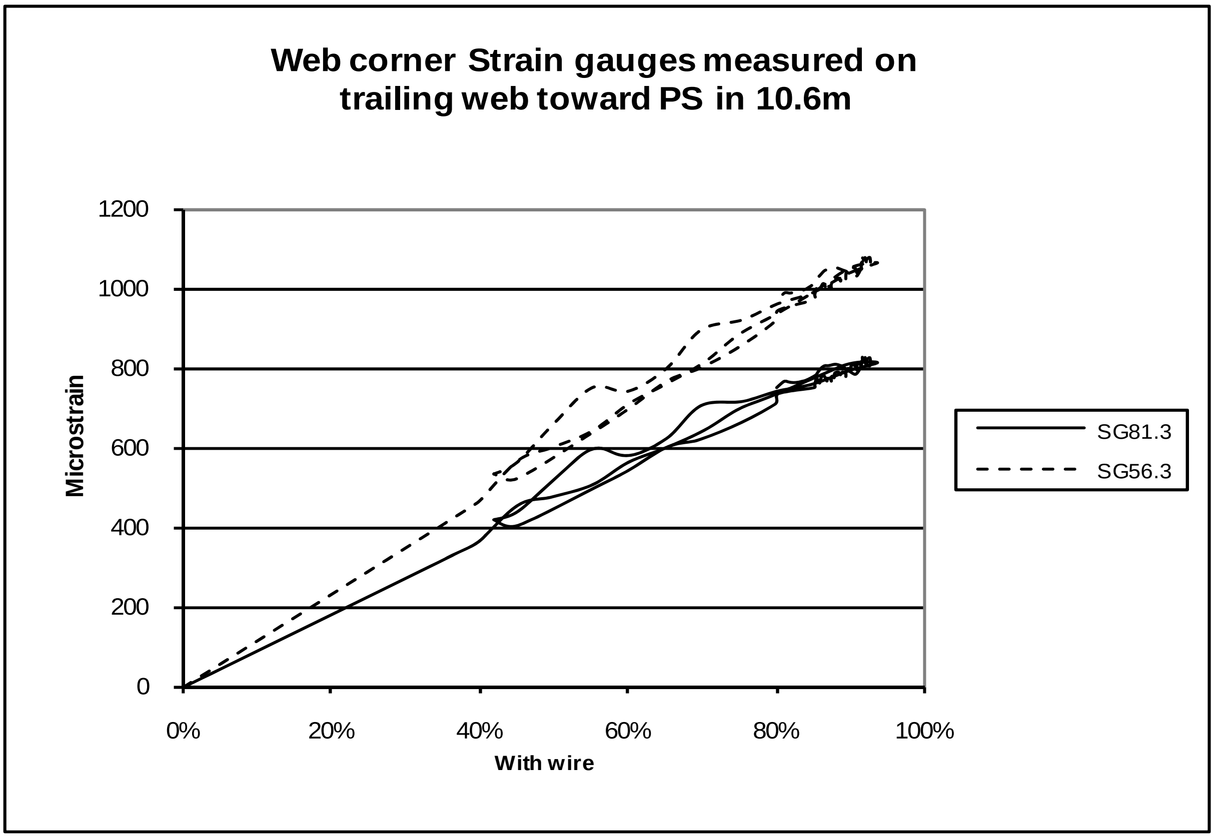


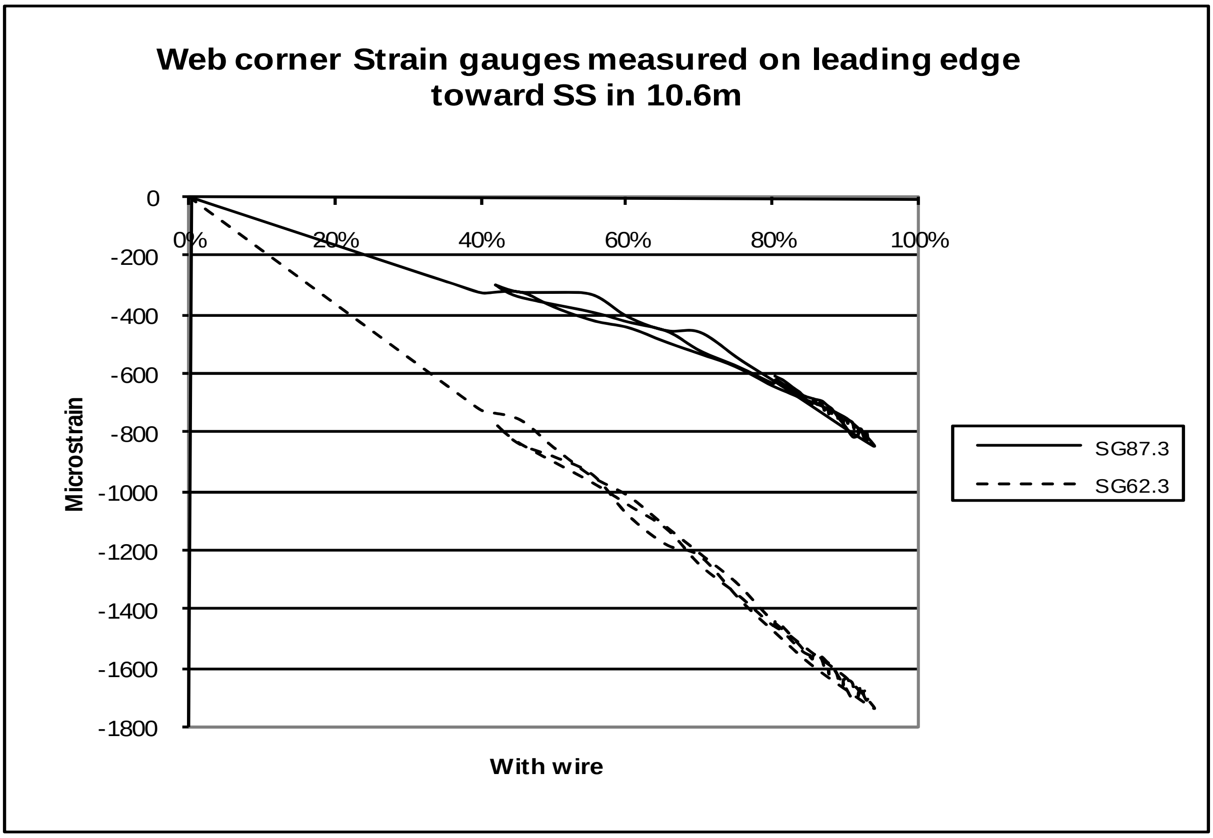
45° Strain gauges measured on leading web toward SS in 10.6m
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG67.3
SG42.3

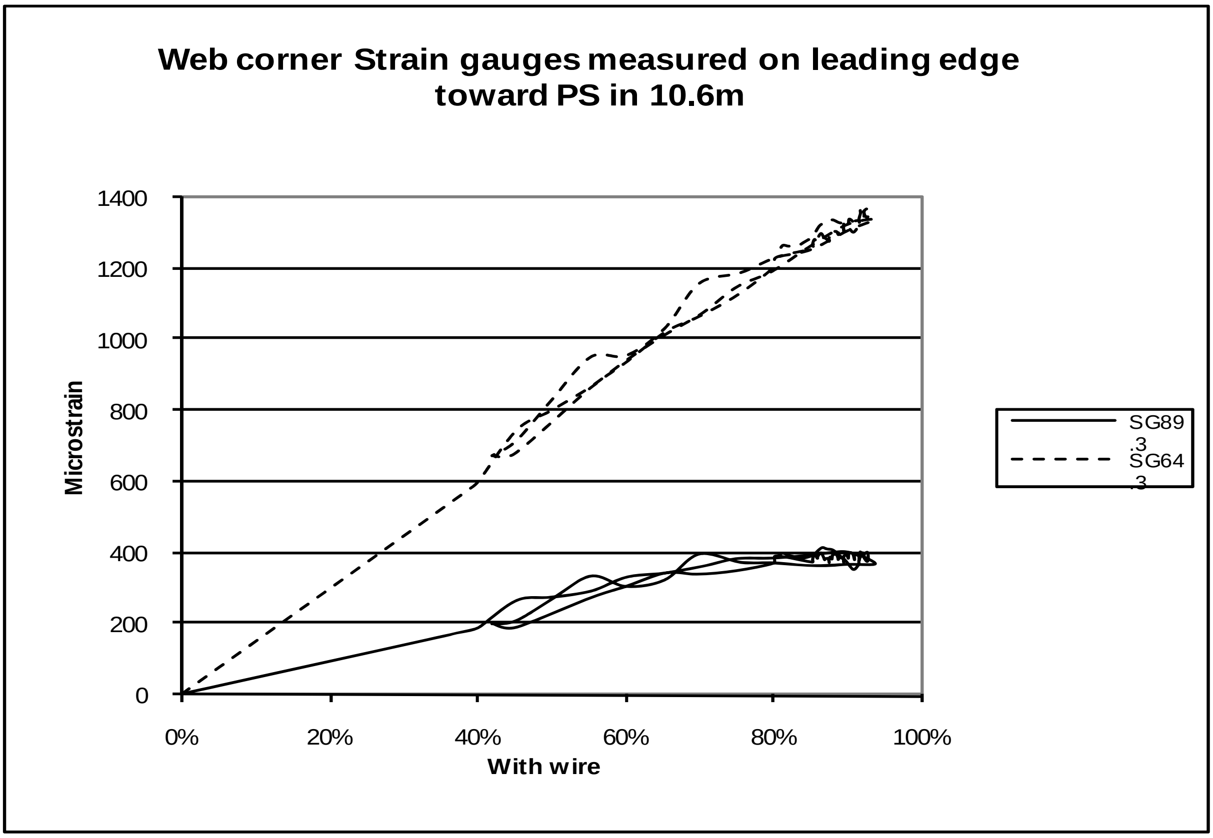


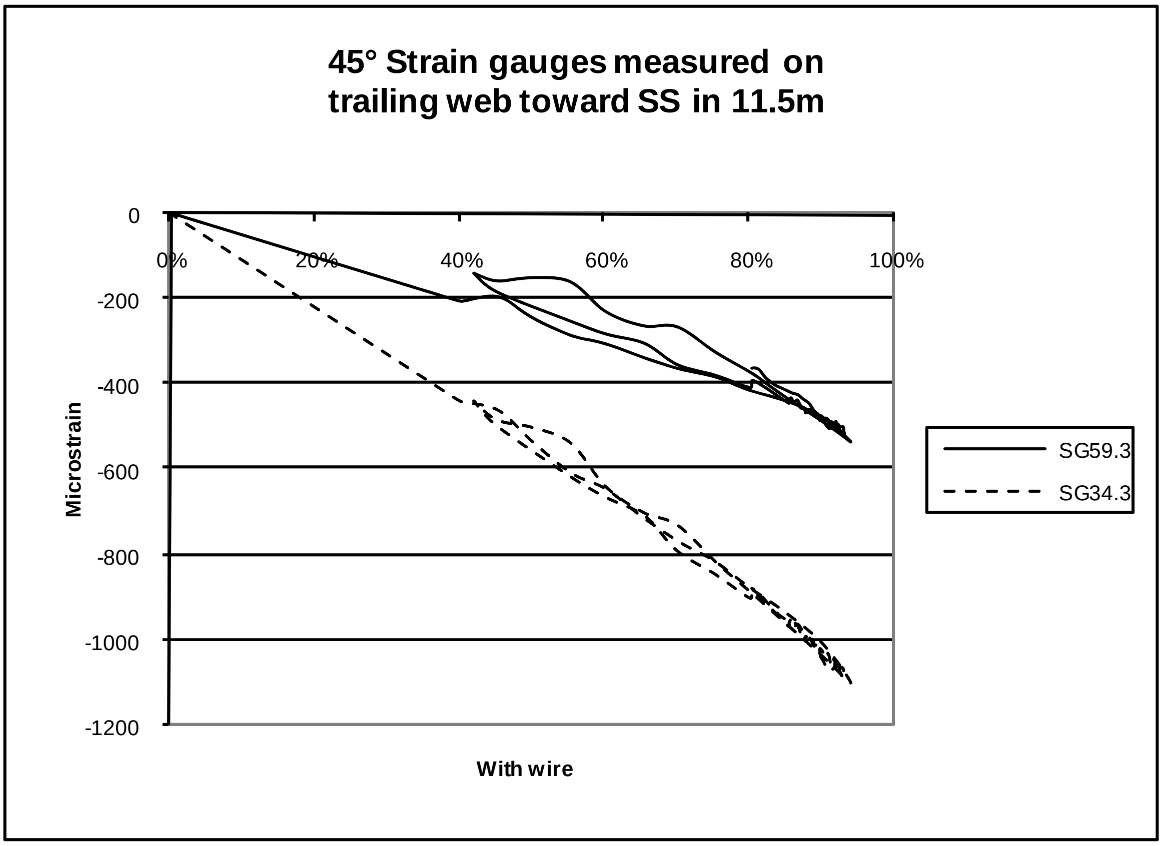
45° Strain gauges measured on leading web toward PS in 10.6m
200
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG69.3
SG44.3


Web corner Strain gauges measured on trailing edge
toward SS in 10.6m
0
-200
-400
-600
-800
-1000
-1200
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG79.3
SG54.3

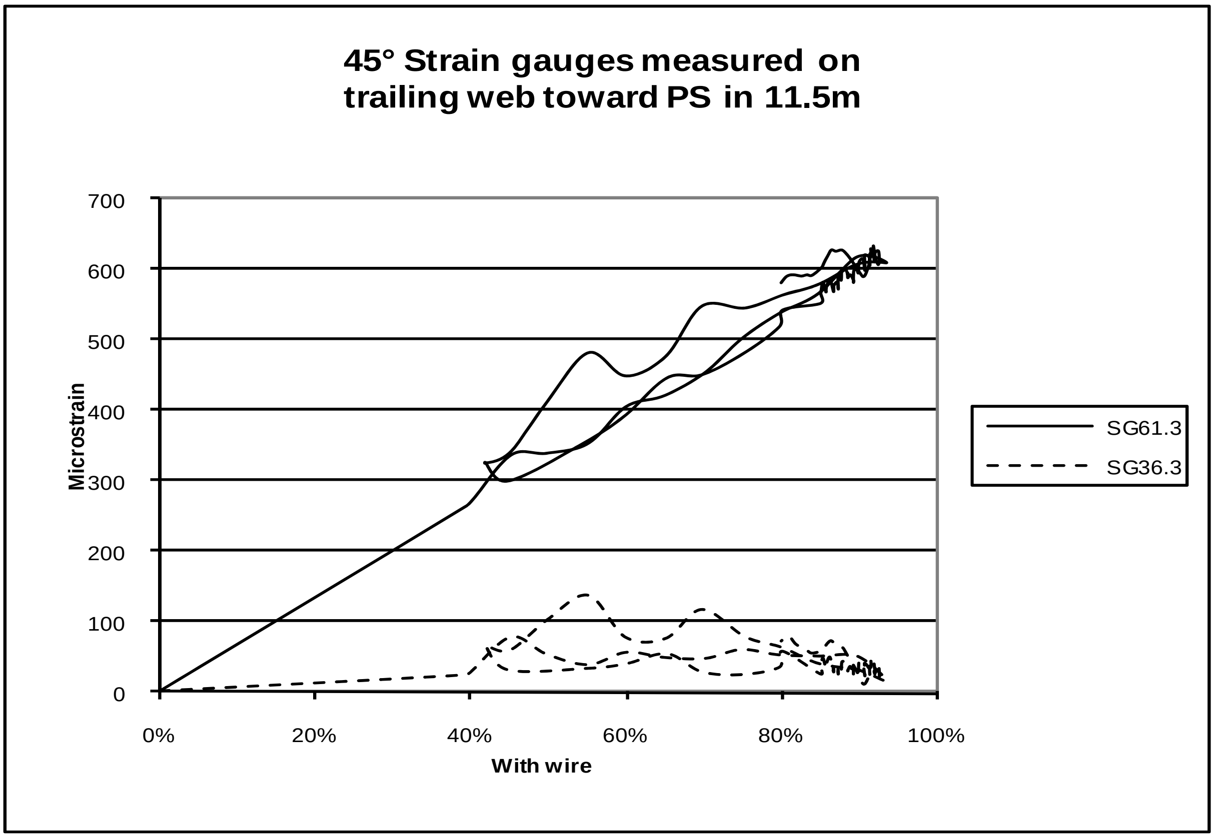

Web corner Strain gauges measured on
trailing web toward PS in 10.6m
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG81.3
SG56.3


Web corner Strain gauges measured on leading edge toward SS in 10.6m
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG87.3
SG62.3

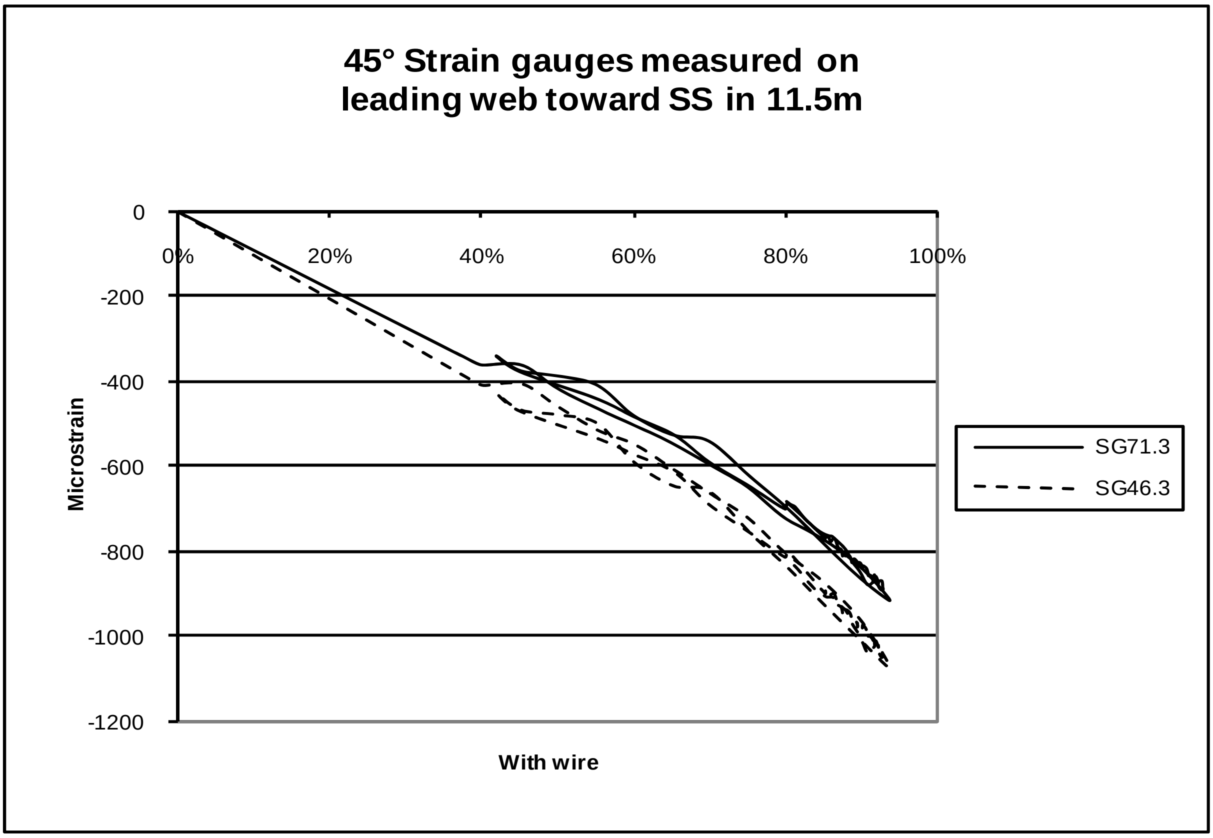

Web corner Strain gauges measured on leading edge toward PS in 10.6m
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG89.3
SG64.3

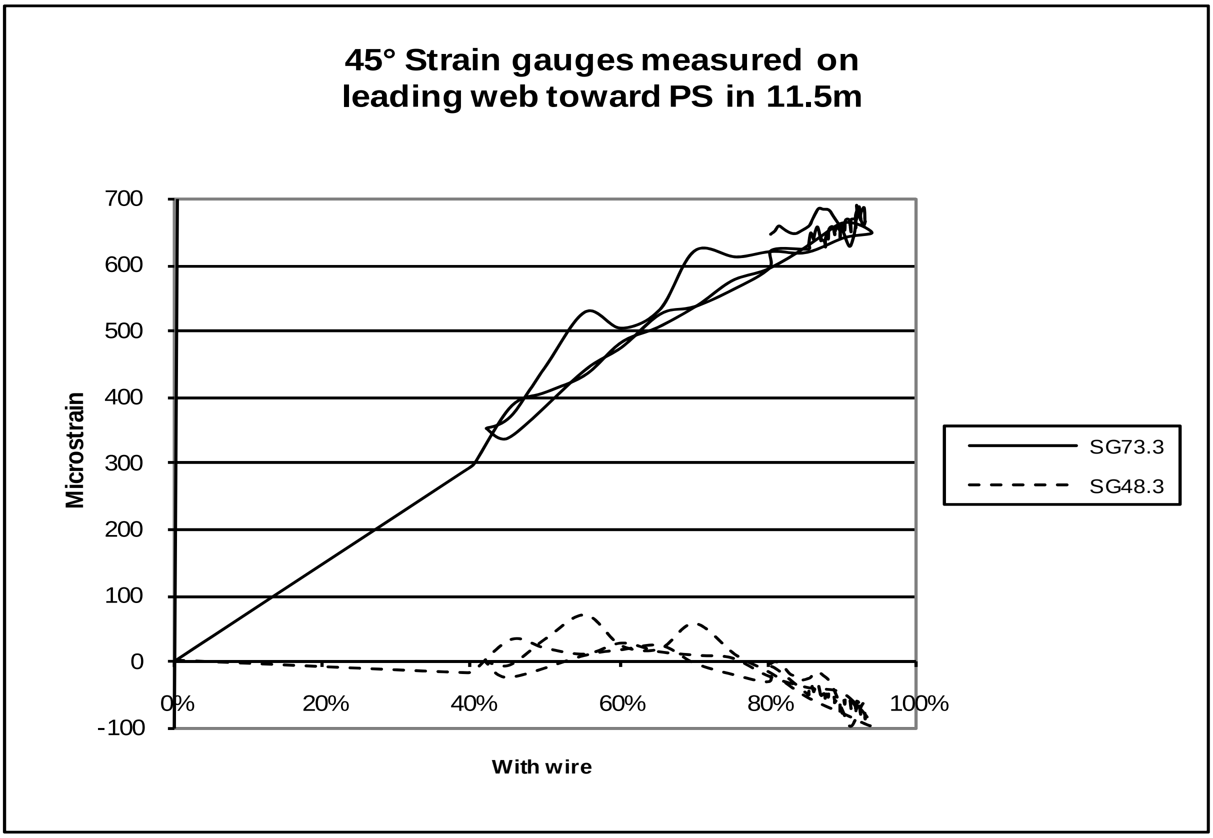


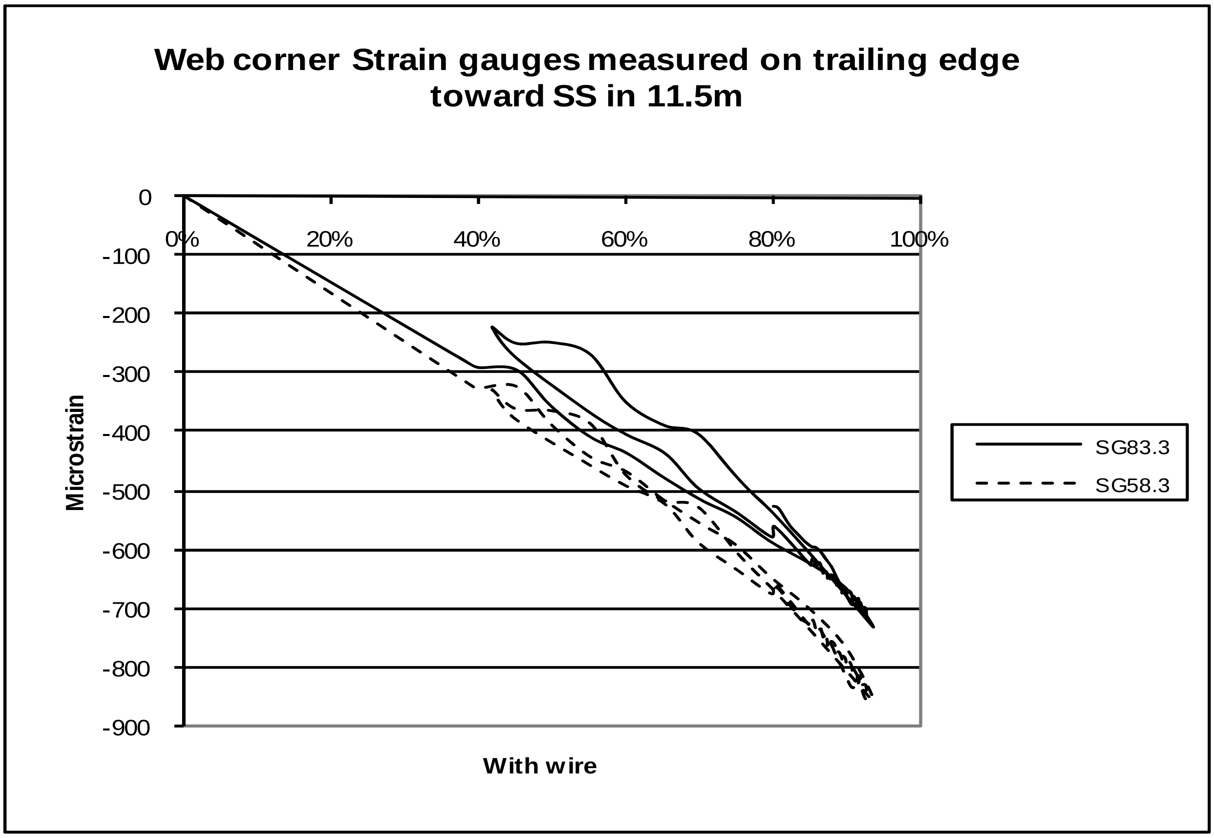
45° Strain gauges measured on trailing web toward SS in 11.5m
0
-200
-400
-600
-800
-1000
-1200
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG59.3
SG34.3



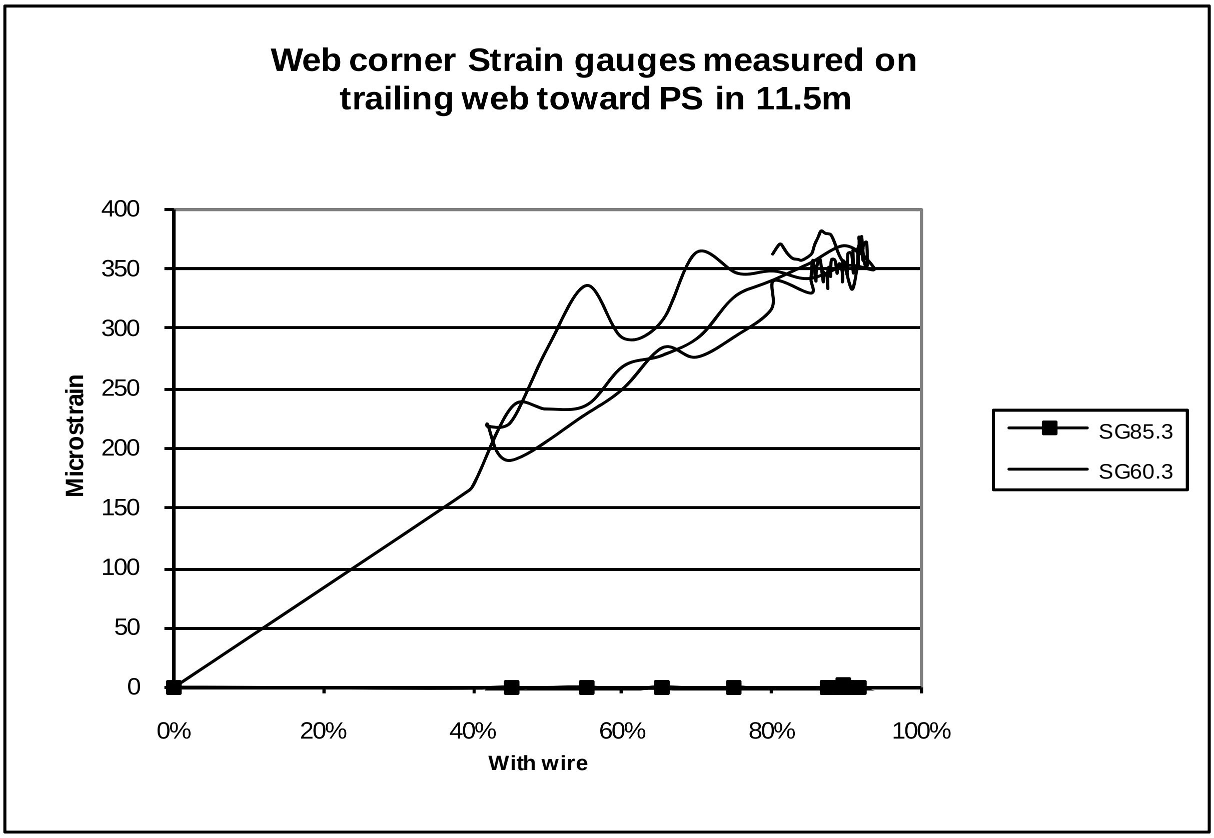
45° Strain gauges measured on trailing web toward PS in 11.5m
700
600
500
400
300
200
100
0
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG61.3
SG36.3


45° Strain gauges measured on leading web toward SS in 11.5m
0
-200
-400
-600
-800
-1000
-1200
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG71.3
SG46.3

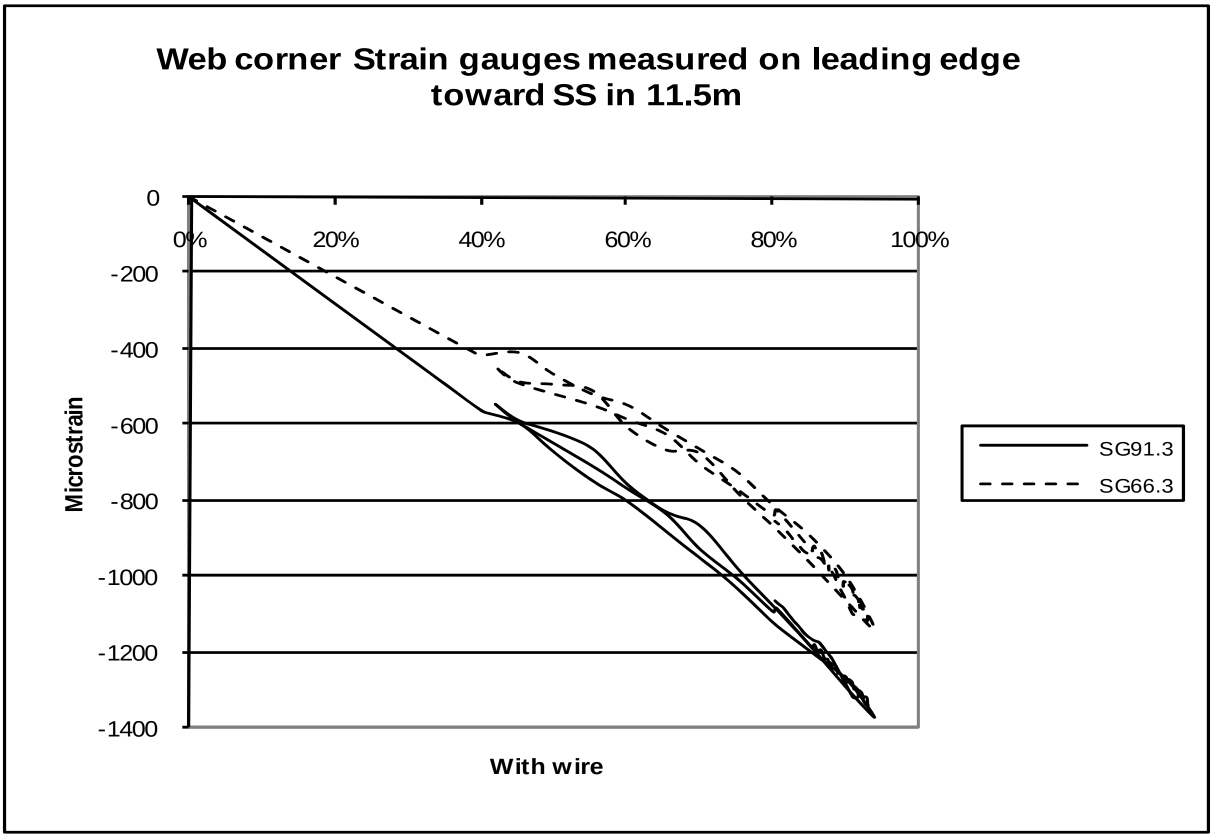

45° Strain gauges measured on leading web toward PS in 11.5m
700
600
500
400
300
200
100
0
-100
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG73.3
SG48.3



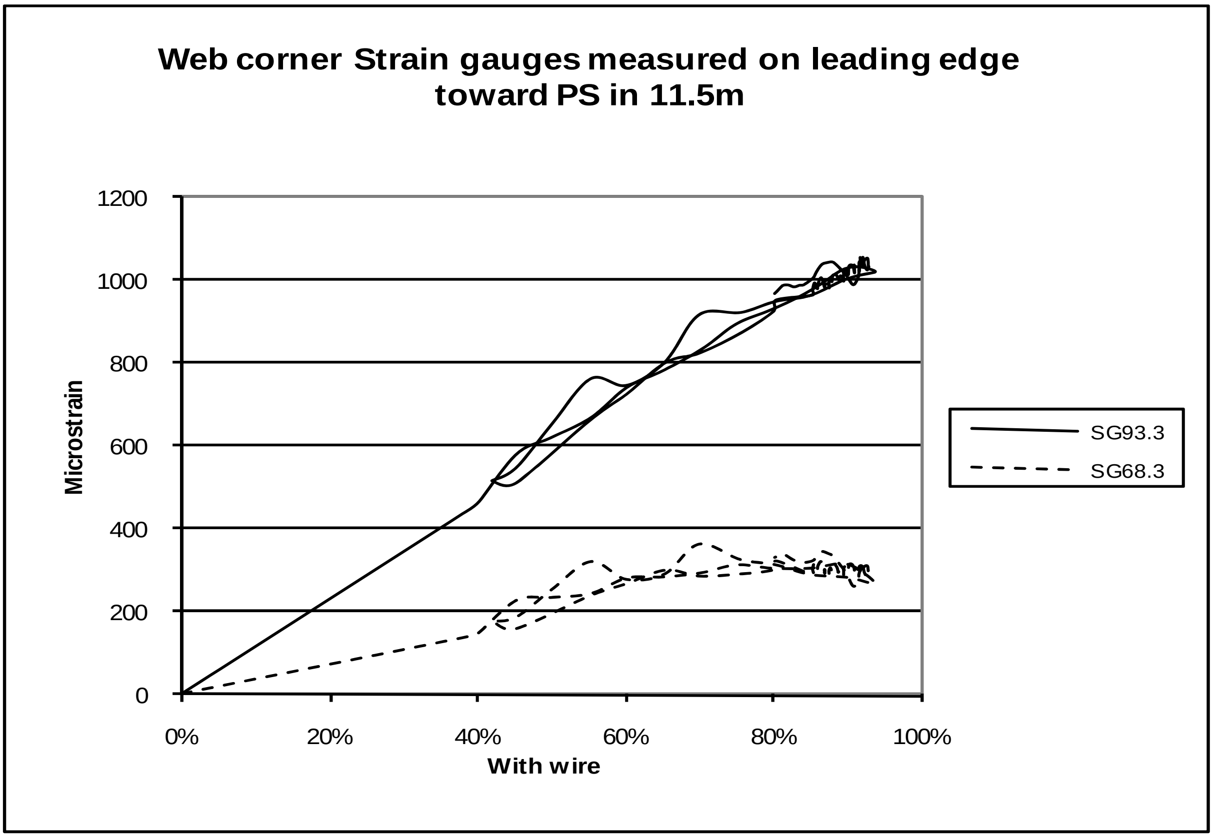
Web corner Strain gauges measured on trailing edge toward SS in 11.5m
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG83.3
SG58.3



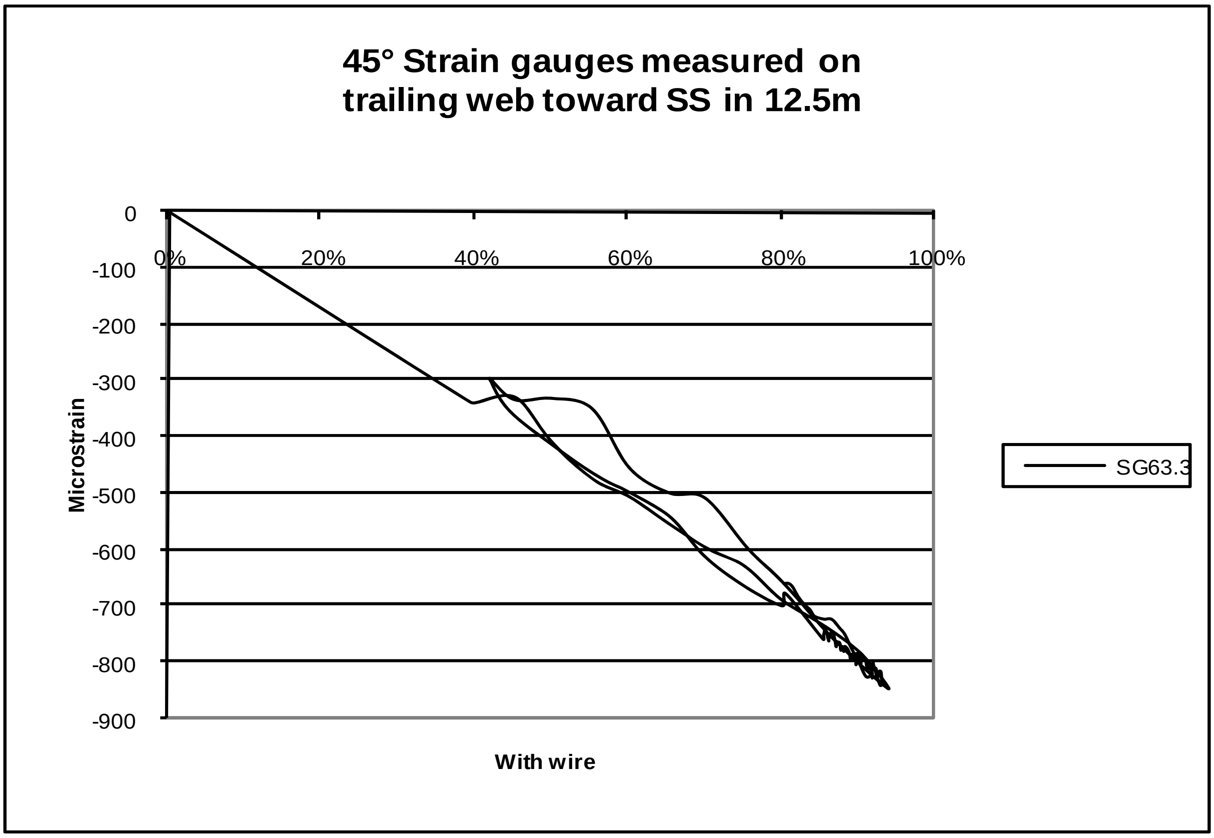
Web corner Strain gauges measured on trailing web toward PS in 11.5m
400
350
300
250
200
150
100
50
0
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG85.3
SG60.3

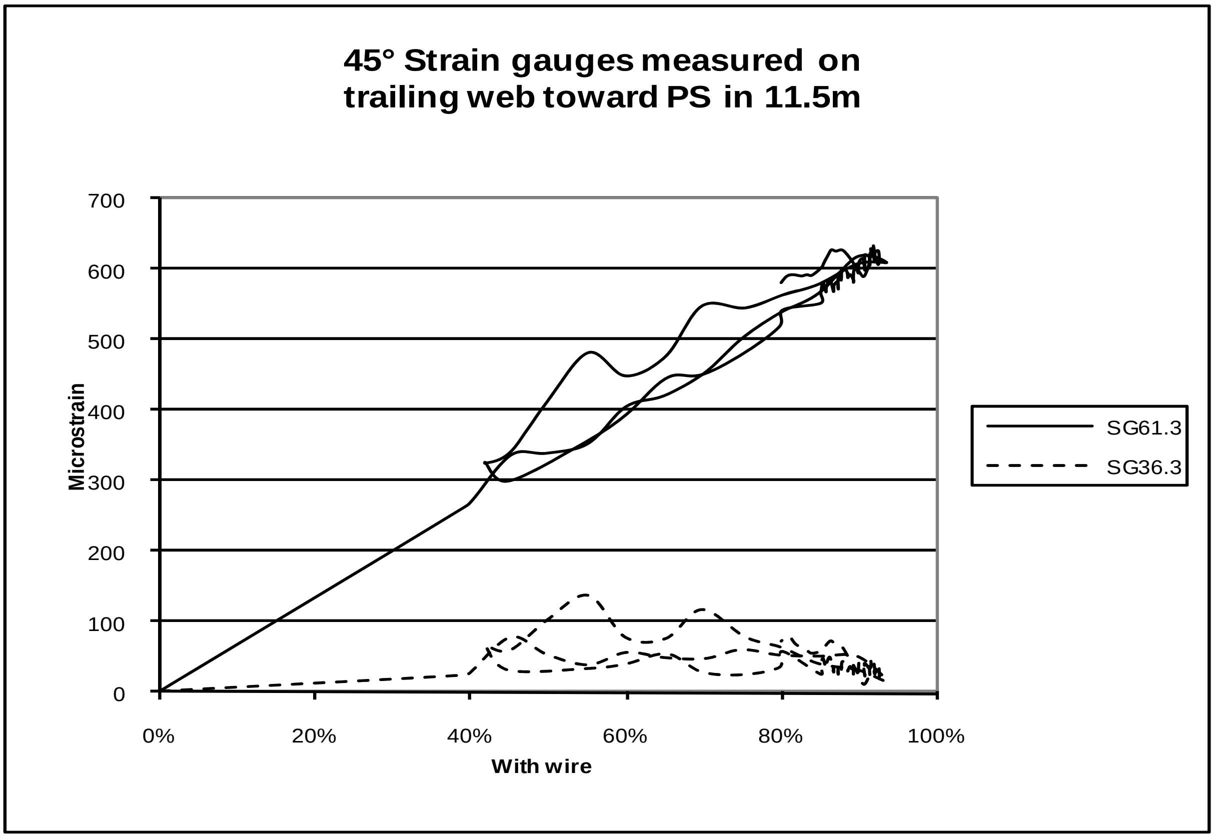


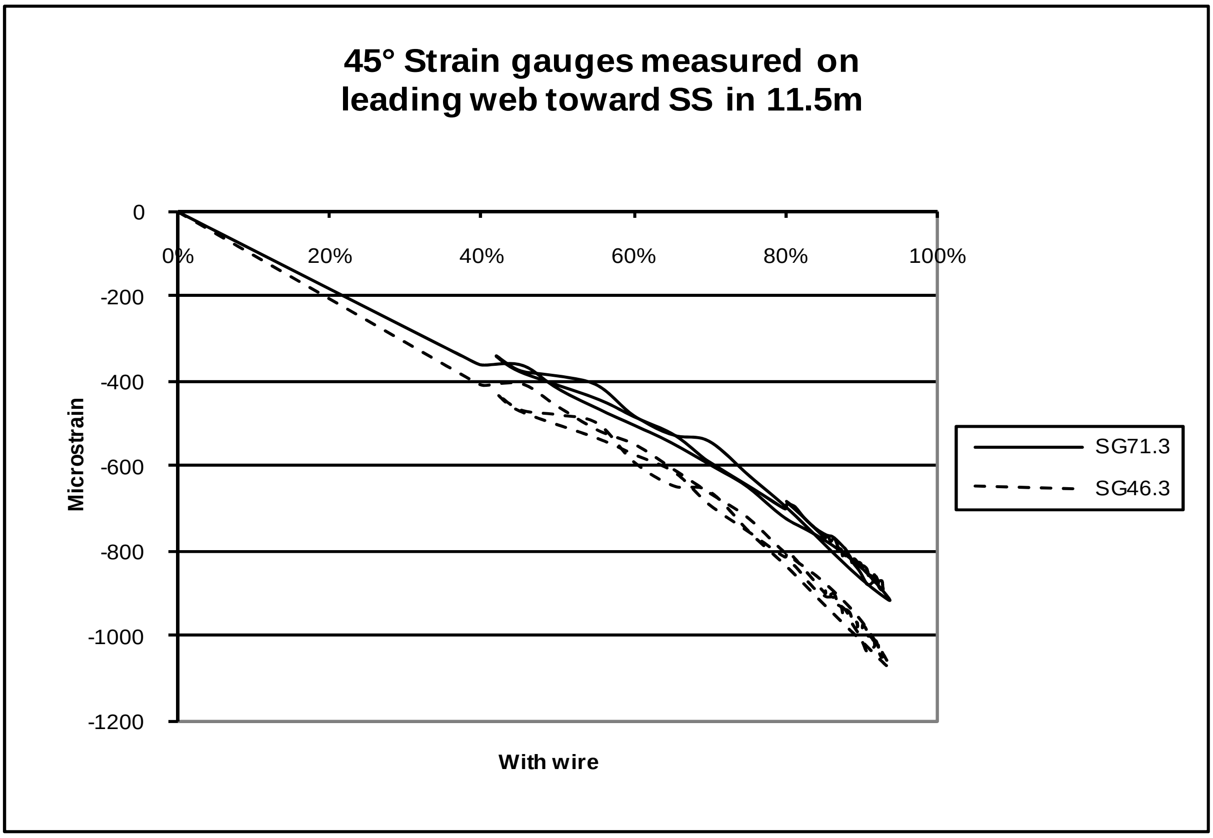
Web corner Strain gauges measured on leading edge toward SS in 11.5m
0
-200
-400
-600
-800
-1000
-1200
-1400
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG91.3
SG66.3

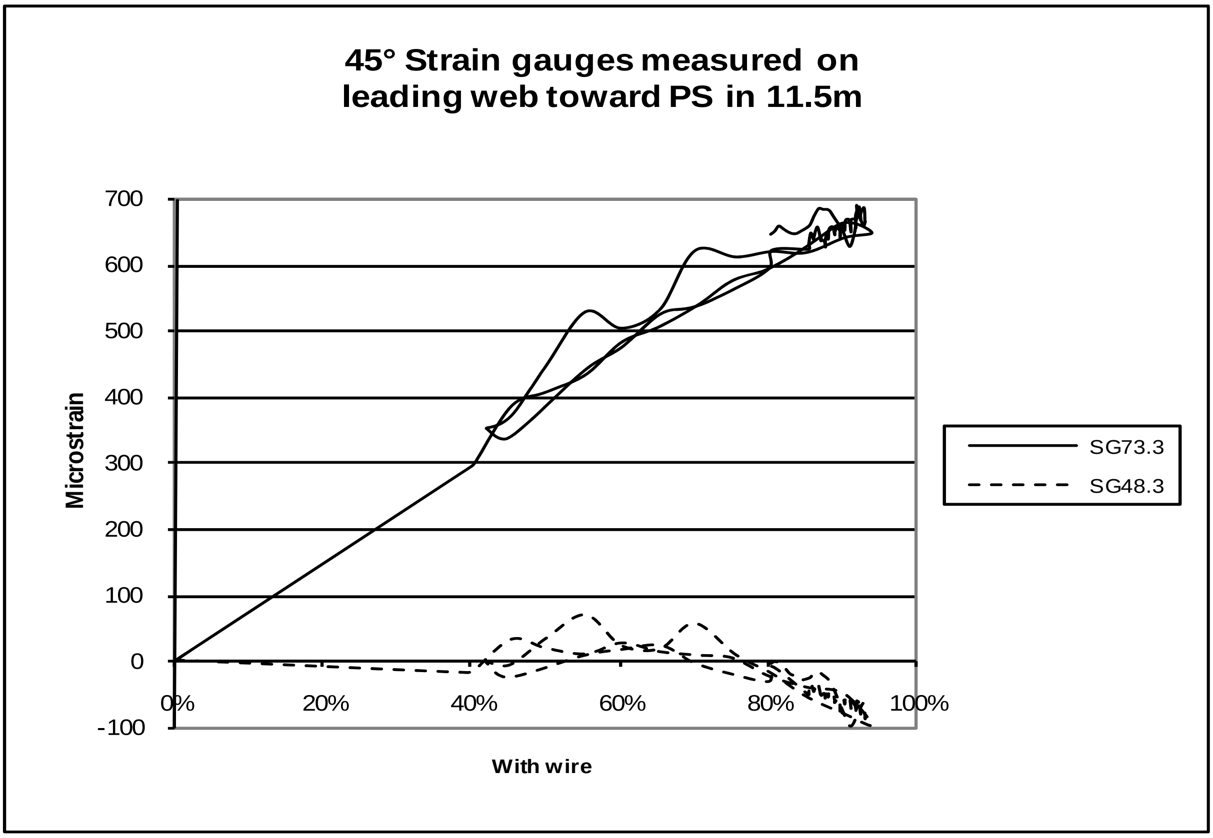


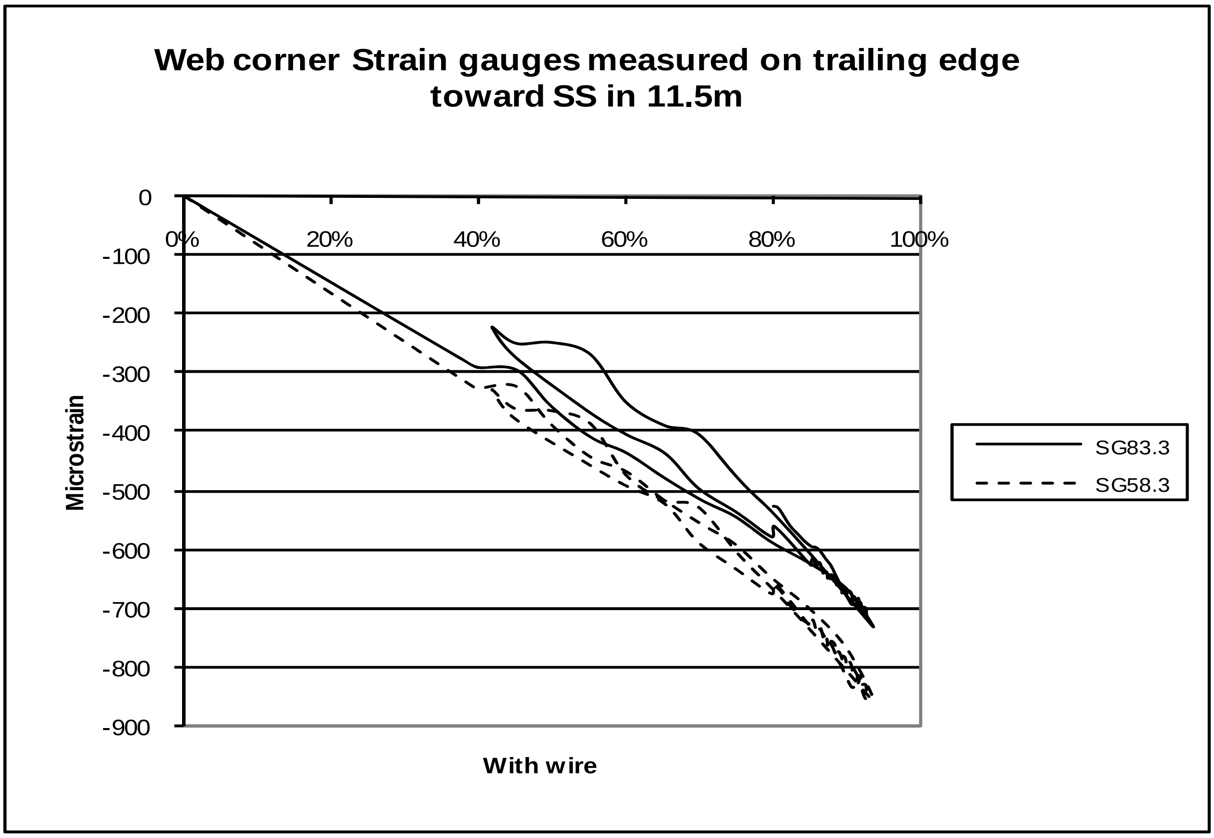
Web corner Strain gauges measured on leading edge toward PS in 11.5m
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG93.3
SG68.3


45° Strain gauges measured on trailing web toward SS in 12.5m
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG63.3

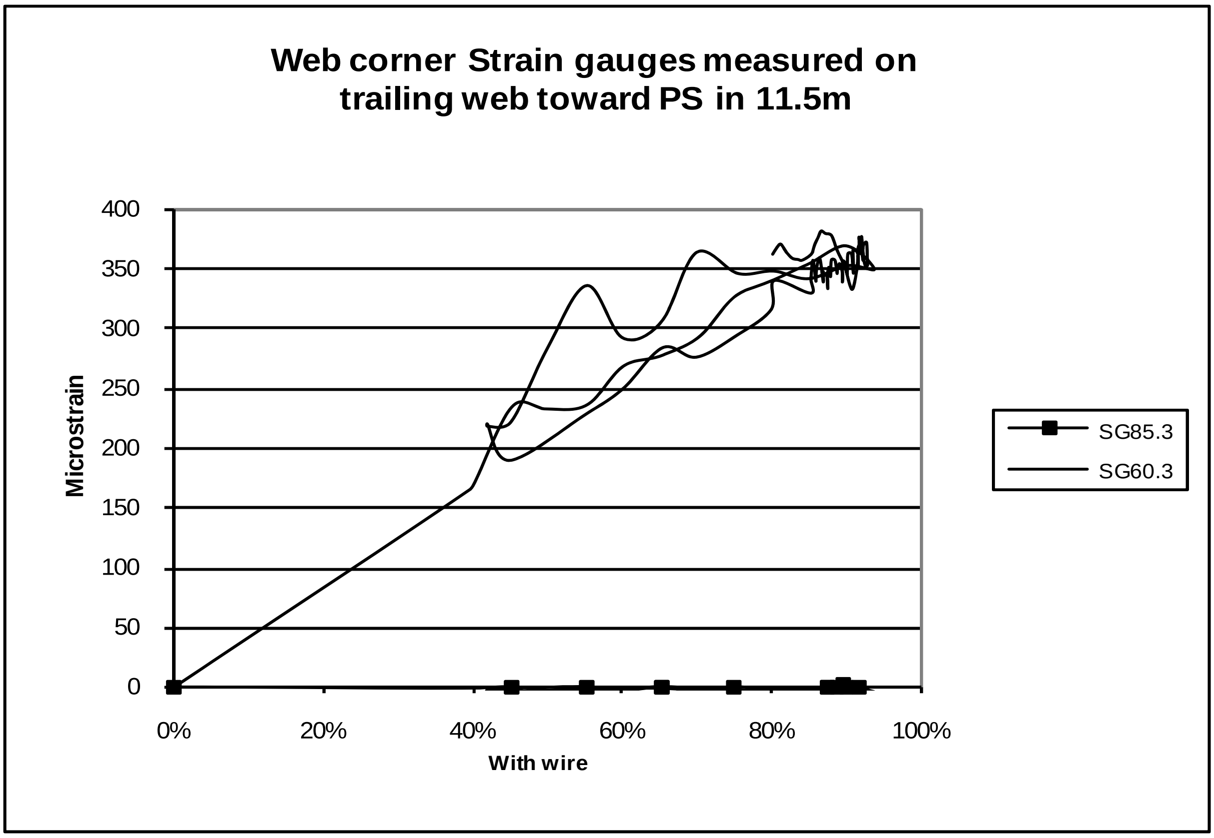

45° Strain gauges measured on trailing web toward PS in 11.5m
700
600
500
400
300
200
100
0
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG61.3
SG36.3


45° Strain gauges measured on
leading web toward SS in 11.5m
0
-200
-400
-600
-800
-1000
-1200
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG71.3
SG46.3

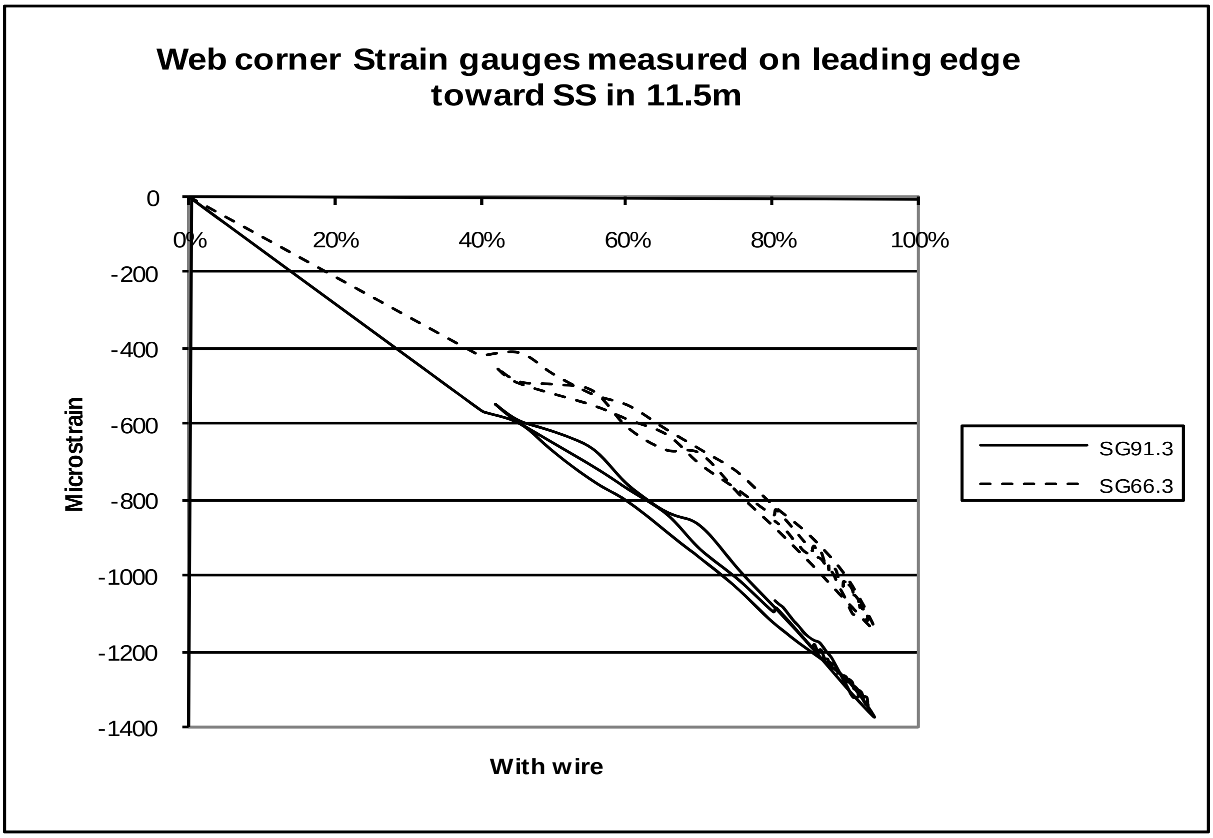

45° Strain gauges measured on
leading web toward PS in 11.5m
700
600
500
400
300
200
100
0
-100
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG73.3
SG48.3



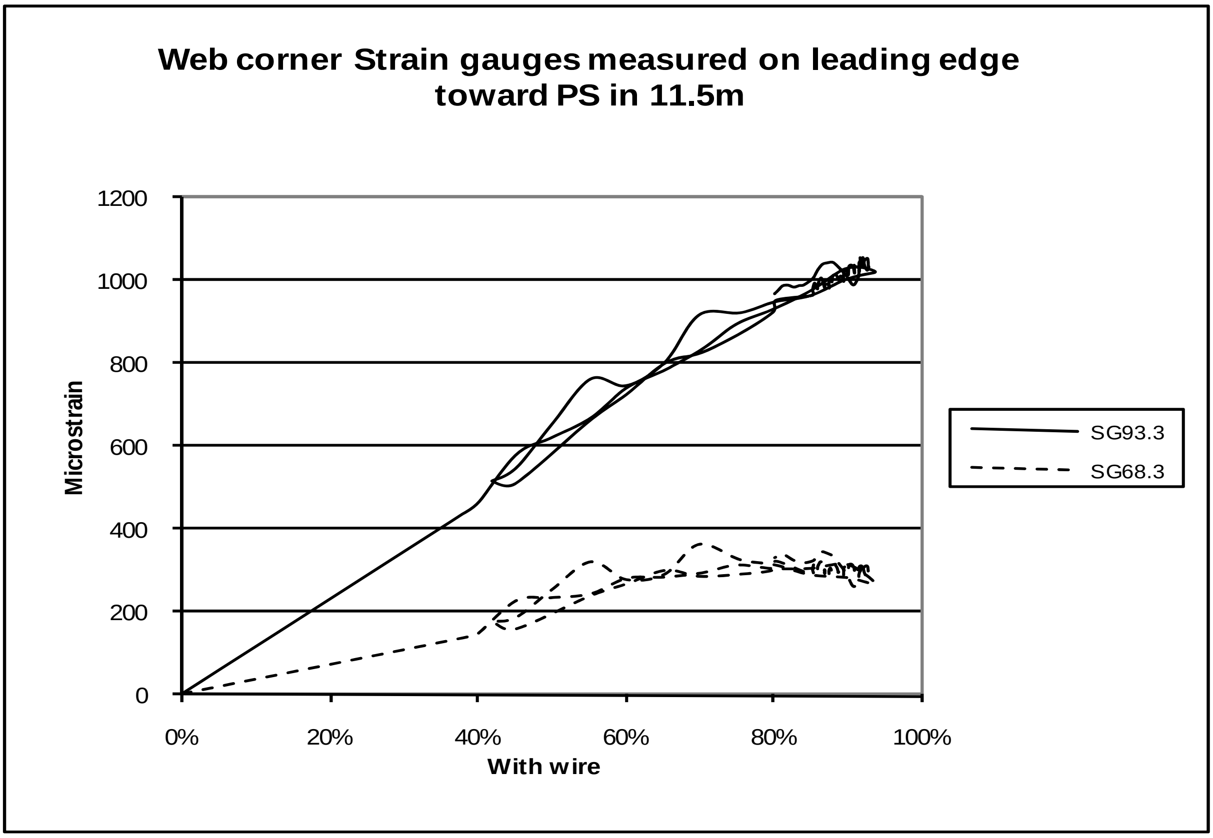
Web corner Strain gauges measured on trailing edge toward SS in 11.5m
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG83.3
SG58.3



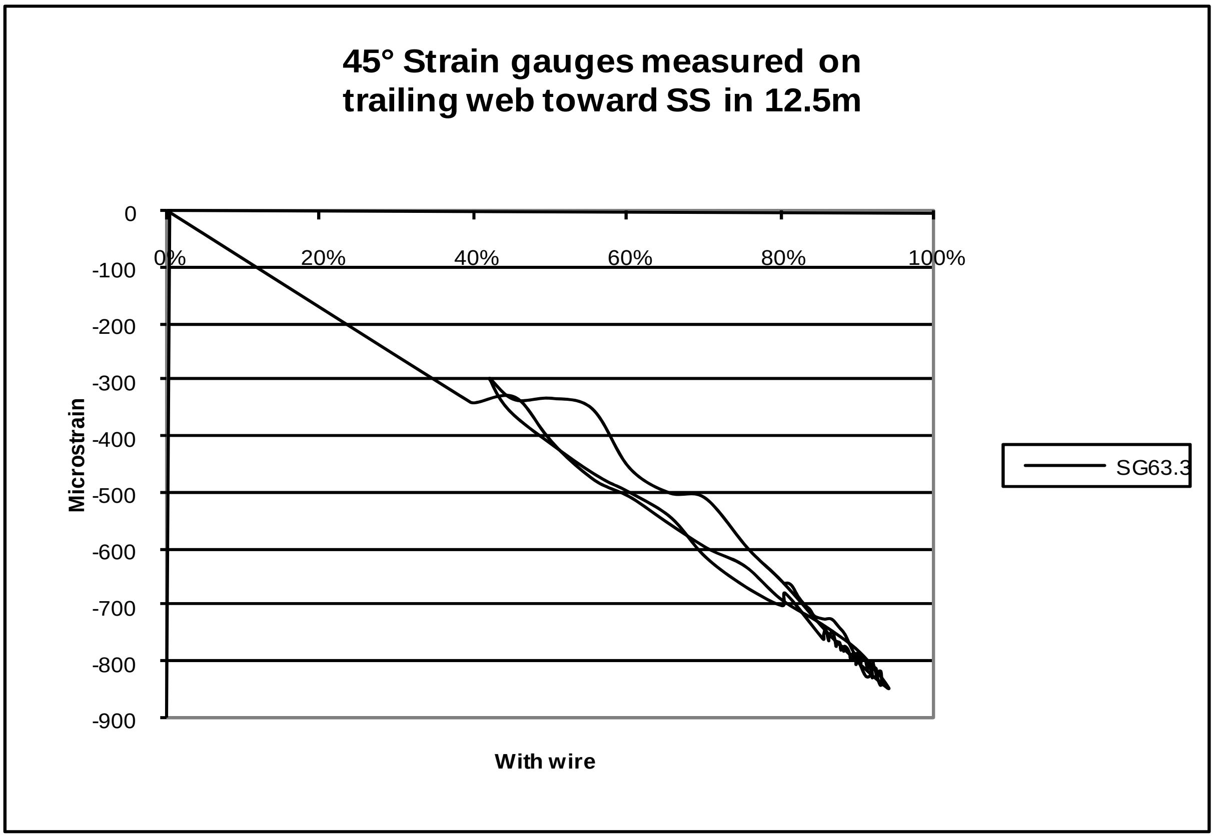
Web corner Strain gauges measured on trailing web toward PS in 11.5m
400
350
300
250
200
150
100
50
0
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG85.3
SG60.3

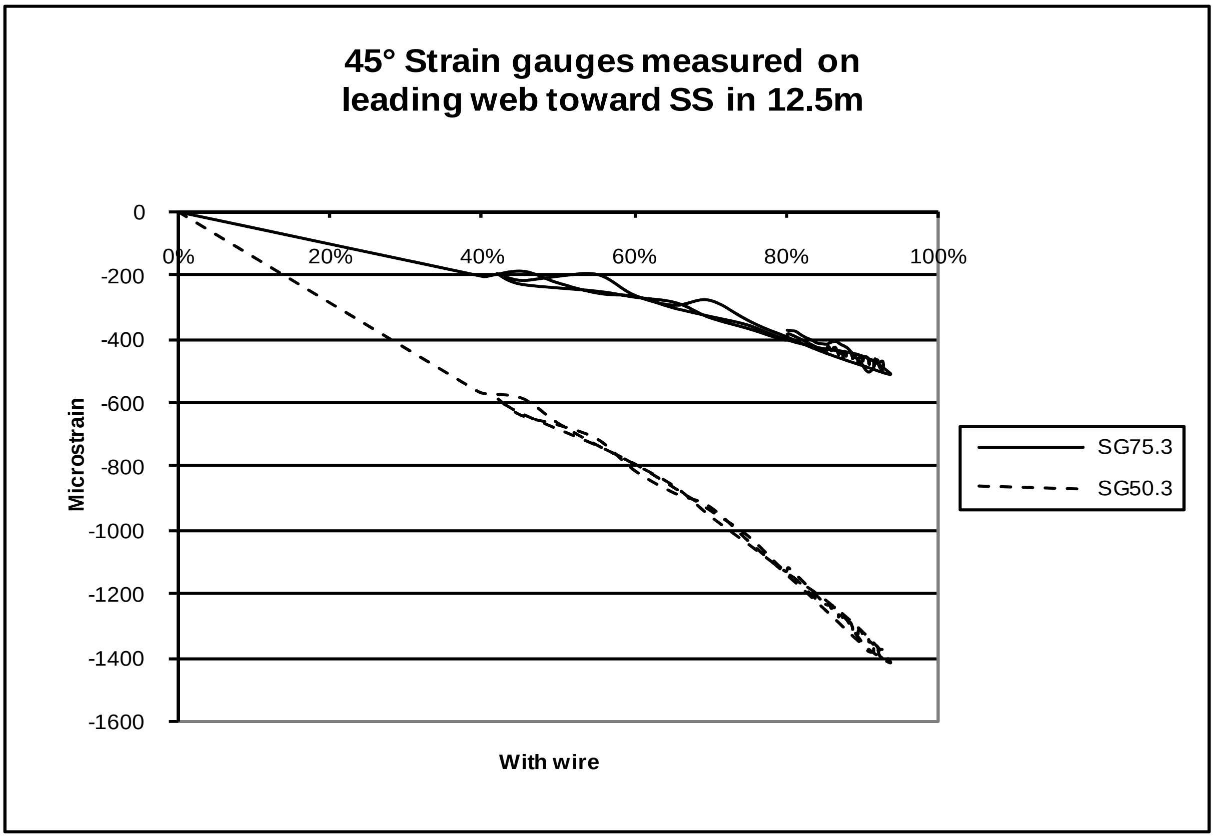


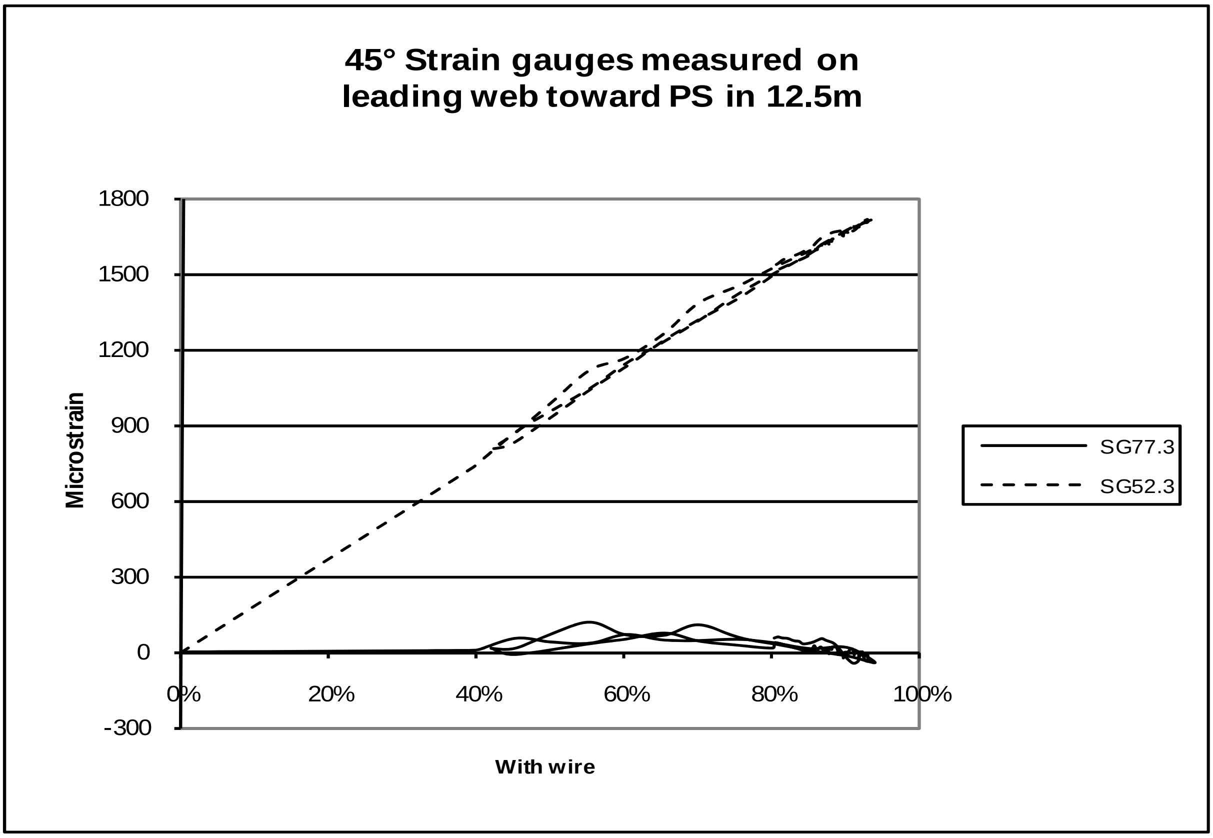
Web corner Strain gauges measured on leading edge toward SS in 11.5m
0
-200
-400
-600
-800
-1000
-1200
-1400
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG91.3
SG66.3



Web corner Strain gauges measured on leading edge toward PS in 11.5m
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG93.3
SG68.3

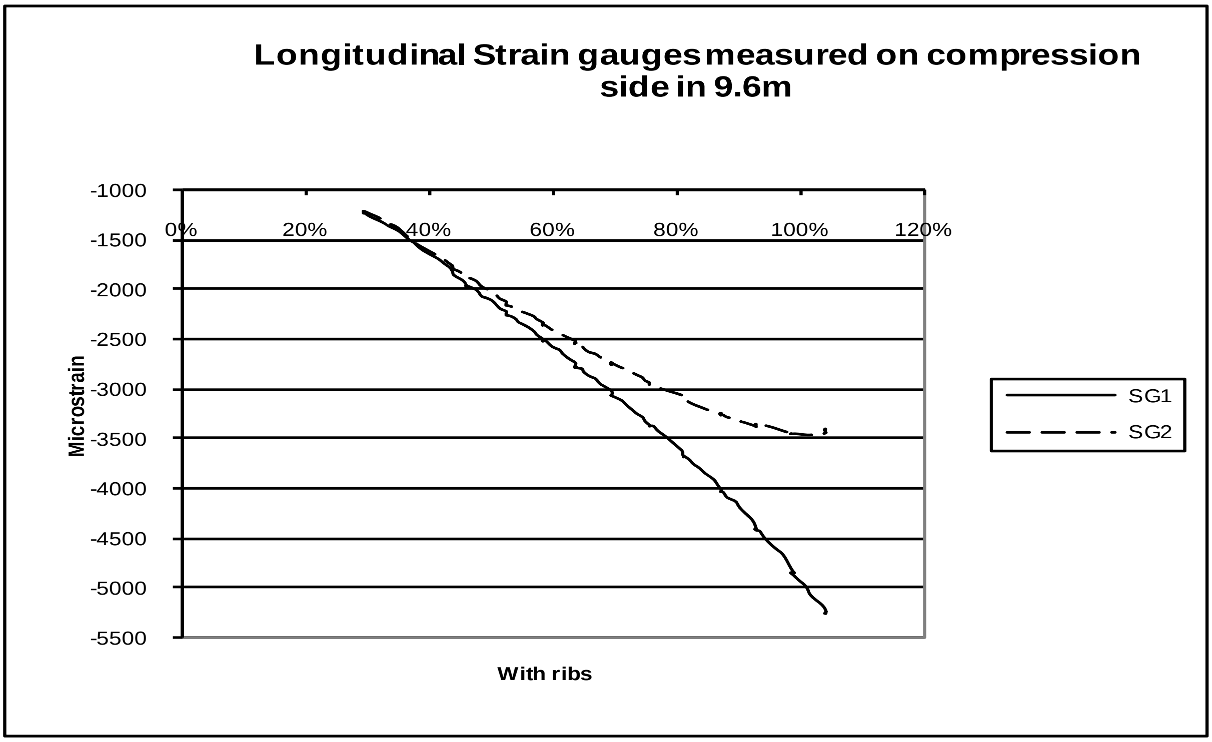

45° Strain gauges measured on trailing web toward SS in 12.5m
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG63.3

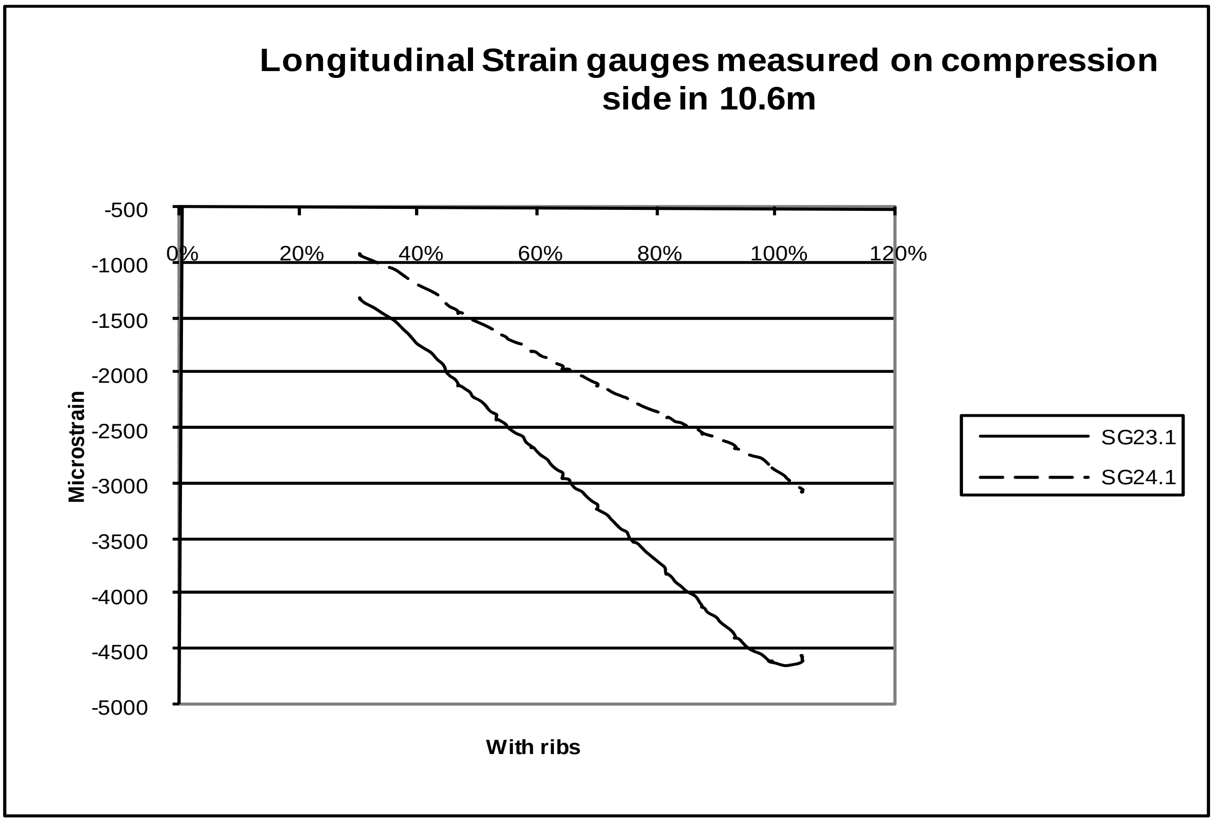

45° Strain gauges measured on leading web toward SS in 12.5m
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
0%
20%
40%
60%
80%
100%
Microstrain
With wire
SG75.3
SG50.3

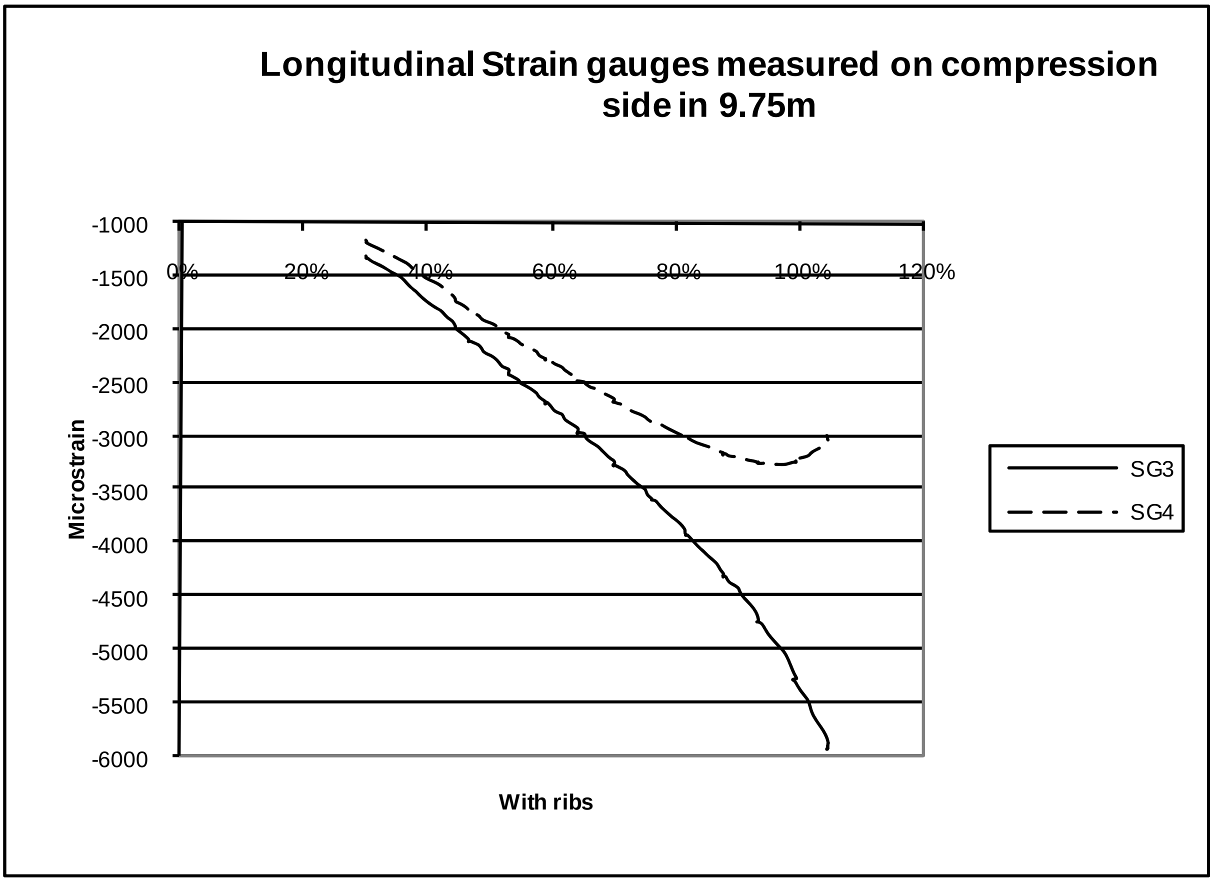

45° Strain gauges measured on
leading web toward PS in 12.5m
1800
1500
1200
900
600
300
0
-300
Microstrain
0%
20%
40%
60%
80%
100%
With wire
SG77.3
SG52.3

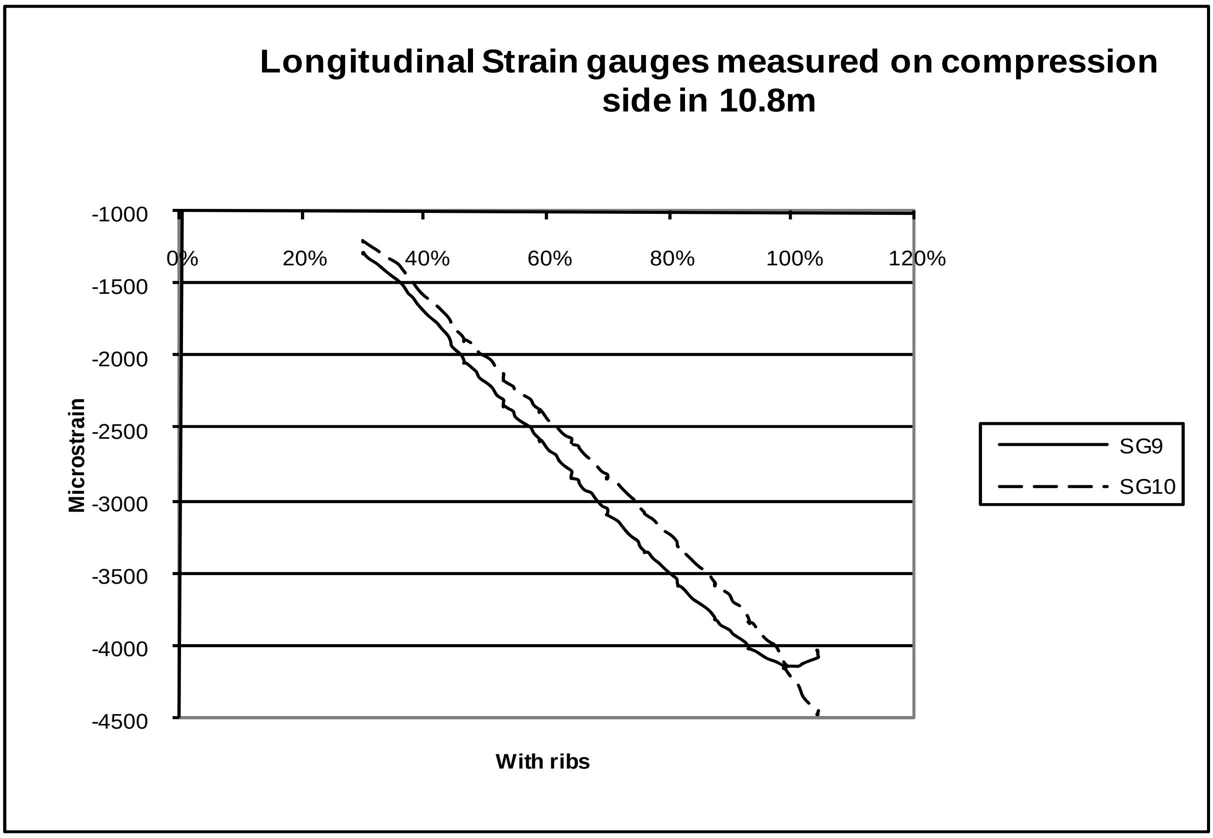
Appendix F: Measured strain gauge results flapwise bending with rib reinforcement

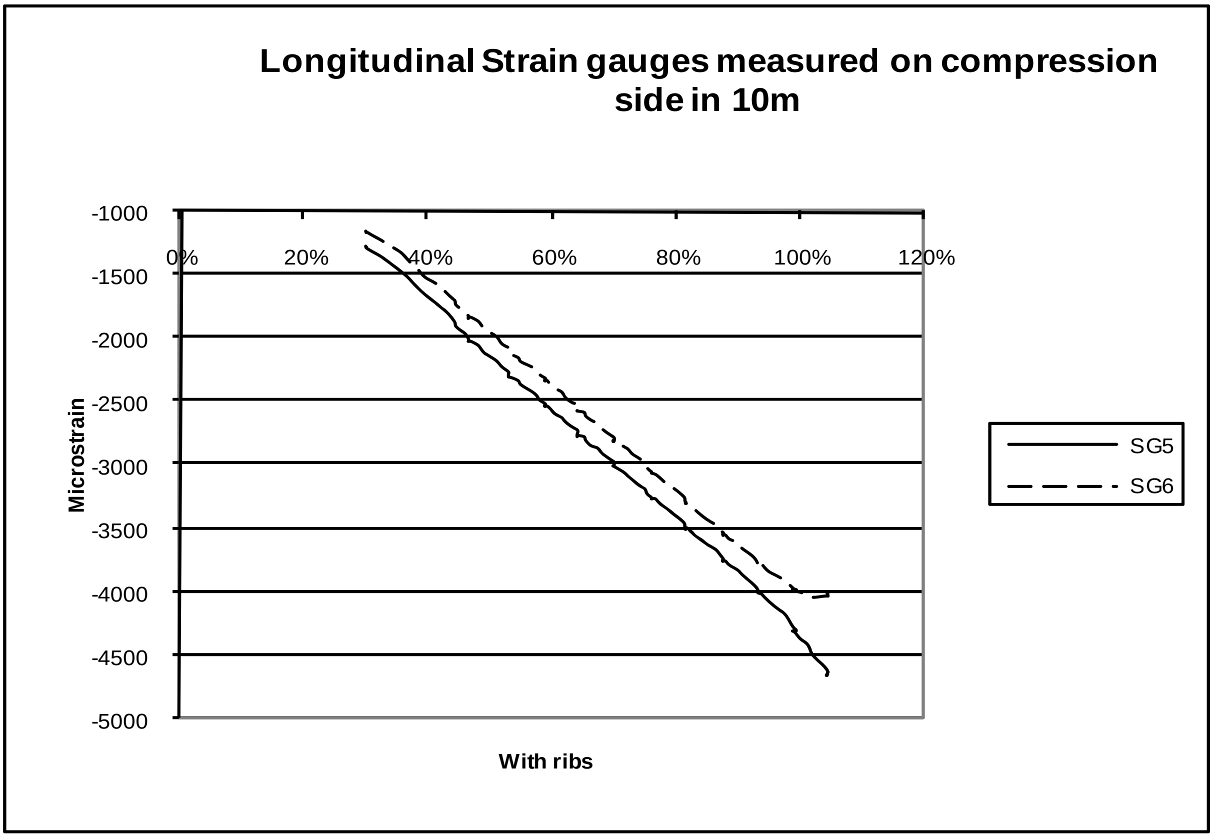
Graphs of Longitudinal measurements with ribs

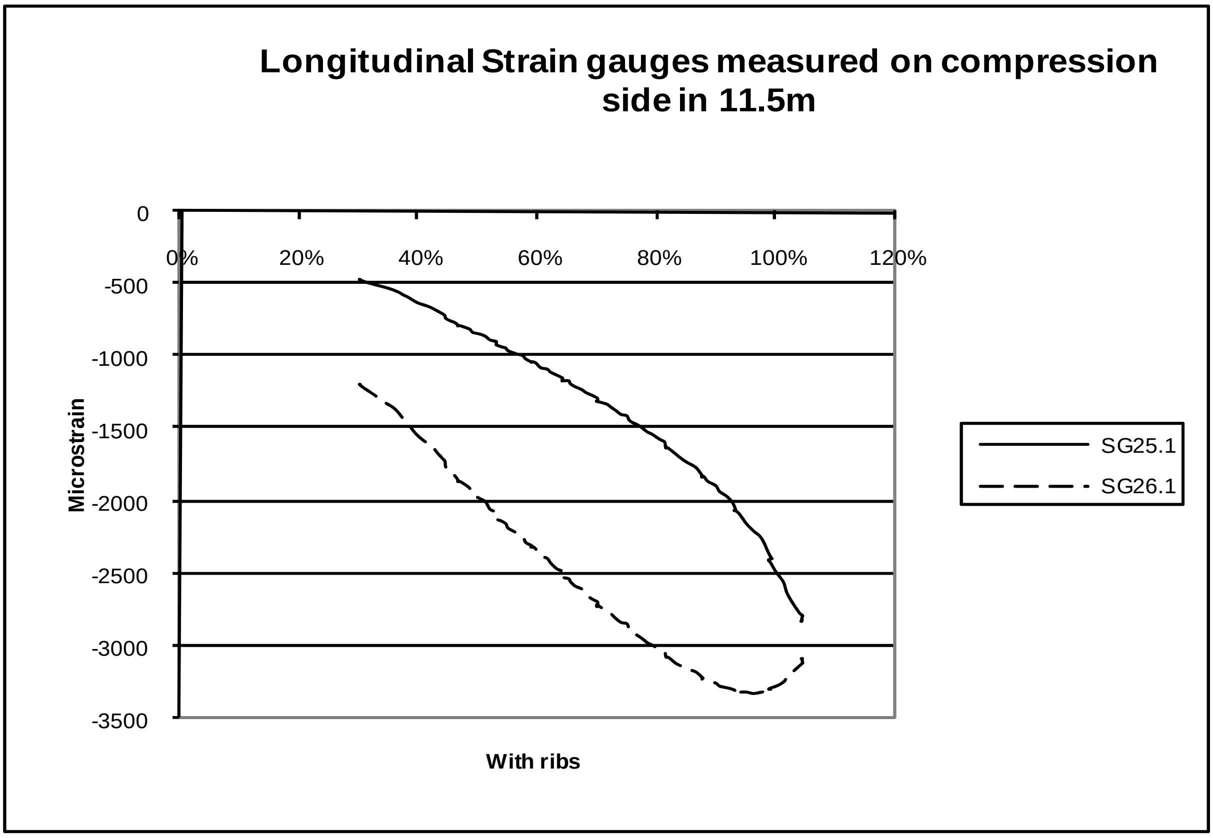


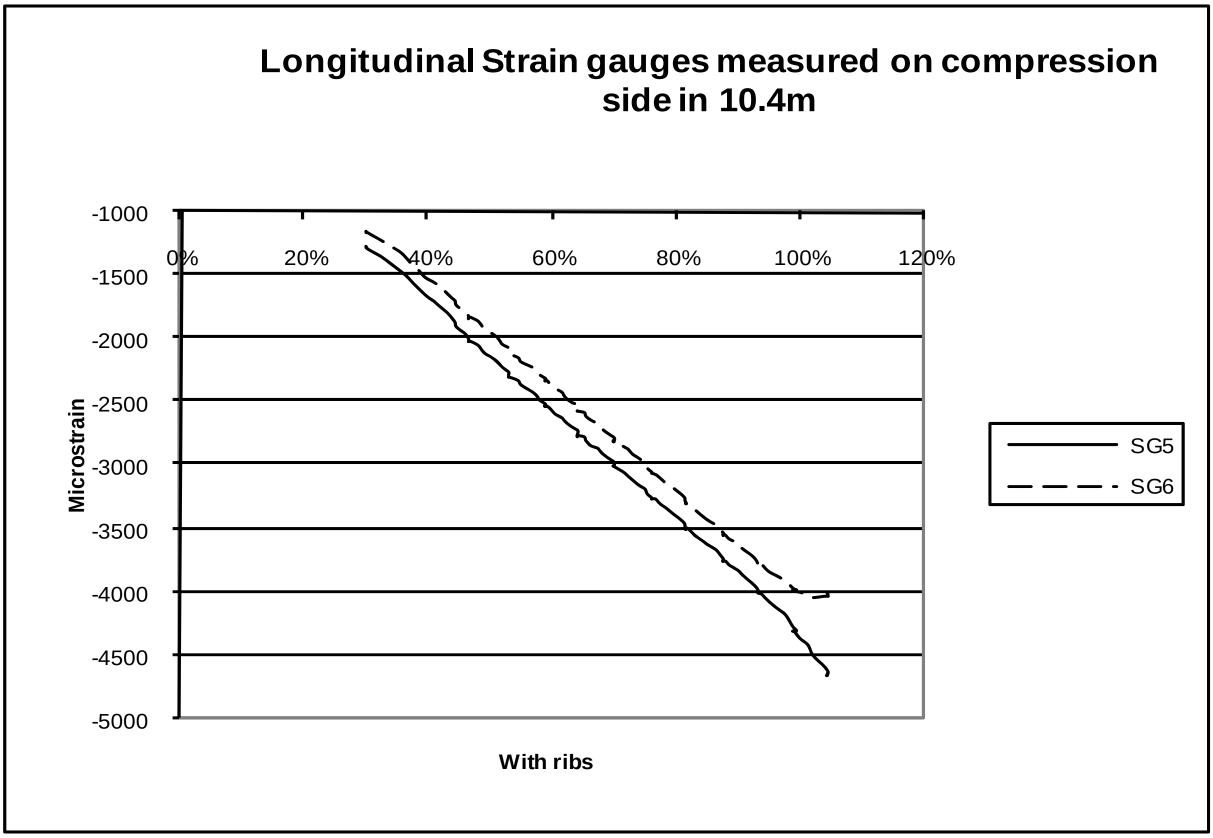


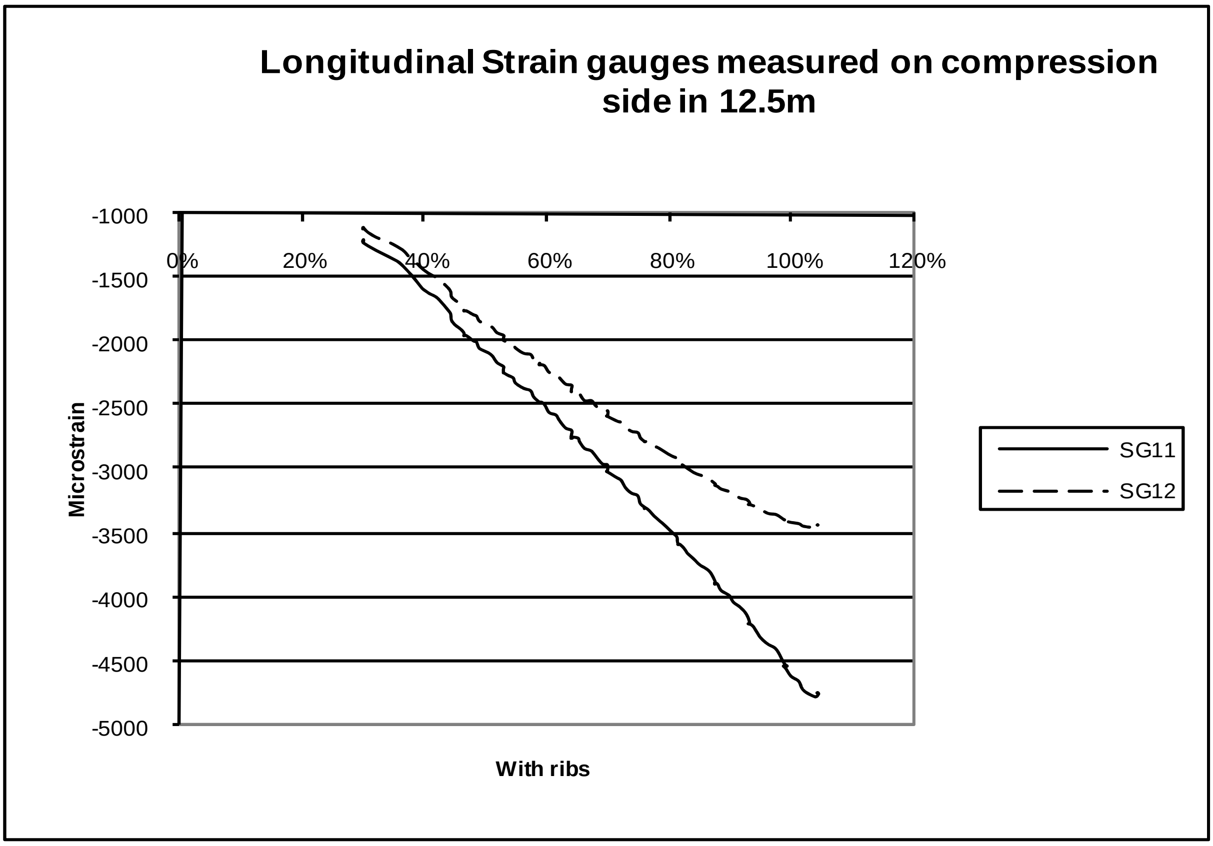

Longitudinal Strain gauges measured on compression side in 9.75m
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
-5500
-6000
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG3
SG4

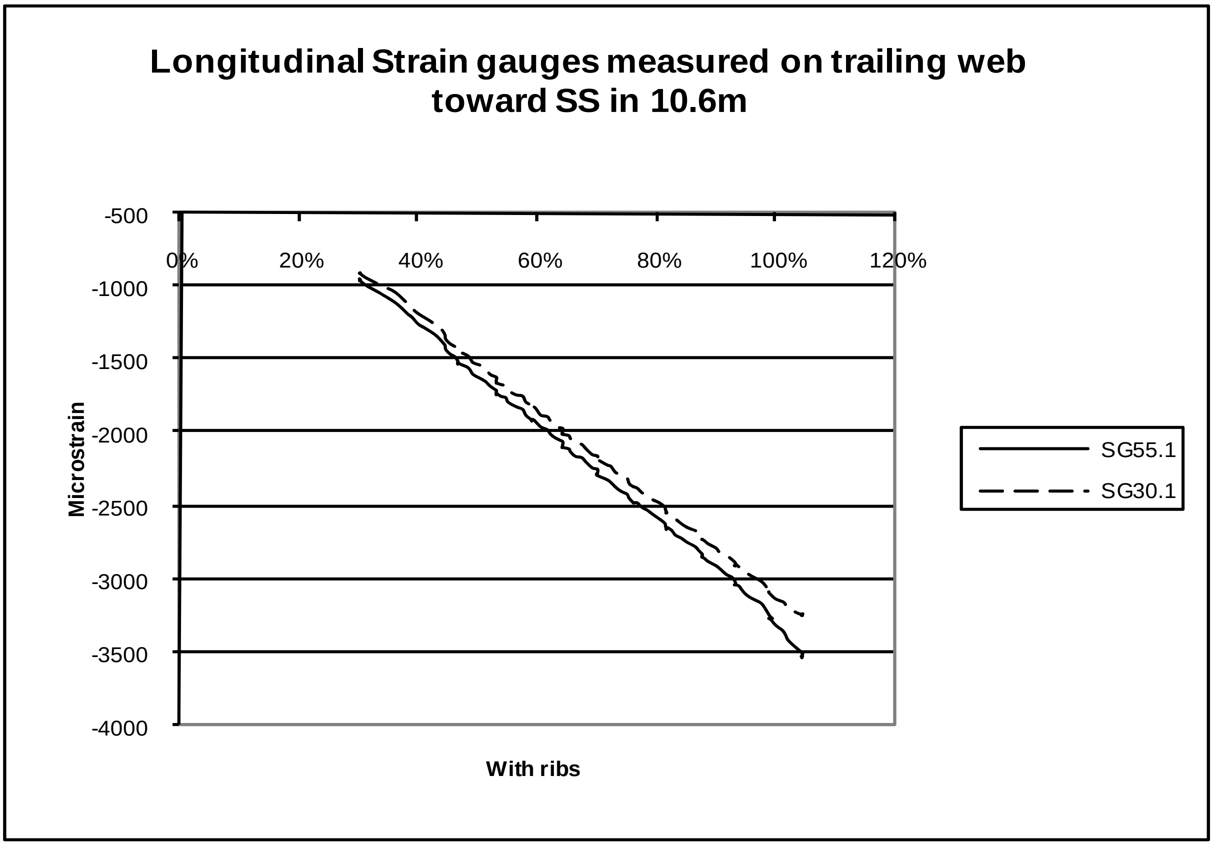

Longitudinal Strain gauges measured on compression side in 10.8m
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG9
SG10


Longitudinal Strain gauges measured on compression side in 10m
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG5
SG6

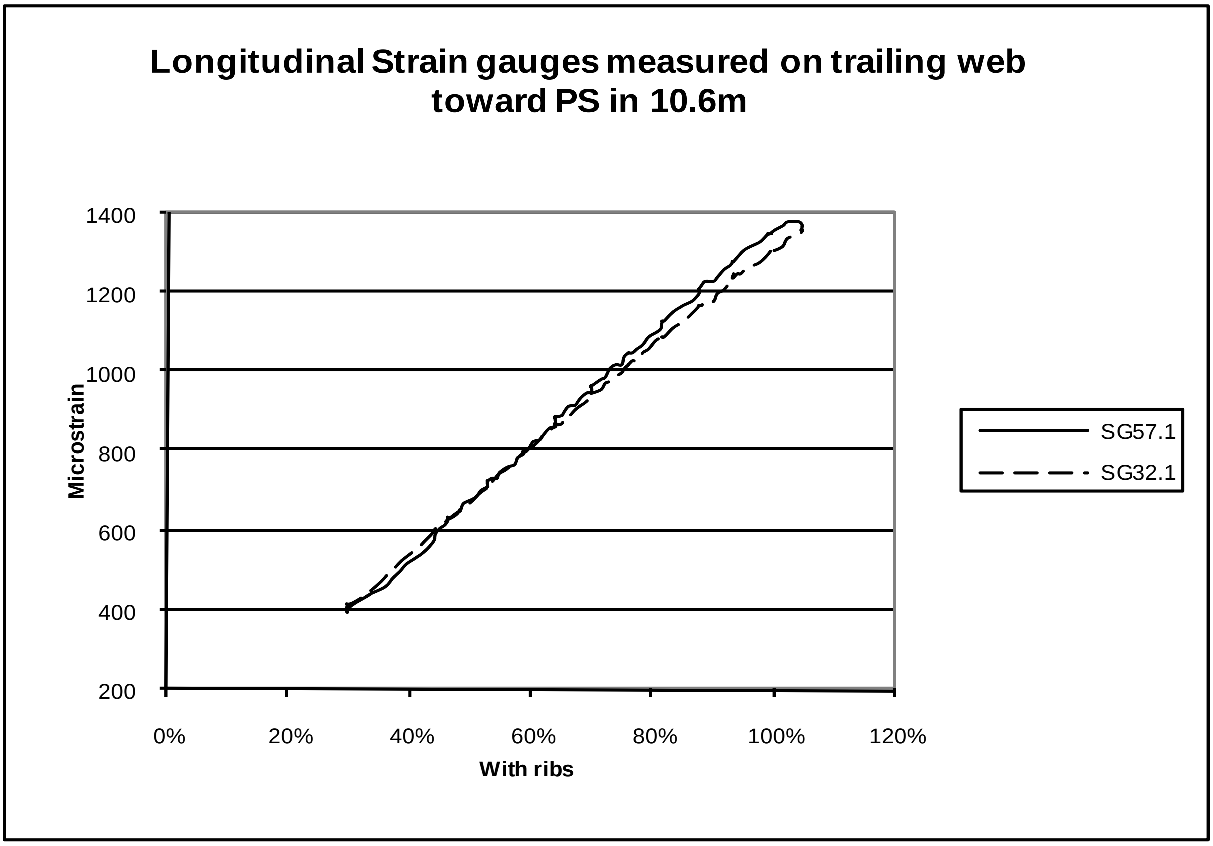

Longitudinal Strain gauges measured on compression side in 11.5m
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG25.1
SG26.1


Longitudinal Strain gauges measured on compression side in 10.4m
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG5
SG6

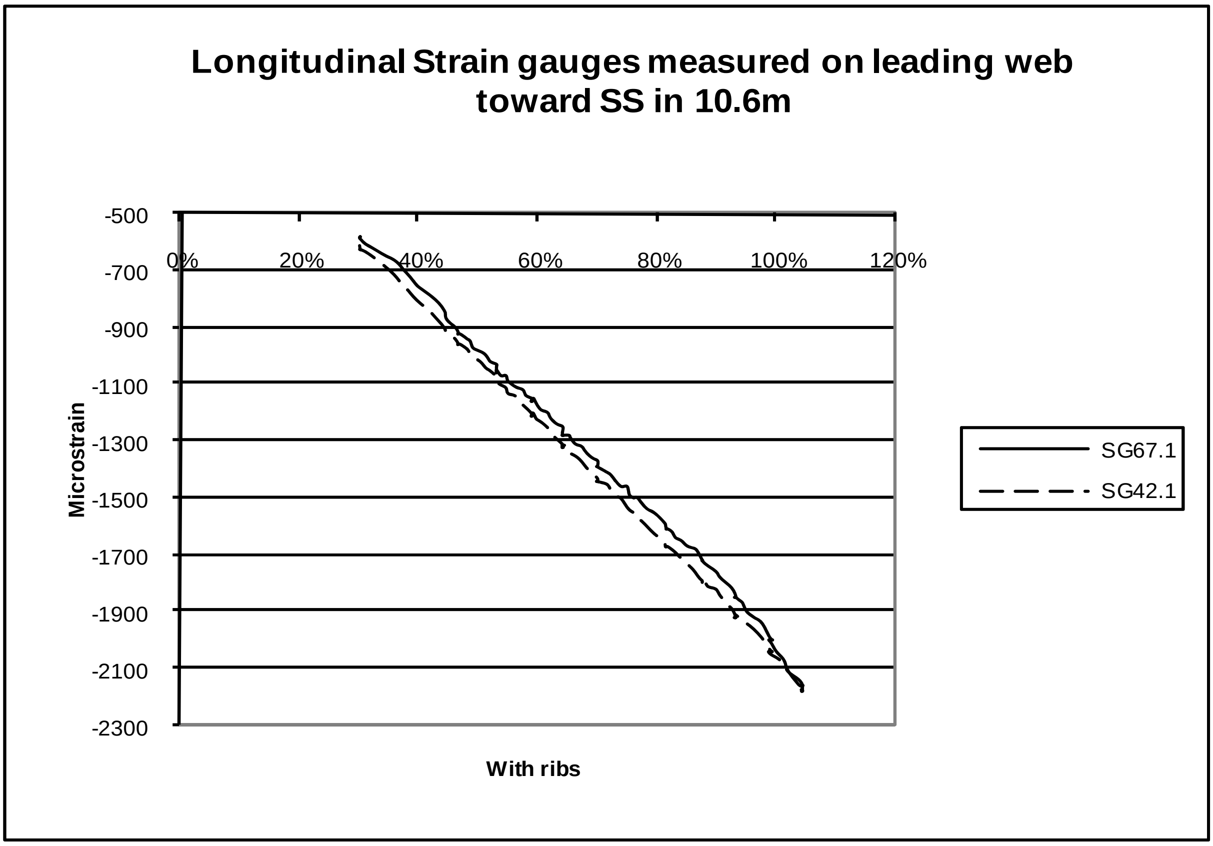

Longitudinal Strain gauges measured on compression side in 12.5m
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG11
SG12

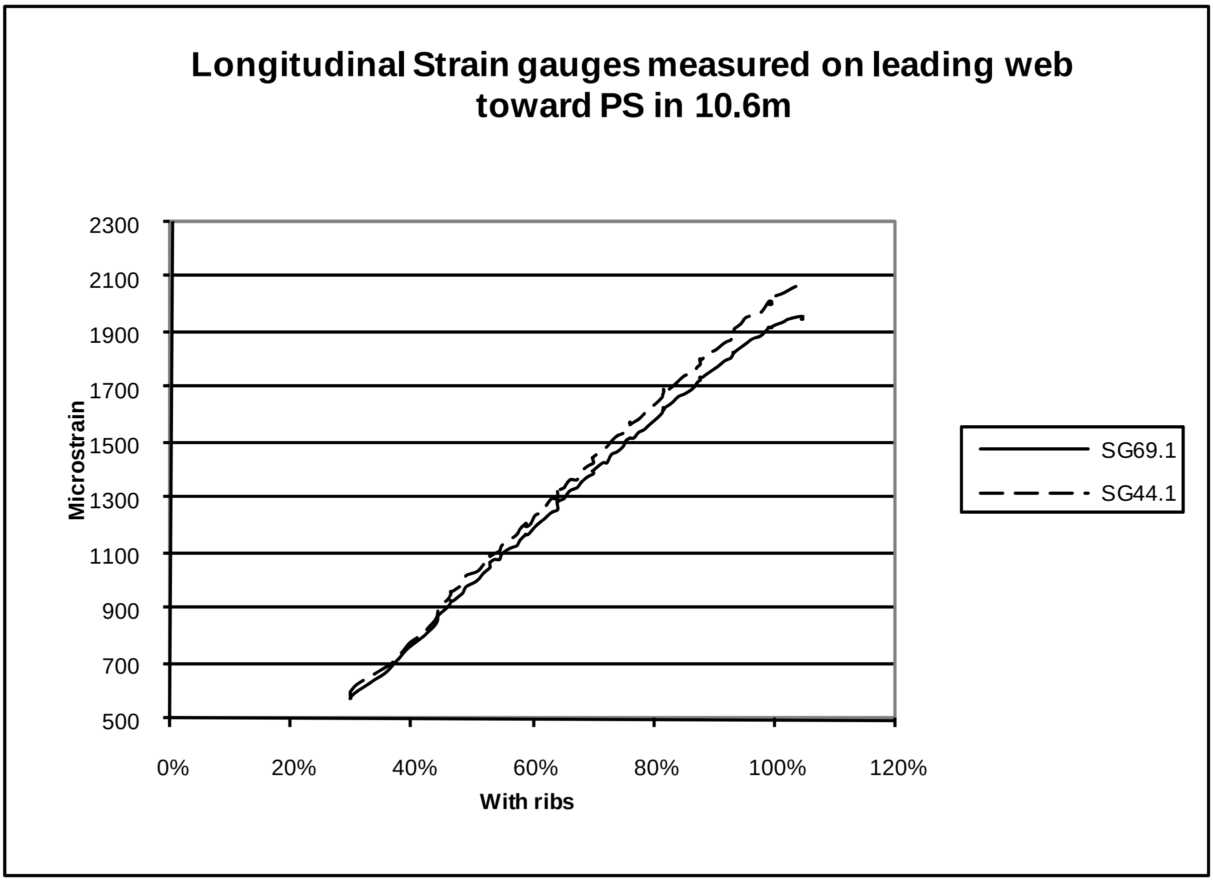


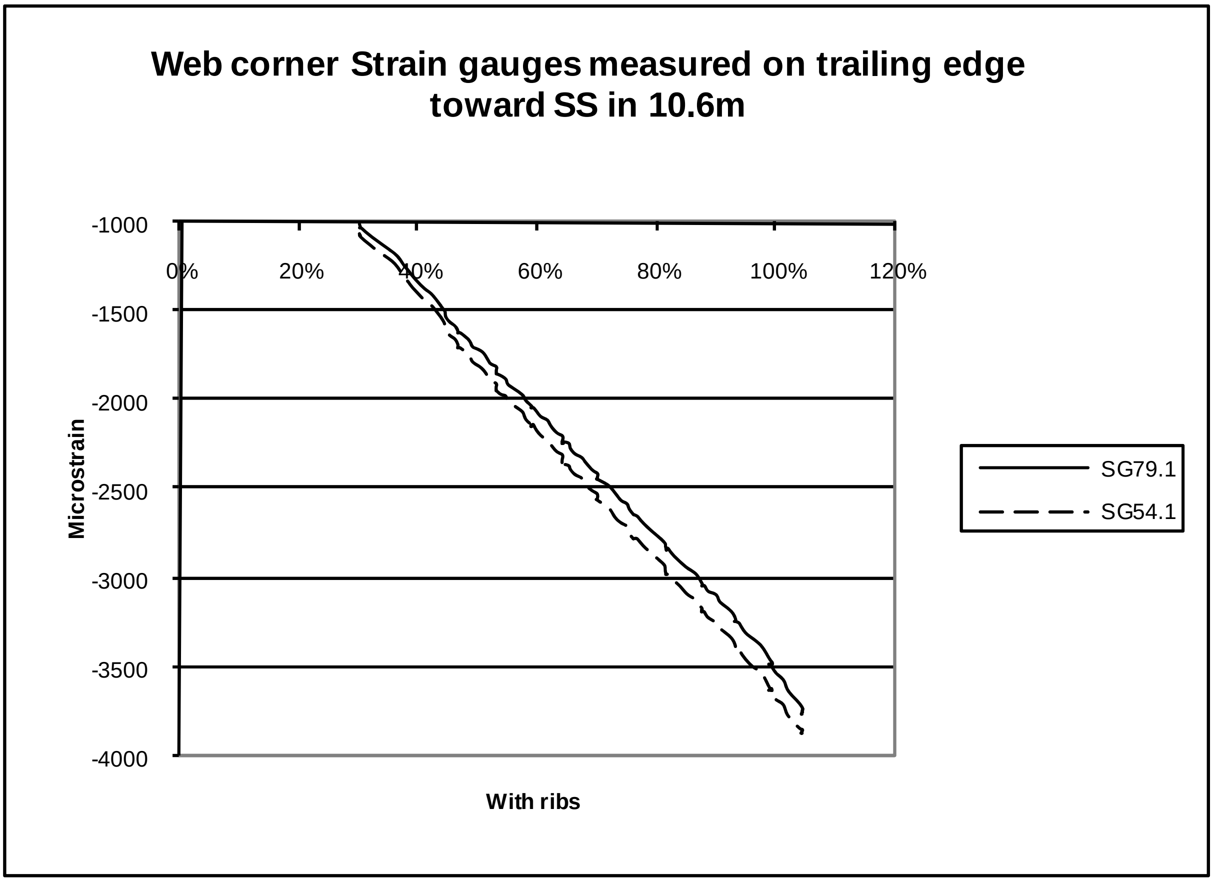
Longitudinal Strain gauges measured on trailing web toward SS in 10.6m
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG55.1
SG30.1

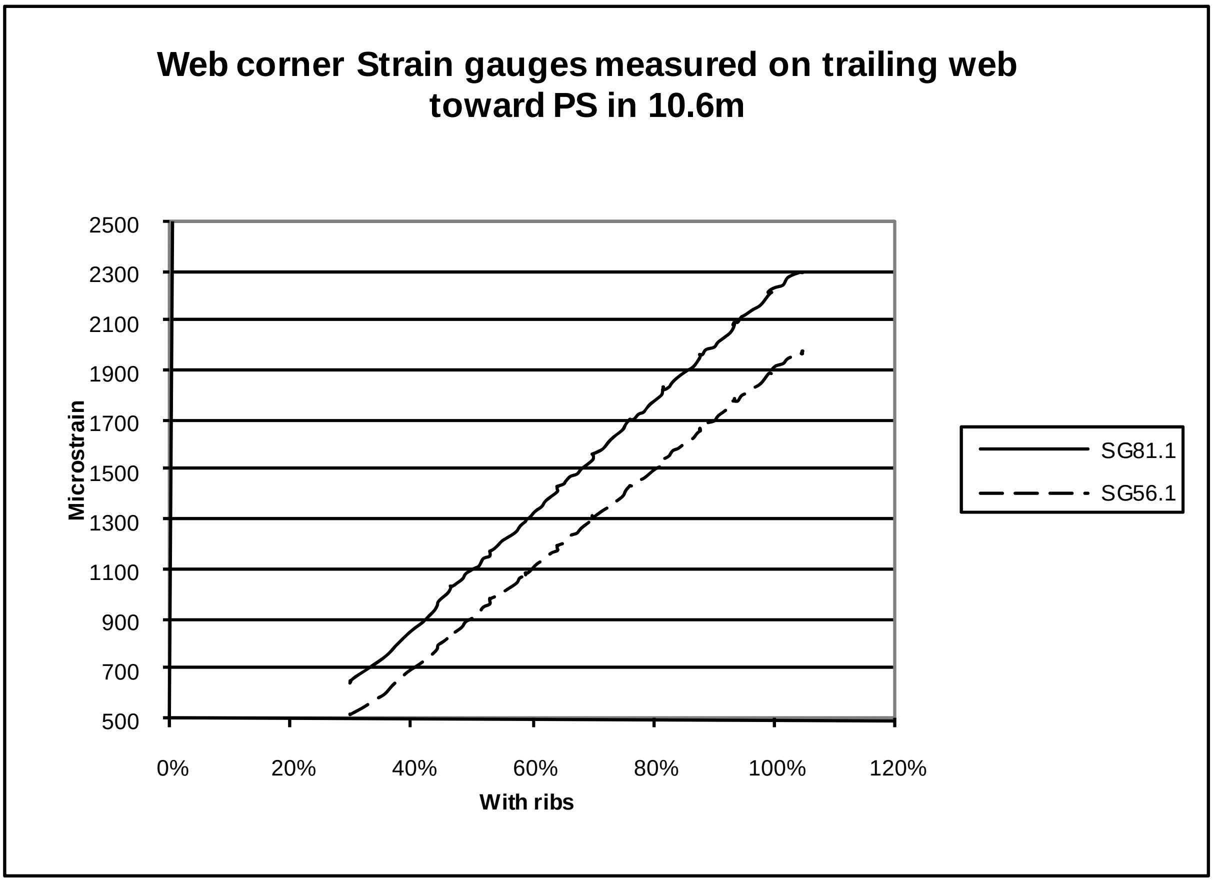


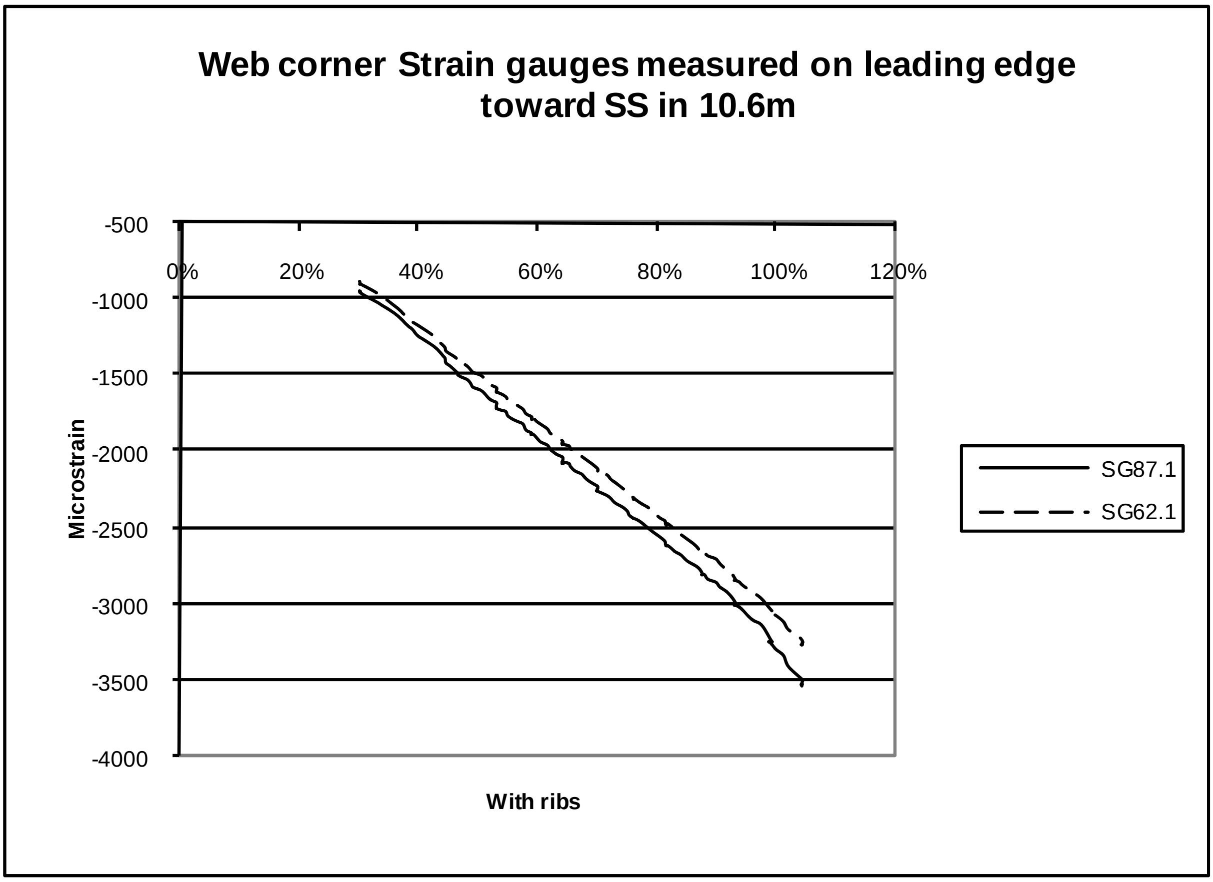
Longitudinal Strain gauges measured on trailing web toward PS in 10.6m
1400
1200
1000
800
600
400
200
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG57.1
SG32.1

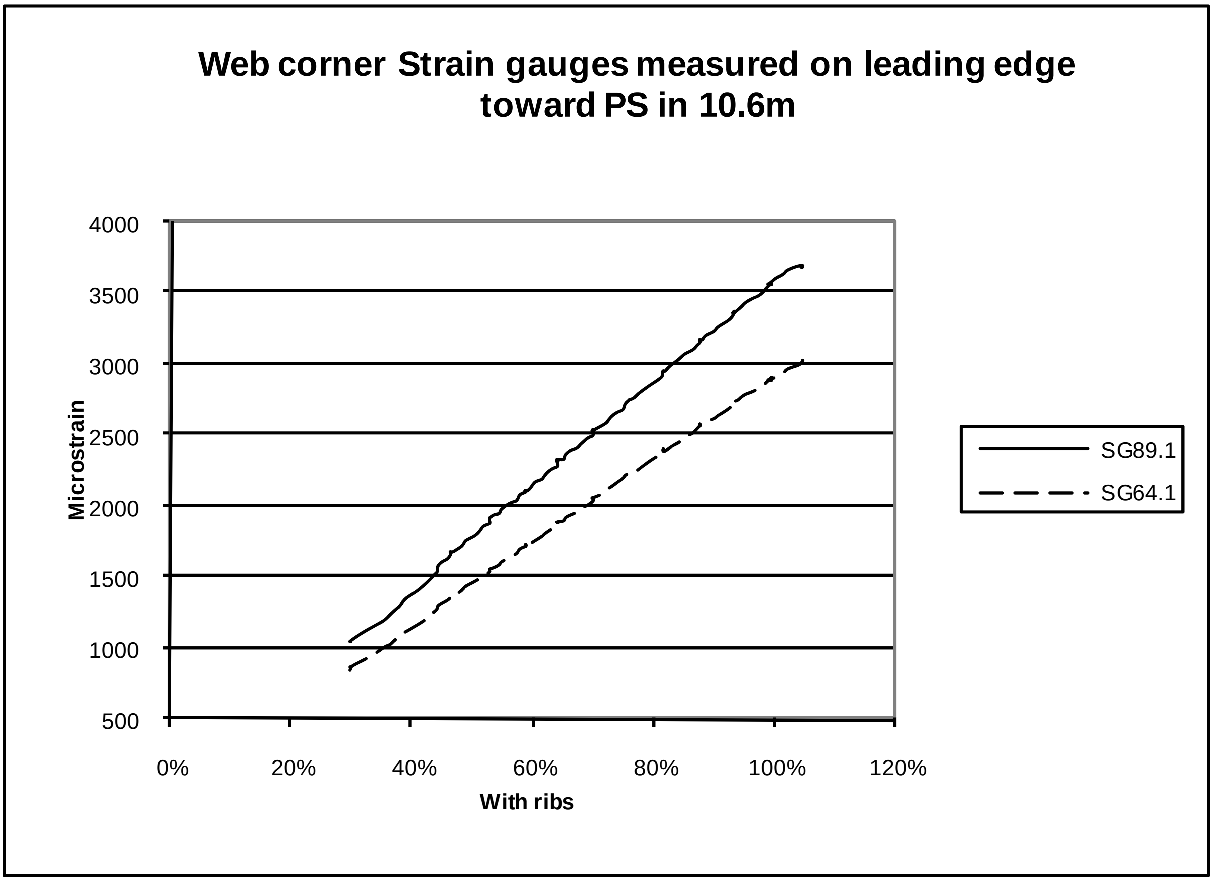

Longitudinal Strain gauges measured on leading web toward SS in 10.6m
-500
-700
-900
-1100
-1300
-1500
-1700
-1900
-2100
-2300
Microstrain
0%
20%
40%
60%
80%
100%
120%
With ribs
SG67.1
SG42.1

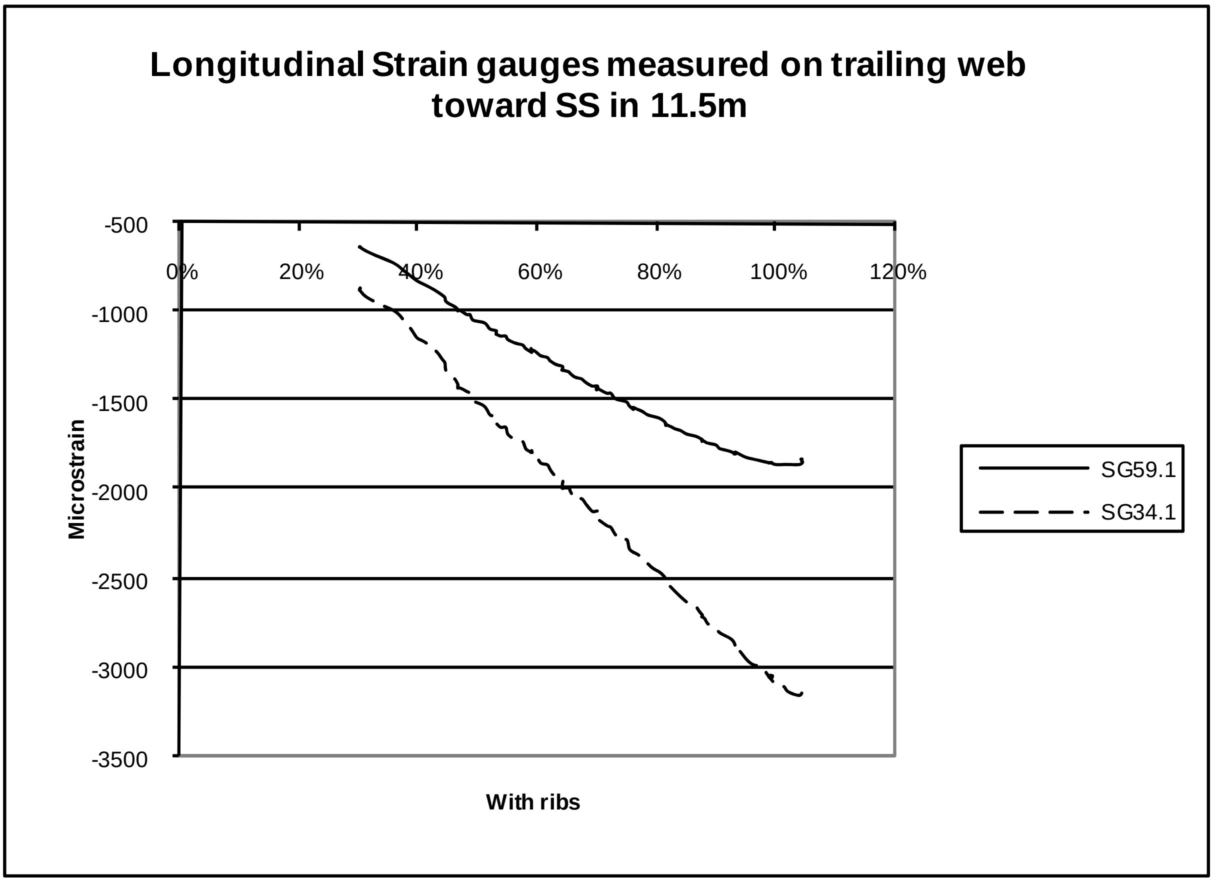

Longitudinal Strain gauges measured on leading web toward PS in 10.6m
2300
2100
1900
1700
1500
1300
1100
900
700
500
Microstrain
0%
20%
40%
60%
80%
100%
120%
With ribs
SG69.1
SG44.1


Web corner Strain gauges measured on trailing edge toward SS in 10.6m
-1000
-1500
-2000
-2500
-3000
-3500
-4000
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG79.1
SG54.1

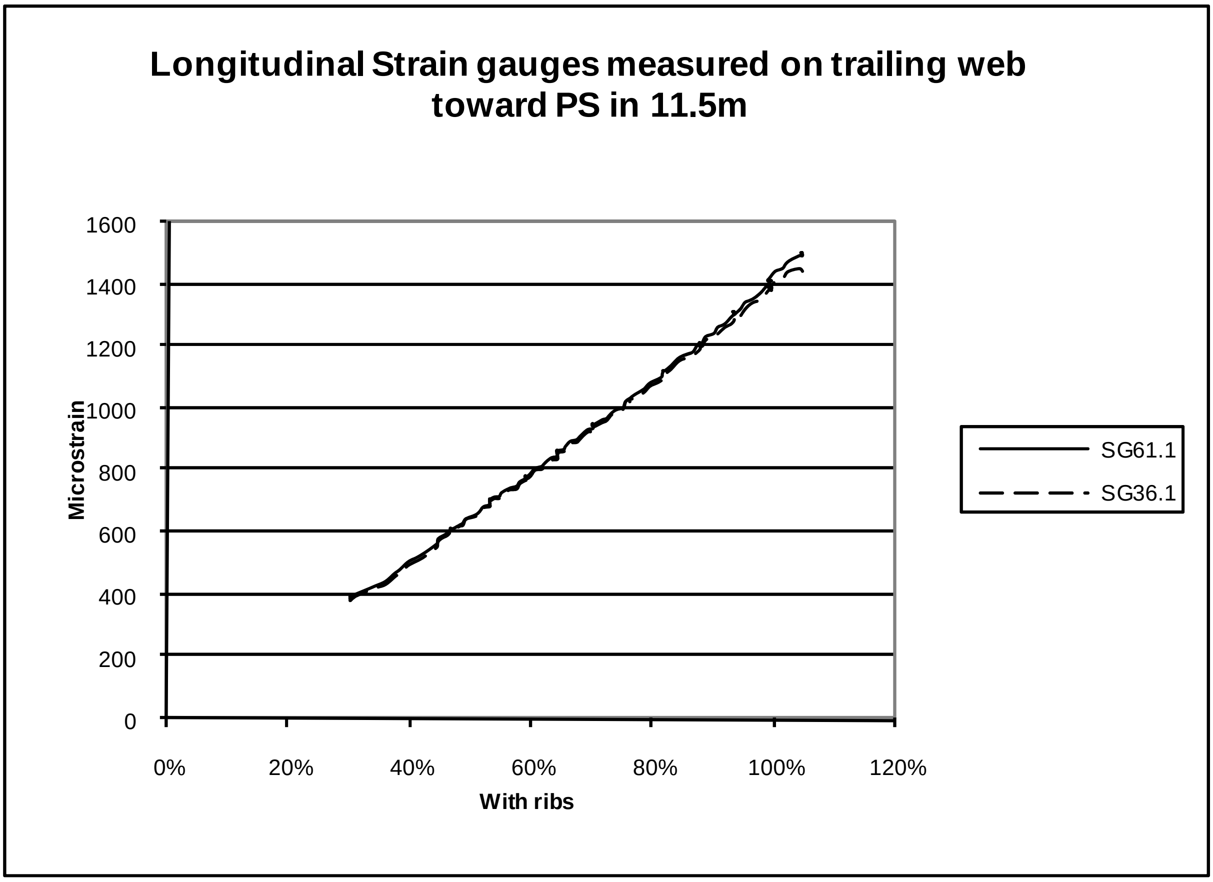

Web corner Strain gauges measured on trailing web toward PS in 10.6m
2500
2300
2100
1900
1700
1500
1300
1100
900
700
500
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG81.1
SG56.1


Web corner Strain gauges measured on leading edge toward SS in 10.6m
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG87.1
SG62.1

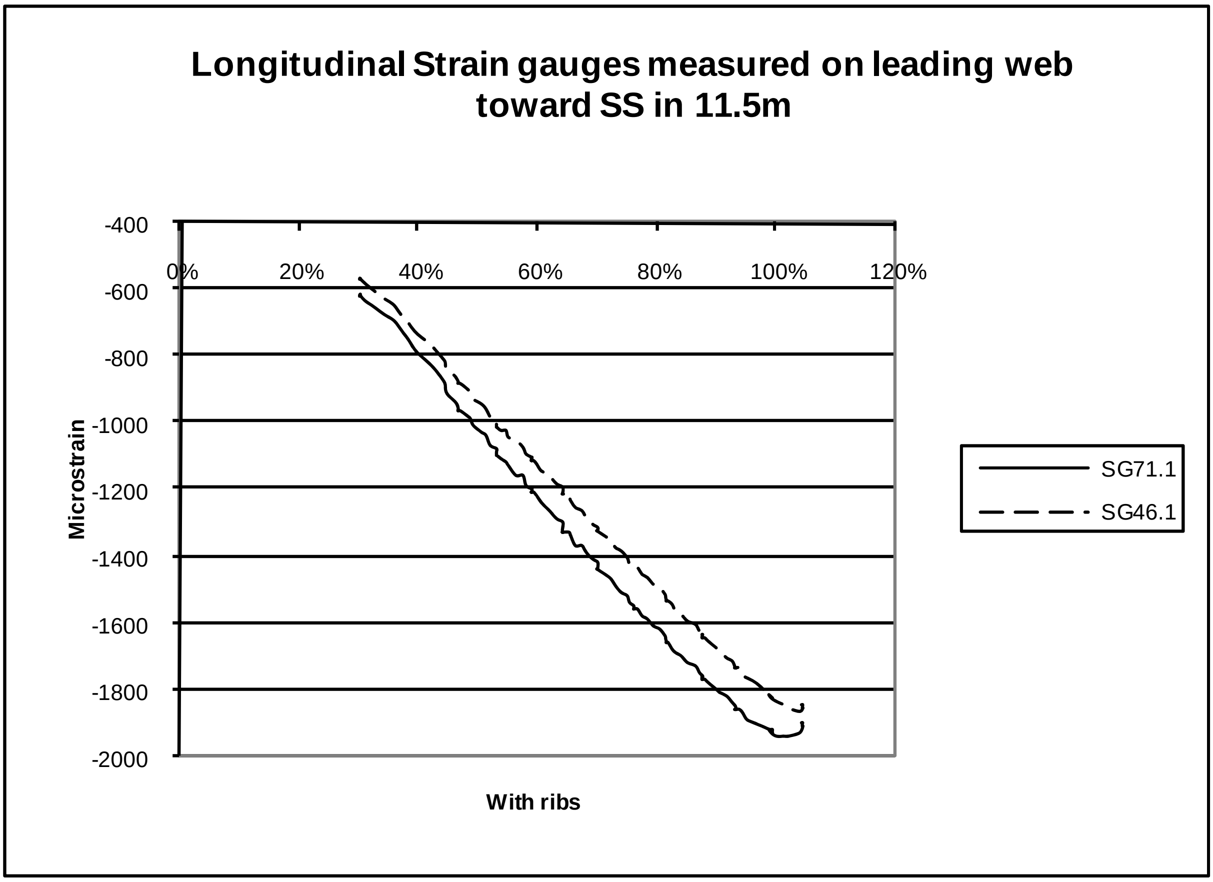

Web corner Strain gauges measured on leading edge toward PS in 10.6m
4000
3500
3000
2500
2000
1500
1000
500
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG89.1
SG64.1

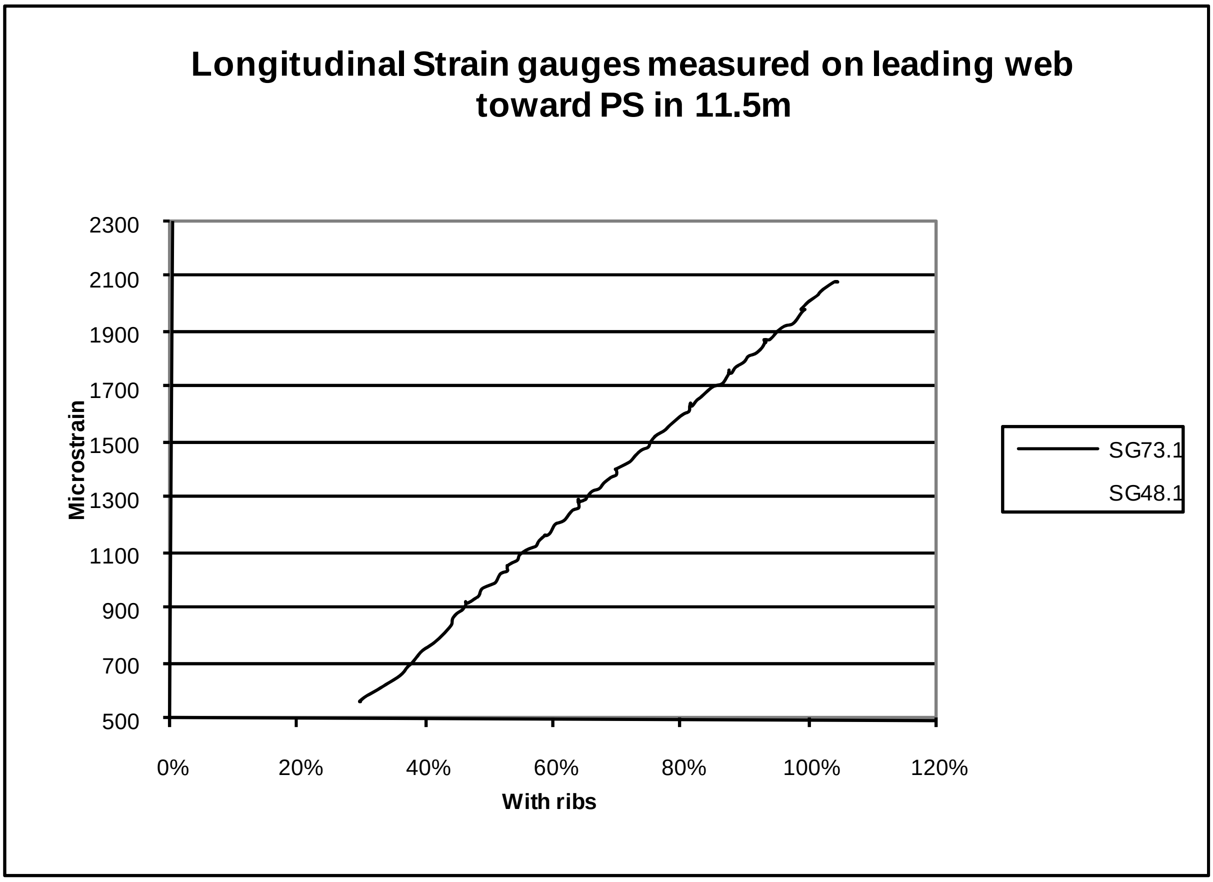


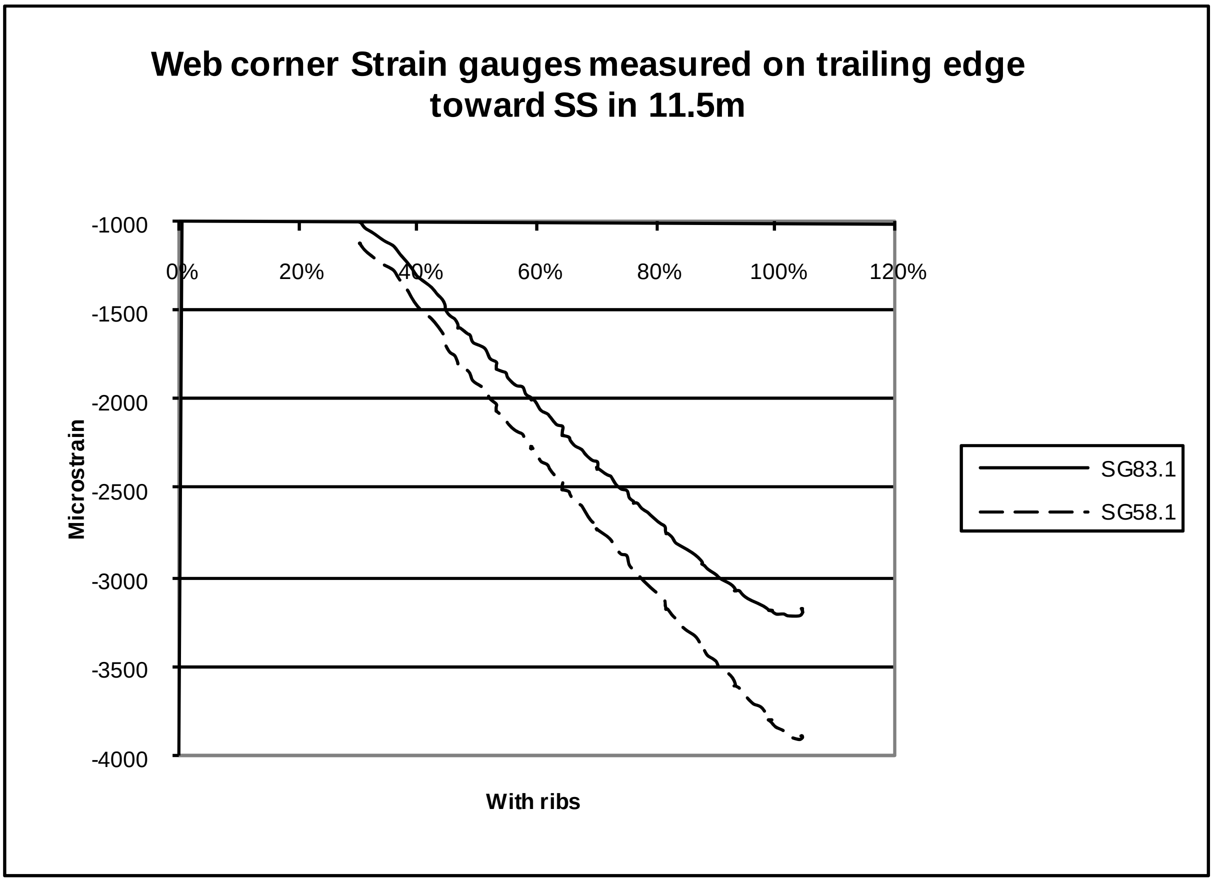
Longitudinal Strain gauges measured on trailing web toward SS in 11.5m
-500
-1000
-1500
-2000
-2500
-3000
-3500
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG59.1
SG34.1

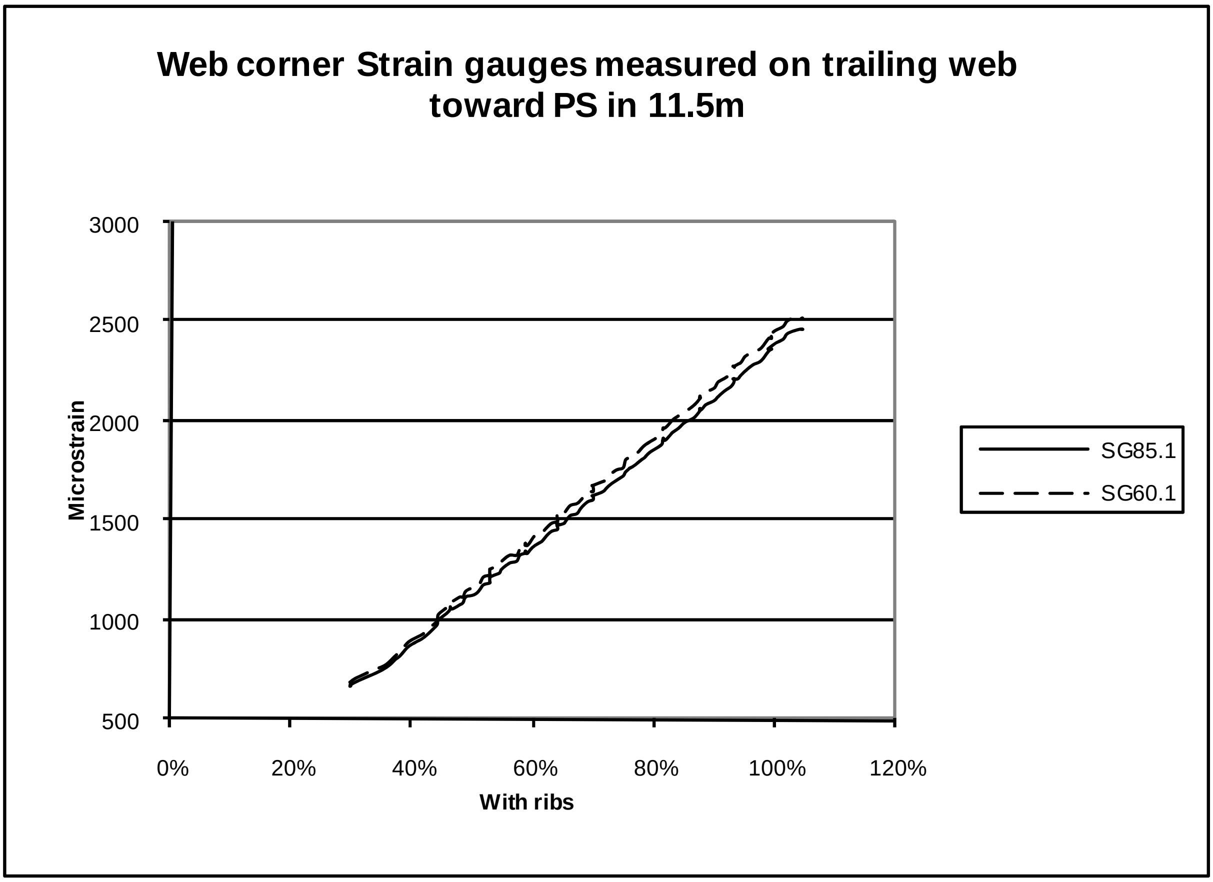


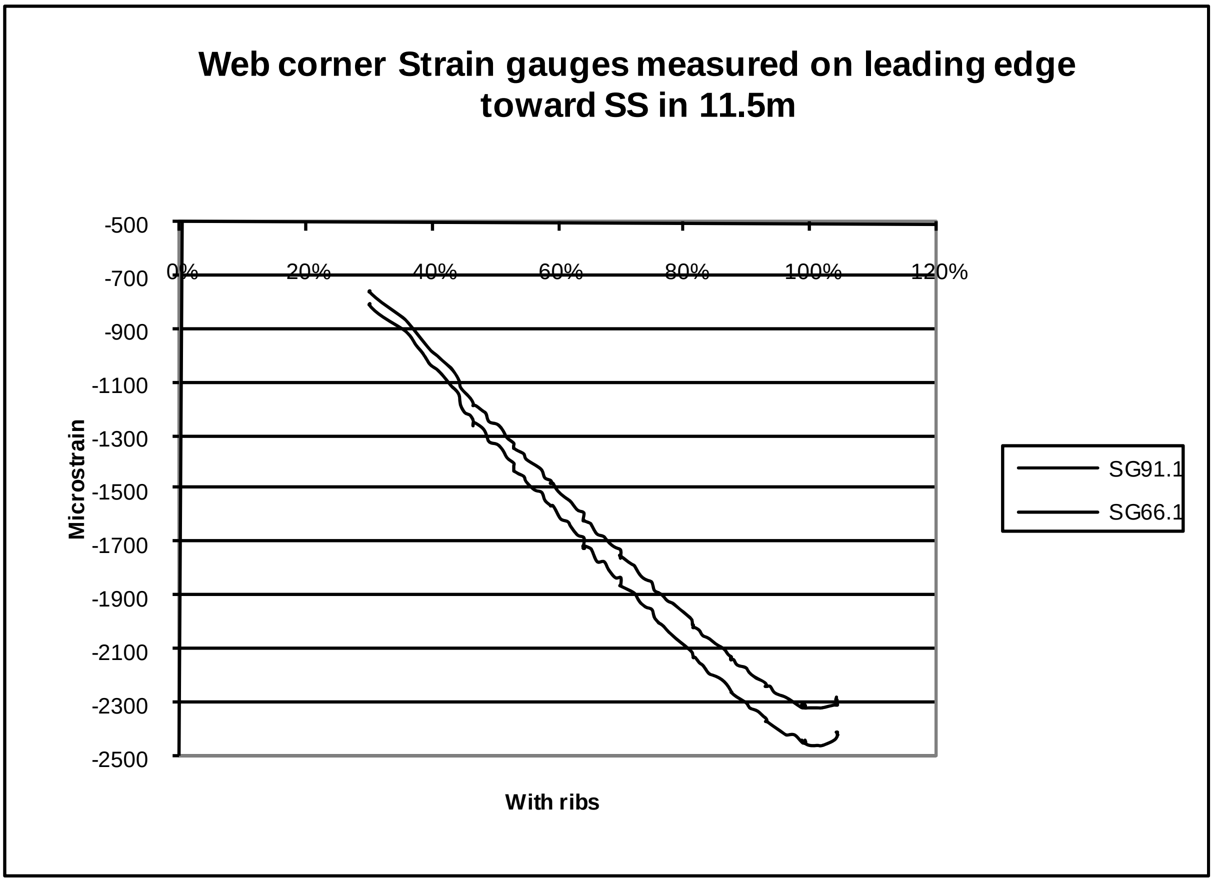
Longitudinal Strain gauges measured on trailing web toward PS in 11.5m
1600
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG61.1
SG36.1

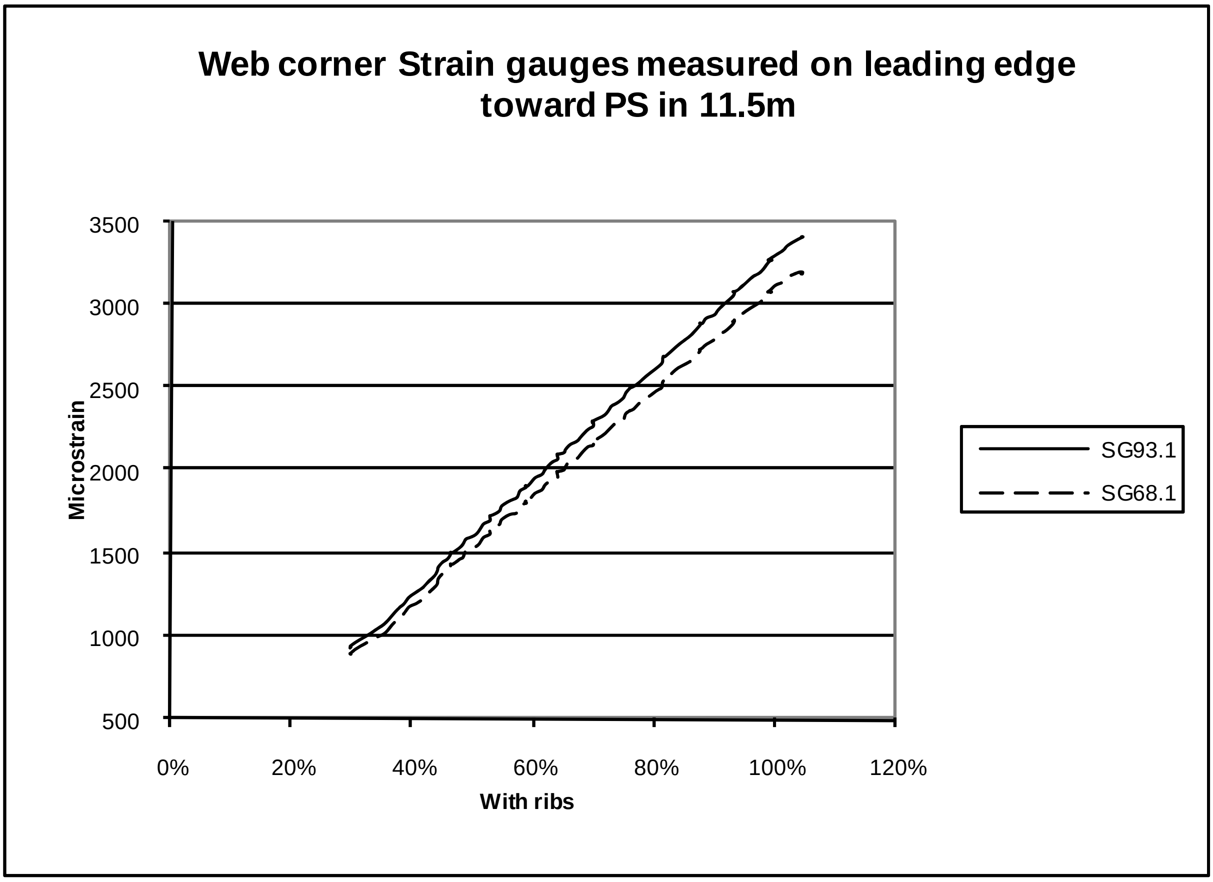

Longitudinal Strain gauges measured on leading web toward SS in 11.5m
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-2000
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG71.1
SG46.1

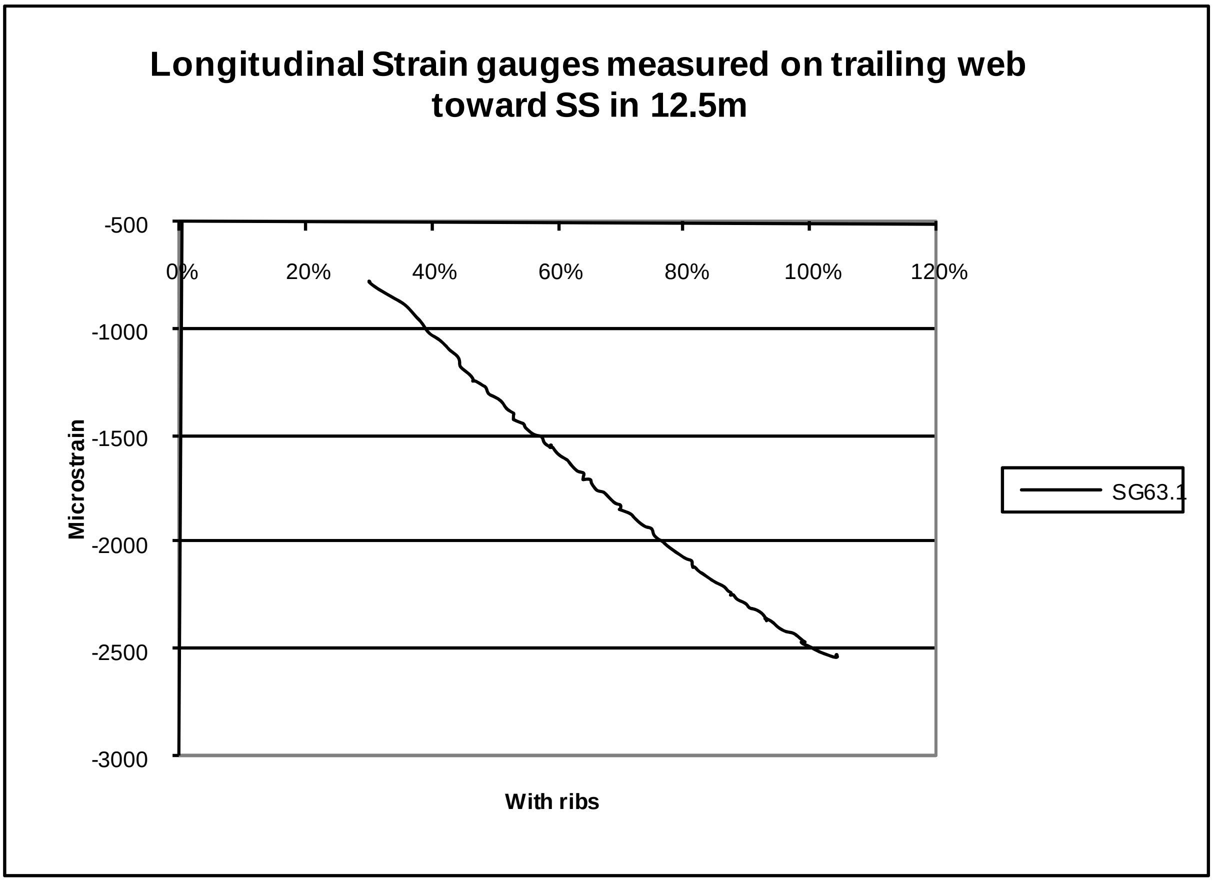

Longitudinal Strain gauges measured on leading web toward PS in 11.5m
2300
2100
1900
1700
1500
1300
1100
900
700
500
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG73.1
SG48.1

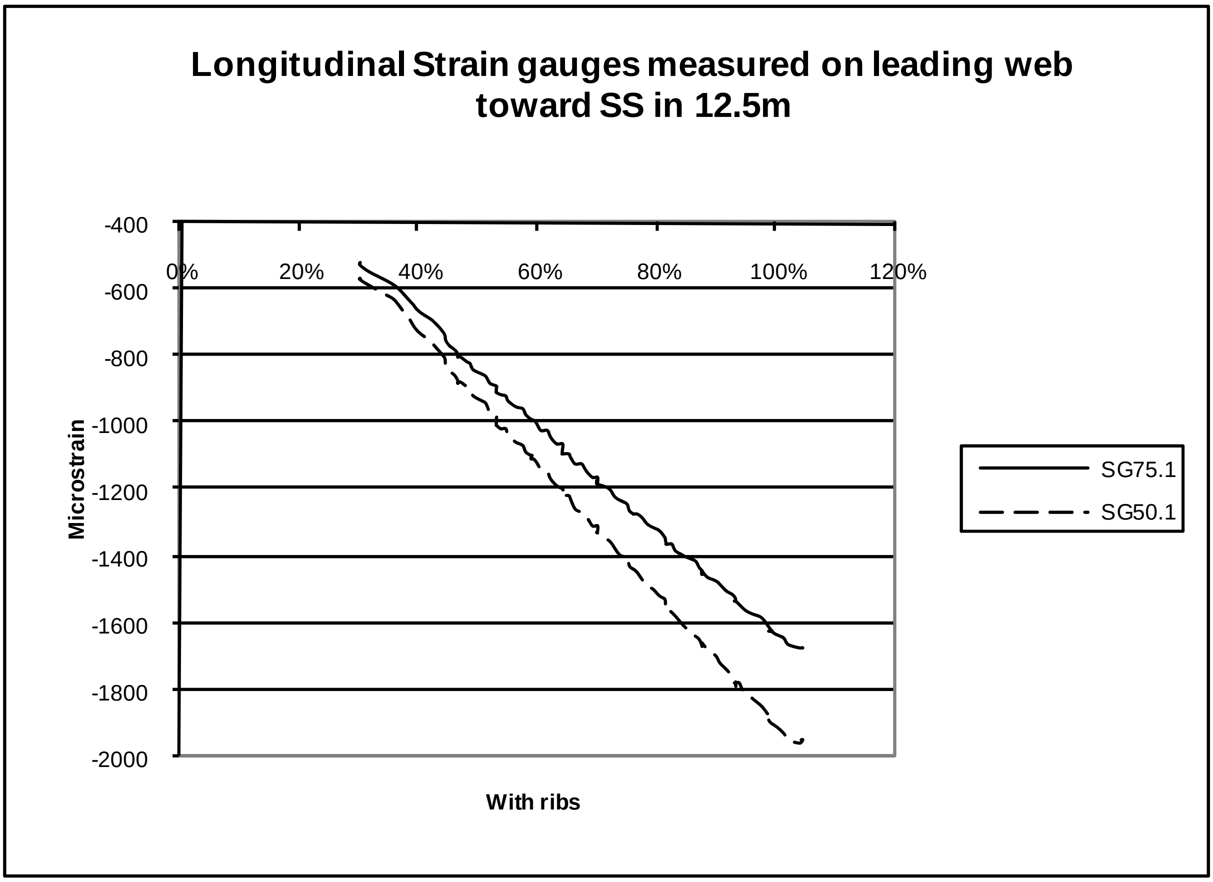

Web corner Strain gauges measured on trailing edge toward SS in 11.5m
-1000
-1500
-2000
-2500
-3000
-3500
-4000
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG83.1
SG58.1

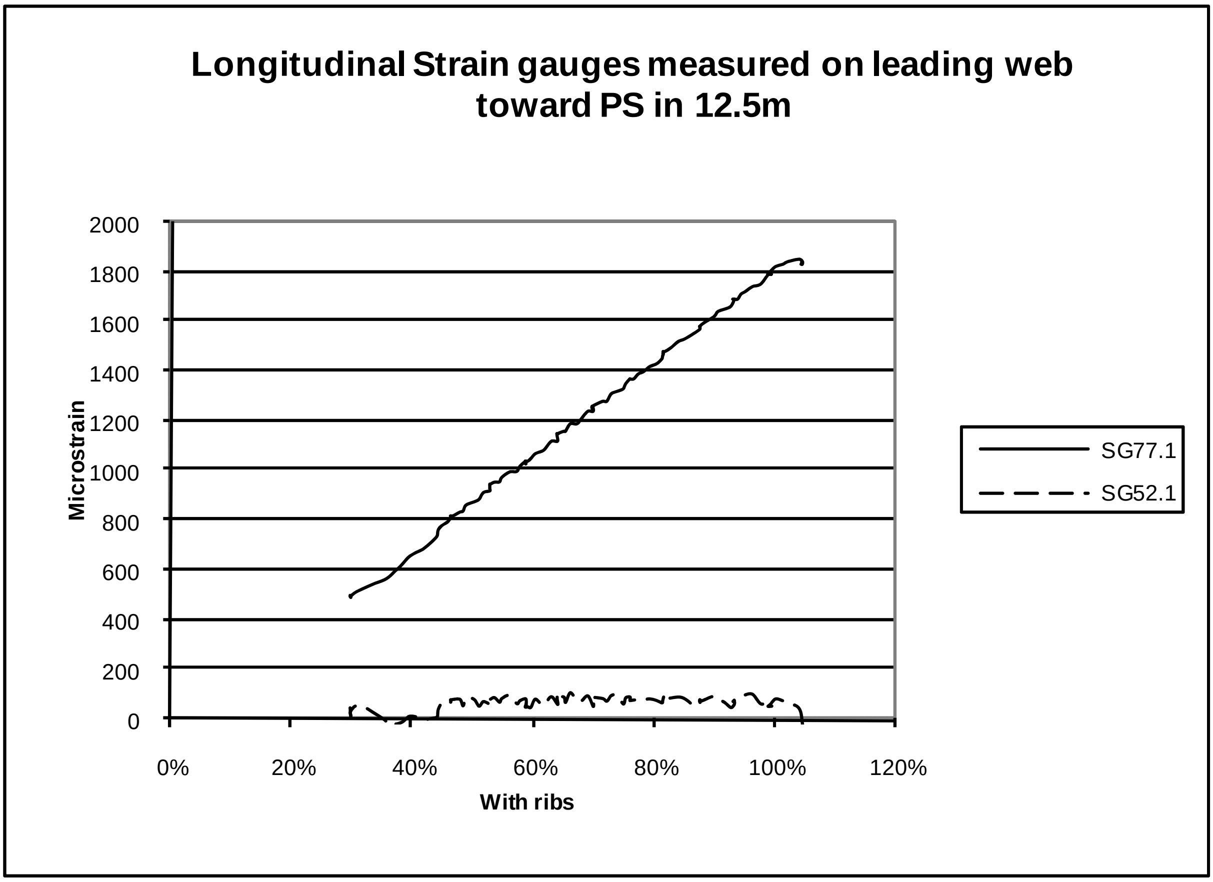

Web corner Strain gauges measured on trailing web toward PS in 11.5m
3000
2500
2000
1500
1000
500
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG85.1
SG60.1


Web corner Strain gauges measured on leading edge toward SS in 11.5m
-500
-700
-900
-1100
-1300
-1500
-1700
-1900
-2100
-2300
-2500
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG91.1
SG66.1


Web corner Strain gauges measured on leading edge toward PS in 11.5m
3500
3000
2500
2000
1500
1000
500
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG93.1
SG68.1

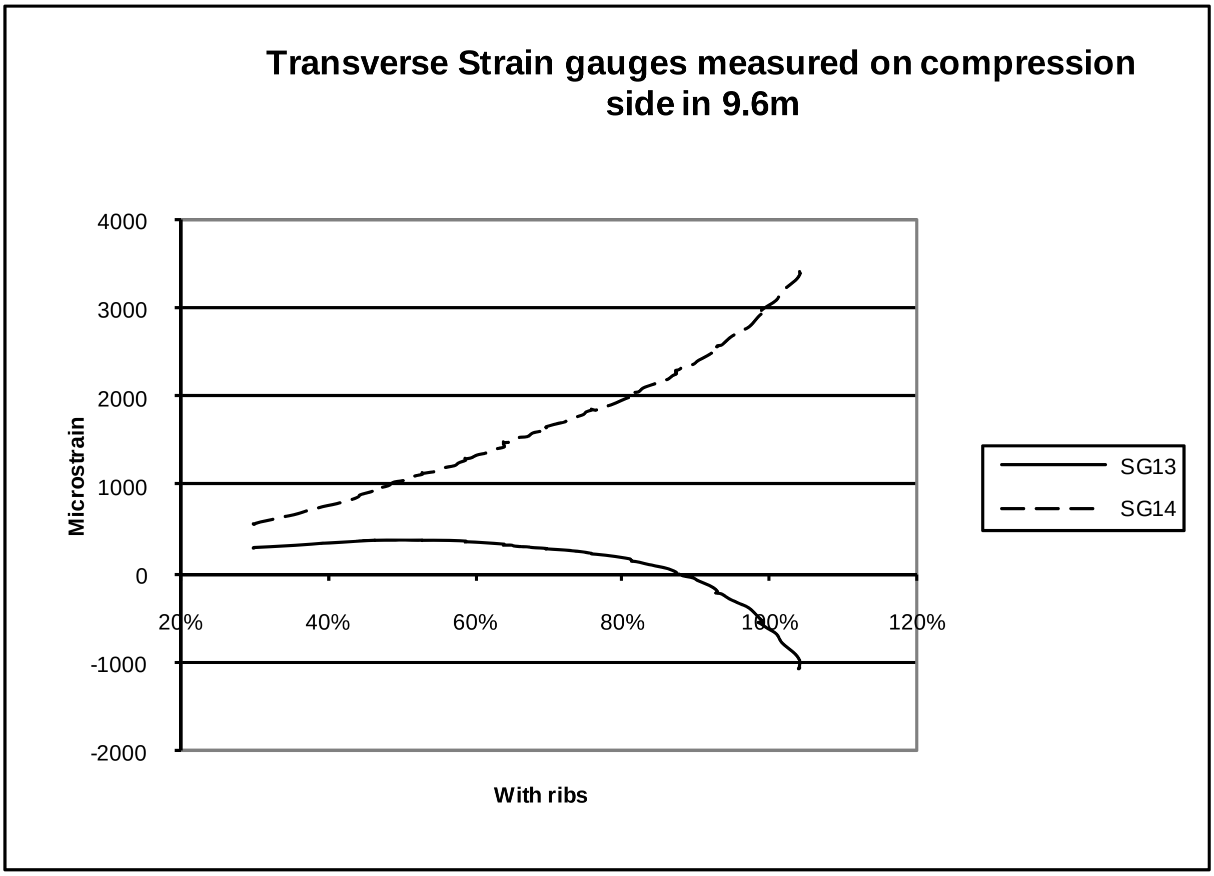

Longitudinal Strain gauges measured on trailing web toward SS in 12.5m
-500
-1000
-1500
-2000
-2500
-3000
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG63.1

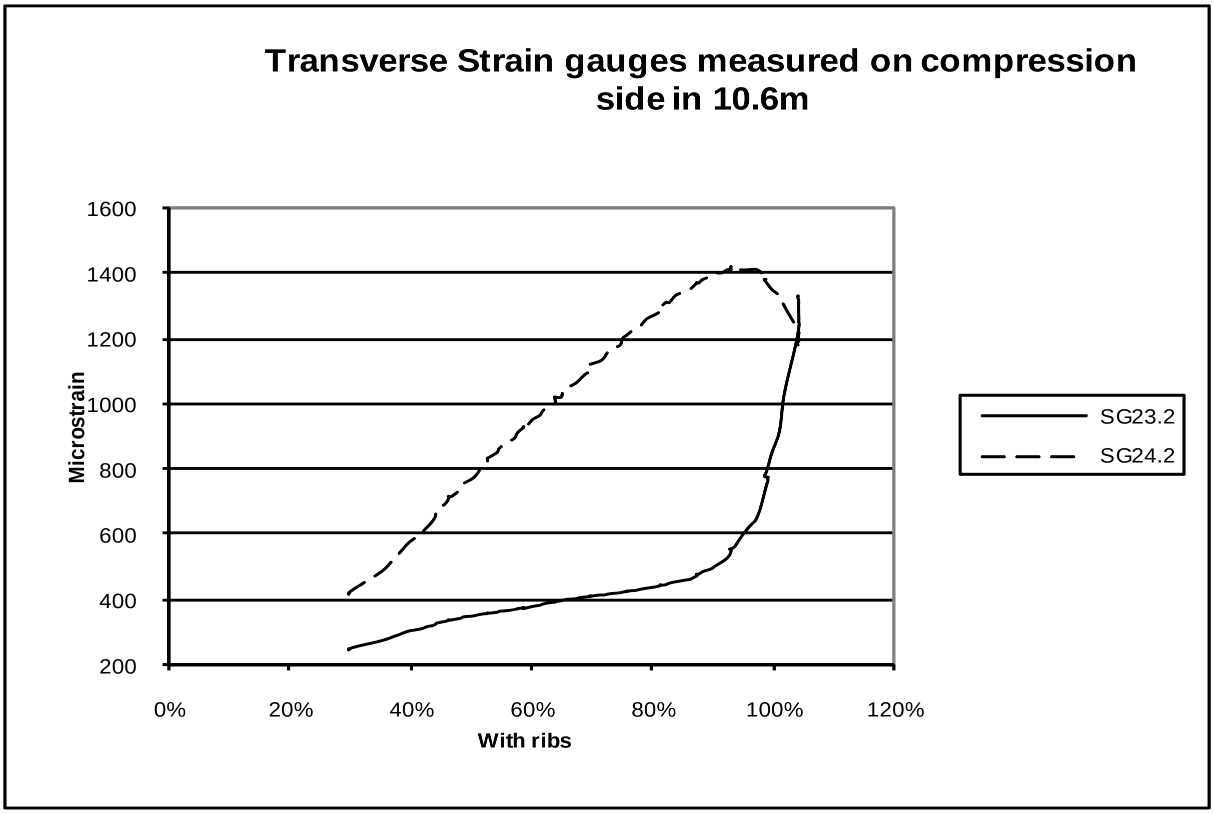

Longitudinal Strain gauges measured on leading web toward SS in 12.5m
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-2000
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG75.1
SG50.1

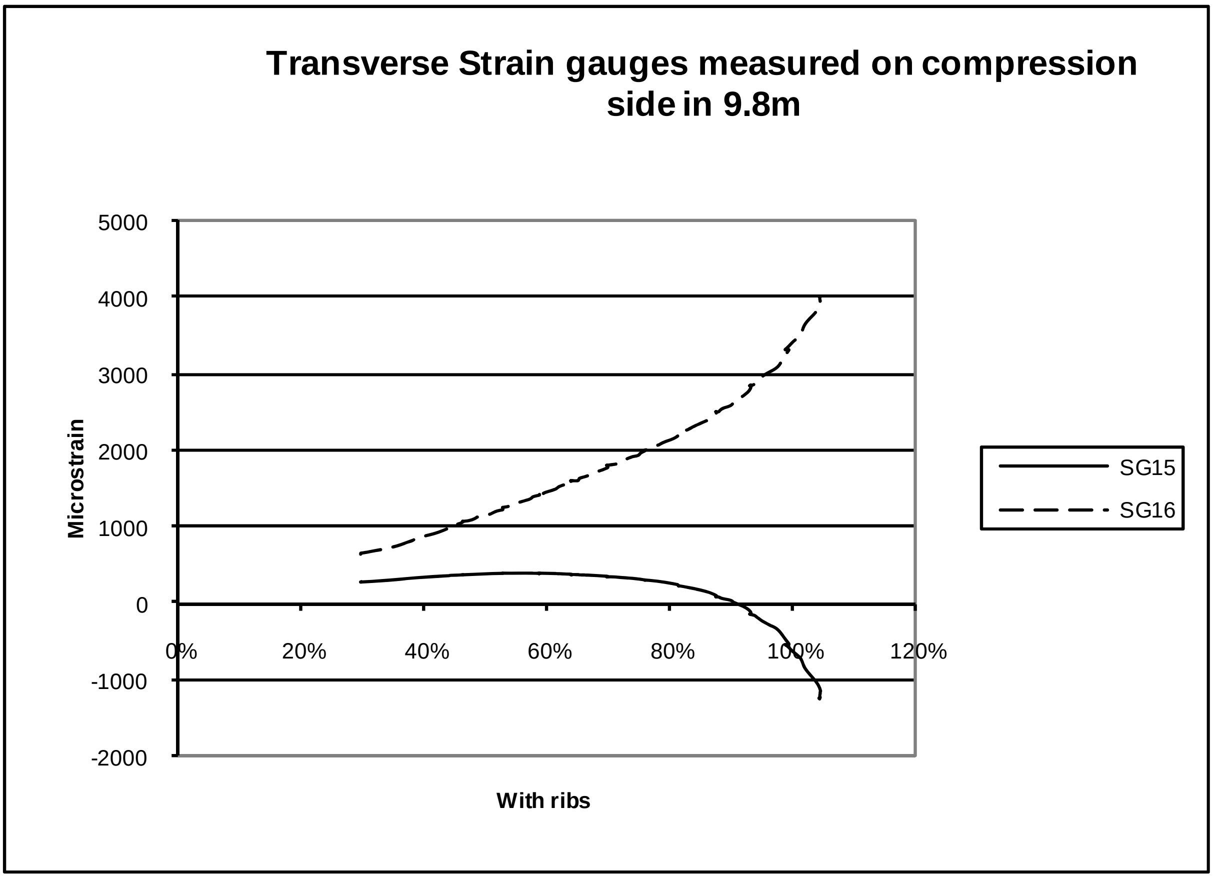


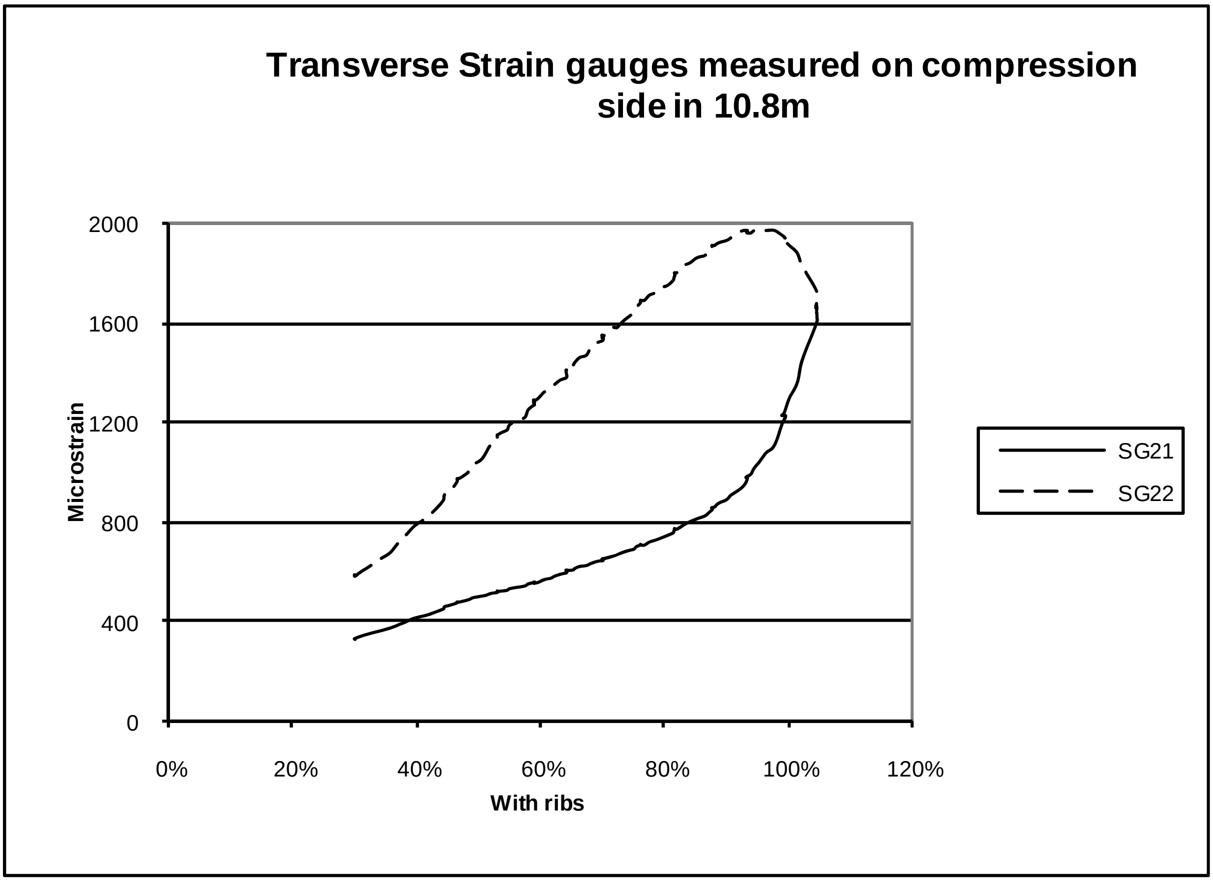
Longitudinal Strain gauges measured on leading web toward PS in 12.5m
Microstrain
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
120%
With ribs
SG77.1
SG52.1

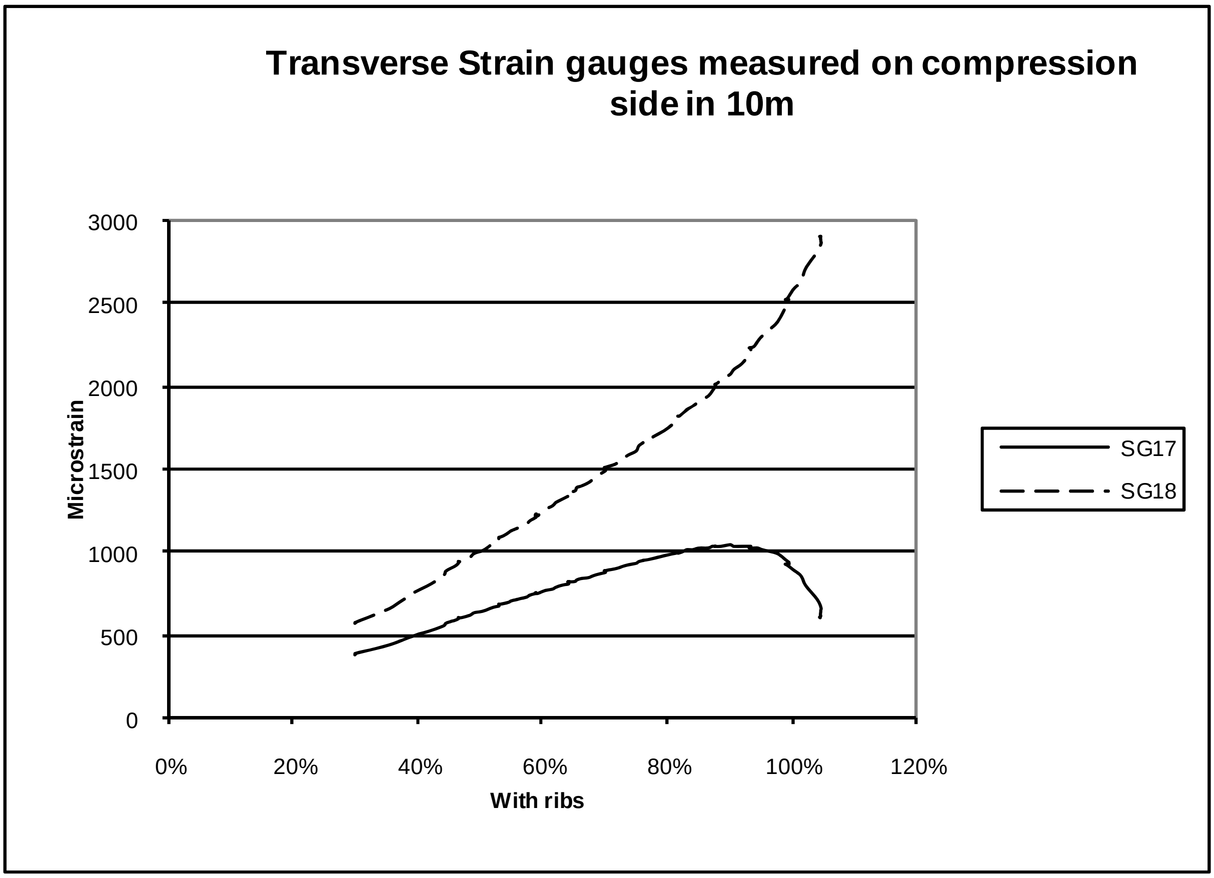
Graphs of Transverse measurements with ribs

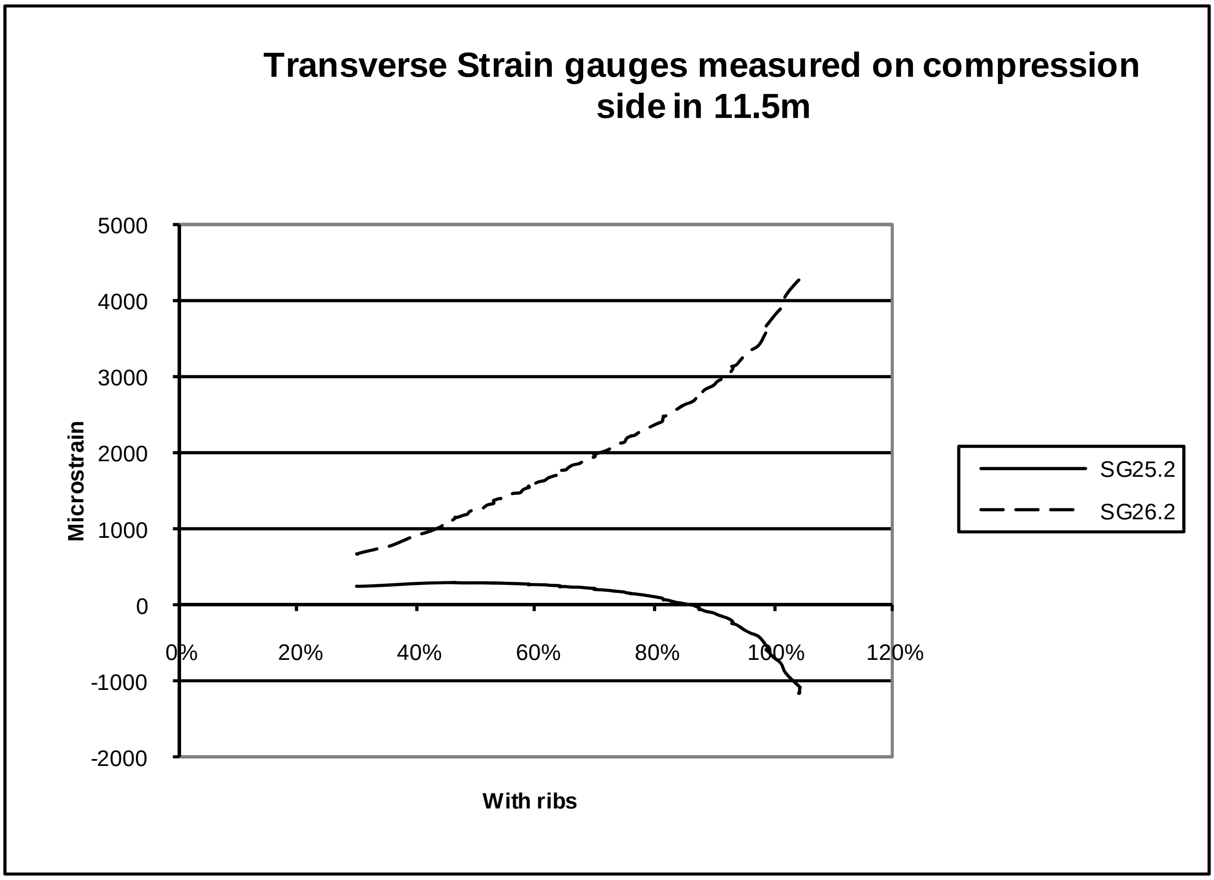


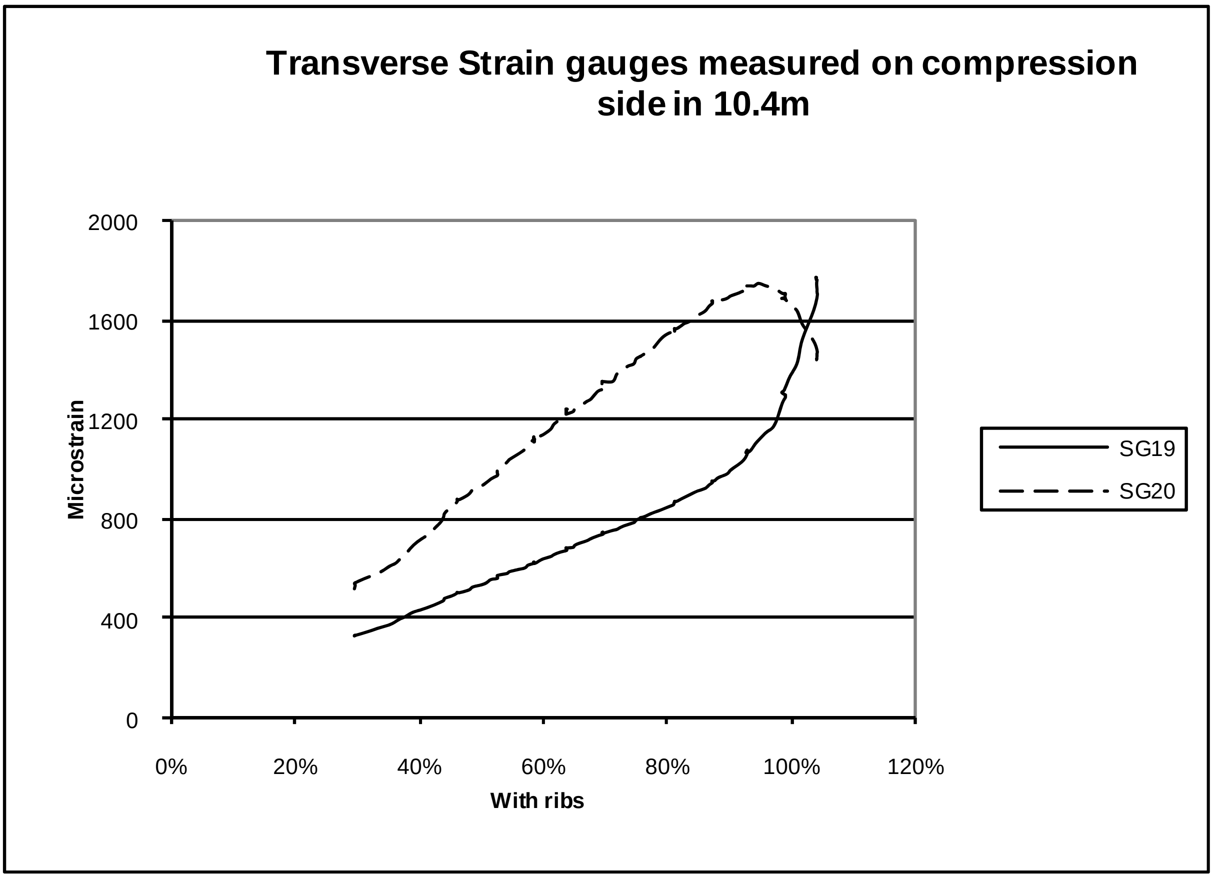



Transverse Strain gauges measured on compression side in 9.8m
5000
4000
3000
2000
1000
0
-1000
-2000
Microstrain
0%
20%
40%
60%
80%
100%
120%
With ribs
SG15
SG16

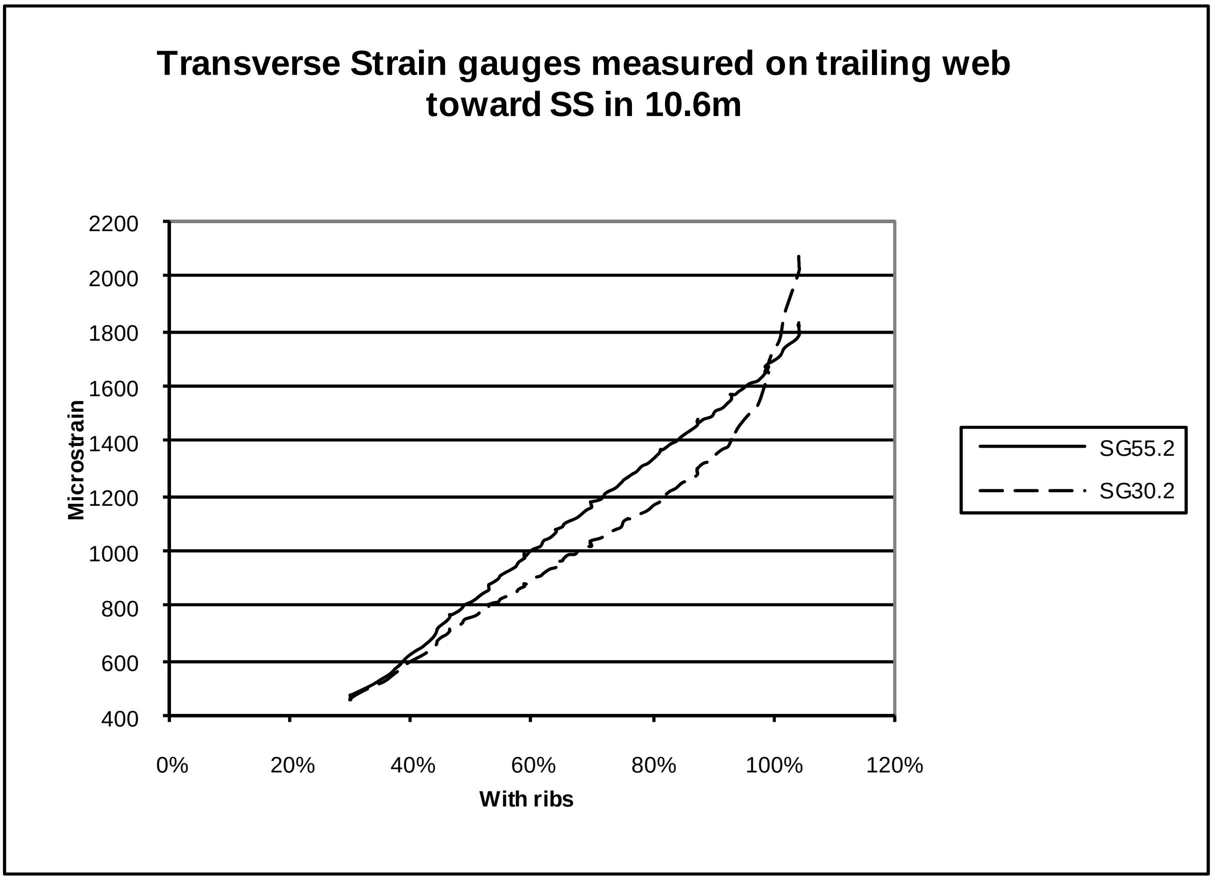

Transverse Strain gauges measured on compression side in 10.8m
2000
1600
1200
800
400
0
Microstrain
0%
20%
40%
60%
80%
100%
120%
With ribs
SG21
SG22


Transverse Strain gauges measured on compression side in 10m
Microstrain
3000
2500
2000
1500
1000
500
0
0%
20%
40%
60%
80%
100%
120%
With ribs
SG17
SG18

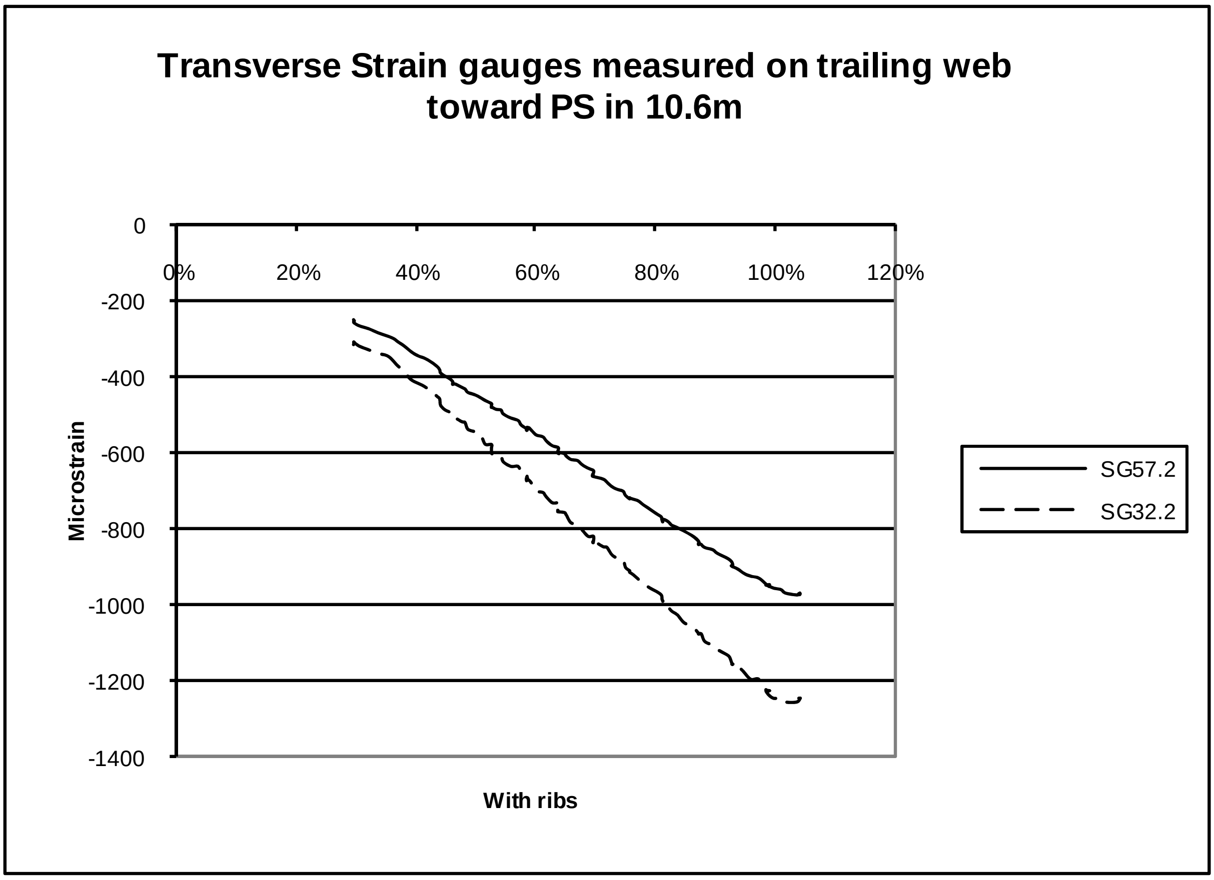

Transverse Strain gauges measured on compression side in 11.5m
Microstrain
5000
4000
3000
2000
1000
0
-1000
-2000
0%
20%
40%
60%
80%
100%
120%
With ribs
SG25.2
SG26.2

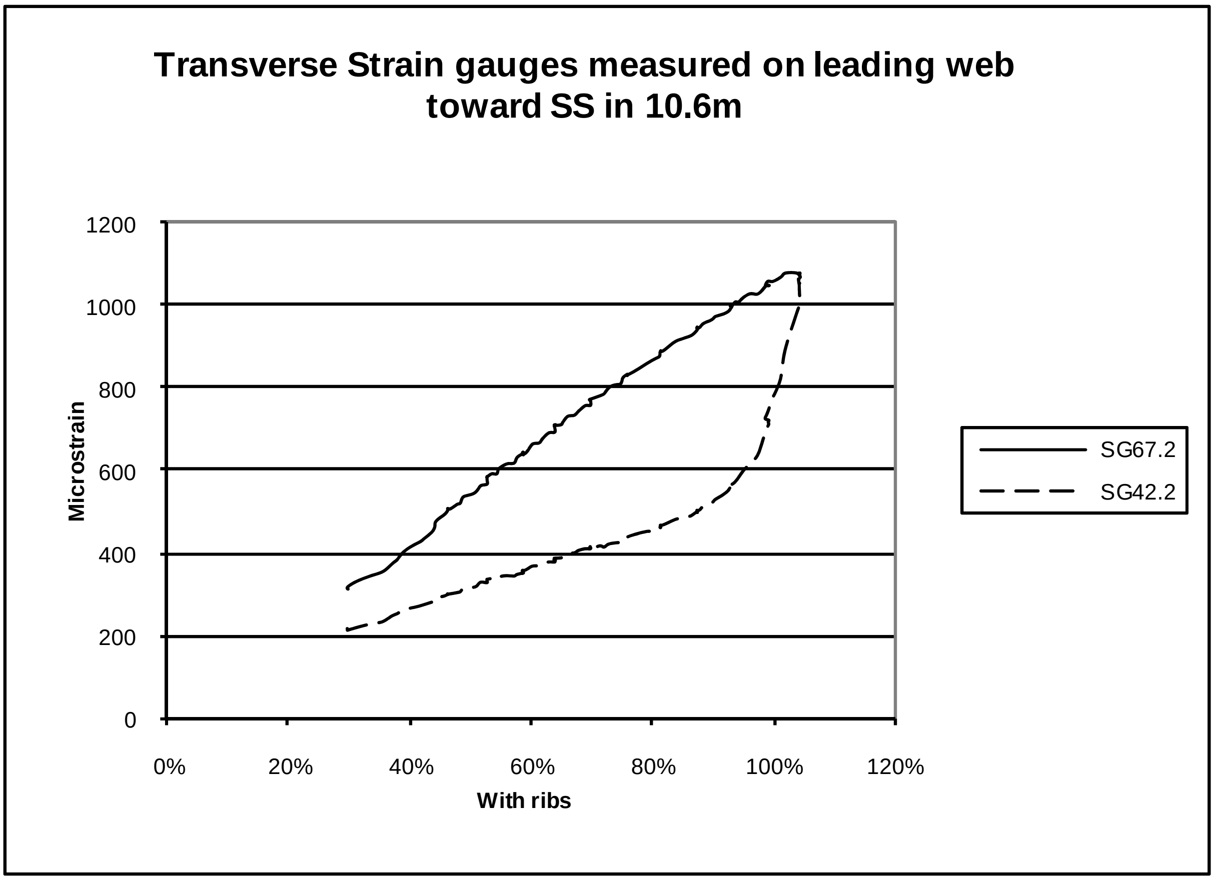


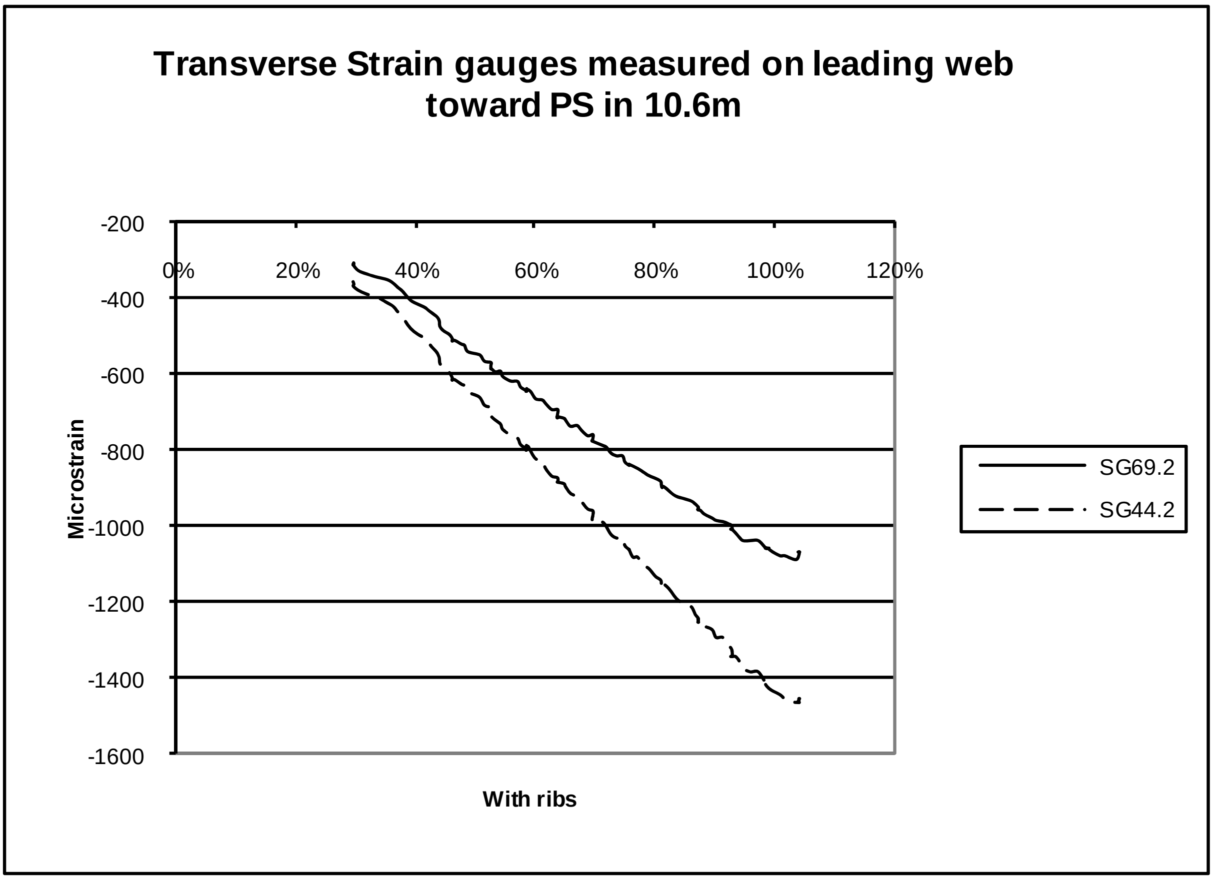
Transverse Strain gauges measured on compression side in 10.4m
2000
1600
1200
800
400
0
Microstrain
0%
20%
40%
60%
80%
100%
120%
With ribs
SG19
SG20

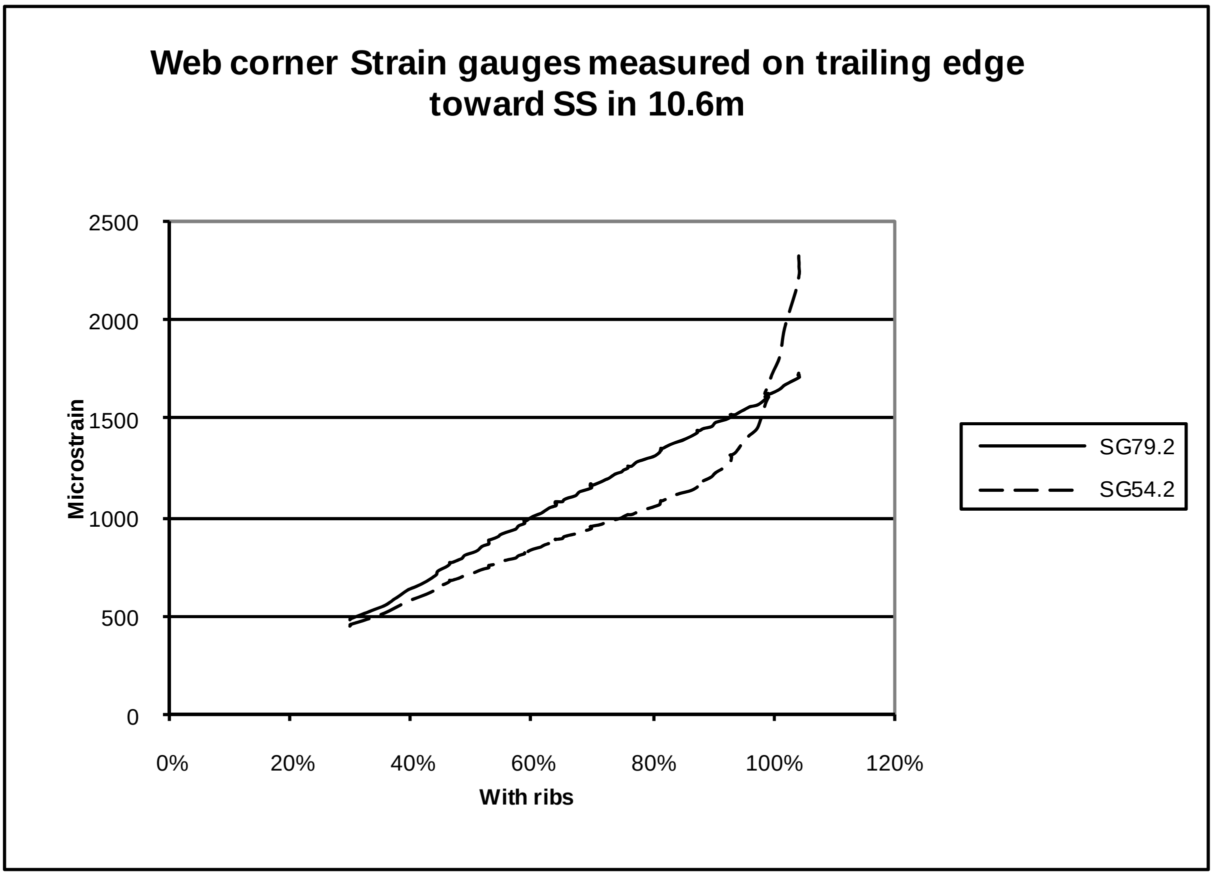


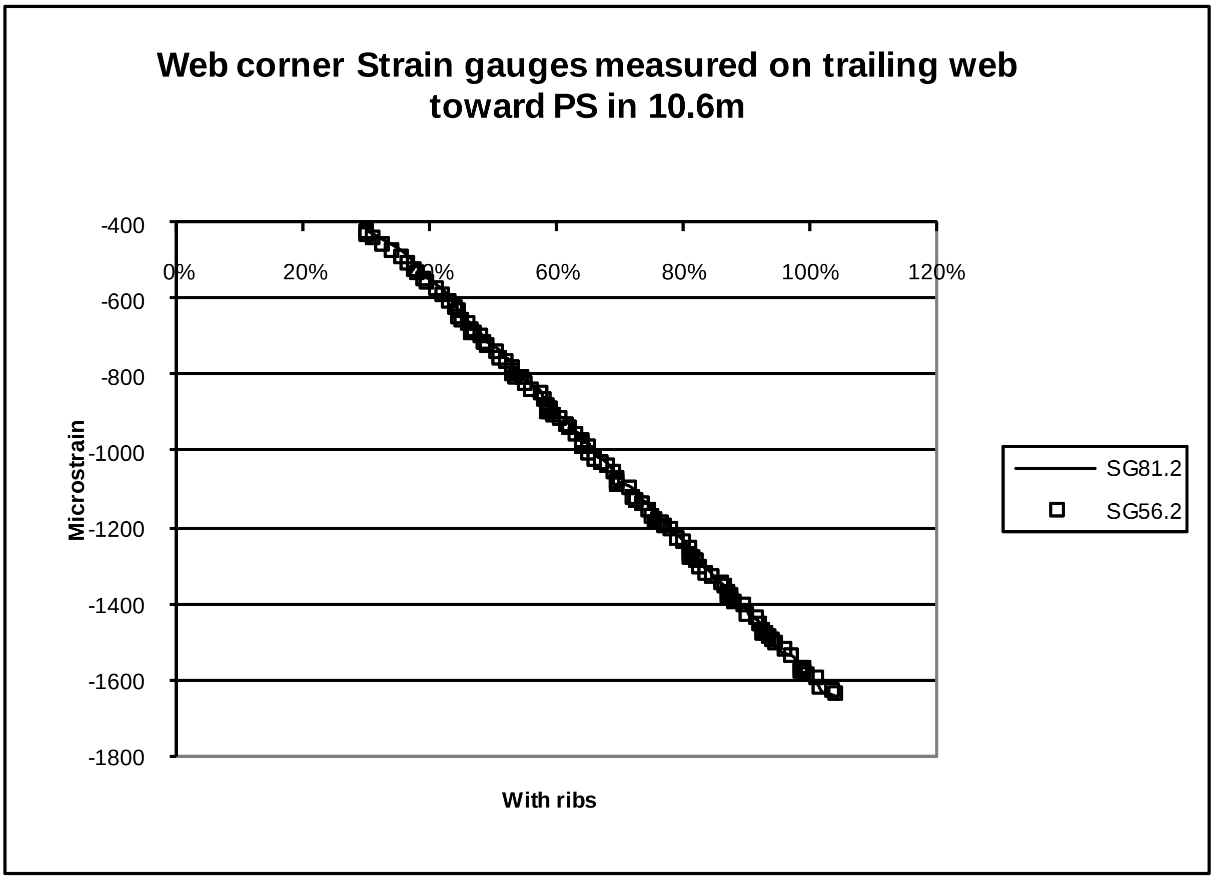
Transverse Strain gauges measured on trailing web toward SS in 10.6m
2200
2000
1800
1600
1400
1200
1000
800
600
400
Microstrain
0%
20%
40%
60%
80%
100%
120%
With ribs
SG55.2
SG30.2


Transverse Strain gauges measured on trailing web toward PS in 10.6m
0
-200
-400
-600
-800
-1000
-1200
-1400
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG57.2
SG32.2

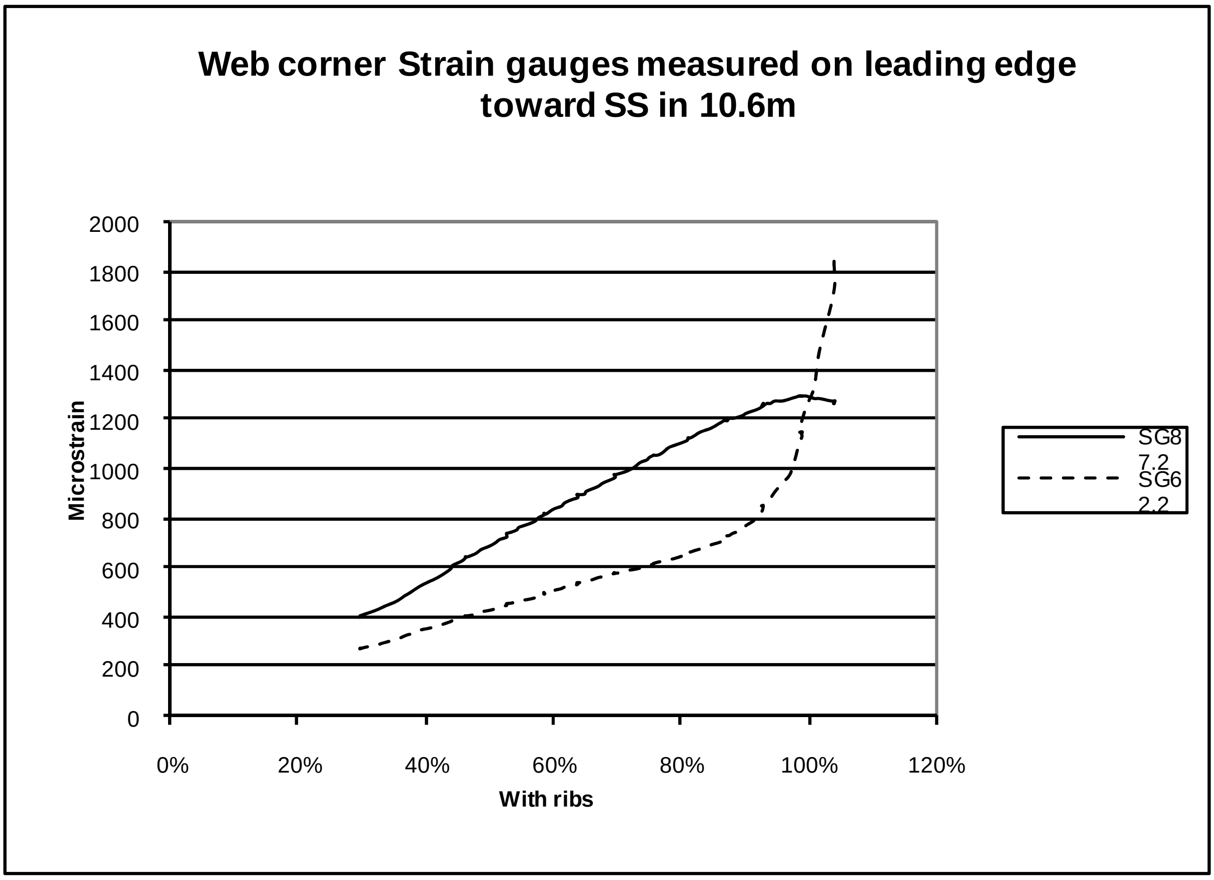

Transverse Strain gauges measured on leading web toward SS in 10.6m
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG67.2
SG42.2


Transverse Strain gauges measured on leading web toward PS in 10.6m
-200
-400
-600
-800
-1000
-1200
-1400
-1600
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG69.2
SG44.2

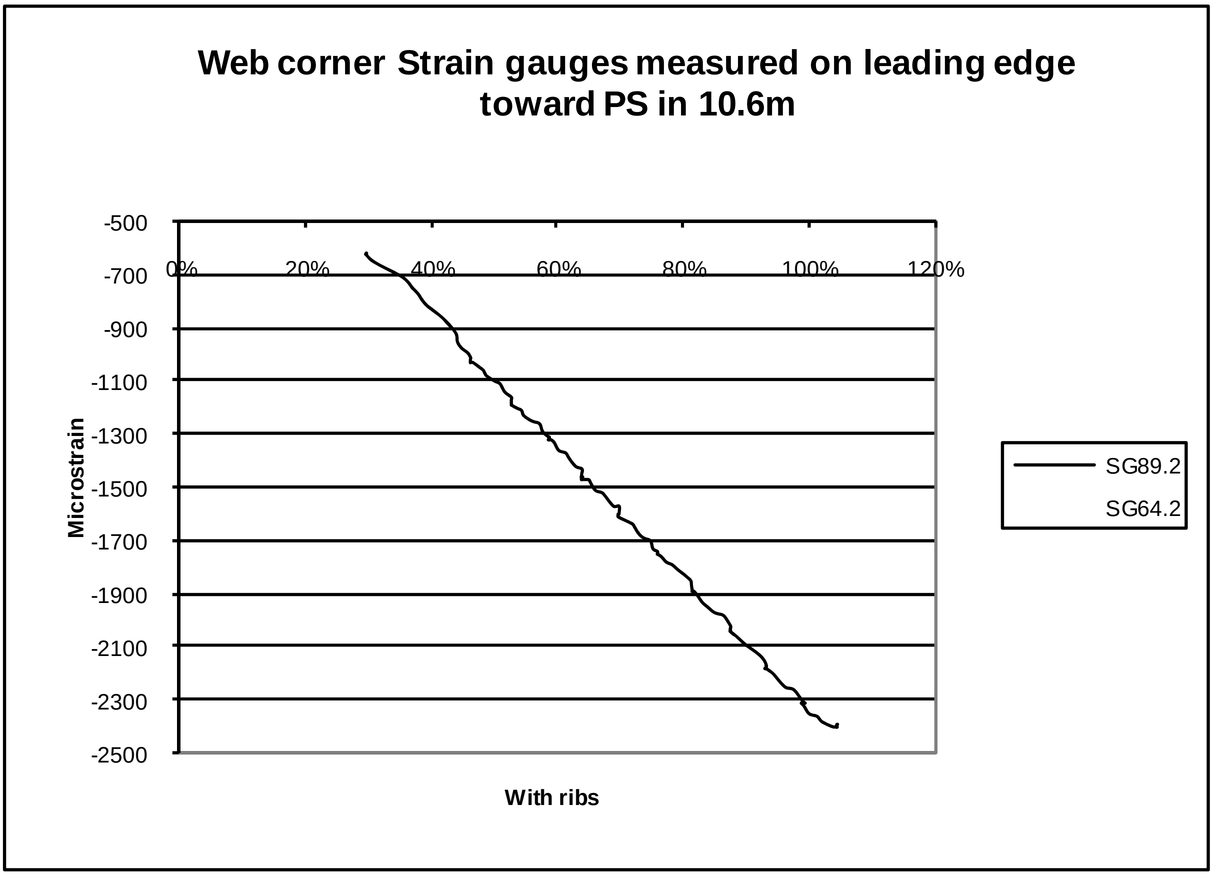

Web corner Strain gauges measured on trailing edge toward SS in 10.6m
2500
2000
1500
1000
500
0
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG79.2
SG54.2

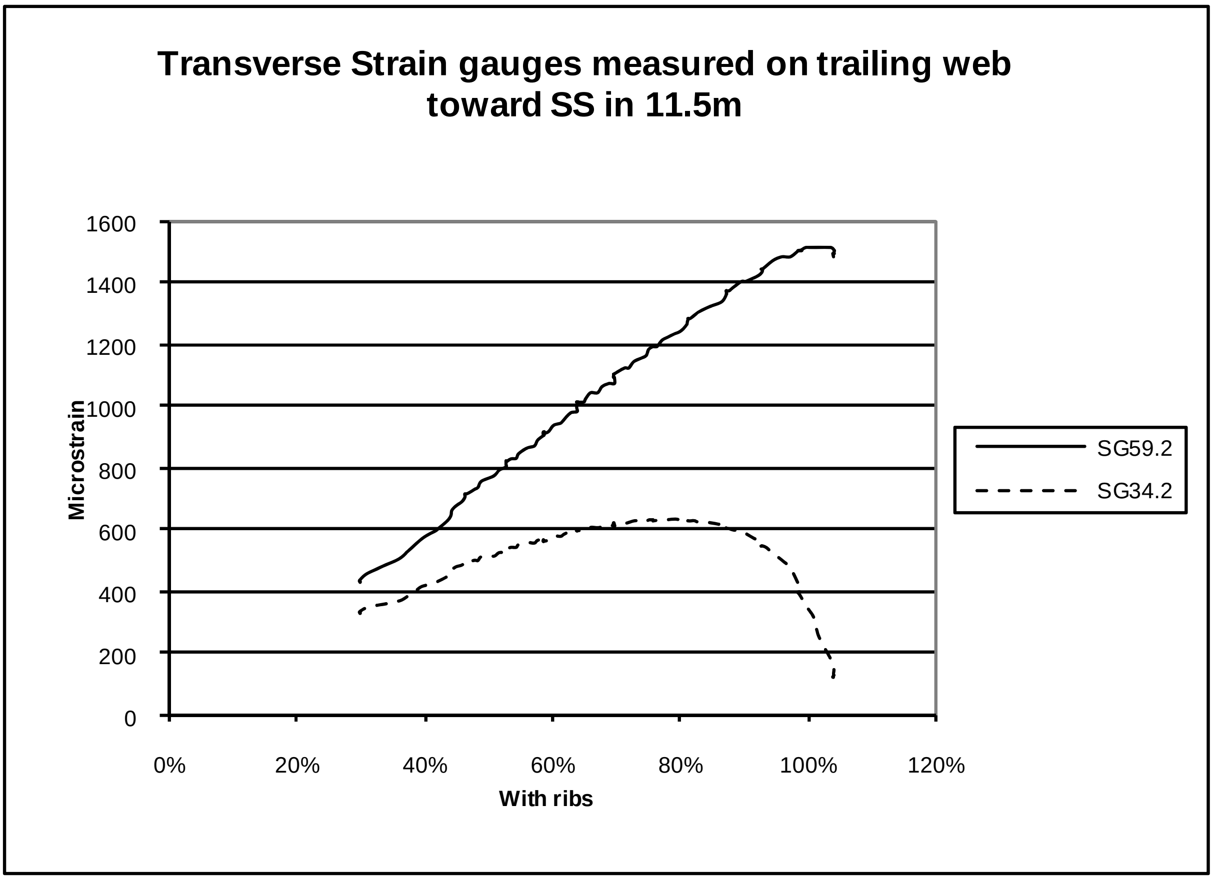


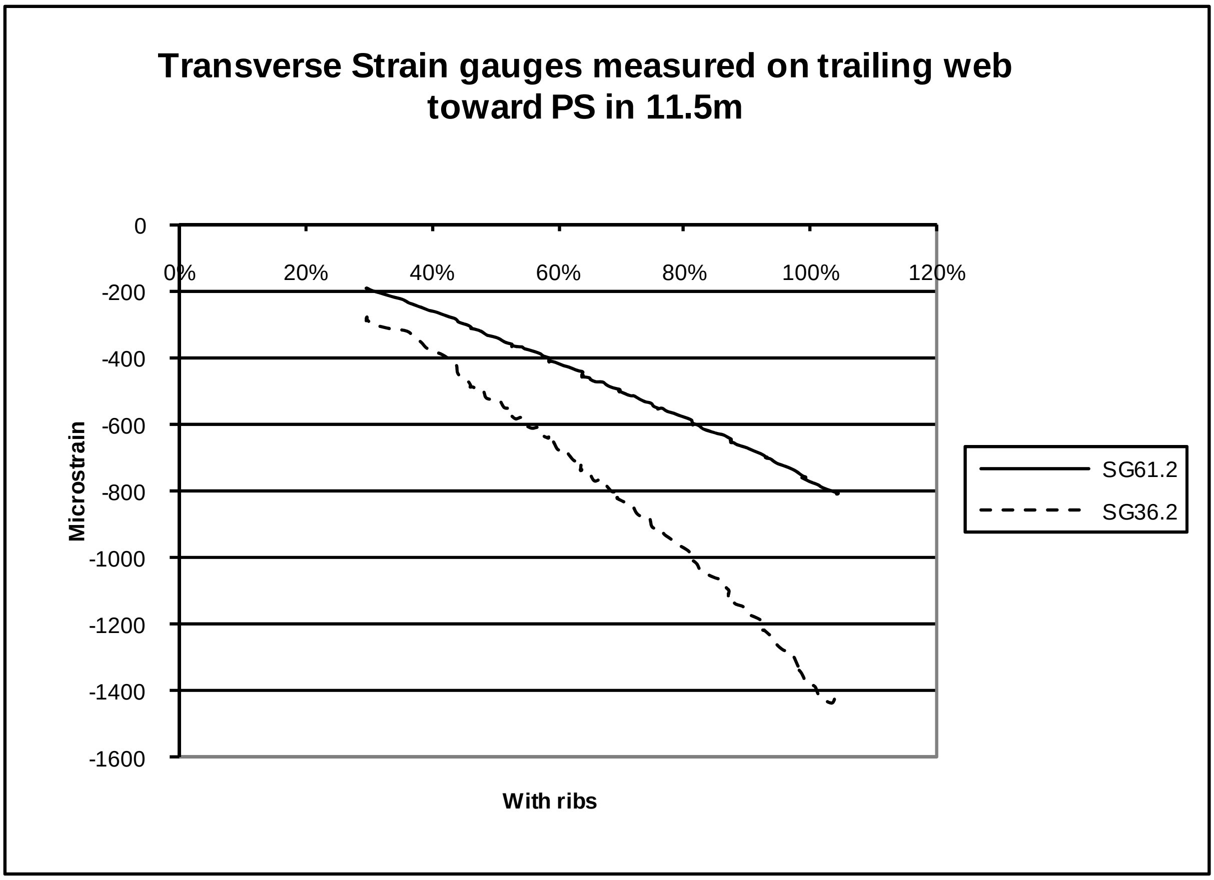
Web corner Strain gauges measured on trailing web toward PS in 10.6m
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
Microstrain
0%
20%
60%
80%
100%
120%
With ribs
SG81.2
SG56.2

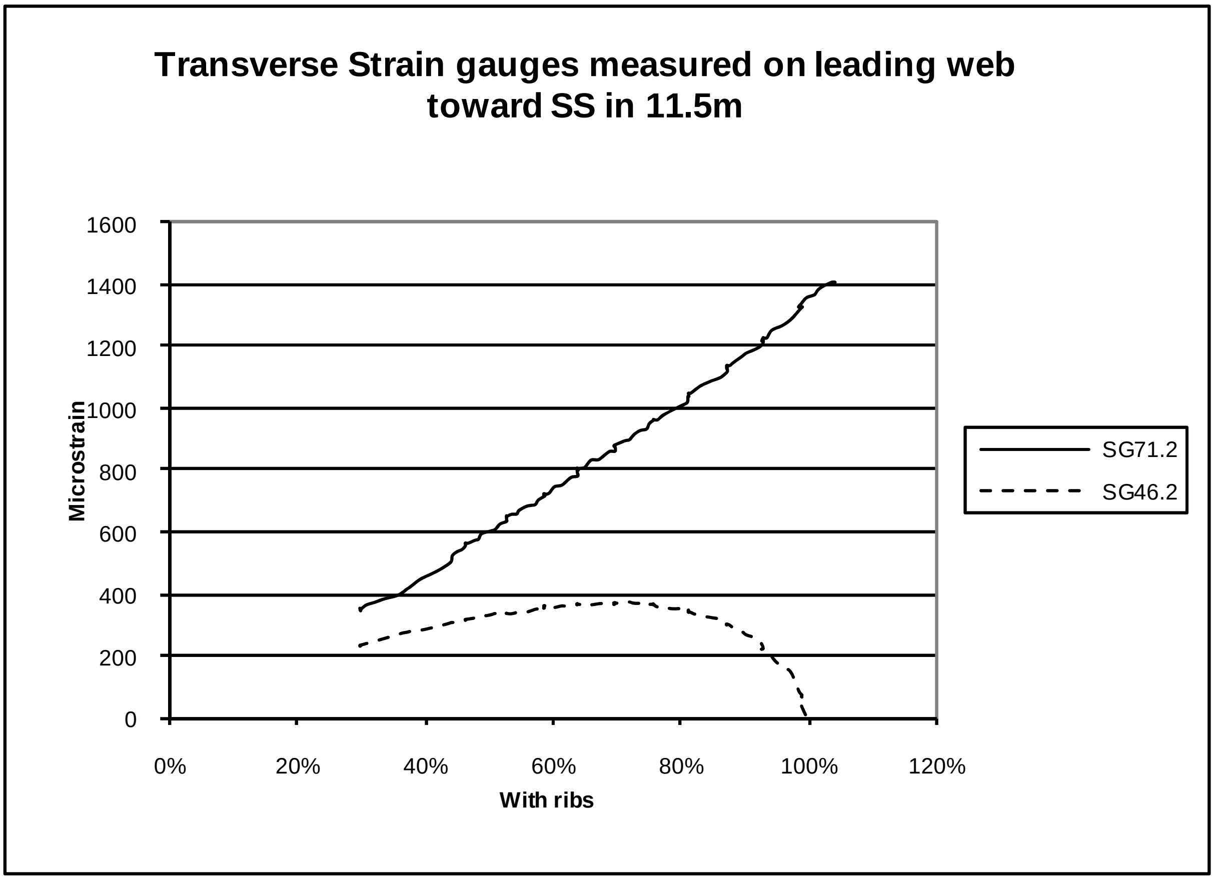


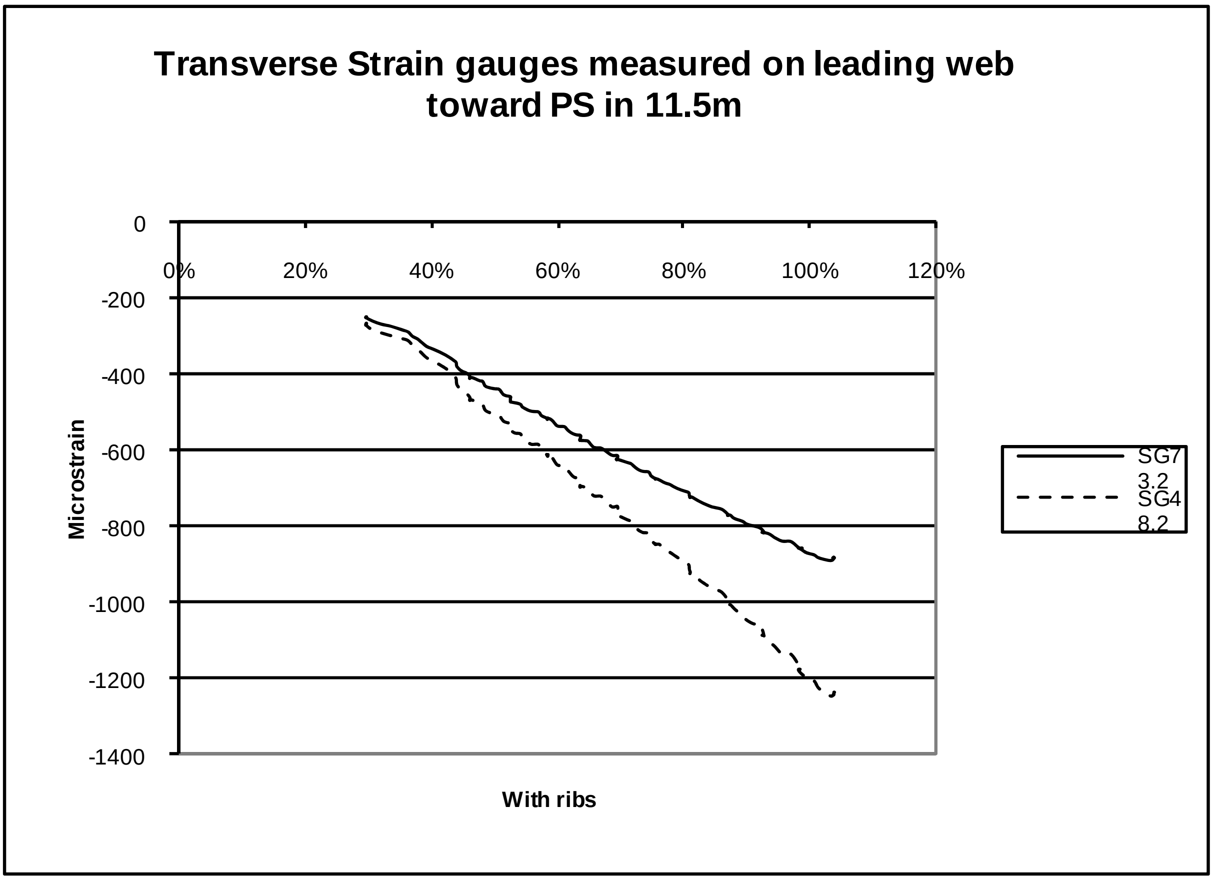
Web corner Strain gauges measured on leading edge toward SS in 10.6m
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Microstrain
0%
20%
40%
60%
80%
100%
120%
With ribs
SG87.2
SG62.2


Web corner Strain gauges measured on leading edge toward PS in 10.6m
Microstrain
-500
-700
-900
-1100
-1300
-1500
-1700
-1900
-2100
-2300
-2500
0%
20%
40%
60%
80%
100%
120%
With ribs
SG89.2
SG64.2

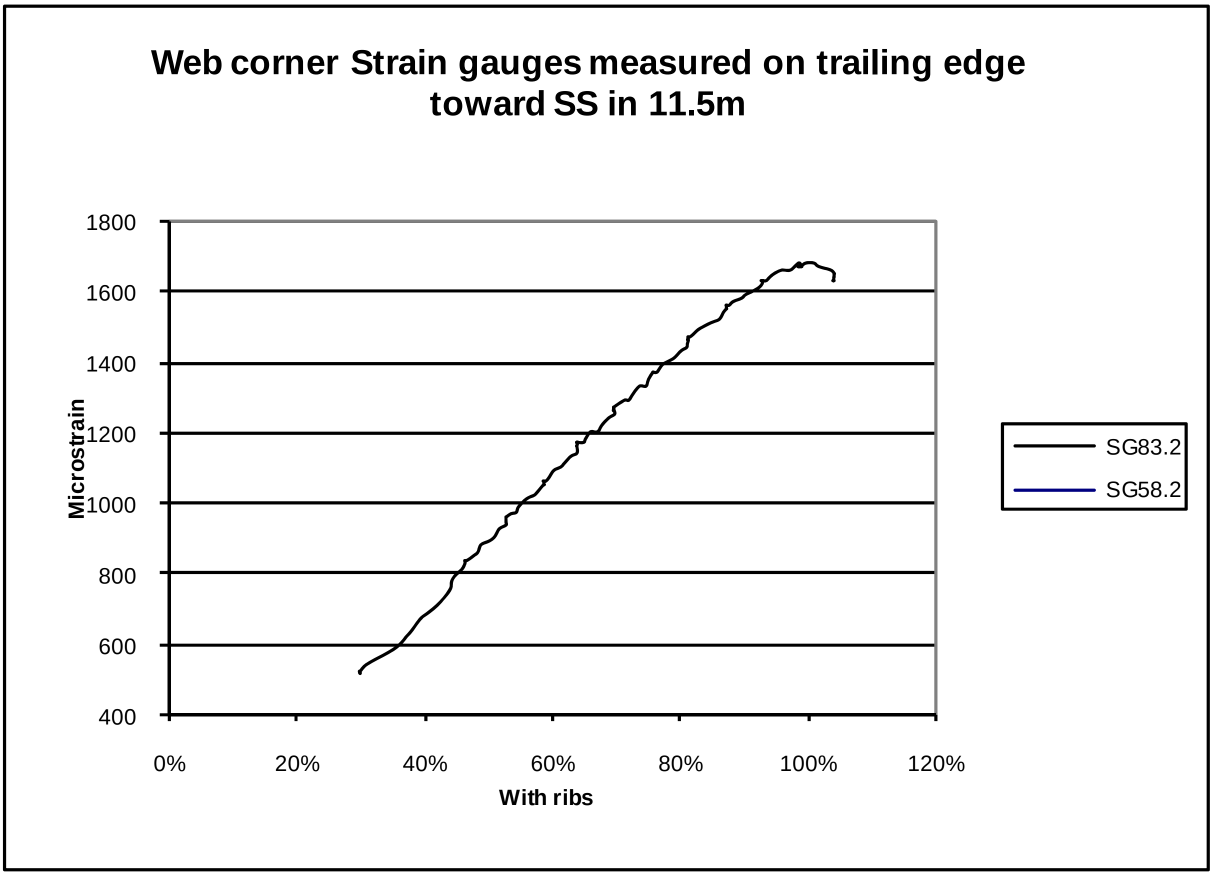

Transverse Strain gauges measured on trailing web toward SS in 11.5m
Microstrain
1600
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
120%
With ribs
SG59.2
SG34.2


Transverse Strain gauges measured on trailing web toward PS in 11.5m
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG61.2
SG36.2

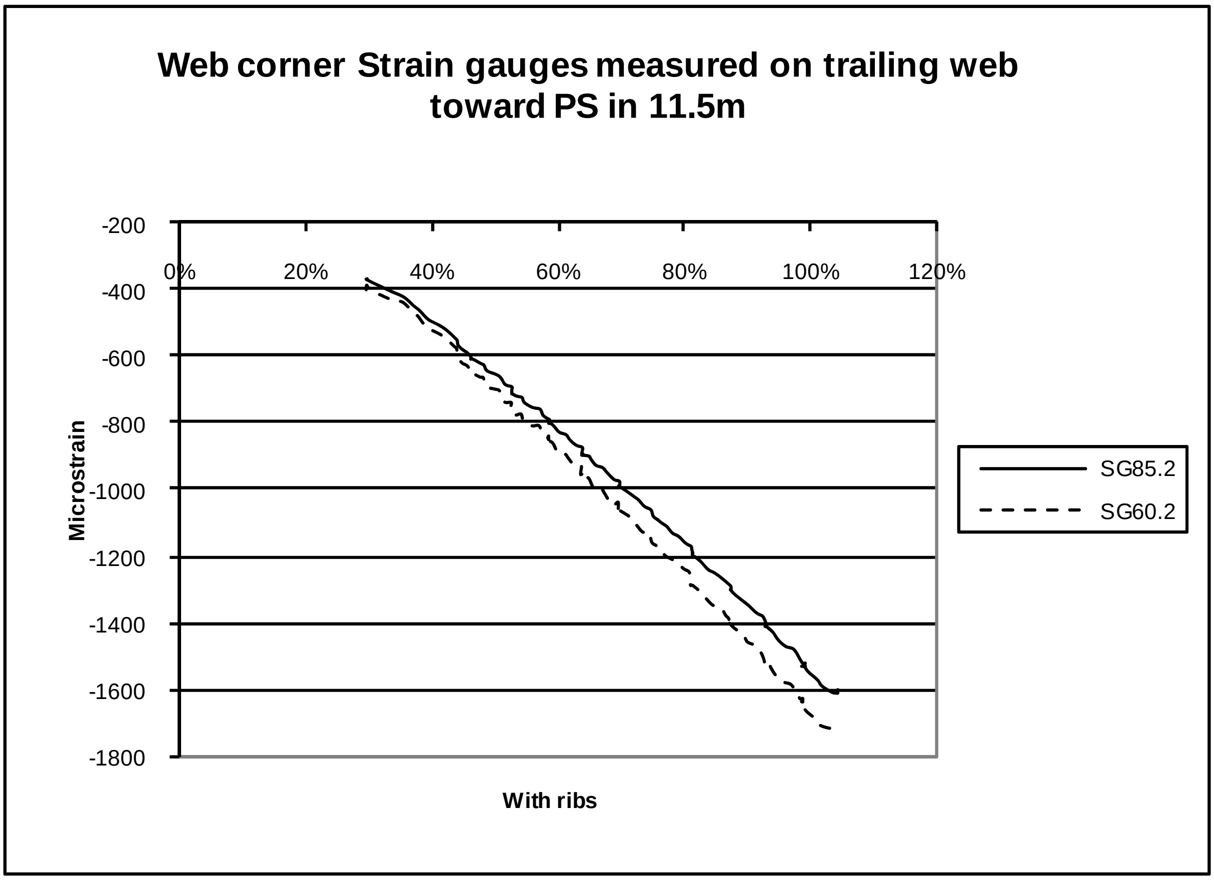

Transverse Strain gauges measured on leading web toward SS in 11.5m
1600
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG71.2
SG46.2

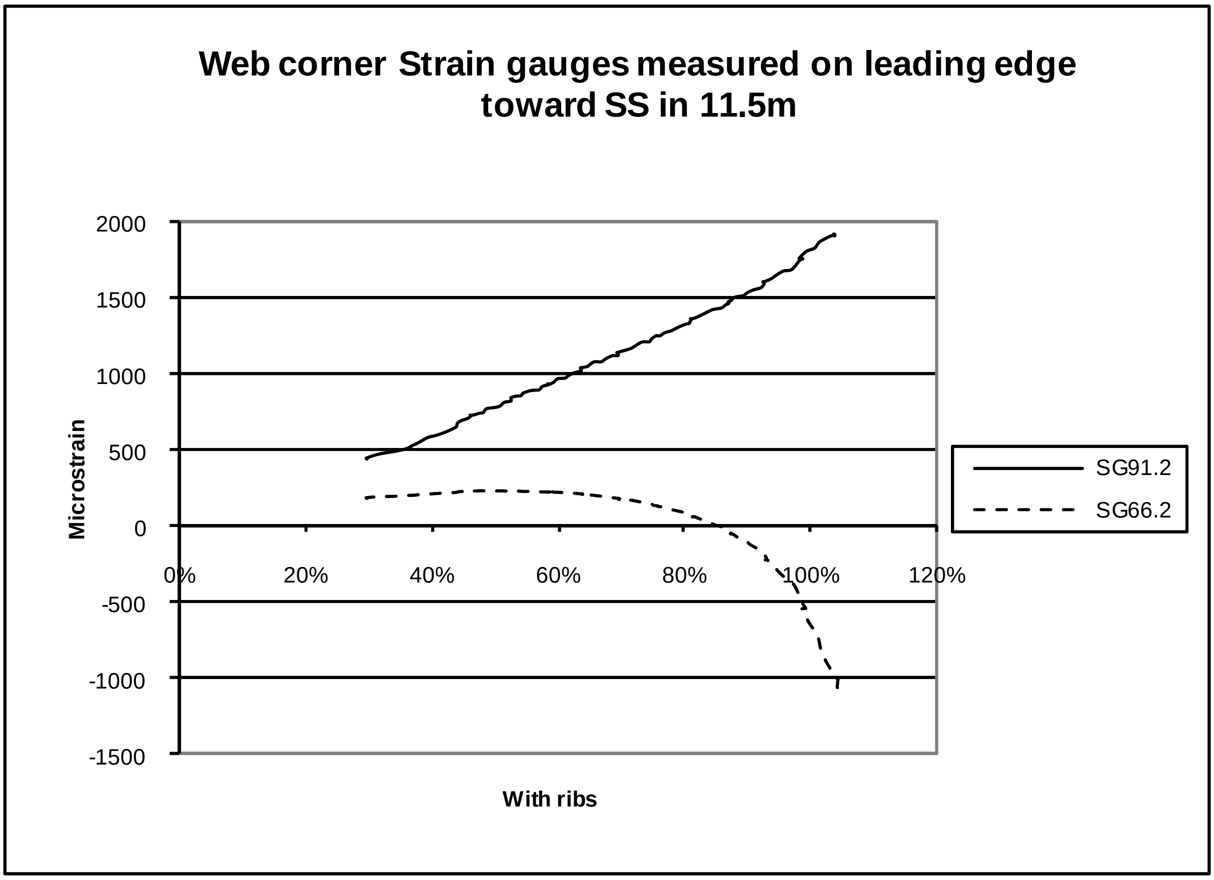


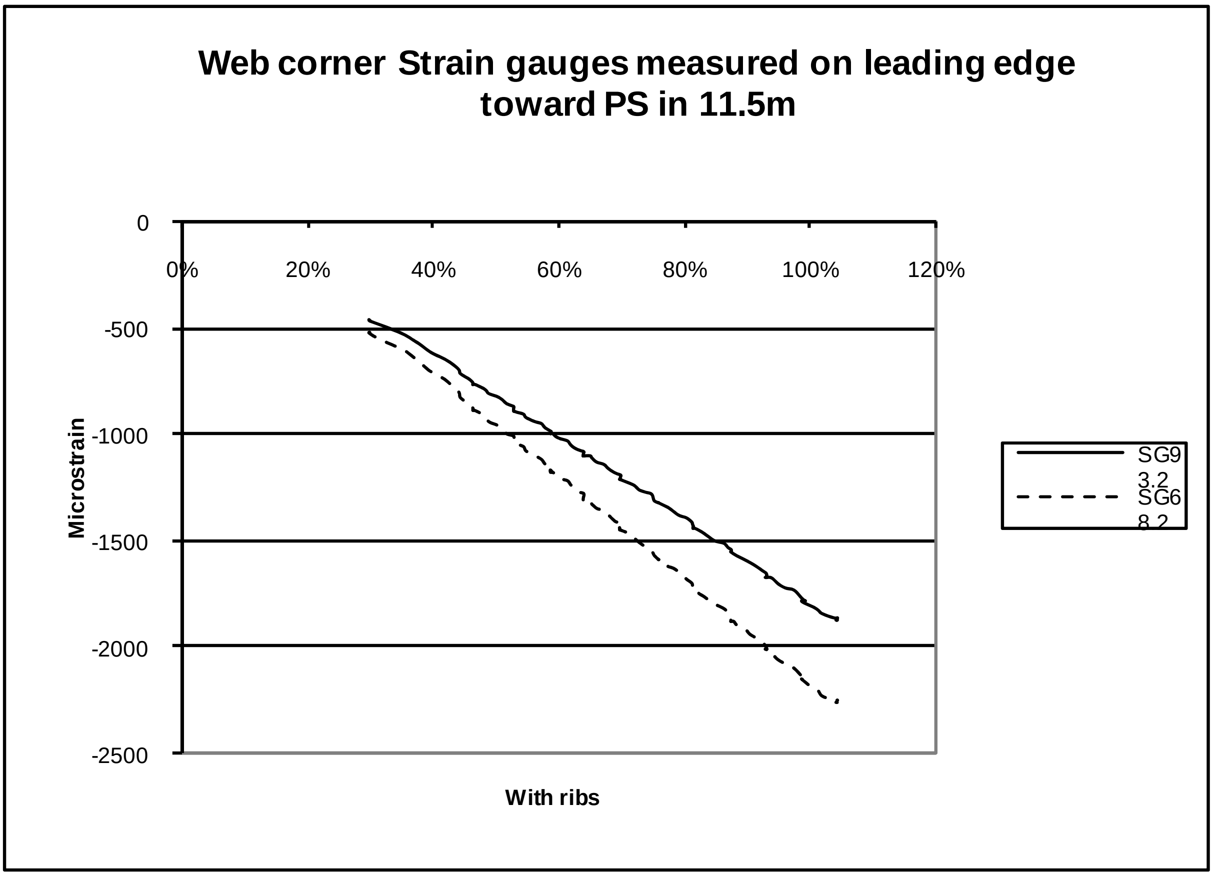
Transverse Strain gauges measured on leading web toward PS in 11.5m
0
-200
-400
-600
-800
-1000
-1200
-1400
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG73.2
SG48.2



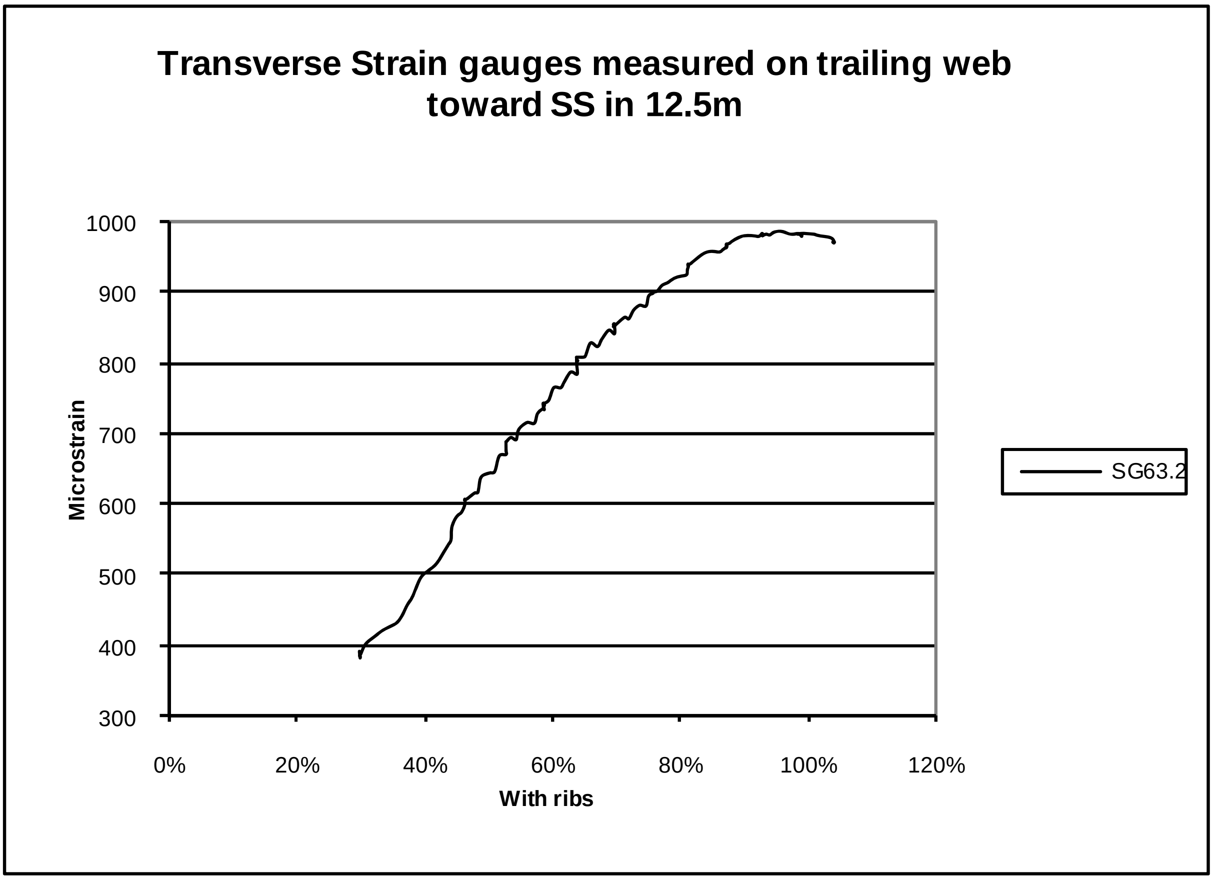
Web corner Strain gauges measured on trailing edge toward SS in 11.5m
1800
1600
1400
1200
1000
800
600
400
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG83.2
SG58.2


Web corner Strain gauges measured on trailing web toward PS in 11.5m
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG85.2
SG60.2

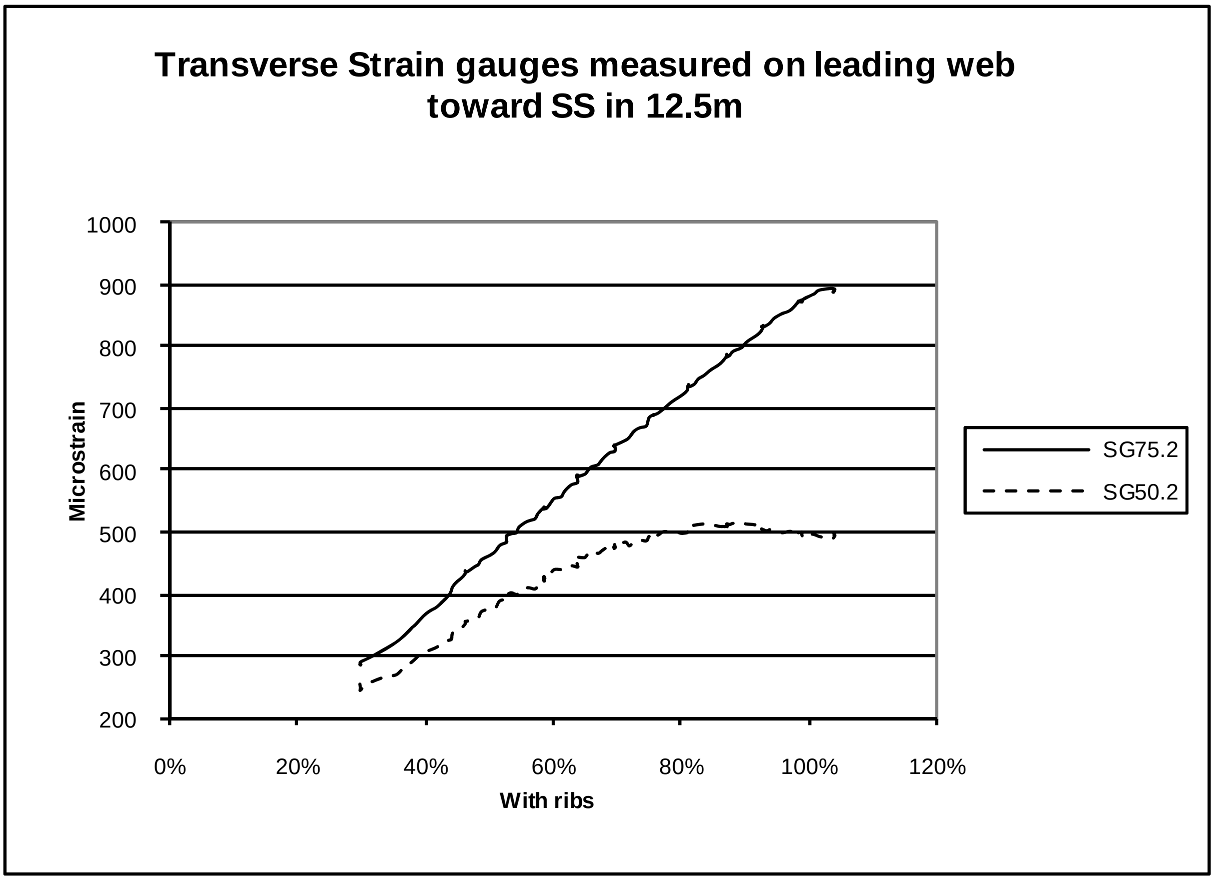

Web corner Strain gauges measured on leading edge toward SS in 11.5m
2000
1500
1000
500
0
-500
-1000
-1500
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG91.2
SG66.2

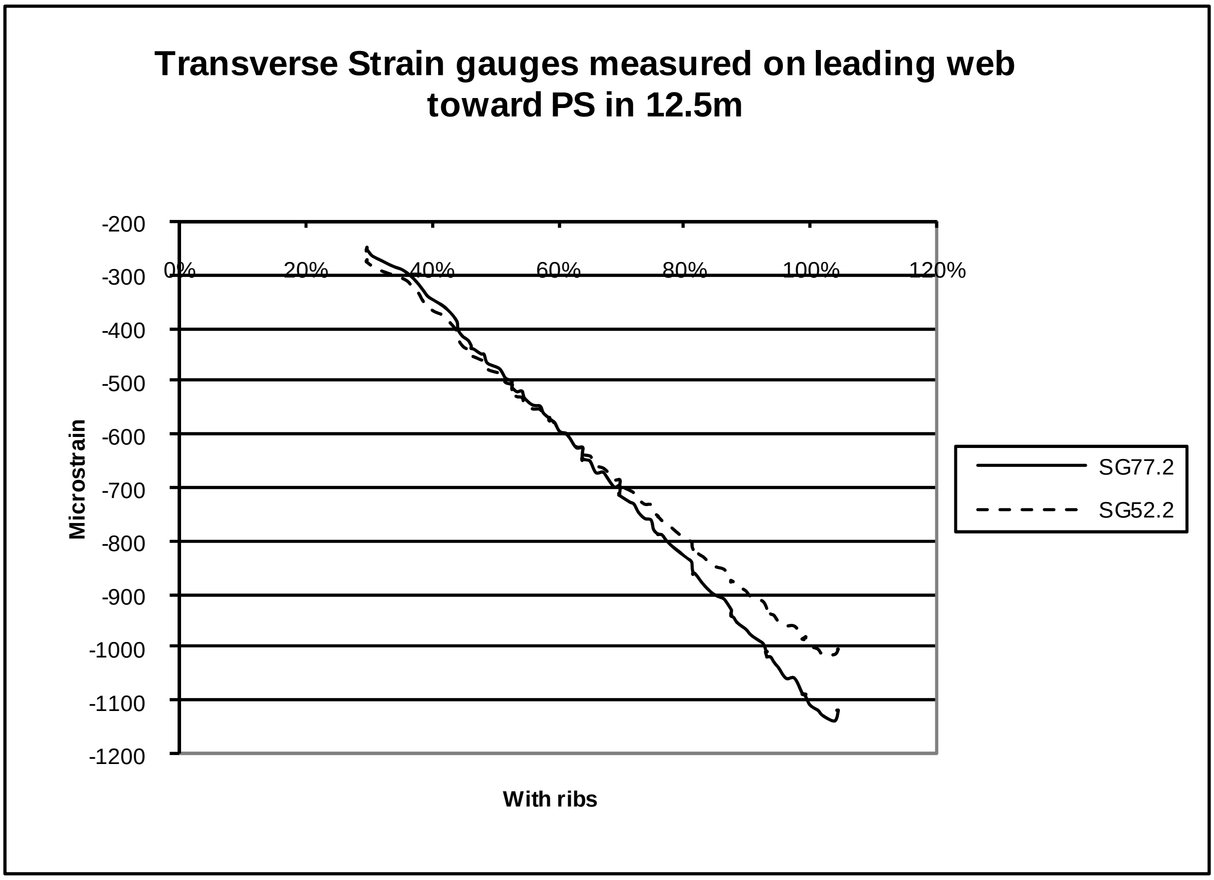


Web corner Strain gauges measured on leading edge toward PS in 11.5m
0
-500
-1000
-1500
-2000
-2500
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG93.2
SG68.2

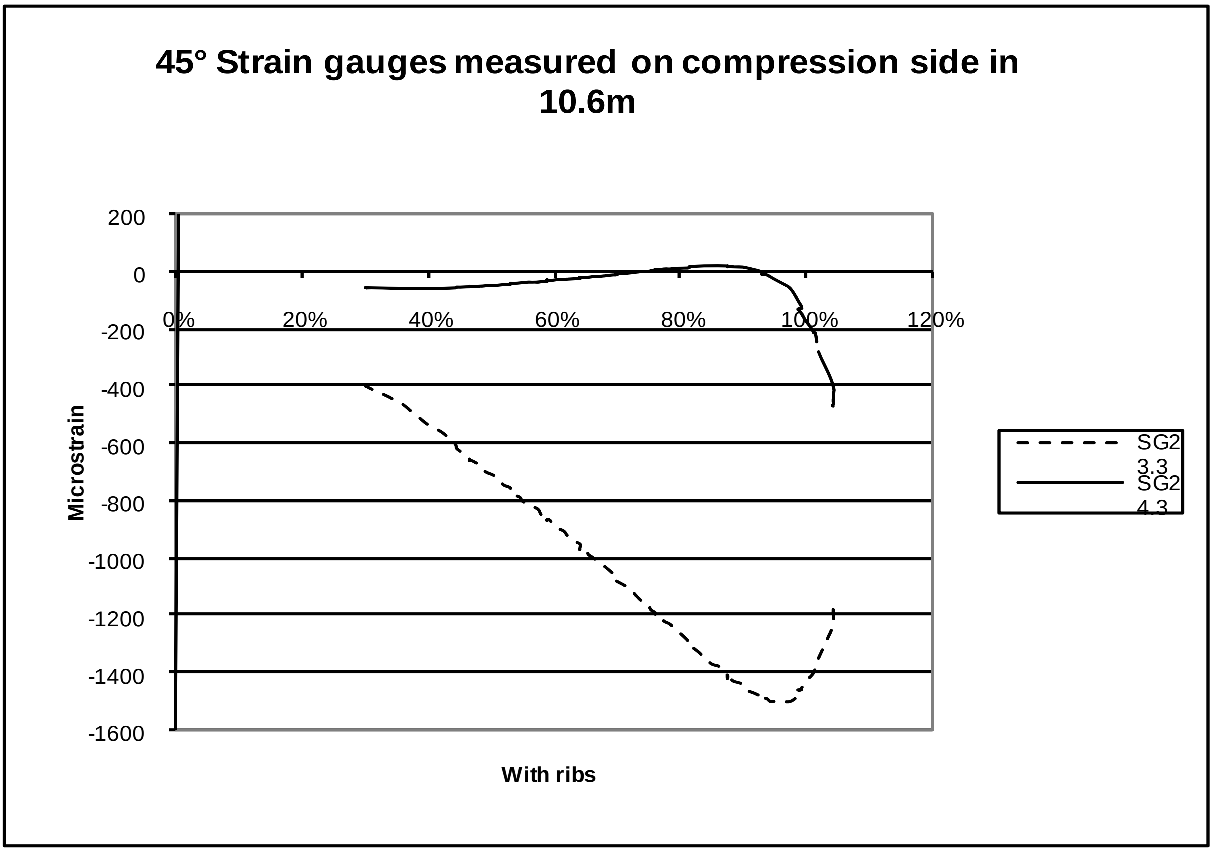


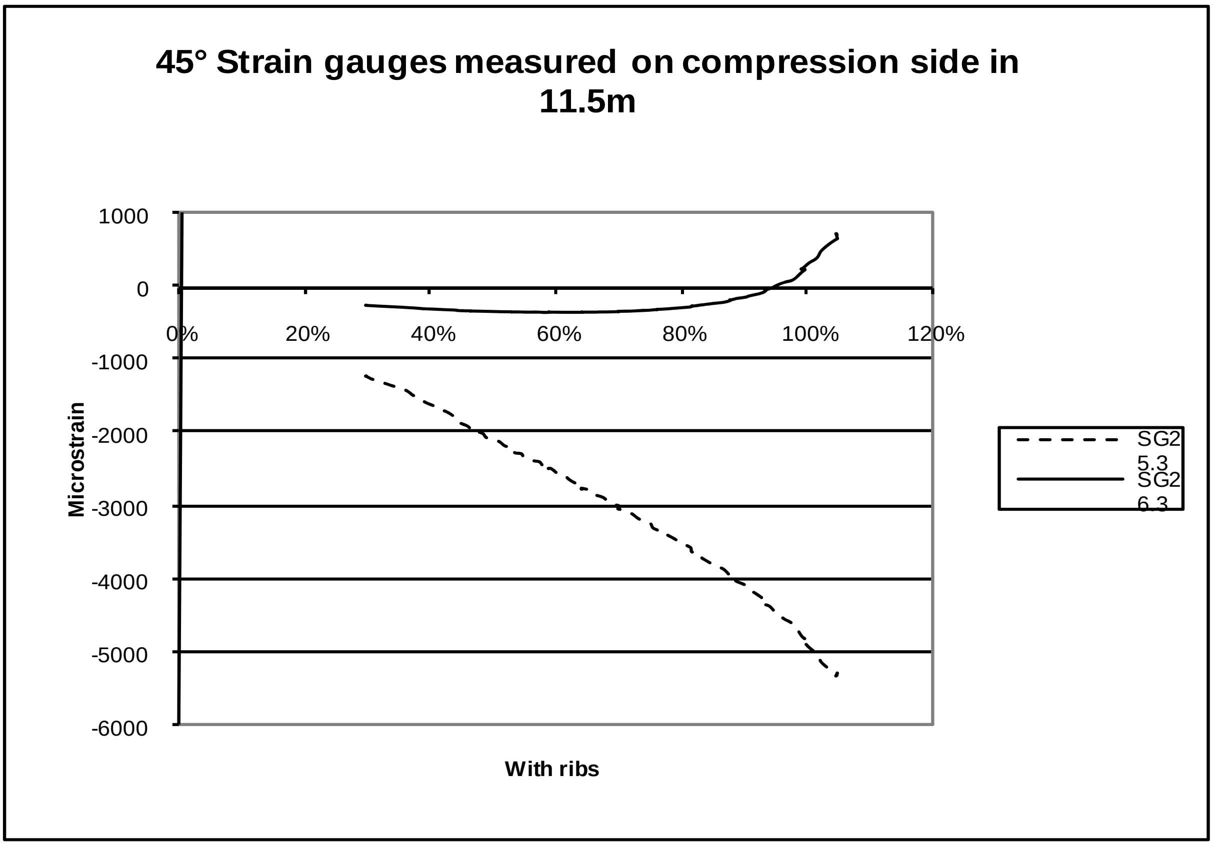
Transverse Strain gauges measured on trailing web toward SS in 12.5m
1000
900
800
700
600
500
400
300
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG63.2

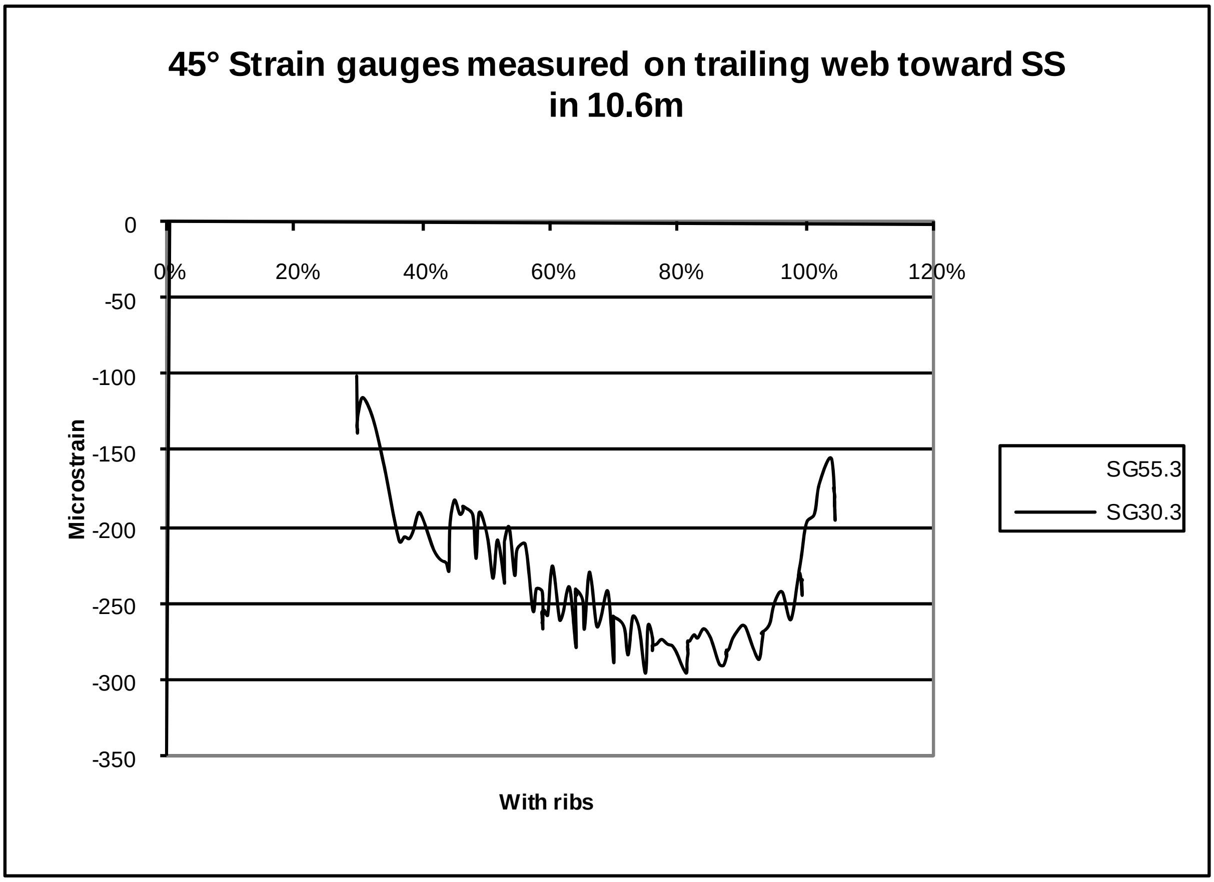

Transverse Strain gauges measured on leading web toward SS in 12.5m
1000
900
800
700
600
500
400
300
200
Microstrain
0%
20%
40%
60%
80%
100%
120%
With ribs
SG75.2
SG50.2

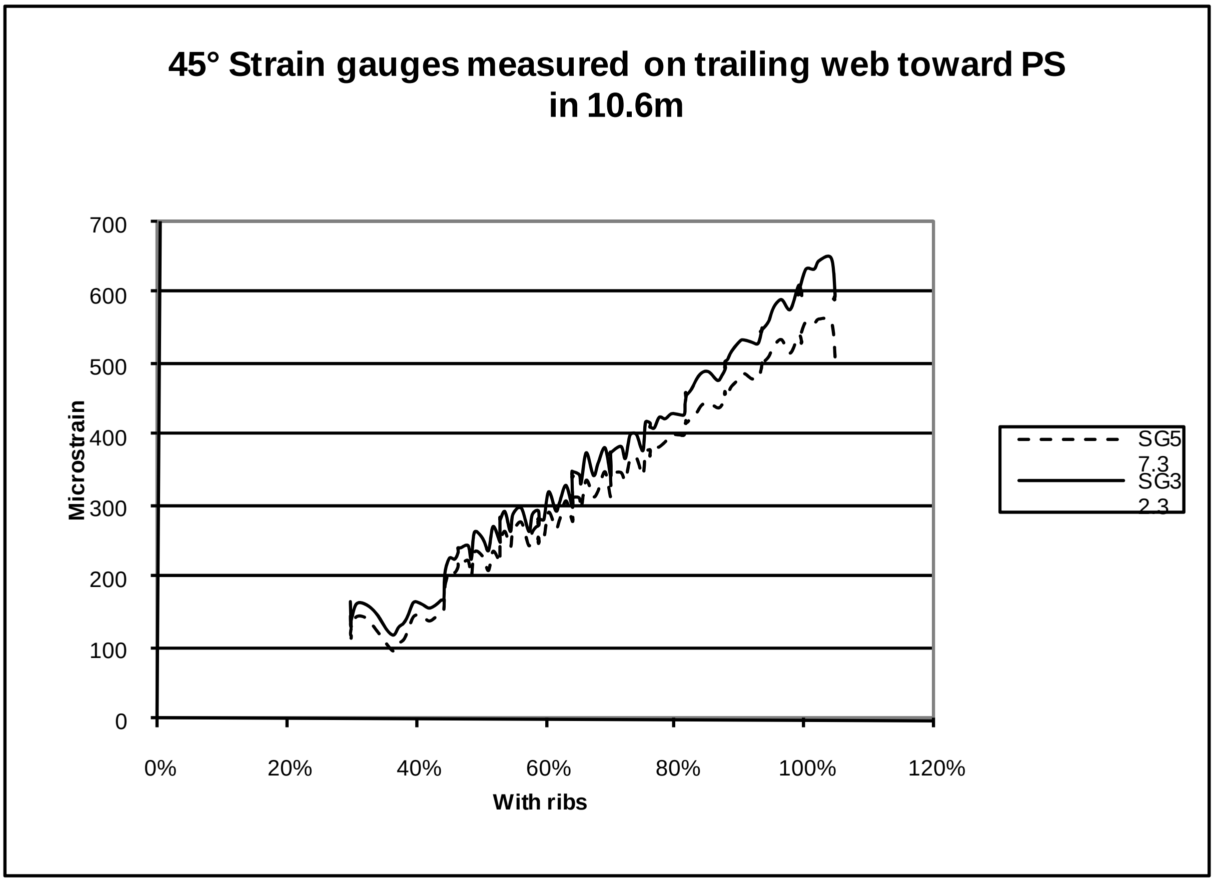

Transverse Strain gauges measured on leading web toward PS in 12.5m
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
Microstrain
0%
20%
40%
60%
80%
100%
120%
With ribs
SG77.2
SG52.2

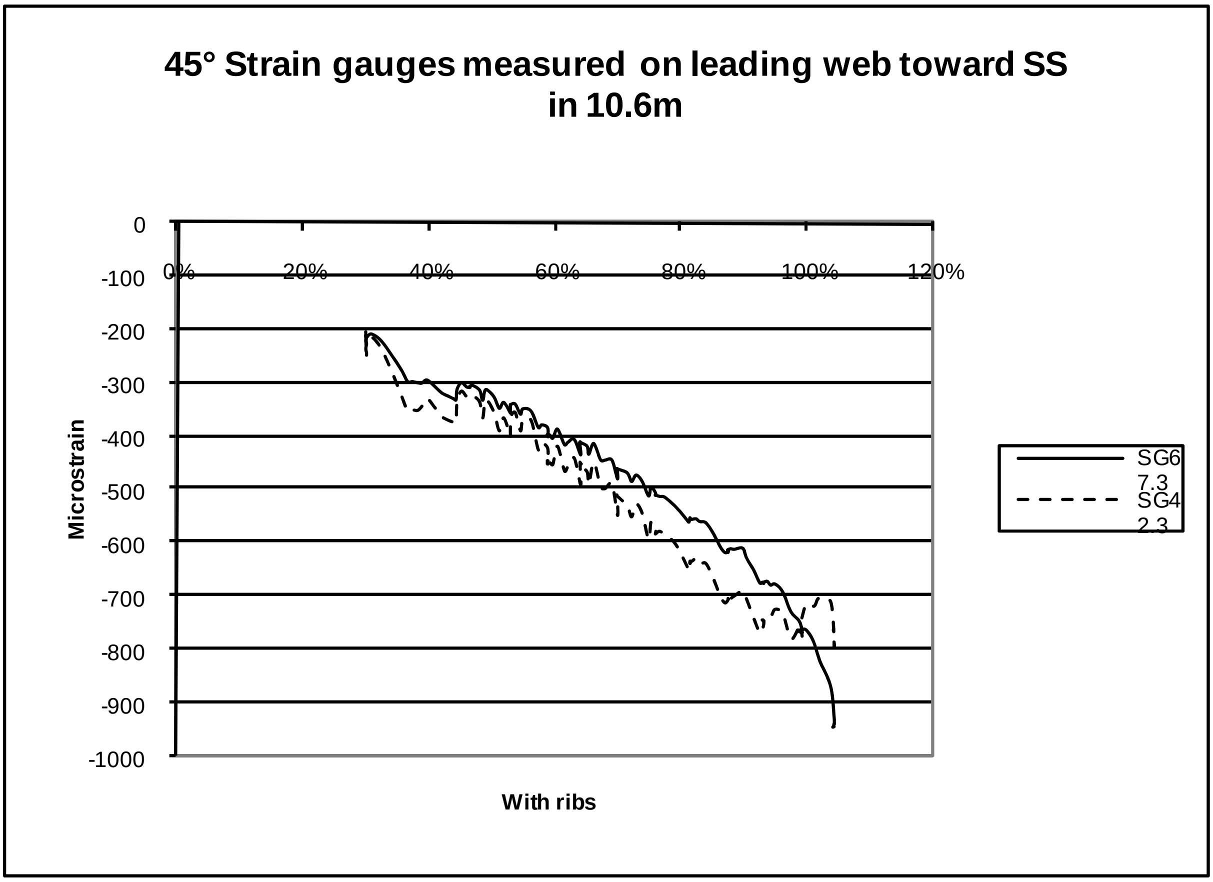
Graphs of 45° measurements with ribs

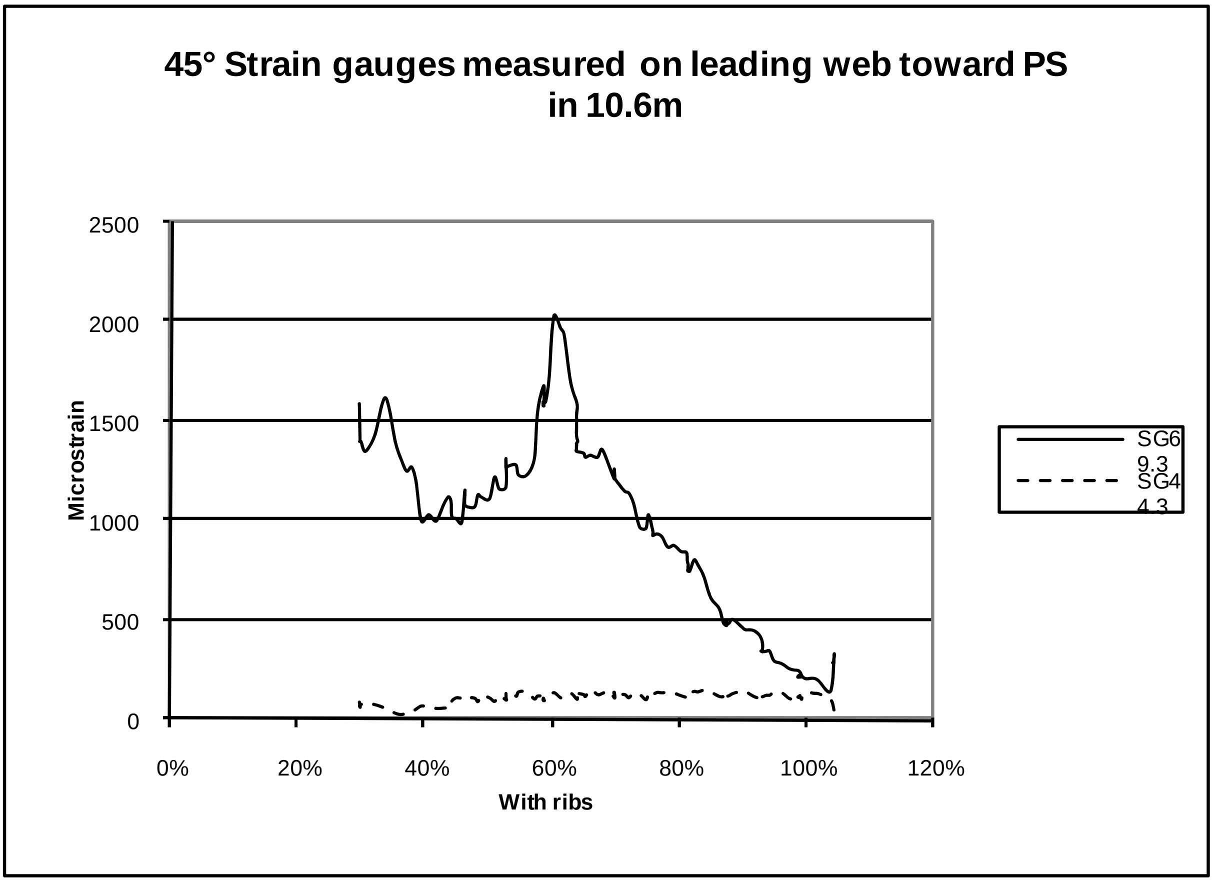


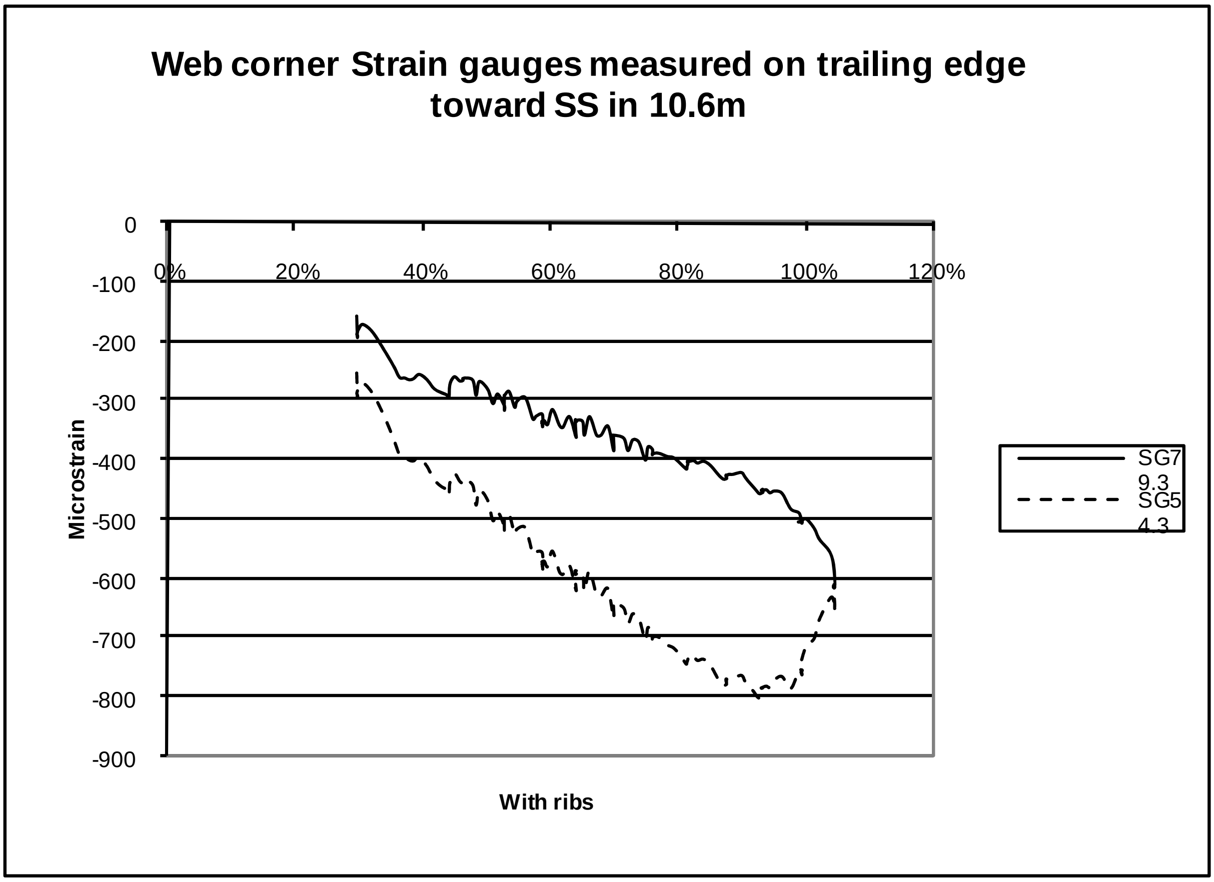


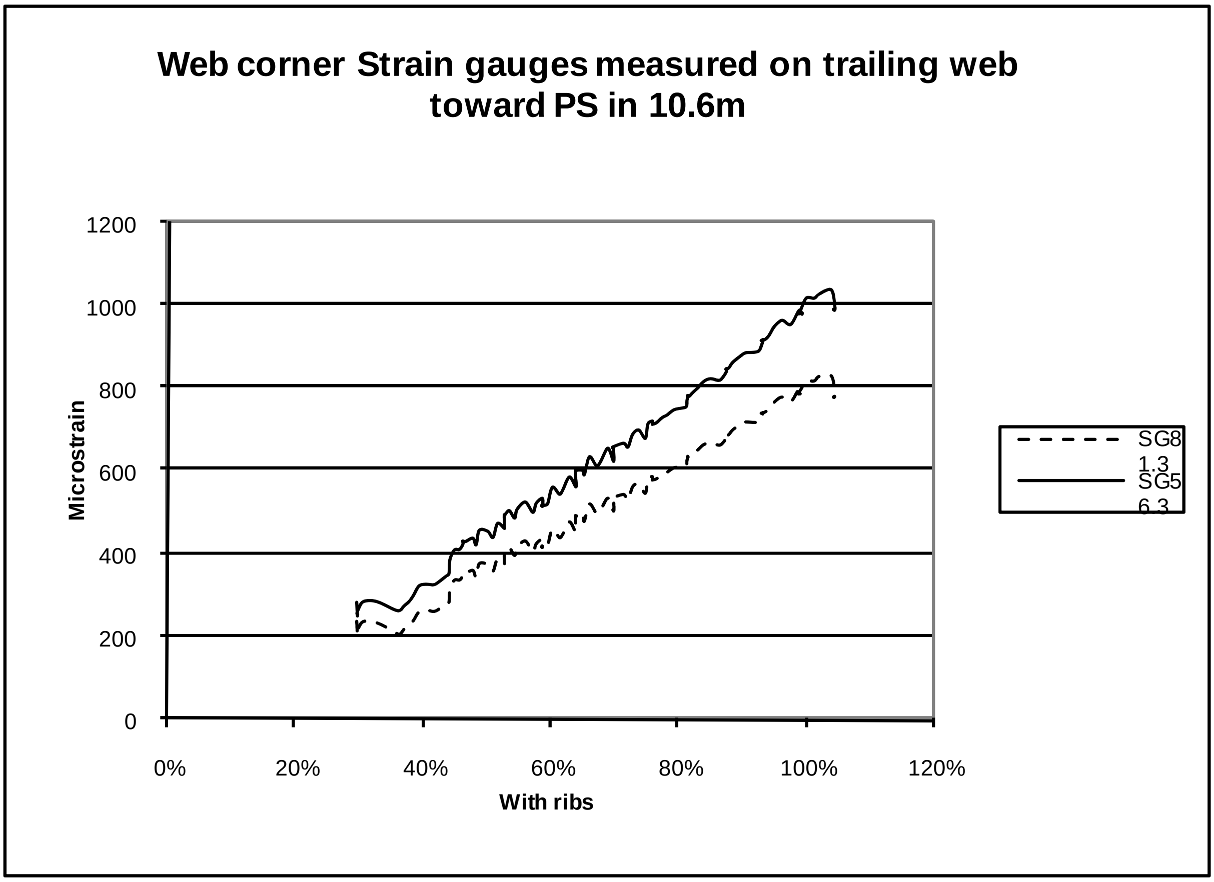

45° Strain gauges measured on trailing web toward SS in 10.6m
0
-50
-100
-150
-200
-250
-300
-350
Microstrain
0%
20%
40%
60%
80%
100%
120%
With ribs
SG55.3
SG30.3

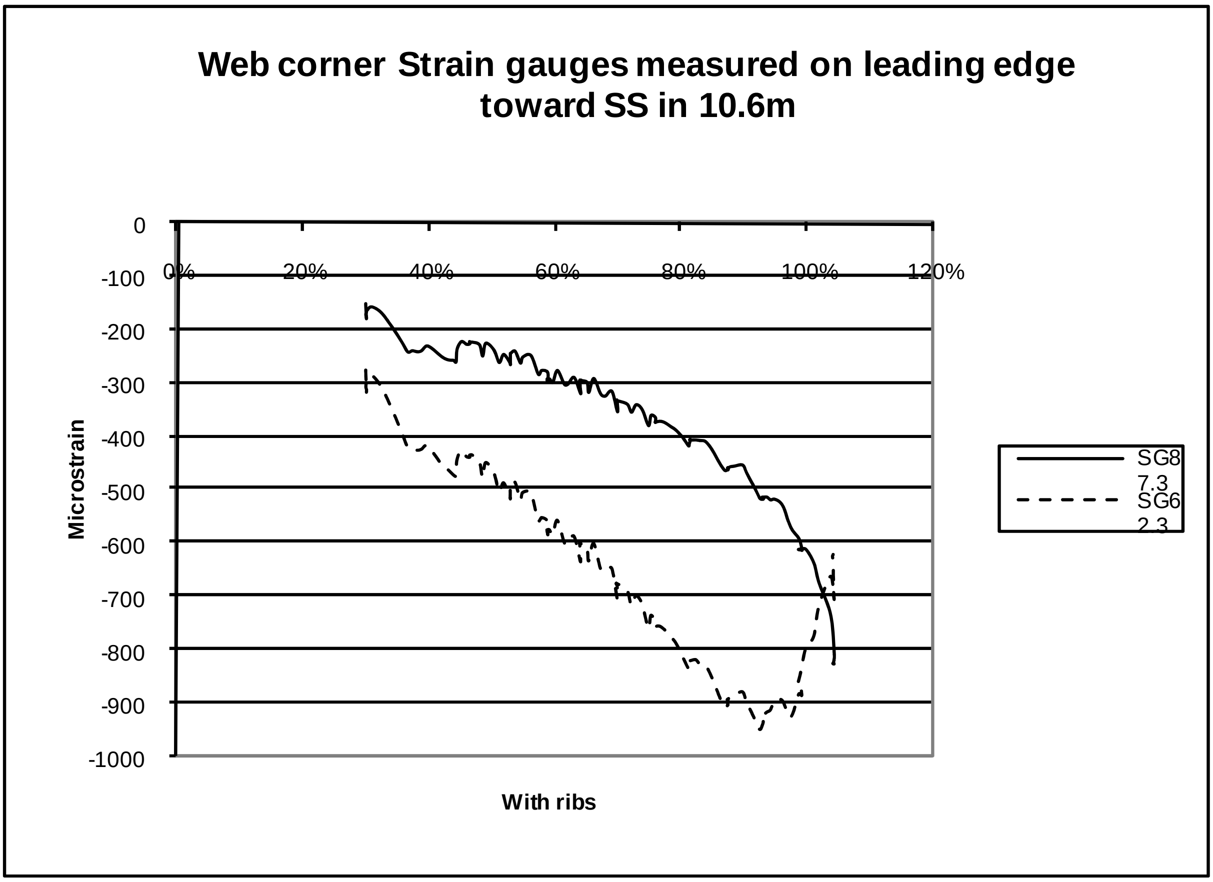

45° Strain gauges measured on trailing web toward PS in 10.6m
700
600
500
400
300
200
100
0
Microstrain
0%
20%
40%
60%
80%
100%
120%
With ribs
SG57.3
SG32.3


45° Strain gauges measured on leading web toward SS in 10.6m
Microstrain
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
0%
20%
40%
60%
80%
100%
120%
With ribs
SG67.3
SG42.3

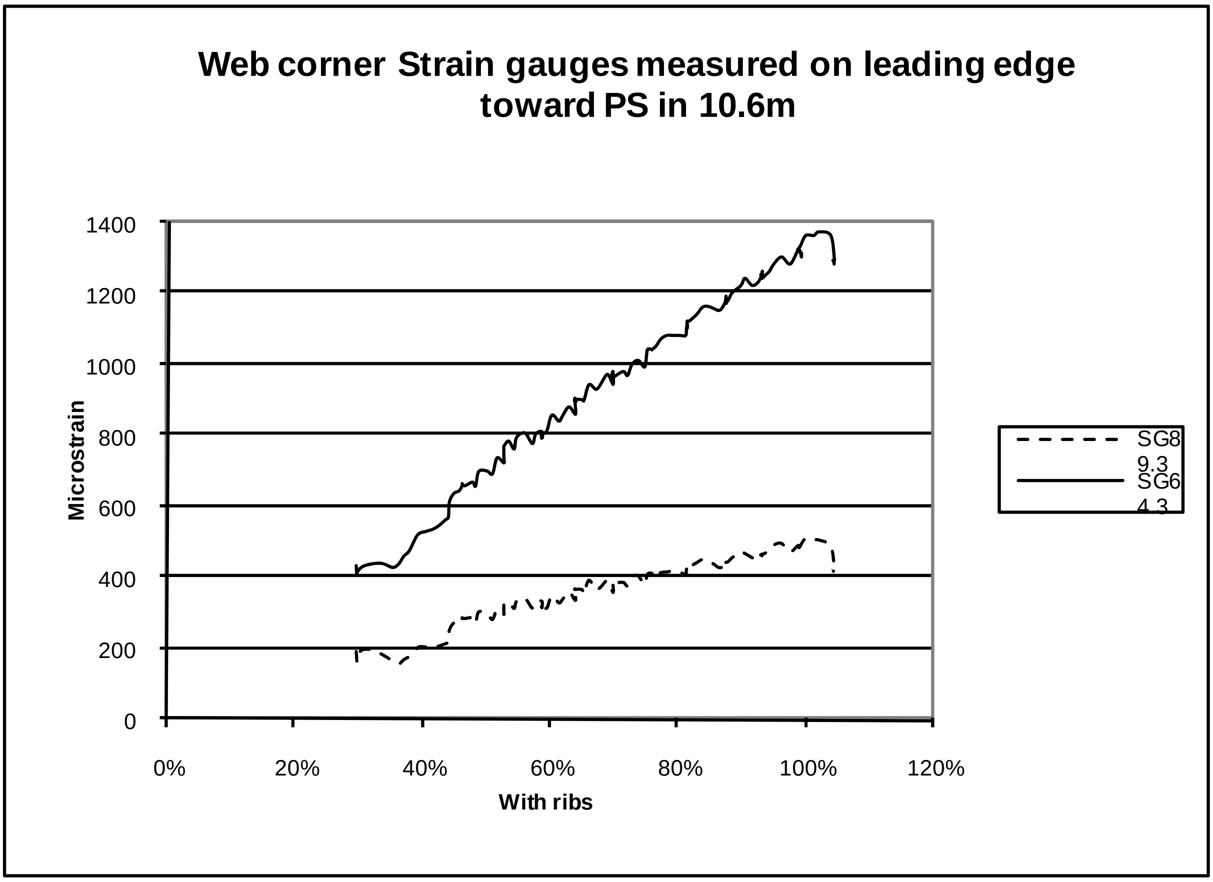

45° Strain gauges measured on leading web toward PS in 10.6m
Microstrain
2500
2000
1500
1000
500
0
0%
20%
40%
60%
80%
100%
120%
With ribs
SG69.3
SG44.3


Web corner Strain gauges measured on trailing edge toward SS in 10.6m
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG7 9.3
SG5 4.3

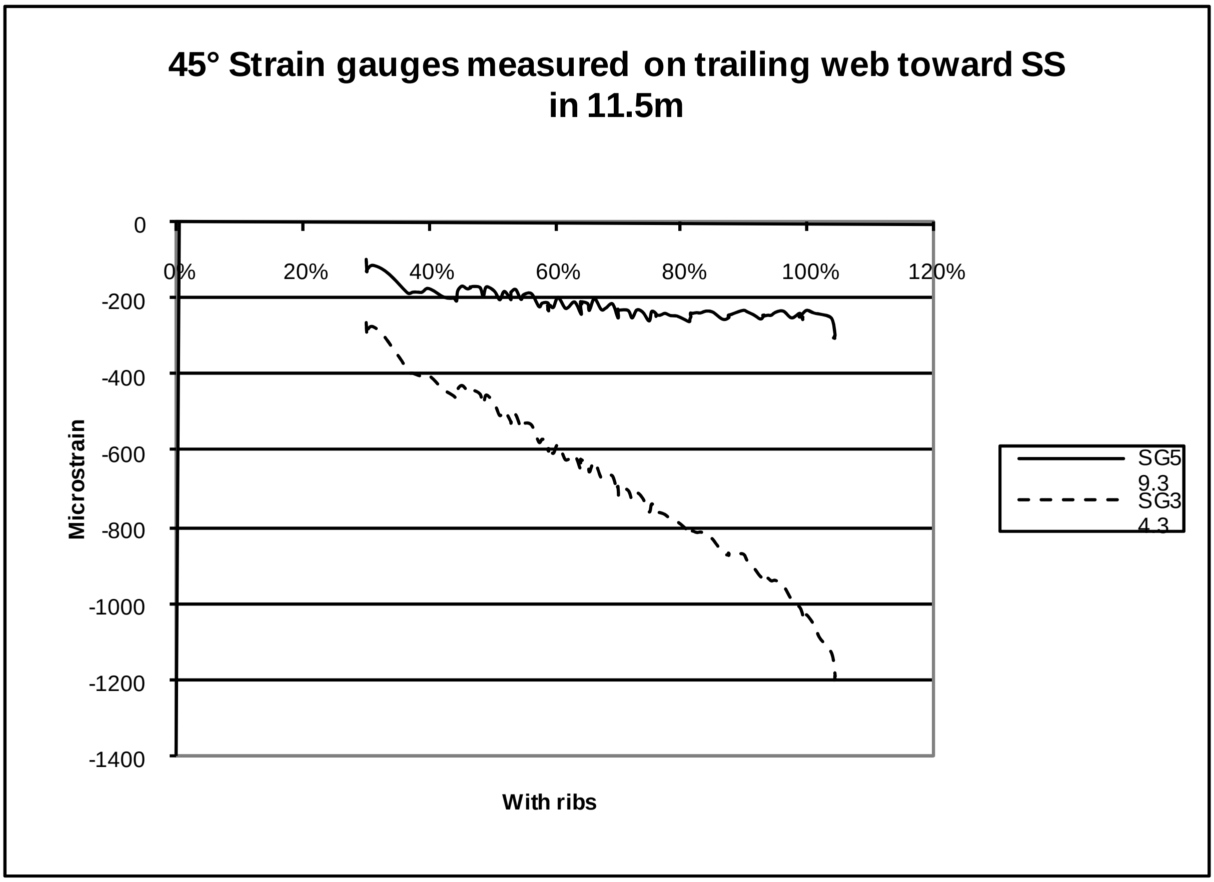

Web corner Strain gauges measured on trailing web toward PS in 10.6m
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG8 1.3
SG5 6.3



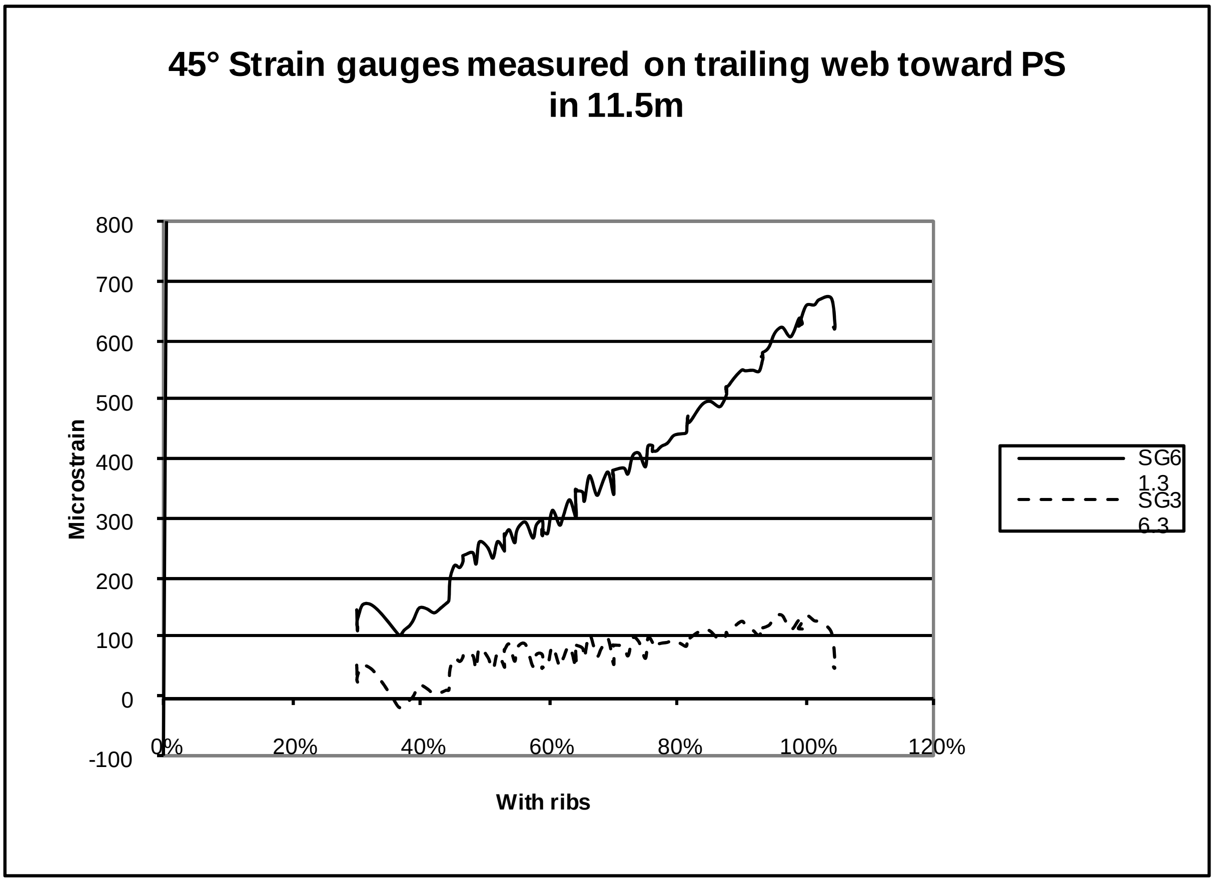
Web corner Strain gauges measured on leading edge toward SS in 10.6m
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG87.3
SG62.3



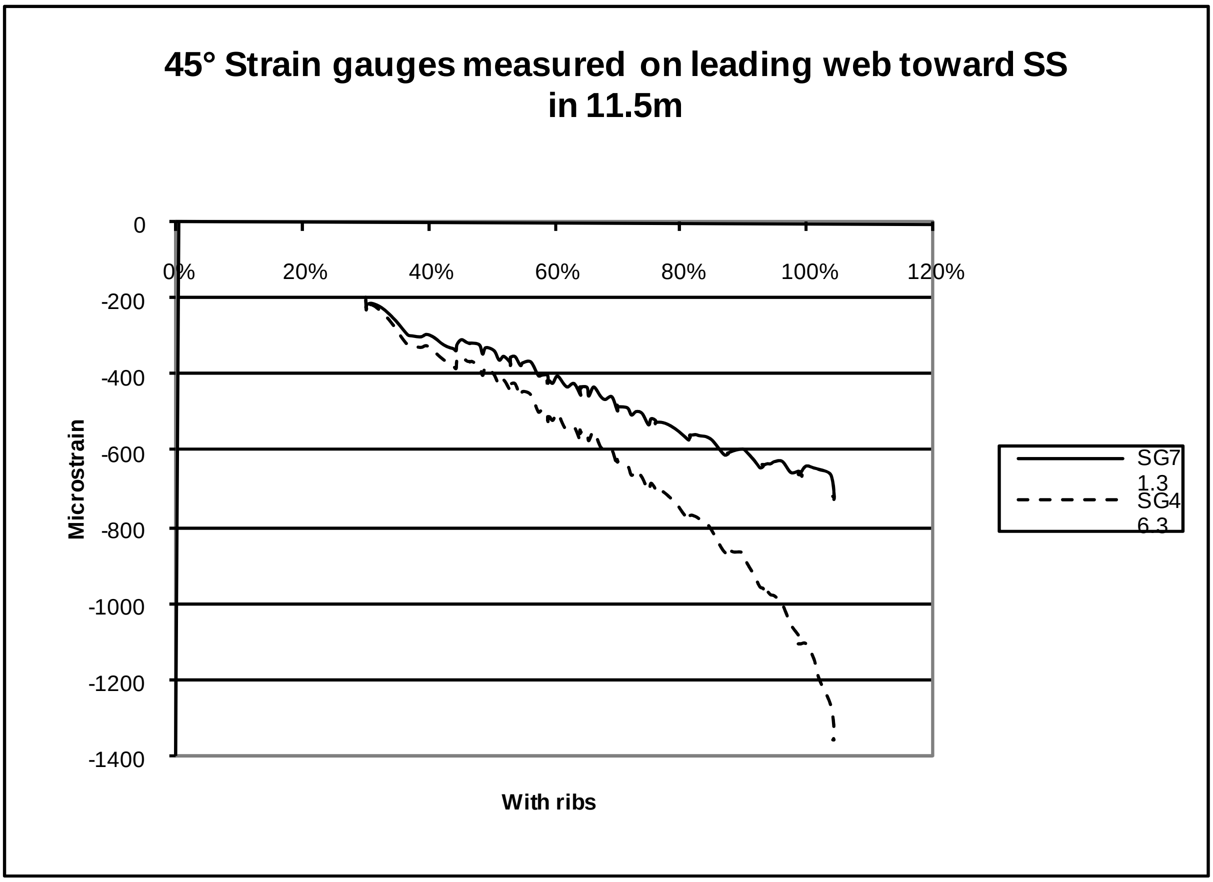
Web corner Strain gauges measured on leading edge toward PS in 10.6m
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG89.3
SG64.3

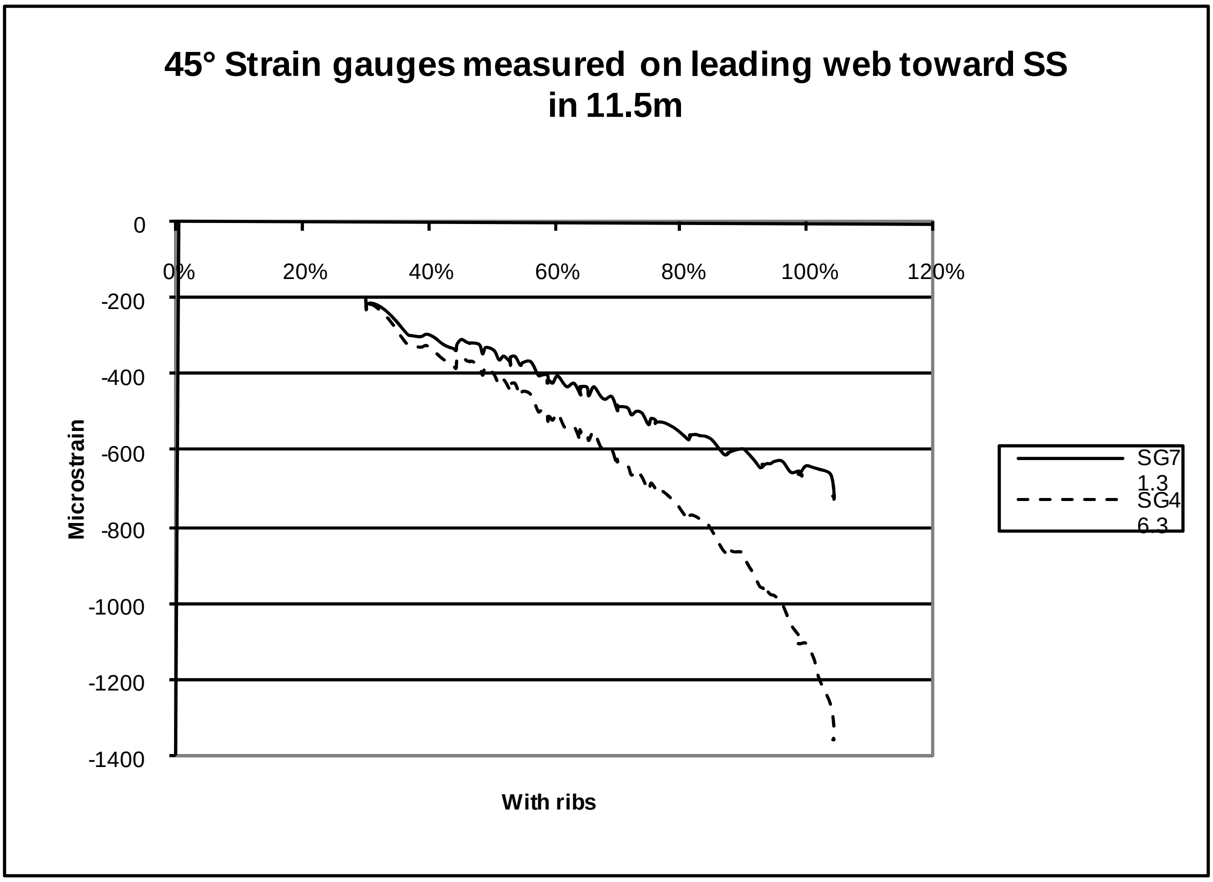


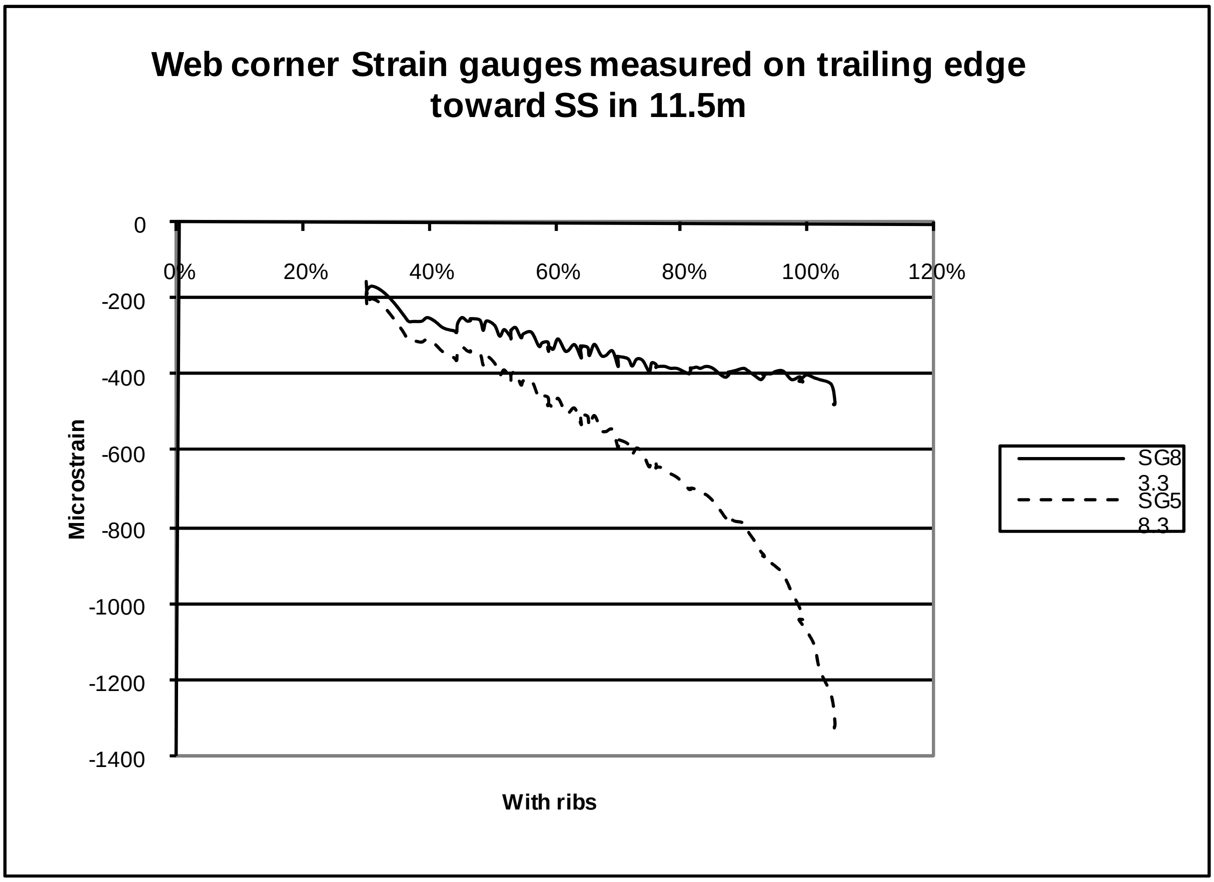
45° Strain gauges measured on trailing web toward SS in 11.5m
Microstrain
0
-200
-400
-600
-800
-1000
-1200
-1400
0%
20%
40%
60%
80%
100%
120%
With ribs
SG59.3
SG34.3



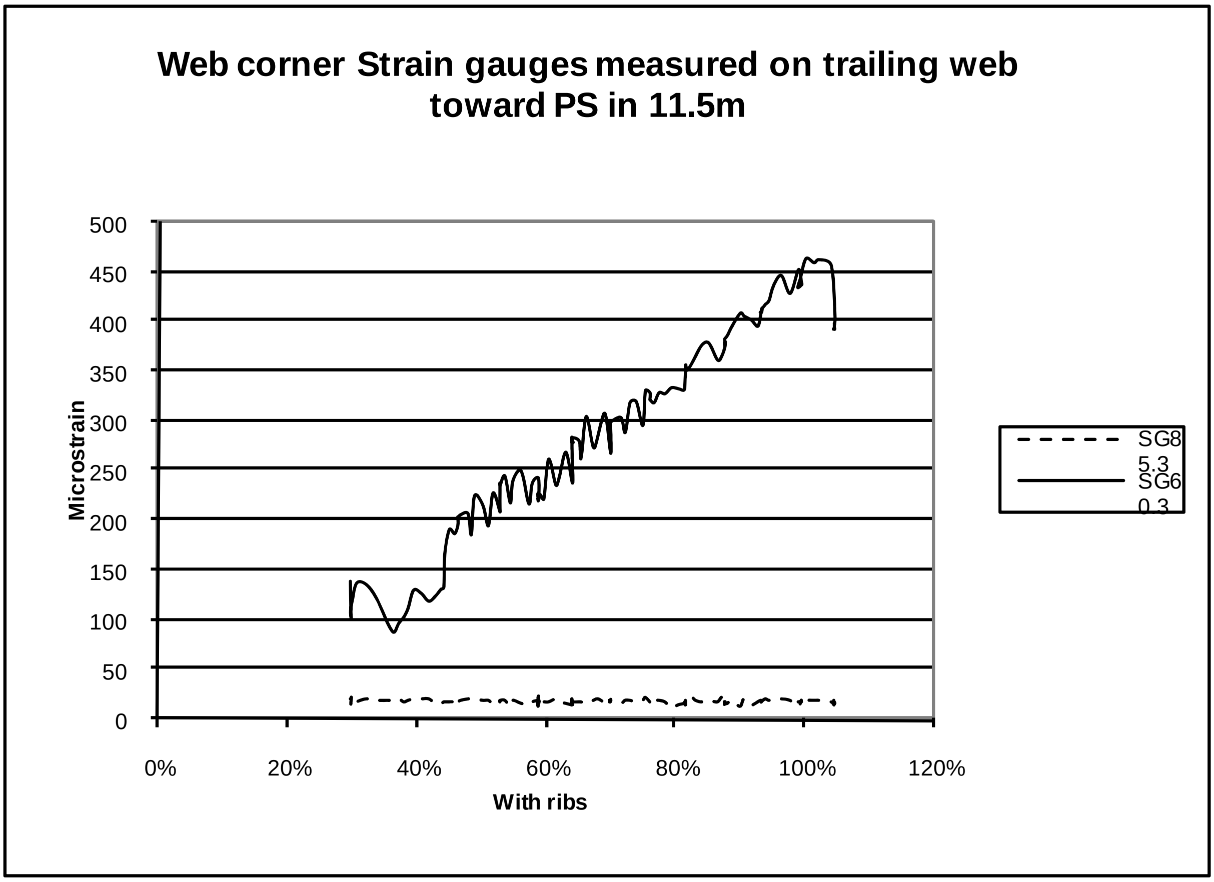
45° Strain gauges measured on trailing web toward PS in 11.5m
Microstrain
800
700
600
500
400
300
200
100
0
-100
0%
20%
40%
60%
80%
100%
120%
With ribs
SG61.3
SG36.3



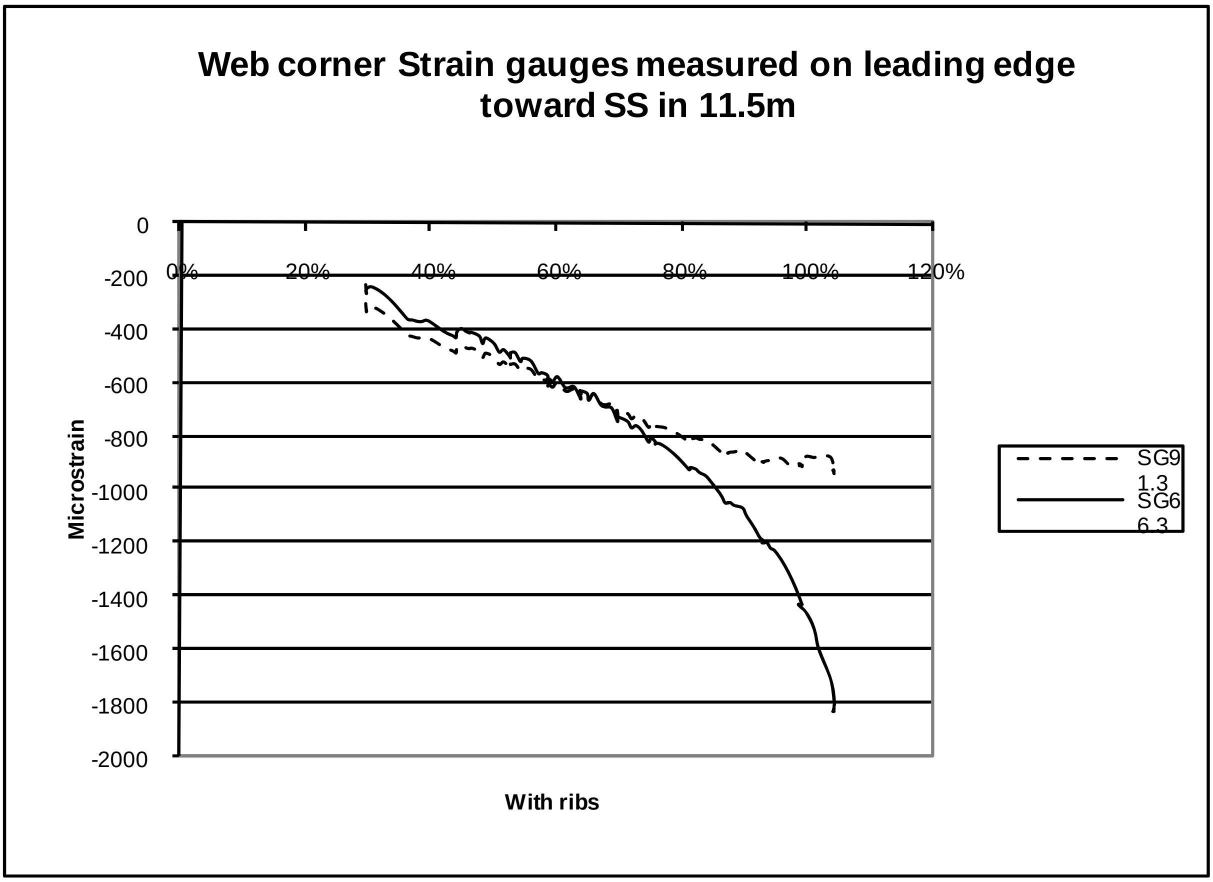

45° Strain gauges measured on leading web toward SS in 11.5m
0
-200
-400
-600
-800
-1000
-1200
-1400
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG71.3
SG46.3

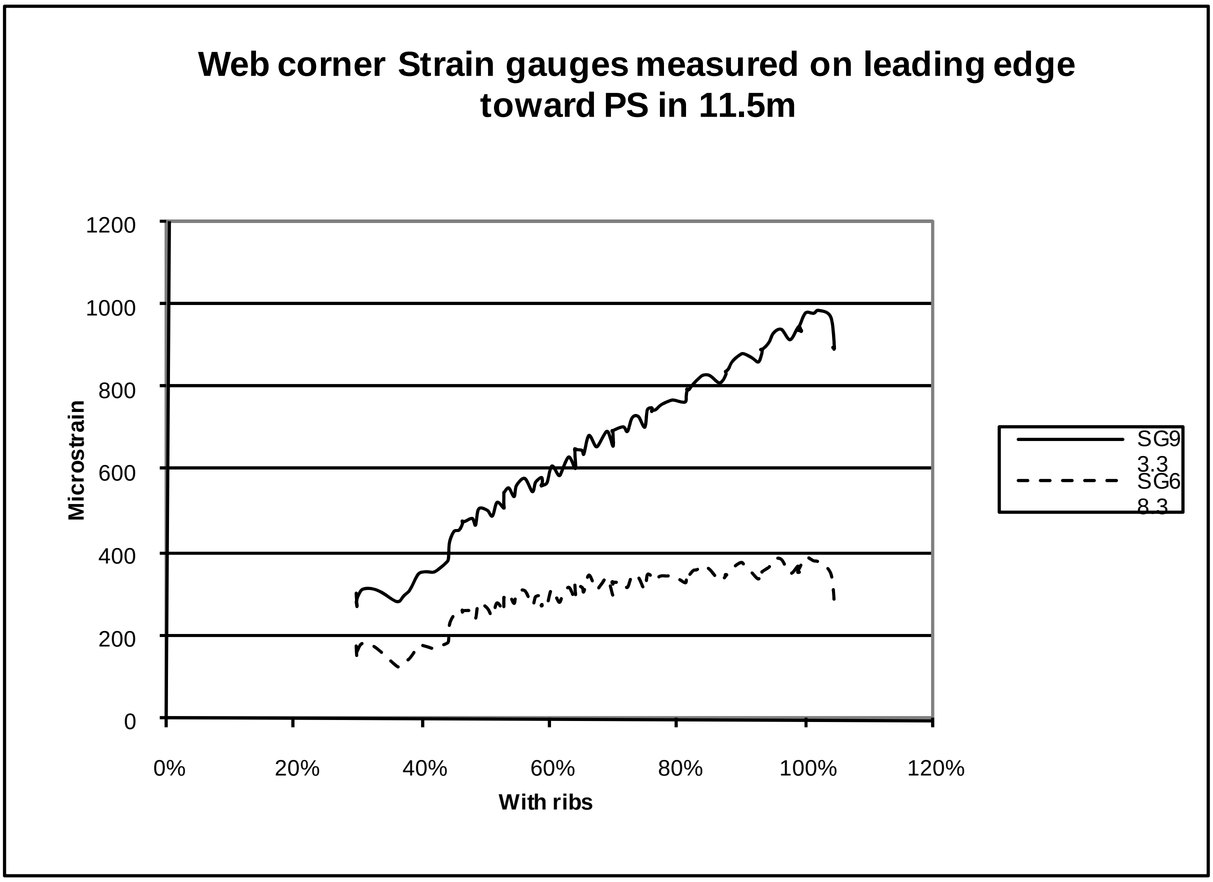


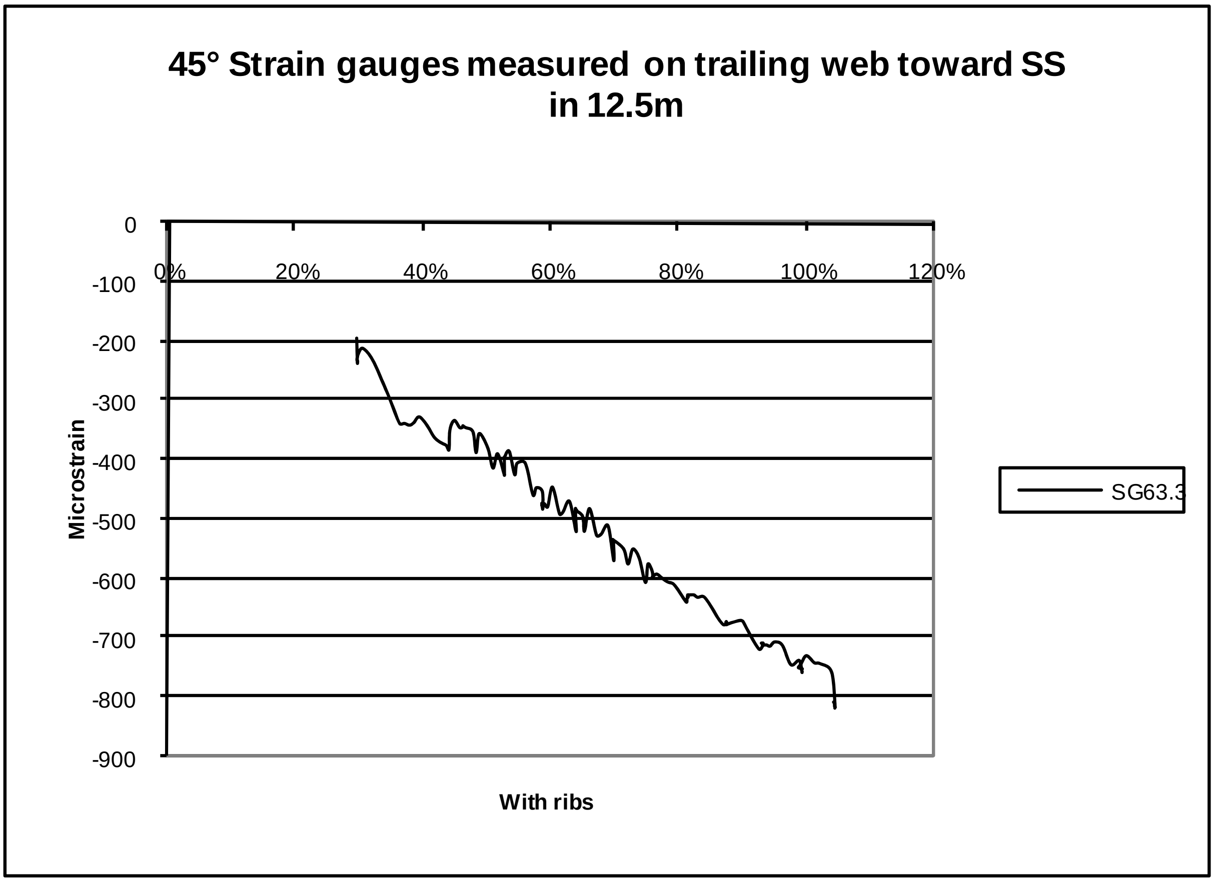
Web corner Strain gauges measured on trailing edge toward SS in 11.5m
0
-200
-400
-600
-800
-1000
-1200
-1400
Microstrain
0%
20%
40%
60%
80%
100%
120%
With ribs
SG83.3
SG58.3

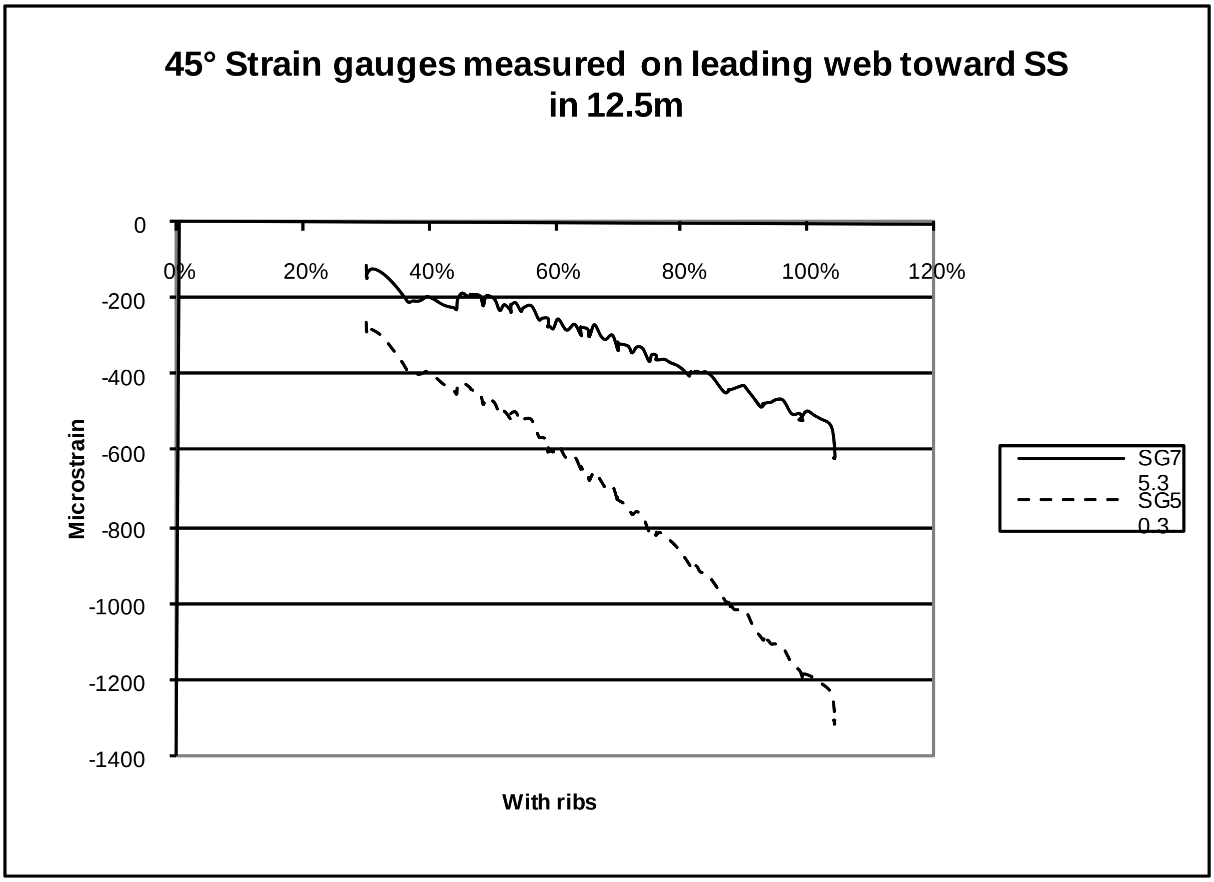


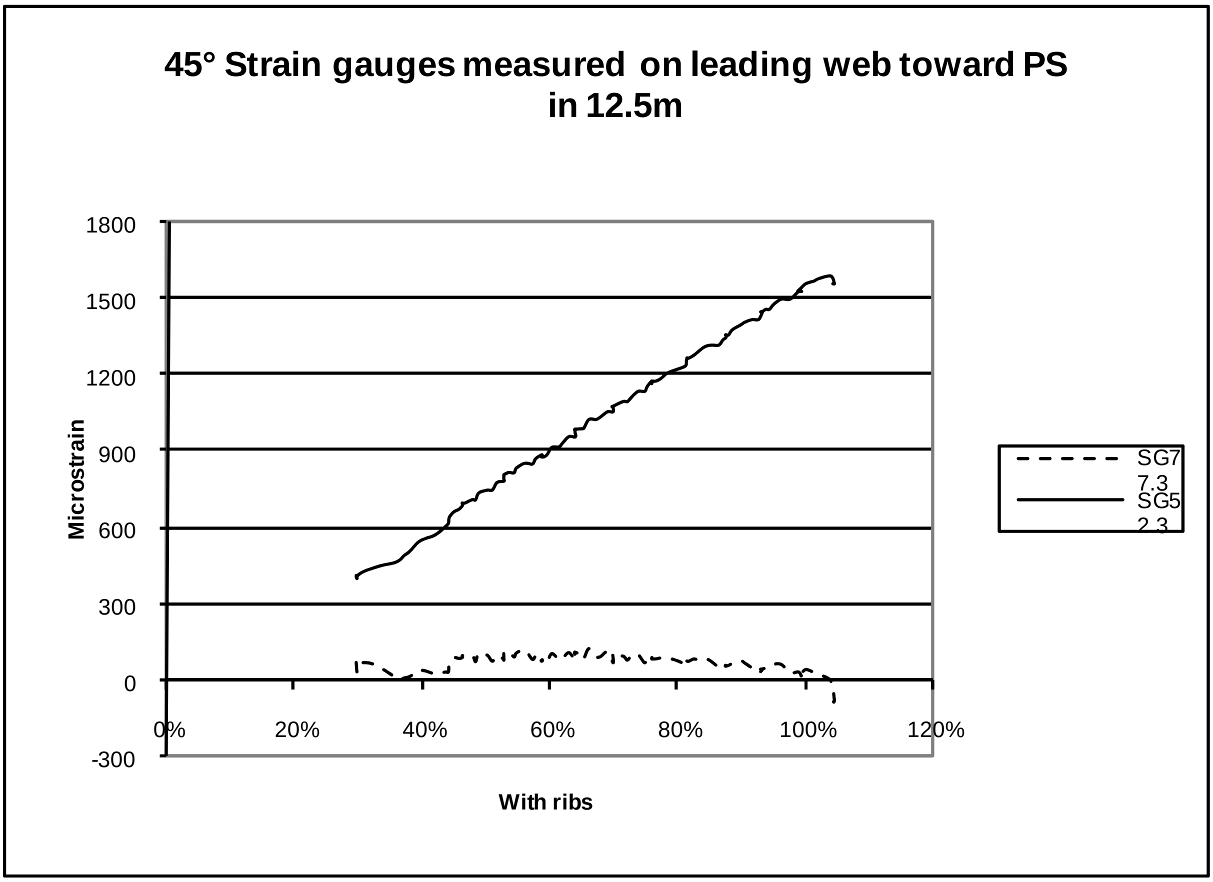
Web corner Strain gauges measured on trailing web toward PS in 11.5m
500
450
400
350
300
250
200
150
100
50
0
Microstrain
0%
20%
40%
60%
80%
100%
120%
With ribs
SG85.3
SG60.3


Web corner Strain gauges measured on leading edge toward SS in 11.5m
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-2000
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG91.3
SG66.3


Web corner Strain gauges measured on leading edge toward PS in 11.5m
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG93.3
SG68.3


45° Strain gauges measured on trailing web toward SS in 12.5m
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG63.3


45° Strain gauges measured on leading web toward SS in 12.5m
0
-200
-400
-600
-800
-1000
-1200
-1400
0%
20%
40%
60%
80%
100%
120%
Microstrain
With ribs
SG75.3
SG50.3


45° Strain gauges measured on leading web toward PS
in 12.5m
1800
1500
1200
900
600
300
0
-300
Microstrain
0%
20%
40%
60%
80%
100%
120%
With ribs
SG7
7.3
SG5
2.3

Risø's research is aimed at solving concrete problems in the society.

Research targets are set through continuous dialogue with business, the political system and researchers.

The effects of our research are sustainable energy supply and new technology for the health sector.

www.risoe.dtu.dk