Strain and strength measurements - Leancon 1:10 wave energy system

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AALBORG UNIVERSITY
DENMARK

Contents

1 Introduction

This report is made at Department of Mechanical and Manufacturing Engineering, M-tech at Aalborg University for Leancon Wave Energy. The report has two purposes: 1) Determine strains from strain gauge measurements conducted on Leancon wave energy system scale 1:10 located at Nissum Breding, Denmark. 2) Determine the tensile strength of the composite material of which the wave energy system is made from in one direction along the arm of the wave energy system. From the strain and the strength measurements of the degree of utilization of the material for the investigated load scenarios can be indicated at the location of the strain gauges.

The Leancon 1:10 wave energy system have been instrumented with 58 strain gauges where 47 strain gauges active in the data analysed here (Fig. 2). The are 11 rectangular rossettes of which 6 are active in the data analysed here.

2 Method used for the strain calculations

The strain calculations for each strain gauge is calculated using the basic equation for a quarter bridge (Wheatstone bridge) [1].

$$\epsilon = \frac{4V_o}{kV_s} \tag{1}$$

where V_o is the output voltage, V_s is the supply voltage, and k is the k-factor. Temperature compensation and transverse strain compensation have not been applied.

The rosettes consists of three strain gauges where the angle between strain gauge 1 and 3 is 90 degrees and angle between 1 and 2 is 45 degrees (Fig. 1).

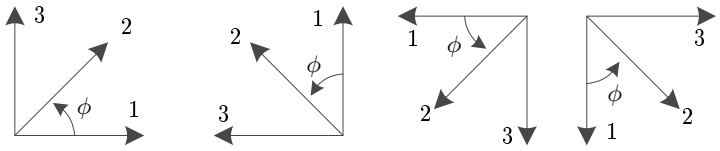


Figure 1: Rectangular rosette.

The principal strains ϵ_P and ϵ_Q are determined as [2]

$$\epsilon_P = \frac{\epsilon_1 + \epsilon_3}{2} + \frac{1}{\sqrt{2}}\sqrt{(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2} \tag{2}$$

$$\epsilon_Q = \frac{\epsilon_1 + \epsilon_3}{2} - \frac{1}{\sqrt{2}}\sqrt{(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2} \tag{3}$$

The corresponding principal directions are given as [2]:

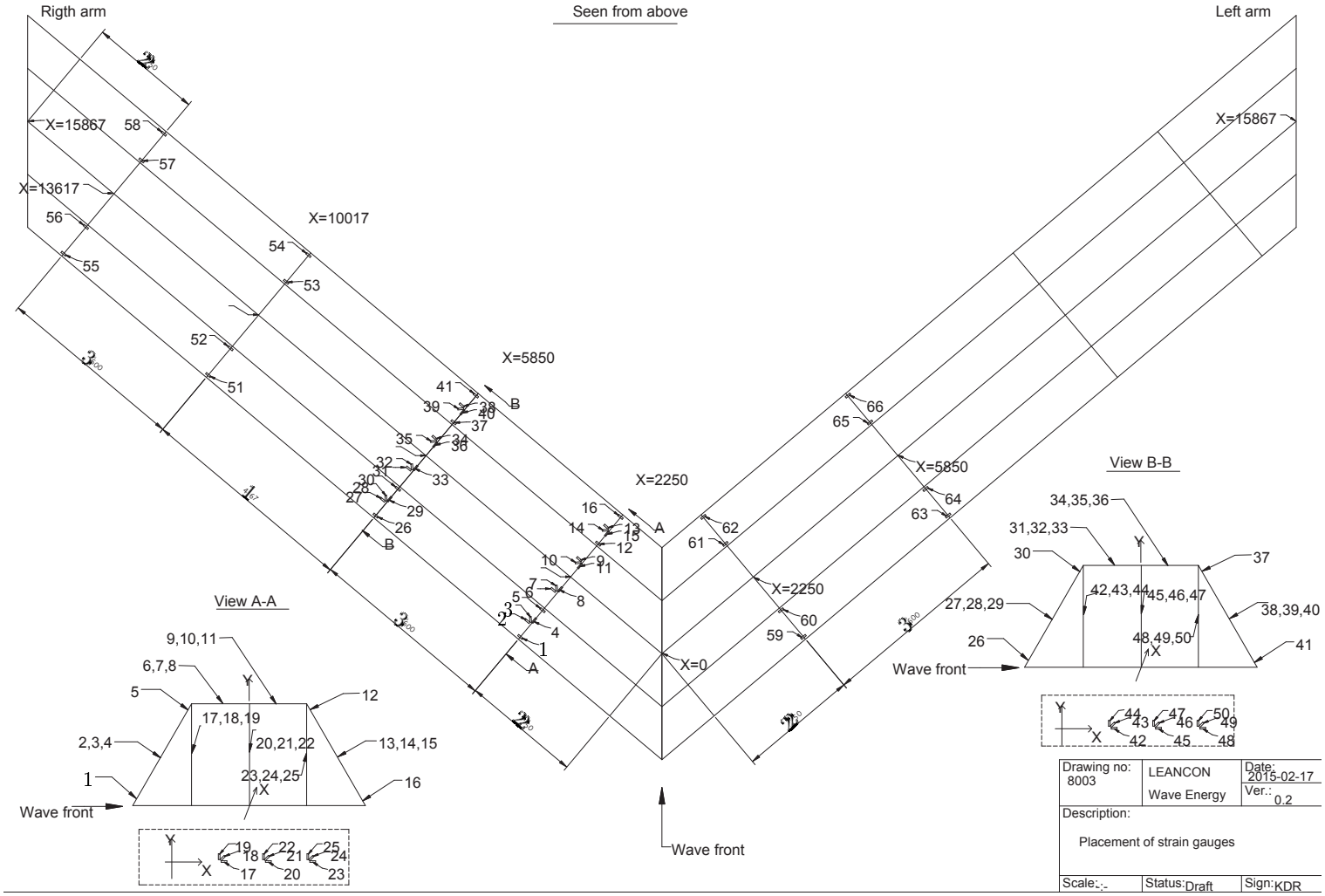


Figure 2: Placement of strain gauges on the Leancon 1:10 wave energy system.

$$\phi_{P,Q} = \frac{1}{2}\tan^{-1}\left(\frac{2\epsilon_2 - \epsilon_1 - \epsilon_3}{\epsilon_1 - \epsilon_3}\right) \tag{4}$$

- if $\epsilon_1 > \epsilon_3$, then $\phi_P = \phi_{P,Q}$ and $\phi_Q = \phi_{P,Q} + 90$
- if $\epsilon_1 < \epsilon_3$, then $\phi_{P,Q} = \phi_Q$ and $\phi_P = \phi_{P,Q} - 90$
- if $\epsilon_1 = \epsilon_3$ and $\epsilon_2 < \epsilon_1$, then $\phi_{P,Q} = \phi_P = -45°$
- if $\epsilon_1 = \epsilon_3$ and $\epsilon_2 > \epsilon_1$, then $\phi_{P,Q} = \phi_P = 45°$
- if $\epsilon_3 = \epsilon_3 = \epsilon_3$, then $\phi_{P,Q}$ is indeterminate (equal biaxial strain).

The principal direction is gives the orientation of the principal strains by the angle ϕ in the rosette coordinate system, cf. Fig. 1. In order to filter out the principal directions associated with small strains values the calculation of the principal direction is not done if the size of the principal strains are below a threshold value of 5 μ m/m ($e_P < 5\mu$m/m and $e_Q < 5\mu$m/m). This is because the noise in the measurements in this case makes the principal direction calculation meaningless.

The strain gauges are from HBM and the data sheet is shown in App. B. The sample rate during testing was 10 Hz, the bridge factor = 1.0, the k-faktor $k = 2.09$, and the supply voltage $V_s = 3.3$.

3 Results - strain gauge measurements

The results are presented as the strain measured at each strain as shown in figure 3 where the variation of the strain is plotted and the maximum and minimum value is indicated.

For the rosettes the variation of the principal strains, ϵ_P and ϵ_Q, and principal direction ϕ_P are presented as shown in figure 4.

The strain output for all strain gauges and the principal strains and principal directions for all the rosettes are shown in App. A for the dataset "Sq_151007_150205 - 12 m/s fra Øst". The maximum and minimum values is presented in the following.

- Minimum strain measured for a single strain gauge is -45 micro strain and is measured at strain gauge 59.
- Maximum strain measured for a single SG: 45 micro strain and is measured at strain gauge 16.
- Minimum principal strain ϵ_Q is -23 micro strain in the principal direction -21° in rosette coordinate system for the rosette consisting of strain gauges 38, 39, 40.

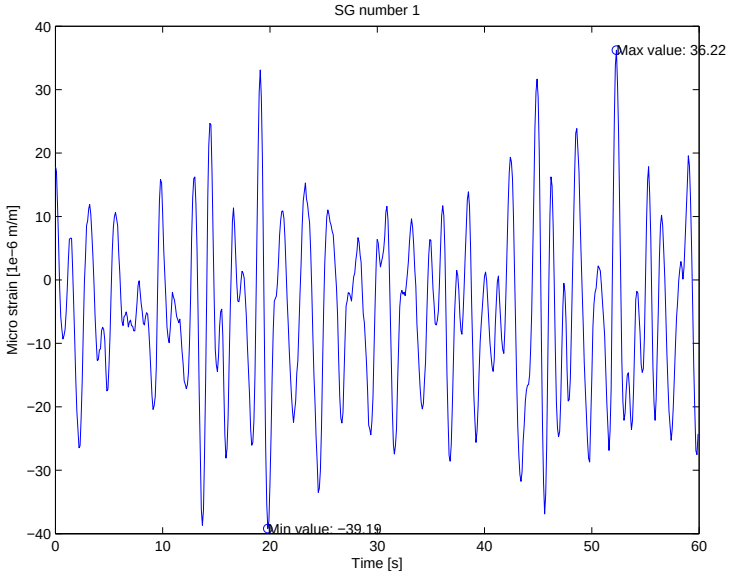


Figure 3: Strain gauge 1

- Maximum principal strain ϵ_P is 19 micro strain in the principal direction 0.8° in rosette coordinate system for the rosette consisting of strain gauges 38, 39, 40.

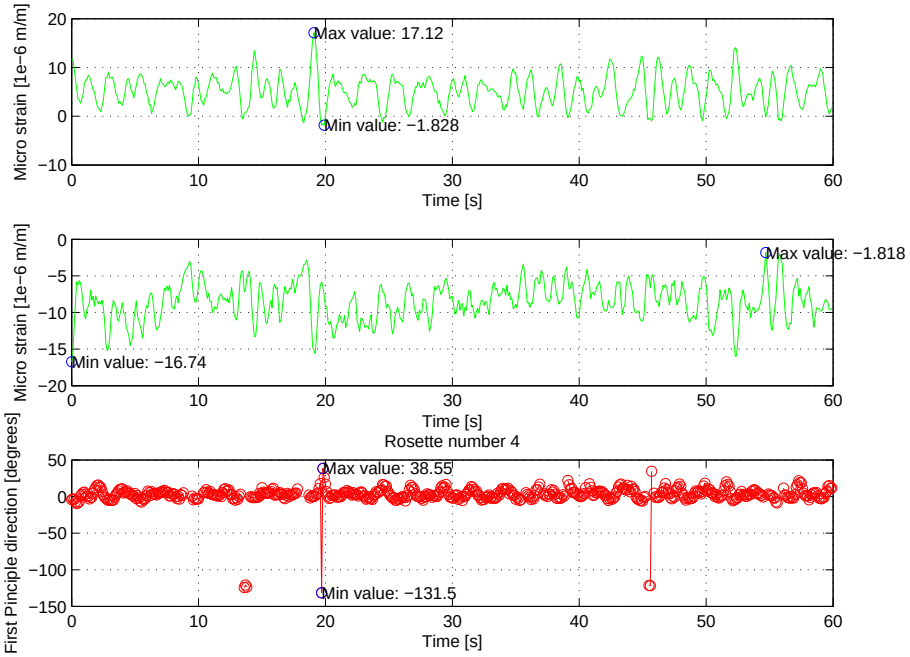


Figure 4: Rosette 4

4 Tensile strength test setup

The tensile test was conducted using a Zwick tensile testing machine with a 50 kN load cell and grips. During the tests the cross head displacement and applied force were recorded.

The specimens have been cut out of a part of the wave energy system as shown in figure 5 and table 1.

Specimen	distance from corner edge [mm]
2	38.9-64.4
3	66.3-91.8
6	149.0-174.0

Table 1: Location from which the test specimens have been cut out of the leancon wave energy system arm.

At these locations the material is made in a glass-epoxy-foam sandwich configuration. In order to test the tensile strength along the lines in figure 5 the inner skin layer and foam layer have been cut away leaving only the outer skin layer. Before adding taps to the specimens the outer coating, the foam and the resin channels have been removed using sandpaper. The removal was stopped

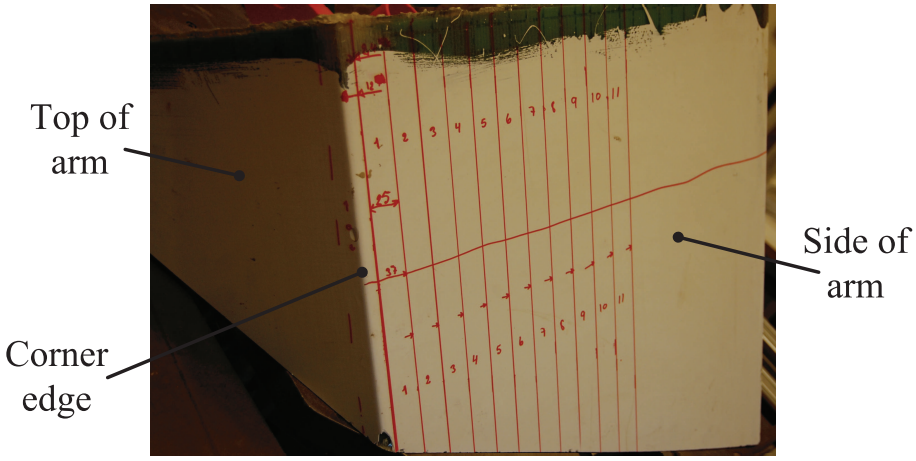


Figure 5: Orientation of the specimens on the arm of the 1:10 Leancon wave energy system.

before damaging the glass-epoxy laminate which implied that some coating and foam were still on the specimen when the taps were attached with an epoxy adhesive.

Six specimens where prepared from the locations 2, 3 and 6 shown in Fig. 5. The layup of the outer skin laminate at these locations is described in Tab. 2.

Specimen 2	Specimen 3	Specimen 6
Gelcoat	Gelcoat	Gelcoat
50/50 900	ELM 1250	ELM 1250
ELM 1250	ELM 1250	45°/-45° 600
ELM 1250	45°/-45° 600	
unifilo 225		
45°/-45° 600		

Table 2: Layup table for the test specimens. ELM 1250 consists of 1150 g/m^2 UD in 0° orientation, 50 g/m^2 UD in 90° orientation and 50 g/m^2 CSM. 50/50 900 consists of a 0°, 90 °, and CSM layer of 300 g/m^2 each. 45°/-45° 600 constists of a 45° and -45° layer of 300 g/m^2.

Based on the laminate plans for production it is thus expected that the two specimens made of 2, 3 and 6, respectively, are the same.

5 Results - tensile strength tests

The results of the tensile tests are shown in Fig. 6 and Tab. 3. The results for specimen 3b and 6b have been excluded as the adhesive bond of the taps failure before the laminate.

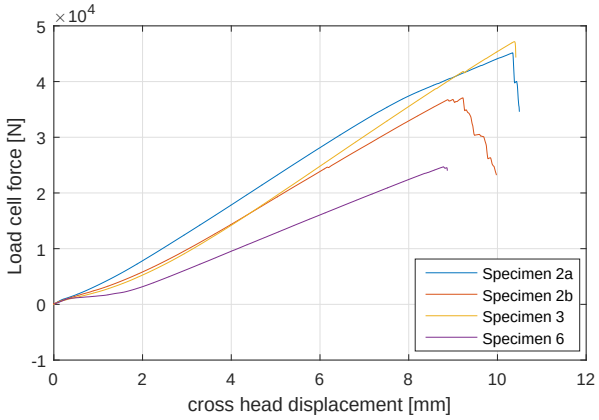


Figure 6: Results from the tensile test up until failure.

Specimen	$F_{\max}$ [N]	$d@F_{\max}$ [mm]	Width [mm]	Thickness [mm]	failure strain [m/m]
2a	45144,8	10,3	25.5	3.7	0.012
2b	37075,3	9,2	25.5	3.7	0.010
3a	47159,2	10,4	25.5	2.7	0.017
3b	taps failed				
6a	38968,7	11,6	25.0	1.6	0.030
6b	taps failed				

Table 3: Maximum load $F_{\max}$ during tensile loading until failure. The displacement at the maximum load is denoted $d@F_{\max}$. The tests of specimen 3b and 6b were disregarded because the adhesive bond of the taps failed before the laminate. The thickness of the specimens is associated with large uncertainties as the foam core was not possible to remove completely.

The strain was not recorded during the test. Thus the failure strain has not been obtained directly however a conservative estimate can be carried out by assuming an upper bound for the specimen longitudinal tensile stiffness equal to 40 GPa and by assuming a linear behavior. This conservative estimate is shown in the table.

It was not possible to test more specimens within the limits of the project. However, this would have provided information of the statistical variance and significance of the tensile strength results.

6 Conclusion

Strain gauge measurements from the test "12 m/s from east - Sq_151007_150205" have been processed. The strain have been determined for all strain gauges and the principal strain and directions have been determined for the rosettes. Tensile strength tests have been conducted at three locations on the wave energy

system arm. Two of the six specimens failed prematurely due to a failure of the taps. The estimated failure strain levels are between 2 and 3 orders of magnitude (10^2 to 10^3) above the measured strain on the wave energy system. This indicates a potential for reducing amount of material in the areas of the strain gauges.

References

[1] K. Hoffmann, An introduction to measurements using strain gages.

[2] TN-515, Strain Gage Rosettes: Selection, Application and Data Reduction, Tech. rep., Micro Measurements, www.micro-measurements.com (2014).

APPENDIX

A Results - strain gauge measurements

A.1 12 m/s from east - Sq_151007_150205

In the figures 7-53 the strain measured at strain gauge 1 to 47 is presented.

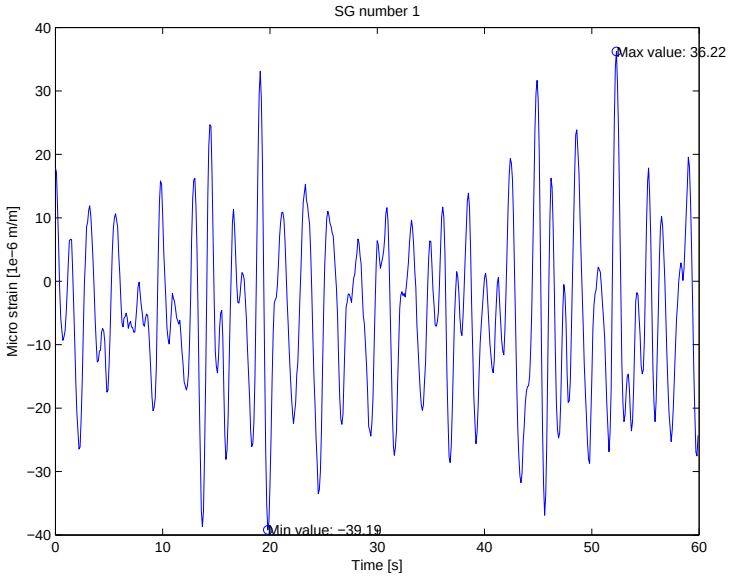


Figure 7: Strain gauge 1

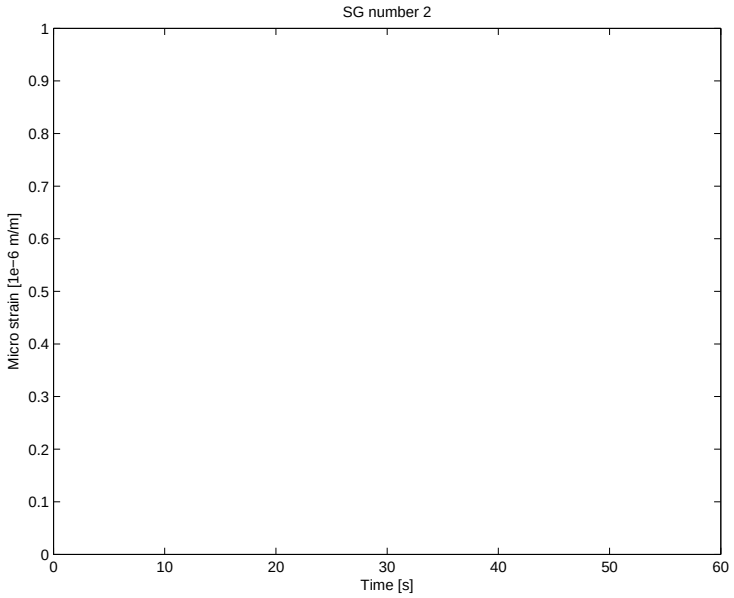


Figure 8: Strain gauge 2

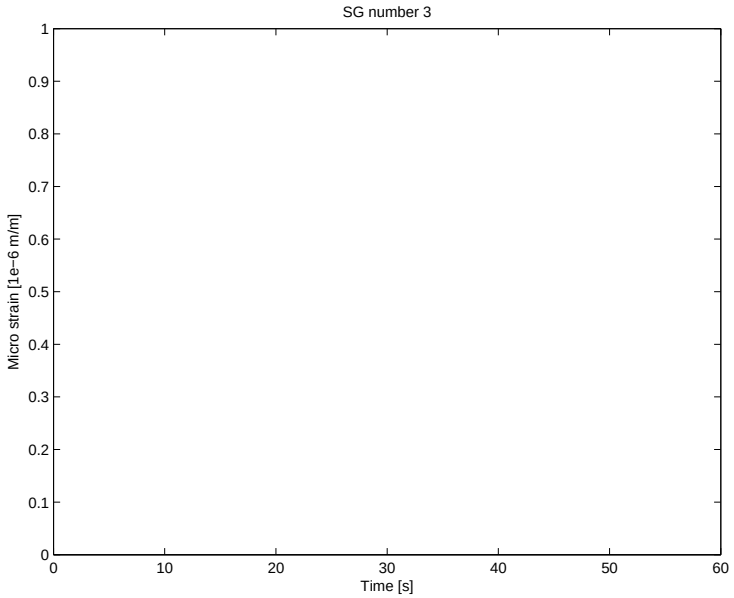


Figure 9: Strain gauge 3

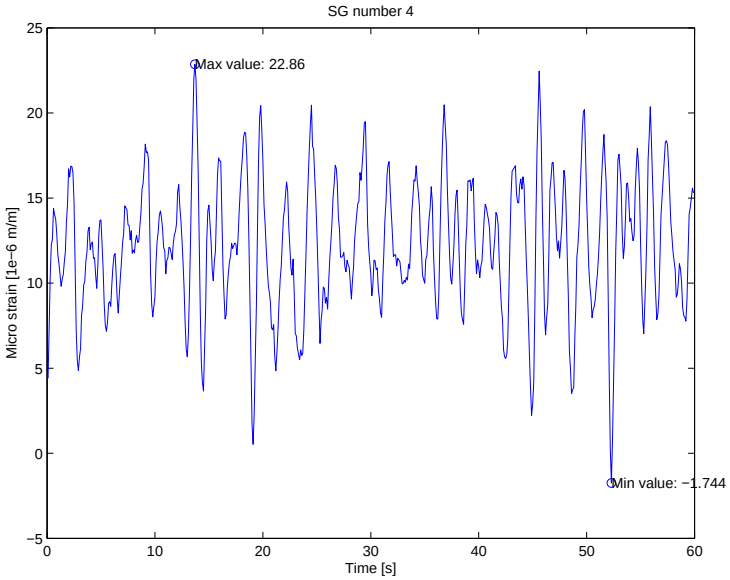


Figure 10: Strain gauge 4

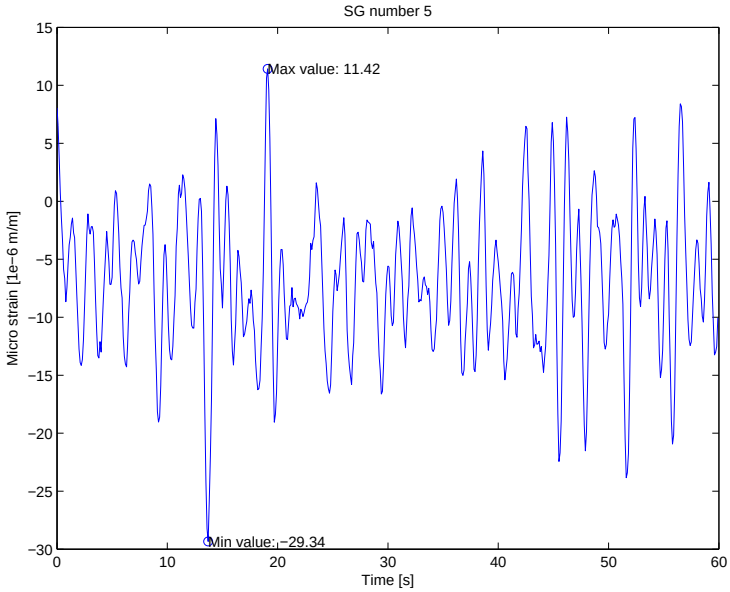


Figure 11: Strain gauge 5

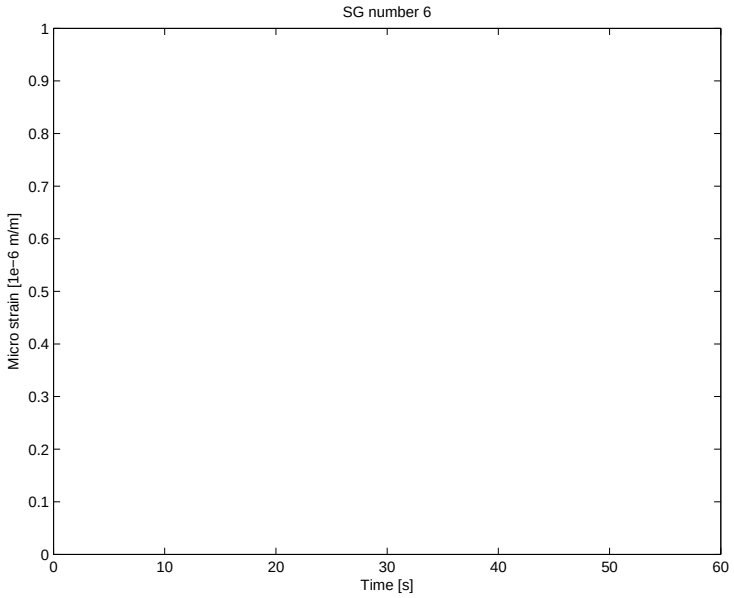


Figure 12: Strain gauge 6

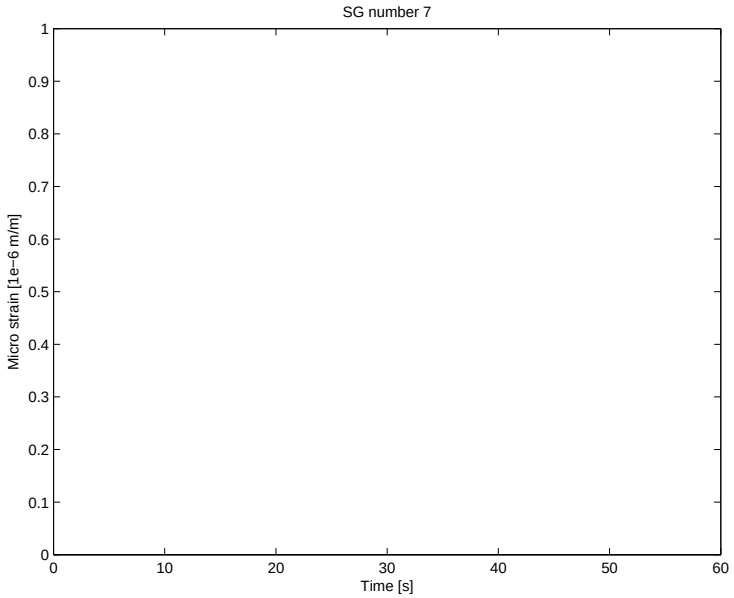


Figure 13: Strain gauge 7

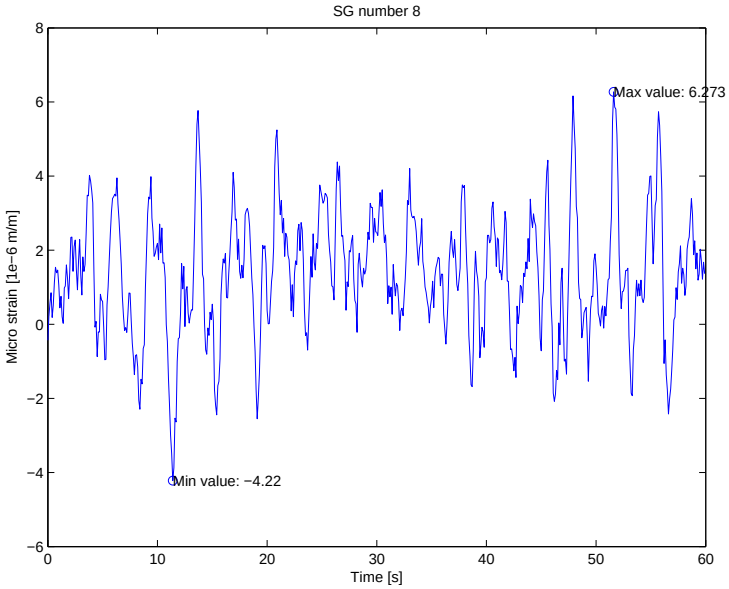


Figure 14: Strain gauge 8

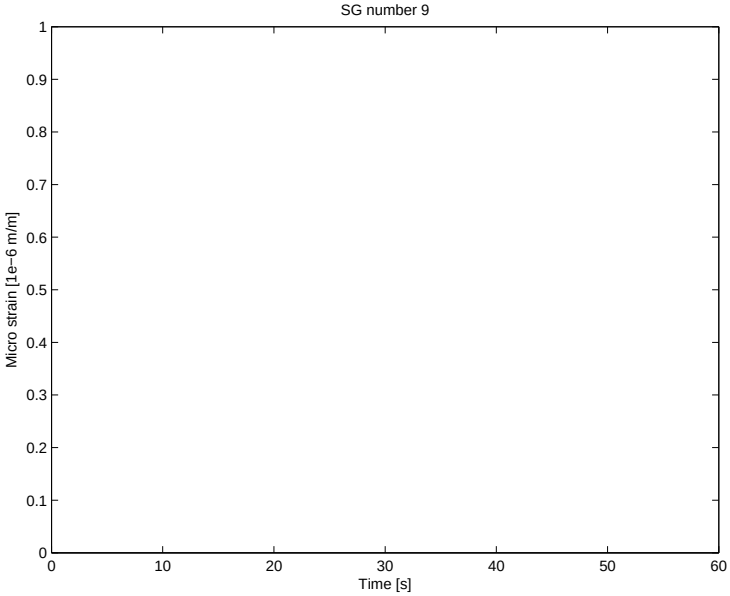


Figure 15: Strain gauge 9

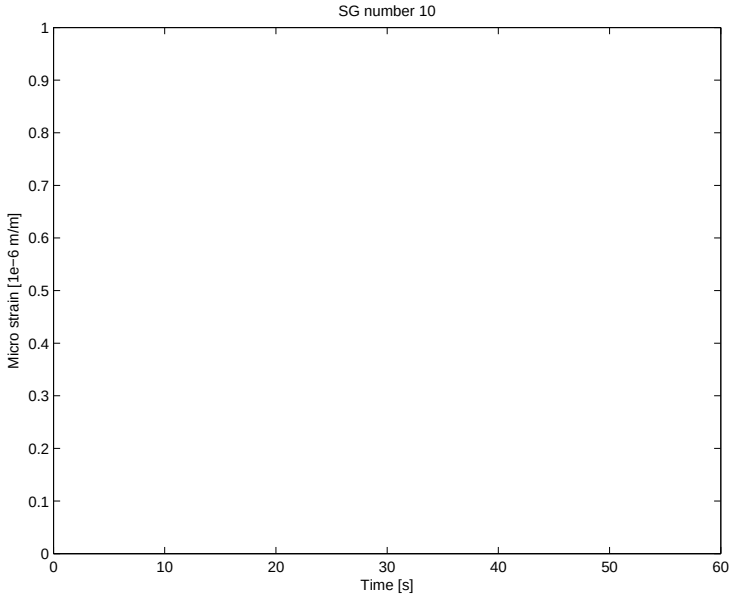


Figure 16: Strain gauge 10

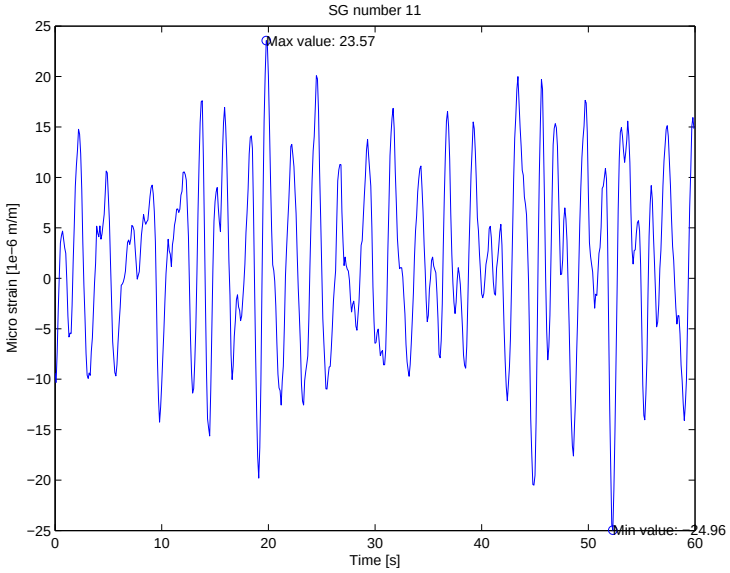


Figure 17: Strain gauge 11

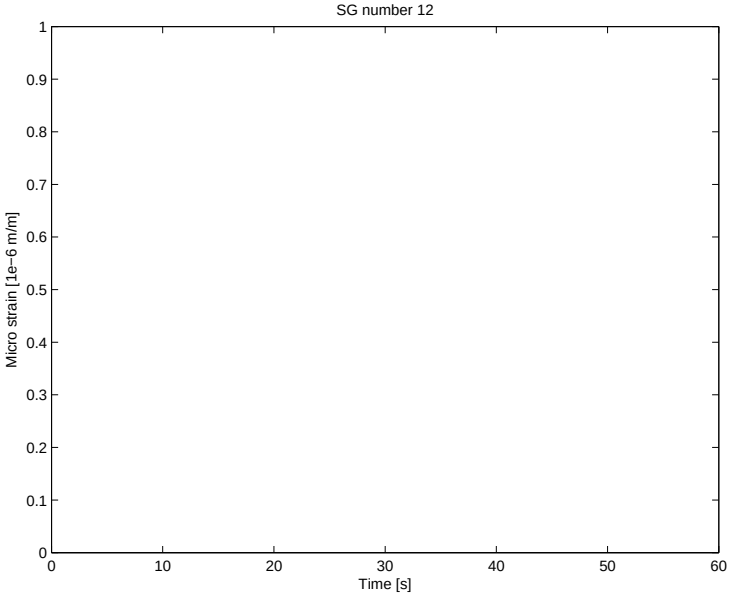


Figure 18: Strain gauge 12

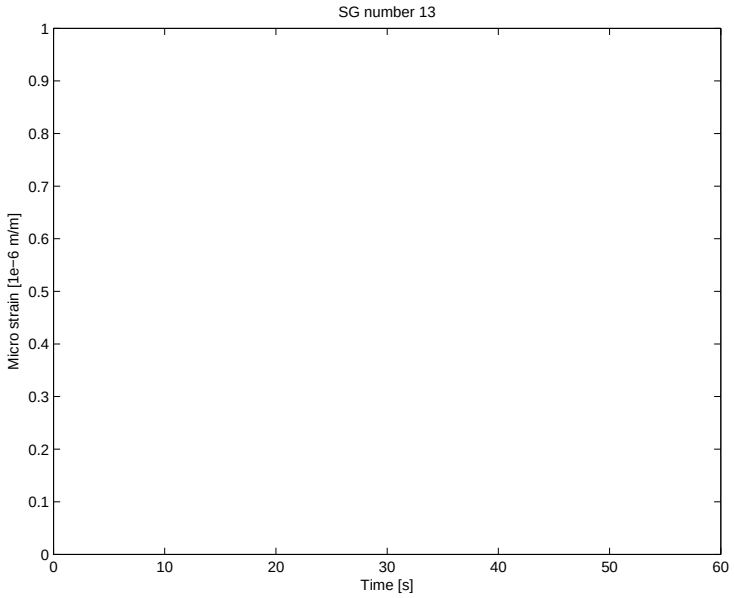


Figure 19: Strain gauge 13

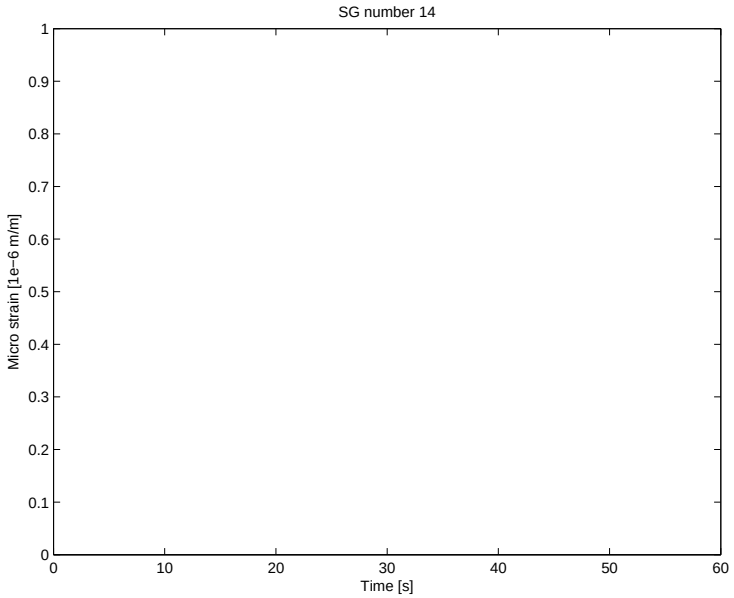


Figure 20: Strain gauge 14

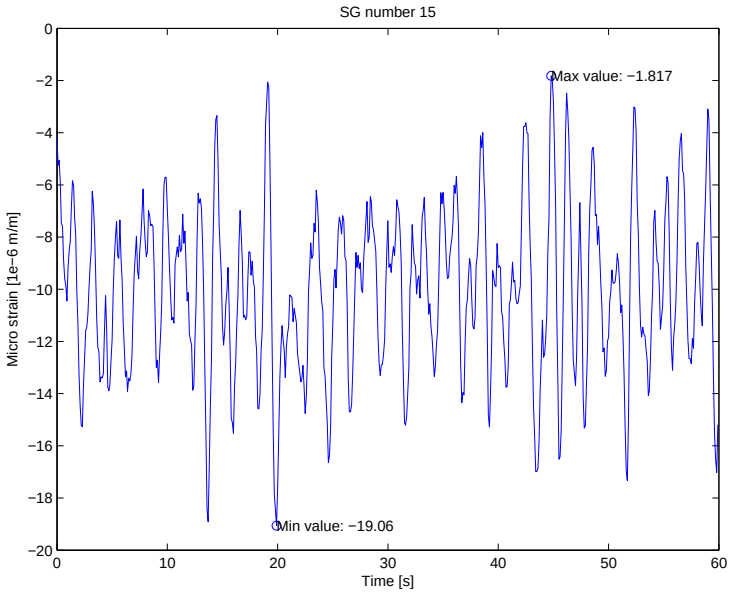


Figure 21: Strain gauge 15

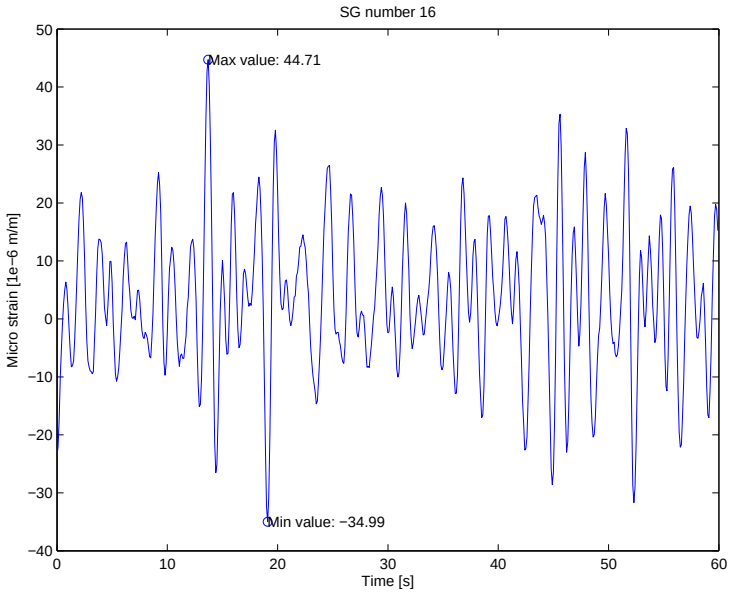


Figure 22: Strain gauge 16

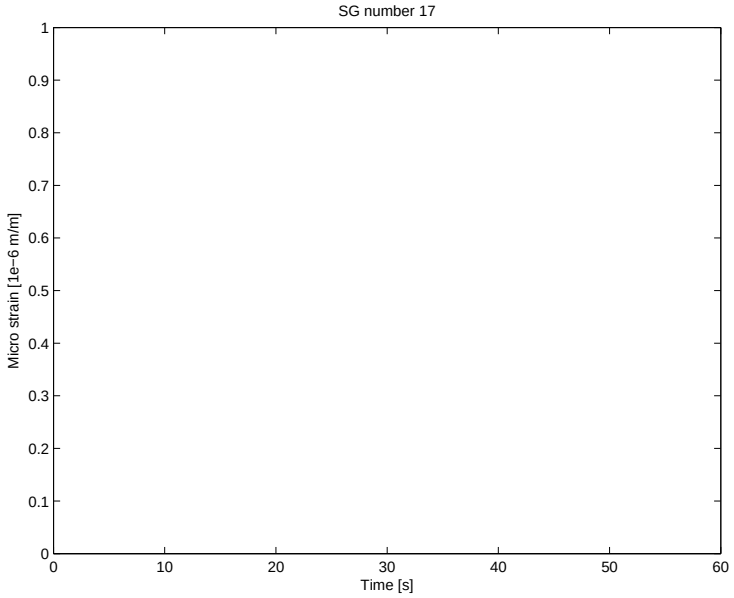


Figure 23: Strain gauge 17

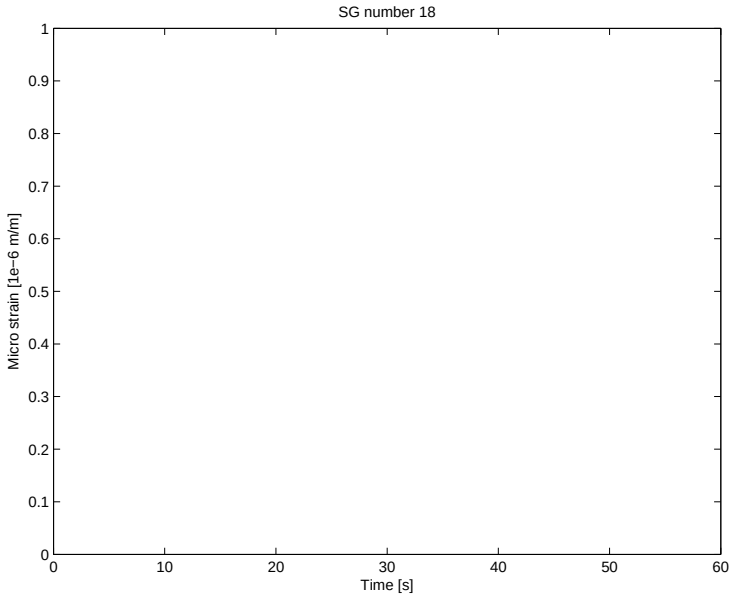


Figure 24: Strain gauge 18

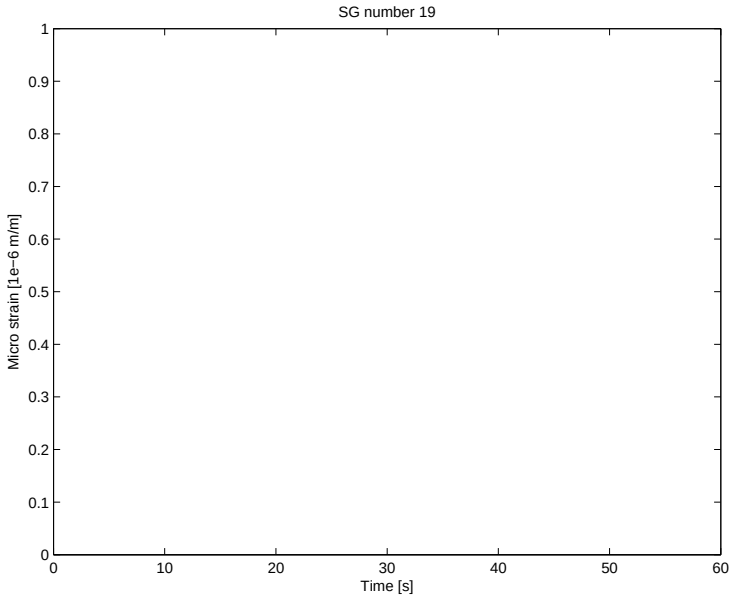


Figure 25: Strain gauge 19

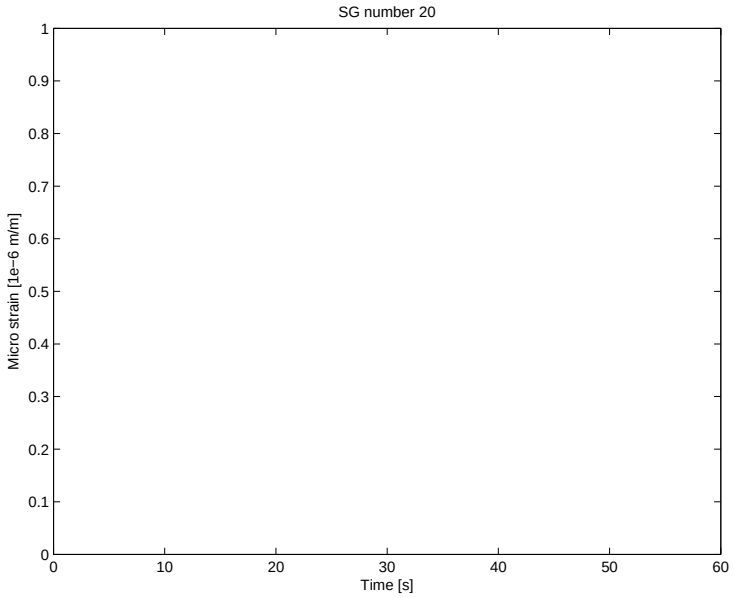


Figure 26: Strain gauge 20

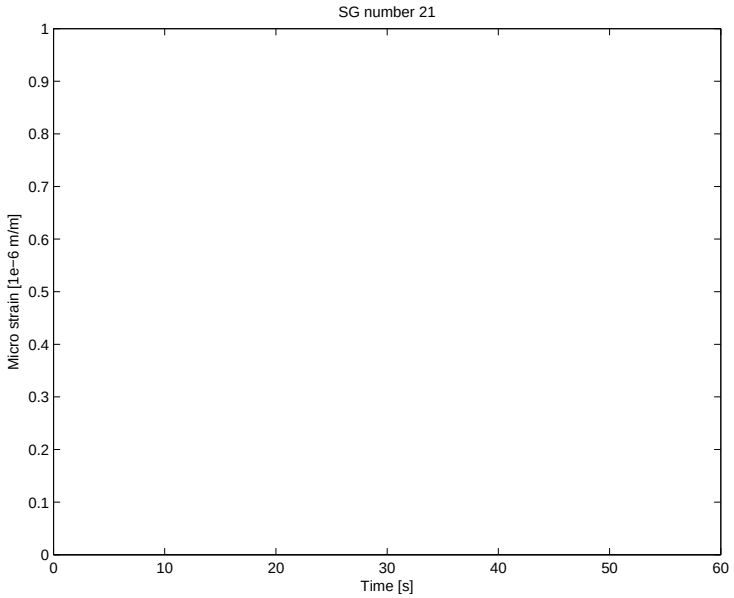


Figure 27: Strain gauge 21

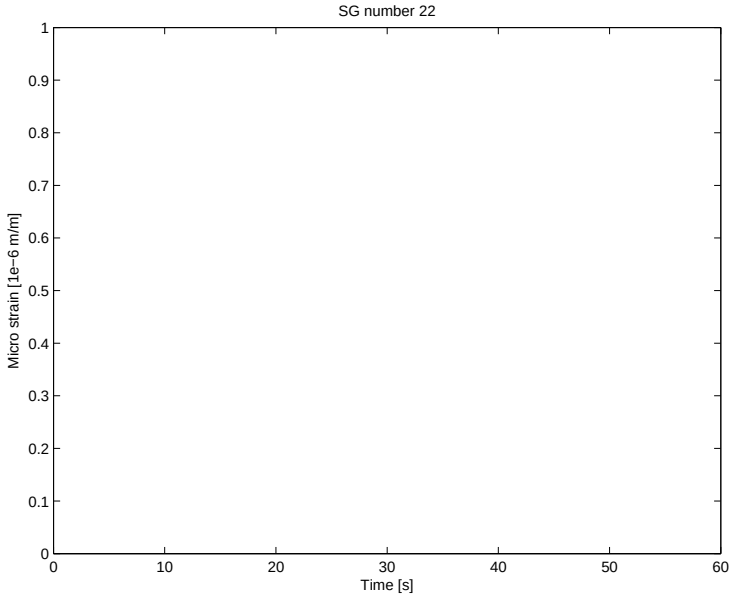


Figure 28: Strain gauge 22

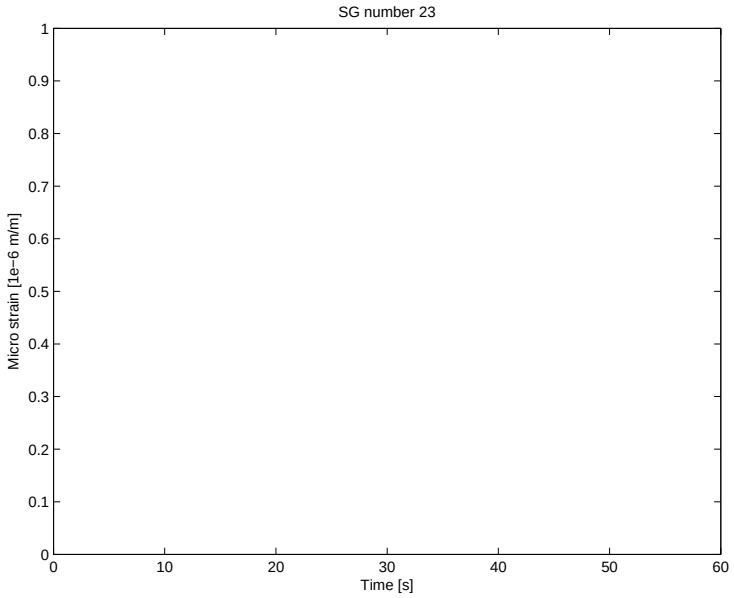


Figure 29: Strain gauge 23

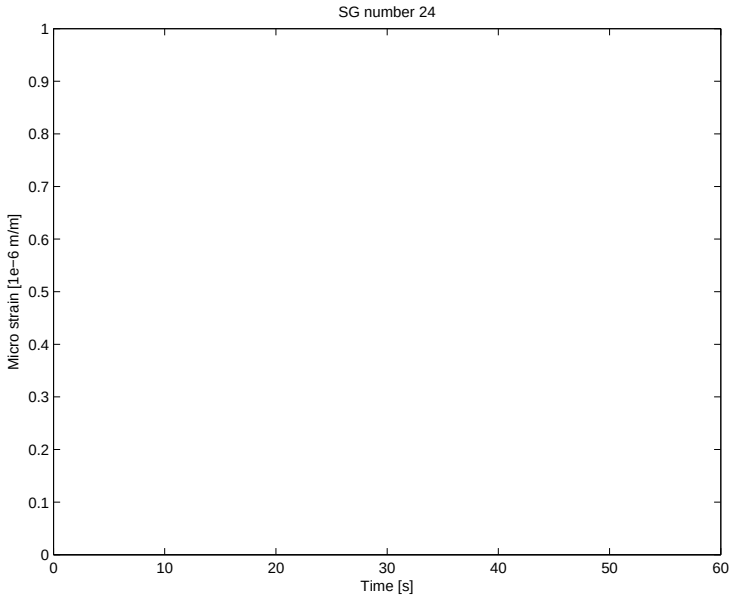


Figure 30: Strain gauge 24

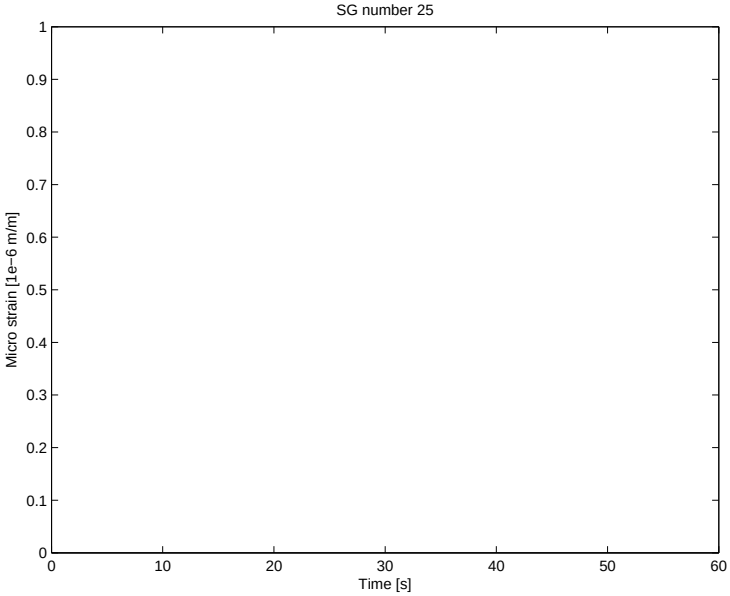


Figure 31: Strain gauge 25

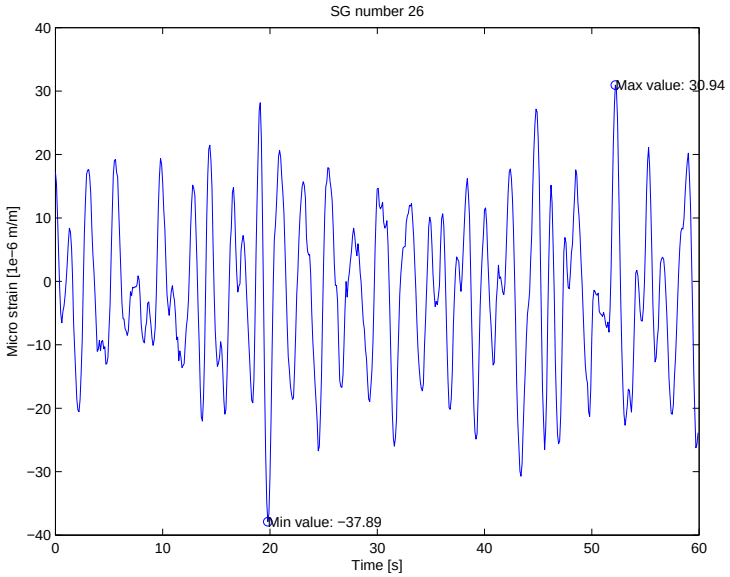


Figure 32: Strain gauge 26

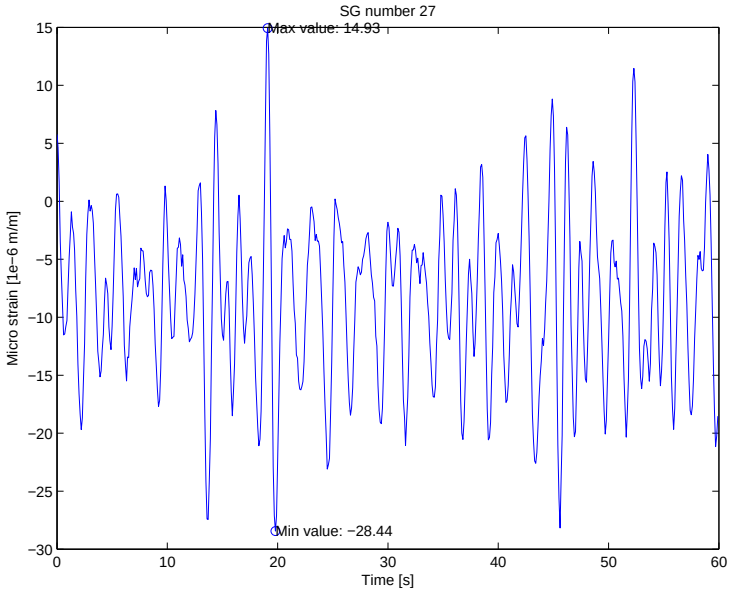


Figure 33: Strain gauge 27

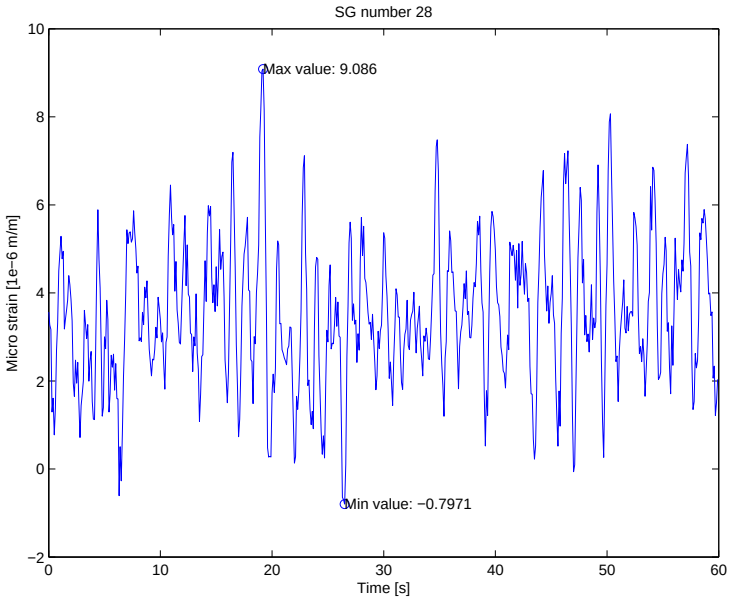


Figure 34: Strain gauge 28

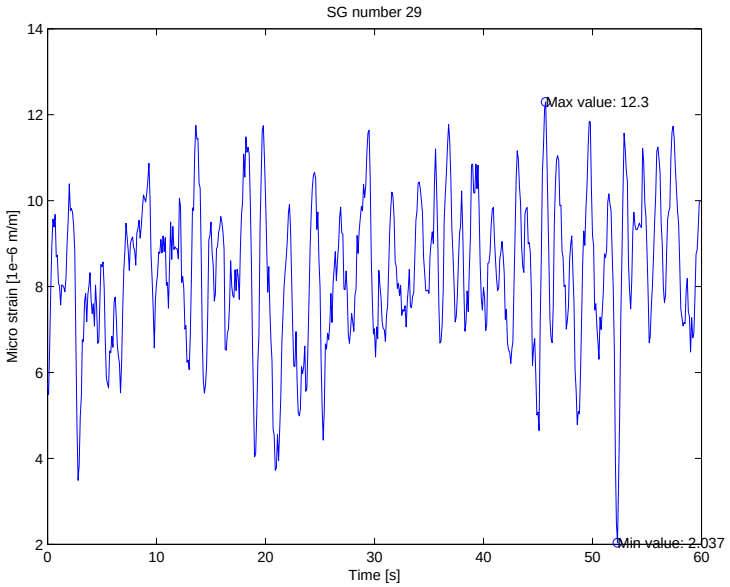


Figure 35: Strain gauge 29

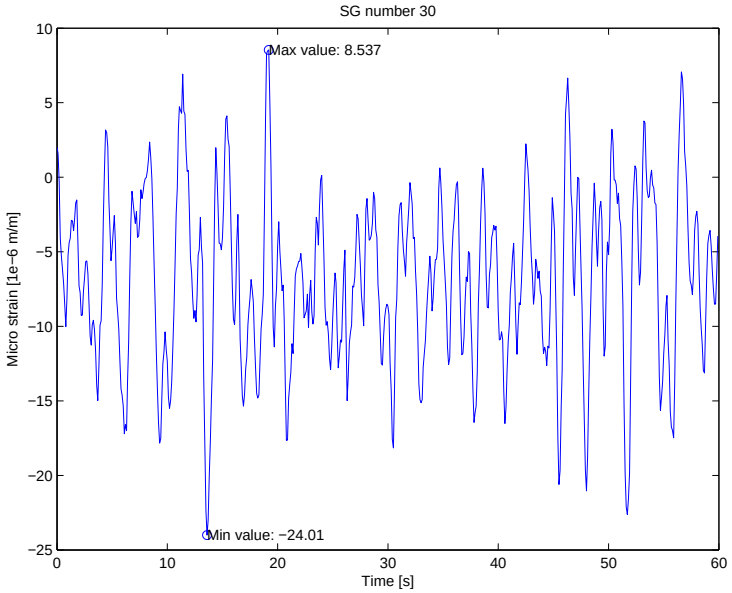


Figure 36: Strain gauge 30

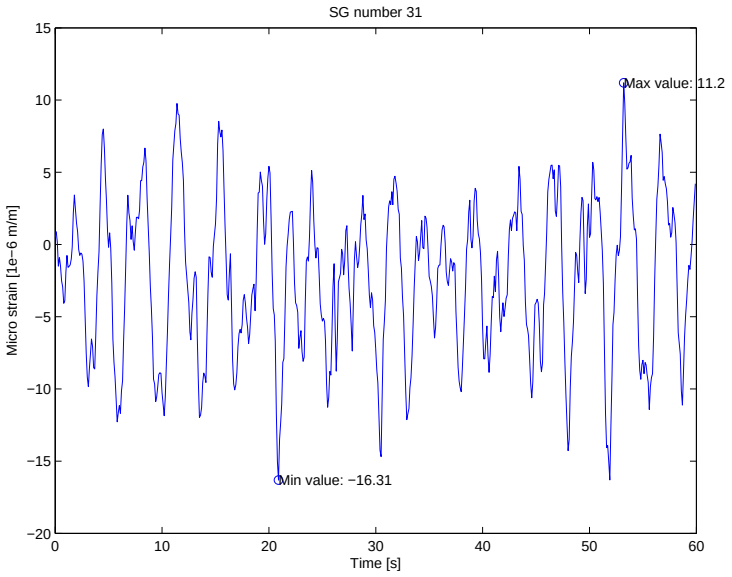


Figure 37: Strain gauge 31

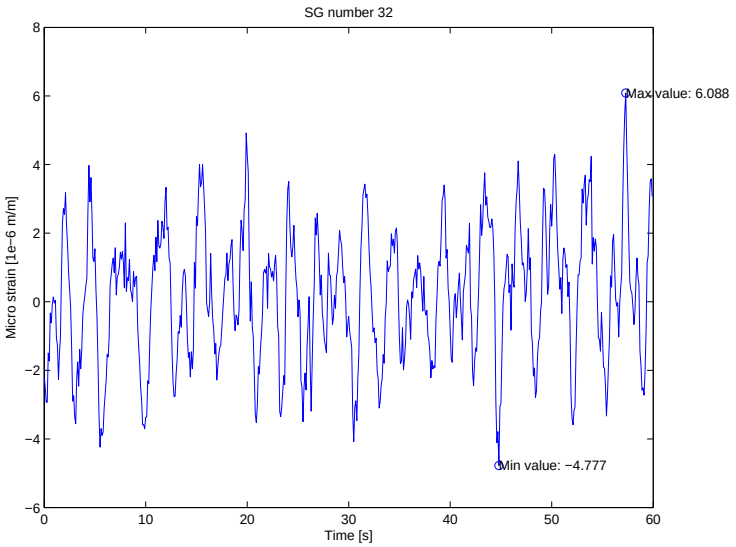


Figure 38: Strain gauge 32

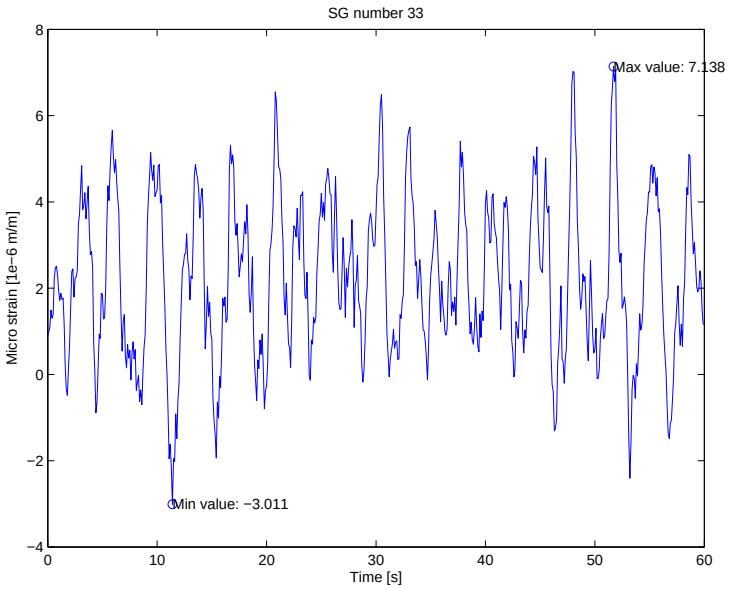


Figure 39: Strain gauge 33

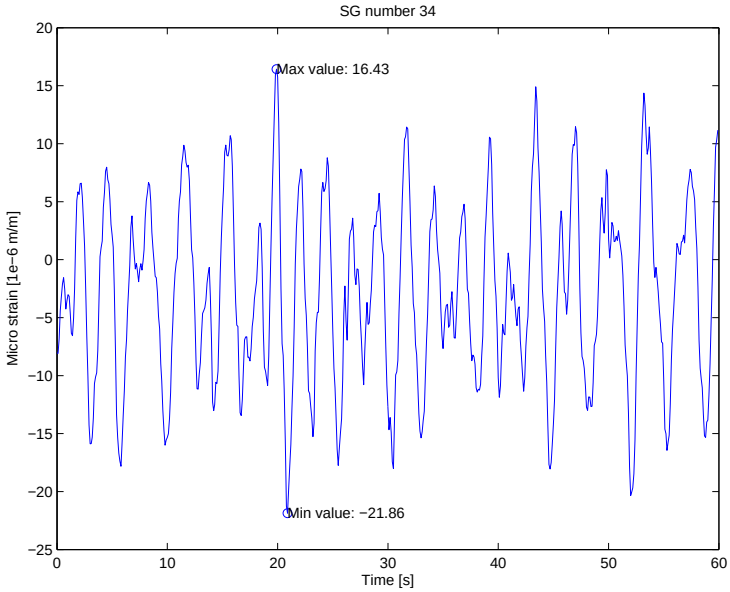


Figure 40: Strain gauge 34

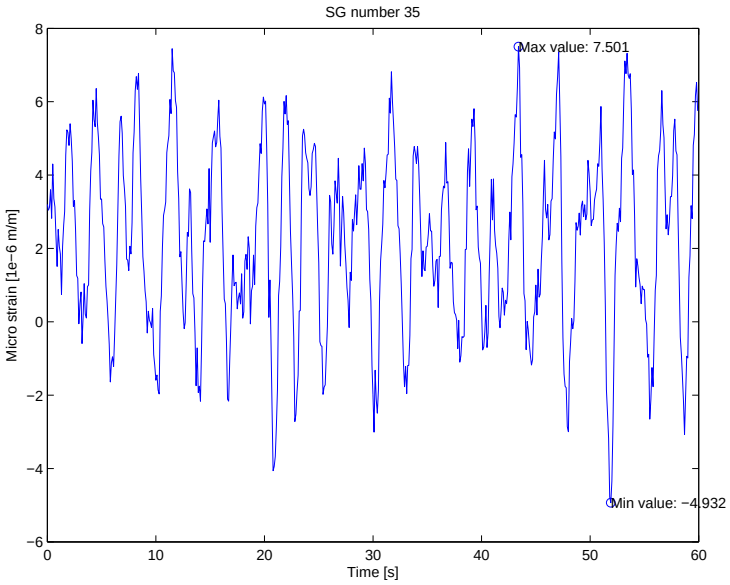


Figure 41: Strain gauge 35

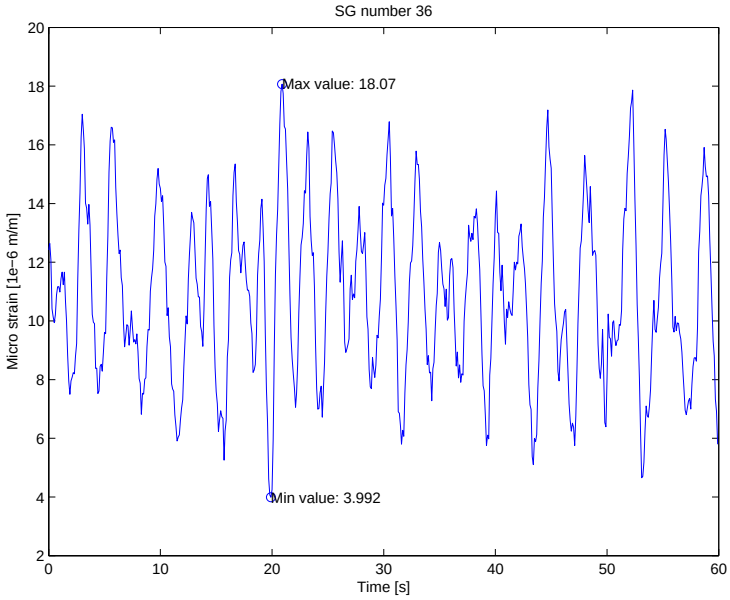


Figure 42: Strain gauge 36

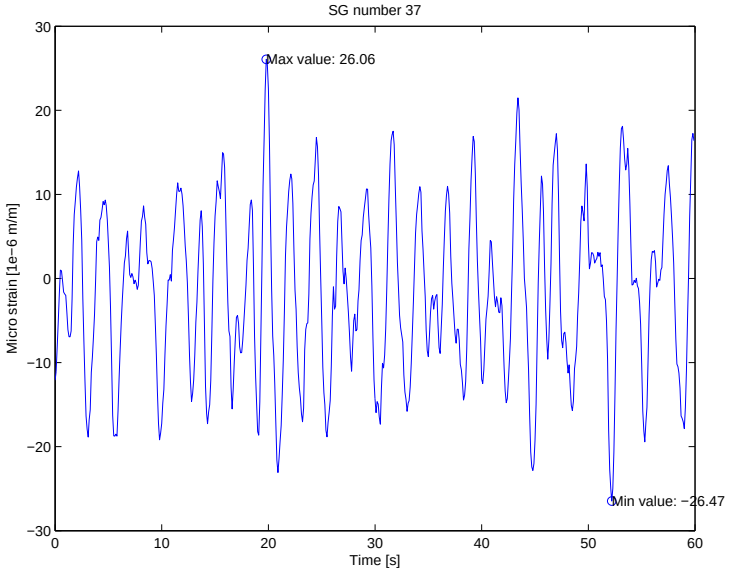


Figure 43: Strain gauge 37

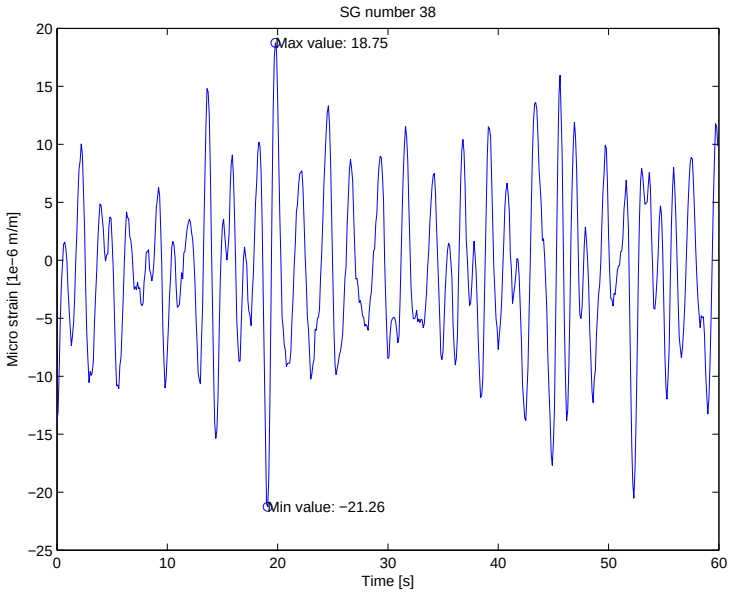


Figure 44: Strain gauge 38

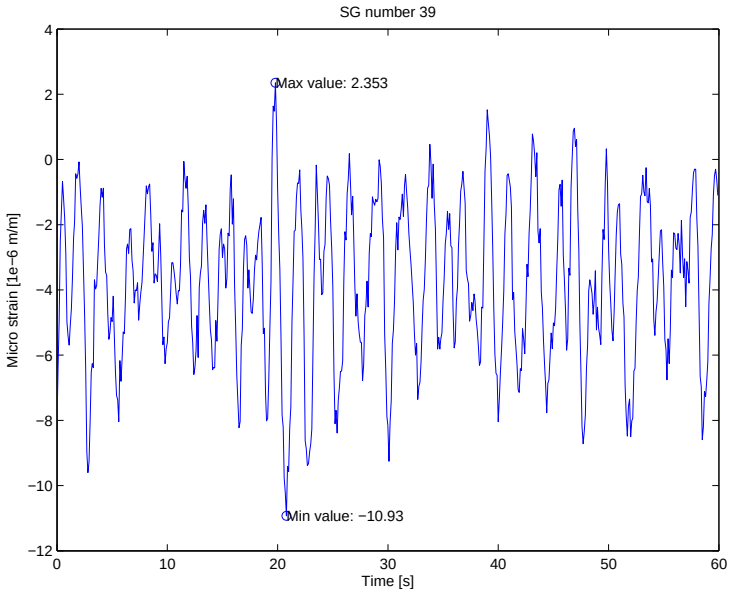


Figure 45: Strain gauge 39

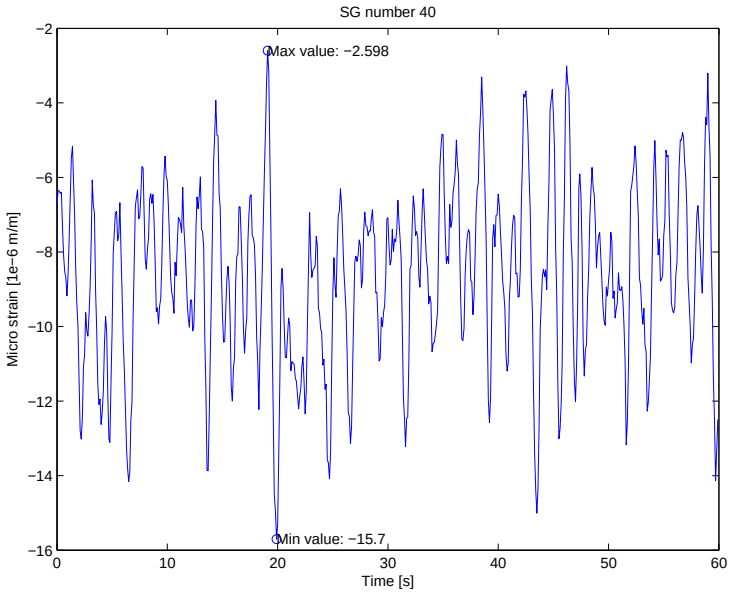


Figure 46: Strain gauge 40

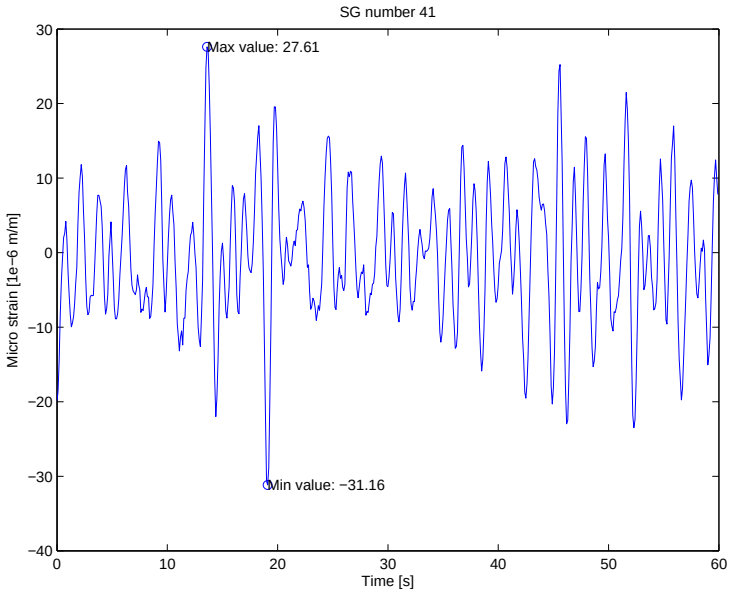


Figure 47: Strain gauge 41

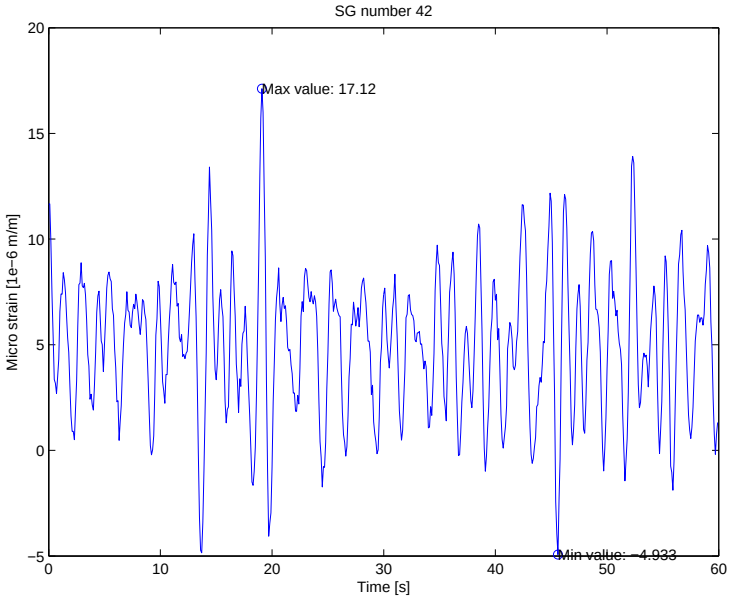


Figure 48: Strain gauge 42

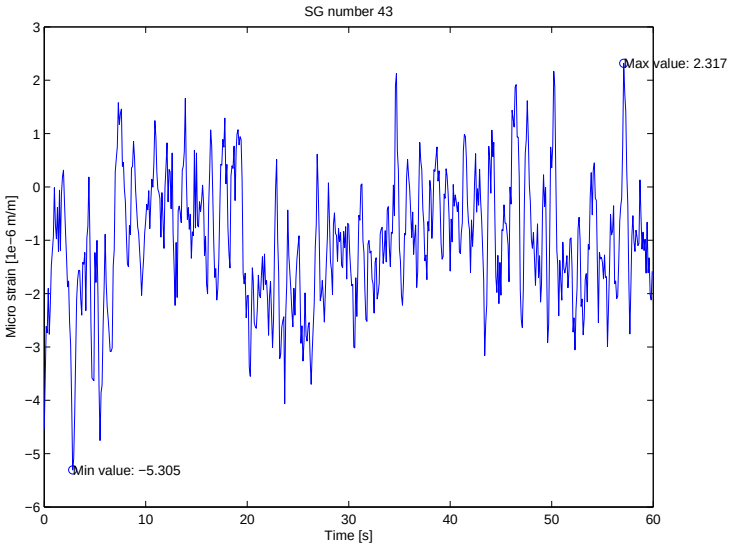


Figure 49: Strain gauge 43

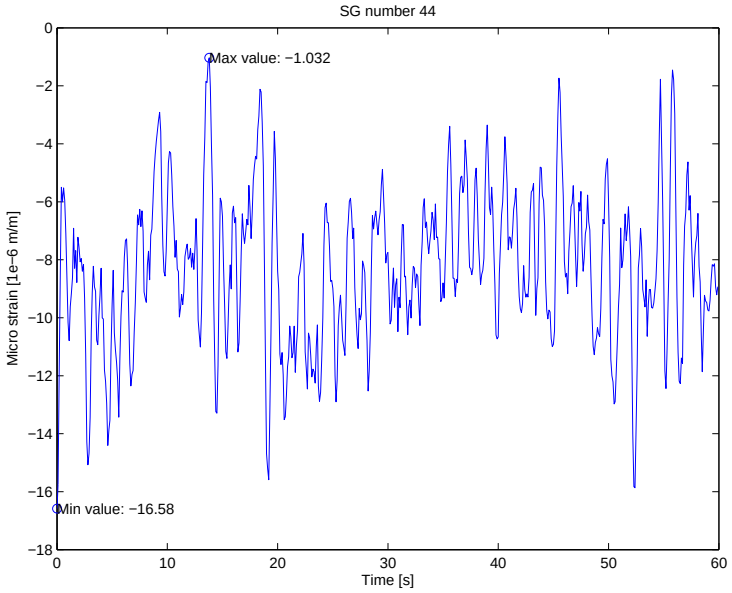


Figure 50: Strain gauge 44

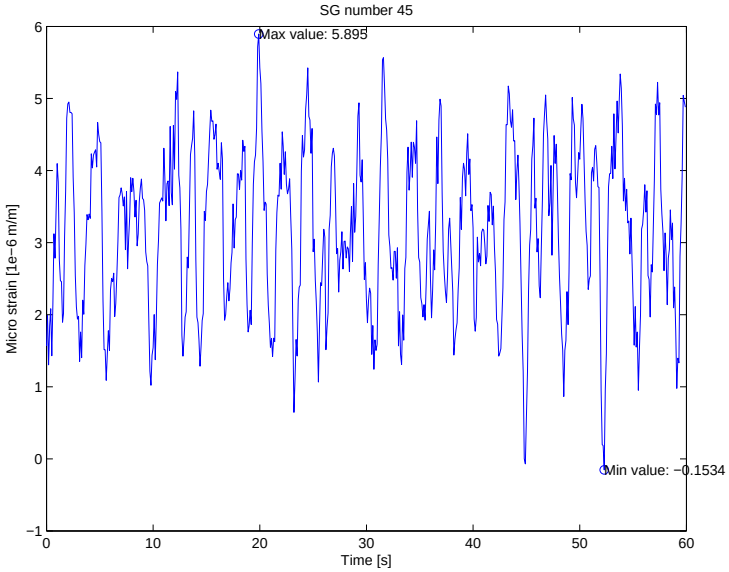


Figure 51: Strain gauge 45

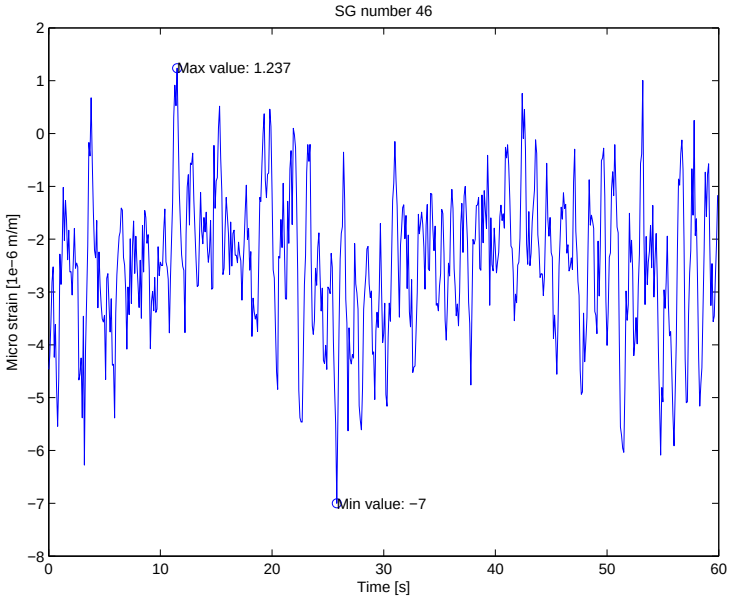


Figure 52: Strain gauge 46

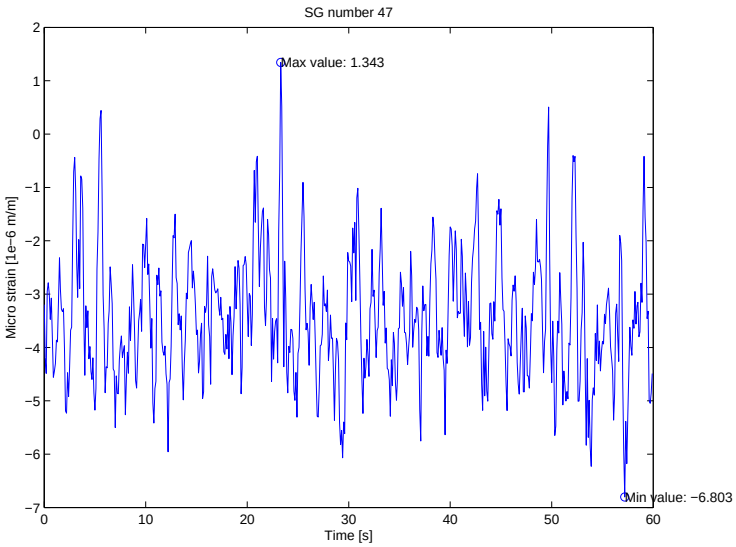


Figure 53: Strain gauge 47

In the figures 54-59 the principal strain and principal direction in the rosette coordinate system are given for the rosettes 1 to 6, respectively.

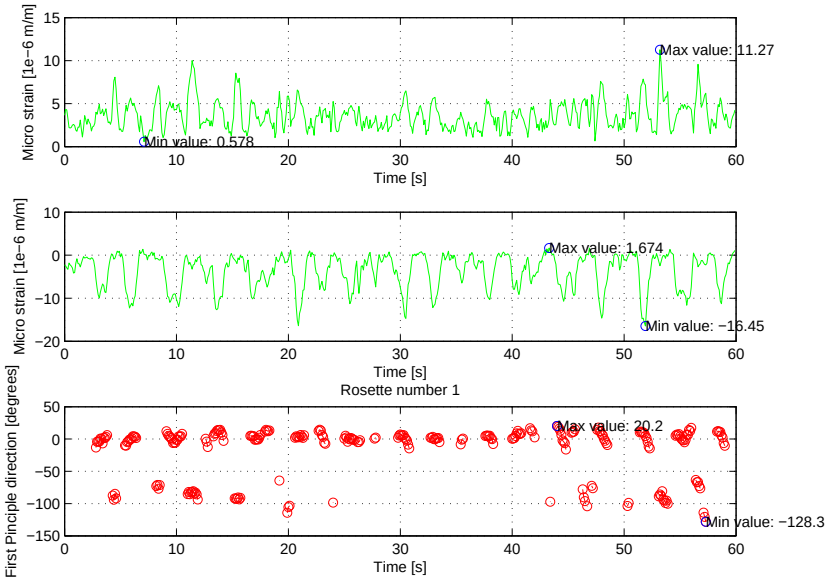


Figure 54: Rosette 1

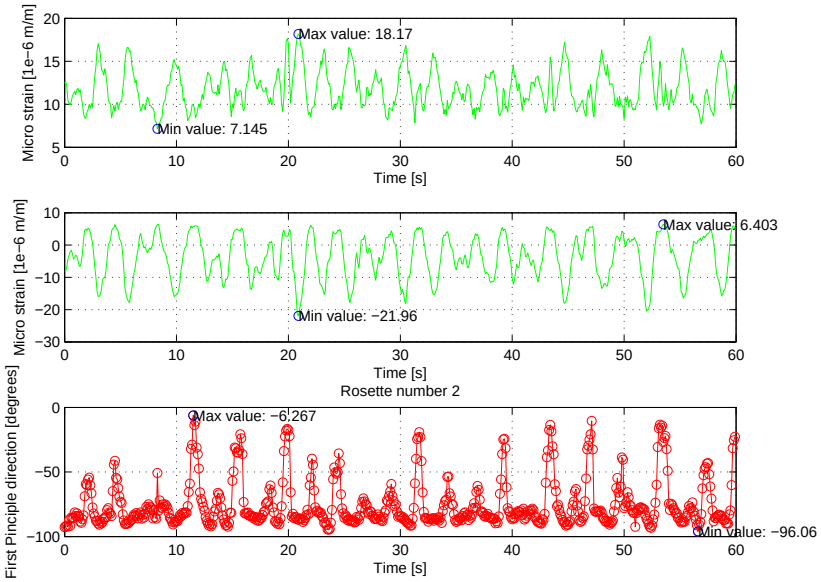


Figure 55: Rosette 2

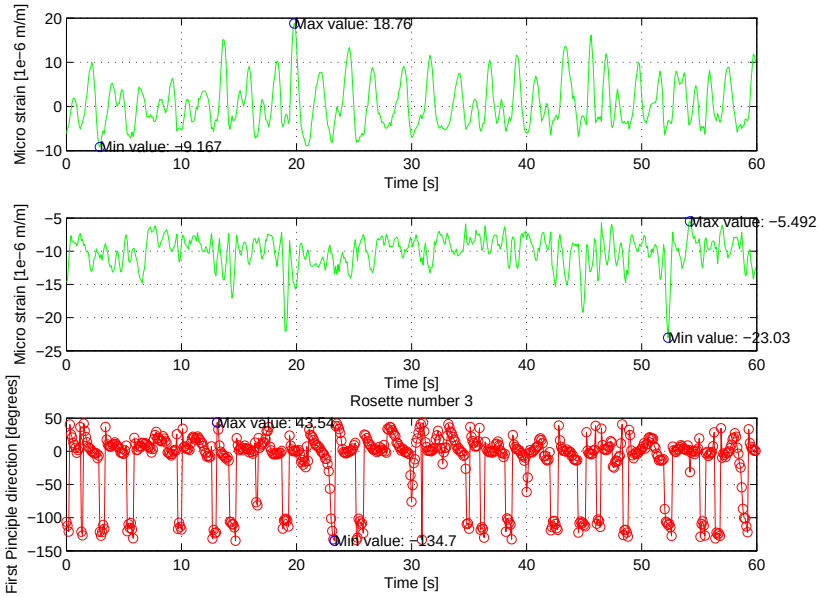


Figure 56: Rosette 3

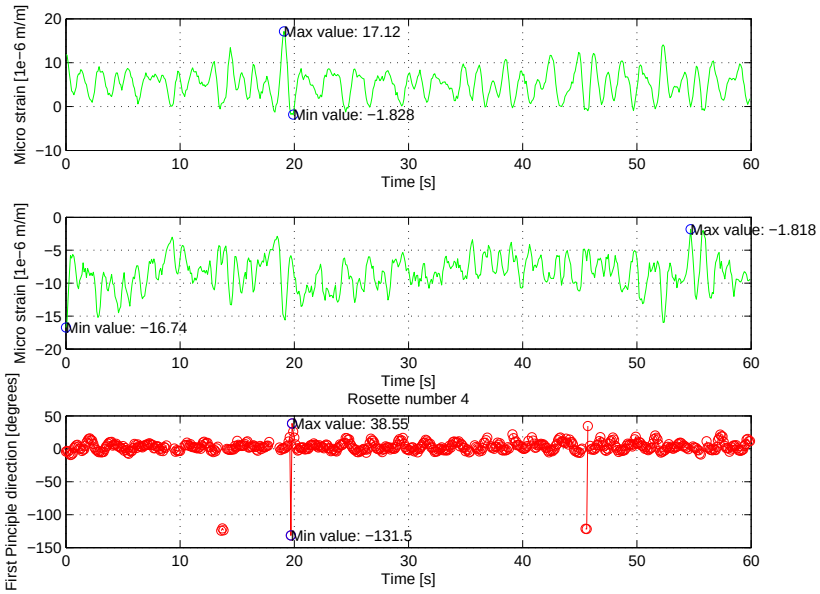


Figure 57: Rosette 4

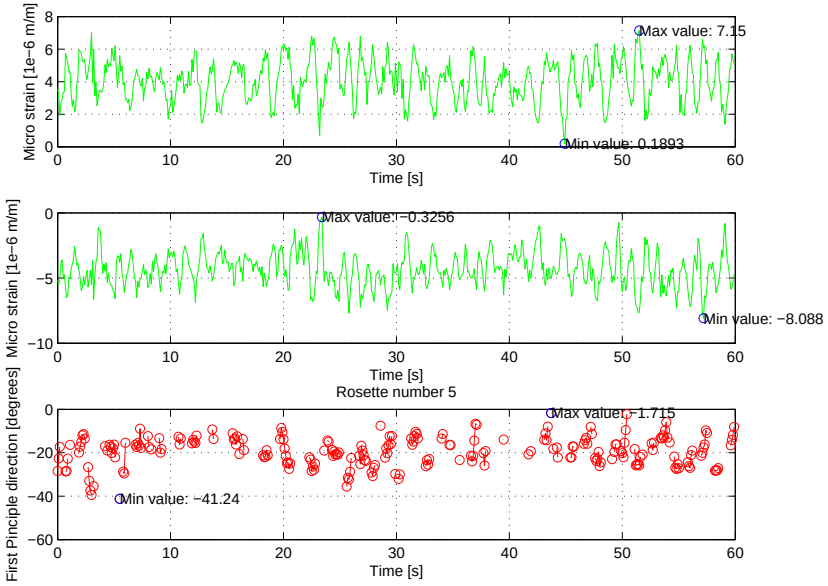


Figure 58: Rosette 5

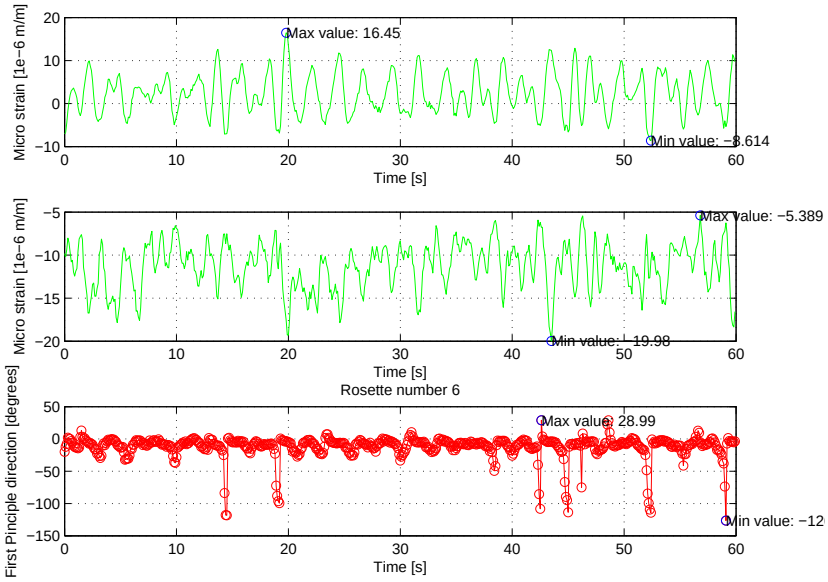


Figure 59: Rosette 6

B Strain gauge data sheet

HBM

Dehnungsmeßstreifen
Strain Gauges
Jauges d'extensométrie

Bestellnummer / Order No. / No. de réference: **1-LY61-10/350**

Typ / Type / Type: 10/350LY61

Widerstand / Resistance / Résistance: 350 Ω ± 0.3 %

Stückzahl / Contents / Quantité: 10

k-Faktor / Gauge factor / Facteur k: 2.09 ± 1 %

Temperaturkoeffizient des k-Faktors / Temperature coefficient of gauge factor / Coefficient de température du facteur k: 93 ±10 [10^{-6} / °C] (-10...+45°C)

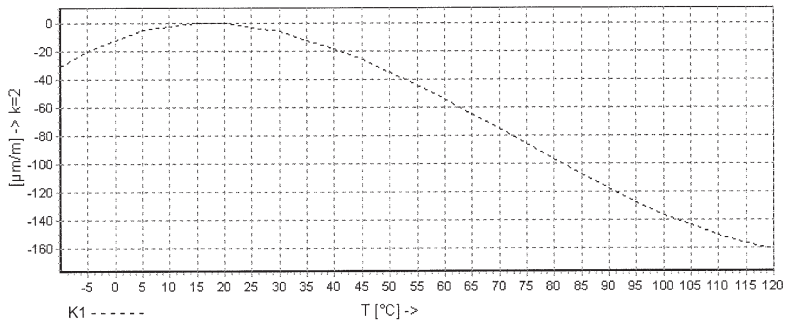
Querempfindlichkeit / Transverse Sensitivity / Sensibilité transverse: 0.5 %

Folienlos / Lot / Lot de la feuille: A405/22

Herstellungslos / Batch / Lot de fabrication: 812043244

Temperaturkompensation: Angepaßt für / Temperature Compensation: Compensated for / Compensation de température: Compensation pour: Ferritischen Stahl mit / Steel with / Acier avec

α = 10.8 [10^{-6} / °C]



Alle technischen Daten nach OIML IR 62, bei Beachtung der abweichenden Toleranzangaben auch nach VDI/VDE 2635. Geben Sie bei Rückfragen bitte DMS-Typ und Herstellungs-Los an.

All technical data in accordance with OIML IR 62, also compliant with C`VDI/VDE 2635 if deviating tolerances are observed. In case of further inquiries please indicate gauge type and batch number.

Toutes caractéristiques techniques selon OIML IR 62 et VDI/VDE 2635 pour les indications différentes de tolérance. Pour toutes questions, indiquer le type de la jauge ainsi que le lot de fabrication.

Temperaturgang der Dehnungsmeßstreifen bei Applikationen mit umseitig angegebenen Wärmeausdehnungskoeffizienten α. Gemessen bei kontinuierlicher Temperaturänderung.

Kennlinie 1: DMS ohne Anschlußbändchen

Comportement en température des jauges d'extensométrie appliquées sur des matériaux dont les coefficients de dilatation termique α sont indiqués au verso. Mesuré au d'une variation continue de la température. .

Courbe 1: Jauges sans fils de sortie

The **Thermal output** refers to strain gauges when bonded to materials with coefficient of thermal expansion α given overleaf. Values are measured at a continous temperature progression. .

Curve 1: Gauges without connecting leads