Measurement of Small Strains using Semiconductors in Centrifuge Tests

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Notation

b	width of wall at prototype
DC	direct current
E	Young's modulus of elasticity
E_c	Young's modulus of elasticity of concrete
E_m	Young's modulus of elasticity of dural
e	electronic charge
g	the Earths gravity
G.F.	gauge factor
h_m	thickness of model wall
K_o	lateral pressure coefficient 'at-rest'
M	bending moment of the wall at prototype scale
n	ratio of centrifugal acceleration to the Earths gravity
N_i	number of charge carriers
I	second moment of area
I_c	second moment of area for concrete at prototype scale
t	thickness
ε	strain
Π_L	longitudinal piezoresistive coefficient
ρ	resistivity
ρ_o	reference resistivity
$\Delta\rho$	change of resistivity
σ	applied stress
μ_{ave}	average mobility of charge carriers
ν	Poisson's ratio

1.0 Introduction

1.1 Background

The Transport Research Laboratory (TRL) have commissioned two series of centrifuge model tests to examine the fundamental behaviour of integral bridge abutments subjected to cyclic loading as a result of expansion and contraction of the bridge deck during daily and seasonal variations of temperature. These two series of integral bridge abutments investigate:

1. a relatively flexible piled wall with a stiff deck
2. a stiff spread-base abutment with the same stiff deck

Centrifuge results of these two test series have been reported by Norrish(1993, 1994) and Ng(1995) respectively.

During the design of a centrifuge model for the stiff spread-base abutment, it was estimated that the bending strains induced in the stem of the abutment could be very small under fully active conditions. For conventional foil gauges, strains less than 10^{-5} are very difficult to measure accurately in the Cambridge Geotechnical Centrifuge Centre due to electrical noise. This led to the consideration of using semiconductor strain gauges for accurate measurement of small bending strains.

In this technical report, the evaluation processes for Kulite 120 ohm SAJCP- 120-090 E2 semiconductor gauges are described. In addition, the use of these gauges in some centrifuge tests is reported.

1.2 Design of model abutment wall

TRL specified a typical 6-7m height reinforced concrete wall (1.0m thick) to be modelled in the centrifuge. The concrete was assumed to have E_c=28MPa and it was reinforced with 1.5% of steel by cross sectional area. At ng, the model thickness of the wall is given by the following equation:

$$h_m = \sqrt[3]{\frac{12E_cI_c}{bE_m}}\left(\frac{1}{n}\right) \qquad \text{.......} \qquad (1)$$

For a given full-scale bending moment (M) in the wall, bending strain can be calculated as follows:

$$\varepsilon = \sqrt[3]{\frac{12E_cI_c}{bE_m}}\left(\frac{M}{2E_cI_c}\right) \qquad \text{.......} \qquad (2)$$

Dural was selected as the model abutment material, which has a Young’s modulus of 69 MPa. Fig. 1 shows the design chart for the model wall to be tested at 60g. Fully cracked concrete section was assumed in the calculations. For a given prototype 1000mm thick reinforced concrete wall, the required model wall thickness was found to be 9.9mm. This was based on the estimation that the minimum bending moment in the wall was about 40 kNm/m (prototype) when the wall was loaded under the fully active conditions. It can be seen that the induced bending strain is in the order of 10 microstrains which can be very difficult to measure accurate using’conventional foil strain gauges because of electrical noise. This led to the considerations of using some other more sensitive strain gauges such as semiconductors. Fig. 2 shows the general arrangement of the model spread-base integral bridge abutment.

2.0 Kulite semiconductor strain gauges

2.1 General principles (from Kulite semiconductor strain gauge manual)

The principle employed in these semiconductor gauges is the piezoresistance effect, which is defined as the change in electrical resistivity with applied stress. All materials exhibit this effect to some degree, but in certain semiconductors the effect is very large, and appreciable change in resistivity occurs with applied stress. The resistance change occurs under all conditions of static and dynamic strain.

For a semiconductor, the resistivity ρ is inversely proportional to the product of the number of charge carriers N_i and their average mobility μ_{ave}. This may be expressed as :

$$\rho = \frac{1}{eN_i\mu_{ave}} \quad \text{...} (3)$$

where e is the electronic charge.

The effect of an applied stress is to change both the number of carriers and their average mobility. The magnitude and the sign of the change will depend on the specific semiconductors, their carrier concentration and their crystallographic orientation with respect to the applied stress. For a simple tension or compression, when the current through the gauge is along the stress axis, the relative change in resistivity $\Delta\rho/\rho_o$ is given by

$$\frac{\Delta\rho}{\rho_o} = \sigma\Pi_L \quad \text{...} (4)$$

where Π_L is the longitudinal piezoresistive coefficient and σ is the applied stress.

Gauge factor (G.F.) is defined as the fractional change in resistance of a gauge with applied strain. The larger the gauge factor is, the higher the resistance change and the resulting output and resolution will be. The relationship between the piezoresistive coefficient (Π_L) and conventional gauge factor is given by the following equation,

$$G.F. = 1 + 2\nu + E\Pi_L \quad (5)$$

The first two terms represent the change in resistance due to dimensional changes while the last term represents change in resistivity with strain.

The semiconductor crystals, from which the strain sensitive elements for Kulite gauges are obtained, are grown with a controlled impurity content to obtain the desired characteristics. The final characteristics of the gauge can be altered by changing the type and quantity of the electrically active impurities or by modifications in the processing procedures. The combination of these technique provides an extremely wide latitude of gauge characteristics. Other details of the semiconductors are given in the Kulite semiconductor strain gauge manual.

Metal wire and foil gauges have gauge factors between 2 and 4, whilst Kulite semiconductor gauges have gauge factors between 45 and 200. For the semiconductors (120 ohm Kulite S/UCP-120-090 E2) used in the CWWN tests, they have a gauge factor of approximately 100 between 10 and 50 °C, which is about 50 times more sensitive than the foil gauges commonly adopted in the centrifuge centre (gauge factor=2). Details of calibration of the semiconductor transducers are given in the following sections.

2.2 Resolution

To evaluate the performance of the semiconductors, two types of transducers, one which consisted of four semiconductor gauges and the other composed of four conventional foil gauges were connected to form two full bridge circuits. These two transducers were mounted on a 9.3mm thick, 140mm wide and 260mm long dural plate. They were supplied with a constant 5 V DC power input. Signals were amplified by 100 in a junction box before recording. The dural plate was stressed by applying a knife edge load 150mm away from the positions of these two transducers. Three load-unload cycles were applied. The transducer signals and room temperature were recorded during the test. Applied bending strain at the locations of the transducers is calculated by:

$$\varepsilon = \frac{Mt}{2EI} \quad (6)$$

Fig. 3 shows the comparison of measurements recorded by the semiconductor and foil gauges. For a given change of strain, the semiconductor transducer exhibited a much larger piezoresistance effect than the conventional foil gauges. The average slopes of the two lines are 0.023 volt/microstrain and 0.0004 volt/microstrain for semiconductor and foil gauges respectively. The ratio of these two slopes is 58 which indicates that the semiconductor gauges are 58 times more sensitive than the foil gauges. Although the calibration line for the semiconductor was slightly curved and it exhibited some hysteresis behaviour, these characteristics were not observed for any subsequent calibrations for other semiconductor transducers mounted on the stem and base of the model abutment. It is likely that this behaviour can be attributed to an improvement in mounting skill and familiarisation of the mounting techniques for the semiconductors. Some typical subsequent calibration results are shown in Figs. 4 & 5.

2.3 Temperature effect

The characteristics of these semiconductor strain gauges are temperature dependent. In particular, the resistance of an unbonded gauge increases with temperature while the strain sensitivity, or gauge factor, decreases with temperature. To properly utilise these semiconductor gauges for accurate measurements of mechanical strain, it is necessary to compensate the gauge output signals against undesirable temperature effects.

The gauge resistance of a bonded gauge changes with temperature due to two principal causes, the inherent positive temperature coefficient of resistivity of the semiconductor and the differential thermal expansion coefficients between semiconductor ($3.7\text{x}10^{-6}$ /°C) and substrate (2.0x10-6 /°C for dural in this case). This apparent strain occurs independently of any applied mechanical strain and must be minimised or taken into account for accurate static measurements. Compensation can generally be accomplished with some circuit techniques, for example, four gauges connected to form a fully active bridge circuit. Temperature induced resistance changes of adjacent arms of a bridge tend to cancel out, but perfect compensation is rarely achieved due to uncontrollable variations between matched gauges themselves and the manner in which they are mounted. Other compensation techniques are given in the Kulite semiconductor strain gauge manual.

Fig. 6 shows the apparent bending strain with change of temperature. It can be seen that the apparent strain varies with temperature in a fairly linear fashion. For a small range of temperature variations, say less than 2 °C during a typical centrifuge test in the centrifuge centre, the adverse effects of temperature variations on induction of apparent strains can be accounted for or ignored. Measures were taken to ensure this was the case by recording temperature variations and introducing two dummy transducers in all centrifuge tests.

Two temperature transducers were installed in the strong box of a centrifuge package. One was put beneath the sand layer on the retained soil side (refer to Fig. 2) and the other was located above the lead shot on the excavated side. The measured temperatures during swing up and cyclic loading of a typical test are shown in Figs. 7 & 8 respectively. The recorded temperatures confirmed that the maximum variations of temperature in the tests was indeed less than 2 °C during swing up. As expected, larger variations of temperature were recorded in the air than within the sand layer. Once steady conditions were established after swing up, temperature variations at both locations were less than 0.5 °C (see Fig. 8). This suggests that the adverse effects on strain measurement due to temperature variations can be either accounted for or ignored in this series of centrifuge tests.

2.4 Zero shift

A zero shift test of the semiconductors was carried out over 4 days. The observed results are shown in Fig. 9. An apparent strain of 1 microstrain was observed during this period. This apparent strain is probably due to the variations of temperature, rather than the actual zero shift. Effects of zero shift can therefore be assumed to be negligible for a relatively short centrifuge test duration which typically lasts only for a few hours.

3.0 Performance of the strain gauges in the centrifuge

3.1 During swing-up

Since this was the first time semiconductors were used in centrifuge tests at the Cambridge Geotechnical Centrifuge Centre, some conventional foil gauges were mounted at certain key positions of the 9.9mm thick model wall to verify measurements recorded by these two types of gauges. Each transducer consisted of four strain gauges connected in a full bridge circuit. For semiconductor and foil gauges, 120 ohm Kulite S/UCP-120-090 E2 and 350 ohm Techni-Measure Ltd type FLA2-350-2h-23 were adopted respectively. They were all supplied with a constant 5 V DC power input. Signals were amplified by 10 or 100 for semiconductors and by 100 for foil gauges in a junction box mounted on top of the strongbox. High frequency electrical noise was filtered before amplification. For semiconductors, a fairly large off-set voltage was observed in some gauges. This problem can be readily resolved by using bridge balancing techniques.

Fig. 10 shows the recorded strains in the stem of the abutment during swing up. The signals recorded by the conventional foil and semiconductor gauges have been amplified by 100 and 25 respectively in the junction box. It can be seen that the conventional foil gauge transducer gave very noisy readings over the whole range of strains at each stage of centrifugal acceleration: lg, 100g and 60g. In particular, the variations at lg were over +/- 50% at small strain range. On the other hand, the readings recorded by the semiconductor transducer were very smooth. At 60g, the recorded minimum bending strains in the wall were about 35 microstrain when the wall was loaded by K_o lateral stresses, which were artificially enhanced by increasing the centrifugal acceleration to 100g before reducing to 60g. This observed microstrain was consistent with the predicted minimum strain (9 microstrain) in the wall under the fully active loading conditions. At the selected acceleration (60g) for testing, the measured variations of bending strains using the foil gauge transducer were up to +/- 20% of the mean values, whereas the semiconductor gauges gave a set of smooth readings.

By comparing the measurements by these two transducers, it is evident that the performance of the semiconductor gauges was not as affected by the magnitude of acceleration as those conventional foil gauges.

3.2 During cyclic loading of the abutment

Controlled cyclic horizontal displacements at +/- 0.1mm, +/- 0.2mm, +/- 0.5mm and +/- 1.0mm were applied to the wall at the deck level to simulate the expansion and contraction of the bridge deck as a result of daily and seasonal temperature variations (Norrish, 1993 & 1994; Ng, 1995). Fig. 11 shows the comparison between the recorded readings of both types of transducers just before and during +/- 0.1mm controlled cyclic displacements. At small strains, the conventional foil gauge gave substantial electrical noise as during swing up. However, during the actual cyclic loading, the difference in the measured values between these two types of gauges was not very significant. Similar behaviour was observed during the larger displacement controlled cycles.

4.0 Conclusions

Semiconductor strain gauges have been evaluated for the first time, with respect to their use in centrifuge tests. It was found that these semiconductor gauges were about 50 times more sensitive than the conventional foil gauges. This is because of their high piezoresistivity characteristics which lead to large gauge factors. For a wide range of strains, they recorded electrical signals virtually without electrical noise. On the other hand, foil gauges exhibited very noisy characteristics for a fairly large range of strains.

The performance of the semiconductors did not seem to be influenced by the magnitude of centrifugal acceleration. Based on the zero shift test over 4 days, it can be concluded that the zero shift of the semiconductors is insignificant and it should not be a problem for typical centrifuge tests which normally last for only a few hours.

High off-set voltages were measured in some semiconductors. Bridge balancing technique may be required to nullify any off-set voltage. Since the performance of the semiconductors depends on temperature, it is essential to have a self-compensating circuit for accurate strain measurements. For general applications at room temperatures with small variations, this type of semiconductor strain gauge can be very useful for strain measurements, particularly for small strains.

5.0 References

Norrish, A.R.M. (1993, 1994). *Cyclic loading of soil behind bridge abutments.* Centrifuge test data reports I, II and III.

Ng*, C.W.W. (1995).** ***Cyclic loading of sand behind a spread-base bridge abutment. Centrifuge test data reports VI and V.

Kulite semiconductor strain gauge manual.

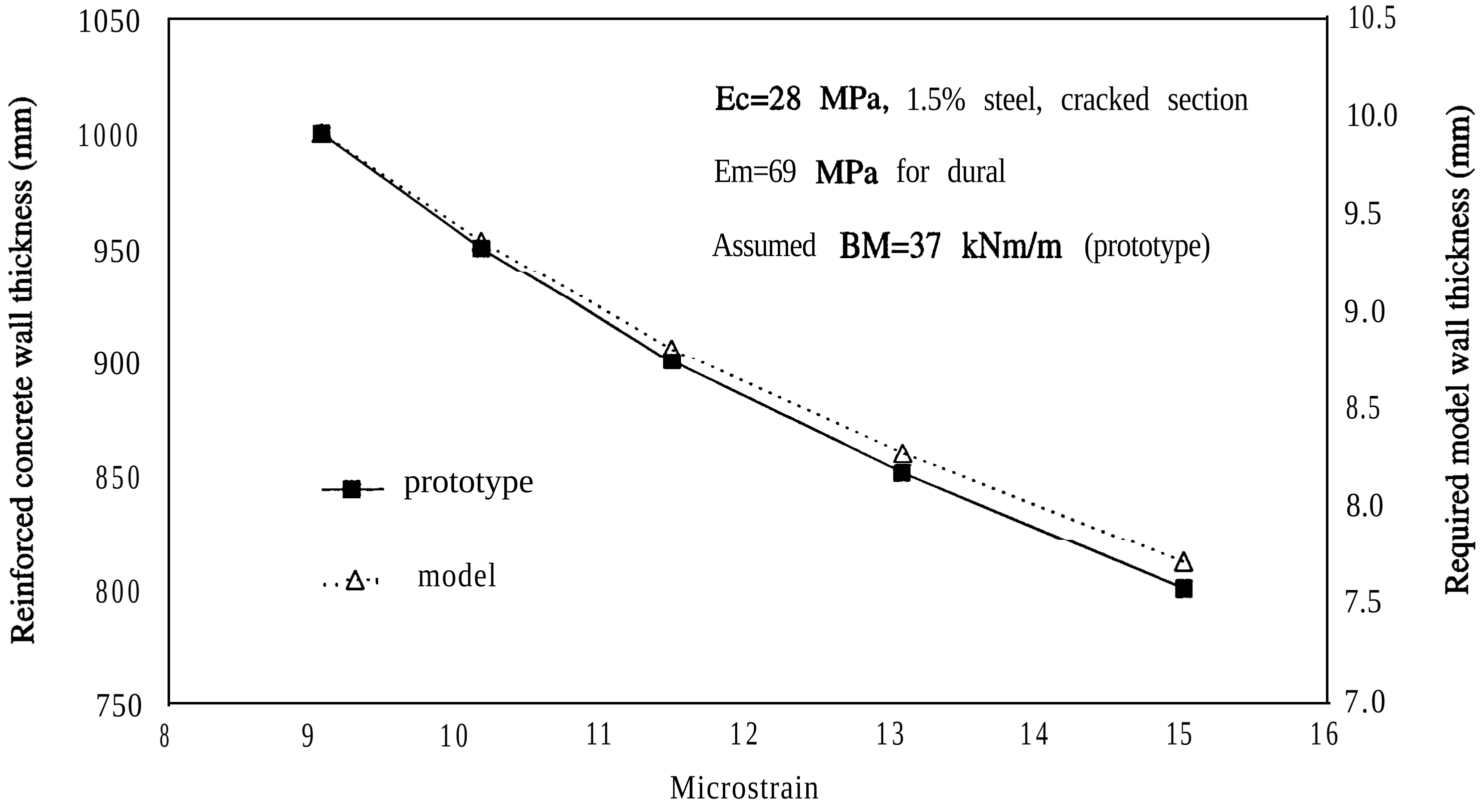

Fig. 1 - Design of model abutment stem at 60g

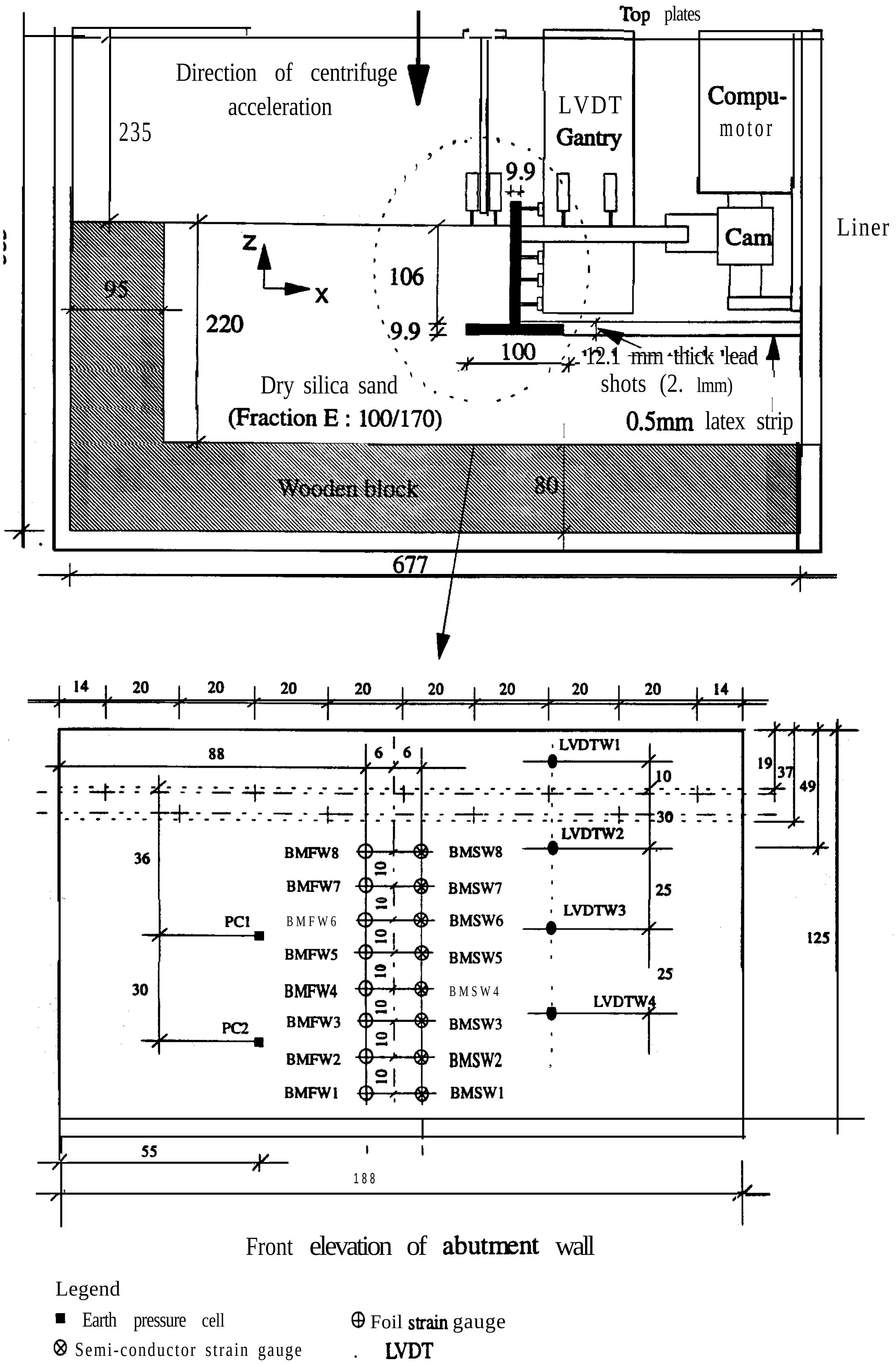

Fig.2 - General arrangement for CWWN test series

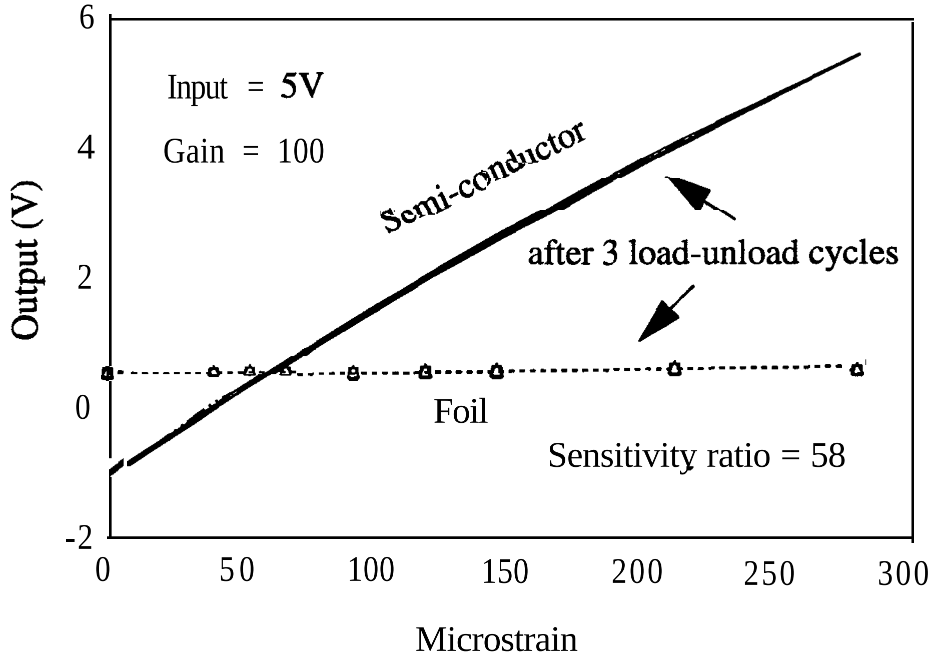

Fig.3 - Comparison of semiconductor and foil strain gauges

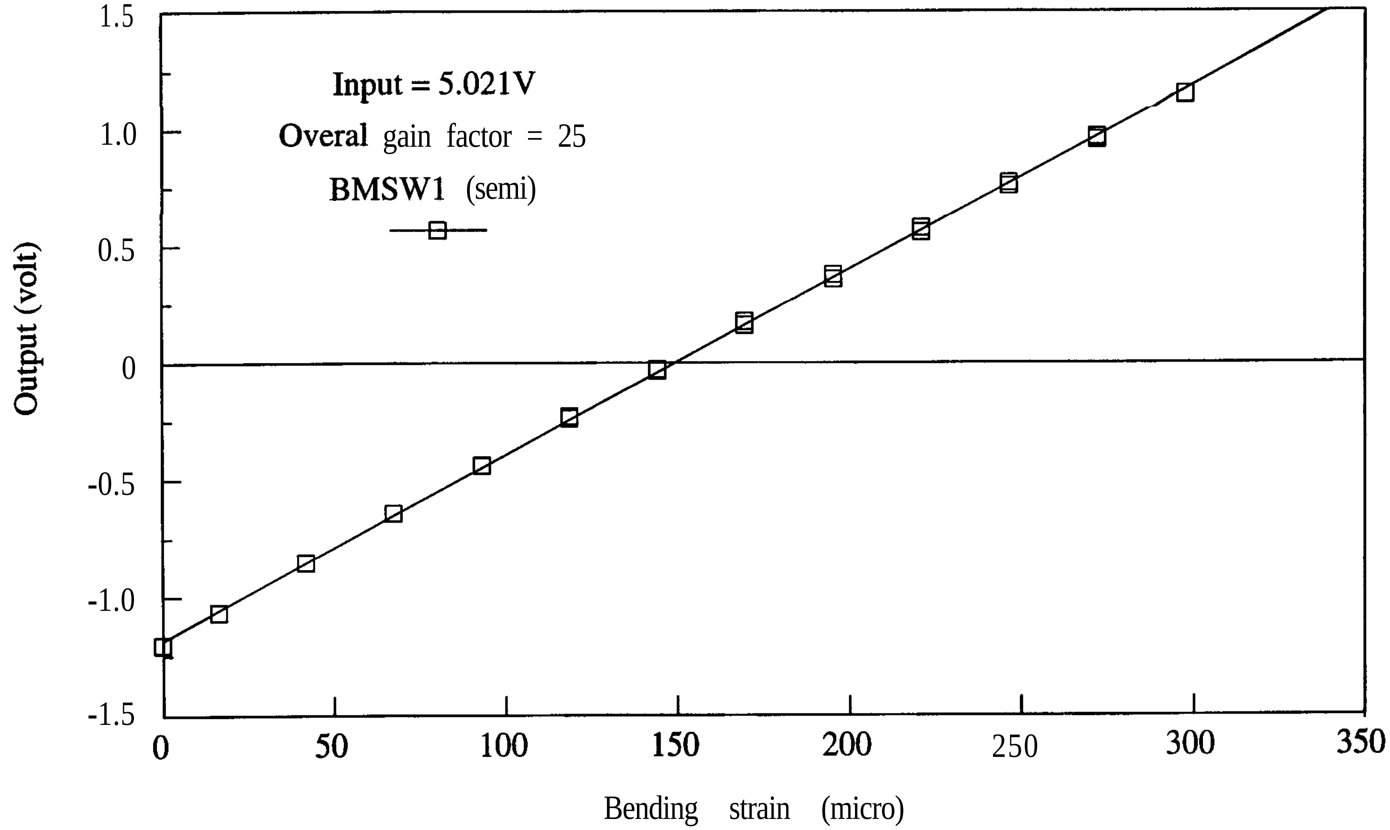

Fig.4 - Calibration curves for BMSW 1 after 1 load-unload cycle

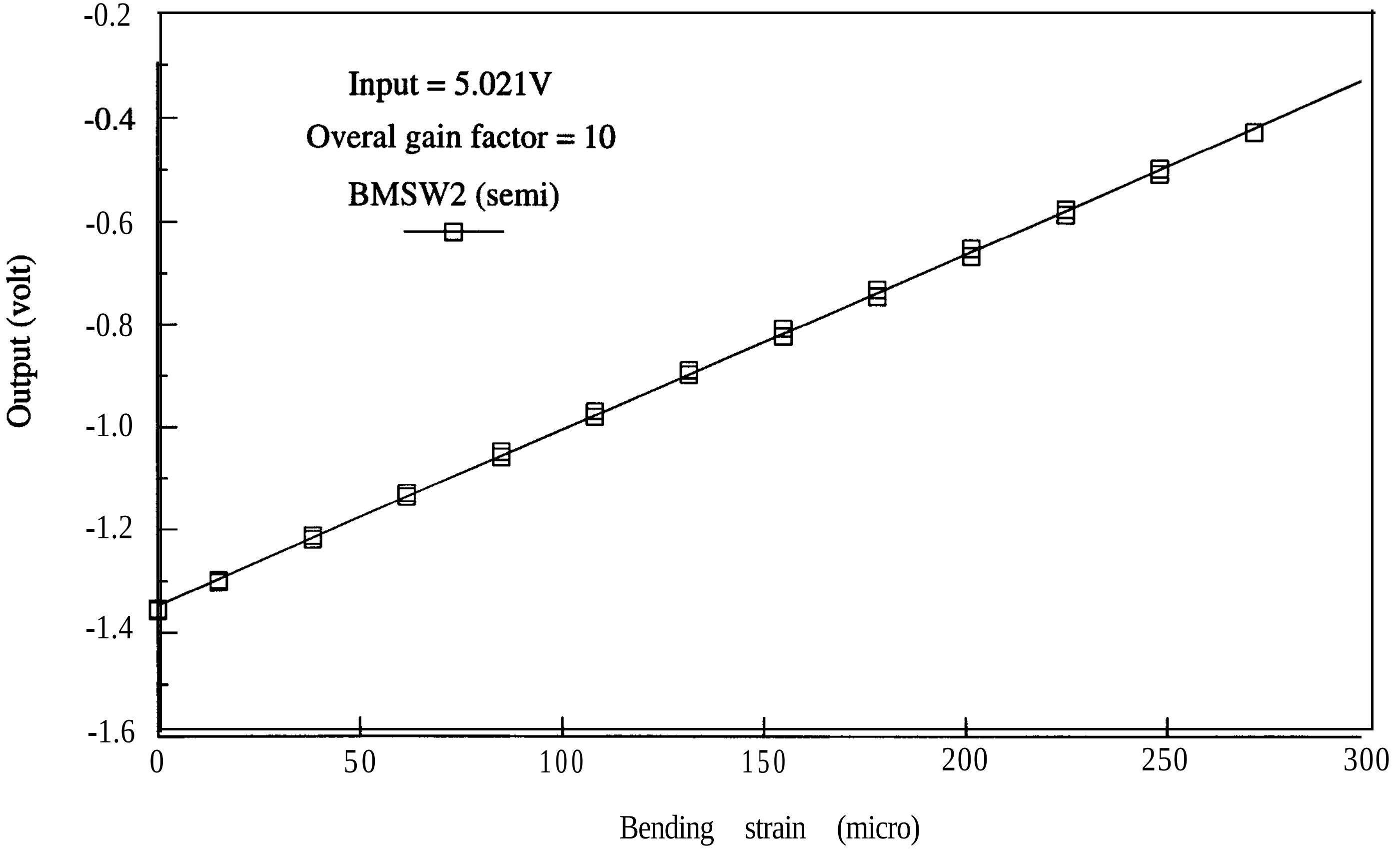

Fig.5 - Calibration curves for BMSW2 after 1 load-unload cycle

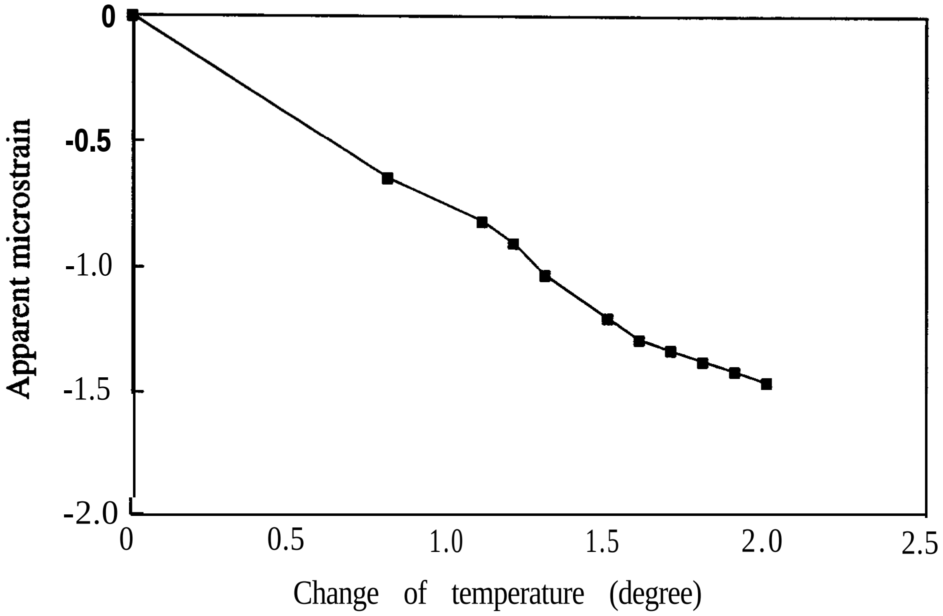

Fig.6 - Temperature effects on semiconductors

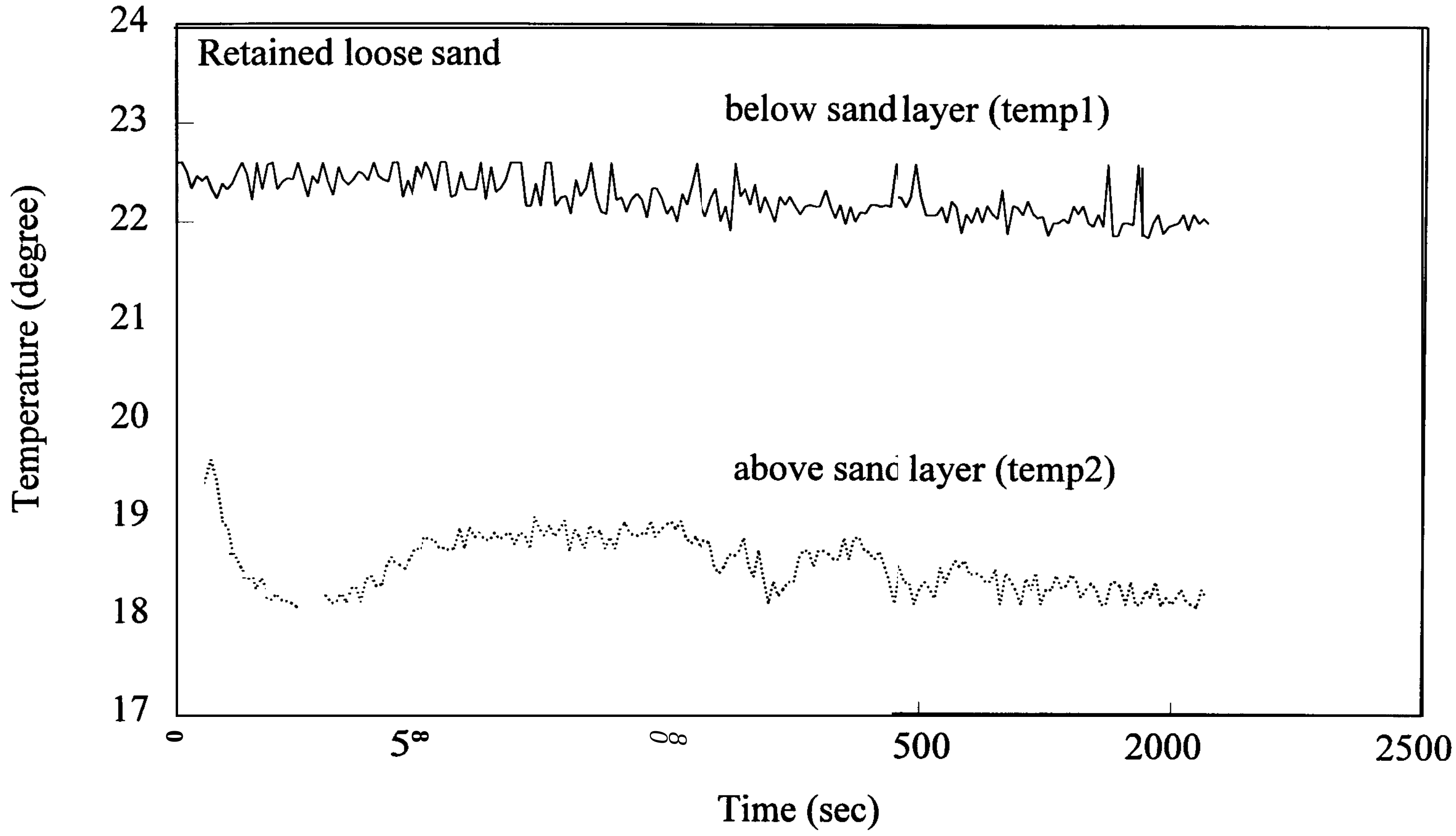

Fig.7 - Temperature variations during swing-up (CWWN2)

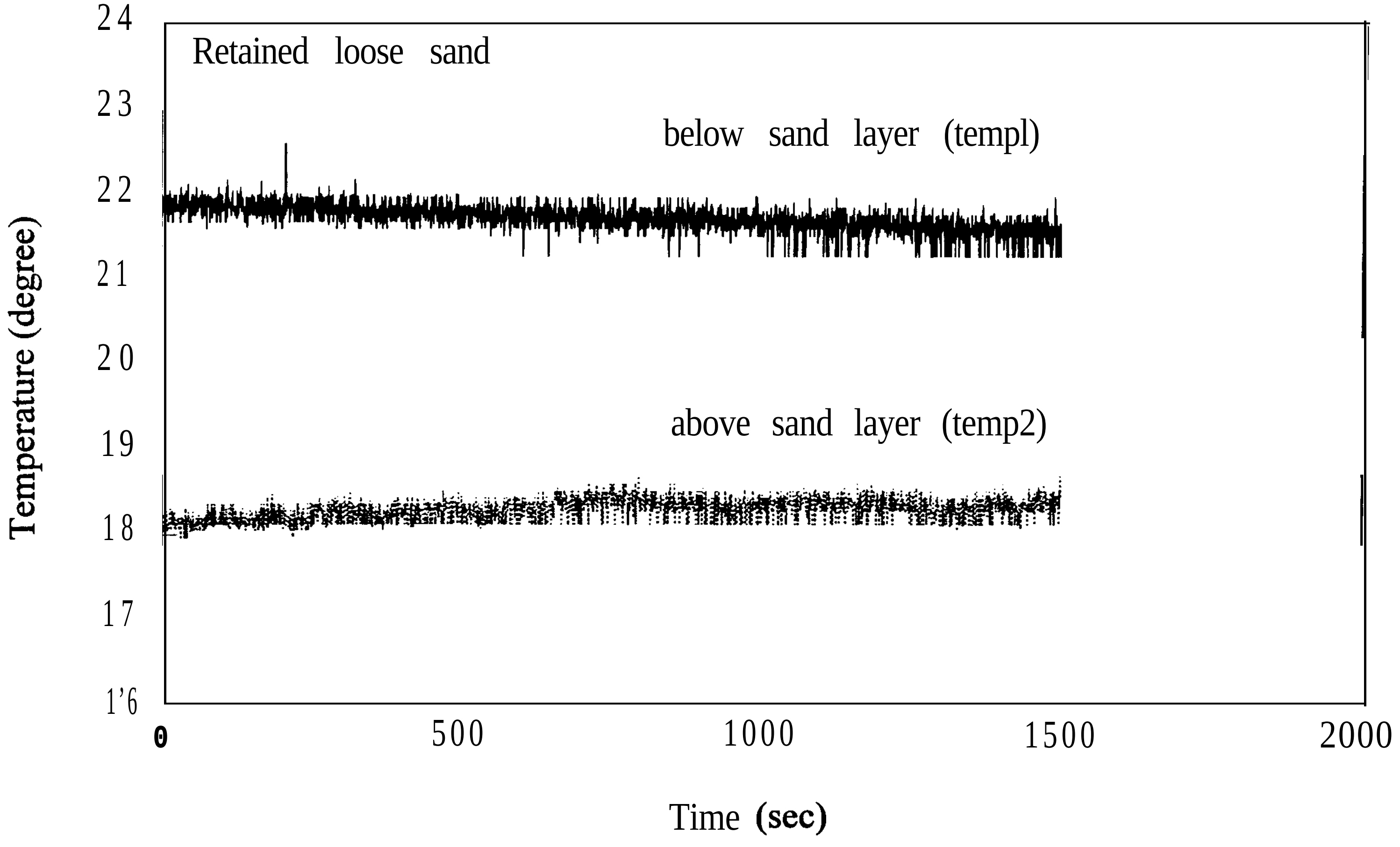

Fig.8 - Temperature variations during +/- 0.1 mm excitation (CWWN2)

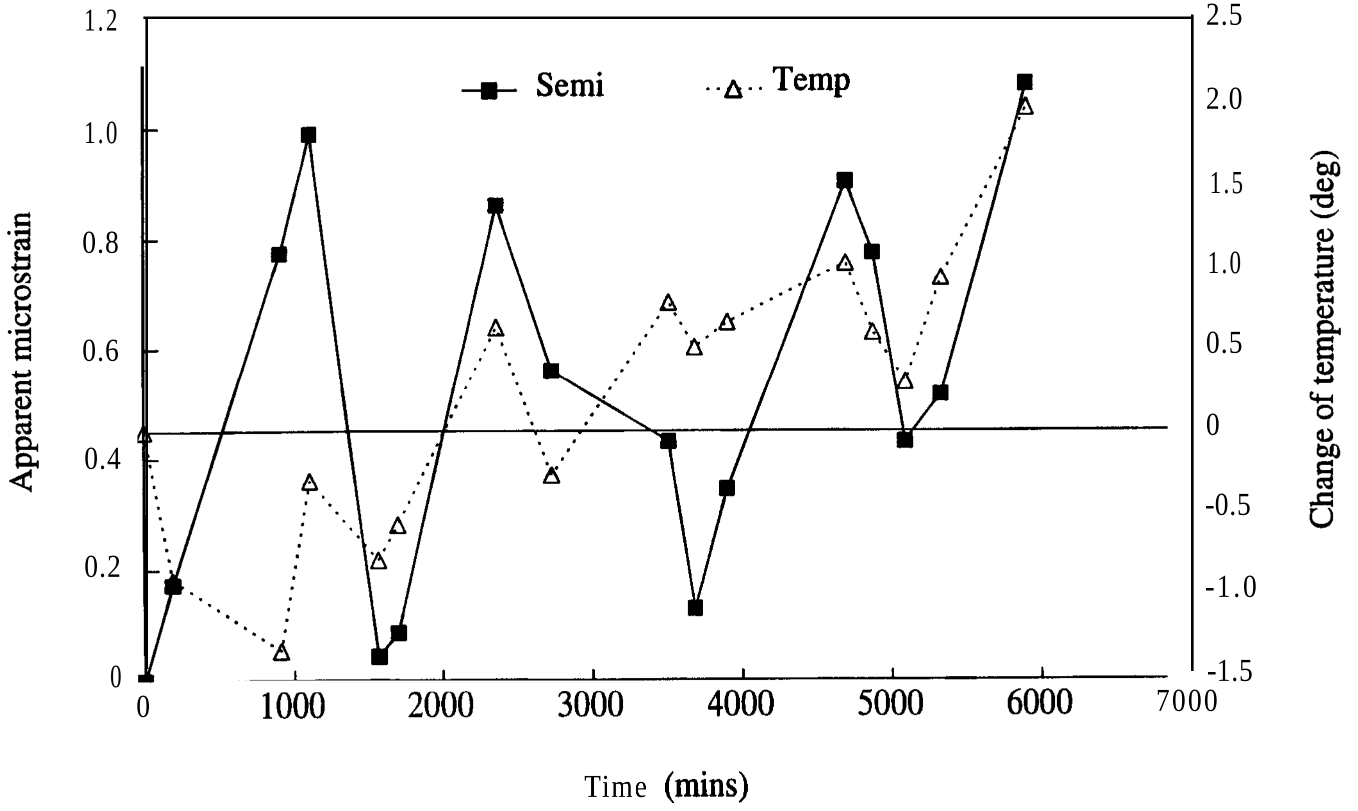

Fig.9 - Zero drift of semiconductors

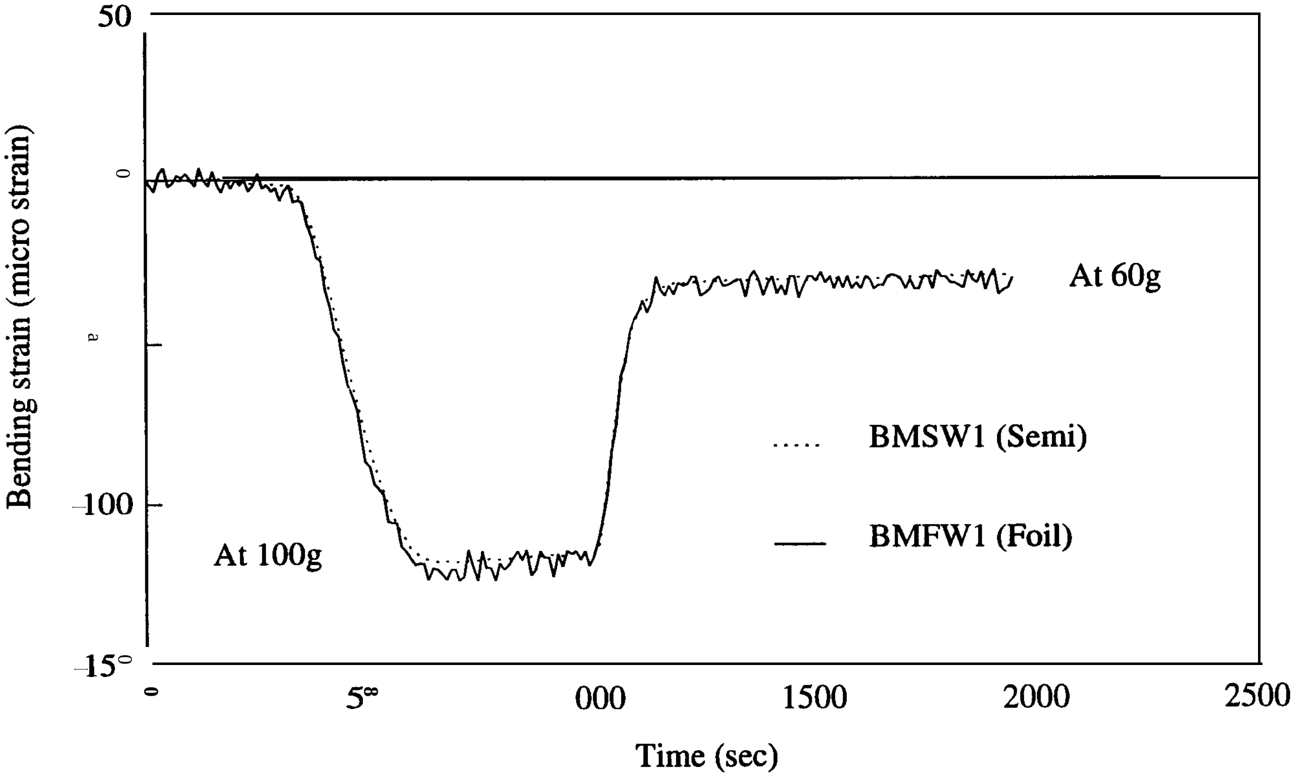

Fig.10 - Bending strain in wall during swing-up (CWWN1

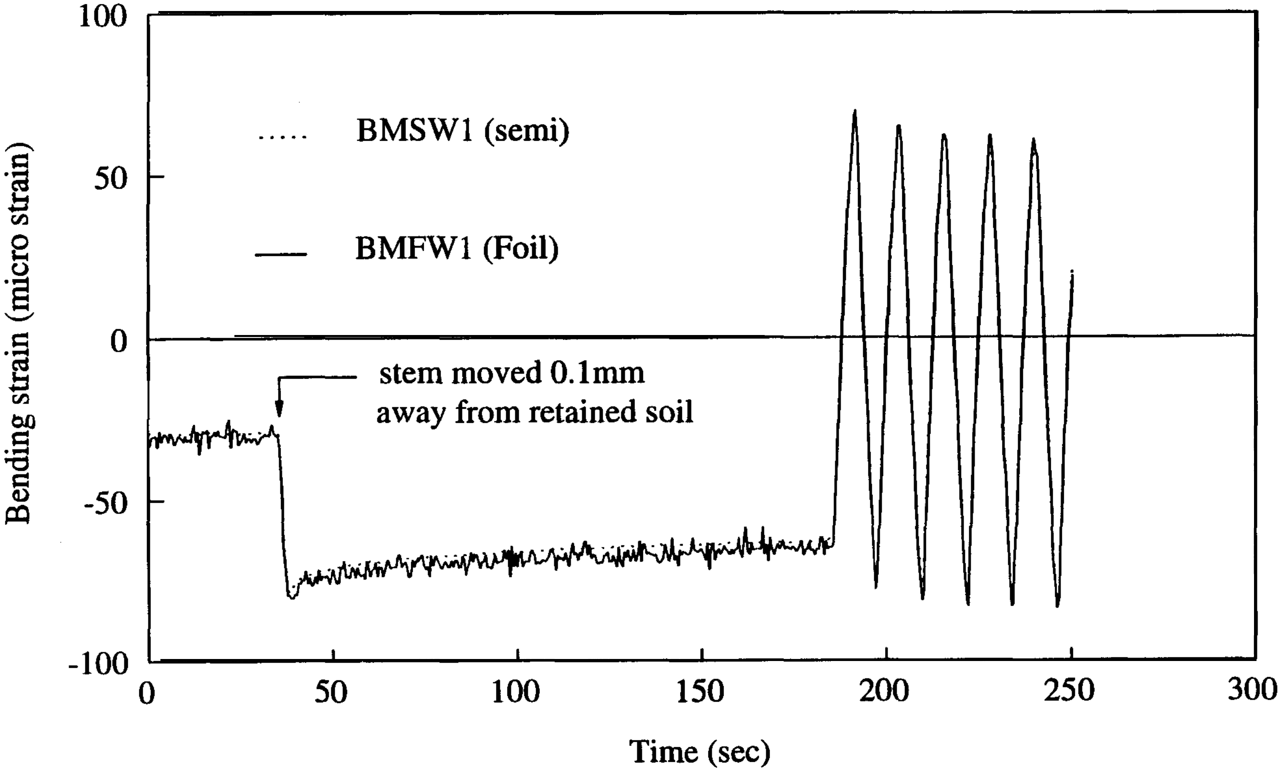

Fig.11 - Bending strain in wall during +/- 0.1mm excitation (CWWN1)

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