June 10-15, 2007, San Diego, California, USA

OMAE2007-29185

STRESS MEASUREMENTS AT HOT SPOTS USING STRESSPROBE

I. Lotsberg
DNV
Oslo
Norway

M. M. Salama
ConocoPhillips
Houston
USA

W. D. Dover, R. F. Karé, N. Stone
TSC Inspection Systems, Wolverton Mill,
Milton Keynes
UK

ABSTRACT

The estimation stress concentration factor (SCF) of weld details of floating structures is critical parameter for fatigue life predictions. The common practice for predicting the SCF value is the use of code-specified empirical equations and through detailed finite element analysis (FEA) for critical joints. Under certain conditions, it becomes necessary to re-assess the SCF value while the structure is in service. The most accurate approach is to measure the SCF value on the real joint since variations in FEA results always exist due to variation on modeling techniques by different analysts. While the use of strain gauges is the standard approach, applying strain gauges in service can be extremely complicated. Therefore, an alternative approach for direct measurement that does not require removal of coating and bonding to the surface is attractive. The StressProbe that takes advantage of the change in the magnetic permeability of steel due to the presence of a mechanical stress offers the required alternative as a non-contacting strain measurement method. The paper presents the results of a study to assess that capability of the StressProbe in measuring SCF value by measuring variations in strain in a high strain gradient region of a hopper corner detail that is typical in floating structures and compare the results with those obtained using both strain gauges and finite element analysis. The results show that the StressProbe can be used for the determination of the SCF at a weld under various scenarios and it can also be used to monitor cyclic stresses during periods when there is wave loading. While there is some variability in the StressProbe results but given the variability found with strain gauges it is considered that the StressProbe could be used to replace strain gauges.

Key Words: Fatigue, stress measurements, hot spot, stress concentration factors.

Abbreviations:

ACFM	Alternating Current Field Measurement
ACPD	Alternating Current Potential Drop
ACSM	Alternating Current Stress Measurement
C/L	Center line
DNV	Det Norske Veritas
FPSO	Floating Production Storage and Offshore loading
HHI	Hyundai Heavy Industries
SCF	Stress Concentration Factor
TSC	Technical Software Consultants Limted
UCL	University College London

1. INTRODUCTION

Uncertainty in hot spot stress response at details in structures is one of the contributions to uncertainty in assessment of fatigue life. Here the stress response at a typical hot spot area in a floating production vessel is investigated using the StressProbe developed by TSC Inspection Systems.

The StressProbe was first used offshore mid 1990s on repair clamps. The StressProbe uses the magnetostriction effect, which basically means that the magnetic permeability is changed by the presence of a mechanical stress and this change is measured and interpreted by the StessProbe.

The use of the StressProbe would allow a far simpler and more comprehensive study of stress concentrations near weld toes in welded structures as it provides a non-contacting method that can be quickly moved around the structure.

A hopper corner detail fabricated by HHI in Korea was selected for stress measurements. Measurements were performed by TSC at DNV laboratories in Oslo.

The results using StressProbe are compared with measured stress from strain and finite element analysis. Stress concentration factors resulting from different methodologies are compared.

2. BACKGROUND

For some time it has been known that stress will have an effect on permeability in steel and hence on the surface field strength used in the alternating current field measurement technique. Earlier work using ACPD (1985, ref. /1/) showed this feature in ramp loading tests and it was explored in more detail in later papers (1986 – 1988, refs. /2,3/).

Although stress will affect both conductivity and permeability it is the latter which has the largest effect, particularly in magnetic materials such as ferritic steels. In these materials it is convenient to consider the magnetised regions or ‘domains’ to have a particular orientation and that in a demagnetised state the alignment is such that the overall magnetisation is zero.

Magnetisation forces can produce volume changes and hence effects like residual stress and internal strains. If there is magnetisation due to domain realignment then there will be an overall strain effect. Mechanical strain in turn will influence domain shapes and sizes.

In general magnetic, electric and stress fields are non-uniform and hence interact in a complex way. UCL and TSC have concentrated on using, initially with ACPD, probes and electronics that give uniform electrical and magnetic fields. More recently the non-contacting version of ACPD, known as ACFM, has been introduced and this also attempts to use a uniform field approach. ACFM type instrumentation, capable of measuring absolute value of electrical fields, and in particular field perturbations around cracks, can also detect permeability changes caused by mechanical stress. The interaction between uniform electrical and mechanical stress fields should be simpler to understand and interpret and this proved to be the case with ACPD. It is evident that ACFM instrumentation would detect the same changes and given this background the ACFM type stress prediction technique has come to be known as ACSM (Alternating Current Stress Measurement).

The directional nature of the strains and magnetic fields produces anisotropy in the material properties. A theoretical interpretation of measured electrical or magnetic properties would therefore require solutions for anisotropic behaviour.

Recent work (ref. /4/ from 1997) has shown that a theoretical approach proposed previously (ref. /5/ from 1984), an isotropic solution, could be extended to allow different conductivity and permeability components for each axis. In this work an analytical solution was produced for a half-space anisotropic conductor and shown to be capable of explaining measured effects of mechanical stress on magnetic permeability.

The theoretical background to ACSM is largely contained in ref. /4/ from 1997 which provided an analytical solution to the electromagnetic induction problem involving both electrical and magnetic anisotropy. Reference is also made to ref. /6/ for description of theory.

3. THE STRESSPROBE CONCEPT

StressProbe makes measurements of an electromagnetic field close to the surface of a material. There is an induced input field and sensors measure particular components of the magnetic field. The magnetic field is affected by the stress level in the material so as the stress changes, the system responds.

StressProbe systems are capable of providing different levels of information. All StressProbe systems require calibration information for the material under investigation. This is often not as onerous as it seems because many 'families' of steel have similar responses. However it is not possible to use calibration data from Mild steel to predict the behaviour of a high alloy steel. Calibration takes the form of measuring the material response to applied stress and is often achieved by making measurements on simple test pieces in the lab, these generally take the form of simple bending or uniaxial loads. StressProbe responds to both tensile and compressive loads.

In its simplest form, StressProbe can measure dynamic load cycles. These are typically required for fatigue analysis for example, or for measuring the effect of an event - this could be a lorry passing over a bridge, the welding of a component or perhaps the effect of removing a support. The emphasis here is on dynamic loading because simple StressProbe systems are not able to make absolute measurements of stress but can accurately measure changes from a particular starting position. This is possible because the calibration curves are essentially linear responses. In practice this means one can measure the load cycle range without knowing the value of the mean.

The mean load is more difficult to determine using simple systems - and is often not required for basic fatigue analysis of welded structures. If one needs to measure the mean more information is needed in order to consider what has happened to the steel in the past. Many steels exhibit a hysteresis effect due to previous loading and this can be pronounced when making magnetic measurements. In this situation a demagnetisation process is used to shake down the material into a known state. By measuring in that state a better estimate of the mean load in the material is obtained. Some StressProbe systems contain a demagnetisation facility which provides controlled harmonisation of the material. This type of measurement has been successfully used to measure the static load in structural clamp studs, thereby determining the distribution of loads in the system.

StressProbe really responds to material strain and thus can be considered analogous to a "non-contacting strain gauge" - but with some important differences.

It is not possible to apply strain gauges to a loaded structure and determine the load. Also it is not possible to apply strain gauges through coatings without damaging the protective coating. But one can use the StressProbe which can measure the response of the steel through coating - up to around 5mm depending on the probe. However, the interpretation of strain gauge data is well established whereas interpretation of data from StressProbe requires special operator training. It is important to note that the StressProbe will only work on magnetic material, but it is possible to stick or insert magnetic material onto a non-magnetic one and still get meaningful data.

TSC Inspection Systems have developed the StressProbe technology and produced equipment that can be used in a wide range of in-service and construction applications. These can include the measurement of static and dynamic stress and in some cases residual stress. Examples of possible applications are measurement in transport vehicles (axles, wheels, suspension), environmental loading situations (wave or wind loading on offshore structures, ships, risers, mooring lines), on bridges and masts, for plant situations where the operating pressures are varying (pressure vessels, piping) and for monitoring long range residual stresses during welding.

StressProbe can also be used to map the stress distribution in structures. It can for example be used for measuring the distribution along a loaded beam or alternatively the stress at a particular site e.g. the flange and web distributions around a cross-section.

Although TSC produce standard instrumentation, it is rarely possible to pick up an instrument and immediately make measurements. Correct choice of probe and the procedures for making the measurements are extremely important. Each application needs careful consideration and TSCs experience will prove invaluable in this regard.

4. TESTS

4.1 Structure of tests/type

The tests were designed to assess the performance of a new StressProbe probe, with sensors closer to the enclosure edge than usual. This innovative design allows the probe to be positioned close to the weld toe and also allows rotation of the probe.

A number of tests were devised in order to assess possible StressProbe procedures. For example, the use of a demagnetisation yoke is often employed to ‘shake down’ the magnetic domains of a given sample. This technique is usually not used for cyclic work as the domains have enough energy to move freely, while for static work the magnetic history of the sample is usually unknown. In such a situation the demagnetisation yoke is an ideal solution. To fully investigate the need for such a demagnetisation cycle the tests were designed to incorporate both non demagnetised and demagnetised stress cycles.

Recent research has also shown that taking orthogonal readings allows a more reliable way to determine stress. The procedure requires two sets of data to be taken with the probe being rotated at each stress point. The tests procedure included this technique of data collection. For this set of data all of the readings were taken after a demagnetisation cycle.

Two types of loading were used in the tests, incremental loading and cyclic loading. The incremental loading tests allowed the discrete load points to be identified so that accuracy of the measurements could be verified against strain gauge values. The cyclic loading allowed verification that each load cycle is equal in amplitude over time.

The probe was a differential type. This means that the response to stress is a resultant of several measurements and therefore will not comply with Poisson’s ratio when the probe is rotated. The rotated probe will give the same magnitude of response to the same stress level, but one will be a positive response while the other will be negative. Each probe has an inbuilt biased direction. Thus, for example, if the probe is placed laterally across the sample, the response to stress along the sample would be positive. If the probe is placed along the sample the response to stress along the sample would be negative.

4.2 Test setup

The geometry of the test specimen is described in Appendix D of DNV-RP-C203, ref. /7/. It was also used as a test specimen in the FPSO Fatigue Capacity JIP (refs. /8-12/).

The test setup is shown in Figure 1. Loading of the test specimen is illustrated in Figure 2. Different probe placements are shown in Figures 3-5. Measurement points are shown in Figures 6 and 7.

4.3 Measurements

Incremental Loading of Sample.

The effect of using a Demagnetisation Cycle.

The test consisted of an initially unloaded sample and interrogation with the StressProbe. Due to the presence of the strain gauges on both sides of the sample the probe could only be placed in one position on each side of the sample. After readings were taken for 5, 15 and 25 mm the loading was increased to 10, 20 and 30 kN. Readings were taken at each load level.

Figures 8 and 9 show the data from two of these tests showing the influence of demagnetisation. It can be seen that the response is greater with the demagnetisation cycle but using the 5/15 data to evaluate the SCF gives similar predictions for the SCF. The SCF is calculated as the ratio of the values at the 5mm and 15mm from the weld toe for the 10, 20 and 30 kN load levels.

Bi-Directional presentation of data

Using the data from lateral and longitudinal plots allows one to produce the difference plot incorporating data from the two orthogonal directions. This form of averaging reduces the scatter obtained particularly for the data in the lateral direction but it retains the SCF data. Figure 10 shows an example of this.

The cyclic loading tests give an alternative method for the estimation of SCF when the stress is varying continuously. Figure 11 shows a typical data set obtained with the StressProbe during cycling. The Figure also contains the equivalent strain gauge data (G). It is seen that there is correspondence between data from StressProbe (presented as voltage in arbitrary units) and the strain gauges.

5. ASSESSMENT OF MEASURED DATA

Figure 12 shows the measured strains obtained using the StressProbe (a very approximate calibration has been used). The data is the bi-directional interpretation and shows the gradual decay in strain from the weld toe at three sites, near the centre line, 10 and 20 mm from the C/L.

A similar plot can be produced for the cyclic data and this is shown in Figure 13. This has similar characteristics to those seen in Figure 12 but the strains are slightly lower. This is because the response is lower under cyclic loading but, in the absence of a proper calibration, the calibration used for the static loading has been used for the cyclic loading.

Using the Classification Society definition for stress concentration factor this data can be reinterpreted as an SCF for each site (with extrapolation of stresses to the weld toe from positions 0.5t and 1.5t from the weld toe where t = plate thickness). In the present case the nominal and local stress at the weld toe has been used to derive the SCF. These results are shown in Figure14 for static load data.

The SCF data from the three sites look very similar and suggest that the SCF is about 2 but that there could be small variations along the weld toe, ref. Figure 14.

It is observed that measured values shows a slightly less uniform stress along the weld toe than that derived from three-dimensional finite element analyses at the same region, ref. Figure 15 showing stress distribution at a position 0.5t from the weld toe. (Centre line at y = 65 mm). However, similar SCF values are derived by measurements as from analysis when extrapolating the stresses to the weld toe from positions 0.5t and 1.5t from the weld toe. A summary of stress concentration factors at the centre line derived by StressProbe (static and dynamic), from strain gauge measurements and a number of different FE analyses performed in the FPSO Fatigue Capacity JIP is presented in Table 1. The FE analyses were performed by 5 different companies. Not all companies included the actual eccentricity at the hot spot region in their analyses using shell elements. The three-dimensional analyses included this eccentricity. Thus, the target SCF value is considered to be within the range calculated by the three-dimensional analyses. It is observed that the StressProbe results fall into the same region of results as obtained by strain gauge measurements and FE analysis.

The tests have shown that the StressProbe can be used for determination of the SCF at a weld toe under various scenarios. In particular in calm waters, during say ballasting, the data from an FPSO would be similar to the incremental loading test described here and a high response demagnetisation procedure could be used to give SCFs. In contrast during periods when there is wave loading, equivalent to the cyclic load test here, it is possible to avoid the demagnetisation procedure and still obtain good predictions of the SCF.

There is some variability in the StressProbe results but given the variability found previously with strain gauges it is considered that the StressProbe could be used to replace strain gauges.

Future work should include a detailed calibration of the StressProbe response, if strain values are required rather than simply SCFs, together with the production of an SCF probe with sensors at both 5 and 15 mm so that the SCF can be determined with one placement of the probe.

Table 1 Stress concentration factor from different methods

Method	SCF
StressProbe (Static) (Figure 12)	1.89
StressProbe (dynamic) (Figure 13 and 10 mm from CL)	1.92
Strain gauge measurements	1.79
FEA (3-D solid) by 5 different companies	1.78 - 2.13
Mean	1.98
FEA (8- node shell element) by 5 different companies	2.16 – 2.34
Mean	2.26
FEA (4- node shell element) by 5 different companies	2.12 – 2.46
Mean	2.34

6. CONCLUSIONS

Uncertainty in hot spot stress response at details in structures is one of the contributions to uncertainty in assessment of fatigue life. In this project the stress response at a typical hot spot area in a floating production vessel is investigated using the StressProbe developed by TSC Inspection Systems. A hopper corner detail fabricated by HHI in Korea was selected for stress measurements. Measurements were performed by TSC Inspection Systems at DNV laboratories in Oslo.

A series of tests have been conducted in order to determine the SCF using a non-contacting stress measurement technique, the StressProbe. Two methods were used, an incremental step load change procedure and a continuous cyclic load procedure.

The results using StressProbe are compared with measured stress from strain and finite element analysis. Stress concentration factors resulting from different methodologies are compared and are found to be of similar magnitude.

The tests have shown that the StressProbe can be used for determination of the SCF at a weld under various scenarios. In particular in calm waters, during say ballasting, the StressProbe data from an FPSO would be similar to the incremental loading test described here and a high response demagnetisation procedure could be used to give SCFs. In contrast during periods when there is wave loading, equivalent to the cyclic load test here, it is possible to avoid the demagnetisation procedure and still obtain good predictions of the SCFs.

There is some variability in the StressProbe results but given the variability found previously with strain gauges it is considered that the StressProbe could be used to replace strain gauges.

7. REFERENCES

1. Topp, D. A. and Dover, W. D., “Crack shape monitoring using A-C field measurements”, Automated Test Methods for Fracture and Fatigue Crack Growth, ASTM STP 877, Editors W H Cullen, R W Langdgraf, L R Kaisand and J R Underwood, American Society for Testing and Materials, Philadelphia, pp 86-100, 1985.
2. Lugg, M. C., Dover, W. D., Kilpatrick, I and Cargill, J., “An assessment of factors that influence the skin depth in a.c.f.m. crack sizing”, Review of Progress in Quantitative Nondestructive Evaluation, Vol. 5A, Editors D O Thomson and D E Chimenti, Plenum Press, New York, pp 207-214, 1986.
3. Lugg, M. C., “The effect of stress on the ACFM technique”, Non-Destructive Testing, Proceedings of the 4th European Conference, London, 13-17 Sept., 1987, Editors Farley and R W Nichols, Pergamon Press, Oxford, pp 2596-2605, 1988.
4. Zhou, J. and Dover, W. D., “Electromagnetic induction in anisotropic half-space and electromagnetic stress model”, NDE Centre, Department of Mechanical Engineering, University College London, 1997.
5. Beissner, R. E. and Sablik, M. J., “Theory of eddy currents induced by a nonsymmetric coil above a conducting half-space”, J. Appl. Phys 56, pp 448-454, 1984.
6. Zhou, J., Collins, R. and Michael, D. H., “Half-space induction by a rectangular coil with rounded corners: local uniformity and ACFM”, Review of Progress in Quantitative Nondestructive Evaluation, Vol. 13, Editors D O Thomson and D E Chimenti, Plenum Press, New York, pp 335-342, 1994.
7. DNV-RP-C203 “Fatigue Design of Offshore Steel Structures”. August 2005.
8. DNV Technical Report. FPSO Fatigue Capacity Phase II Report No. 2002-1114 Additional Fatigue Tests on Small Scale Test Specimens January 2002.
9. Kim, W. S. and Lotsberg, I., “Fatigue Test Data for Welded Connections in Ship Shaped Structures”. OMAE-FPSO'04-0018, Int. Conf. Houston 2004. Also in Journal of Offshore and Arctic Engineering, Vol. 127, Issue 4. November 2005, pp 359-365.
10. Lotsberg, I. and Sigurdsson, G., “Hot Spot S-N Curve for Fatigue Analysis of Plated Structures”. OMAE-FPSO'04-0014, Int. Conf. Houston 2004.
11. Storsul, R., Landet, E. and Lotsberg, I., “Convergence Analysis for Welded Details in Ship Shaped Structures”. OMAE-FPSO'04-0016, Int. Conf. Houston 2004.
12. Salama, M. M. and Lotsberg, I., (2004), "Fatigue Performance of Repaired FPSO Details using Stitch Friction Welding Process". OMAE-FPSO'04-0054. Int. Conf. Houston 2004.

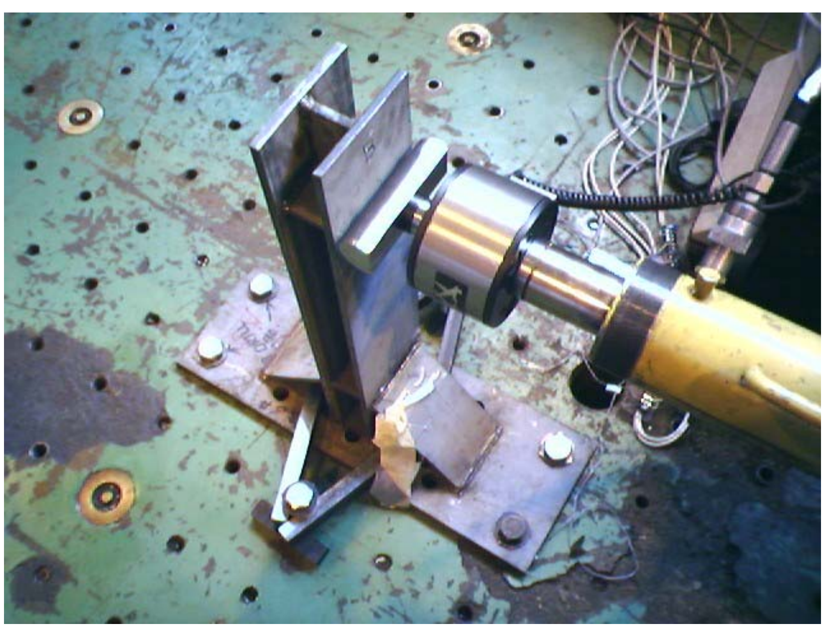


Figure 1 Test arrangement in laboratory showing test specimen and hydraulic actuator

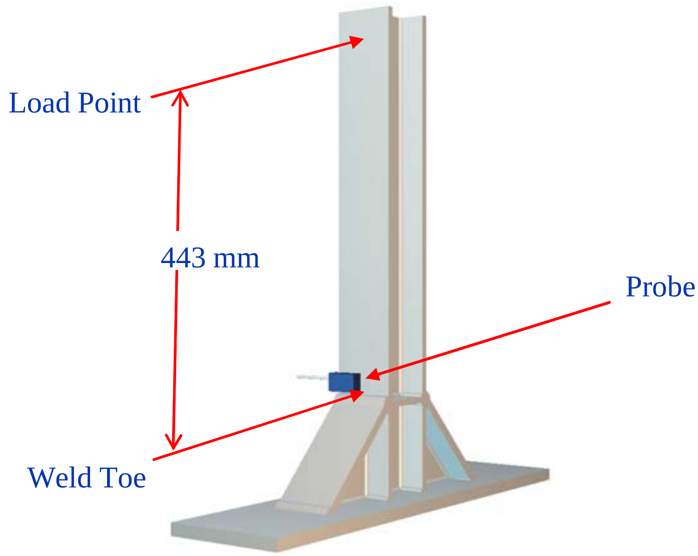


Figure 2 Loading configuration

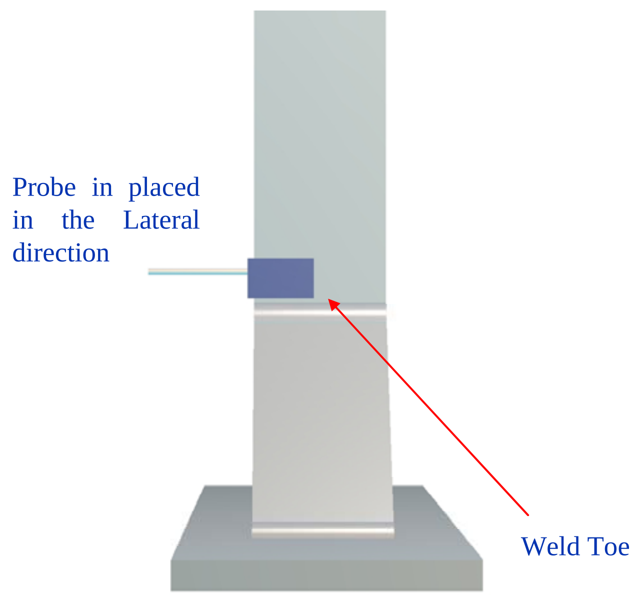


Figure 3 Lateral probe placement demonstration

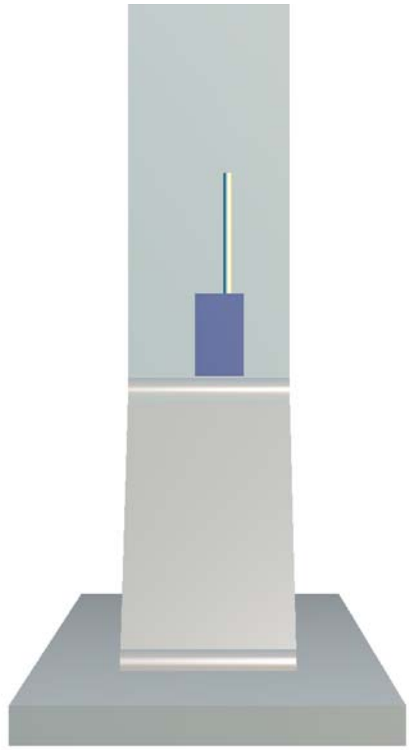


Figure 4 Longitudinal probe placement demonstration

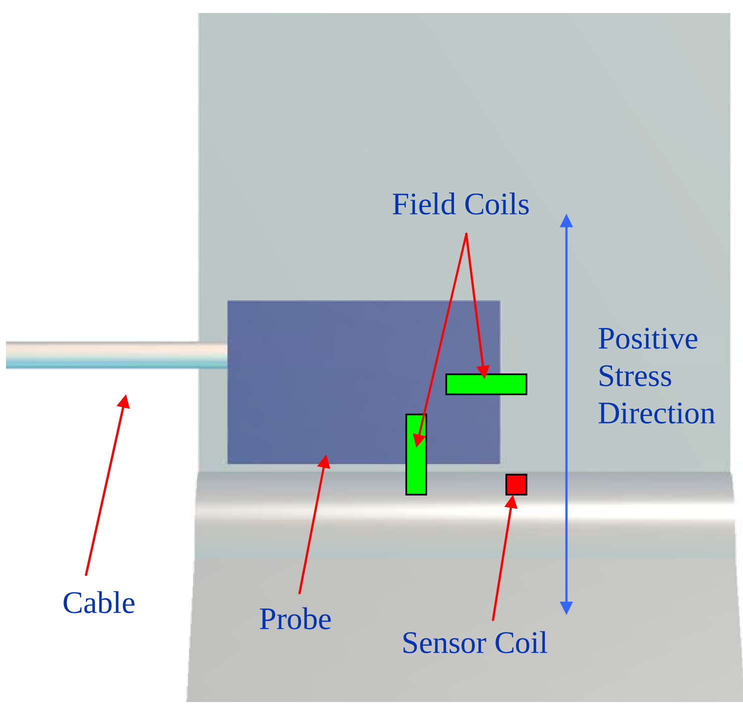


Figure 5 Probe coil configuration

Figure 6 Tension measurement points

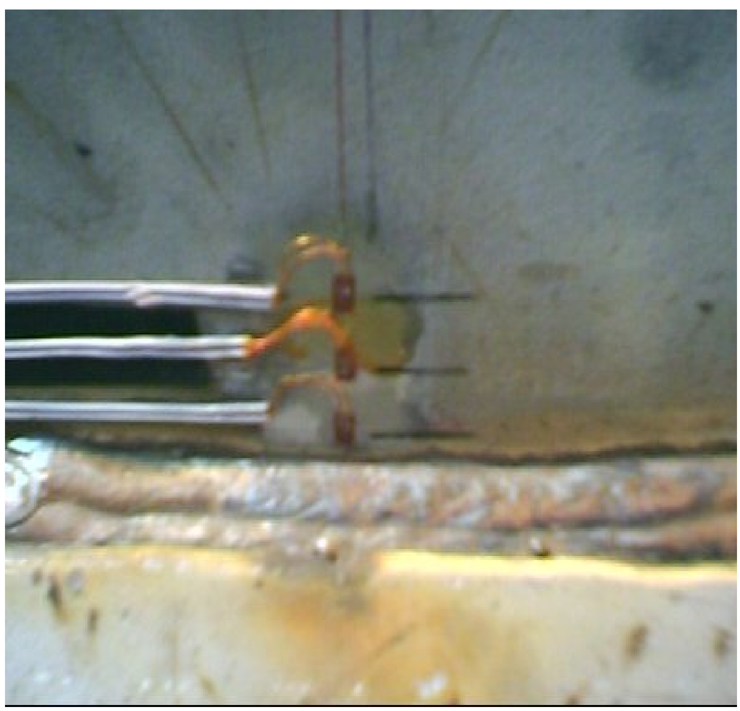


Figure 7 Compression face measurement points next to strain gauges

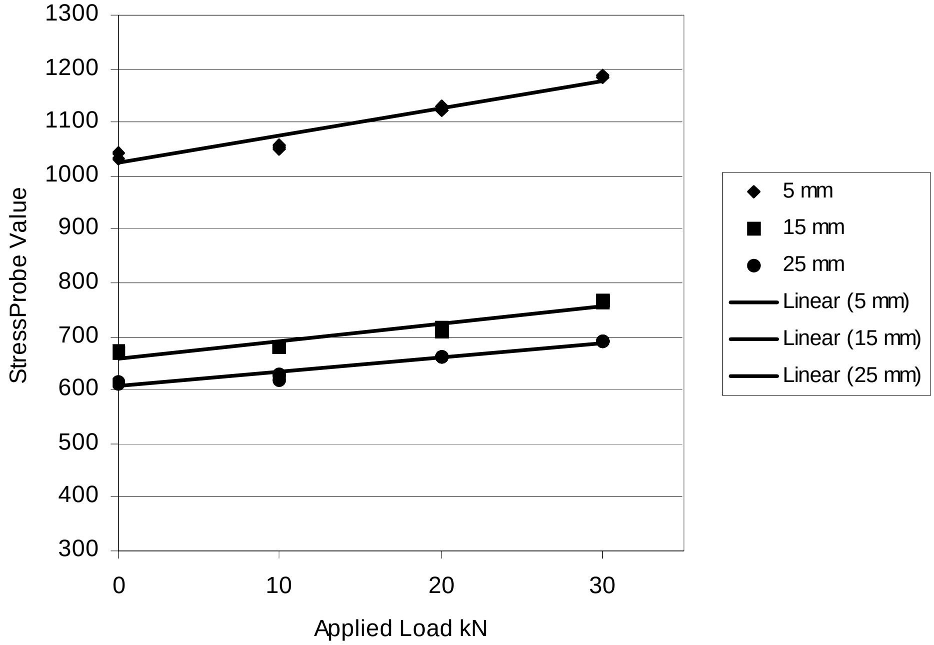


Figure 8 Probe B on the compression face next to the strain gauges (Longitudinal direction)

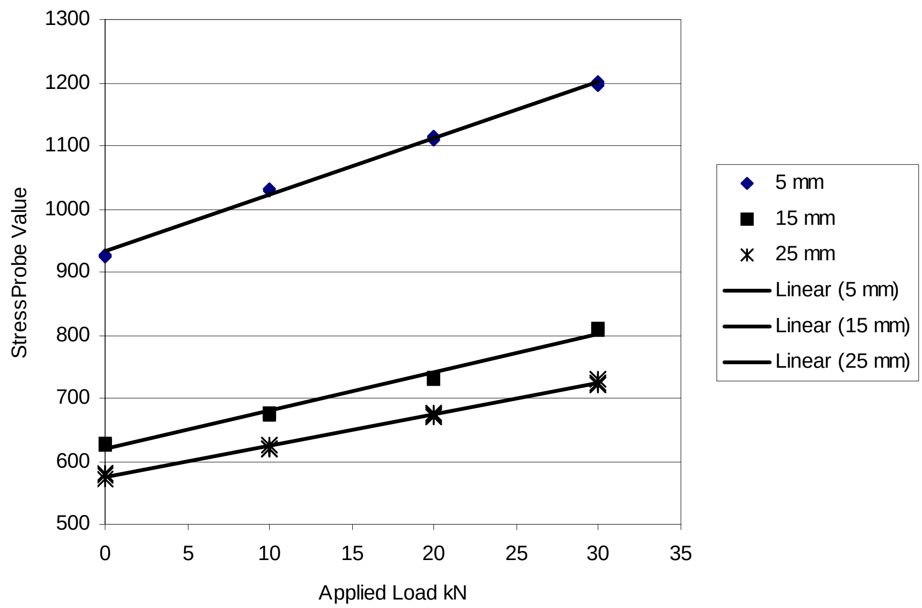


Figure 9 Probe B on the compression face next to the strain gauges (Longitudinal direction with demagnetization)

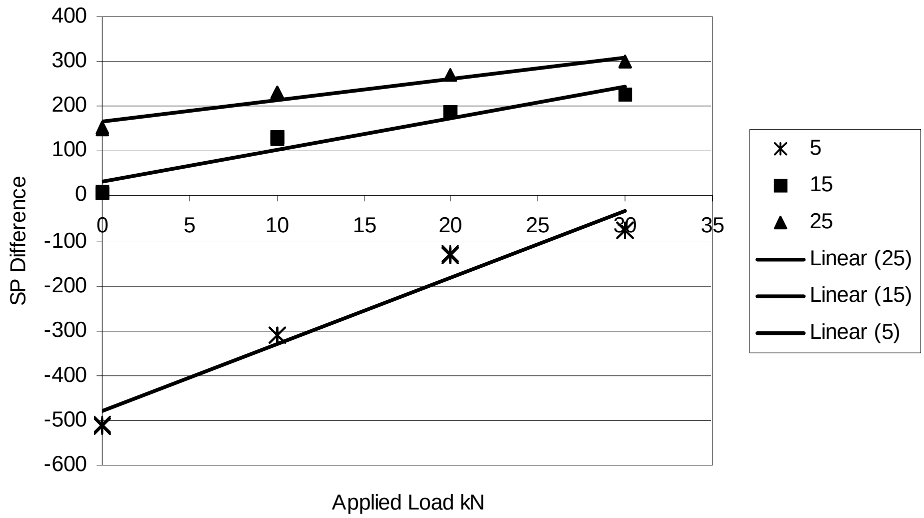


Figure 10 Probe B Difference Plot, tension side 10 mm from center line

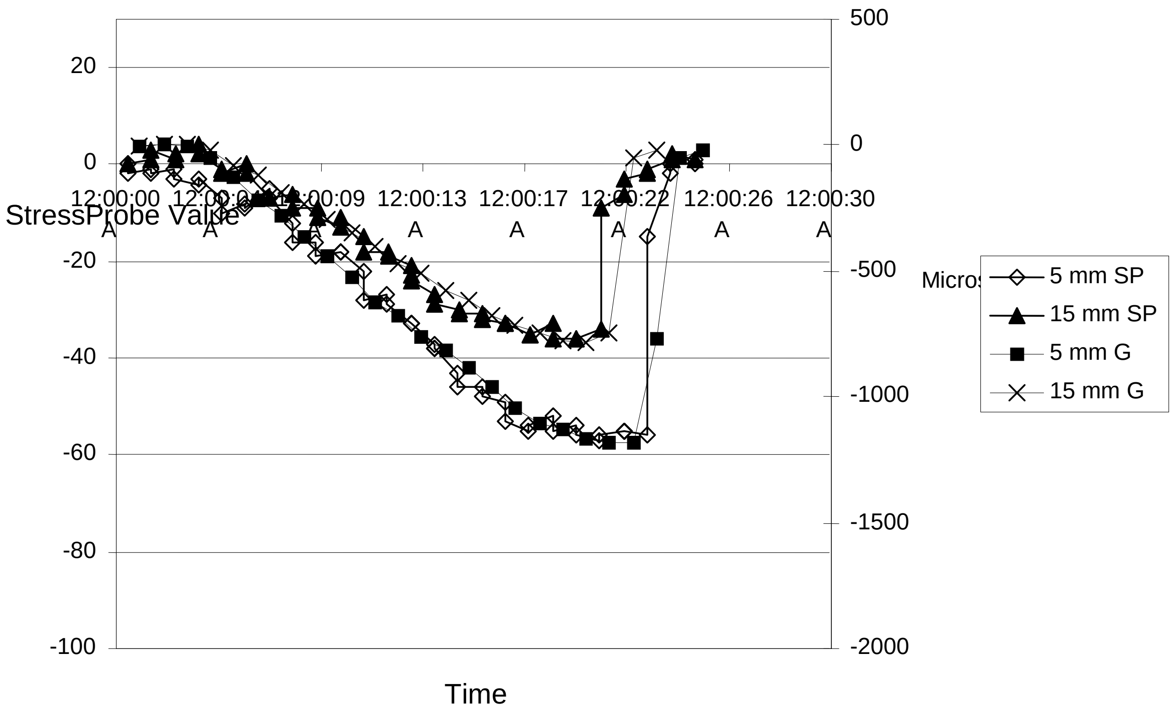


Figure 11 Probe B on the tension side 10 mm from the center line laterally placed

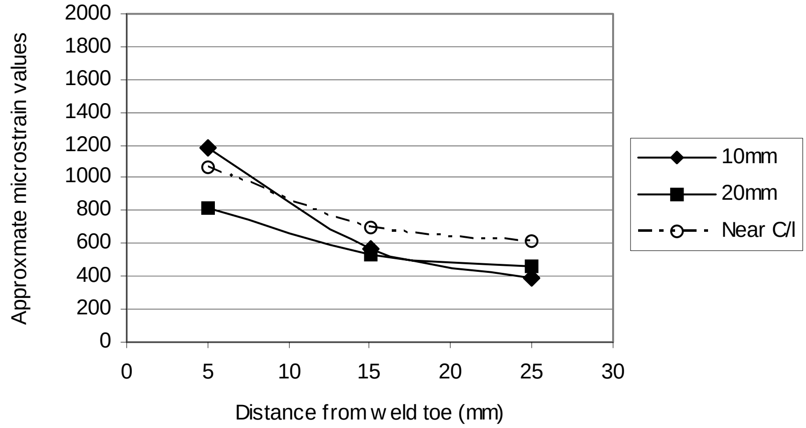


Figure 12 Measured strain using StressProbe

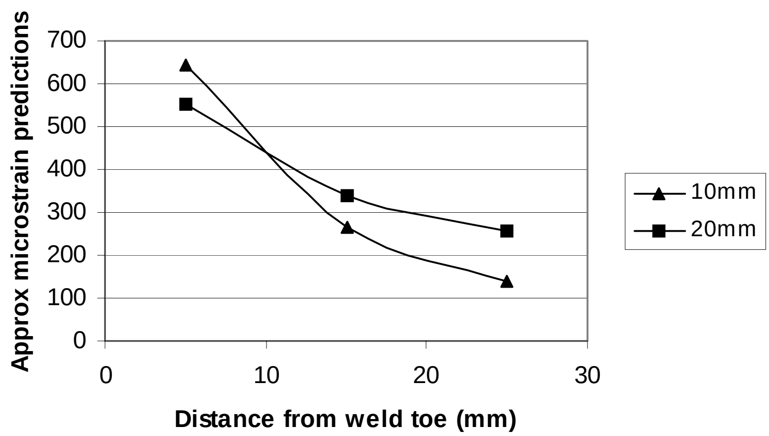


Figure 13 Strain predictions from cyclic data

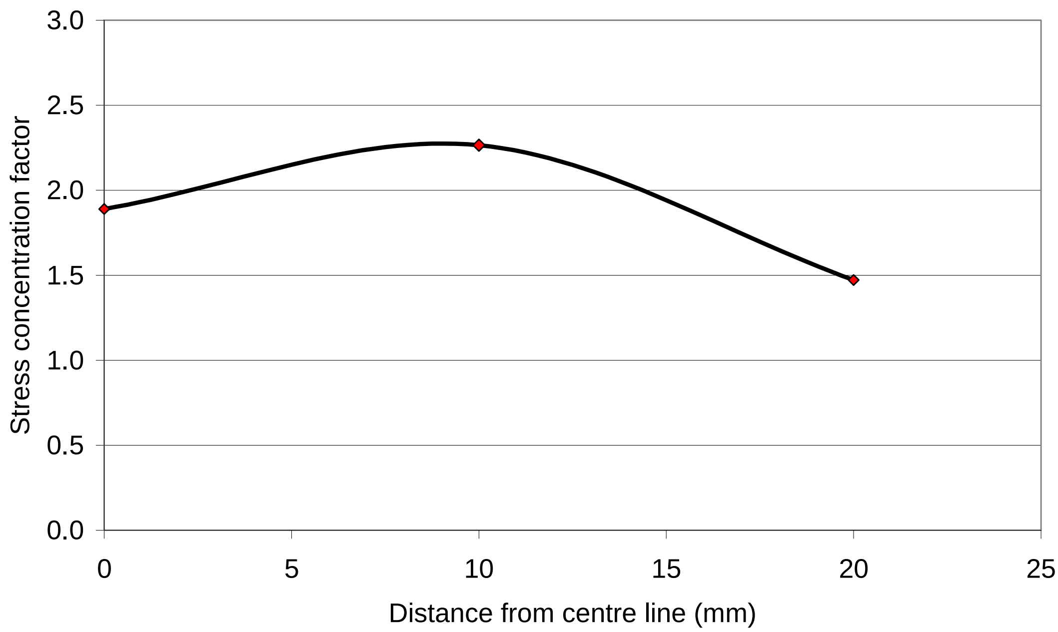
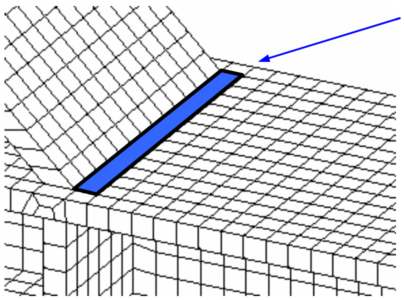


Figure 14 SCF along the weld toe from StressProbe measurements (Static)



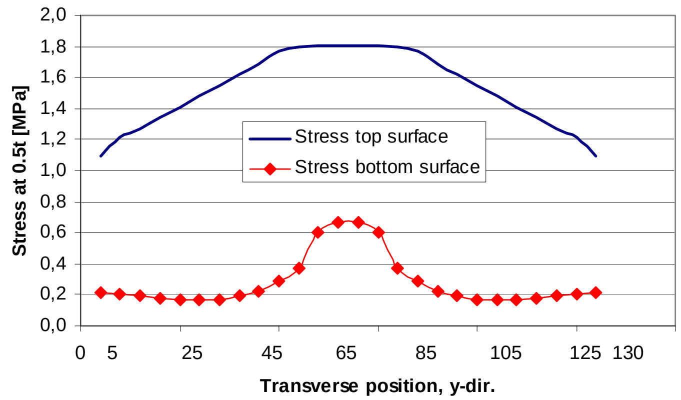


Figure 15 Calculated stresses in a section 0.5t from the weld toe (from Ref. /11/)