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Misalignment in Fatigue Testing Machines, a Nordic Laboratory Intercomparison

NICe project 04149

SP Building Technology and Mechanics
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Abstract

A laboratory intercomparison of misalignment in fatigue testing machines is reported in this report. Test specimens instrumented with strain gauges where distributed to the participants. The strain was measured during clamping and during a specified load cycle. The study is showing that many fatigue testing machines are misaligned. In the worst case bending stresses as large as 200-300 MPa is introduced. This lead to underestimation (about 50 times) of the fatigue life

Key words: fatigue test, misalignment, testing machines, intercomparison

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1 Introduction and background

Fatigue testing is a problematic area where there are many potentials for mistakes, as has not least been shown in a Nordic interlaboratory study [1-3]. One of the most important findings in that particular study was that few of the participants included bending stresses caused by misalignment in their measurement uncertainty calculations, if they indeed performed such calculations at all. The problem with bending stresses induced by misalignment has been known for a long time. Many laboratories align/check the alignment before (sometimes after) a test. Even though many are aware of the problem, there seems to be a lack of knowledge of the size of the problem, i.e. the magnitude of the bending stresses that are introduced due to misalignment if nothing is done to align the testing machine, and how this affects the fatigue life. Knowledge of the size of the bending stresses would be of great value in simplifying measurement uncertainty calculations for fatigue tests.

Some general conclusions were presented in the project described in [1-3], for example:
- The effect of uncertainty of measurement (how to calculate, define, report and interpret) in fatigue testing, and particularly Wöhler-curve definition, is not well understood in many laboratories
- There is a tendency for laboratories to include only easily obtained uncertainty sources, e.g. from calibrated gauges, while omitting uncertainty sources of which the magnitude is difficult to determine
- None of the participating laboratories estimated the influence of misalignment of the testing machine on the overall uncertainty of measurement
- The influence of the operator (mounting the test specimen) on the test results was not estimated.

In addition, the study raised a number of questions:
- How large is the influence of misalignment of the testing machine on the overall uncertainty of measurement?
- How large is the influence of the operator on the uncertainty of measurement?
- Is it possible to make a general estimation of the influence of test machine misalignment and the operator on the uncertainty of measurement in fatigue testing?

A new project was planned in order to answer these questions. The project was also partly performed as a Nordic intercomparison project, which is described in this report. The influence of the operator is described in another report.

2 Laboratory inter-comparison

When the participants signed up for the intercomparison they were required to choose between three different options:

1) To choose which of the geometries of the test specimens - circular, rectangular or both - they would like to test

2) Which size of test specimen - two for each shape of specimen (for details, see Table 1 and 2) - they would like to test

3) Whether they would like to use the strain measurement equipment offered by the organisers or to use their own equipment.

In addition to the choices mentioned above, the participants had to choose which testing machine/machines to use.

2.1 Instructions

No real fatigue test was performed in the project, but only mounting and dismounting of instrumented test specimens. The purpose of the project was to obtain a realistic estimate of the misalignment problem, which meant that the round-robin test should therefore be performed as close to "normal testing" conditions as possible. Optionally, the participants could make repeats of the test after more rigorous preparation (alignment) of the machine. There was also a prescribed load sequence to be applied to each test specimen. The strain of the test specimens was to be recorded during the mounting, dismounting and the prescribed load sequence.

The participants received the following instructions:

1) Check the conditions of the test specimens and the amplifier on arrival.

2) Mount the specimens with the actuator of the machine in two different positions: the first position of the actuator to be close to the middle of the stroke, and the second position to be close to the maximum stroke.

If possible, set load limits in the range [-0.1F 1.1F] to protect the specimens during mounting. Adjust the grip pressure in accordance with the machine supplier's instructions, in order to avoid damaging the specimens. The yield strength of the material is 600N/mm^2.

3) Mount the test specimen in the testing machine in the same way as during a "normal" test and zero the amplifier while one of the grips is still open, and keep this setting during this test setup.

4) Record the signals from the strain gauges and the load cell after completion of mounting.

5) Adjust the load to zero.

6) Apply the following sequence to the test specimen: 0 F, 0.25 F, 0.5 F, 0.75 F, 1 F, 0.75 F, 0.5 F, 0.25 F and 0 F. Dismount the specimen, and then remount it*. Repeat this loading and

mounting sequence three times, and record the signals from the strain gauges for each load level. F is 75% of the plastic yield stress of the specimen.

For the round specimens, F=35kN
For the rectangular specimens, F=65kN

7) After the load sequences have been performed, open one of the grips and record the signals from the strain gauges.

8) Adjust the actuator of the machine to maximum stroke and repeat points 3-7.

9) Optional: Adjust the machine alignment as well as possible and repeat points 2-8.

* The instructions were clarified after the first two laboratories had received the specimens, since the first laboratories misunderstood the instructions and did not dismount the test specimens completely.

Point 9) was optional, and none of the participants chose to perform the load sequence once more after aligning the testing machine.

There were also detailed instructions for the use of the strain measuring equipment. There were no indications that there were any mistakes during the strain measurements due to unclear instructions, and so a detailed description of the instructions for the strain measuring system has been omitted from the report.

2.2 Equipment and test specimens in the inter-comparison

Four different specimens were available: two with a rectangular cross-section, and two with a circular cross-section. The specimens are described in Tables 1 and 2 and in Figures 1 and 2. Figures 3 and 4 show two different types of specimens when mounted in testing machines. The specimens were machined from ordinary steel. Each was instrumented with eight strain gauges, arranged in two rings with four gauges in each. The design of the gauge rings is shown in Figure 2.

The organisers offered the participants the opportunity to borrow equipment for strain measurement. Details of the equipment and the strain gauges are given in Table 3, while Figure 5 shows the equipment.

Specimen	Geometry	D (mm)	d	l	L	a	Comments
C2	Circular	12	10	75	205	37	
C3	Circular	12	10	75	205	45	
D1	Circular	20	10	75	215	45	
D2	Circular	20	10	75	215	45	

Table 1. Dimensions of the circular specimens.

Specimen	Geometry	x	Y	y	z	b	s	Comments
A1	Rectangular	210	15	5	30	40	10.8	
A2	Rectangular	210	15	5	30			
B2	Rectangular	210	5	5	30	40	10.8	
B4	Rectangular	210	5	5	30	40	10.8	

Table 2. Dimensions of the rectangular specimens

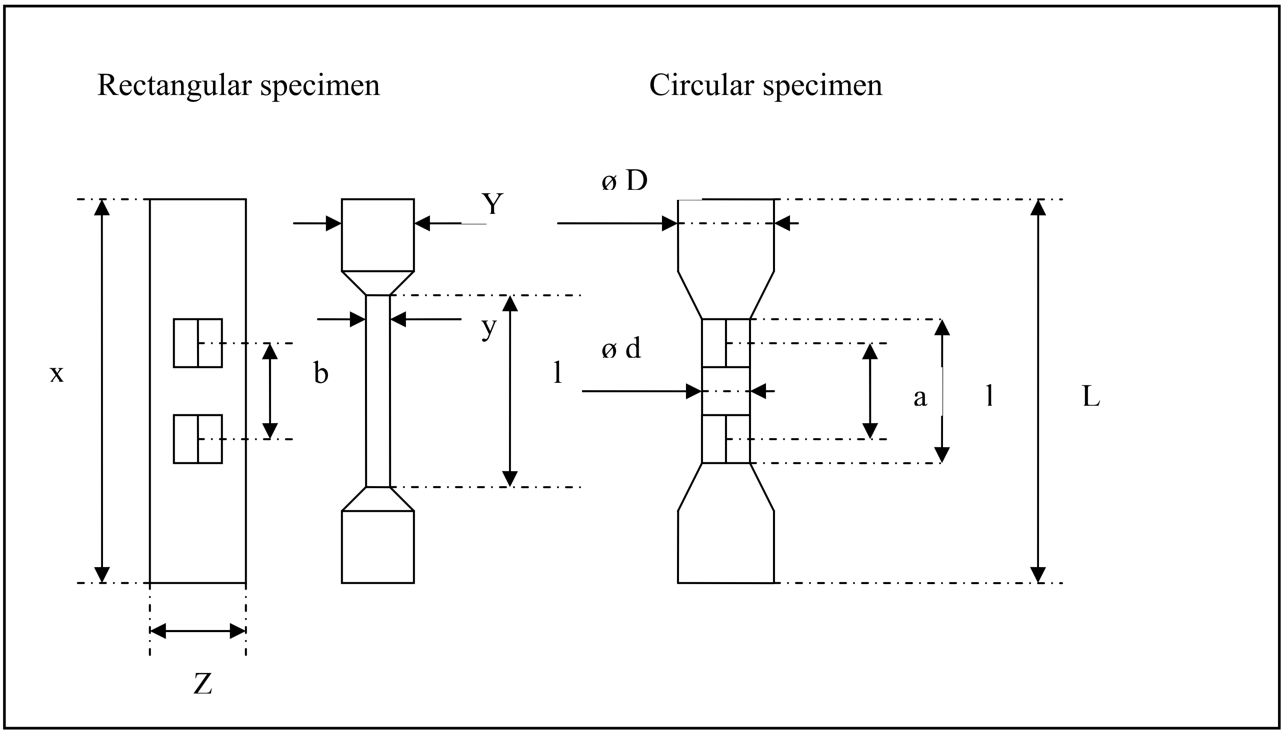

Figure 1. The two different types of specimen

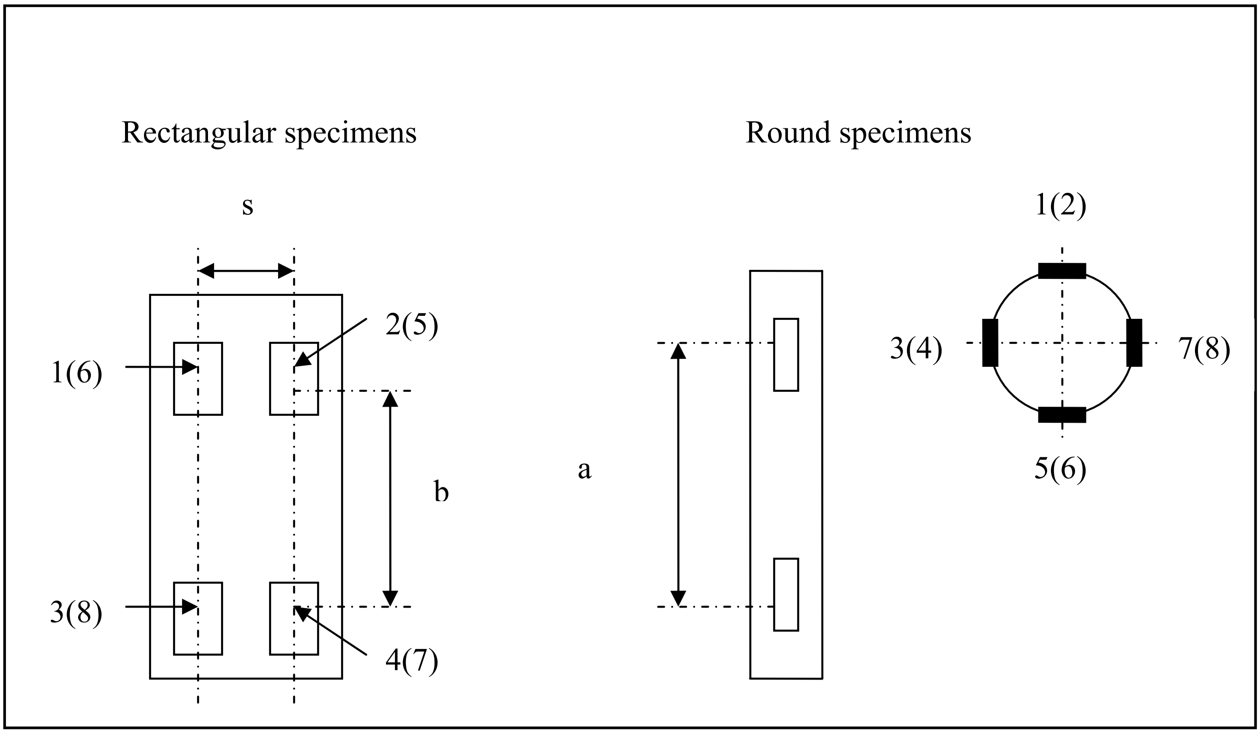

Figure 2. Strain gauge positions. The numbers show the gauge numbers. Numbers in parentheses indicate gauge on the back of the specimen or in the lower ring of gauges.

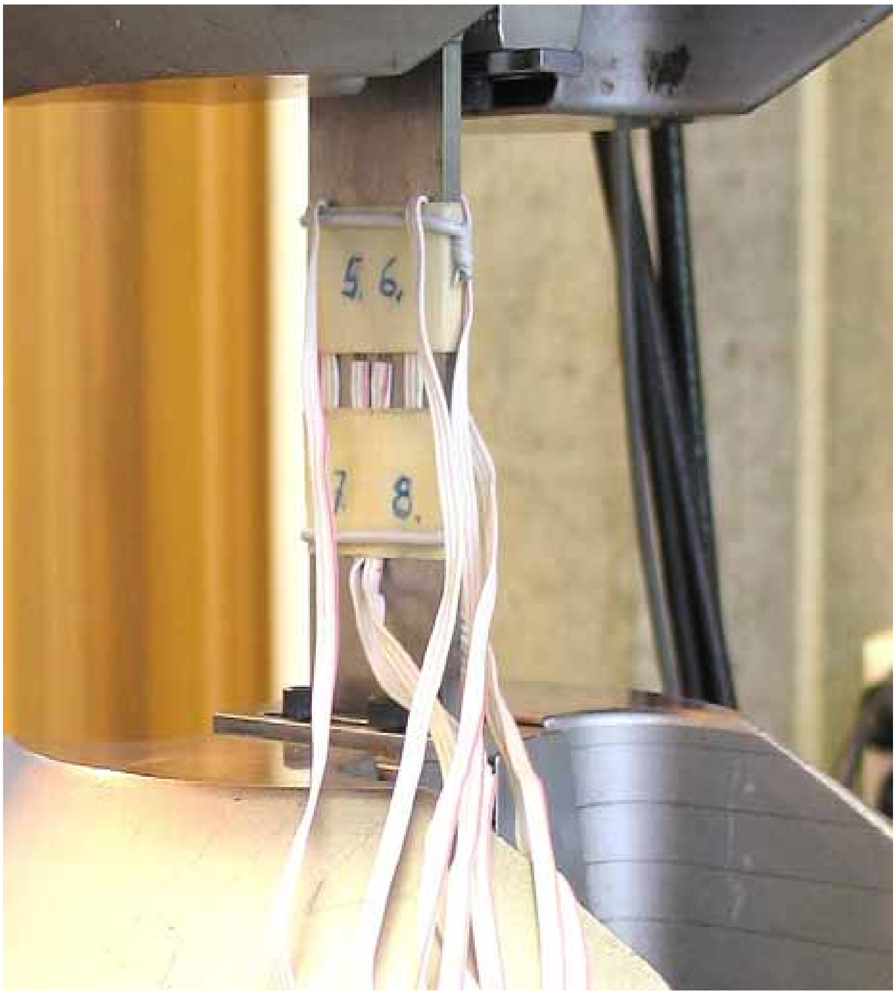

Figure 3. Rectangular test specimen mounted in hydraulic grips in one of the participants' testing machines.

Figure 4. Round test specimen mounted in hydraulic grips in one of the participant's testing machines.

Equipment	Name	Description
Strain gauges	KYOWA KFG -5-120-C1-11L3M3R	5 mm 3-wire strain gauge, temperature-compensated for steel
Amplifier [1]	P 3500 Strain indicator	Manufactured by the Measurement Group
Switch unit [1]	SB-10 Switch and balance unit	Manufactured by the Measurement Group

[1] Equipment offered by the organisers

Table 3. Data for the strain measuring equipment

Figure 5. The strain measuring system

2.3 The participants and their equipment

The invitation to participate was circulated through the NORTEST/NICe network to laboratories in the Nordic countries. Among those invited were the participants in the previously mentioned NORDTEST project and the members of UTMIS (the Swedish fatigue network). There was considerable interest in the intercomparison, and initially 13 laboratories signed up for participation. Due to lack of time and technical difficulties, one laboratory did not report any results and did not perform the exact experimental sequence. Two of the others could not participate in the exactly prescribed way, and their results are not included in this report.

Each participant used its own fatigue testing equipment for intercomparison, but some used the strain measuring system that had been offered (see above). Most of the participants use "standardised" equipment which is commercially available.

The participants and their most important equipment are described below.

Table 4 the participants and their equipment

SP Swedish National Testing and Research Institute			
SP is a technology institute laboratory which performs fatigue tests in internal research projects and for external industrial customers.			
Name of testing machine	INSTRON 1273	INSTRON 1341	INSTRON 8501
Type of testing machine	Servo-hydraulic	Servo-hydraulic	Servo-hydraulic
Capacity of the testing machine	± 250 kN	± 100 kN	± 25 kN

(min-max, kN)			
Stroke	±50mm	±60mm	±75mm
Grips	Hydraulic wedge	Hydraulic wedge	Hydraulic wedge
Control system	INSTRON 8500	INSTRON 8500	INSTRON 8500
Calibration	Yearly	Yearly	Yearly
Alignment before the test	No special arrangements	No special arrangements	No special arrangements
Strain measurement equipment	The equipment offered by the organisers	The equipment offered by the organisers	The equipment offered by the organisers

Force Technology				
Force is a technology institute laboratory which performs fatigue tests in internal research projects and for external industrial customers.				
Name of testing machine	MTS 100 kN	MTS 500 kN	Amsler 100 kN	Amsler 150 kN
Type of testing machine	Servo-hydraulic	Servo-hydraulic	Resonance	Resonance
Capacity of the testing machine (min-max, kN)	± 100 kN	± 500 kN	± 100 kN	± 150 kN
Stroke	300 mm	150 mm	N/A	N/A
Grips	Hydraulic wedge	Hydraulic wedge	3-way mechanical wedge	3-way mechanical wedge
Control system	MTS	MTS	Amsler	Amsler
Calibration	Yearly	Yearly	Yearly	Yearly
Alignment	No special arrangements	No special arrangements	No special arrangements	No special arrangements
Test procedure	As for normal use	As for normal use	As for normal use	As for normal use
Strain measurement equipment	HBM Spider 8 Hard ware and Catman software	HBM Spider 8 Hard ware and Catman software	HBM Spider 8 Hard ware and Catman software	HBM Spider 8 Hard ware and Catman software

DNV		
DNV is an inspection, certification and risk assessment body, and performs fatigue tests in internal research projects as well as for external industrial customers.		
Name of testing machine	50 kN MTS	300 kN Instron
Type of testing machine	Servo hydraulic	Servo hydraulic
Capacity of the testing machine (min-max, kN)	±50 kN	±300 kN

Stroke	150 mm total stroke (+/-75)	150 mm total stroke (+/-75)
Grips	MTS hydraulic grips	Instron hydraulic grips
Control system	Instron 8800 controller	Instron 8500 controller
Calibration	Calibration: 2004-06-01	Calibration: 2004-05-08 Calibration check: 2005-06-01
Alignment	No special alignment of grips or load cell was performed prior to testing. The grips of the machine are removed from the machine quite often to install other equipments. During mounting of the grips, a flat dummy specimen is mounted in the machine and the grips are fixed at near maximum load capacity.	No special alignment of grips or load cell was performed prior to testing. The grips of the machine are normally not removed.
Strain measurement equipment	For strain measurements, two Spider 8 data loggers and Catman 4.5 software from HBM was used (Cal Check:May/June 2004). The supplied 25 way connector and terminal block were used for the connection to the two Spider 8s.	

<table>
<tr><th colspan="2">Lappenranta University of Technology</th></tr>
<tr><td colspan="2">The Laboratory of Fatigue and Strength of Materials at Lappeenranta University of Technology is a university laboratory, mainly performing fatigue tests in research projects, but also for external industrial customers.</td></tr>
<tr><td>Name of testing machine</td><td>FISKARS with INTERFACE 1020AF-25K load cell</td></tr>
<tr><td>Type of testing machine</td><td>Servo-hydraulic</td></tr>
<tr><td>Capacity of the testing machine (min-max, kN)</td><td>±150 kN</td></tr>
<tr><td>Stroke</td><td>200 mm</td></tr>
<tr><td>Grips</td><td>MTS 646.105 hydraulic collet grips</td></tr>
<tr><td>Control system</td><td>MTS</td></tr>
<tr><td>Calibration</td><td>by VTT Technical Research Centre of Finland</td></tr>
<tr><td>Alignment</td><td>MTS 605 Alignment fixture</td></tr>
<tr><td>Strain measurement equipment</td><td>ECTRON Mod. No. 4001Y-M579 amplifiers. Strain gauge K-factor was 2.09 and shunt Calibration was for 2500 micro Strain with resistance 22.85 kOhm. 1V equivalent to 250 micro strain and 1V equivalent to 20 kN.</td></tr>
<tr><td>Other</td><td>Between sequences the specimen was dismounted from grips and was rotated 90 deg around longitudinal axis counter clock wise. Data acquisition with PC with National Instruments measuring board M1016E-with DA v.2.2 software</td></tr>
</table>

BYG.DTU	
BYG.DTU is the Department of Civil Engineering at Technical University of Denmark. The laboratory performs fatigue tests in research projects and also for external industrial customers.	
Name of testing machine	Instron 1343
Type of testing machine	Servo hydraulic universal testing machine
Capacity of the testing machine (min-max, kN)	±500 kN
Stroke	±50 mm
Grips	Instron grip type 2718-034.
Control system	Instron 8500+
Calibration	The calibration status of the machinery has been verified by experiments with a traceable calibrated load cell.
Alignment	No information
Strain measurement equipment	The equipment supplied by the project organisers

Scania CV AB	
Scania is a truck producer. Its laboratory mainly performs fatigue tests for use within the Scania group.	
Name of testing machine	MTS 810 rig
Type of testing machine	Servo hydraulic
Capacity of the testing machine (min-max, kN)	±250 kN
Stroke	100mm
Grips	MTS 647 hydraulic wedge grips and wedges for specimens with both circular and rectangular cross section
Control system	MTS Test Star 2 Classic
Calibration	The rig has recently been calibrated.
Alignment	No aligning of the rig has been done.
Strain measurement equipment	The equipment supplied by the project organisers

Semcon Sweden AB	
Semcon Test Center is a laboratory in a consultancy organisation. It mainly performs fatigue tests for external industrial customers. .	
Name of testing machine	MTS 810 MTS 661.20 Force transducer
Type of testing	Servo hydraulic

machine	
Capacity of the testing machine (min-max, kN)	0-100kN
Stroke	200mm
Grips	MTS 647 Hydraulic Wedge Grip
Control system	MTS 407 Servo Controller
Calibration	2004-08
Alignment	No information
Strain measurement equipment	IOtech Wavebook 516, data logger; calibrated 2002-11 and IOtech WBK16, bridge amplifier; calibrated 2002-11

Ovaka Imatra	
Ovaka Imatra is a steel producer. Its laboratory mainly performs fatigue tests for the Ovako Imatra organisation.	
Name of testing machine	MTS hydraulic material testing system
Type of testing machine	Servo hydraulic
Capacity of the testing machine (min-max, kN)	± 250 kN
Stroke	± 150 mm
Grips	Hydraulic grips
Control system	MTS TestStar II
Calibration	The machine was calibrated 2005-03-08
Alignment	The alignment was not checked
Strain measurement equipment	The equipment supplied by the project organisers

Risö National Laboratory	
The Materials Research Department of Risö National Laboratory is a technology institute laboratory which performs fatigue tests in research projects and for external industrial customers.	
Name of testing machine	Instron 8842
Type of testing machine	Servo hydraulic
Capacity of the testing machine (min-max, kN)	±100 kN
Stroke	+/- 50 mm
Grips	Hydraulic grips
Control system	Instron
Calibration	Calibrated 2004-03-23
Alignment	None special

Strain measurement equipment	The equipment supplied by the project organisers
Other	Following the “Instructions with amplifier” for balancing and calibrating the amplifier the reading was 4718 µS (should be around 4730). It seems like there was a problem with gage 2 on specimen B2, since the gage tended to drift.

Volvo Powertrain Corporation	
Volvo Powertrain is coordinating Volvo’s activities concerning parts such as diesel engines, transmissions and shafts.	
Name of testing machine	MTS + MTS load cell GKT 7
Type of testing machine	Servo hydraulic
Capacity of the testing machine (min-max, kN)	± 100 kN
Stroke	200 mm
Grips	MTS 646 Hydrualic collet grip
Control system	MTS
Calibration	Valid until 060406
Alignment	MTS 609 Alignment fixture
Strain measurement equipment	Conditioner Burster SEMMEG 9000 (BFS 1) Calibrated 050922 - Volmeter Reading: National Instruments MIO 16 in computer. Calibrated against Fluke 8062 A(UID 3) Fluke Calibrated 050927

Table 4. The participants and their equipment

3 Calculations

All participants reported the procedures and the test results in reports and in Excel sheets. The results were reported as micro-strain for each strain gauge at specific load levels.

The following calculations were made from the results in the Excel sheets

It was assumed that the specimens were subjected to an axial load and to bending moments in two directions around axes in their cross section, but not subjected to any twisting moment. The latter condition is true for a servo-hydraulic testing machine, where the piston can rotate in the actuator with almost insignificant friction.

Equation systems relating the strains in the gauges in the upper and lower circles to these loads can easily be established.

$$\begin{bmatrix} \varepsilon_i \\ \varepsilon_j \\ \varepsilon_k \\ \varepsilon_l \end{bmatrix} = \frac{1}{EA}\begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} F + \frac{1}{EI_x}\begin{bmatrix} y_i \\ y_j \\ y_k \\ y_l \end{bmatrix} M_x + \frac{1}{EI_y}\begin{bmatrix} x_i \\ x_j \\ x_k \\ x_l \end{bmatrix} M_y \qquad (1)$$

where F is the axial load and M_x and M_y the bending moments around the x- and y-axes, E is Young's Modulus, A is the cross-sectional area and I_x and I_y are the moments of inertia.

As there are four gauges in each circle, but only three external loads, the equation systems are over determined and a solution can be obtained using the least squares method. A benefit of using more gauges than loads is that residuals of the least squares solution can be calculated. If the residuals are large, the measurement is of poor quality. This can be due to poorly placed gauges, temperature drift in the gauges or their cables, poor calibration of the amplifier or misreading of the instrument. As the specimens were loaded in different machines, and none of them showed large residuals in any of the machines, the problem of poorly placed gauges can be ignored. A further check of the quality of the measurements can be provided by checking the loads calculated from the measured strains against the loads measured by the load cell of the testing machine.

In most measurements, the loads calculated from the measured strains and the loads measured by the testing machine load cell differed by only 1-2 %, and the calculated residuals were only a few micro-strains. Measurements with residuals larger than 20 micro-strains were not used in the evaluation.

The calculated bending moments can be used for comparing different testing machines when the same type of specimen was used. The larger the maximum bending moment, the worse the misalignment. The variation in the moment along the length of the specimen can also be used for finding the type of misalignment, see Section 4.1 Misalignment modes. However, the reduction in fatigue life is determined by the stresses caused by the moments. It is therefore interesting to calculate these stresses and, from Wöhler curves for different materials, see how much the fatigue lifetime given by a test may be reduced by using a poorly aligned testing machine.

3.1 Moment

By solving the least squares problem, we have calculated four bending moments, i.e. two bending moments around perpendicular x- and y-axes in both the upper and lower positions with strain gauges.

For each position, a resulting moment can be calculated from

$$M_{\max} = \sqrt{M_x + M_y} \qquad (2)$$

The gauges in the upper and lower circles were separated by different distances for specimens C2 and C3. The moment for specimen C2 was therefore extrapolated to distances of ±22.5 mm from the centre of the specimen.

For both the circular and the rectangular specimens, the maximum moment in either the upper or lower position was used when the different testing machines were compared.

3.2 The resulting stresses from this moment

The bending moments give rise to stresses which vary linearly over the cross section of the test specimen. If the bending moment is described by its components along two orthogonal *x*- and *y*-axes in the respective cross sections, the axial stress in the test specimen will have a bending stress contribution in the cross section (in addition to the stress due to the axial force) that is given by

$$\sigma_z(x,y) = \frac{M_x}{I_x} \cdot y - \frac{M_y}{I_y} \cdot x \tag{3}$$

Positive stresses correspond to tension, and negative stresses correspond to compression. The bending moments M_x and M_y that arise due to misalignment in the testing machine will first have a value when the specimen is inserted in the testing machine. Later on, this value may also vary during load cycling. One could therefore identify a mean value and an amplitude value of each moment component during a load cycle. The corresponding misalignment stress according to Equation (3) will then also show corresponding mean and amplitude values during load cycling.

3.3 Fatigue life

In order to find out the effects of misalignment on life length predictions, it is illustrative to relate the misalignment stress to an error in life length prediction. One way of doing this is to distinguish between the cyclic mean and amplitude stresses from the misalignment.

Denote the largest mean stress contribution (over the cross section and for the different positions along the test specimen) due to misalignment during a load cycle by $\sigma_{m,err}$, and the largest amplitude stress contribution due to misalignment during a load cycle by $\sigma_{a,err}$. The mean and amplitude stresses due to the nominal axial loading (*i.e.* without misalignment) are denoted by σ_m and σ_a respectively. The influence of $\sigma_{m,err}$ and $\sigma_{a,err}$ on the predicted fatigue life length will now be considered separately.

3.3.1 Influence of mean stress error due to misalignment

If the critical amplitude stress for fatigue failure in a certain material after N cycles at mean stress σ_m is denoted by $\sigma_{ac}(\sigma_m, ,N)$, Goodman's rule relates this to the corresponding critical amplitude stress for the case with zero mean stress as

$$\frac{\sigma_{ac}(\sigma_m, N)}{\sigma_{ac}(0,N)} + \frac{\sigma_m}{\sigma_u} = 1 \tag{4}$$

where σ_u is the tensile strength of the material. There are other similar rules for mean stress influence (for instance, the Gerber rule with a parabolic relation instead of a linear relation). The Goodman rule is chosen here for its simplicity, with the purpose of merely illustrating the misalignment errors in terms of fatigue life errors.

In a fatigue test, we have a mean stress that is composed of both the nominal mean stress and the mean stress error due to misalignment. Insertion of this misalignment case in Goodman's rule gives, in a similar way with Equation (4):

$$\frac{\sigma_{ac}(\sigma_m + \sigma_{m,err}, N)}{\sigma_{ac}(0,N)} + \frac{\sigma_m + \sigma_{m,err}}{\sigma_u} = 1 \tag{5}$$

Elimination of the critical amplitude at zero mean stress between Equations (4) and (5) gives

$$\frac{\sigma_{ac}(\sigma_m + \sigma_{m,err}, N)}{\sigma_{ac}(\sigma_m, N)} = 1 - \frac{\sigma_{m,err}}{\sigma_u - \sigma_m} \tag{6}$$

The fatigue test will give a fatigue life related to the largest tensile mean stress error, since the point with the highest stress will generally fail first. Consequently, the mean stress error contribution is positive (tensile) and the right-hand side of Equation (6) will be less than unity. As a result, the critical amplitude for fatigue after a certain number of cycles with misalignment present will be less than what it would be without misalignment error.

In order to relate critical fatigue amplitudes to the fatigue life *N*, as shown on the left-hand side of Equation (6), the shape of a Wöhler curve for a specific material must be used. A general Wöhler curve is often described by Basquin´s equation as

$$N = a \cdot \{\sigma_{ac}(\sigma_m, N)\}^{-b} \tag{7}$$

where *a* and *b* are positive parameters estimated from the experimental data. The misalignment will lead to a lower Wöhler curve than would be obtained without misalignment. An estimate of the reduction in critical amplitude due to misalignment is obtained from Equation (6) as

$$\Delta\sigma_{ac} = \sigma_{ac}(\sigma_m, N) - \sigma_{ac}(\sigma_m + \sigma_{m,err}, N) = \sigma_{ac}(\sigma_m, N) \cdot \frac{\sigma_{m,err}}{\sigma_u - \sigma_m} \tag{8}$$

Loading at a stress amplitude σ_a in the absence of misalignment error will, according to Basquins equation (7), lead to a fatigue life

$$N = a \cdot \{\sigma_a\}^{-b} \tag{9}$$

In the presence of misalignment an erroneous fatigue life instead be obtained, as

$$N_{err} = a \cdot \{\sigma_a + \Delta\sigma_{ac}\}^{-b} \tag{10}$$

Inserting a specific load of $\sigma_a = \sigma_{ac}(\sigma_m, N)$ in Equation (8) gives, together with the use of Equations (8) and (9),

$$\begin{aligned} N_{err} &= a \cdot \{\sigma_{ac} + \Delta\sigma_{ac}\}^{-b} = a \cdot \left\{\sigma_{ac}(\sigma_m, N) + \sigma_{ac}(\sigma_m, N) \cdot \frac{\sigma_{m,err}}{\sigma_u - \sigma_m}\right\}^{-b} = \\ &= a \cdot \{\sigma_{ac}(\sigma_m, N)\}^{-b} \left\{1 + \frac{\sigma_{m,err}}{\sigma_u - \sigma_m}\right\}^{-b} = N \cdot \left\{1 + \frac{\sigma_{m,err}}{\sigma_u - \sigma_m}\right\}^{-b} \end{aligned} \tag{11}$$

and consequently the quotient between erroneous and correct fatigue life time is related to the misalignment contribution to mean stress as

$$\boxed{\frac{N_{err}}{N} == \left(1 + \frac{\sigma_{m,err}}{\sigma_u - \sigma_m}\right)^{-b}} \tag{12}$$

The mean stress influence of a misalignment will thus lead to conservative fatigue life predictions, since parameter *b* is positive and so the exponent is negative.

3.3.2 Influence of amplitude stress error due to misalignment

The influence of an incorrect amplitude stress on the fatigue life estimation could be obtained directly from Basquin's equation (7). In this case, the mean stress influence is not considered and Basquin's equation gives a relation between the fatigue life and the critical amplitude stress

$$N = a \cdot \sigma_{ac}^{-b} \tag{13}$$

In the case of no misalignment, an amplitude stress σ_a. is used during the testing. If this stress is inserted as the critical amplitude in Equation (13), a corresponding life length is obtained. However, due to misalignment, we have an additional amplitude stress of $\sigma_{a,err}$. Due to this, the fatigue life is erroneously estimated as

$$N_{err} = a \cdot \left\{\sigma_a + \sigma_{a,err}\right\}^{-b} \tag{14}$$

Dividing Equation (14) by Equation (13) gives the quotient between erroneous and correct fatigue life, related to the misalignment contribution to amplitude stress, as

$$\boxed{\frac{N_{err}}{N} = \left(1 + \frac{\sigma_{a,err}}{\sigma_a}\right)^{-b}} \tag{15}$$

3.4 Statistical calculations

The results from two of the laboratories were used to calculate the reproducibility and the repeatability of the strain gauges. When performing the tests, these laboratories did not open the hydraulic grips between the load sequences. This meant that the measurements with round test specimens instrumented with strain gauges and the amplifier and switch unit were rather "isolated" from other error sources. The systematic error of the strain gauges has been estimated by adding them pair-wise after reduction of the mean stress. In this way, the bending stresses are eliminated, with the exception of deviations from the 180°. Variance analysis has been performed for these sums for the four pairs of gauges.

	r	**R**	**df**
Laboratory 1	**5.5**	**11.5**	**24**
Laboratory 2	**5.8**	**13.8**	**6**

Table 5. Reproducibility and repeatability

These values represent the variance in the difference between two gauges, and thus the repeatability can be calculated by using:

$$r_\varepsilon = \sqrt{\frac{5.5^2 + 5.8^2}{2} \Big/ 2} = 4.0\ \mu S \tag{16}$$

This value represents the variability in one strain gage together with the amplifier, i.e. it corresponds to the standard deviation in repeated readings from the same gage"

The reproducibility is calculated by using:

$$R_{\varepsilon} = \sqrt{\frac{24 \cdot 11.5^2 + 6 \cdot 13.8^2}{30 \cdot 2}} = 8.5\ \mu S \qquad (17)$$

This value represents the variability between different strain gages including their mounting, i.e. it corresponds to the standard deviation of readings at a random choice of mounted strain gages.

4 Results

There are several different results from the inter-comparison. Most of them are reported in detail to the individual laboratories in that way giving the laboratory information about the misalignment of the testing machines they participated with.

4.1 Misalignment modes

There are different types of misalignment:

1) Misalignment caused by translational movement of one of the grips (see figure 6a)

2) Misalignment caused by angular movement of one of the grips (see figure 6b)

3) Combinations of 1 and 2 (see figure 6c)

4) Twisting. This misalignment mode is unlikely to appear in servo-hydraulic testing machines where the piston in the actuator can be considered as being free to rotate and therefore no twisting is introduced to the test specimen. This study has been concentrated mainly on servo-hydraulic testing machines (even though other types have also been used), and so the twisting mode is not further considered here.

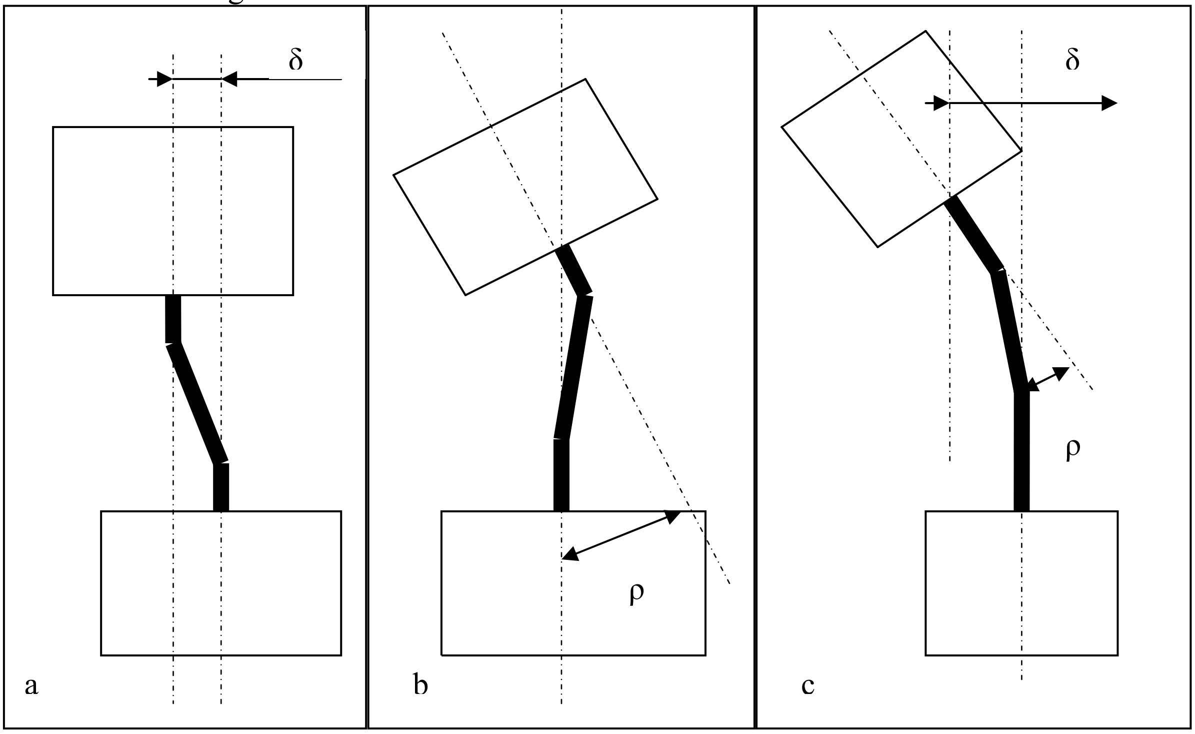

Figure 6
a) Translation
b) Angular
c) Combination of a and b

By presenting diagrams with strain results from each of the strain gauges, it is possible to determine which of the modes a, b or c the testing machines is affected by. The figures below show some typical examples of misalignment modes.

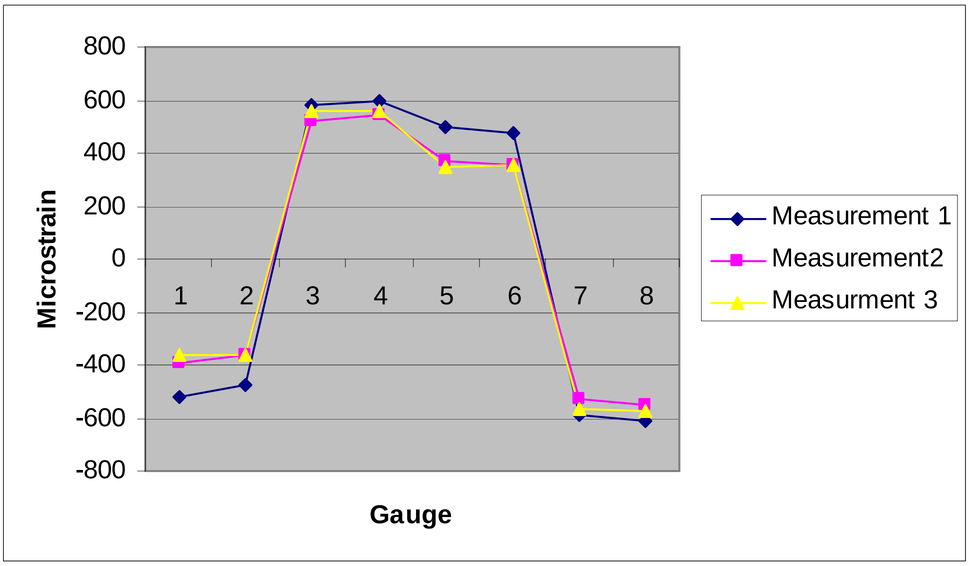

Figure 7. Example of a testing machine with misalignment mode a) caused by translational movement.

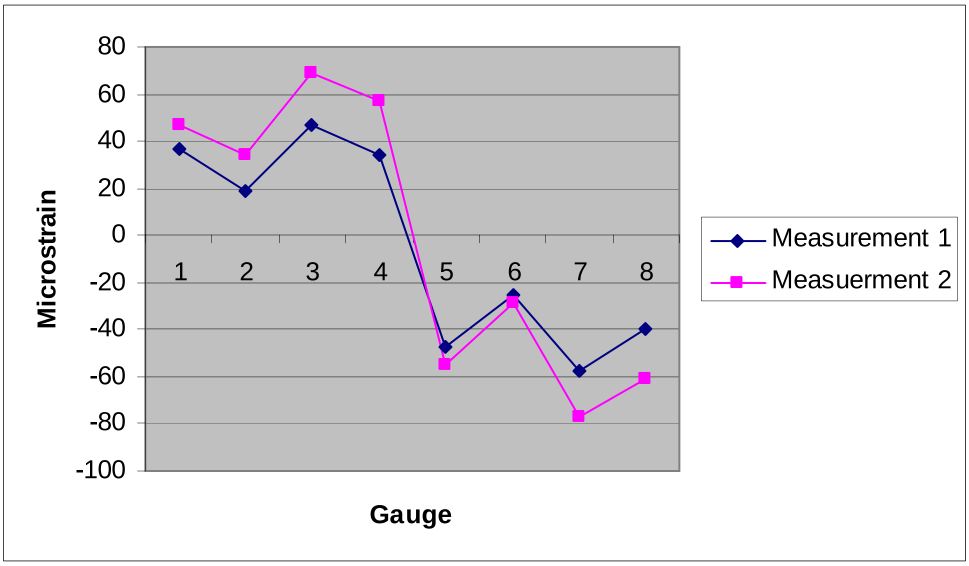

Figure 8. Example of a testing machine with misalignment mode b) caused by angular movement.

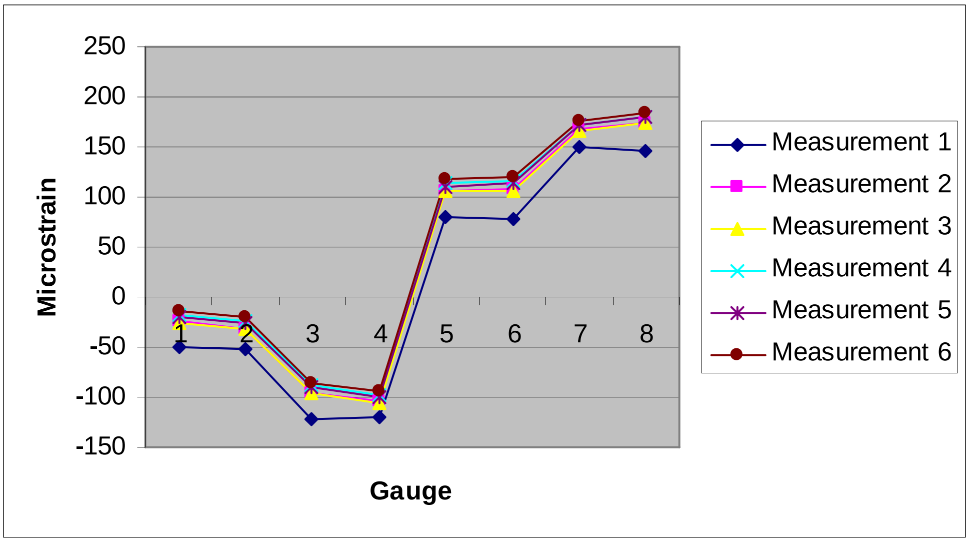

Figure 9. Example of a testing machine with misalignment mode c) caused by a combination of angular and translational movement.

Generally, most of the misalignment is caused by the clamping of the test specimen in hydraulic grips, but in some cases the actual vertical movement of the actuator applying the load affects the misalignment. One such example is shown in Figure 10, while one where this is not the case is shown in Figure 11.

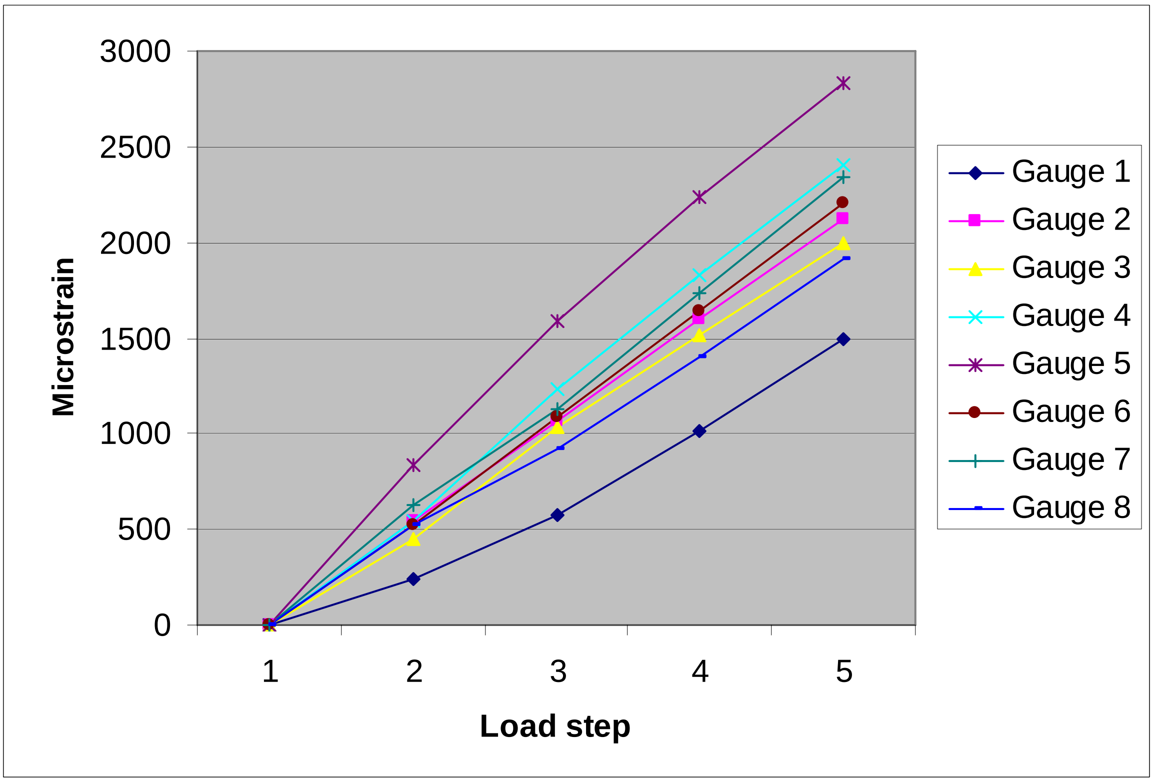

Figure 10. An example of a testing machine where the misalignment increases with the applied load. The strain has been set to 0 for 0 load to be able to study the effect of increasing load on the misalignment.

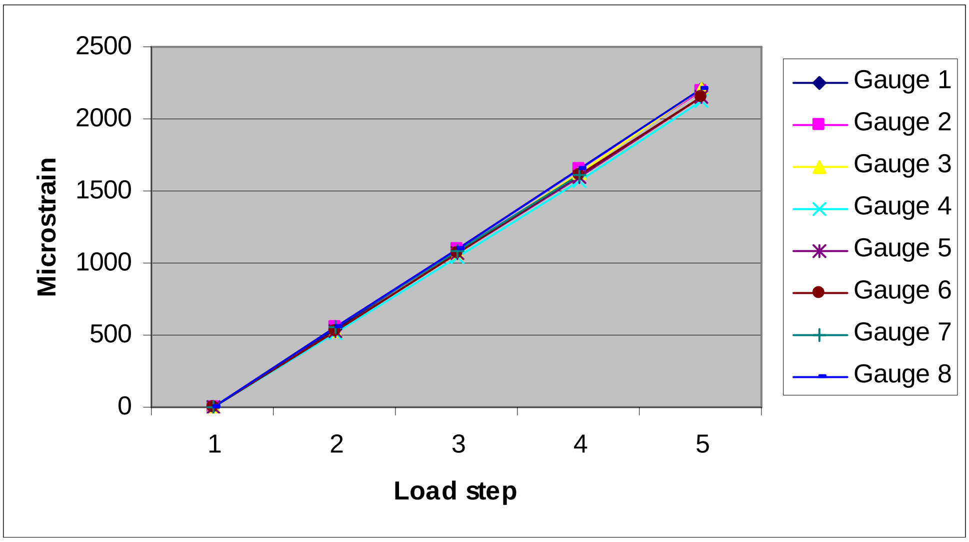

Figure 11. Example of a testing machine where the vertical movement does not affect the misalignment.

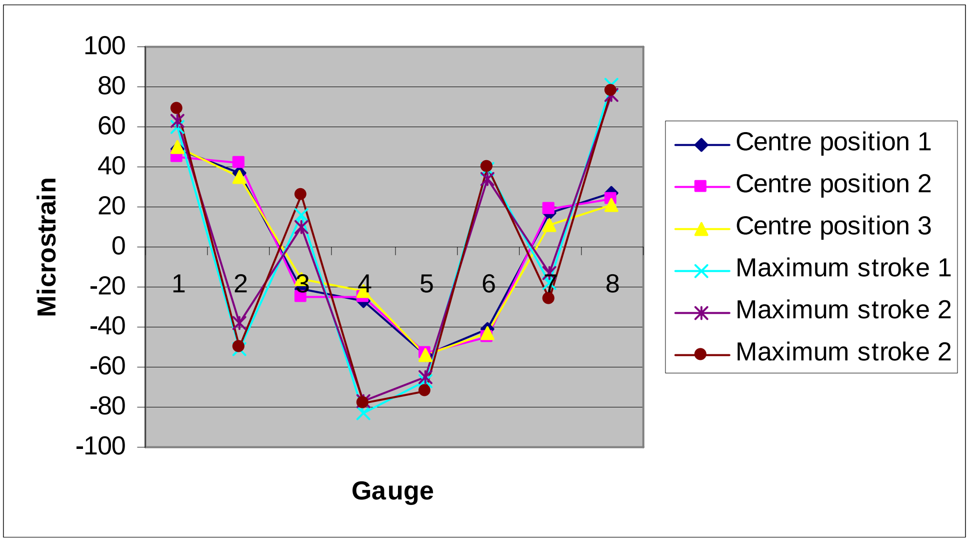

Figure 12. Example of a testing machine where the actuator position is affecting the misalignment mode.

4.2 Moments

The maximum moment M_{max} is used as a measure of the misalignment of a testing machine. Some results are shown in the figures below. From them, it is possible to see the influences of the testing machine, actuator position, zero or maximum load and round or rectangular test specimens. There are different combinations of testing machines, test specimens, actuator position and load. Each of these combinations is treated as a specific test case.

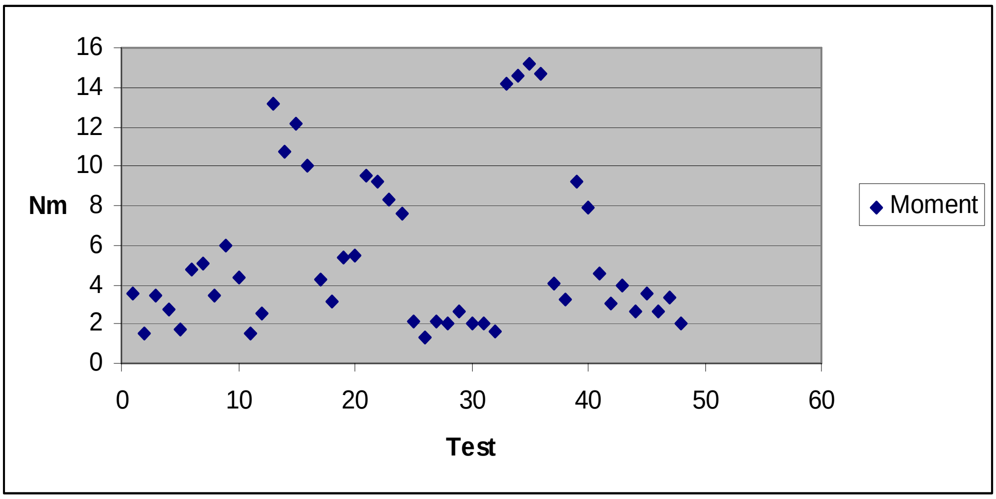

Figure 13. Maximum moment for round test specimens for different testing machines, at zero and maximum load and with the actuator in two positions (middle and top position). Each combination of testing machine, load and actuator position is denoted as an individual test

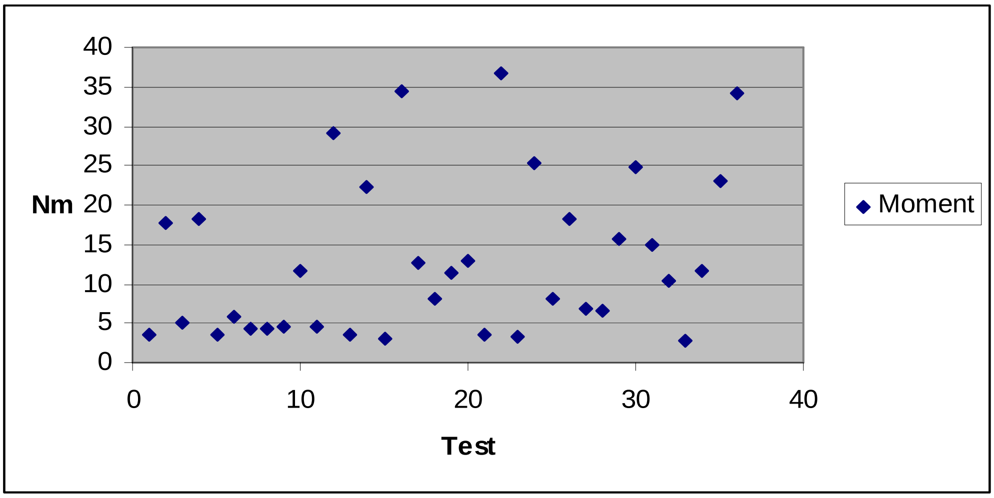

Figure 14. Maximum moment for rectangular test specimens for different testing machines, at zero and maximum load and with the actuator in two positions (middle and top position). Each combination of testing machine, load and actuator position is denoted as an individual test.

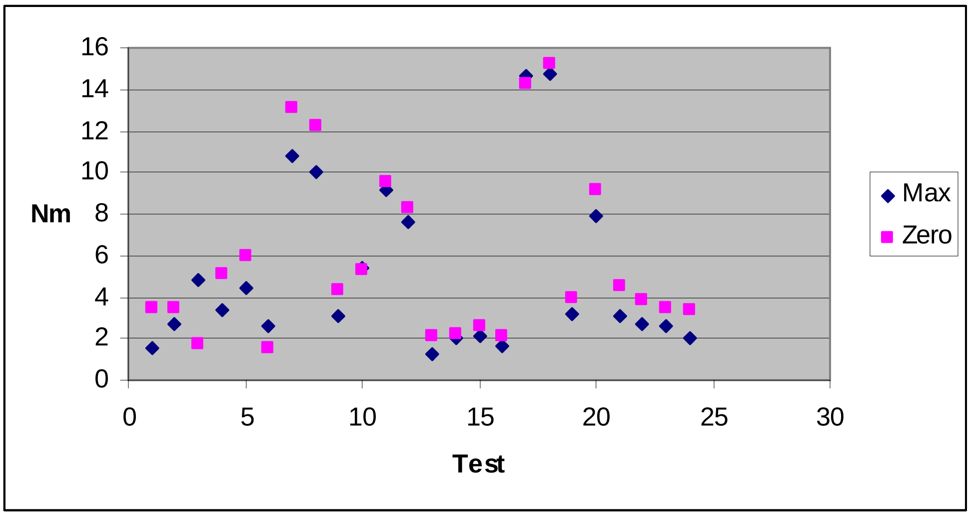

Figure 15. This figure shows the maximum moment for round specimens at zero and maximum load.

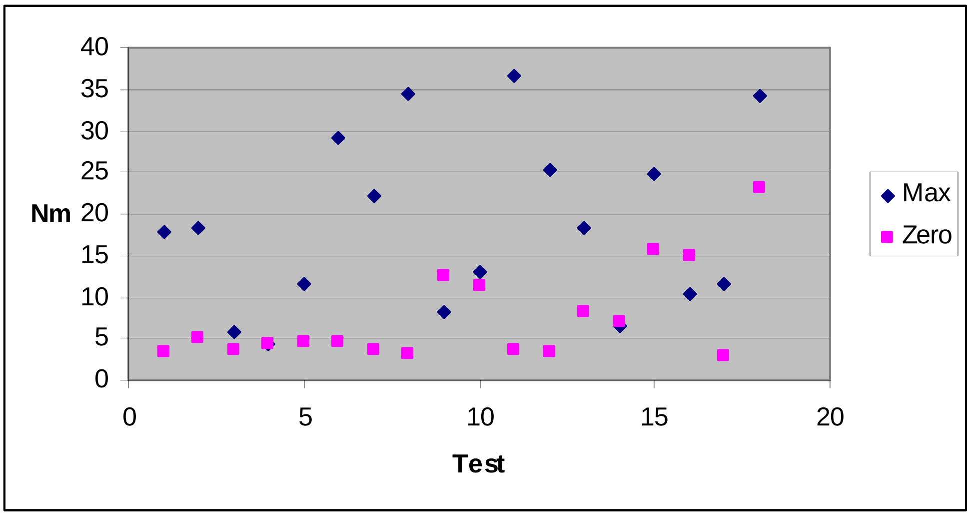

Figure 16. This figure shows the maximum moment for rectangular specimens at zero and maximum load.

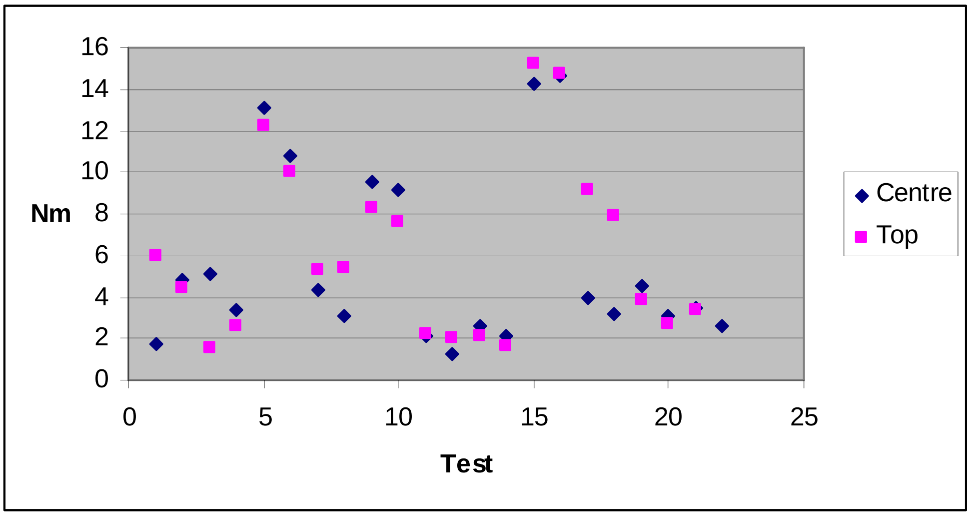

Figure 17. The influence of actuator position on the round specimen results.

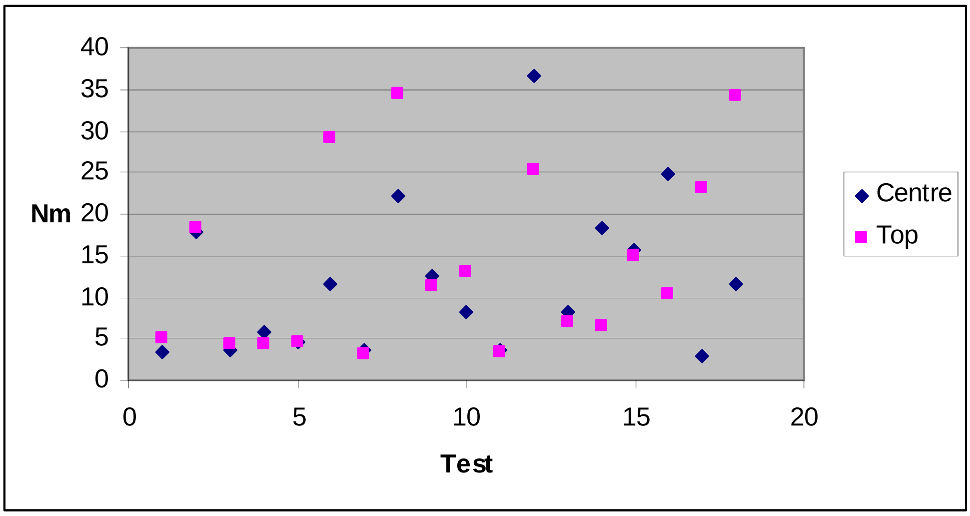

Figure 18. The influence of actuator position on the rectangular specimen results.

4.3 Stresses

All the testing machines in this comparison showed a stress at zero load, but only for some of the machines did this stress change when the specimen was loaded. The histogram in Figure 18 was calculated from the maximum stress obtained when the grips were closed at zero load.

A stress increasing with increasing load was found for some of the investigated testing machines. Figure 21 shows the worst case.

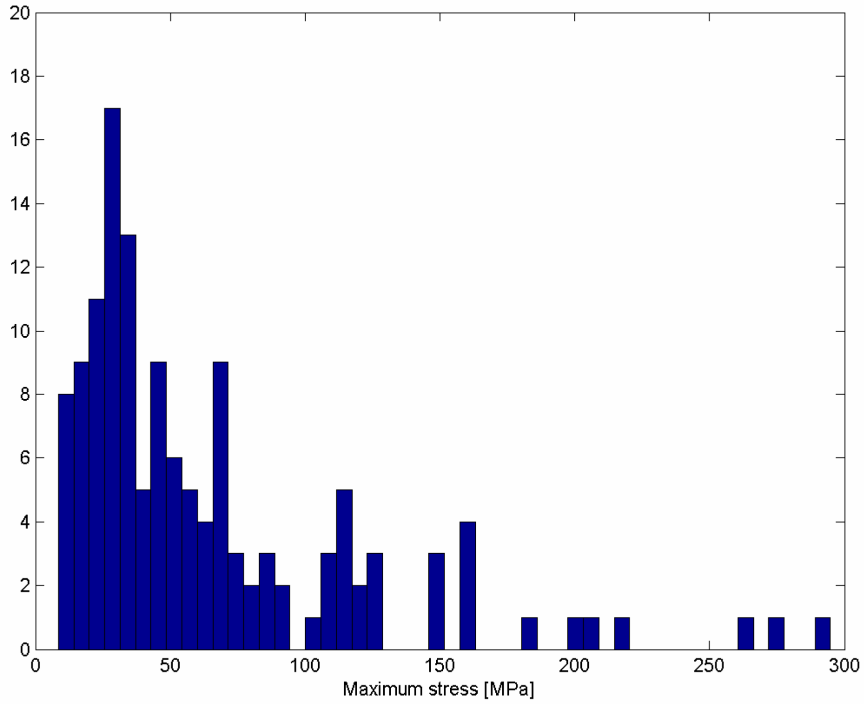

Figure 19. Maximum stress during clamping.

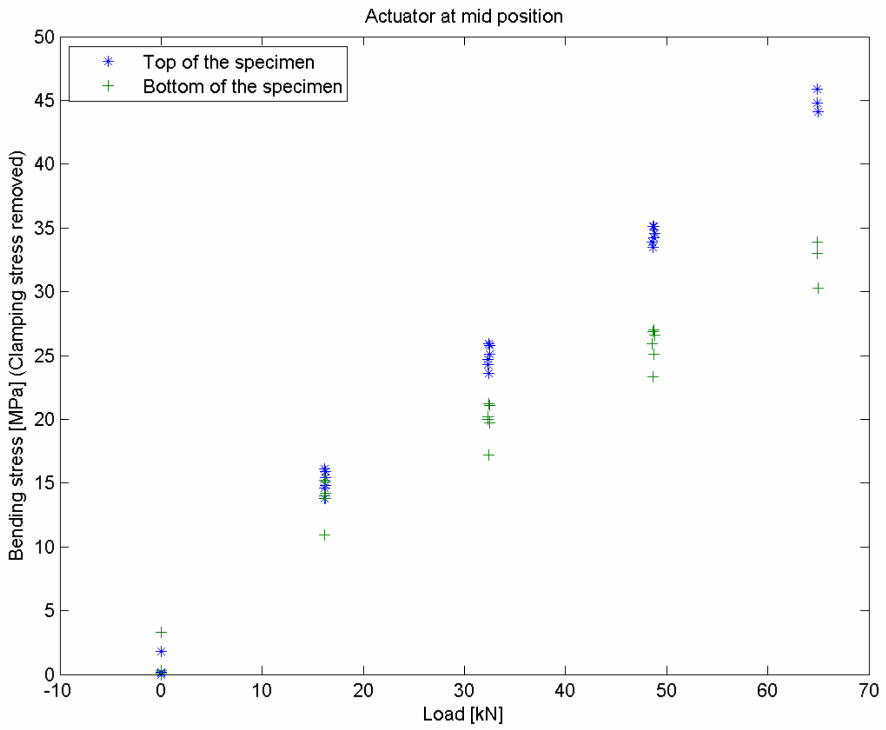

Figure 20. Example of a testing machine where bending stress increases with increasing load.

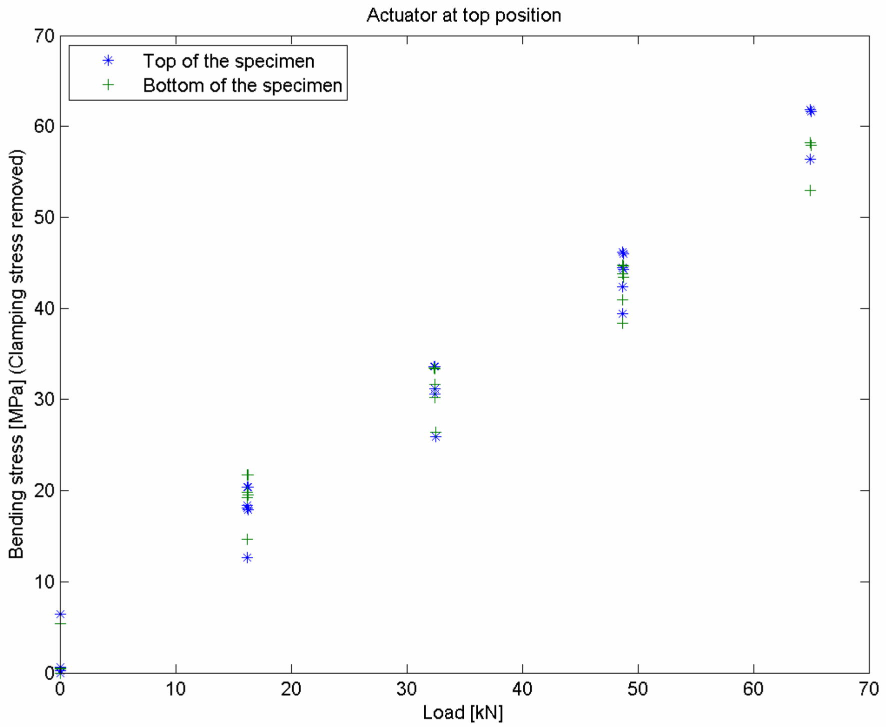

Figure 21. Example of a testing machine where bending stress is increasing with increased load.

4.4 Fatigue life

The effect of misalignment was to contribute additional mean stresses during load cycling, as shown in Figure 19. For specific materials, this can be related to an error factor in the predicted life in accordance with Equation (12). The results depend on the material data (tensile strength σ_u and Basquin exponent b) and on the nominal mean stress load σ_m. Different situations are shown in the table below for AISI1015 material with a tensile strength of 415 MPa and a Basquin exponent b=7, [4].

Mean stress error /MPa	Mean stress /MPa	N_{err}/N
300	0	0.02
100	0	0.22
50	0	0.45
50	100	0.36

Table 6. Estimated influence of misalignment on fatigue life

The corresponding influence of misalignment amplitude stress is obtained from Equation (15). From the laboratory result in Figure 20, which was an extreme case among the laboratories investigated, it can be seen that there was a stress range of 60 MPa due to misalignment when the load range was 65 kN. This load range corresponds to a stress range of 430 MPa. Insertion into Equation (15) gives N_{err}/N=0.40. Since this was the most extreme case among the laboratories, a comparison with the results from the mean stress above indicates that the mean stress contribution from misalignment has, in practice, the greatest influence.

4.5 Statistics

The repeatability of the strain measurements was estimated to $r_\varepsilon = 4.0$ µS and the reproducibility of the strain measurement was estimated to $R_\varepsilon = 8.5$ µS.

5 Discussions

A laboratory intercomparison of fatigue testing machines has been performed, investigating the misalignment introduced during mounting (including clamping). 13 laboratories and 19 testing machines participated originally. This report describes the results from ten laboratories and 16 testing machines. The participants were university laboratories, industrial laboratories, institute laboratories and commercial laboratories.

The participants' laboratories are well equipped and the participants are experienced in fatigue testing. Most of the testing machines used in the intercomparison were of servo-hydraulic type, although some electro-dynamic testing machines were also used. The largest testing machines could apply a maximum load of 500 kN, and the smallest could apply a load of 25 kN. Maximum stroke was 300 mm, and the minimum stroke was 50 mm. The testing machines are calibrated on a regular basis. Most of them have a calibration interval of one year, although some have an interval of two years.

The participants were offered two options for strain measurement: either, together with the test specimens, to use the equipment (amplifiers, switch unit) offered by the organisers, or to use their own equipment with the test specimens. The repeatability and reproducibility show that strain measurement is not a problem.

The distance between the gauges (a in Figure 2) on the round specimens differed from the rest. This difference was compensated during the moment calculations by linear interpolation.

Laboratory tests

The first two participants interpreted the instructions provided by the organisers such that the grips were not opened between the different load cycles. This led to a clarification of the instructions sent to the rest of the participants.

Some of the participants align the testing machines before a test is started; some simply check the alignment, while others merely perform the tests without any special arrangements concerning the alignment

During the test some of the test specimens were damaged. Either the grips were deformed during too high grip pressure or some of the gauges or the cables connected to the gauges were also damaged. The results from the tests where this has happened has been omitted.

Results, misalignment modes

It is possible to decided which of the modes (figure 6a-c) the misalignment of testing machine is belonging to be studying the figures where strain is plotted versus gauge. Such plots are shown in figures 7-9. All testing machines in the study show some misalignment when strain is plotted versus gauges even though there were big differences between the magnitudes of the strain. This is obviously a good way to investigate if a testing machine is misaligned and also to find which sort of (mode) misalignment there is.

A few of the testing machines in the study is showing a dependence of the applied load on the introduced misalignment. One example of a test performed in such a testing machine is shown in figure 10, while a test performed in a testing machine without this problem is shown in figure 11. It is however rare that the applied load is influencing the misalignment.

Figure 12 is showing a situation where the actuator position is affecting the misalignment mode. In this case the misalignment mode is shifting but the magnitude of the misalignment (maximum moment) is almost not affected at all.

The plots of strain versus gauge also show that in some situations the test specimens may have been subject to stresses close to or above the yield strength of the test specimen material.

Moment

A maximum moment was calculated for each test situation to get a measure of what is influencing the misalignment of a testing machine. These moments are shown in figures 13 to 18.

In figure 13 all the test situations (testing machine, actuator position and load level) for round specimens are shown. Figure 14 is showing the same for flat specimens. The largest moments for round specimens are around 15 Nm and for the flat specimens around 30-35 Nm.

In figure 15 and 16 the maximum moment for zero load and maximum load are plotted for round respectively flat specimens. In figure 16 almost all tests with maximum load lead to a higher moment than those with zero load. The situation is different in figure 15 where there seem to be little effect of the load level. If there is any effect of load level at al on the round specimens it seems to the opposite to the one in figure 16 but much smaller. The reason for this is not clear and it will be further investigated.

From figure 17 and 18 it is clear that there is little effect of the actuator position on the maximum moment. Figure 12 is however showing that the actuator position may affect the misalignment mode.

Stresses

In figure 19 the constant bending stress caused by misalignment is showed for each testing machine in the intercomparison. There are some very high stresses, almost 300 MPa in the most extreme cases. This has also been indicated by the strain versus gauge plots and the moment plots.

Too many (28) of the tests are resulting in bending stresses higher than 100 MPa. All of these tests are performed in large testing machines (>250 kN). There are however examples of large testing machines where the bending stresses introduced due to misalignment are well below 100 MPa.

There are also a lot (33) of testing machines were the bending stresses are between 50 and 100 MPa which in fatigue is a large error.

About three fifths (72) of the tests lead to bending stresses below 50 MPa.

In figure 20 and 21 the situation where the applied load is affecting the misalignment. It is clear from the figures that in extreme cases an addition to the amplitude stress in a fatigue may be as large as 70 MPa.

Fatigue life

The stresses shown in figures 19-21 were used to calculate some examples where the influence of the misalignment on fatigue life was investigated. The calculations show that the contribution to the mean stress is most critical and the most extreme case (300 MPa) leads to 50 times shorter fatigue life. The most extreme contribution to the amplitude stress, 60MPa, leads to a decrease of fatigue life of about 60%. Also smaller mean tress contributions are leading to considerable reduction of fatigue life. A mean stress contribution of 100 MPa lead to a reduction of about 80% and 50 MPa leads to a fatigue life reduction of about 50%.

This study shows that there are many fatigue testing machines where there are considerable misalignment. Even though the contribution from misalignment always is reducing the tested fatigue life and in that sense always is leading to conservative fatigue design, misalignment is causing incorrect test results which in turn are leading to incorrect fatigue design of products.

This is of course finally leading to increased costs etc. It is therefore of great importance to try to reduce the misalignment during fatigue test as much as possible. This study shows the importance of using the correct testing machine for a test. A too large machine seems to increase the risk for misalignment.

Statistics

The repeatability and reproducibility calculations show that the strain measurement is very accurate and the equipment is reliable.

6 Conclusions

From this study the following conclusions may be drawn:

- Many fatigue testing machines are misaligned.

- There three different modes of misalignment (angular, translational and a combination of them) and all three modes were found during this study.

- The misalignment can affect the stress state in the test specimens either by a constant stress introduced when clamping the test specimen and/or by a bending stress which is increasing with increased load. The second case is however more rare.

- Mean stress contribution from misalignment may be as big as 300 MPa but most of the testing machines have a misalignment leading to a mean stress contribution of less than 50 MPa. 50 MPa is the median mean stress contribution in this study.

- Misalignment is causing incorrect test results. In the extreme case the test results may be 50 times lower than a correct fatigue life

- The contribution to the mean stress is the most critical while the contribution to the amplitude stress is less critical and is also much rarer

- It is important to choose the correct (size) of testing machine for the tests

7 Acknowledgement

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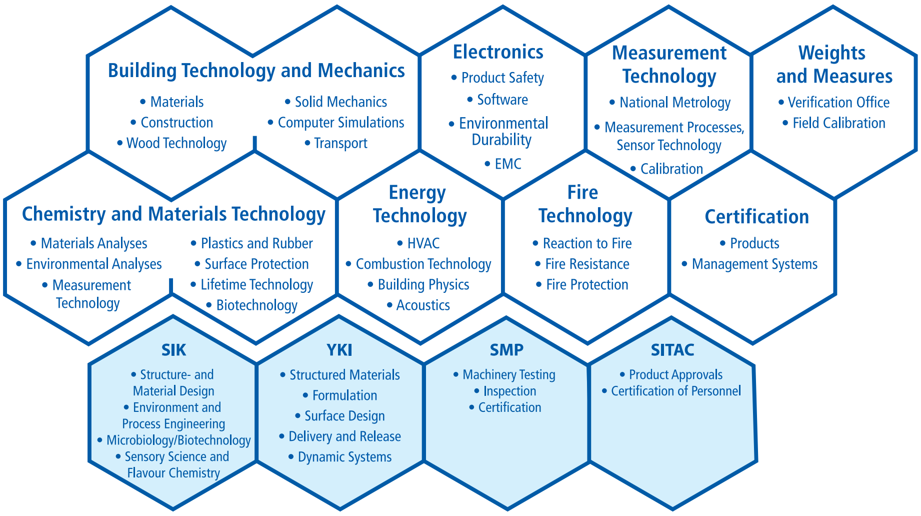

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