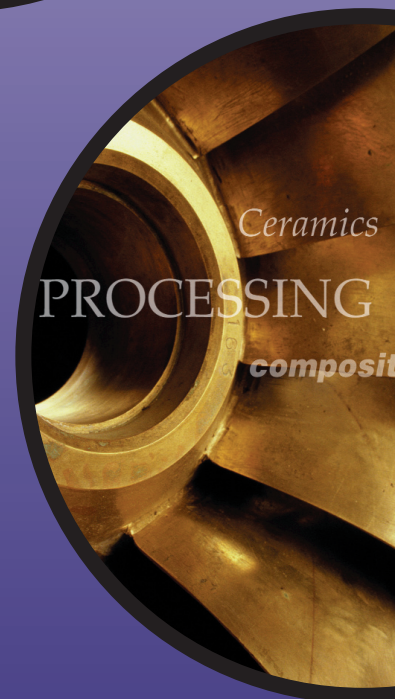
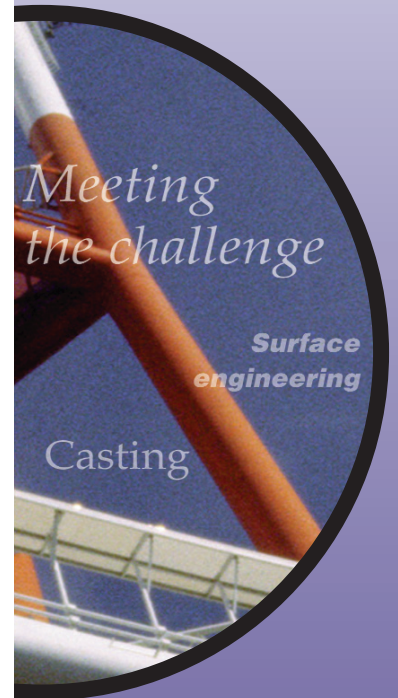


Measurement Good Practice Guide

Measurement of bending in uniaxial low cycle fatigue testing

F A Kandil



Measurement Good Practice Guide No. 1

Measurement of Bending in Uniaxial Low Cycle Fatigue Testing

Fathy Kandil

Centre for Materials Measurement and Technology
National Physical Laboratory

Abstract: This guide incorporates a method for measuring bending caused by misalignment of loading in uniaxial fatigue testing under specific conditions that are as consistent as practically possible with those encountered in the fatigue test. The method explores (for the first time) the effects on bending when a specimen is subjected to plastic as well as elastic deformation. Recommendations for acceptable levels of alignment in fatigue testing machines for metallic materials are given.

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National Physical Laboratory
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For further information on *Materials Measurement* contact the Materials Enquiry Point at the National Physical Laboratory:

Tel: 0181-943 6701

Fax: 0181-943 7160

E-mail: materials@npl.co.uk

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Measurement of Bending in Uniaxial Low Cycle Fatigue Testing

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Foreword

This guide was prepared for the UK Low Cycle Fatigue Forum Group. It describes methods for the verification of alignment of fatigue testing machines and determination of errors due to bending in uniaxial fatigue tests. This guide also provides recommendations concerning specifications, manufacture and use of alignment cells.

In the drafting of this guide, it has been assumed that the execution of its provisions is entrusted to appropriately qualified and experienced people. The methods also require the use of relatively sophisticated test equipment.

This guide has been incorporated and will be subjected to a full experimental validation exercise in a European Community project entitled "*Quantifying data uncertainties and the validation of a Code of Practice for measurement of bending in uniaxial fatigue testpieces*". The procedures in this document are subject to revision in 1997 and it is anticipated that this guide or a revised version will form the basis of future BSI, CEN and ISO Standards. In order to prepare for this revision, any inputs regarding this guide, particularly regarding experience in use, are invited and will be put on record and considered.

This guide is not intended to include a comprehensive review of the literature related to the measurement and analysis of misalignment-induced bending. Readers requiring such information may obtain a complete list of references from Dr Kandil at NPL.

UK Low Cycle Fatigue Forum Advisory Group

Mr J F Aldridge	Zwick Testing Machines Ltd
Dr D H Allen	GEC - Alsthom European Gas Turbines Ltd
Mr R E M Ball	Dartec Ltd
Dr M C Hardy	Defence Research Agency
Mr M Hill	ESH Testing Ltd
Dr S R Holdsworth	GEC-Alsthom Turbine Generators Ltd
Mrs S de la Hoyde	Defence Research Agency
Mr M Jones	Rover Group Ltd
Mr M Large	British Steel plc
Mr R B Laycock	GEC - Alsthom European Gas Turbines Ltd
Dr R D Lohr	Instron Ltd
Mr M McElhone	Rolls-Royce plc
Dr J Monaghan	Materials Ireland
Mr C J Rees	National Power plc
Mr P Smith	PowerGen plc
Mr N H Solomons	ESH Testing Ltd
Mr D Woodings	Zwick Testing Machines Ltd

1 Scope

This guide covers procedures for (a) alignment verification of fatigue testing machines and (b) bending error determination in a specific fatigue test programme.

This guide applies to the testing of cylindrical, hour-glass, and flat specimens.

This guide is intended primarily for use with metallic specimens. However, the procedures presented here may be equally applicable to orthotropic non-metallic specimens.

This guide addresses, but is not restricted to, conditions relating to low cycle fatigue testing in which metallic specimens are generally subject to both elastic and plastic deformations resulting in failure within a number of cycles typically less than 10^5 .

This guide is only concerned with bending errors at ambient temperature and arising from initial misalignment in uncracked specimens.

2 Definitions

For the purposes of this guide the following definitions apply.

2.1 Alignment

The geometrical conformance between the loading axes of a testing machine load train components. Departure from such conformance may introduce bending moments or shear forces or a combination of the two into the specimen during tensile or compressive loading.

2.2 Alignment cell

A device instrumented with strain gauges for use in the verification of alignment of the testing machine. An alignment cell is required to be used for successive alignment verifications. Therefore, unlike a test cell, it must only be subjected to elastic deformation.

2.3 Axial strain (ϵ_0)

The average longitudinal strain measured at the surface of an alignment cell or test cell by strain gauges with transverse axes located in the same strain measurement plane.

2.4 Axial strain range ($\Delta\epsilon_o$)

The algebraic difference between the maximum and minimum axial strain values in the fatigue cycle.

2.5 Bending strain

The difference between the strain at the surface and the axial strain. In general, the bending strain varies from point to point around and along the reduced section of the alignment cell or the test cell.

2.6 Bending strain range ($\Delta\epsilon_b$)

The algebraic difference between the maximum bending strain at the surface of the test cell under a tensile force that corresponds to a given maximum load in a fatigue cycle, and the bending strain at the same geometrical location on the test cell surface when the force corresponds to the minimum load in the fatigue cycle.

2.7 Fatigue bending error (ψ)

The bending strain range, $\Delta\epsilon_b$, divided by the corresponding axial strain range, $\Delta\epsilon_o$.

2.8 Load

The force applied to the alignment cell or the test cell.

2.9 Maximum bending strain

The largest value of tensile bending strain in the cross-section at which bending is measured. It is a vector with magnitude ϵ_b and angle θ .

2.10 Maximum load

The load having the highest value in the fatigue cycle, tensile being considered positive and compressive being considered negative.

2.11 Maximum percent bending ($\beta_{\max}$)

The higher value of percent bending determined on the two cross-sections at which bending is measured.

2.12 Minimum load

The load having the lowest value in the fatigue cycle, tensile being considered positive and compressive being considered negative.

2.13 Minimum section (in hour-glass specimens)

The section perpendicular to the longitudinal axis of the specimen where the cross sectional area is at a minimum.

2.14 Modulus of elasticity (E)

The ratio of stress to corresponding strain below the proportional limit strain.

2.15 Parallel length (l_p)

The length on an alignment cell or a test cell of the uniformly reduced section.

2.16 Percent bending (β)

The maximum bending strain times 100 and divided by the axial strain.

2.17 Proportional limit strain

The greatest axial strain which a material is capable of sustaining without any deviation from proportionality of stress to strain (Hooke's law).

2.18 R-direction

A fixed reference direction with respect to the frame of the testing machine (see Figure 8).

2.19 Strain measurement plane

The transverse plane in the alignment cell or the test cell in which the transverse axes of the strain gauges are positioned; the upper plane corresponds to gauges G1 to G4 and the lower plane corresponds to gauges G5 to G8 [see Figure 6 (a,c and d)].

2.20 Strain-gauge axial separation (l_g)

The distance on the alignment cell or the test cell between the upper and lower strain measurement planes [see Figure 6(a,c and d)].

2.21 Strain-gauge transverse separation (s)

The distance on the broad face of a rectangular alignment cell or test cell between the measurement axes of strain gauges [see Figure 6(d)].

2.22 Test cell

A test specimen instrumented with strain gauges for the purpose of determining bending errors in a specific fatigue test programme. The test specimen must be randomly picked from the batch to be tested.

2.23 Test span (L)

The distance between the test machine's support references for the loading bars [see Figure (1)].

3 Symbols

For the purpose of this guide the following symbols and designations apply.

Symbol	Designation
--------	-------------

b	Width of parallel section of flat cells
d	Diameter of parallel section of cylindrical cells; or Diameter of the minimum section in hour-glass cells
D	Diameter of grip end of cylindrical or hour-glass cells
E	Modulus of elasticity
L	Test span
l_g	Strain-gauge axial separation ($= 0.75 l_p$)
l_p	Parallel length
r	Transition radius between parallel section and grip end
$\hat{r}$	Profile radius of hour-glass cells
s	Strain-gauge transverse separation ($= 0.8 b$)
t	Thickness of flat cells
w	Width of grip end of flat cells
β	Percent bending
$\beta_{\max}$	Maximum percent bending
ϵ_o	Axial strain
$\Delta\epsilon_o$	Axial strain range
$\epsilon_1, \epsilon_2, \dots$ etc	Strain readings of individual gauges

ε_b	Maximum bending strain
$\Delta\varepsilon_b$	Bending strain range
$\varepsilon_{b(c)}$	Maximum bending strain at minimum load
$\varepsilon_{b(t)}$	Maximum bending strain at maximum load
θ	Angle (clockwise seen from above) of the maximum bending strain vector with respect to the R-direction
ϕ	Angle of the maximum bending strain vector measured from the strain gauge with the greatest reading (negative value means counter clockwise direction)
λ	Angle between vectors $\varepsilon_{b(t)}$ and $\varepsilon_{b(c)}$; ($0 \leq \lambda \leq 180$)
ψ	Fatigue bending error ($= \Delta\varepsilon_b/\Delta\varepsilon_o$)
ω	Angle (clockwise) between the R-direction and the location of the strain gauge with the greatest reading

4 Significance of measurement

Among all the mechanical tests that involve applying tensile or compressive loading, fatigue seems to present the worst conditions to be affected by inadvertent bending caused by misalignment between the applied load and specimen axes (see Appendix 1). Although this has been well recognised, there have been few published accounts of efforts to measure it thoroughly and in a systematic manner.

Current measurements of bending are invariably made in the elastic range, and may use one, two or three sets of strain gauges placed at arbitrarily defined locations on a specimen that is subjected to an unspecified single force. The interpretation of information obtained using these practices can be vague. Moreover, because bending parameters are load dependent, it is inappropriate to compare the results obtained from different procedures directly. These inconsistencies in current procedures render many bending measurements reported in the literature as, at best, useless and, at worst, misleading.

Recent studies^{1,2} have highlighted that bending parameters are also dependent on the ratio between the stiffness of the specimen and the stiffness of the other load train components. In low cycle fatigue testing, the stiffness of the specimen changes continuously during every cycle (as deformation evolves or alternates between pure elastic and plastic states) and throughout the test as the material hardens or softens and as cracks develop. A further complication may arise in testing at high temperatures due to possible distortions of the machine's loading bars as well as that of the specimen. Such distortions could result from non-uniform (side-to-side) temperature distributions.

The key objective of this guide is to provide a detailed reference to be used in recommended procedures for measuring and reporting bending parameters under well-specified conditions that are as close as practically possible to those encountered in the fatigue test. A further

objective is to advance the use of new as well as common terminology. Use has been made whenever possible of terminology already recommended by ASTM E1012-93a³.

5 Apparatus

5.1 Testing machine

The machine should have great lateral rigidity and accurate alignment between the test space support references. The load train should be as short and as stiff as possible. Errors in parallelism < 0.2 mm/m and in concentricity (lateral offset) of 0.03 mm may allow the alignment requirement specified in section 6.6 to be met for a test span (see Figure 1) not greater than 500 mm. These values may be obtained by iterative adjustment to the axial and angular positions of the load train components or by appropriate alignment systems.

The gripping device shall be designed so that during the gripping operation no torsion stresses are introduced into the specimen and that the assembly of the specimen to the gripping device is reproducible. It is therefore necessary to limit the number of components of which these gripping devices are composed in order to reduce the number of mechanical interfaces to a minimum.

The testing machine shall comply with Class 1 of BS EN 10002-2: 1992⁴ for tension and Grade I of BS 1610: Part 1: 1992⁵ for compression.

Note: for the purposes of this guide, determination of relative reversibility error in BS EN 10002-2 1992 is not necessary.

5.2 Alignment cell

5.2.1 Material

A suitable material for an alignment cell shall have:

- (1) a sufficiently high elastic working range;
- (2) an elastic modulus representative of those materials typically used in the fatigue tests;
- (3) a high degree of metallurgical stability coupled with freedom from appreciable internal stress in order to ensure dimensional stability.

Composite materials are not suitable for this purpose and therefore an alternative monolithic material (orthotropic, homogenous, continuous) with the same longitudinal elastic modulus to the test material shall be used.

5.2.2 Alignment cell design

Since the alignment cell dimensions affect the measured bending strains, it shall have the same geometry and dimensions as the fatigue specimen normally used and shall fit into the machine grips in the same way as the specimen, so that use of special adaptors is avoided.

Figures 2 to 5 show the requirements for concentricity, cylindricity, parallelism and perpendicularity for the four basic alignment cell configurations. The table below shows the recommended proportions which are generally consistent with those recommended for fatigue specimens in References 6 to 9.

Note: the requirements for dimensional tolerances in Figures 2 to 5 may be tighter than would normally be required for fatigue specimens.

Cells possessing other dimensions may be used successfully within the scope of this guide; however, significant variations in dimensions might preclude direct comparison with measurements from the recommended cells. See Appendix 2 for recommendations for design of specimen and cell end grips.

Dimension	Requirement	Ref	Comments
b	$\geq t$ and ≥ 5 mm	6,7	
d	≥ 5 mm	6,7,9	A maximum diameter of 10 mm is recommended ⁶
D			A minimum dimension of 2.5d to 3.5d, depending on the material, is recommended ^{6,7}
l_p	2d to 4d	6-8	For fully reversed (tension-compression) fatigue, $2d \leq l_p \leq 3d$ is recommended
	2t to 4t	6,7	
r	$> 2d$	6,7	$2d < r \leq 4d$ is adequate for most materials ⁶
	4t to 8t	6	
$\hat{r}$	6d to 8d	7,8	
t	≥ 3 mm	6,7	
w			A dimension of 3t to 5t but not less than 1.5b is recommended

5.2.3 Machining

Small and decreasing cuts with an adequate supply of coolant shall be used for finishing so that the metallurgical structure and properties are not affected and that undue residual stresses are not induced in the cell material. Care must be exercised in the machining of alignment cells with waisted uniform parallel sections to avoid undercutting at the ends of the parallel portion.

Note: for effective bonding of strain gauges, the optimum surface finish for the alignment cell should be in the range 0.8 to 1.6 micrometers. For the test cell, fatigue testing requirements dictate that surface finish should be within 0.2 to 0.4 micrometers.

5.2.4 Inspection before attaching strain gauges

The alignment cell shall be carefully inspected with an optical comparator or a shadowgraph before strain gauges are attached to ensure that dimensional and concentricity requirements are met. After the strain gauges are applied, it will no longer be possible to inspect the cell with this method, so care must be exercised in handling and using it.

5.3 Strain gauges

5.3.1 Selection

Strain gauges having active lengths between 0.76 and 2.54 mm and active (grid) widths between 0.51 and 2.03 mm are commercially available and are suitable for the purposes of this guide. It is recommended that the selected strain gauge has an active length of approximately $0.1 l_p$ but not greater than this value. It is recommended also that the gauge width should be as narrow as possible in order to minimise strain averaging. All strain gauges used shall be from the same batch.

5.3.2 Temperature compensation

The bending parameters in this guide are determined from the ratios of the measured strains and they should not, therefore, be affected by temperature changes. Temperature-compensated gauges matched to the alignment cell (or the test cell) material are however preferred, especially if accurate determination of the absolute axial average strain, such as in modulus measurement, is also needed.

5.3.3 Bonding configurations for cylindrical and flat cells

Figure 6 shows the recommended strain gauge configurations, numbering systems and bonding locations for alignment cells (and test cells). For cylindrical and flat type cells, an array of eight strain gauges shall be used. The gauges shall be arranged in two sets of four

with each set mounted on one of two strain measurement planes. In Figure 6 (a,b and c) the strain gauges are equally spaced (90° apart) around the circumference of the cell. In Figure 6(d) the gauges are placed in pairs of back-to-back sensors which are equidistant from the longitudinal centre line of the cell. The configuration shown in Figure 6(c) is suitable for flat cells with a width-to-thickness ratio $b/t = 1$ to 3. For higher (b/t) values the configuration in Figure 6(d) is recommended.

With reference to Figure 6, the following dimensions are recommended.

Dimension	Requirement
l_g	$= 0.75 l_p$
s	$= 0.8 b$

Note 1: for the purposes of this guide, for the non-waisted flat cell with rectangular cross-section geometry shown in Figure 5 the distance l_p is defined in Figure 7.

Note 2: the distance $l_g = 0.75 l_p$ is consistent with the recommendations in ASTM C1273-94 and ASTM C1275-94 standards. It also represents the maximum feasible separation that should avoid interaction of strain gauges with stress concentration effects associated with the change of section at the specimen shoulders. See also note in section 6.5.3.

Note 3: some procedures, including ASTM I012³, recommended the use of a three-gauge configuration as well as the four-gauge configuration with circular alignment cells. The three-gauge configuration, however, is prone to errors that can be difficult to detect if one or more of the gauges are damaged during installation or by repeated use¹⁰. This disadvantage can be largely overcome by using four gauges. The recommendations in this guide are made for this reason.

In all cases, the strain gauges should be symmetrically located about the middle of the parallel length of the cell.

5.3.4 Bonding configuration for hour-glass cells

It should be noted that hour-glass type geometry is not generally recommended for a fatigue specimen if the option of using a cylindrical geometry exists⁷. With hour-glass alignment cells (or test cells) only one set of four strain gauges shall be used and be located at the minimum section as shown in Figure 6(b).

5.3.5 Alignment of strain gauges

It is essential to ensure that the gauges are bonded (using manufacturer's recommended procedures) at the specified locations to within ± 0.10 mm and their measurement axes¹¹ are aligned to within $\pm 2^\circ$ of the longitudinal axis of the alignment cell or the test cell. After installation of the gauges, their alignment shall be checked and confirmed using a suitable instrument such as an angular optical projector or a circular graticule in a low-power microscope before applying any protective coating.

5.3.6 Adhesion

For alignment cell applications, an adhesive such as a heat cured epoxy phenolic type shall be used to ensure long term stability. With test cells (intended for short term use), cyanoacrylate adhesive may be used.

Note: care should be taken to avoid the use of curing temperatures that could alter the characteristics of the cell material.

5.3.7 Coating

It is essential to protect strain gauges and adhesives from effects due to moisture and other degrading contaminants. It is recommended, therefore, that after installation of the gauges a layer of a protective coating material such as strain-gauge-grade silicone rubber is applied.

5.3.8 Lead wires

A temperature-compensating three or four lead wire system shall be used in $\frac{1}{4}$ bridge configuration.

5.3.9 Strain measuring equipment

All strain measuring equipment and data acquisition systems shall be calibrated as appropriate and typically have an accuracy to within $\pm 0.5\%$ of indicated reading or ± 3 microstrain, whichever is greater, and a resolution of 1 microstrain.

5.4 Test cell

The test cell shall be constructed from a specimen picked at random from the batch to be used in the test programme. Recommended strain gauge configurations and specifications are the same as those for alignment cells, see section 5.3 and Figure 6.

6 Procedure A: Verification of machine alignment

6.1 Purpose of verification

The purpose of this verification Procedure is to demonstrate that the grip interface and load train couplings are in an alignment condition such that the test system consistently meets the limit on percent bending as specified in section 6.6. It is recommended that this Procedure be incorporated within the overall maintenance strategy of the test system.

6.2 Frequency of measurement

This Procedure shall be carried out when one or more of the following conditions apply:

- the load train is replaced or damage to it is suspected;
- the machine's cross-head is moved, unless it has already been demonstrated that such movements do not affect alignment; and
- a 12 month (or 100 tests) period has elapsed since last verification. It may be advisable to perform this Procedure immediately after load cell calibration.

6.3 Measuring device

This Procedure requires that an alignment cell be used. For comparative purposes, it is recommended that the same cell, if possible, is used for successive verifications.

6.4 Procedure

1. Connect the lead wires of the strain gauges to the conditioning equipment and allow the system to equilibrate under power for at least 30 minutes prior to making any measurements.
2. Define the R-direction that is most suitable for the test set up. This will determine where gauge 1 will initially be located, see Figures 8 and 9.
3. Mount one end of the alignment cell in the grip interface. Then zero the strain gauges.
4. Mount the other end of the cell in the grip interface, then record the strain gauge readings. If maximum bending strain due to gripping (see section 6.5) is greater than about 100 microstrain, it is recommended that the cell is removed from the machine, the load train is re-aligned as necessary, and this Procedure is repeated from above.

5. With the load limits set to produce an elastic axial strain amplitude within the range (750 to 1500) microstrain ($\epsilon_o = 0.075\%$ to 0.15%), apply at least five fatigue cycles either in the fully reversed mode or in tension-tension mode, depending on the type of test usually performed on the machine. This may alleviate any mechanical instability in the load train.

6. Apply steady tensile forces to achieve three successive levels of mean strain, ϵ_o , of approximately 500, 1000, and 2000 microstrain. At each step, record the load and the strain gauge readings.

Note 1: to avoid damage to the alignment cell, the highest strain gauge reading must not exceed approximately 0.7 the material's proportional elastic strain limit.

Note 2: if, as a result of Note 1 above, $\epsilon_o = 2000$ microstrain cannot be applied, then only 500 and 1000 shall be used.

Note 3: during the measurement and recording of all strains, the applied force shall not change by more than $\pm 0.5\%$ of its nominal value.

7. If the machine is used for performing reversed fatigue tests, apply equivalent forces to those used in 6 in compression and record the corresponding strain gauge readings.

8. If the alignment cell can be rotated without affecting in any way the alignment condition of the load train couplings, repeat 3 to 7 above after rotating the cell 180° about its longitudinal axis.

9. If the alignment cell cannot be rotated, disassemble it completely from the machine grips, then repeat 3 to 7 above.

10. Calculate the values of $\beta_{\max}$ and θ corresponding to the ϵ_o values used in and (if applicable) as described in 5. Then validate the machine alignment according to the recommendations in section 6.6.

Note: it is not unusual for θ to change by a few degrees as ϵ_o increases. Sudden or erratic changes, however, may indicate mechanical instability in the loading system.

11. If the alignment criteria in section 6.6 are not satisfied, re-align the machine's load train as necessary and then repeat the whole of this Procedure.

6.5 Determination of maximum percent bending

6.5.1 Cases in Figure 6(a,b,c)

6.5.1.1 Referring to Figure 6(a,b,c) for the strain gauge numbers, calculate percent bending on the plane where gauges G1, G2, G3 and G4 are located [the upper plane in Figure 6(a) and (c) and hereafter referred to as such] as follows:

$$\beta = \frac{\epsilon_b}{\epsilon_o} \times 100 \quad (1)$$

where

$$\epsilon_b = 1/2 \sqrt{(\epsilon_1 - \epsilon_3)^2 + (\epsilon_2 - \epsilon_4)^2} \quad (2)$$

and

$$\epsilon_o = (\epsilon_1 + \epsilon_2 + \epsilon_3 + \epsilon_4)/4 \quad (3)$$

Note that the strain gauge readings are in units of strain and compressive strains are negative.

6.5.1.2 Similarly, for Figure 6(a) and (c) only, percent bending on the lower plane (where gauges G5, G6, G7 and G8 are located) is calculated according to equation (1) where ϵ_b and ϵ_o are now given by:

$$\epsilon_b = 1/2 \sqrt{(\epsilon_5 - \epsilon_7)^2 + (\epsilon_6 - \epsilon_8)^2} \quad (4)$$

and

$$\epsilon_o = (\epsilon_5 + \epsilon_6 + \epsilon_7 + \epsilon_8)/4 \quad (5)$$

6.5.1.3 For any set of four strain gauges as shown in Figure 9, the position of maximum bending strain, θ , is determined as follows:

$$\theta = \omega + \phi \quad (6)$$

where ω is the angle in the cross-section (in clockwise rotation) from the R direction to the strain gauge with the greatest reading and ϕ is the angle in the cross-section between the point of maximum bending strain and the strain gauge with the greatest reading and is given by¹⁰:

$$\phi = \arctan \left[\frac{\epsilon_n - \epsilon_o}{\epsilon_m - \epsilon_o} \right] \quad (7)$$

where m and n respectively refer to the gauges with the largest strain and the next largest strain in the set of four. The angle ϕ , which should be in the range 0 to 90°, is measured from m towards n. A counter clockwise rotation from m to n means a negative value of ϕ must be entered in equation (6).

Alternatively, the angle ϕ may be given by:

$$\phi = \arccos \left[\frac{\epsilon_m - \epsilon_o}{2\epsilon_b} \right] \quad (8)$$

Note: in practical measurement, there may be small differences in the results obtained from equations (7) and (8). Such differences are deemed not critical and either value can be used with confidence.

6.5.2 Case in Figure 6(d)

6.5.2.1 In this case, an equivalent system to Figure 6(c) is established where the equivalent strains at the centre of the four faces at the upper plane are given by³

$$\epsilon_{1e} = (\epsilon_1 + \epsilon_2)/2 \quad (9)$$

$$\epsilon_{3e} = (\epsilon_3 + \epsilon_4)/2 \quad (10)$$

$$\epsilon_{2e} = \epsilon_o - [\epsilon_o - (\epsilon_1 + \epsilon_3)/2] (b/s) \quad (11)$$

and

$$\epsilon_{4e} = \epsilon_o - [\epsilon_o - (\epsilon_2 + \epsilon_4)/2] (b/s) \quad (12)$$

where ϵ_o is the axial strain, given by

$$\epsilon_o = (\epsilon_1 + \epsilon_2 + \epsilon_3 + \epsilon_4)/4 \quad (13)$$

b is the width of the broad face of the alignment cell and s is the strain-gauge transverse separation.

Equations for determining percent bending, β , and direction of the maximum bending strain, θ , are the same as in 6.5.1.1. and 6.5.1.3, respectively, but ϵ_1 , ϵ_2 , ϵ_3 and ϵ_4 are substituted by ϵ_{1e} , ϵ_{2e} , ϵ_{3e} and ϵ_{4e} .

6.5.2.2 Similarly, the equivalent strains at the centre of the four faces at the lower plane, are given by:

$$\epsilon_{5e} = (\epsilon_5 + \epsilon_6)/2 \quad (14)$$

$$\epsilon_{7e} = (\epsilon_7 + \epsilon_8)/2 \quad (15)$$

$$\epsilon_{6e} = \epsilon_o - [\epsilon_o - (\epsilon_5 + \epsilon_7)/2] (b/s) \quad (16)$$

and

$$\epsilon_{8e} = \epsilon_o - [\epsilon_o - (\epsilon_6 + \epsilon_8)/2] (b/s) \quad (17)$$

Equations for determining maximum bending strain, ϵ_b , and direction of maximum bending strain, θ , are the same as in 6.5.1.2 and 6.5.1.3, respectively, but ϵ_5 , ϵ_6 , ϵ_7 and ϵ_8 are substituted by ϵ_{5e} , ϵ_{6e} , ϵ_{7e} and ϵ_{8e} .

6.5.3 Maximum percent bending

$\beta_{\max}$ is the higher value of β as determined on the upper and lower strain measurement planes.

Note: the above maximum percent bending is the highest value within the strain-gauge axial separation, l_g , of the alignment cell which corresponds to the test section of a typical fatigue specimen. The absolute maximum bending strain on the alignment cell surface may however take place outside the distance l_g , see Appendix 3 for more discussion.

6.6 Recommendations for levels of machine alignment

For low cycle fatigue testing machines for metallic materials, it is recommended that:

1. $\beta_{\max}$ does not increase as ϵ_o (numerically) increases; and
2. the average of the two values of the maximum per cent bending, $\beta_{\max}$ obtained at the $\theta = 0^\circ$ position [see 6.4 (6 and 9)] and the $\theta = 180^\circ$ position [see 6.4(8)] at $\epsilon_o = 1000$ microstrain and (if applicable) at $\epsilon_o = -1000$ microstrain shall not exceed 5%.

7 Procedure B: Bending error determination in a specific fatigue test programme

7.1 Purpose of measurement

The purpose of this Procedure is to quantify the fatigue bending error parameter ψ so that uncertainties in fatigue lifetime results can be assessed^{1,2}. This procedure involves loading conditions similar to those to be encountered in a specific test programme and, therefore, it should involve no more care in setting up than for routine testing. Unlike Procedure A, this Procedure may involve subjecting the test cell to plastic deformation as well as elastic deformation.

This Procedure shall be performed according to customer needs and is recommended to be carried out immediately prior to the commencement of the test programme. No adjustments that could affect alignment should be made during the period between performing this Procedure and the completion of the test programme. If, for whatever reason, misalignment of the load train is suspected and adjustment is carried out, this Procedure should be repeated.

7.2 Measuring device

The bending measuring device for this Procedure is a test cell (see 5.4). It should be noted that after performing this Procedure, because of plastic deformation the test cell may no longer be useful as a bending measuring device and, therefore, should be discarded.

Note: some materials such as near- α titanium alloys show room temperature creep, particularly at stresses above yield. Care must be taken to ensure that the strain gauge reading system is sufficiently fast to take all gauge readings while the load is constant within the specified tolerance of $\pm 0.5\%$. Otherwise, significant errors in strain measurement may be introduced.

7.3 Procedure

1. Follow the same steps in 6.4 (1 to 5) for Procedure A.

Note: for added benefit, the whole of Procedure A may be performed if the test cell also fulfils the requirements of an alignment cell (see 5.2.1 to 5.2.3).

2. With the machine in position control mode, drive the system manually to the estimated maximum load in the fatigue cycle with the smallest total strain range in the fatigue programme. This is shown as point 1 in Figure 10 for a typical reversed LCF stress-strain diagram with increasing hysteresis. Record the strain gauge readings.

Note: load control mode may be used, but should be avoided in the case of cyclically-softening materials.

3. Reverse the drive system to the estimated minimum load in the fatigue cycle with the smallest total strain range in the fatigue programme. This is shown as point 2 in Figure 10. Record the strain gauge readings.

4. Repeat 2 and 3 above after increasing the load incrementally to a higher level. Then record the corresponding readings.

5. Repeat 4 above until reaching the estimated maximum and minimum loads in the fatigue cycle with the largest total strain range in the fatigue programme. These are represented by points 9 and 10 respectively in Figure 10. In total, five load levels at least should be used.

7.4 Determination of fatigue bending error parameter

Fatigue bending error, ψ , is a measure of reversibility of bending during the fatigue cycle^{1,2} (see Appendix 1) and is determined as follows:

For each fatigue cycle in section 7.3 calculate

$$\psi = \Delta\epsilon_b / \Delta\epsilon_o \quad (18)$$

where $\Delta\epsilon_b$ is the bending strain range given by

$$\Delta\epsilon_b = \epsilon_{b(t)} - \epsilon_{b(c)} \cos \lambda \quad (19)$$

Equation (19) is illustrated graphically in Figure 11.

Note 1: it should be noted that the level of $\epsilon_{b(t)}$ alone determines which strain measurement plane is to be considered for this analysis. It should also be noted that $\epsilon_{b(c)}$ is measured on the same plane as $\epsilon_{b(t)}$. This value of $\epsilon_{b(c)}$ may not be the highest value measured by the test cell at the minimum load.

Note 2: it also follows that the value of θ to be reported is that associated with $\epsilon_{b(t)}$.

Note 3: according to the theoretical analysis in References 1 and 2, it is the level of ψ (and not β_{max}) that determines the extent of bending effects on fatigue lifetime data (at least for materials that are not very sensitive to relatively low levels of mean stresses or mean strains).

Note 4: at the time of writing this guide, however, there is no systematic experimental evidence that justifies recommending a limit for the fatigue bending error parameter.

8 Expression of results

8.1 Basic information for Procedure A

The record of each verification shall include the following:

- 1) reference to this guide;
- 2) type and identification number of test machine;
- 3) material, dimensions and identification number of the alignment cell used in the verification;
- 4) locations of strain gauges;
- 5) name of manufacturer, manufacturer's designation of the strain gauge, batch number, strain gauge resistance, strain gauge factor¹¹ and adhesive used;
- 6) type and identification number of strain measuring equipment, maximum error of the equipment, and the date of its calibration;
- 7) ambient temperature during verification;
- 8) R-direction;
- 9) all readings taken during verification;
- 10) values of $\beta_{\max}$ at $\epsilon_o = 1000 \mu\epsilon$ and (if applicable) at $\epsilon_o = -1000 \mu\epsilon$;
- 11) tabulated values of ϵ_b , θ , the plane (upper or lower) in which $\beta_{\max}$ was determined and a graph showing variation of θ with ϵ_o ; and
- 12) name of operator and date of verification.

8.2 Basic information for Procedure B

The record of each measurement shall include, as appropriate, the same information in section 8.1 (except for item 3 for alignment cell read test cell) in addition to the following:

- 1) Values and a graph of ψ against $\Delta\epsilon_o$;
- 2) Values of θ associated with $\epsilon_{b(t)}$; and
- 3) The plane (upper or lower) in which ψ was determined.

8.3 Special information

Any deviations from the Procedures given in this guide shall be stated and described.

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11. BS 6888: 1988, "Methods for Calibration of Bonded Electrical Resistance Strain Gauges", British Standards Institution.

Other related standards and codes of practice

ASTM C1273-94, Standard Test Method for "Tensile strength of monolithic advanced ceramics at ambient temperatures", 'Appendix X1. Verification of load train alignment', American Society for Testing and Materials.

ASTM C1275-94, Standard Test Method for "Monotonic tensile strength testing of continuous fibre-reinforced advanced ceramics with solid rectangular cross-section specimens at ambient temperatures", 'Appendix X1. Verification of load train alignment', American Society for Testing and Materials.

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Bressers, J (ed), "A code of practice for the measurement of misalignment induced bending in uniaxially loaded tension-compression test pieces", Working Party on Alignment of the High Temperature Mechanical Testing Committee, EC Inst. Advanced Materials, Petten, The Netherlands, January 1995.

M J Sanders, "FRAG requirements for the alignment of fatigue test machines", Report No. BAe/WME/RP/GEN/004359, British Aerospace Defence Ltd, Military Aircraft Division, Warton, Preston, April 1995.

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Appendix 1 Sources of misalignment

A1.1 Bending mechanisms encountered in fatigue testing are likely to be combinations of simpler ones^{1-3,10}. Figure 12(a) shows an **angular offset** of the specimen grips; the grips are only allowed to move vertically and no lateral displacement exists between their centre lines. The specimen will be bent during the gripping operation and, because it is under a pure bending moment, it will deform into a circular arc called a C-shaped-bend (or simply C-bend). During a tension-compression fatigue cycle, the maximum bending strain remains effectively constant^{1,2}.

A1.2 Figure 12(b) shows a **lateral offset** where the centre lines of the ideally rigid grips are axially offset with respect to each other by an amount e . Unlike the angular offset, in this case bending will vary along the specimen with a resulting deformation into an S-shaped-bend (or S-bend). Note that the cross-section at the middle of the specimen will have no bending. It should be noted that, since the average strain measured by an extensometer is equal to the strain at the centre of its gauge length¹⁰, the extensometer will therefore read zero bending strain for a lateral offset when the eccentricities at each end of the gauge length are equal and opposite.

A1.3 **Load-train offset** Lateral offsets (in a non-rigid system) of the centre lines of the grips with respect to either the machine's cross-head or the ram can cause 'reversed bending'^{1,2} of the specimen as a result of the deformation of the machine components. So that, as the applied load changes mode from, for example, tension to compression, bending strains at given locations on the specimen change sign and therefore contribute to cyclic straining; figure 13 illustrates this point schematically.

Load-train offset is believed to be more damaging to fatigue testing than angular or lateral offsets. See References 1 and 2 for more discussion.

Appendix 2 Recommendations for design of cylindrical specimen and alignment cell grip ends

The reader should refer to BS 7270⁶ and ASTM E606⁸ for more detailed recommendations for the dimensions and specifications of specimen grip ends.

A2.1 Straight sided cylindrical end specimens and alignment cells

This design relies on frictional forces between the grip jaws and the ends of the specimen to apply the cyclic loads. Sufficient clamping force is often achieved by using a tapered or conical seating for the jaws⁸ (similar to that shown in Figure 7) so that they tighten onto the specimen when a tensile load is applied. The load alignment is therefore dependent on the coincidence of the axes of the specimen and the machine's gripping-fixture components.

A2.2 Threaded end specimens and alignment cells

In general, designs in which specimen alignment depends entirely on screw threads are not recommended. Reference 6 contains one design which involves a specimen with flat end face. The specimen is aligned at each end by a collar and a locking nut (see Figure 7 in Reference 6). The coincidence between the specimen axis and the grip axis can be further improved by terminating the threaded end of the specimen in a cone (as shown in Figure 14) which is seated in a matching conical surface in the grip body.

A2.3 Button end specimens and alignment cells

In this type, either the major or the minor diameter of the button head (see References 6 and 8, respectively) provides the alignment surface. The gripping feature may involve the use of a locking nut which clamps the load bearing faces together⁶, or a split collar⁸.

Appendix 3 Variation of bending strain on the alignment or test cell surface

In order to correlate bending strain measurements obtained according to this guide with measurements that might have been obtained using differing strain-gauge axial separation, it is useful to show how bending strains at other locations may be determined.

A3.1 In general bending strain varies from point to point around and along the parallel length of the specimen or the alignment cell. Except for the simple case of bending due to angular offset where the bending strain field is the same in all cross-sections, maximum bending strain almost always occurs at or near either end of the specimen's parallel length. Therefore, the strain measurement planes should be as far apart as feasible (see section 5.3.3) but not close to the high stress-concentration zone which is of the order of one mm at either end of the parallel length of a typical LCF specimen such as shown in Figure 14.

A3.2 The magnitude and direction of the maximum bending strain vector on cross-sections in the parallel length other than the two considered in this guide may be determined as described in References 1 and 10. As a cautionary remark, the reader is reminded that the main assumptions here are that:

- (1) curvature (either inherent from bad machining or due to bending) of the alignment or test cell axis is neglected, and
- (2) bending strain varies linearly along the alignment or test cell surface.

This method is, therefore, not suitable when curvature is significant or indeed if plastic deformation occurs in the test cell.

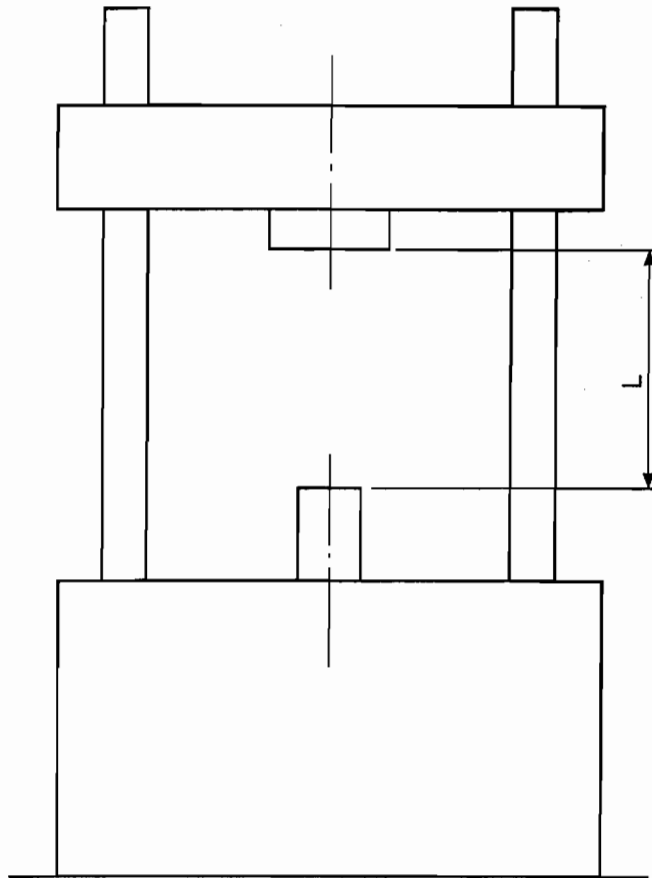
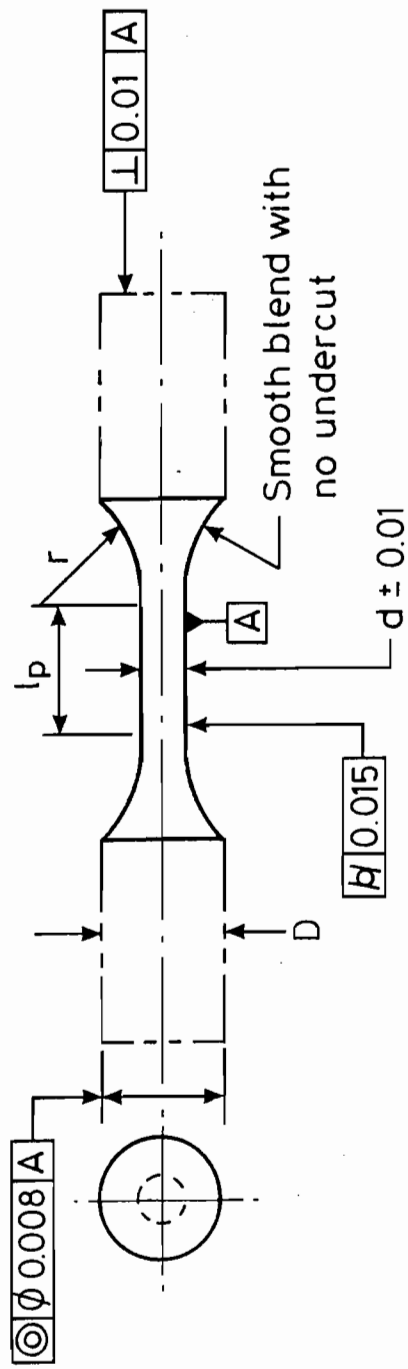
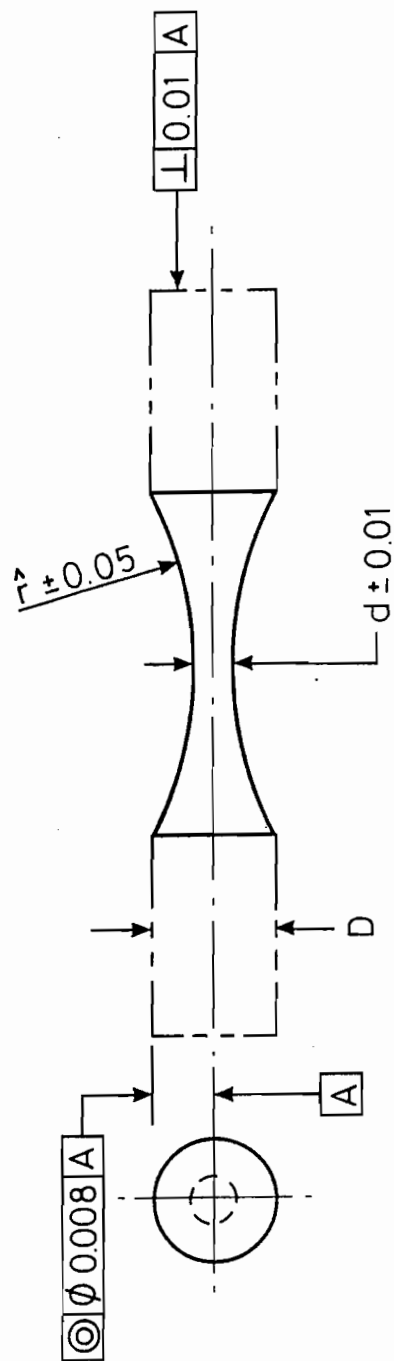


Figure 1. Schematic diagram showing definition of the test span (L).



- Note 1: All dimensions are in millimetres
- Note 2: For definitions of symbols for geometrical tolerances see BS 308 : Part 3 : 1990
- Note 3: The perpendicularity requirement of the gripped ends applies to any surfaces used for alignment.

Figure 2. Measurement-section profile for cylindrical alignment cells
(based on figure 3 in Reference 6).



- Note 1: All dimensions are in millimetres
- Note 2: For definitions of symbols for geometrical tolerances see BS 308 : Part 3 : 1990
- Note 3: The perpendicularity requirement of the gripped ends applies to any surfaces used for alignment.

Figure 3. Measurement-section profile for hour-glass alignment cells.

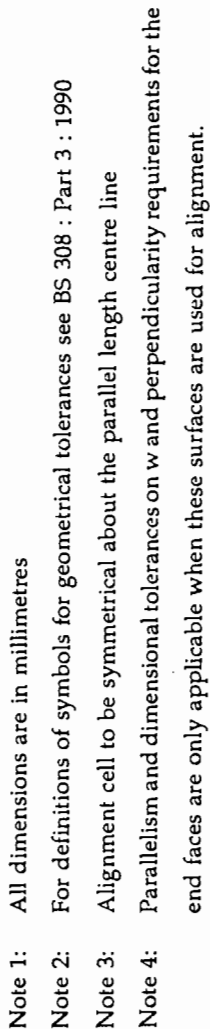
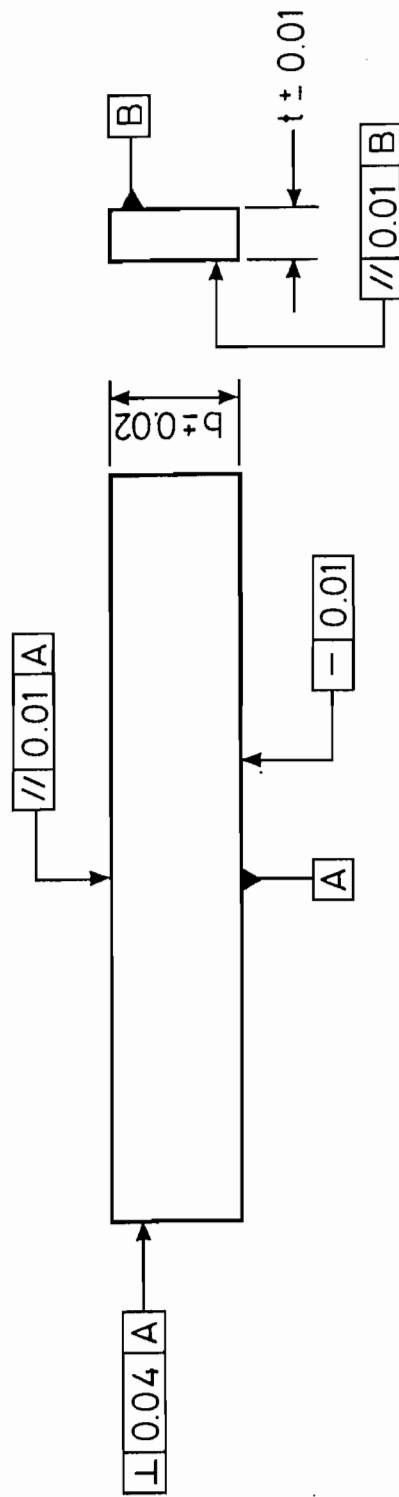


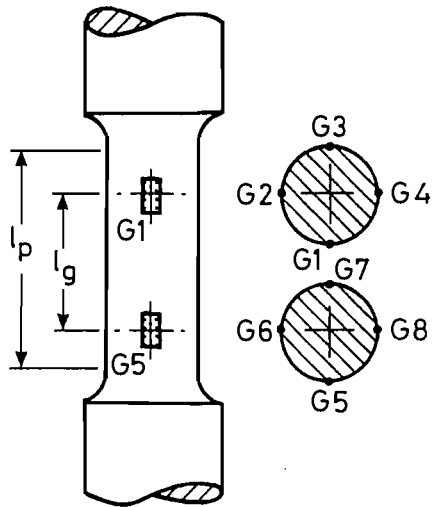
Figure 4. Measurement section profile for flat alignment cells (based on figure 5 in Reference 6).



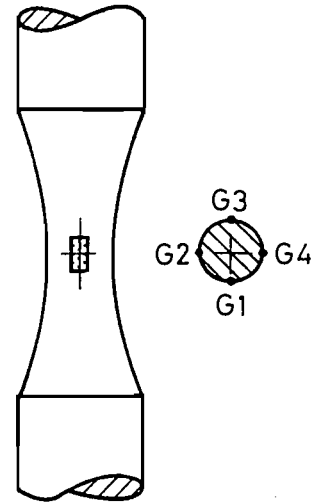
Note 1: All dimensions are in millimetres.

Note 2: For definitions of symbols for geometrical tolerances see BS 308 : Part 3 : 1990

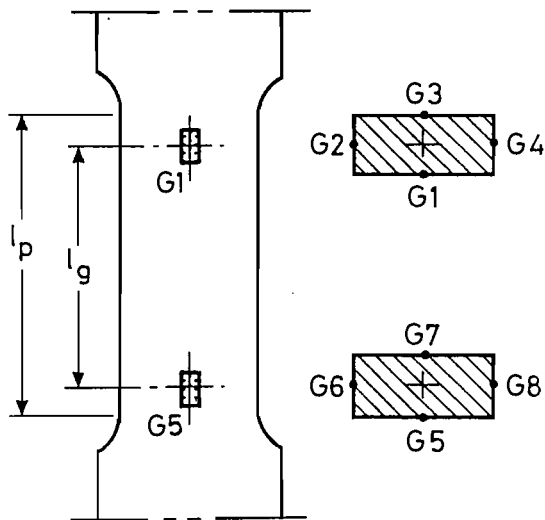
Figure 5. Profile for non-waisted flat alignment cells.



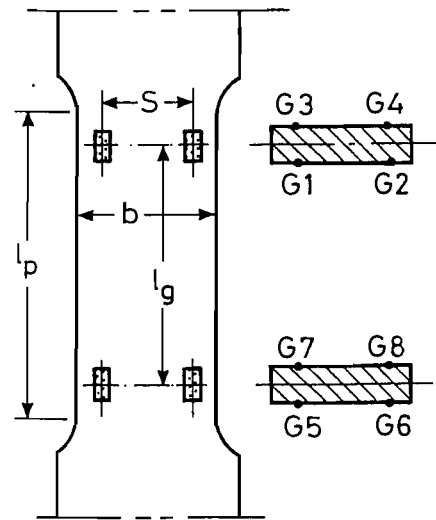
(a)



(b)



(c)



(d)

Figure 6. Strain gauge configurations for alignment cell and test cell geometries: (a) cylindrical; (b) hour-glass; (c and d) flat.

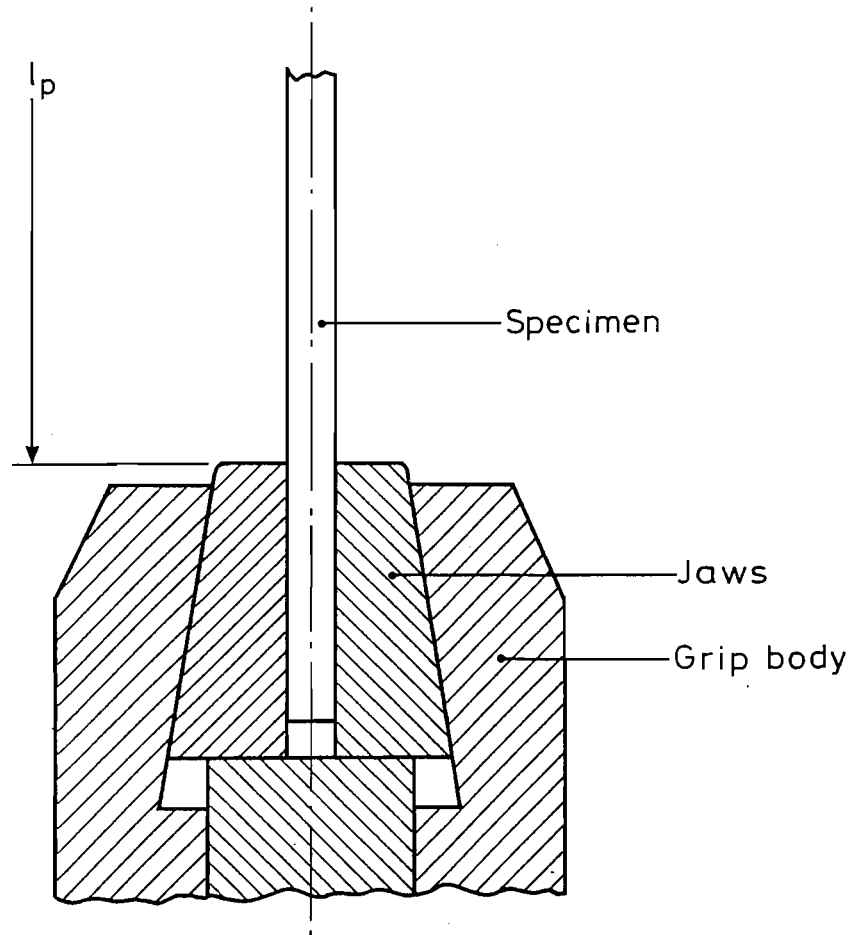


Figure 7. Schematic diagram showing the (active) parallel length of non-waisted flat alignment cells and test cells.

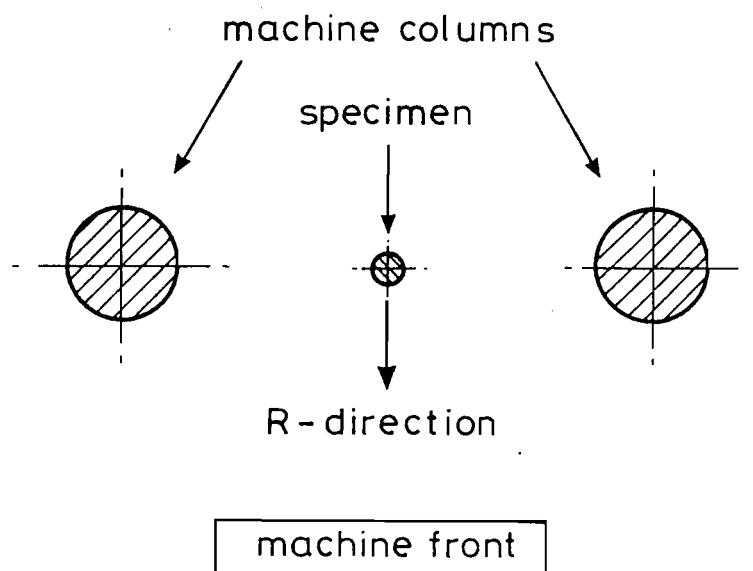


Figure 8. Schematic diagram of an example of the R-direction for a typical 2-column test system (top view).

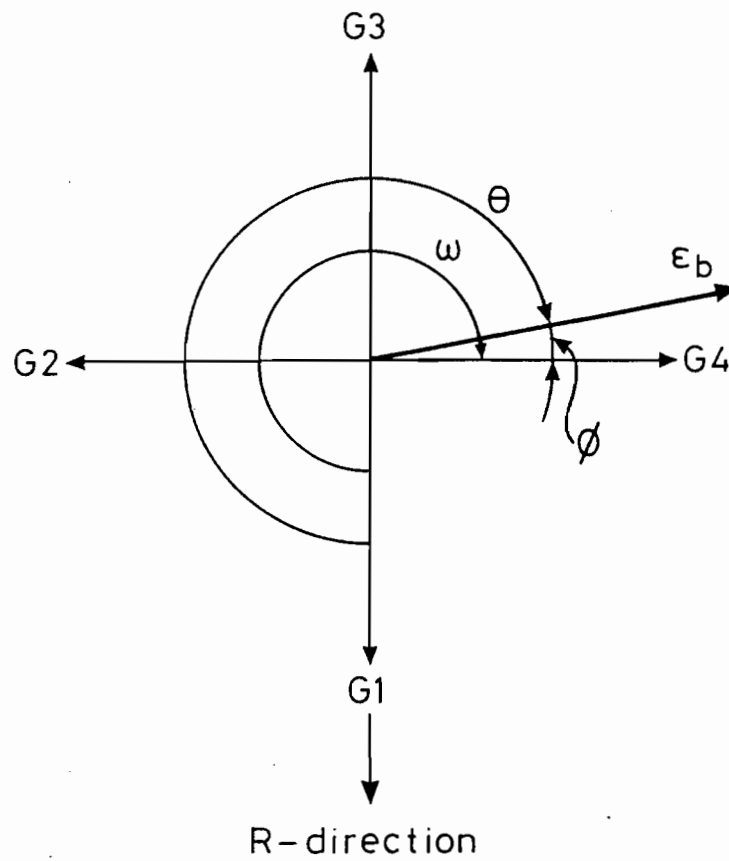


Figure 9. Example of graphical representation of the maximum bending strain vector on the upper strain measurement plane in which G4 is the gauge with the greatest reading (top view).

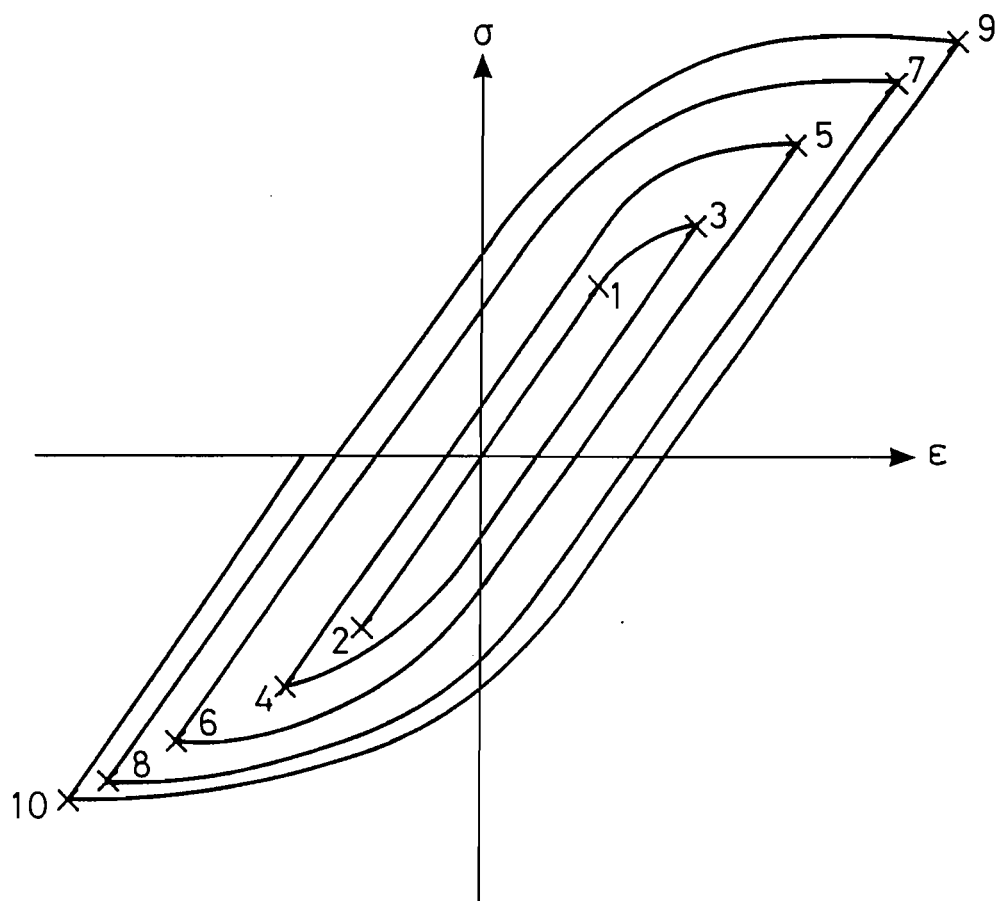


Figure 10. Schematic sequence of hysteresis loading for bending measurements according to Procedure B (section 7).

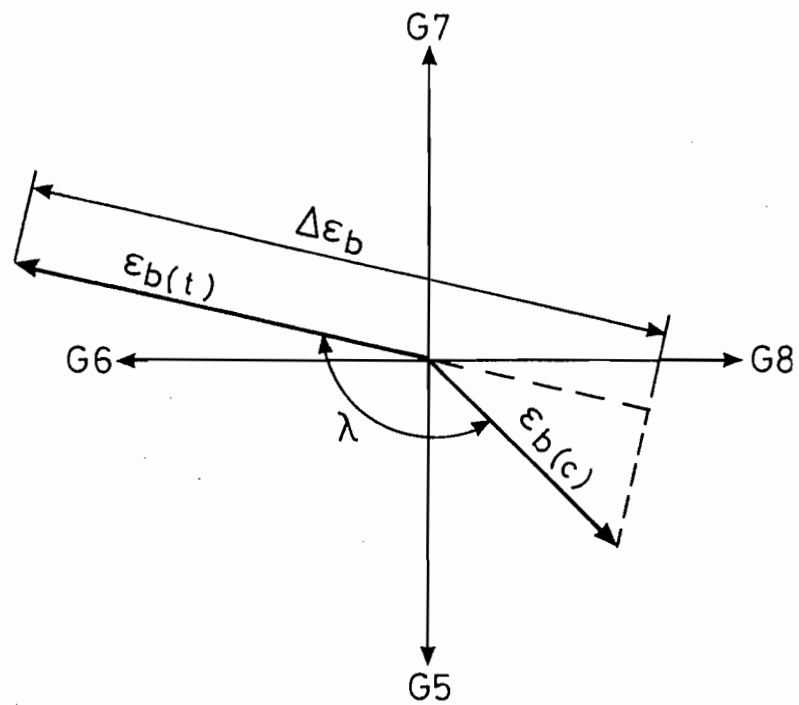


Figure 11. An example of a vector diagram in which the bending strain range, $\Delta\epsilon_b$, is determined graphically.

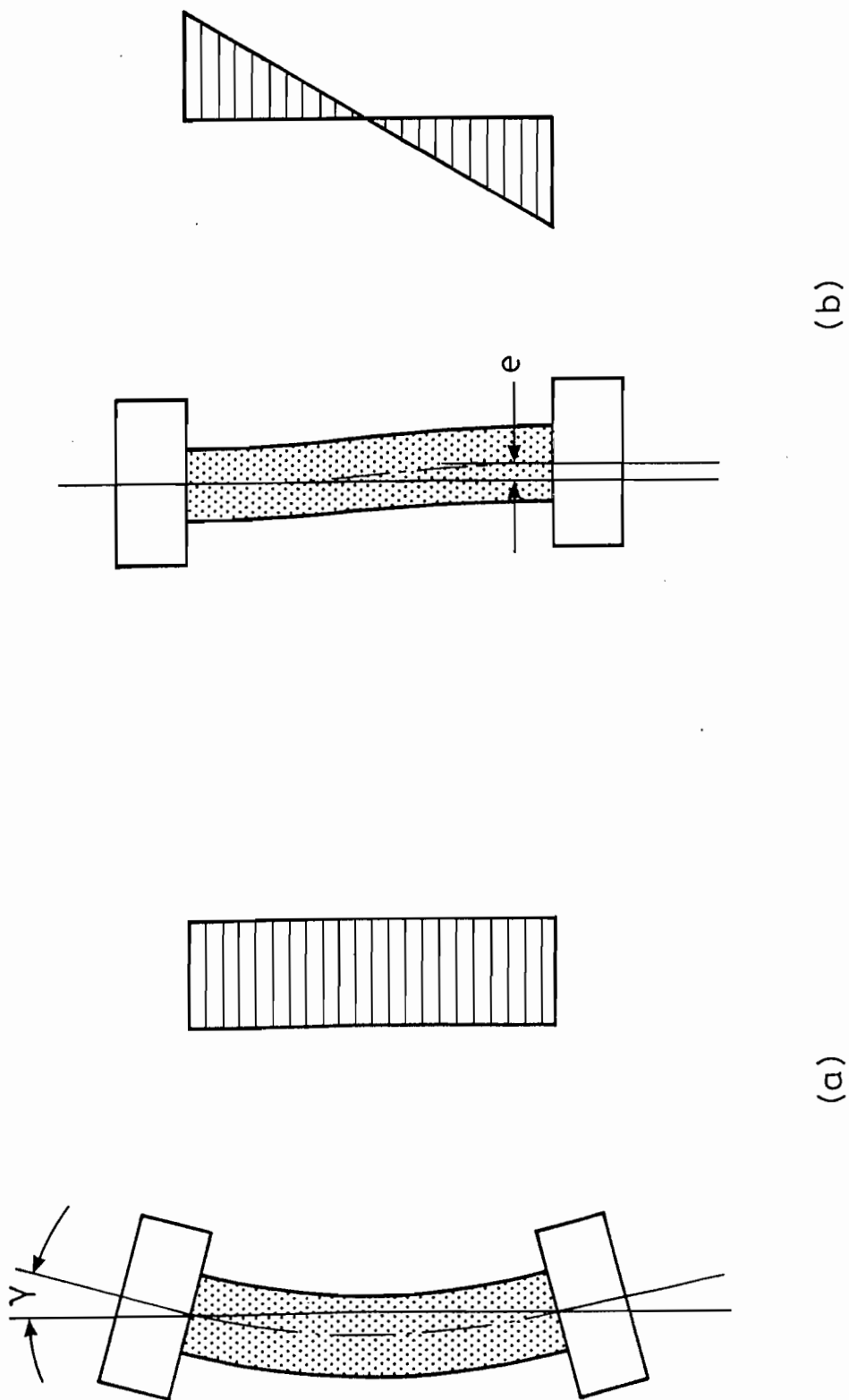


Figure 12. Basic bending mechanisms with associated bending moment distributions: (a) C-bend due to an angular offset; (b) S-bend due to a lateral offset.

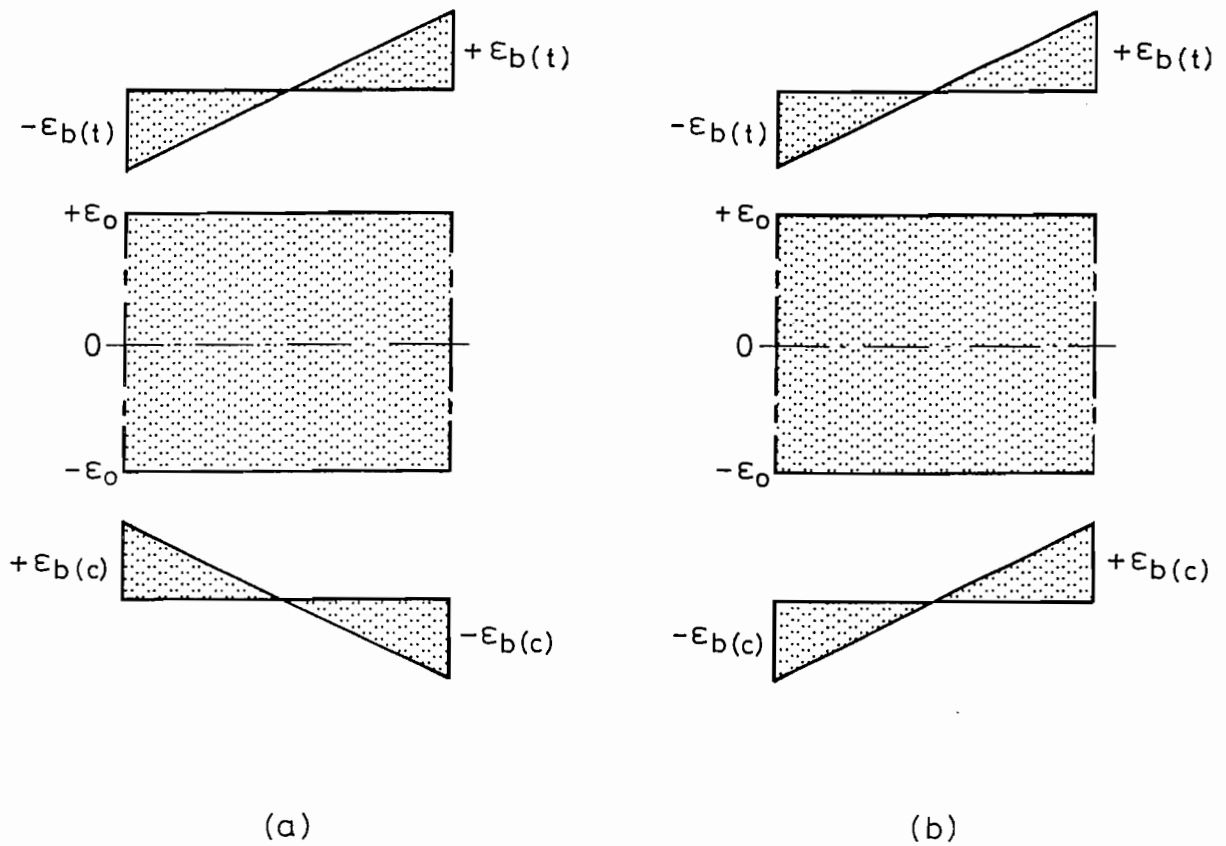


Figure 13. Schematic representation of superimposed strain components at the maximum and minimum loads in a tension-compression fatigue cycle: (a) Reversed bending; (b) Non-reversed bending [After Reference 2].

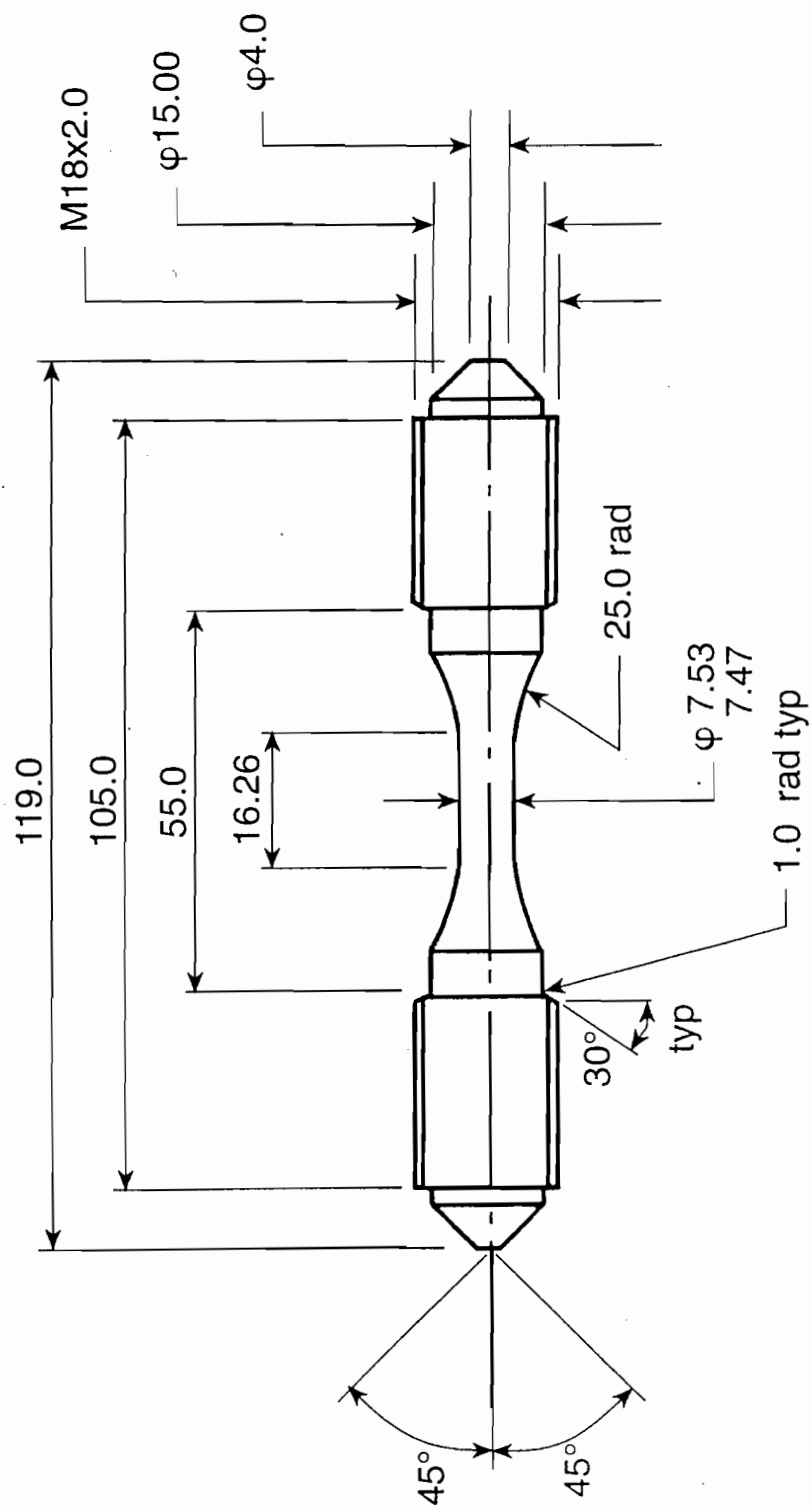


Figure 14. Example of an NPL-designed cylindrical specimen and alignment cell geometry with threaded ends.

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