TECHNICAL REPORT

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Fatigue — Fatigue testing of welded components — Guidance

Fatigue — Essais de fatigue sur composants soudés — Lignes directrices

Reference number
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Foreword

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In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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ISO/TR 14345 was prepared by the International Institute of Welding, which has been approved as an international standardizing body in the field of welding by the ISO Council.

Requests for official interpretations of any aspect of this part of ISO/TR 14345 should be directed to the ISO Central Secretariat, who will forward them to the IIW Secretariat for an official response.

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Introduction

Fatigue tests of welded specimens are the basis of all the main fatigue design codes and standards for welded components and structures. However, inevitably these are not fully comprehensive and there is a constant need for new data to extend them. Recognizing this, there is a growing tendency to allow the user to deviate from the rules by performing special fatigue tests to validate a design. This Technical Report addresses both these situations by providing guidance on the production of welded test specimens and their fatigue testing for producing data either for general application or to validate a specific design.

Welded metallic structures can be large and complex, incorporating many weld details and structural configurations. Furthermore, the loading that they are required to withstand in service can also be complex. Therefore, the scope for performing fatigue tests on full-scale welded structures under truly representative loading conditions is very limited, and usually expensive. Consequently, for both technical and economic reasons, it is rarely attempted. Instead, in many circumstances, it is sufficient to isolate individual weld details and incorporate them in small-scale specimens to test them. An important condition is that the resulting specimens should be realistic in terms of features in real structures that affect fatigue strength, such as material type, section thickness, plate preparation, weld type and welding conditions, residual stresses and the nature of the fatigue loading. This Technical Report provides guidance on the production and fatigue testing of specimens representing weld details. Reference is made to other IIW guidance on the fatigue testing of large-scale specimens representing sub-assemblies or structural components (Reference [1]); more detailed guidance on the loading required for variable-amplitude testing is given in Reference [2] and the statistical evaluation of fatigue data in Reference [3].

By its nature, this Technical Report covers two distinct disciplines, welding and mechanical testing. If reliable fatigue data are to be obtained, both need to be truly representative of practical conditions. Thus, the laboratory test specimens need to duplicate actual welded structures and the test conditions need to duplicate real-life loading and operating conditions. Apart from the provision of design data, use of the recommendations in this Technical Report is intended to facilitate comparison of fatigue test data and avoid biased statistics if results obtained from different sources are combined.

Use of this Technical Report is intended to allow, on the one hand, more adequate comparison of the results from different origins (e.g. same welded joint but from another workshop or testing laboratory) and, on the other hand, the plotting of more reliable fatigue curves for design purposes.

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Fatigue — Fatigue testing of welded components — Guidance

1 Scope

This Technical Report gives guidance on best practice for fatigue testing under constant- or variable-amplitude loading of welded components in the medium- and high-cycle regimes, corresponding to applied loading that results in nominal stresses that do not exceed yield. Low-cycle fatigue testing under strain control is not specifically covered, although the same test specimens can be suitable for either low- or high-cycle fatigue testing. The different steps involved in the manufacture and preparation of the welded specimens and the final presentation and evaluation of the test results are also covered.

This Technical Report does not cover corrosion or high-temperature fatigue testing.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
failure criterion
specimen damage chosen for ending the test

2.2
flank angle
θ
contact angle between the weld face and the plate at the weld toe

2.3
irregularity factor
I
ratio of the number of mean crossings, N_0, with positive slope to number of peaks or valleys in the given load history, N_p

$$I = \frac{N_0}{N_p}$$

NOTE See Figure 1.

2.4 Maxima

2.4.1
maximum load range
ΔF_{max}
maximum load range encountered in a variable-amplitude applied load spectrum

2.4.2
maximum stress range
$\Delta \sigma_{max}$
maximum stress range encountered in a variable-amplitude applied stress spectrum

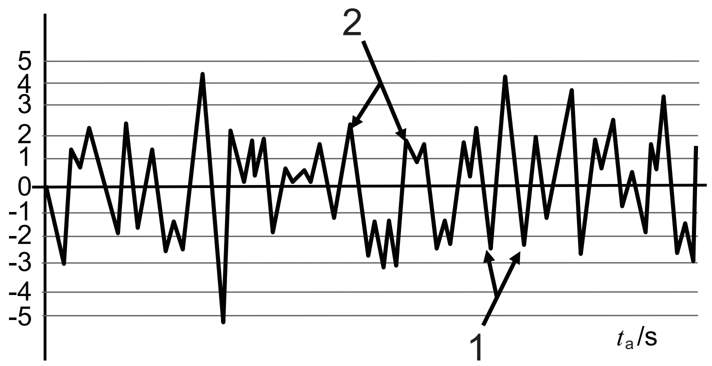
2.5
number of cycles to failure
N_f
number of cycles when the failure criterion is reached

2.6
peak factor
ratio of the maximum value attained in the applied load (or stress) history to the mean load (or stress)

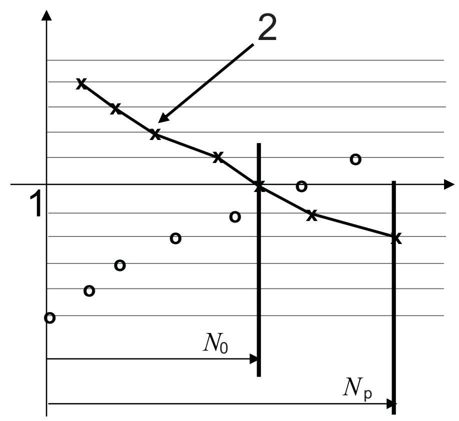
2.7
range
algebraic difference between the maximum and minimum values of a quantity under cyclic loading

2.8
standard deviation
positive square root of the mean of the squared deviations of a variable from its arithmetic mean

2.9
weld toe radius
ρ
contact radius between the weld toe and the plate



a) Random signal: load levels versus time



b) Counting for irregularity factor definition: load level versus number of peaks

Key

1 negative peaks
2 positive peaks
t_a time

Key

1 mean level
2 number of level crossings up
N_0 number of mean crossings
N_p number of peaks or valleys in the given load history
× cumulative distribution of peaks
○ cumulative distribution of valleys

Figure 1 — Random signal and counting for irregularity factor definition

3 Symbols and abbreviated terms

See Table 1.

Table 1 — Symbols and abbreviated terms

Symbol	Quantity	Designation
a, b, d	Length	Dimensions used to calculate misalignment parameters
ΔF	Force	Load range
ΔF_{max}	Force	Maximum load range in the spectrum
$\Delta\sigma_{\text{nom}}$	Stress	Nominal stress range
$\Delta\sigma$ (or S)	Stress	Stress range
$\Delta\sigma_{\text{m}}$	Stress	Membrane stress range
$\Delta\sigma_{\text{S}}$	Stress	Secondary bending stress range
$\Delta\sigma_{\text{max}}$	Stress	Maximum stress range in the spectrum
$\Delta\sigma_{\text{D}}$	Stress	Fatigue limit for parent material
$\Delta\sigma_{\text{cor}}$	Stress	Corrected stress range including secondary bending stress due to misalignment
$\Delta\sigma_{\text{shs}}$	Stress	Structural hot-spot stress range
$\Delta\varepsilon$	Length/length or %	Strain range
e	Length	Axial misalignment
ϕ	Radians	Angular distortion
h	Length	Weld leg length
I	—	Irregularity factor, N_0/N_{p}
L	Length	Distance over which misalignment extends
l	Length	Distance from weld toe to radius measuring circle
λ	Dimensionless	Correction factor dependent on restraint on misaligned cruciform joints
N_{f}	Cycles	Number of cycles to failure
N_0	—	Number of mean crossings with positive slope in spectrum loading sequence
N_{p}	—	Number of peaks or valleys in spectrum loading sequence
R	—	Stress ratio, $S_{\text{min}}/S_{\text{max}}$
ρ	Length	weld toe radius
S_{min}, S_{max}	Stress	Minimum and maximum (algebraic) applied stress (tension positive, compression negative)
S_N	Stress	Fatigue strength at life N cycles
s (or Stdv)	—	Standard deviation
$s_{\log N}$	—	Standard deviation of log N
$s_{\log S}$	—	Standard deviation of log S
s_S	Stress	Standard deviation of S_N
σ_{m}	Stress	Membrane stress
σ_{S}	Stress	Secondary bending stress
t	Length	Plate thickness
θ	Degrees	Weld toe flank angle

4 Specimen design and manufacture

4.1 Specimen design

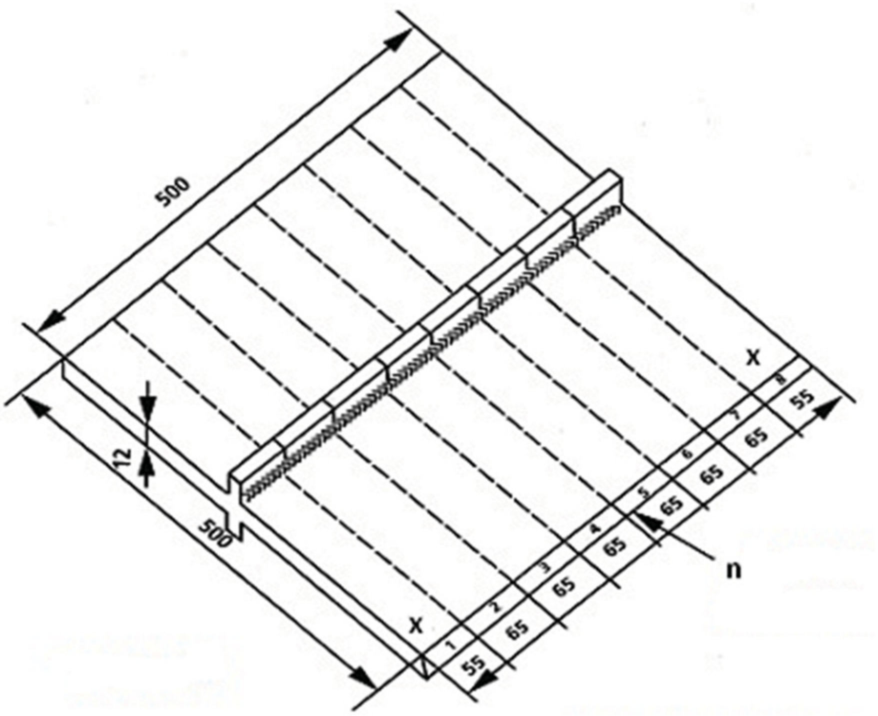
4.1.1 General

The specimen design depends on the objectives of the tests, together with any practical limitations such as the available type of fatigue-testing equipment, material and time. If the specimen is intended to model a welded joint in an actual structure, it shall be as representative as possible of that joint in terms of material, weld detail, geometry, dimensions, and manufacturing quality. In addition, the specimen design should take account of how loads are applied to the test section to ensure consistency with the original structural element. A relevant example to illustrate this point is given in Reference [4].

If it is required to produce several nominally identical specimens, e.g. to produce an S–N curve, a suitable technique is to extract them from larger panels, as shown in Figure 2. Normally, extension pieces are welded at each end to allow the test weld to traverse the entire width of the panel. These are then removed and the resulting edges ground smooth. Similarly, several strip specimens can be extracted from a single butt or fillet welded girth joint between two tubes. However, these approaches can only be used if the weld detail is a continuous weld oriented transverse to the direction of fatigue loading. In other cases, such as those shown in Figure 3, each specimen shall be fabricated individually.

An important feature of welded structures is the nature of the residual stresses due to welding and subsequent manufacturing operations. In most cases, these can be very high, up to yield, and tensile. Their effect under fatigue loading is the same as that of an applied high tensile mean stress. Most fatigue design rules provide design data that include the effect of such tensile residual stress. However, small-scale welded specimens are unlikely to embody high residual stresses from welding. One option with steel specimens is to induce them by spot heating (Reference [5]), or their effect can usually be simulated by the choice of loading (see 6.3).

Dimensions in millimetres



Key

1 unused

n specimen identification number

Figure 2 — Example of a welded panel and the extraction of narrower fatigue test specimens

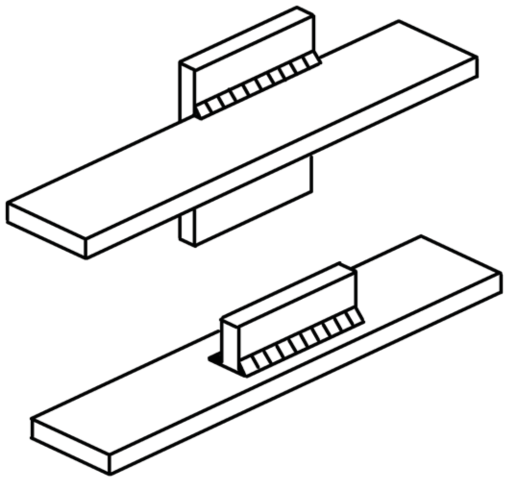
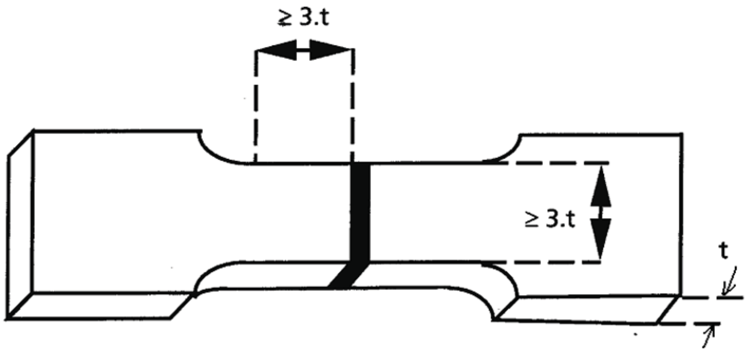


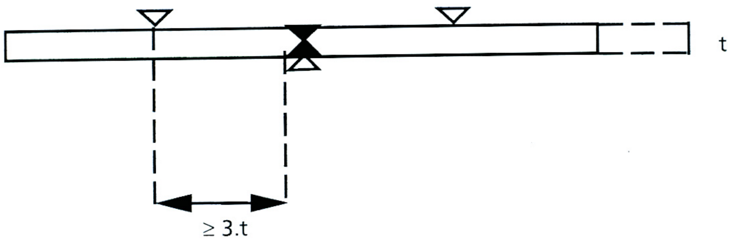
Figure 3 — Examples of fatigue test specimens that would need to be made individually

4.1.2 Influence of method of loading

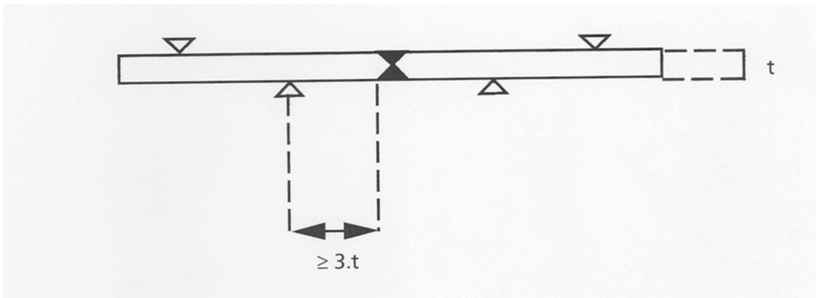
Care is needed to ensure that fatigue failure of the test specimen occurs at the weld detail of interest, rather than prematurely at some location associated with the method of testing. In this respect, there is always the risk that axially loaded plate specimens gripped in wedge jaws fail in that region as a result of the notching effect of the jaws if they indent the specimen. This problem is particularly acute if the weld detail is one with relatively high fatigue strength. It can usually be avoided by the use of waisted specimens that are narrower in the test section than where they are gripped. Similarly, specimens loaded in bending can fail at the load points if they indent the specimen or the local shear stress in the specimen is too high. General recommendations on the dimensions of fatigue test specimens are given in Figure 4.



a) Axial



b) 3-Point bending



c) 4-Point bending

Figure 4 — Geometrical characteristics of welded specimens loaded in tension or bending

4.2 Manufacture of test specimens

4.2.1 Material

The test specimens should be manufactured from material of the same specification, form, and thickness as that used for the component or structure that the specimen is intended to represent. Since the fatigue performance of some welded joints is effectively independent of material tensile strength, some flexibility is possible on the choice of material grade. Similarly, some tolerance on material form and thickness may be possible. Any such deviations should be justified and recorded.

4.2.2 Welding procedure

The welding operation should conform to those performed on components or structures of the type and material that the specimen is intended to represent, in compliance with recognized codes. Panels used to produce several small-scale specimens (Figure 2) should be assembled so as to maintain the thermal conditions and disposition of the welds in the real structure. When relevant, the rolling direction of a plate should be the same as that in the original structure.

To simulate practical conditions, it is prudent to include weld runs containing start-stops.

If the tests are being performed to validate a particular component or structure, each type of welded joint should be accurately characterized in terms of relevant dimensions and parameters. For example, in the case of arc welding, the following characteristics may be relevant:

— plate thickness;

— base metal type;

— rolling direction;

— welding process;

— shielding gas type, if any;

— welding position (flat, overhead, etc.);

— travel speed;

— preheat temperature;

— post-weld heat treatment, if any;

— electrical parameters of the welding process;

— size and shape of the welds;

— type and diameter of the electrodes;

— sequence of the different passes;

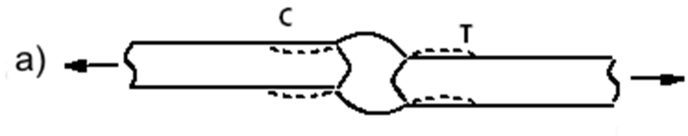
— locations of any start-stop positions.

Additionally, it is helpful to mark locations where the characteristics of the weld may have changed, e.g. due to a change in welding position or direction, or at a repair.

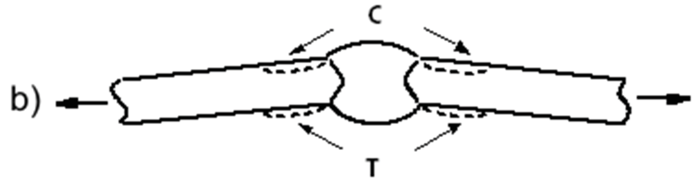
Unless it is a feature of the test, care should be taken to ensure that the finished weld is not cleaned by wire brushing or shot blasting or coated with oil or grease, since such treatments are likely to influence the fatigue performance of the welded specimen.

4.2.3 Joint alignment

Welded joints, particularly butt and cruciform joints, are highly susceptible to misalignment, arising mainly from distortion during welding, variations in section shape or thickness and practical difficulties of achieving perfect alignment during assembly. The two general types of misalignment are axial, due to a mismatch of the centrelines of abutting parts, and angular, usually due to distortion, as illustrated in Figure 5. Misalignment can affect the fatigue performance of the welded specimen in that it may influence the weld profile (Reference [6]) or, as shown in Figure 5, because it leads to the introduction of secondary bending stress when the joint is loaded (Reference [7]). Thus, care is needed to ensure that any misalignment in the specimen is representative of that in the actual structure and, ideally, that its effect as a source of secondary stress is quantified (see 5.3.3).



a) Axial misalignment



b) Angular misalignment

Key

C under compression

T under tension

Figure 5 — Secondary bending stresses arising under tensile axial loading in misaligned welded joints

4.2.4 Specimen preparation

If specimens are extracted from a welded panel (Figure 2) or tube, it is preferable to produce them by saw cutting or machining. If there is no alternative to flame cutting, care is needed to avoid distorting the specimens, and the flame-cut edges should be machined or ground smooth. It may be necessary to allow for this loss of width when deciding on the size to be removed by flame cutting.

To avoid fatigue crack initiation at the edges of the specimen, these should be filed, ground, or machined smooth in the longitudinal direction. For an even smoother finish, they can then be polished longitudinally with grade 600 grit emery paper until all filing and finishing marks have been removed.

Similarly, any weld spatter should be removed and the surface ground smooth, taking care not to scratch or grind the weld or the plate near the toe of the weld.

Welded specimens are not usually perfectly straight and it may be necessary to straighten them, e.g. to facilitate testing under axial loading. This can be done by local bending, but in so doing it is vitally important to avoiding bending in the vicinity of the test weld, especially the weld toes, since this can induce favourable residual stresses that have a marked effect on the fatigue performance of the welded specimen. One consequence of this is that any misalignment of the welded joint (see Figure 5) is unaffected by the straightening operation and therefore its effect as a source of secondary bending stress still needs to be taken into account (see 5.3.3).

Each specimen should be identified with a unique number and marked permanently before it is tested. Ink, paint or stamping can be used for marking. Any stamping should be applied to the ends of the specimen so as to avoid introducing potential points of stress concentration. If the specimen is to be tested to complete failure, it is prudent to apply the specimen identification number to both ends of the specimen.

4.3 Specimen characteristics

4.3.1 Material

Details of the type of material used to make the test specimen, its specification, chemical composition, and tensile properties should be recorded. In some circumstances it may also be relevant to note its fracture toughness and hardness, particularly in the regions where fatigue cracking takes place.

4.3.2 Geometry and dimensions

A full description of the test specimen type and geometry should be recorded, preferably including a sketch. The relevant dimensions should also be measured and recorded. Normally, these include the width and thickness in the test section, the wider width of a waisted specimen, the specimen length, and the size of any welded attachment or secondary member.

4.3.3 Specimen distortion and alignment

Special care is needed when conducting fatigue tests on welded specimens under axial loading since the presence of misalignment leads to the introduction of secondary bending, with the result that the stress adjacent to the weld experiences either additional tension or compression, as indicated for tensile loading in Figure 5. The same situation arises in tests in bending on welded sections if the misaligned welded joint is in a region of low stress gradient that approximates to axial loading conditions (e.g. the flange of an I-beam, the wall of a pipe or tube). However, secondary bending does not arise if the loading produces only shell bending, or indeed from the bending stress component for combined axial and bending stresses.

The secondary bending stresses due to misalignment should be taken into consideration when determining the stress range experienced by the welded specimen in the fatigue test.

If the misalignment can be measured, the formulae in Table 2 can be used to calculate the secondary bending stress σ_S in terms of the nominal applied membrane stress component σ_m (Reference [7]). Figure 6 shows an arrangement that can be used to determine the axial misalignment due to centreline mismatch e and the angular distortion α in a joint between two plates. Each side shall be linear and the deviation from perfect alignment shall be small. Sometimes local deformation occurs in a limited region, which can be only measured using modelling compound or by scanning measurement using dial gauges, mechanical length measuring instruments, laser comparators, etc.

In the case of assessment of angular misalignment, note that unless use is made of the non-linear tanh corrections in the formulae in Table 2,

$$\frac{\Delta\sigma_S}{\Delta\sigma_m} = \frac{\sigma_S}{\sigma_m}$$

otherwise σ_S needs to be established at the minimum and maximum applied stresses in the test in order to calculate $\Delta\sigma_S$. The resulting total corrected stress range is then $\Delta\sigma_{cor} = \Delta\sigma_m + \Delta\sigma_S$.

However, it is generally easier and more accurate to determine the actual stresses arising in the vicinity of a misaligned welded joint by measurement during the test, typically using electrical resistance strain gauges attached to the surfaces of the specimen in the region of interest. In such cases, the corrected stress range, $\Delta\sigma_{cor}$, is given by Equation (1):

$$\Delta\sigma_{cor} = \Delta\sigma_m \left(1 \pm \frac{\Delta\varepsilon_B - \Delta\varepsilon_F}{\Delta\varepsilon_B + \Delta\varepsilon_F}\right) \quad (1)$$

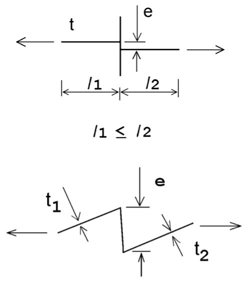
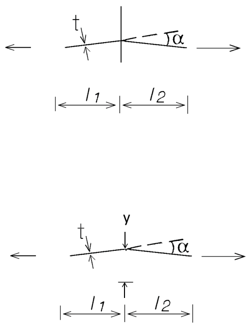
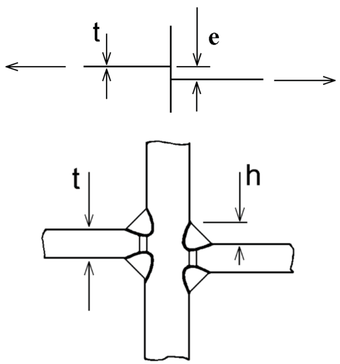
where

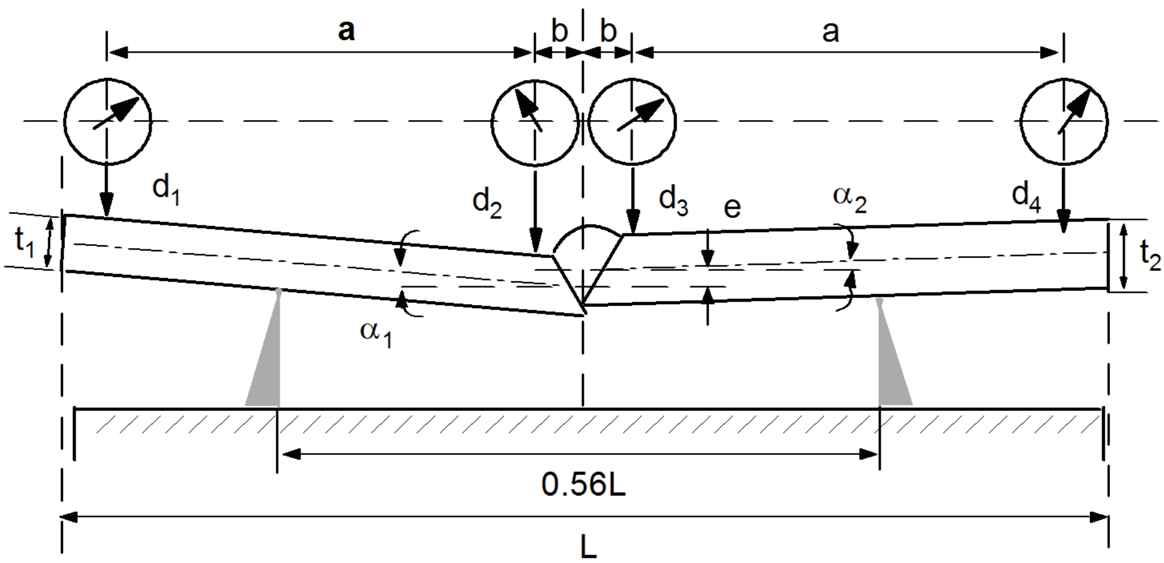
$\Delta\sigma_m$ is the nominal applied axial, or membrane, stress;

$\Delta\varepsilon_B$ is the measured strain on the back surface of the specimen;

$\Delta\varepsilon_F$ is the measured strain on the front surface of the specimen.

Table 2 — Formulae for the calculation of the secondary bending stresses due to misalignment in cruciform or butt joints

Type	Detail	Secondary bending stress, σ_S	Remarks
Axial misalignment		$\frac{\sigma_S}{\sigma_m} = \lambda \frac{e}{t_1}\left(\frac{l_1}{l_1+l_2}\right)\left(\frac{t_1^n}{t_1^n+t_2^n}\right)$ where λ is a factor dependent on restraint. Examples in the case of cruciform joints are: $\lambda = 6$ for unrestrained butt or cruciform joints.	a) Refers to the plate surfaces adjacent to the weld in the loaded plates, and hence to potential fatigue failure from a weld toe. b) For remotely loaded joints, assume $l_1 = l_2$. c) Some experimental support for n = 1,5
Angular distortion	$l_1 \geq l_2$, α in radians	Assuming boundary conditions equivalent to: fixed ends: $\frac{\sigma_S}{\sigma_m} = \frac{3y}{t}\left[\frac{\tanh(\beta/2)}{\beta/2}\right] = \frac{3\alpha l}{2t}\left[\frac{\tanh(\beta/2)}{\beta/2}\right]$ pinned ends: $\frac{\sigma_S}{\sigma_m} = \frac{6y}{t}\left[\frac{\tanh(\beta)}{\beta}\right] = \frac{3\alpha l}{t}\left[\frac{\tanh(\beta)}{\beta}\right]$ where $\beta = \frac{2l}{t}\sqrt{\frac{3\sigma_m}{E}}$	a) Refers to the plate surfaces adjacent to the weld in the loaded plates, and hence to potential fatigue failure from a weld toe. b) For remotely loaded joints, assume $l_1 = l_2$. c) The tanh correction (in brackets) allows for reduction in angular misalignment due to straightening of joint under tensile loading. It is negligible for $(l_1 + l_2)/t < 10$ and it is independent of the assumed end fixing condition for $(l_1 + l_2)/t > 100$
Axial misalignment in fillet welded cruciform joints		$\frac{\sigma_S}{\sigma_m} = \frac{e}{t+h}$	Refers to weld root in loaded plate and hence to potential fatigue failure in weld throat from root



Angular distortion, α, is given by Equation (2)

$$\alpha = \alpha_1 + \alpha_2 = \frac{(d_2 - d_1) + (d_3 - d_4)}{a} \quad (2)$$

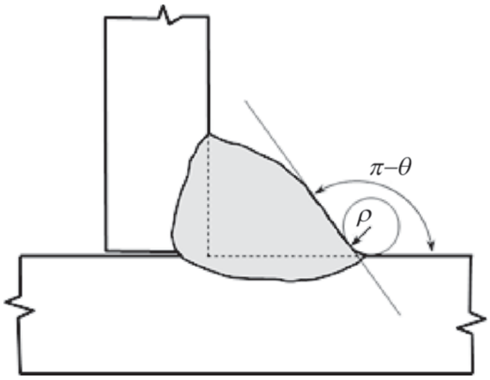
Axial misalignment, e, is given by Equation (3)

$$e = (d_2 - d_3) + (d_2 - d_3 + d_4 - d_1)\frac{b}{a} + \frac{t_1 - t_2}{2} \quad (3)$$

Figure 6 — Procedure for measuring misalignment parameters using dial gauges

4.3.4 Local weld geometry

It is sometimes useful or necessary to measure the local weld geometry. This is usually described in terms of two parameters, the contact angle, θ, and the radius, ρ, between the weld face and plate surface at the weld toe, as shown in Figure 7. The depth of any undercut would also be relevant. The weld toe radius and depth of any undercut can be measured directly using a standard welding gauge or a radius gauge. However, the most accurate measurements are made from cross-sections of welds, particularly if these can be enlarged by typically 5 to 10 times. These could be obtained from the end of the actual weld, after first machining or grinding it square with the plate edge, or from an off-cut of the original welded panel (see Figure 2), if the specimen was produced in this way. Alternatively, they can be reproduced in casting material (e.g. plaster, resin), if necessary, after first producing a mould (e.g. silicon rubber). Enlarged views of the resulting cross-sections can be produced from photographic images or using a profile projector (Reference [8]). Procedures for making the measurements are described in Annex A.



Key

ρ radius between the weld face and plate surface at the weld toe

θ contact angle

Figure 7 — Definition of the radius and the flank at the weld toe

4.3.5 Residual stress measurement

4.3.5.1 General

The nature and distribution of residual stresses due to welding can have a marked influence on fatigue performance. Therefore, it is sometimes useful to measure the residual stresses in a test specimen, especially in the region of fatigue crack initiation. Such measurements should be performed on untested specimens since the application of cyclic loading or the presence of fatigue cracking could redistribute the original residual stresses. A complete description of the measuring procedure should be reported, especially the positions and sizes of the measurement area.

Various techniques (4.3.5.2 to 4.3.5.4) are available.

4.3.5.2 Sectioning

An electrical resistance strain gauge is bonded on to the area of interest and its reading recorded. The area is then cut out to relax the residual stress in that area. Apart from cutting around the strain gauge, it may also be necessary to cut away the material beneath it to achieve full residual stress relaxation. Care is needed to ensure that the cutting method does not itself induce or modify the residual stresses. The strain gauge output is then recorded again and the change in strain corresponds to the initial residual stress.

4.3.5.3 Hole drilling method

This method utilizes purpose-built equipment for measuring near-surface residual stresses by drilling a hole in the centre of a special strain gauge rosette. The drilling operation is usually performed by an abrasive jet to minimize the possibility of affecting the residual stresses. In view of the need to gain access to the rosette for hole drilling, it is not possible to use this technique to measure residual stresses less than around 5 mm from the weld toe.

4.3.5.4 X-ray diffraction

This method does allow residual stresses very close to a weld toe to be measured. Provided the residual stresses along the weld toe are reasonably uniform, the method can be used to determine the residual stress gradient in the vicinity of the weld toe along a narrow path less than 1 mm wide (Figure 8).

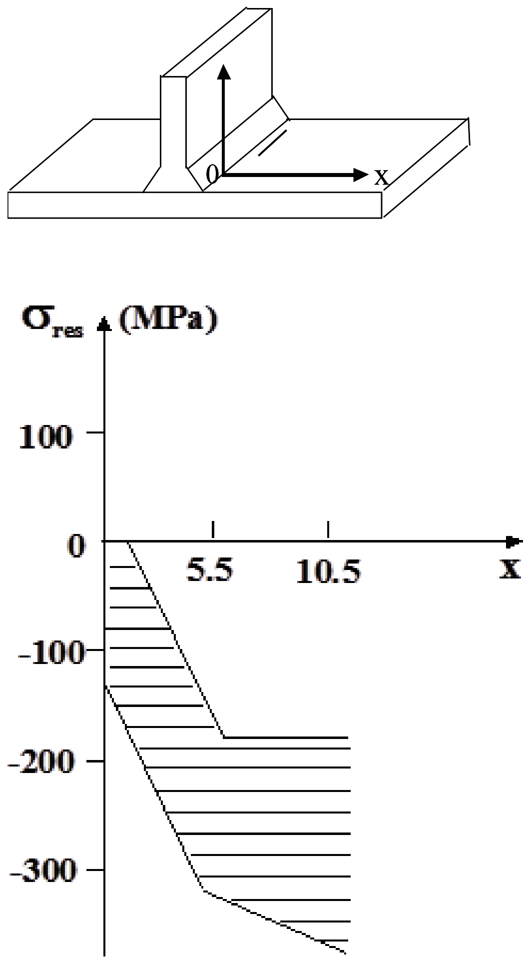


Figure 8 — Residual stress and width of X-ray diffraction peak in the vicinity of a weld toe (Reference [9])

4.4 Fatigue testing

4.4.1 Testing machine calibration

The testing equipment should be regularly calibrated, for both static and dynamic loading, in accordance with the appropriate national or International Standard.

More generally, uncertainty aspects of the measurement may need to be considered (Reference [10]).

4.4.2 Cyclic loading conditions

The cyclic loading waveform shape and the frequency have no significant effect on fatigue performance in passive environments. Therefore, in general, sinusoidal loading at the highest frequency achievable from the testing equipment is selected to reduce the testing time. However, the test frequency should be selected to avoid undesirable out-of-plane bending stresses due to resonance and excessive heating of the specimen. It should be kept within a small range during a test programme.

Tests in corrosive or otherwise harmful environments and tests at elevated temperature are not covered by this Technical Report. However, it may be noted that the effect of such test conditions on fatigue performance is generally time-dependent. Therefore, testing frequency, and even test duration, can be highly significant and should be chosen to represent specific service conditions.

4.4.3 Specimen grips or supports

As a rule, tests on welded plate specimens are performed under either axial or out-of-plane bending loading.

For specimens loaded in tension–tension ($R > 0$) or in tension-compression ($R < 0$), the grips and the axis of the test specimen should occupy a coaxial position; this should be checked frequently by calibration (e.g. ASTM E1012[38]).

5 Testing procedures

5.1 Definition of the nominal stress (or strain) range

Most current fatigue design S–N curves for welded joints express the fatigue strength in terms of the nominal stress range in the region of potential fatigue crack initiation referred to by the design S–N curve. For consistency with such rules, the same stress should be used to present the results of the test. Definitions of the nominal stress range, $\Delta\sigma_{nom}$, for the example of weld toe failure in a test specimen consisting of a plate with a transverse fillet welded stiffener, under tensile or bending loading, are indicated in Figure 9.

In the case of excessive distortion or misalignment, $\Delta\sigma_{nom}$ shall take into account any additional secondary bending stress (see 5.3.3).

In the case of welded specimens that fail in the weld throat after crack initiation at the root, the corresponding nominal stress range is related to the applied load and the weld throat area, calculated by a recognized method (Reference [11]).

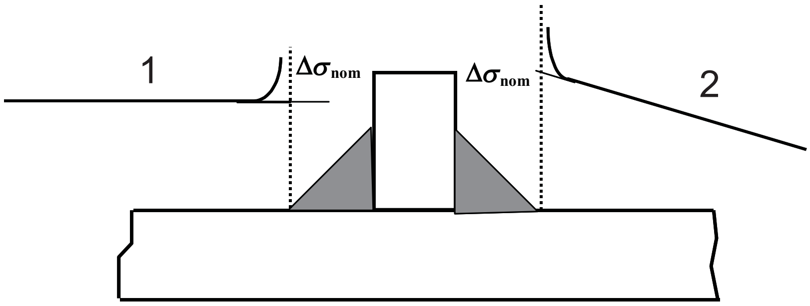
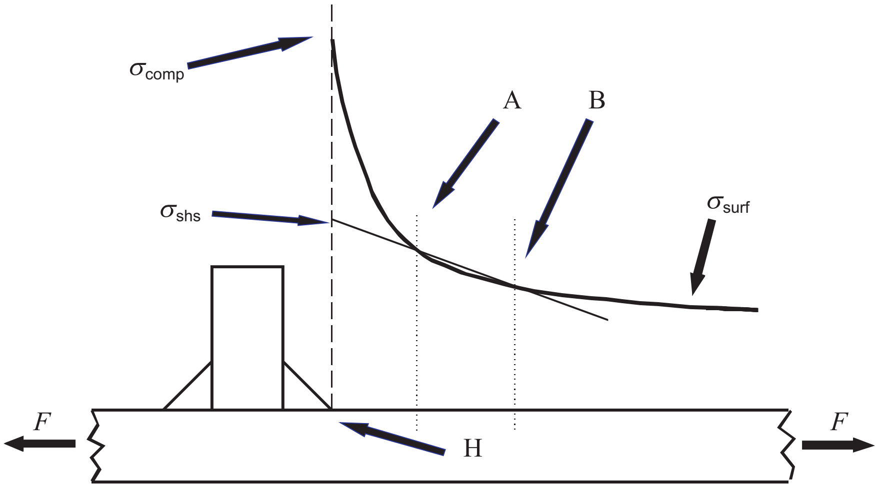


Figure 9 — Definition of the nominal stress range, $\Delta\sigma_{nom}$, in the case of a fillet weld loaded either in tension or in bending

5.2 Definition of the structural hot-spot stress (or strain) range

For the assessment of potential fatigue failure from a weld toe, increasing use is being made of the structural hot-spot stress range, $\Delta\sigma_{shs}$, rather than the nominal stress. This is defined as the stress range local to the weld toe that includes the stress concentration effect of the welded joint geometry and any secondary stresses, such as those due to misalignment, but excludes the very local notch effect of the weld toe itself (Reference [12]). If it is required to consider the test result in terms of the structural hot-spot stress range, it can be determined from the stress distribution approaching the weld toe, usually obtained from strain measurements on the surface of the test specimen, as illustrated in Figure 10. Alternatively, it can be calculated from the surface or through-thickness stress distribution near the weld toe, obtained by finite element stress analysis of a model of the specimen (Reference [13]). In some special cases, notably tubular joints (Reference [14]), parametric formulae are available for calculating the structural hot-spot stress concentration factor.



Typically the position of A is in the range 0,4t to 0,5t and the position of B is in the range t to 1,5t from toe, where t is plate thickness.

Key

A,B reference points

H hot spot

σ_{shs} structural hot-spot stress

σ_{comp} computed total stress

σ_{surf} surface stress

Figure 10 — Determination of the structural hot-spot stress at weld toe by linear extrapolation from surface stress distribution approaching weld toe

5.3 Conservative loading conditions

In order to reproduce the effect of the very high tensile residual stresses that are expected to be present in real welded structures (see 5.1.1) in a small-scale specimen, the testing should be carried out under a high stress ratio (typically $R > 0,5$) or high tensile mean or maximum applied stresses. The most stringent condition, which yields the most conservative results (References [15]–[17]), is cycling down from tensile yield. *S–N* curves produced under these high tensile cyclic stress conditions are generally lower and steeper than those produced under less severe loading. However, these would be the characteristics of an *S–N* curve produced under any fatigue loading conditions from the same welded joint in the presence of yield magnitude tensile residual stress (Reference [18]).

Note that care is needed before adopting the above approach in that it may be too conservative in some circumstances (Reference [17]). To illustrate, it may not be appropriate for situations in which the local residual stress near the weld toe has been modified, e.g. by peening to improve its fatigue resistance. Similarly, it may be too severe if the local residual stress could be modified as a result of the applied cyclic loading, notably under some variable-amplitude load spectra.

5.4 Definition of the fatigue life

5.4.1 Failure criterion

The failure criterion should be selected before embarking on a fatigue test series and the same criterion used for every test. Typical failure criteria are complete failure of the specimen, the attainment of a specific fatigue crack (e.g. detectable, crack of specific depth, through-thickness cracking), the attainment of some limit dictated by the testing equipment or loading condition (e.g. excessive deflection, inability of the testing equipment to maintain the required load accurately) or the achievement of a specific endurance.

NOTE The failure criterion associated with most fatigue design S–N curves for welded joints is effectively the attainment of through-thickness cracking, together with the end-of-test criterion of the achievement of an endurance corresponding to the assumed fatigue limit (e.g. 10^7 cycles) without any evidence of fatigue cracking.

Whatever the choice, the failure criterion should be recorded on the test sheet.

5.4.2 Crack measurements

Various methods are available for detecting fatigue crack initiation and hence the endurance at which a fatigue crack is definitely present (Reference [18]). These include:

- strain gauge measurement near the weld toe;
- potential drop method;
- differential compliance method;
- absolute compliance method;
- ultrasonic method;
- visual detection with the aid of soap solution and a magnifying glass;
- micro-crack replicating method.

Some of these techniques can also be used to monitor the propagation of the fatigue crack during the test. Alternatively, those that produce beach-marks on the fracture surface, such as applying soap solution or other fluids that stain the fracture, can be used to determine the crack size and shape at known endurances after the test, from measurements of the beach-marks on the fracture surface. Variable-amplitude loading also usually produces beach-marks and these can be used in the same way. Any information gained about the size and shape of fatigue cracking should be recorded on the test sheet.

6 Testing plan

6.1 Testing procedure

Established testing procedures should be adopted to determine an $\Delta\sigma$–N (S–N) curve, the fatigue strength at a specified endurance or the fatigue limit (e.g. ASTM E466[34] or E468[36]).

6.2 Determination of the fatigue strength at N cycles

Generally, the fatigue strength, $\Delta\sigma_N$ or S_N, is determined either at 2×10^6 cycles ($\Delta\sigma_{2\times10^6}$ cycles), as a reference and to save time, or at 10^7 cycles ($\Delta\sigma_{10^7}$).

Various statistical methods (References [17][19][20]) permit evaluation of the fatigue strength and its standard deviation, s, in the region of the S–N curve being investigated.

The staircase method, illustrated in Table 3, is commonly used. This entails loading a specimen at a stress range determined by the results obtained in the preceding test. If the preceding specimen, j, failed at the level S_j, the next stress level is $S_{j+1} = S_j - d$, where d is a predefined difference in applied stress levels (ideally between s and $2s$). If the preceding specimen was not broken, $S_{i+1} = S_i + d$.

Table 3 — Staircase test procedure

i	$\Delta\sigma$ MPa	Test sequence 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	f_i	if_i	i^2f_i
4	180		×		×				×		×						0	0	0
3	160	○		○		×		○		○		×					4	12	36
2	140						○						×				1	2	4
1	120													×		○	1	1	1
0	100														○		1	0	0

○ = specimen unbroken at specified endurance (run-out)

× = specimen failed

Less frequent event : ○

$$F = \sum_i f_i = 7;\ A = \sum_i (if_i) = 15;\ B = \sum_i (i^2 f_i) = 41$$

Giving:

$$S_N = 100 + 20\left(\frac{15}{7} + \frac{1}{2}\right) = 152{,}9\ \text{MPa}$$

$$s = 1{,}62 \times 20\left(\frac{7 \times 41 - 15^2}{7^2} + 0{,}029\right) = 41{,}9\ \text{MPa}$$

Generally, 11 to 15 specimens are sufficient to determine the required fatigue strength. This is estimated using the number of run-outs obtained at each stress level f_i, where i = 0 corresponds to the lowest stress level used, and the parameters F, A, and B defined in Table 3. Then, the mean value of the required fatigue strength at the specified endurance S_N is:

$$S_N = S_0 + d\left(\frac{A}{F} \pm 0{,}5\right)$$

where S_0 is the lowest stress level (i = 0) for which the less frequent event (run-out or failure) appears. The value +0,5 is used when the least frequent event is a run-out, and −0,5 when it is a failure.

An approximation of the standard deviation of S_N is given by:

$$s = 1{,}62d\left(\frac{FB - A^2}{F^2} + 0{,}029\right)$$

Values of S_N and s for the test results indicated are included in Table 3.

6.3 *S–N* curve

Depending on the requirement, an *S–N* curve is normally established over a specific range of endurances. Attention is usually focused on the finite life regime and the establishment of that part of the *S–N* curve that is linear on a log–log basis. In such a case, it is prudent to limit the testing conditions to the achievement of lives of no more than 2×10^6 cycles to avoid the need to account for test results that lie in the transition region approaching the fatigue limit (e.g. target lives from 10^5 to 2×10^6 cycles). However, a range of target lives extending to the endurance associated with the fatigue limit would be required if it were necessary to define the complete *S–N* curve (e.g. $10^4 < N < 10^7$ cycles). Then three or four regularly spaced levels of $\Delta\sigma$ are defined within the interval between these fatigue life extremes. In view of the statistical variation in fatigue performance, ideally "as many specimens as possible" should be tested to establish an S–N curve. However, depending on the availability of such factors as time, material, and funding, in practice the number of tests is limited. Even so, a minimum of 8 to 10 tests is recommended, with two or more tests at each stress level.

If a log S–log N linear equation is verified, two stress range levels are sufficient.

In other cases, statistical analysis allows the plotting of curves for equal failure probability (Reference [21]); the methods used are based on knowledge of the statistical distribution of fatigue lives (mean and standard deviation estimates) (see Clause 11).

6.4 Testing order of the specimens

In order to limit any effects related to specimen manufacturing conditions and testing procedure, specimens for testing should be selected at random from the batch available. This can be done with the aid of tabulated random numbers or a random number generator.

7 Fatigue testing

7.1 Fatigue loading

Fatigue-testing equipment should be calibrated regularly to an appropriate standard. Thus, it should have the means to provide an accurate indication of the force applied to the test specimen. Depending on the loading mode (e.g. axial, bending, torsion) and the specimen condition (e.g. section shape, alignment) this can then be used to calculate the stress or strain experienced in the region of the specimen under test. However, if this is not possible, supplementary measures, notably the application of electrical resistance strain gauges, might also be required. Such measures would almost certainly be needed if the hot spot stress were to be determined. It may be more convenient to make such measurements under static loading, in which case care shall be taken to ensure that the applied load does not exceed the maximum to be applied in the fatigue test.

7.2 Cyclic load control

It is absolutely necessary to check for constant-amplitude loading conditions and to record for variable-amplitude loading conditions the actual stresses being applied to the specimen, in order to access the response of the loading device under optimum automatic control parameter settings.

The difference between controlled and checked loads should be less than ±1 % of the maximum applied load.

7.3 Variable-amplitude loading

Sufficient information should be obtained and recorded about a variable-amplitude test spectrum to enable the test to be repeated (Reference [2]). Thus, complete details of the sequence of applied stresses should be described and such parameters as the irregularity factor and peak factor defined. If some low stresses in the original spectrum have been omitted to reduce the testing time (e.g. on the basis that they are effectively non-damaging), this should also be recorded.

7.4 Crack monitoring

The methods mentioned in 5.4.2 are suitable for detecting fatigue crack initiation and some of them for monitoring subsequent fatigue crack propagation.

8 Post-mortem examination

Valuable information can be obtained after a fatigue test by careful examination of the fatigue fracture surface, the fatigue crack initiation site, and the general condition of the specimen. Depending on the failure criterion, the specimen may not be completely broken at the end of a test (see 5.4.1). For examination of the crack surface, excessive deformation of the residual neck should be avoided when the specimen is broken open. A useful technique is to embrittle the specimen by first soaking it in liquid nitrogen. Examination of the fracture surface should reveal the fatigue crack initiation site and possible information about the fatigue crack size and shape at known numbers of cycles of testing (see 5.4.2). It may also be necessary to make measurements of any misalignment of the welded joint in order to correct the nominal applied stress for the presence of the secondary bending stress introduced (see 4.3.3).

9 Presentation and reporting of the test results

9.1 Test sheet

All details of the specimen and testing conditions that influence the fatigue test result should be recorded for each test in a test sheet. Such information is required for thorough evaluation and reporting of the results, but it should also be sufficient to enable the test to be repeated independently. Essential information includes details of the material, specimen type (perhaps with a sketch), relevant dimensions, a note of any post-weld treatments, details of any instrumentation (e.g. strain gauge types and locations), description of the fatigue-testing equipment and loading conditions used, relevant stresses, description of failure, and the fatigue life. An example indicating the range of information that might be recorded is presented in Annex A.

If tests are performed under variable-amplitude loading, the following information should be reported:

— diagram showing the stress sequence (maximum stress, stress distribution, total number of cycles);

— table giving data of stepped stress sequence for the purpose of a cumulative damage calculation.

9.2 Graphs

9.2.1 Constant-amplitude loading

The results of fatigue tests are plotted on log $\Delta\sigma$–log N or $\Delta\sigma$–log N (S–N) diagrams. Figure 16 presents an example of the former.

9.2.2 Variable-amplitude loading

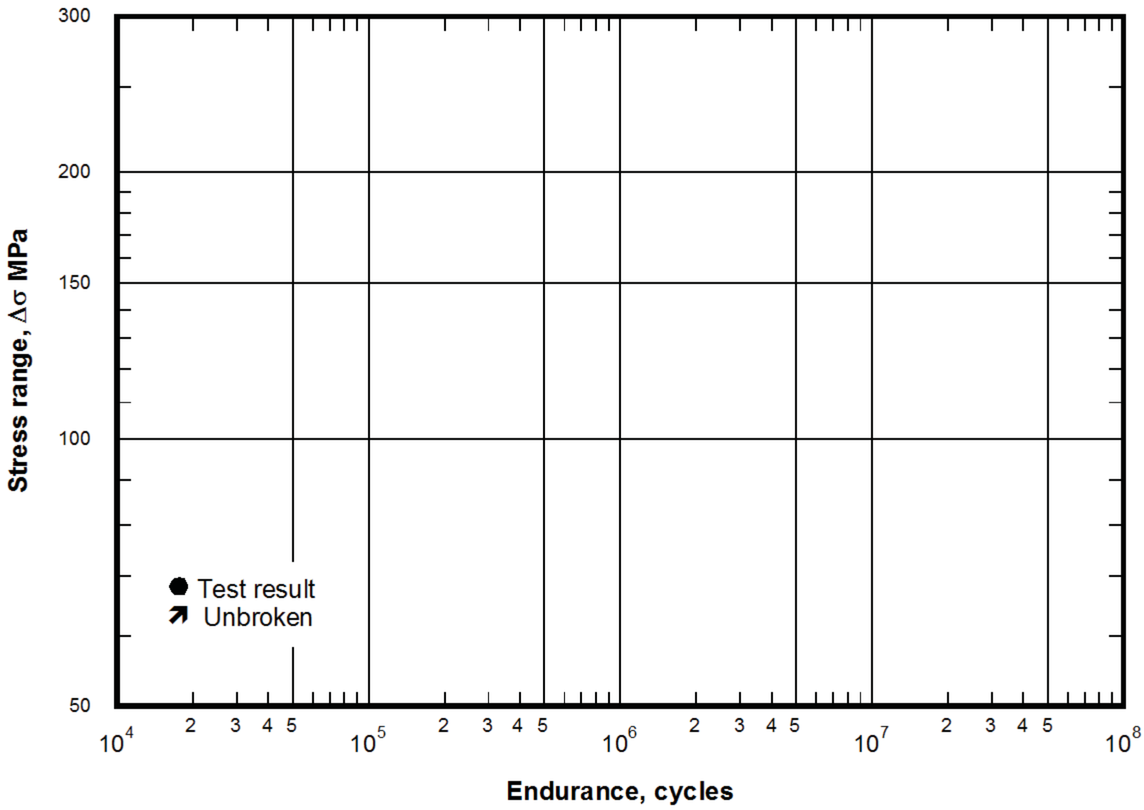
The fatigue life is generally plotted against the following parameters (Reference [22]):

— $\Delta\sigma_{\text{max}}$, the maximum stress range in the spectrum in the area/region of interest;

— $\Delta\sigma_{\text{RM}m}$, the value of the mth moment of stress range:

$$\Delta\sigma_{\text{RM}m} = \frac{1}{N}\left[\sum_{i=1}^{N} N \quad \Delta\sigma_i^m\right]^{1/m}$$

where m is the slope of the constant amplitude S–N curve assuming that it is linear when plotted in terms of log S and log N (see Table 3).



Key

$\Delta\sigma$ stress range

N endurance, cycles

● test result

➚ unbroken

Figure 11 — Example of a $\Delta\sigma$–N diagram

10 Statistical analysis of test results

10.1 General

The relevant documents to be considered are:

— NF A03-405;[31]

— ASTM E739;[37]

— ISO 12107.[28]

Different statistical methods can be used to analyse the fatigue test results, determine statistical parameters, and plot S–N curves incorporating specific probabilities of failure.

Table 4 specifies the main characteristics of the methods studied by Working Group 1 of Commission XIII of the International Institute of Welding (Reference [20]).

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Table 4 — Methods for the statistical analysis of the test results

Method of analysis	S–N curve equation	Method and assumptions	Parameters
A	$\log N = \log C - m\log S$ or $S^m N = C$	Linear regression of log N on log S, ignoring run-outs	C m $s\log N$
B	$\log N = \log C - m\log S$ or $S^m N = C$	Linear regression of log N on log S and log S on log N, ignoring run-outs. Mean line bisecting the two regression lines	C m $s\log N$
C	$\log N = \log C - m\log S$ or $S^m N = C$	Maximum likelihood, including run-outs	C m $s\log S$
D	$\log N = \log C - m\log S$ or $S^m N = C$	Linear regression of log N on log S, including run-outs	C m $s\log S$
E	$N = \dfrac{A \exp\left(-\left[S-E\right]^C / B\right)}{S-E}$ (C = 1)	Multiple non-linear regression analysis, including run-outs	A B E sS

Details of the methods are given in 10.2 to 10.6.

10.2 Method A

Linear log S–log N curve obtained by regression analysis using the method of least squares, neglecting run-outs (Reference [3]). Analysis is performed assuming log N is the dependent variable and standard deviation of log N, $s$log N, is used to define confidence limits. This is the method most widely used to establish the S–N curves contained in standards for the fatigue design of welded joints.

Method A does not take into account unbroken specimens (run-outs).

10.3 Method B

Two S–N curves are fitted to the data by linear regression analysis using the method of least squares, one assuming that log N is the dependent variable (i.e. method A) and the other assuming that log S is the dependent variable, neglecting run-outs in both cases. The mean S–N curve is then obtained by drawing a line bisecting the two regression lines (References [22][23]).

Method B does not take into account unbroken specimens (run-outs).

10.4 Method C

Utilization of the method of maximum likelihood to plot the straight lines on log S–log N axis. This method amounts to curve fitting in compliance with the equation:

$$NS^m = K$$

Method C takes into account results from unbroken specimens (run-outs) (Reference [24]).

10.5 Methods D and E

Methods D and E both allow various forms of the S–N curve to be fitted by supplementing a basal computer program with sub-programs. Two models may be considered (Reference [25]).

For method D:

$$NS^m = C$$

where C is a constant.

For method E:

$$N\left(S-E\right) = A\exp\left[-\left(\frac{S-E}{B}\right)^C\right]$$

where A, B, C, E are statistically derived parameters.

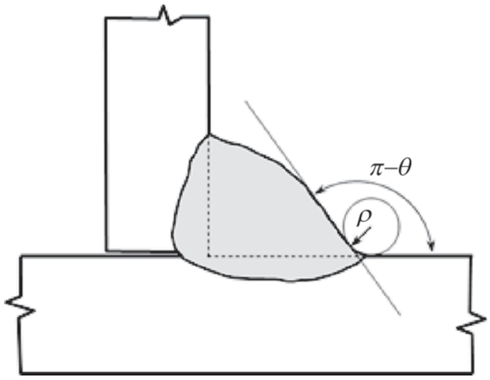
Methods D and E take into account results from unbroken specimens (run-outs) (Reference [22]).

Annex A
(informative)

Weld profile measurement

A.1 General

The techniques described in this annex are concerned with the measurement of the weld toe radius, ρ, and angle, θ, indicated in Figure A.1, from either the actual weld profile or an image of it, preferably enlarged by 5 to 10 times.



Key

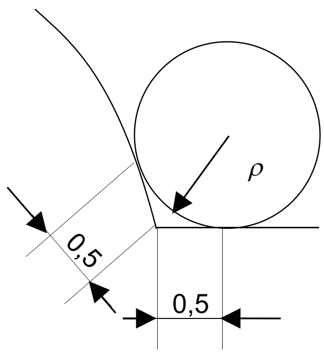
ρ radius between the weld face and plate surface at the weld toe

θ contact angle

Figure A.1 — Definition of the radius and the flank at the weld toe

A.2 Method of the circle tangent at the distance 1

Figure A.2 shows the application of this method, for the example of l = 0,5 mm.



Key

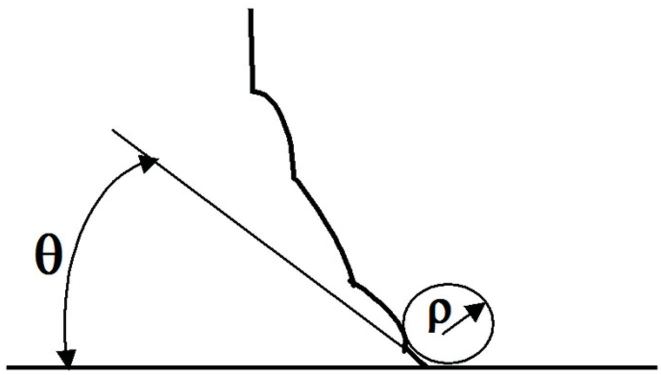
ρ radius between the weld face and plate surface at the weld toe

Figure A.2 — Local radius less than measured (l = 0,5 mm)

A.3 Method of the least radius

This method, illustrated in Figure A.3, consists of superimposing circles of different diameters, drawn on transparent paper (Figure A.4), over the weld toe. The smallest circle fitting into the weld toe geometry defines the ρ value. Because of the difficulty of finding an arc of contact or a tangent on rough surfaces, this should be defined as the circle touching the profile (i.e. weld face and plate) on at least three points.

The point at which the circle becomes tangential to the weld toe defines of the contact angle θ.



Key

ρ radius between the weld face and plate surface at the weld toe

θ contact angle

Figure A.3 — Method of the least radius

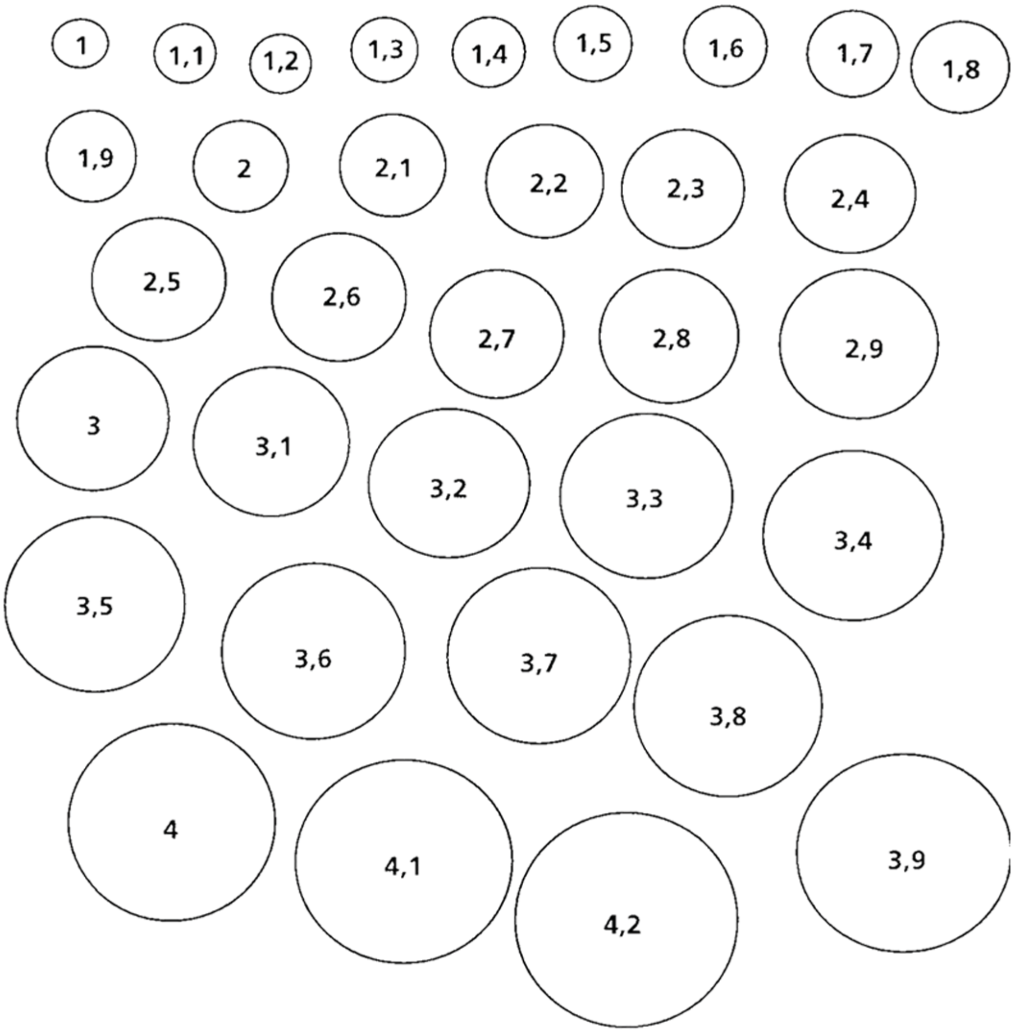


Figure A.4 — Sized circles for measuring weld toe radius (for illustration only, not to consistent scale)

Annex B
(informative)

Example of a fatigue data sheet for reporting the results of fatigue tests on welded joints

Title:

Authors:

Reference:

Parent material

Grade

Chemical composition

(% by mass)

heat treatment

Mechanical properties

YS	UTS	Elong	R.A.	KVC	
MPa	MPa	%		J/cm2	

Endurance limit at ... cycles R = $\Delta\sigma_D$ = ... MPa s = ... MPa

Welding

Welding process: Position:

Electrode: Flux: Gas:

Chemical composition of the filler metal

Mechanical properties of the deposit metal

YS	UTS	elong	R.A.	KCV	

Pass No.	**Electrode size**	**Intensity** A	**Voltage** V	**Speed** cm/min	**Plate preparation**	**Preheat temperature**

Improvement

surface treatment after welding

mechanical treatment after welding

Intensity	**Voltage**					

Specimen

Thickness: ... mm Width: ...mm Length: ... mm

Observations:

Fatigue-testing conditions

Test machine: R = Temperature:

Loading mode: Frequency: Environment:

Wave form: σ_{mean}:

Nominal area:

Failure criterion:

Test results

Ref: as welded $\Delta\sigma$ (2 × 10[6] cycles/50 %) = ... MPa s = ... MPa

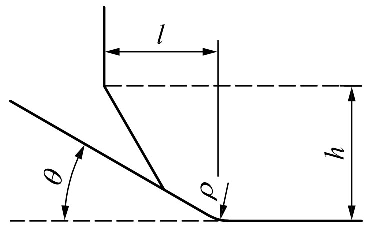
Nominal stress range $\Delta\sigma$ MPa	N cycles	Observations[a]

[a] F: failed specimen (with initiation site, e.g. toe or root, embedded flaw); NF: did not fail after N cycles.

$\Delta\sigma$ (2 ×10[6] cycles/50 %) = ... MPa

s = ... MPa

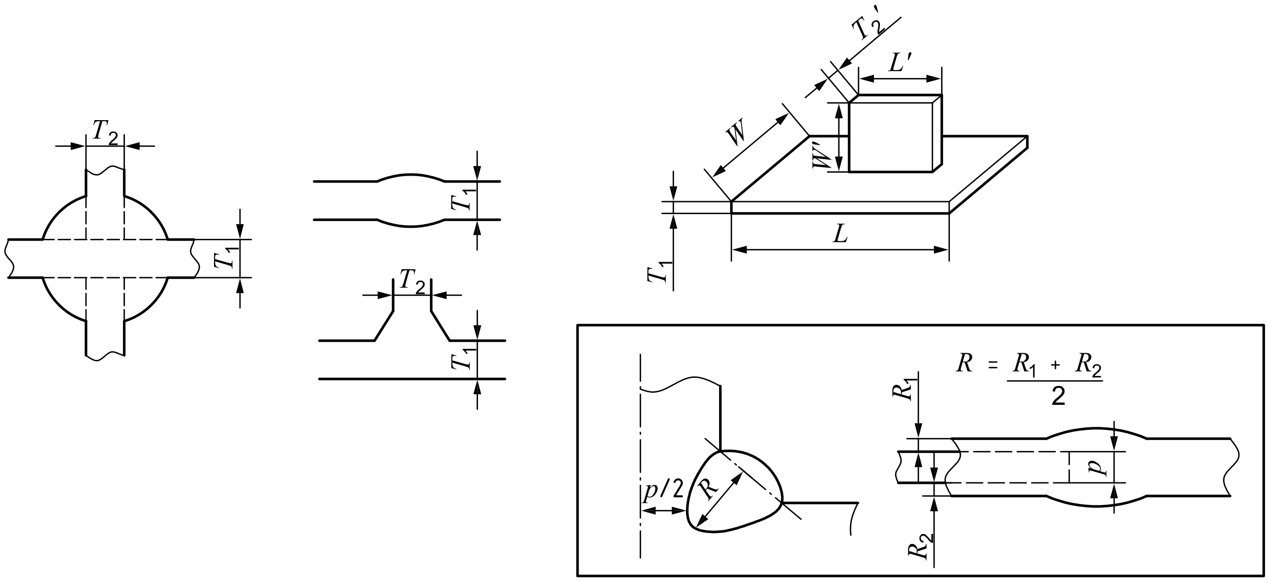
Local geometry



ρ = ... mm θ = ...°

l = ... mm h = ... mm

Global geometry



T_1 = ... mm T_2 = ... mm

W' = ... mm L' = ... mm

R = ... mm p = ... mm

Type of joints (mark the crack initiation location on the sketch)

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