DRAFT FOR DEVELOPMENT

DD ENV 1999-2:2000

Eurocode 9: Design of aluminium structures —

Part 2: Structures susceptible to fatigue

ICS 91.010.30; 91.080.10

National foreword

This Draft for Development is the official English version of ENV 1999-2:1998.

This publication is not to be regarded as a British Standard.

It is being issued in the Draft for Development series of publications and is of a provisional nature. It should be applied on this provisional basis, so that information and experience of its practical application may be obtained.

Comments arising from the use of this Draft for Development are requested so that UK experience can be reported to the European organization responsible for its conversion into a European Standard. A review of this publication will be initiated 2 years after its publication by the European organization so that a decision can be taken on its status at the end of its three-year life. The commencement of the review period will be notified by an announcement in *Update Standards*.

According to the replies received by the end of the review period, the responsible BSI Committee will decide whether to support the conversion into a European standard, to extend the life of the prestandard or to withdraw it. Comments should be sent in writing to the Secretary of BSI Subcommittee B/525/9, Structural use of aluminium, at 389 Chiswick High Road, London W4 4AL, giving the document reference and clause number and proposing, where possible, an appropriate revision of the text.

A list of organizations represented on this committee can be obtained on request to its secretary.

Cross-references

The British Standards which implement international or European publications referred to in this document may be found in the BSI Standards Catalogue under the section entitled “International Standards Correspondence Index”, or by using the “Find” facility of the BSI Standards Electronic Catalogue.

Summary of pages

This document comprises a front cover, an inside front cover, the National Application Document (10 pages), the ENV title page, pages 2 to 90, an inside back cover and a back cover.

The BSI copyright notice displayed in this document indicates when the document was last issued.

This Draft for Development, having been prepared under the direction of the Sector Committee for Building and Civil Engineering, was published under the authority of the Standards Committee and comes into effect on 15 December 2000

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Amendments issued since publication

Amd. No.	Date	Comments

Contents of
National Application Document

National Application Document

Introduction

This National Application Document (NAD) has been prepared under the direction of Technical Committee B525, Building & Civil Engineering structures, (by sub-committee B525/9). It has been developed from:

a) a textural examination of ENV 1999-2:1998;

b) a parametric calibration against BS 8118, supporting standards and test data;

c) trial calculations

1 Scope

This NAD provides information to enable ENV 1999-2:1998 (Eurocode 9 Part 2) to be used for the design of buildings and civil and structural engineering works in the UK or parts thereof which are susceptible to fatigue.

2 References

2.1 Normative References

This NAD incorporates, by reference, provisions from specific editions of other publications. These normative references are cited at the appropriate points in the text. Subsequent amendments to, or revision of, any of these publications apply to this NAD only when incorporated in it by updating or revision.

2.2 Informative References

This NAD refers to other publications that provide information or guidance. Editions of these publications current at the time of issue of this standard are listed, but reference should be made to the latest editions.

3 Partial safety factors, combination factors and other values

a) The values for partial load factors (γ) should be those given in DD ENV 1999- 2: 1998 Clause 3.4

b) The values for partial safety factors (γ_m) should be those given in ENV 1999-2: 1998 Clause 5.2.1(3). [see also 6.1.1 d) below re. γ_m for adhesively bonded joints].

4 Loading Codes

Guidance on loading specifically for fatigue may be obtained from:

BS2573 Part 1: 1983
Rules for the design of cranes
Part 1: "Specification for classification, stress calculations and design criteria for structures"

BS2573 Part 2: 1980
Rules for the design of cranes
Part 2: "Specification for classification, stress calculations and design of mechanisms"

BS5400 Part 10: 1980
Steel, concrete and composite bridges.
Part 10: "Code of practice for fatigue"

BS8100 Part 1: 1986
Lattice towers and masts
Part 1: "Code of practice for loading"

BS8100 Part 2: 1986
Lattice towers and masts
Part 2: "Guide to the background and use of part 1 "Code of practice for loading".

5 Reference Standards

The supporting standards to be used are listed in Tables 2 to 11.

6 Additional Recommendations

6.1 Guidance on Eurocode 9 : Part 1.1

Note. **6.1.1** to **6.1.5** should be followed when designing in accordance with Eurocode 9: Part 2

6.1.1 *Chapter 1 General*

a) *Clause 1.1.1(2) Damage tolerance*
The use of damage tolerant designs [ref Eurocode 9: Part 2 clauses 2.1.6(2) and 2.3.1] should be limited to any structural applications that would normally be subjected to regular inspections for fatigue damage.

b) *Clause 1.1.3 products*
Designers wishing to employ castings under fatigue conditions should consult the manufacturers and consider prototype fatigue testing of components.

c) *Clause 1.1.5*
Range of materials. Use of aluminium alloy products listed in the British Standards given in Table 1 is also permitted.

NOTE: This provision is to enable the use of materials held in stock which were produced prior to the adoption of the EN material standards.

d) *Clause 1.1.6 Joining Methods*
Whilst adhesive bonding is listed in this clause, they should not be used under fatigue conditions without consultation with the manufacturers and representative testing of a sufficient number of samples.

6.1.2 Section 2 Basis of Design

a) *Clause 2.1.6(2) Damage tolerant design* – see notes above re Clause 1.1.1.

b) *Clause 3 – Damage tolerant design –* see notes above re Clause 1.1.1.

6.1.3 Section 3 – Loading

a) *Clause 3.1(2)* Delete reference to ENV 1991 and use loading codes relevant to particular application (see also section 4 above) or actual data as available.

6.1.4 Section 4 – Loading

a) Clause 4.2.2(1)e) Delete "(see Part 1 of this Prestandard)" and replace with "In a web in shear the modified nominal stress should be calculated using an effective thickness of $1.7\rho_v t_w$ (but not more than t_w). The value of ρ_v should be taken from clause 5.12.4 and 5.12.5 of DD ENV 1999-1-1."

6.1.5 Section 5 Fatigue Strength Data

a) *Clause 5.2.3 (3)*
Adhesive bonding should not be used in fatigue conditions without representative test data. (See ref to Clause 1.1.6 above). Delete the sentence "otherwise a high value of γ_{mf} should be used".

b) Table *5.1.5 and Fig 5.2.5*
The fatigue curve and detail category should only be used for non-critical applications or for preliminary design prior to representative testing.

TABLE 1: Permitted British Standards for Alloys

BS 1470:1987 Wrought aluminium and aluminium alloys for general engineering purposes: plate, sheet and strip.
BS 1471:1972 Specification for wrought aluminium and aluminium alloys- Drawn tube.
BS 1472:1972 Specification for wrought aluminium and aluminium alloys- Forging stock and forgings
BS 1474:1987 Specification for wrought aluminium and aluminium alloys for general engineering purposes: bars, extruded round tubes and sections
BS 1475:1972 Specification for wrought aluminium and aluminium alloys- Wire
BS 1490:1988 Specification for aluminium and aluminium alloy ingots and castings for general engineering purposes
BS 4300-1:1967 Specification (supplementary series) for wrought aluminium and aluminium alloys Part 1: Aluminium alloy longitudinally welded tube
BS 4300-4:1973 Specification (supplementary series) for wrought aluminium and aluminium alloys for general engineering purposes- Part 4:6463 Solid extruded bars and sections suitable for bright trim/reflector applications
BS 4300-5:1973 Specification (supplementary series) for wrought aluminium and aluminium alloys for general engineering purposes- Part 5:2011 Free cutting bar and wire
BS 4300-12:1969 Specification (supplementary series) for wrought aluminium and aluminium alloys- Part 12:5454 Bar, extruded round tube and sections
BS 4300-15:1973 Specification (supplementary series) for wrought aluminium and aluminium alloys Part 15:7020 Bar, extruded round tube and sections

Table 2: Reference standards common to different product forms	
BS EN 515:1993	Aluminium and aluminium alloys- Wrought products- Temper designations.
BS EN 573-3:1995	Aluminium and aluminium alloys- Chemical composition and form of wrought products- Part 3: Chemical composition.
BS EN 573-4:1995	Aluminium and aluminium alloys- Chemical composition and form of wrought products- Part 4: Forms of product.

Table 3: Reference Standards for Aluminium and Aluminium alloy Plate, Sheet and Strip (Replaces BS 1470:1987)	
BS EN 485-1:1995	Aluminium and aluminium alloys- Sheet, strip and plate- Part 1: Technical conditions for inspection and delivery.
BS EN 485-2:1995	Aluminium and aluminium alloys- Sheet, strip and plate- Part 2: Mechanical properties.
BS EN 485-3:1994	Aluminium and aluminium alloys- Sheet, strip and plate- Part 3: Tolerances on shape and dimensions for hot rolled products.
BS EN 485-4:1994	Aluminium and aluminium alloys- Sheet, strip and plate- Part 4: Tolerances on shape and dimensions for cold rolled products.

Table 4: Reference Standards for Aluminium and Aluminium Alloy Drawn Tube. (Replaces BS 1471: 1972)	
BS EN 754-1:1997	Aluminium and aluminium alloys- Cold drawn rod/bar and tube- Part 1: Technical conditions for inspection and delivery.
BS EN 754-2:1997	Aluminium and aluminium alloys- Cold drawn rod/bar and tube- Part 2: Mechanical properties.
BS EN 754-7:1998	Aluminium and aluminium alloys- Cold drawn rod/bar and tube- Part 7: Seamless tubes, tolerances on dimensions and form.
BS EN 754-8:1998	Aluminium and aluminium alloys- Cold drawn rod/bar and tube- Part 8: Porthole tubes, tolerances on dimensions and form.

Table 5: Reference Standards for Aluminium an Aluminium Alloy Forging Stock and Forgings (Replaces BS 1472: 1972	
BS EN 586-1: 1998	Aluminium and aluminium alloys- Forgings- Part 1: Technical conditions for inspection and delivery.
BS EN 586-2: 1994	Aluminium and aluminium alloys- Forgings- Part 2: Mechanical properties and additional property requirements.
BS EN 603-1: 1997	Aluminium and aluminium alloys- Wrought forging stock- Part 1: Technical conditions for inspection and delivery.
BSEN 603-2: 1997	Aluminium and aluminium alloys- Wrought forging stock- Part 2: Mechanical properties.
BS EN 604-1: 1997	Aluminium and aluminium alloys- Cast forging stock- Part 1: Technical conditions for inspection and delivery.
BS EN 604-2: 1997	Aluminium and aluminium alloys- Cast forging stock- Part 2: Tolerances on dimensions and form

Table 6: Reference Standards for Aluminium and Aluminium Alloy Bars, Extruded Round Tubes and Sections. (Replaces BS 1474: 1987, BS4300-12; and BS 4300-15:1973)	
BS EN 755-1: 1997	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 1: Technical conditions for inspection and delivery
BS EN 755-2: 1997	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 2: Mechanical properties.
BS EN 755-3: 1996	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 3: Round bars, tolerances on dimensions and form.
BS EN 755-4: 1996	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 4: Square bars, tolerances on dimensions and form.
BS EN 755-5: 1996	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 5: Rectangular bars, tolerances on dimensions and form.
BS EN 755-6: 1996	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 6: Hexagonal bars, tolerances on dimensions and form.
BS EN 755-7: 1998	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 7: Seamless tubes, tolerances on dimensions and form.
BS EN 755-8: 1999	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 8: Porthole tubes, tolerances on dimensions and form.
EN 755-9:	Aluminium and aluminium alloys- Extruded rod/bar, tubes and profiles- Part 9: Profiles, tolerances on dimensions and form.
EN 12020-1	Aluminium and aluminium alloys- Extruded precision profiles in alloys EN AW 6060/EN AW 6063- Part 1: Technical conditions for inspection and delivery.
EN 12020-2	Aluminium and aluminium alloys- Extruded precision profiles in alloys EN AW 6060/EN AW 6063- Part 2: Tolerances on dimensions and form.

Table 7: Reference Standards for Aluminium and Aluminium Alloy Wire (Replaces BS 1475: 1972)	
BS EN 1301-1: 1997	Aluminium and aluminium alloys- Drawn wire- Part 1: Technical conditions for inspection and delivery.
BS EN 1301-2: 1997	Aluminium and aluminium alloys- Drawn wire- Part 2: Mechanical properties.
BS EN 1301-3: 1997	Aluminium and aluminium alloys- Drawn wire-Part 3: Tolerances on dimensions.

Table 8: Reference Standards for Aluminium and Aluminium Alloy Ingots and Castings for General Engineering Purposes. (Replaces BS 1490: 1988)	
BS EN 1559-1: 1997	Founding- Technical conditions of delivery- Part 1: General.
EN 1559-4:	Founding- Technical conditions of delivery- Part 4: Additional requirements for aluminium castings (under preparation).
BS EN 1676: 1997	Aluminium and aluminium alloys- Alloyed ingots for remelting- Specifications.
BS EN 1706: 1998	Aluminium and aluminium alloys- Castings- Chemical composition and mechanical properties.

Table 9: Reference Standards for Aluminium and Aluminium Alloy Longitudinally Welded Tube. (Replaces BS 4300-1: 1967)	
BS EN 1592-1: 1998	Aluminium and aluminium alloys- HF seamwelded tubes- Part 1: Technical conditions for inspection and delivery.
BS EN 1592-2: 1998	Aluminium and aluminium alloys- HF seamwelded tubes- Part 2: Mechanical properties.
BS EN 1592-3: 1998	Aluminium and aluminium alloys- HF seamwelded tubes- Part 3: Tolerances on dimensions and form of circular tubes.
BS EN 1592-4: 1998	Aluminium and aluminium alloys- HF seam welded tubes- Part 4: Tolerances on dimensions and form for square, rectangular and shaped tubes.

Table 10: Reference Standards for Aluminium and Aluminium Alloy Solid Extruded Bars and Sections suitable for bright trim/reflector applications. (Replaces BS 4300-4: 1973)	
BS EN 755-1: 1997	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 1: Technical conditions for inspection and delivery.
BS EN 755-2: 1997	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 2: Mechanical properties.

Table 10: Reference Standards for Aluminium and Aluminium Alloy Solid Extruded Bars and Sections suitable for bright trim/reflector applications. (Replaces BS 4300-4: 1973) (Cont'd)	
BSEN 755-3: 1996	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 3: Round bars, tolerances on dimensions and form.
BS EN 755-4: 1996	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 4: Square bars, tolerances on dimensions and form.
BS EN 755-5: 1996	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 5: Rectangular bars, tolerances on dimensions and form.
BS EN 755-6: 1996	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 6: Hexagonal bars, tolerances on dimensions and form.
EN 755-9	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 9: Profile, tolerances on dimensions and form.

Table 11: Reference Standards for Aluminium and Aluminium Alloy Free Cutting Bar and Wire. (Replaces BS 4300-5: 1973).	
BS EN 754-1: 1997	Aluminium and aluminium alloys- Cold drawn rod/bar and tube- Part 1: Technical conditions for inspection and delivery.
BS EN 754-2: 1997	Aluminium and aluminium alloys- Cold drawn rod/bar and tube- Part 2: Mechanical properties.
BS EN 754-3: 1996	Aluminium and aluminium alloys- Cold drawn rod/bar and tube- Part 3: Round bars, tolerances on dimensions and form.
BS EN 754-6: 1996	Aluminium and aluminium alloys- Cold drawn rod/bar and tube- Part 6: Hexagonal bars, tolerances on dimensions and form.
BS EN 755-1: 1997	Aluminium and aluminium alloys- Extruded rod/bar, tubes and profiles- Part 1: Technical conditions for inspection and delivery.
BS EN 755-2: 1997	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 2: Mechanical properties.
BS EN 755-3: 1996	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 3: Round bars, tolerances on dimensions and form.
BS EN 755-6: 1996	Aluminium and aluminium alloys- Extruded rod/bar, tube and profiles- Part 6: Hexagonal bars, tolerances on dimensions and form.

EUROPEAN PRESTANDARD
PRÉNORME EUROPÉENNE
EUROPÄISCHE VORNORM

ENV 1999-2

May 1998

ICS 91.010.30; 91.080.10

Descriptors: civil engineering, steel construction, aluminium, design, building codes, computation, mechanical strength

English version

Eurocode 9: Design of aluminium structures - Part 2: Structures susceptible to fatigue

Eurocode 9: Conception et dimensionnement des structures en aliminium - Partie 2: Structures sensibles à la fatigue

Eurocode 9: Bemessung und Konstruktion von Aluminiumbauten - Teil 2: Ermüdungsanfällige Tragwerke

This European Prestandard (ENV) was approved by CEN on 26 October 1997 as a prospective standard for provisional application.

The period of validity of this ENV is limited initially to three years. After two years the members of CEN will be requested to submit their comments, particularly on the question whether the ENV can be converted into a European Standard.

CEN members are required to announce the existence of this ENV in the same way as for an EN and to make the ENV available promptly at national level in an appropriate form. It is permissible to keep conflicting national standards in force (in parallel to the ENV) until the final decision about the possible conversion of the ENV into an EN is reached.

CEN members are the national standards bodies of Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and United Kingdom.

EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

Central Secretariat: rue de Stassart, 36 B-1050 Brussels

Ref. No. ENV 1999-2:1998 E

Contents

Foreword

Objectives of the Eurocodes

The Structural Eurocodes comprise a group of standards for the structural and geotechnical design of buildings and civil engineering works.

They are intended to serve as reference documents for the following purposes:

a) As a means to prove compliance of building and civil engineering works with the essential requirements of the Construction Products Directive (CPD).

b) As a framework for drawing up harmonised technical specifications for construction products.

They cover execution and control only to the extent that is necessary to indicate the quality of the construction products, and the standard of the workmanship, needed to comply with the assumptions of the design rules.

Until the necessary set of harmonised technical specifications for products and for methods of testing their performance is available, some of the Structural Eurocodes cover some of these aspects in informative annexes.

Background to the Eurocode Programme

The Commission of the European Communities (CEC) initiated the work of establishing a set of harmonized technical rules for the design of building and civil engineering works which would initially serve as an alternative to the different rules in force in the various Member States and would ultimately replace them. These technical rules became known as the "Structural Eurocodes".

In 1990, after consulting their respective Member States, the CEC transferred the work of further development, issue and updates of the Structural Eurocodes to CEN, and the EFTA Secretariat agreed to support the CEN work.

CEN Technical Committee CEN/TC 250 is responsible for all Structural Eurocodes.

Eurocode programme

Work is in hand on the following Structural Eurocodes, each generally consisting of a number of parts:

EN 1991	Eurocode 1	Basis of design and actions on structures
EN 1992	Eurocode 2	Design of concrete structures
EN 1993	Eurocode 3	Design of steel structures
EN 1994	Eurocode 4	Design of composite steel and concrete structures
EN 1995	Eurocode 5	Design of timber structures
EN 1996	Eurocode 6	Design of masonry structures
EN 1997	Eurocode 7	Geotechnical design
EN 1998	Eurocode 8	Design of structures for earthquake resistance
EN 1999	Eurocode 9	Design of aluminium structures

Separate sub-committees have been formed by CEN/TC 250 for the various Eurocodes listed above.

This part of the Structural Eurocode for Design of Aluminium Alloy Structures, which had been finalised and approved for publication under the direction of CEC, is being issued by CEN as a European Prestandard (ENV) with an initial life of three years.

This Prestandard is intended for experimental practical application in the design of the building and civil engineering works covered by the scope as given in 1.1 and for the submission of comments.

After approximately two years CEN members will be invited to submit formal comments to be taken into account in determining future action.

Meanwhile feedback and comments on this Prestandard should be sent to Secretariat of sub-committee CEN/TC 250/SC 9 at the following address:

Secretariat of CEN/TC 250/SC 9
c/o Norwegian Council for Building Standardization
Postboks 129 Blindern
N - 0314 OSLO

or to your national standards organisation.

National Applications Documents

In view of the responsibilities of authorities in member countries for the safety, health and other matters covered by the essential requirements of the CPD, certain safety elements in this ENV have been assigned indicative values which are identified by □. The authorities in each member country are expected to assign definitive values to these safety elements.

Some of the harmonised supporting prestandards, including the Eurocodes giving values of actions to be taken into account and measures required for fire protection, may not be available by the time this Prestandard is issued. It is therefore anticipated that a National Application Document (NAD) giving definitive values for safety elements, referencing compatible supporting standards and providing national guidance on the application of this Prestandard, will be issued by each member country or its Standards Organisation.

It is intended that this Prestandard is used in conjunction with the NAD valid in the country where the building or civil engineering works are located.

Matters specific to this Prestandard

General

The scope of Eurocode 9 is defined in Part 1.1 and the scope of this Part of Eurocode 9 is defined in 1.1.

In using this Prestandard in practice, particular regard should be paid to the underlying assumptions and conditions given in 1.4.

In developing this Prestandard, background documents have been prepared, which give commentaries on, and justifications for, some of the provisions in the Prestandard.

Use of annexes

The six chapters of this Prestandard are complemented by five Annexes, some normative and some informative.

The normative annexes have the same status as the chapters to which they relate. Most have been introduced by moving some of the more detailed Application Rules, which are needed only in particular cases, out of the main part of the text to aid its clarity.

Concept of reference standards

In order to use this Prestandard reference needs to be made to various CEN and ISO standards. These are used to define the product characteristics and processes which have been assumed to apply in formulating the design rules.

This Prestandard mentions certain "Reference Standards". Each Reference Standard makes reference to the whole or, part of, a number of CEN and/or ISO standards. Where any referenced CEN or ISO standard is not yet available, the National Application Document should be consulted for the standard to be used instead. It is assumed that only those grades and qualities given in normative Annex B of Part 1.1 will be used for buildings and civil engineering works designed to this Prestandard.

Partial safety factors

This Prestandard gives general rules for the design of aluminium structures which relate to the limit states of members and connections which involve structural failure due to fatigue.

Most of the rules have been calibrated against test results in order to obtain consistent values of the partial safety factors for resistance γ_{Mf}.

Guidance is given on appropriate partial factors γ_{Ff} for loading where the loading cannot be obtained from existing loading codes.

Fabrication and erection

Chapter 6 of this Prestandard is intended to indicate some minimum standards of workmanship and normal tolerances that have been assumed in deriving the design rules given in this Prestandard.

It also indicates the information relating to particular fatigue critical parts of a structure that the designer needs to supply in order to define the execution and maintenance requirements.

Design assisted by testing

Section 2.4 is not generally required in the course of routine design, but is provided, together with Annex C, for use in the special circumstances in which it may become appropriate.

1 General

1.1 Scope of Eurocode 9 Part 2

1.1.1 Application

(1) This Part 2 gives the basis for the design of aluminium alloy structures with respect to the limit state of fatigue induced fracture. Design for other limit states is covered in Part 1.

(2) This Part 2 gives rules for design by the following methods:

- Safe life
- Damage tolerance
- Design by testing

(3) This Part 2 contains the manufacturing quality requirements necessary to ensure that the design assumptions are met in practice.

1.1.2 Structural forms

(1) This Part 2 covers:

- Beams and braced and unbraced framed structures
- Latticed structures
- Stiffened plate structures of flat or shell construction
- Solid bodies

(2) This Part 2 does not cover pressurised containment vessels, or pipework.

1.1.3 Basic products

(1) This Part 2 covers:

- Rolled sections
- Extrusions
- Drawn Tubes
- Formed Profiles
- Forgings
- Castings

1.1.4 Member forms

(2) This Part 2 covers open and hollow sections, including members built up from combinations of these products.

1.1.5 Materials

(1) This Part 2 covers the wrought alloys listed with a tick in Table 1.1.1 and the cast alloys listed in Table 1.1.2.

Table 1.1.1: Wrought aluminium alloys for structures

Alloy designation	Process and form of product								
	Rolled (EN 485)			Extruded (EN 755)			Drawn (EN 754)	HF seam-welded (EN 1592)	Forged (EN 586)
	Sheet[1]	Strip	Plate[2]	Rod bar	Tube	Profile	Tube	Tube	Shapes
EN AW-3103	✓	✓	✓					✓	
EN AW-5083	✓	✓	✓	✓	✓	✓[3]	✓		✓
EN AW-5052	✓	✓	✓						
EN AW-5454	✓	✓	✓						
EN AW-5754	✓	✓	✓						✓
EN AW-6060				✓	✓	✓	✓		
EN AW-6061	✓	✓	✓	✓	✓	✓	✓		
EN AW-6063				✓	✓	✓	✓		
EN AW-6005A						✓			
EN AW-6082	✓	✓	✓	✓	✓	✓	✓		✓
EN AW-7020	✓	✓	✓	✓	✓	✓	✓		

Note 1: thicknesses <6mm
Note 2: thicknesses ≥6mm
Note 3: simple profiles only

Table 1.1.2: Cast aluminium alloys for structures

Alloy designation (EN 1706)	Casting type	
	Sand	Permanent mould (chill)
EN AC-42100	✓	✓
EN AC-42200	✓	✓
EN AC-43200	✓	✓
EN AC-44100	✓	✓
EN AC-51300	✓[1]	✓[1]

Note 1: simple shapes only

1.1.6 Joining methods

(1) This Part covers the following joining methods:

- Arc welding (metal inert gas and tungsten inert gas)
- Fastening with threaded components
- Riveting
- Adhesive bonding

1.1.7 Environmental conditions

(1)P This Part covers structural applications exposed to normal atmospheric conditions and temperatures not exceeding +100°C (for fatigue purposes), including marine environments, except for adhesively bonded joints where the temperature limits apply to the range -20°C to 60°C. For aluminium alloy 5083 the data apply to maximum temperatures not exceeding 65°C. Fatigue strength data are not applicable to parts of the structure exposed to environments which are aggressively corrosive to the materials concerned.

(2) If these limits are exceeded resort may need to be made to test data and certification of fabrication technology.

1.2 Normative References

(1) This European PreStandard incorporates by dated or undated reference, provisions from other standards. These normative references are cited at the appropriate places in the text.

EN 287-2	Approval testing of welders - Fusion welding - Part 2: Aluminium and its alloys
EN 288-4	Specification and approval of welding procedures for metallic materials - Part 4 Welding procedure tests for the arc welding of aluminium and its alloys.
EN 485	Aluminium and aluminium alloys - Sheet, strip and plate
EN 586	Aluminium and aluminium alloys - Forgings
EN 719	Welding coordination - Tasks and responsibilities
EN 729-2	Quality requirements for welding - Fusion welding of metallic parts - Part 2: Comprehensive quality requirements
EN 754	Aluminium and aluminium alloys - Cold drawn rod/bar and tube
EN 755	Aluminium and aluminium alloys - Extruded rod/bar, tube and profiles
EN 1011-4	Recommendation for arc welding - Part 4: Specific requirements for aluminium and its alloys
EN 1706	Aluminium and aluminium alloys - Castings
EN 30042	Arc welded joints in aluminium and its weldable alloys - Guidance on quality levels for imperfections
ENV 1991-3	Traffic loads on bridges
ENV 1991-5	Actions induced by cranes and machinery

1.3 Distinction Between Principles and Application Rules

(1) Depending on the character of the individual clauses, distinction is made in this Eurocode between Principles and Application Rules.

(2) The Principles comprise:

- general statements and definitions for which there is no alternative, as well as
- requirements and analytical models for which no alternative is permitted unless specifically stated.

(3) The Principles are identified by the letter P following the paragraph number.

(4) The Application Rules are generally recognised rules which follow the Principles and satisfy their requirements.

(5) It is permissible to use alternative design rules different from the Application Rules given in the Eurocode, provided that it is shown that the alternative rule accords with the relevant Principles and is at least equivalent with regard to the resistance, serviceability and durability achieved by the structure.

(6) In this part the Application rules are identified by a number in brackets, as in this paragraph.

1.4 Assumptions

(1)P The following assumptions shall apply:

- Structures are designed by appropriately qualified and experienced personnel.
- Adequate supervision and quality control is provided in factories, in plants and on site.
- Construction is carried out by personnel having the appropriate skill and experience.
- The construction materials and products are used as specified in this Eurocode or in the relevant material or product specifications.
- The structure will be adequately maintained.
- The structure will be used in accordance with the design brief.

(2)P The design procedures are valid only when the quality requirements for execution and workmanship given in Annex D are complied with, except where specific measures are taken to enable alternative quality standards to be validated by fracture mechanics or test.

(3) Numerical values identified by □ are given as indications. Other values may be specified by Member States.

1.5 Definitions

1.5.1 Terms common to all Eurocodes

(1)P Unless otherwise stated in Part 1 of Eurocode 9 the terminology used in International Standard ISO 8930 applies.

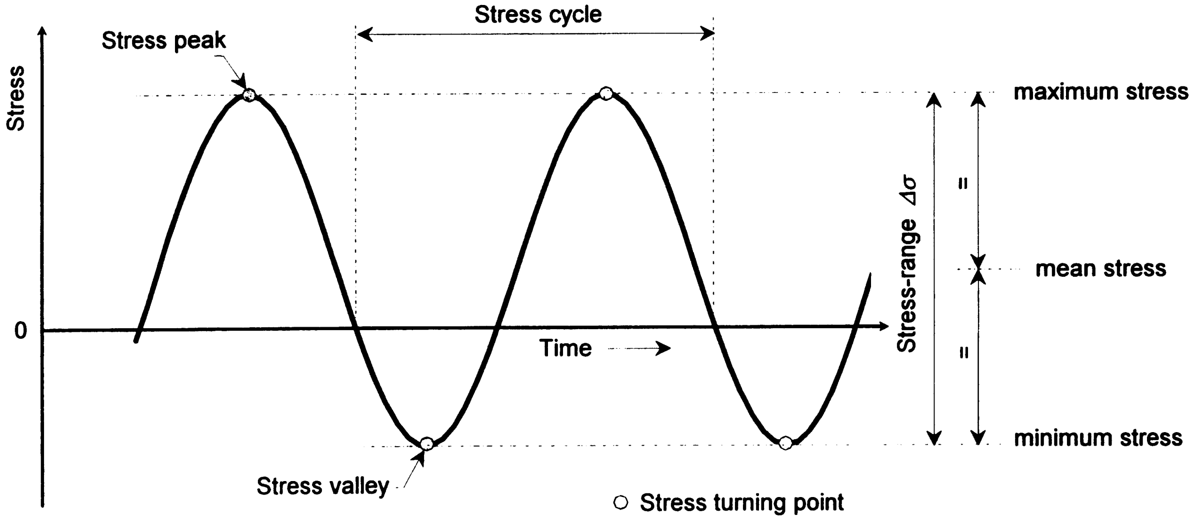
1.5.2 Special terms used in this Part 2 of Eurocode 9

(1)P The following terms are used in Part 2 of Eurocode 9 with the following meanings:

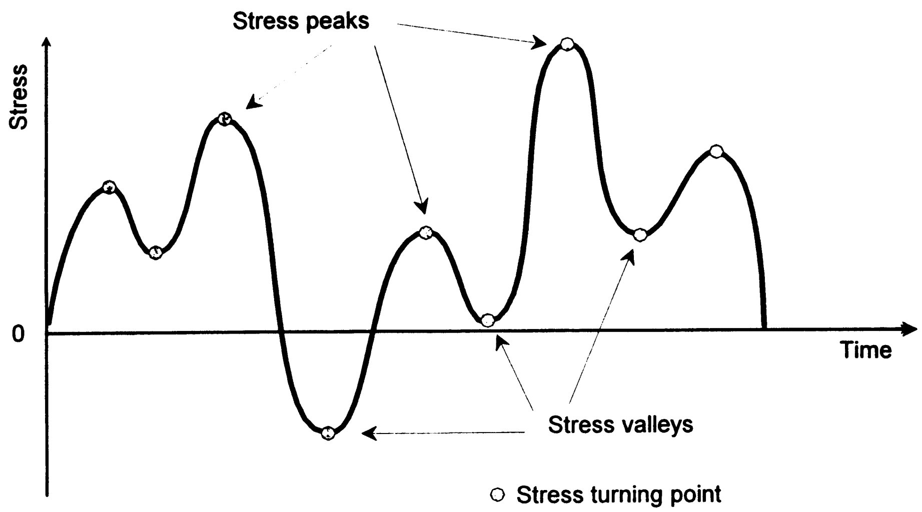
- **Fatigue:** Weakening of a structural part, through gradual crack propagation caused by repeated stress fluctuations.
- **Fatigue loading:** A set of typical load events described by the positions or movements of loads, their variation in intensity and their frequency and sequence of occurrence.
- **Loading event:** A defined loading sequence applied to the structure, which, for design purposes, is assumed to repeat at a given frequency.
- **Nominal stress:** A stress in the parent material adjacent to a potential crack location, calculated in accordance with simple elastic strength of materials theory, i.e. assuming that plane sections remain plane and that all stress concentration effects are ignored.
- **Modified nominal stress:** A nominal stress increased by an appropriate geometrical stress concentration factor K_{gt}, to allow only for geometric changes of cross section which have not been taken into account in the classification of a particular constructional detail.
- **Structural stress (also known as 'geometric stress'):** The elastic stress at a point, taking into account all geometrical discontinuities, but ignoring any local singularities where the transition radius tends to zero, such as notches due to small discontinuities, e.g. weld toes, cracks, cracklike features,

normal machining marks etc. The structural stress is in principle the same stress parameter as the modified nominal stress, but generally evaluated by a different method.

- **Geometrical stress concentration factor K_{gt}:** The ratio between the structural stress evaluated with the assumption of linear elastic behaviour of the material and the nominal stress.
- **Hot spot stress:** The structural stress at a specified initiation site in a particular type of geometry, such as a weld toe in an angle hollow section joint, for which the fatigue strength, expressed in terms of the hot spot stress range, is usually known.
- **Local stress concentration factor of a classified detail K_{cd}:** The ratio between the peak stress evaluated with a particular finite element method (FEM) analysis at the hot spot of a classified detail and the nominal stress.
- **Stress history:** A continuous chronological record, either measured or calculated, of the stress variation at a particular point in a structure, (usually for the duration of a loading event) (see Fig.1.5.1).
- **Stress turning point:** The value of stress in a stress history where the rate of change of stress changes sign (see Fig.1.5.1).



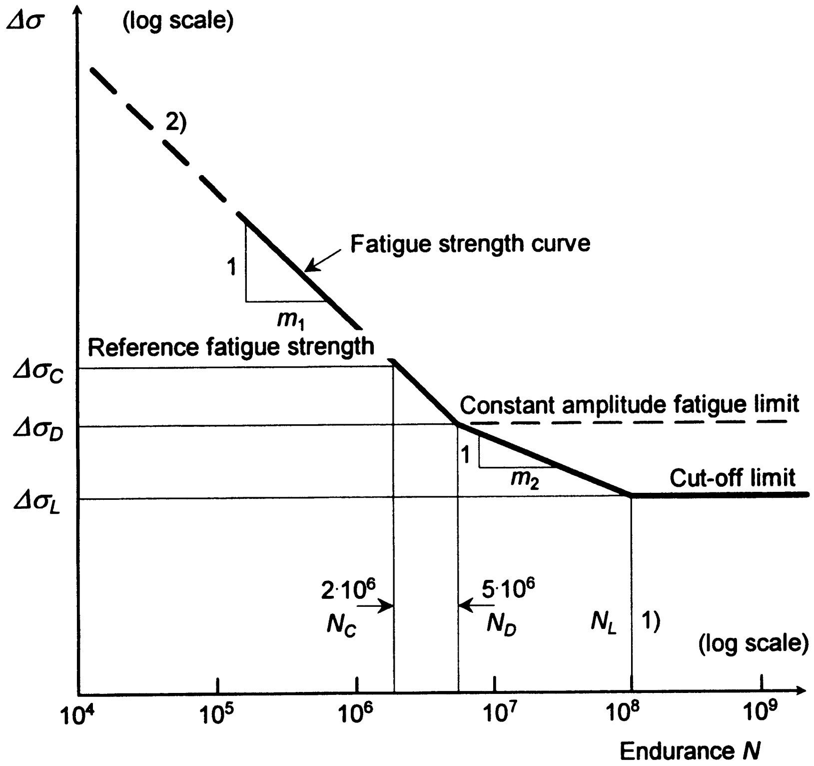
a) Constant amplitude



b) Variable amplitude

Fig.1.5.1 Terminology relating to stress histories and cycles

- **Stress peak:** A turning point where the rate of change of stress changes from positive to negative (see Fig.1.5.1).
- **Stress valley:** A turning point where the rate of change of stress changes from negative to positive (see Fig.1.5.1). (Also known as a 'stress trough').
- **Constant amplitude:** Relating to a stress history where the stress alternates between stress peaks and stress valleys of constant values (see Fig.1.5.1).
- **Variable amplitude:** Relating to any stress history containing more than one value of peak or valley stress (see Fig.1.5.1.)
- **Stress cycle:** Part of a constant amplitude stress history where the stress starts and finishes at the same value but, in doing so passes through one stress peak and one stress valley (in any sequence). Also, a specific part of a variable amplitude stress history as determined by a cycle counting method (see Fig.1.5.1).
- **Cycle counting:** The process of transforming a variable amplitude stress history into a spectrum of stress cycles, each with a particular stress range, e.g. the 'Reservoir' method and the 'Rain flow' method (see Fig.4.4.1).
- **Stress range:** The algebraic difference between the stress peak and the stress valley in a stress cycle.
- **Stress-range spectrum:** Histogram of the frequency of occurrence for all stress ranges of different magnitudes recorded or calculated for a particular loading event (also known as 'stress spectrum'.
- **Design spectrum:** The total of all stress-range spectra relevant to the fatigue assessment.
- **Detail category:** The designation given to a particular fatigue initiation site for a given direction of stress fluctuation in order to indicate which fatigue strength curve is applicable for the fatigue assessment.
- **Endurance:** The life to failure expressed in cycles, under the action of a constant amplitude stress history.
- **Fatigue strength curve:** The quantitative relationship relating stress range and endurance, used for the fatigue assessment of a category of constructional detail, plotted with logarithmic axes in this standard (see Fig.1.5.2).
- **Reference fatigue strength:** The constant amplitude stress range $\Delta\sigma_c$ for a particular detail category for an endurance $N = 2 \times 10^6$ cycles (see Fig.1.5.2).
- **Constant amplitude fatigue limit:** The stress range below which value all stress ranges in the design spectrum must lie for fatigue damage to be ignored (see Fig.1.5.2).
- **Cut-off limit:** Limit below which stress ranges of the design spectrum may be omitted from the cumulative damage calculation (see Fig.1.5.2).
- **Design life:** The reference period of time for which a structure is required to perform safely with an acceptable probability that structural failure by fatigue cracking will not occur.
- **Safe life:** The period of time for which a structure is estimated to perform safely with an acceptable probability that failure by fatigue cracking will not occur, when using the safe life design method.
- **Fatigue damage:** The ratio of the number of cycles of a given stress range which is required to be sustained during a specified period of service to the endurance of the detail under the same stress range.
- **Miner's summation:** The summation of the damage due to all cycles in a stress-range spectrum (or a design spectrum), based on the Palmgren-Miner rule.
- **Equivalent fatigue loading:** A simplified loading, usually a single load applied a prescribed number of times in such a way that it may be used in place of a more realistic set of loads, within a given range of conditions, to give an equivalent amount of fatigue damage, to an acceptable level of approximation.
- **Equivalent stress range:** The stress range at a detail caused by the application of an equivalent fatigue load.



Note 1: for certain environmental conditions see 5.4
Note 2: see 5.3.5 for N< 10^5

Fig. 1.5.2. Fatigue Strength Curve

1.6 Symbols

D	Fatigue damage calculated for a given period of service.
D_L	Fatigue damage calculated for the full design life.
L_{adh}	Effective length of adhesively bonded lap joints.
N	Number (or total number) of stress range cycles.
N_i	Endurance under stress range $\Delta\sigma_i$.
N_C	Number of cycles (2 million) at which the reference fatigue strength is defined.
N_D	Number of cycles (5 million) at which the constant amplitude fatigue limit is defined.
N_L	Number of cycles (100 million) at which the cut-off limit is defined.
R	Minimum stress divided by the maximum stress in a constant amplitude stress history or a cycle derived from a variable amplitude stress history. Also applies in the context of stress intensity.
T_f	Time for a crack to grow from a detectable size to a fracture critical size.
T_i	Inspection interval.
T_L	Design life
T_S	Safe life
$f_{v,adh}$	Characteristic shear strength of adhesive
k_{adh}	Fatigue strength factor for adhesive joints
k_N	Number of standard deviations above mean predicted number of cycles of loading.
k_F	Number of standard deviations above mean predicted intensity of loading.
l_d	Minimum detectable length of crack.
l_f	Fracture critical length of crack
m	Inverse slope constant of a log Δσ - log N fatigue strength curve.

m_1 Value of m for $N \leq 5 \times 10^6$ cycles.

m_2 Value of m for $5 \times 10^6 < N \leq 10^8$ cycles.

n_i Number of cycles of stress range $\Delta\sigma_i$.

γ_{Ff} Partial safety factor for fatigue load intensity.

γ_{Mf} Partial safety factor for fatigue strength.

σ_{max}, σ_{min} Maximum and minimum values of the fluctuating stresses in a stress cycle.

$\Delta\sigma$ Nominal stress range (normal stress).

$\Delta\sigma_{adh}$ Effective shear stress in adhesive.

$\Delta\sigma_C$ Reference fatigue strength at 2 million cycles (normal stress).

$\Delta\sigma_D$ Constant amplitude fatigue limit.

$\Delta\sigma_L$ Cut-off limit.

$\Delta\sigma_R$ Fatigue strength (normal stress).

log Logarithm to base 10.

1.7 Design Documents

1.7.1 Drawings

(1)P The drawings shall contain full details of all connections which are susceptible to fatigue, including component dimensions and fit-up tolerances, sizes and types of fastener, and weld throat, leg and penetration dimensions.

(2)P The required fatigue class shall be indicated for the relevant welded joints in accordance with 6.2.

1.7.2 Manufacturing specification

(1)P The manufacturing specification shall include all special requirements for material preparation, assembly, joining, post treatment and inspection as defined in the relevant Detail Category Tables 5.1.1 to 5.1.5 to ensure that the required fatigue strengths are achieved. See also Annex D.

1.7.3 Operation manual

(1)P The operation manual shall include:

- Details of the fatigue loadings and the design life assumed in the design.
- Any necessary requirements to monitor loading intensity and frequency during service.
- Limitations on future modification of the structure, in particular the making of holes or welding of attachments.
- Instructions for dismantling and reassembly of parts, eg. tightening of fasteners.
- Acceptable repair methods in the event of accidental damage in-service (e.g. dents, penetrations, tears, etc).

1.7.4 Maintenance manual

(1)P The maintenance manual shall include a schedule of any necessary in-service inspection of fatigue critical parts. Where damage tolerant design has been used this shall include:

- The methods of inspection
- The locations for inspection
- The frequency of inspections
- The maximum permissible crack size before correction is necessary
- Details of acceptable methods of repair or replacement of fatigue cracked parts

2 Basis of design

2.1 General

2.1.1 Design objective

(1)P The aim of designing a structure against the limit state of fatigue shall be to ensure, with an acceptable level of probability, that its performance is satisfactory during its entire design life, such that the structure will not fail by fatigue during the design life nor will it be likely to require premature repair of damage caused by fatigue.

2.1.2 Influence of fatigue on design

(1)P Structures subjected to frequently fluctuating service loads may be susceptible to failure by fatigue and shall be checked for that limit state.

(2)P The degree of compliance with the ultimate or serviceability limit state criteria given in Part 1-1 of Eurocode 9 shall not be used as a measure of the risk of fatigue failure (see 2.1.3).

(3)P The extent to which fatigue is likely to control the design shall be established as early as possible. The following factors shall be taken into account:

a) An accurate prediction of the complete service loading sequence throughout the design life shall be made.
b) The elastic response of the structure under these loads shall be accurately assessed.
c)Detail design, methods of manufacture and degree of quality control can have a major influence on fatigue strength, and may need to be controlled more precisely than for structures designed for other limit states (see 5 and Annex D). This can have a significant influence on design and construction cost.

2.1.3 Mechanism of failure

(1)P It shall be assumed that fatigue failure usually initiates at a highly stressed point (due to abrupt geometry change, tensile residual stress or sharp crack-like discontinuities). Fatigue cracks will extend incrementally under the action of cyclic stress change. They normally remain stable under constant load. Ultimate failure occurs when the remaining cross section is insufficient to carry the peak applied load.

(2)P It shall be assumed that fatigue cracks propagate approximately at right angles to the direction of maximum principal stress range. The rate of propagation increases exponentially. For this reason crack growth is often slow in the early stages, and fatigue cracks tend to be inconspicuous for the major part of their life. This may give rise to problems of detection in service (see Annex B).

2.1.4 Potential sites for fatigue cracking

(1)P The following initiation sites for fatigue cracks associated with specified details shall be considered:

a) toes and roots of fusion welds;
b) machined corners;
c) punched or drilled holes;
d) sheared or sawn edges;
e) surfaces under high contact pressure (fretting);
f) roots of fastener threads.

(2)P Fatigue cracks may also initiate at unspecified features, which may nevertheless occur in practice. The following shall be considered where relevant:

a) Material discontinuities or weld flaws;

b) Notches or scoring from mechanical damage;
c) Corrosion pits.

2.1.5 Conditions for fatigue susceptibility

(1) In assessing the likelihood of susceptibility to fatigue, the following should be taken into account:

a) High ratio of dynamic to static load: Moving or lifting structures, such as land or sea transport vehicles, cranes, etc. are more likely to be prone to fatigue problems than fixed structures, unless the latter are predominantly carrying moving loads, as in the case of bridges.

b) Frequent applications of load: This results in a high number of cycles in the design life. Slender structures or members with low natural frequencies are particularly prone to resonance and hence magnification of dynamic stress, even when the static design stresses are low. Structures subjected predominantly to fluid loading, such as wind, and structures supporting machinery should be carefully checked for resonant effects.

c) Use of welding: Some commonly used welded details have low fatigue strength. This applies not only to joints between members, but also to any attachment to a loaded member, whether or not the resulting connection is considered to be 'structural'.

d) Complexity of joint detail: Complex joints frequently result in high stress concentrations due to local variations in stiffness of the load path. Whilst these may often have little effect on the ultimate static capacity of the joint they can have a severe effect on fatigue resistance. If fatigue is dominant the member cross-sectional shape should be selected to ensure smoothness and simplicity of joint design, so that stresses can be calculated and adequate standards of fabrication and inspection can be assured.

e) Environment: In some thermal and chemical environments fatigue strength may be reduced if the surface of the metal is unprotected.

2.1.6 Methods of fatigue design

(1)P **Safe life design:** This method is based on the calculation of damage during the structure's design life using standard lower bound endurance data and an upper bound estimate of fatigue loading. This will provide a conservative estimate of fatigue life and in-service inspection shall not normally be considered essential for safety. The method is given in 2.2.

(2)P **Damage tolerant design**: This method is based on limiting the growth of fatigue cracking by means of a mandatory inspection programme. Once a fatigue crack has reached a pre-determined size the part shall be repaired or replaced. The method is given in 2.3.

NOTE: The method may be suitable to apply in certain applications where a safe life assessment shows that fatigue has a significant effect on design economy and a higher risk of fatigue cracking during the design life may be justified than is permitted using safe life design principles. Whilst the method is intended to result in a risk of ultimate structural failure comparable to that assumed for safe life design, it may result in a higher risk of temporary loss of serviceability.

(3)P **Design by testing:** This method shall be resorted to where the necessary loading data, response data, fatigue strength data or crack growth data are not available from standards or other sources for a particular application. Test data shall only be used in lieu of standard data on condition that they are obtained and applied under controlled conditions. Guidance is given in 2.4 and Annex C.

2.2 Safe Life Design

2.2.1 Prerequisites for safe life design

(1)P The predicted service history of the structure shall be available in terms of a loading sequence and frequency. Alternatively the stress response at all potential initiation sites shall be available in terms of stress histories.

(2) P The fatigue strength characteristics at all potential initiation sites shall be available in terms of fatigue strength curves.

(3)P The quality standards used in the manufacture of the components containing potential initiation sites shall be defined.

2.2.2 Calculation procedure for safe life design

(1) P Potential fatigue crack initiation sites in regions of the structure containing the highest stress fluctuations and/or the severest stress concentrations shall be checked first.

(2)P The basic procedure shall be as follows (see Figure 2.2.1):

a) An upper bound estimate of the service loading sequence for the structure's design life shall be obtained (see 3).
b) The resulting stress history at the potential initiation site being checked shall be estimated (see 4.1 and 4.2 or 4.3).
c) Where nominal stresses are being used, modify the stress history in any region of geometrical stress concentration which is not already included in the detail category, by applying an appropriate stress concentration factor (see 4.2).
d) The stress history shall be reduced to an equivalent number of cycles (n_i) of different stress ranges $\Delta\sigma_i$ using a cycle counting technique (see 4.4).
e) The cycles shall be ranked in descending order of amplitude $\Delta\sigma_i$ to form a stress-range spectrum, where i = 1, 2, 3 etc for the first, second, third band in the spectrum (see 4.5).
f) Categorise the detail in accordance with Tables 5.1.1 to 5.1.5. For the appropriate detail category and design stress range ($\Delta\sigma_i$), find the permissible endurance (N_i, etc.), from 5.2.1.
g) Calculate the total damage D_L for all cycles using Miner's summation where

$$D_L = \Sigma n_i/N_i \qquad (2.1)$$

h) Calculate the safe life T_s, where

$$T_S = T_L/D_L \qquad (2.2)$$

and where the design life of T_L has the same units as T_S
i) If T_s is less than T_L one or more of the following actions shall be taken:

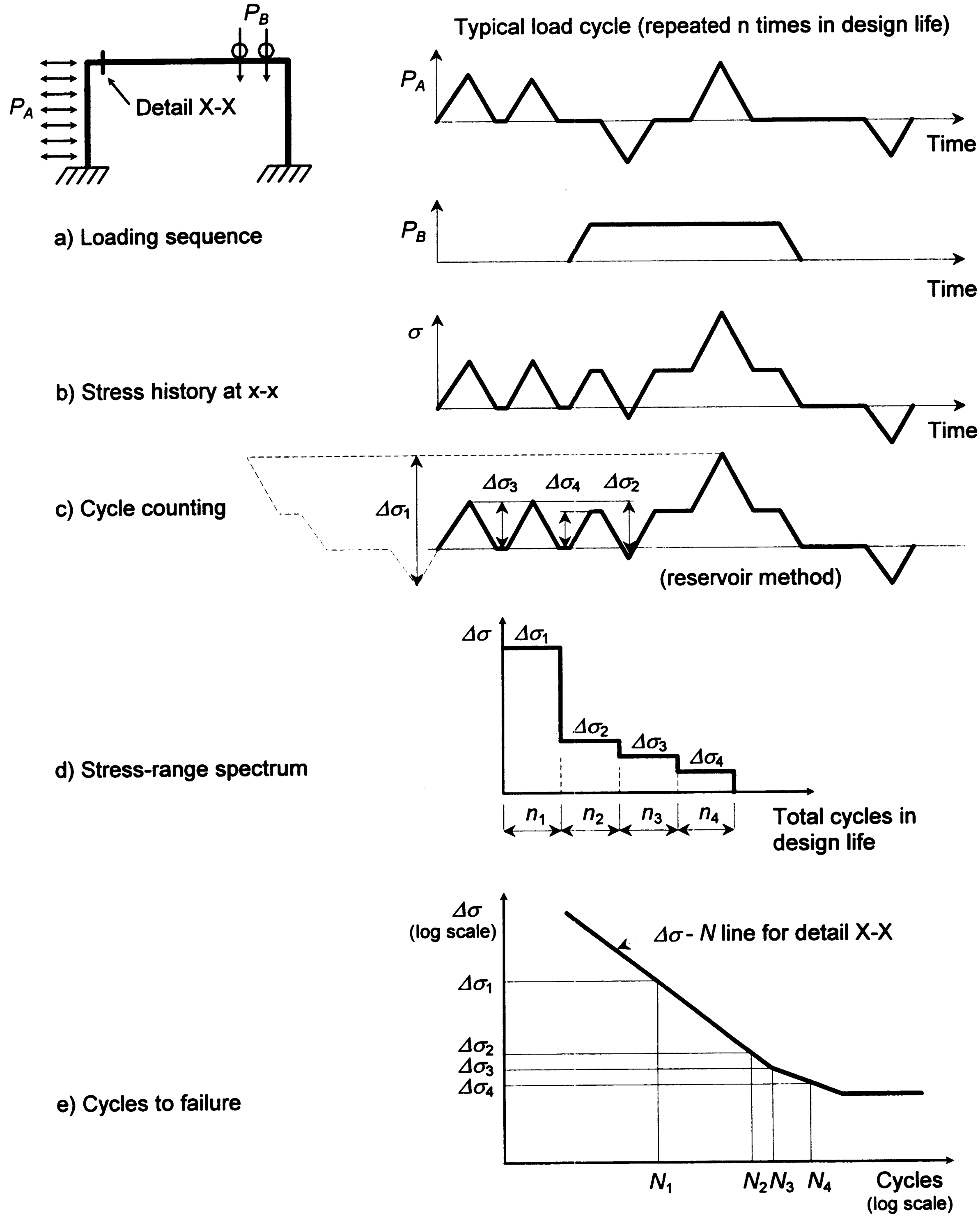
- redesign the structure or member to reduce the stress levels
- change the detail to one with a higher category (see 5.1)
- use a damage tolerant design approach, where appropriate (see 2.3)

2.3 Damage Tolerant Design

2.3.1 Prerequisites for damage tolerant design

(1)P Damage tolerant design shall only be used where the conditions in (2) to (6) below apply.

(2)P Damage tolerant design shall be applied to all initiation sites where the damage D_L for the full design life, calculated in accordance with 2.2, exceeds unity.



$$\sum \frac{n}{N} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \frac{n_4}{N_4} = D_L$$

Figure 2.2.1. Fatigue assessment procedure

(3)P The fatigue crack initiation sites determined in (2) shall be on or close to a surface which shall be readily accessible in service. The only exception shall be where safe alternative load paths are provided and details are designed to ensure that the cracks will be arrested without propagation beyond the first load path.

(4)P The procedure in 2.3.2 shall be applied to determine the inspection frequency and maximum permissible crack size before correction becomes necessary.

(5) Practical inspection methods shall be available which shall be capable of detecting the cracks and measuring their extent well before they have reached their fracture critical size.

(6) The maintenance manual shall specify the information listed in 1.8.4(1) for each crack location determined in (2).

2.3.2 Determination of inspection strategy for damage tolerant design

(1)P At each potential initiation site where the safe life T_s is less than the design life T_L shall be calculated in accordance with 2.2.

(2)P The maintenance manual shall specify that the first inspection of each potential initiation site shall take place before the safe life has elapsed.

(3)P The maintenance manual shall specify that subsequent inspections shall take place at regular intervals T_i, where

$$T_i \leq 0.5\ T_f$$

where T_f is the calculated time for a crack, having initiated at the site being assessed, to grow from a detectable surface length l_d to a fracture critical length l_f (see Fig. 2.3.1).

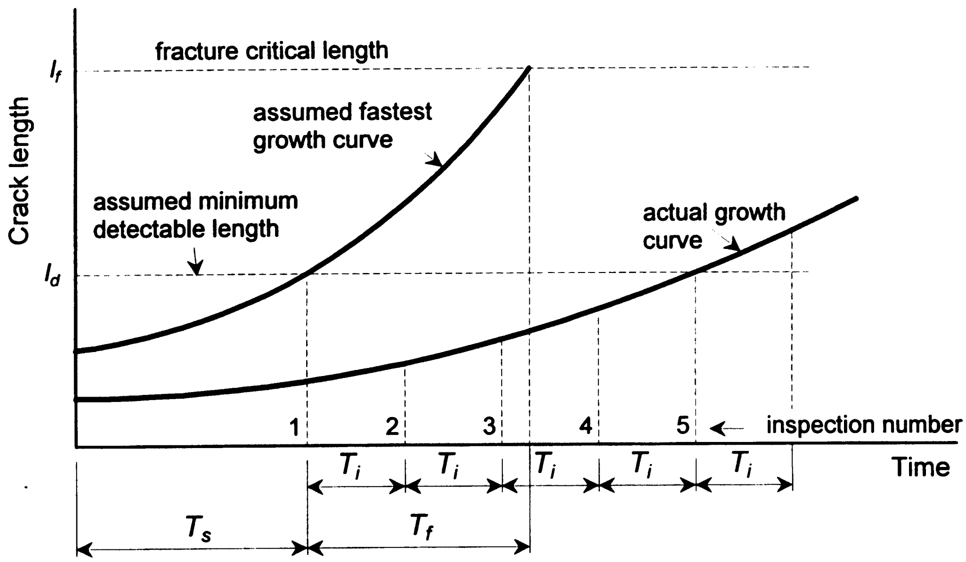


Figure 2.3.1. inspection strategy for damage tolerant design

(4)P The assumed minimum exposed length of surface crack shall take into consideration the accessibility, location, likely surface condition and method of inspection. Unless specific testing is undertaken to demonstrate that shorter lengths can be detected with a probability exceeding 90%, the assumed value of l_d shall not be less than the value in Table 2.3.1 where the full crack length is accessible for inspection.

Table 2.3.1 Minimum safe values of detectable surface crack length in mm.

Method of Inspection	Crack location		
	Plain smooth surface	Rough surface, Weld cap	Sharp corner, Weld toe
visual, with magnifying aid	20	30	50
Liquid penetrant testing	5	10	15
NOTE: The above values assume close access, good lighting and removal of surface coatings.			

(5)P Where any other permanent structural or non-structural part prevents full access to the crack, the obscured length of crack shall be added to the appropriate value in Table 2.3.1 to derive the value of l_d for calculation purposes.

(6) Where heavy constructional thicknesses are used and where the initiation site is on an inaccessible surface, (e.g. the root of a single sided butt weld in a tubular member), it may be appropriate to plan an inspection strategy based on the use of ultrasonic testing to detect and measure cracks before they reach the accessible surface. Such a strategy should not be undertaken without prior testing and evaluation.

(7)P The value of l_f shall be such that the net section, taking into account the likely shape of the crack profile through the thickness, shall be able to sustain the maximum static tensile forces under the factored loading, calculated in accordance with Part 1.1 of this Prestandard, without unstable crack propagation.

(8)P T_f shall be estimated by means of calculation and/or by test, assuming factored loading (see 3.4), as follows:

a) The calculation method shall be based on fracture mechanics principles (see Annex B). An upper bound crack growth relationship shall be used. Alternatively specific crack growth data may be obtained from standard test specimens using the same material as in the crack propagation path. In which case the crack growth rate shall be factored in accordance with the fatigue test factor F (see Table C.1).
b) Where crack growth is obtained from structural or component tests simulating the correct materials, geometry and method of manufacture the relevant applied force pattern shall be applied to the test specimen (see Annex C). The crack growth rates recorded between the crack lengths l_d and l_f shall be factored by the fatigue test factor F (see Table C.1).

(9)P The maintenance manual shall specify the actions to be taken in the event of discovery of a fatigue crack during a regular maintenance inspection, as follows:

a) If the measured crack length is less than l_d no remedial action need be taken.
b) If the measured crack length is equal to or exceeds l_d the component shall be assessed on a fitness-for-purpose basis with a view to determining how long the structure may safely be allowed to operate without rectification or replacement (see Annex B). In the event of continuation of operation consideration shall be given to increasing the frequency of inspection at the location in question.
c) If the measured crack length exceeds l_f the structure shall be immediately taken out of service.

2.4 Design Assisted by Testing

(1)P Verification of the fatigue resistance of a design by appropriate testing shall be accepted as an alternative method to those given in 2.2 and 2.3.

(2)P Where there are insufficient data for complete verification of a design by calculation alone in accordance with 2.1 or 2.2, supplementary evidence shall be provided by a specific testing programme. In which case test data may be required for one or more of the following reasons:

a) The applied loading history or spectrum, for either single or multiple loads, is not available and is beyond practical methods of theoretical calculation (see 3.1 and 3.2). This may apply particularly to moving, hydraulically or aerodynamically loaded structures where dynamic or resonance effects can occur. Guidance on methods of test is given in Annex C.1.
b) The geometry of the structure is sufficiently complex that estimates of member forces or local stress fields are beyond practical methods of calculation (see 4). Guidance on methods of test is given in Annex C.2.
c) The materials, dimensional details, or methods of manufacture of members or joints are different from those given in tables 5.1.1 to 5.1.5. Guidance on methods of test is given in Annex C.3.
d) Crack growth data are needed for damage tolerant design verification.

(3)P Testing may be carried out on complete prototype or production structures or on component parts of those structures. The degree to which the materials, dimensional details and methods of manufacture of the test structure or component shall match the final production structure shall take in to account the type of information being derived from the test.

(4)P Test data shall only be used in lieu of standard data if it is obtained and applied using controlled procedures (see Annex C.3).

3 Loading

3.1 Sources of Fatigue Loading

(1)P All sources of fluctuating stress in the structure shall be identified. The following shall receive particular attention:

a) superimposed moving loads, including vibrations from machinery in stationary structures;
b) environmental loads such as wind, waves, etc.;
c) acceleration forces in moving structures;
d) temperature changes.

(2)P The fatigue loading shall be obtained from ENV 1991 Eurocode 1 or other relevant loading standard, where available.

3.2 Derivation of Fatigue Loading

(1)P Loading for fatigue shall normally be described in terms of a design load spectrum, which defines a range of intensities of a specific live load event and the number of times that each intensity level is applied during the structure's design life. If two or more independent live load events are likely to occur then it will be necessary to specify the phasing between them.

(2)P Realistic assessment of the fatigue loading is crucial to the calculation of the life of the structure. Where no published data for live loading exist, resort shall be made to obtaining data from existing structures subjected to similar effects.

(3)P By recording continuous strain or deflection measurements over a suitable sampling period, loading data may be inferred by subsequent analysis of the response. Particular care shall be taken to assess dynamic magnification effects where loading frequencies are close to one of the natural frequencies of the structure. Further guidance is given in Annex C.1.

(4)P The design load spectrum shall be selected on the basis that it is an upper bound estimate of the accumulated service conditions over the full design life of the structure. Account shall be taken of all likely operational and environmental effects arising from the foreseeable usage of the structure during that period.

(5)P The confidence limit to be used for the intensity of the design load spectrum shall be based on the mean predicted value plus k_F standard deviations, where $k_F = 2$. The confidence limit to be used for the number of cycles in the design load spectrum shall be based on the mean predicted value plus k_N standard deviations, where $k_F = 2$. See also 3.4(2). The confidence limit to be used for the number of cycles in the design load spectrum shall be based on the mean predicted value plus k_N standard deviations, where $k_N = 2$. See also 3.4(2).

3.3 Equivalent Fatigue Loading

(1)P A simplified equivalent loading shall only be used in place of a more realistic fatigue loading if the following conditions are satisfied:

a) The aluminium alloy structure shall fall within the range of basic structural forms and size for which the equivalent fatigue loading was originally derived.
b) The real loading shall be of similar intensity and frequency and be applied in a similar way to that assumed in the derivation of the equivalent fatigue loading.
c) The values of m_1, m_2, N_D and N_L assumed in the derivation of equivalent fatigue loading shall be the same as those appropriate to the detail being assessed.

NOTE: Some equivalent fatigue loadings may have been derived assuming a simple continuous slope where $m_2 = m_1$ and $\Delta\sigma_L = 0$. For many applications involving numerous low amplitude cycles this will result in a very conservative estimate of life.

d) The dynamic response of the structure shall be sufficiently low that resonant effects, which will be affected by differences in mass, stiffness and damping coefficient, will have little effect on the overall damage summation.

(2)P In the event that an equivalent fatigue loading is derived specifically for an aluminium alloy structural application, all the matters addressed in 3.3(1) shall be taken into account.

3.4 Partial Safety Factors for Fatigue Loading

(1) Where the fatigue loading has been derived in accordance with the requirements of 3.2 a partial safety factor on load intensity $\gamma_{Ff} = \boxed{1,0}$ may be assumed to provide an acceptable level of safety.

(2) Where a fatigue loading has been based on other confidence limits than those in 3.2(4), an acceptable level of safety may be assumed to be provided by applying the partial safety factors on loading in Table 3.4.1.

Table 3.4.1: Partial safety factors for fatigue load intensity γ_{Ff}

k_F	γ_{Ff}	
	$k_N = 0$	$k_N = 2$
0	1,5	1,4
1	1,3	1,2
2	1,1	1,0

4 Stress Analysis

4.1 Global Stress Analysis

4.1.1 General

(1)P The method of analysis shall be selected so as to provide an accurate prediction of the elastic stress response of the structure to the specified fatigue loading.

NOTE: An elastic model used for static assessment (ultimate or serviceability limit state) in accordance with Part 1.1 of this Prestandard may not necessarily be adequate for fatigue assessment.

(2)P Dynamic effects shall be included in the calculation of the stress history, except where an equivalent loading is being applied which already allows for such effects.

(3)P Where the elastic response is significantly affected by degree of damping this shall be determined by test (see Annex C).

(4)P No plastic redistribution of forces between members shall be assumed in statically indeterminate structures.

(5)P The stiffening effect of any other materials which are permanently fixed to the aluminium alloy structure shall be taken into account in the elastic analysis.

(6)P Elastic finite element analysis models shall be used for the global analysis of statically indeterminate structures and latticed frames with rigid or semi rigid joints, except where strain data have been obtained from prototype structures or accurately scaled physical models.

NOTE: The term 'elastic finite element analysis' is used to note all analytical techniques where structural members and joints are represented by arrangements of bar, beam, membrane shell, solid or other element forms. The purpose of the analysis is to find the state of stress where displacement compatibility and static (or dynamic) equilibrium are maintained.

4.1.2 Use of beam elements

(1)P Beam elements shall be applicable to the global analysis of beam, framed or latticed structures subject to the limitations in (2) to (8) below.

(2)P Beam elements shall not be used for the fatigue analysis of stiffened plate structures of flat or shell construction or for cast or forged members unless of simple prismatic form.

(3)P The axial, bending, shear and torsional section stiffness properties of the beam elements shall be calculated in accordance with linear elastic theory assuming plane sections remain plane. However warping of the cross-section due to torsion shall be considered.

(4) Welded, bolted or adhesively bonded attachments of length greater than half the member depth should be considered when calculating the section stiffness properties (e.g. cover plates and longitudinal stiffeners).

(5)P Where beam elements are used in structures with open section members or hollow section members prone to warping, which are subjected to torsional forces, the elements shall have 7 degrees of freedom including warping. Alternatively, shell elements shall be used to model the cross-section.

(6)P The section properties for the beam elements adjacent to member intersections shall take into account the increased stiffness due to the size of the joint region and the presence of additional components (e.g. gussets, splice plates, etc.).

(7)P The stiffness properties of beam elements used to model joint regions at angled intersections between open or hollow members where their cross-sections are not carried fully through the joint (e.g. unstiffened tubulars nodes), or where the detail is semi-rigid (e.g. bolted end plate or angle cleat connections), shall be assessed either using shell elements or by connecting the elements via springs. The springs shall possess sufficient stiffness for each degree of freedom and their stiffness shall be determined either by tests or by shell element models of the joint.

(8)P Where beam elements are used to model a structure with eccentricities between member axes at joints or where loads and restraints are applied to members other than at their axes, rigid link elements shall be used at these positions to maintain the correct static equilibrium. Similar springs as in 4.1.2.(7) shall be used when necessary.

4.1.3 Use of membrane, shell and solid elements

(1)P Membrane elements shall only be applicable to those parts of a structure where out-of-plane bending stresses are known to be negligible.

(2)P Shell elements shall be applicable to all structural types except where cast, forged or machined members of complex shape involving 3-dimensional stress fields are used, in which case solid elements shall be used.

(3)P Where membrane or shell elements are used within the global analysis to take account of gross stress concentrating effects such as those listed in 4.2.2, the mesh size shall be small enough in the part of the member containing the initiation site to assess the effect fully (see Annex A).

4.2 Applicability of Nominal, Modified Nominal and Hot Spot Stresses

4.2.1. Nominal stresses

(1)P Nominal stresses shall be used directly for the assessment of initiation sites in simple members and joints where the following conditions apply:

a) The details associated with the site are in reasonable agreement with the appropriate detail category requirements in Tables 5.1.1 to 5.1.5.
b) The detail category has been established by test in accordance with Annex C and where the results have been expressed in terms of the nominal stresses.

c) Gross geometrical effects such as those listed in 4.2.2 are not present in the vicinity of the initiation site.

d) The crack initiation site is located at the root of a fillet weld or a partial penetration butt weld.

4.2.2 Modified nominal stresses

(1)P Modified nominal stresses shall be used in place of nominal stresses where the initiation site is in the vicinity of one or more of the following gross geometrical stress concentrating effects (see Fig.4.2.1) provided that conditions 4.2.1(a) and (b) still apply:

a) gross changes in cross section shape, e.g. at cut-outs or re-entrant corners,
b) gross changes in stiffness around the member cross-section at unstiffened angled junctions between open or hollow sections,
c) changes in direction or alignment beyond those permitted in tables 5.1.1 to 5.1.5,
d) shear lag and distortion in wide plated or hollow members,
e) non-linear out-of-plane bending effects in slender components such as flat plates where the static stress is close to the elastic critical stress, e.g. tension- field in webs (see Part 1 of this Prestandard).

4.2.3 Hot spot stresses

(1)P Hot spot stresses shall only be used where the following conditions apply:

a) The initiation site is a weld toe in a joint with complex geometry where the nominal stress is not clearly defined, or
b) A hot spot detail category has been established by test in accordance with Annex A and C where the results have been expressed in terms of the hot spot stress, for the appropriate loading mode.
c) Shell bending stresses are generated in flexible joints according to 4.1.2 (7).

4.3 Derivation of Stresses

4.3.1 Derivation of nominal stresses

4.3.1.1 Structural models using beam elements

(1)P The axial and shear stresses at the initiation site shall be calculated from the axial, bending, shear and torsional forces at the section concerned using linear elastic section properties.

(2)P The cross-sectional areas and section moduli shall take account of any specific requirements in tables 5.1.1 to 5.1.5.

4.3.1.2 Structural models using membrane, shell or solid elements

(1)P Where the axial stress distribution is linear across the member section about both axes, the stresses at the initiation point may be used directly.

(2)P Where the axial distribution is non-linear across the member section about either axis, the stresses across the section shall be integrated to obtain the axial force and bending moments. The latter shall be used in conjunction with the appropriate cross-sectional area and section moduli in accordance with tables 5.1.1 to 5.1.5 to obtain the nominal stresses.

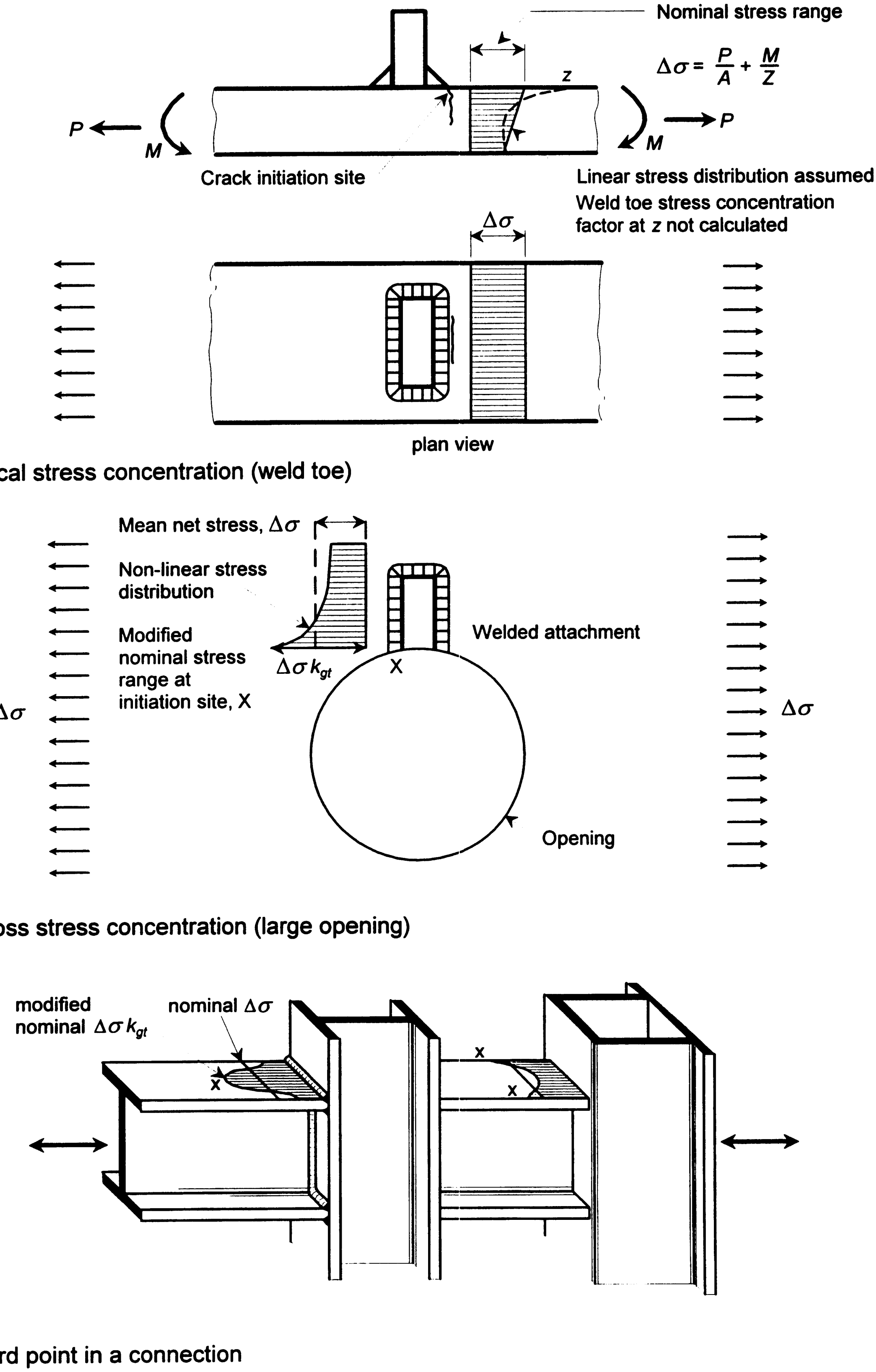


Figure 4.2.1. Effect of stress concentrations on nominal and modified nominal stresses

4.3.2 Derivation of modified nominal stresses

4.3.2.1 Structural models using beam elements

(1)P The nominal stresses shall be multiplied by the appropriate elastic stress concentration factors K_{gt} according to the location of the initiation site and the type of stress field.

(2)P K_{gt} shall take into account all geometrical discontinuities except for those already incorporated within the detail category (see Tables 5.1.1 to 5.1.5).

(3)P K_{gt} shall be determined by one of the following methods:

a) standard solutions for stress concentration factors (see Annex A)
b) substructuring of the surrounding geometry using shell elements taking into account (2), and applying the nominal stresses to the boundaries.
c) Measurement of elastic strains on a physical model which incorporates the gross geometrical discontinuities, but excludes those features already incorporated within the detail category (see (2)).

4.3.2.2 Structural models using membrane, shell or solid elements

(1)P Where the modified nominal stress is to be obtained from the global analysis in the region of the initiation site it shall be selected on the following basis:

a) local stress concentrations such as the classified detail and the weld profile already included in the detail category shall be omitted.
b) the mesh in the region of the initiation site shall be fine enough to predict the general stress field around the site accurately (see Annex A) but without incorporating the effects in (a).

4.3.3. Derivation of hot spot stresses

(1)P The hot spot stress is the principal stress predominantly transverse to the weld toe line and shall be evaluated in general by numerical or experimental methods (see Annex A), except where standard solutions are available. For simple cases, as the one shown in Fig.4.2.1(c), the hot spot stress should be evaluated by multiplying the nominal stress for the geometrical stress concentration factor K_{gt}, defined as the theoretical stress concentration evaluated for linear elastic material omitting all the influences (local or geometric) already included in the design $\Delta\sigma$-N curve of the classified detail considered as a reference.

(2)P In general, for structural configurations for which standard stress concentration factors are not applicable and which therefore require special analysis, the fatigue stress at the weld toe should omit the stress concentration effects due to the classified detail considered as a reference, i.e. the weld toe geometry.

4.3.4 Stress orientation

(1)P The principal stress range shall be greatest algebraic difference between the principal stresses acting in principal planes no more than 45° apart.

(2)P For the purposes of assessing whether a detail is normal or parallel to the axis of a weld if the direction of the principal tensile stress is less than 45° to the weld axis it shall be assumed to be parallel to it.

4.4 Stress range parameters for specific Initiation Sites

4.4.1 Parent material, full penetration butt welds and mechanically fastened joints (see Tables 5.1.5, 5.1.2, 5.1.3 and initiation sites 1,2,3,7 and 9 in Table 5.1.3).

(1)P Cracks initiating from weld toes, fastener holes, fraying surfaces, etc. and propagating through parent material or fully penetrated weld metal shall be assessed using the nominal principal stress range in the member at that point (see Fig.4.2.1).

(2)P The local stress concentration effects of weld profile, bolt and rivet holes, etc. shall be ignored as these are taken into account in the $\Delta\sigma$-N strength data for the appropriate detail class. They shall not be calculated (see tables 5.1.1 to 5.1.5).

4.4.2 Fillet and partial penetration butt welds (see initiation sites 4, 5, 6, 8 and 11 in table 5.1.3).

(1) Cracks initiating from weld roots and propagating through the weld throat should be assessed using the vector sum of the shear forces in the weld metal based on an effective throat dimension (see figure 4.4.1).

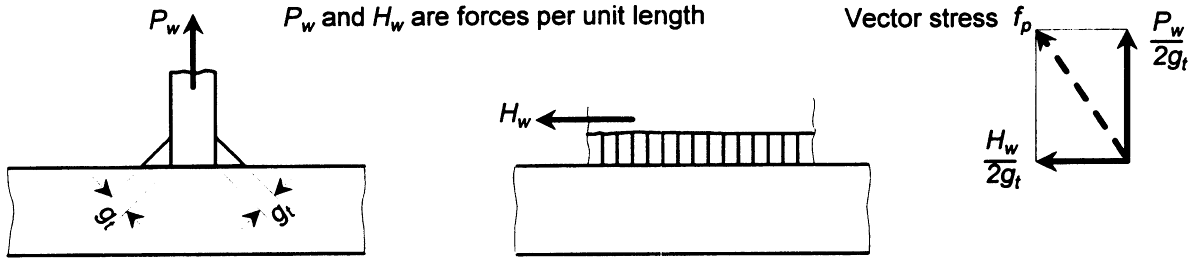


Fig.4.4.1 Stresses in weld throats

(2) In lapped joints in one plane the stress per unit length of weld may be calculated on the basis of the average area for axial forces and an elastic polar modulus of the weld group for in-plane moments (see figure 4.4.2).

(3)P In tee-joints any effect of different axial stiffness along the joint shall be taken into account (see Fig.4.2.1(c)).

(4) Where single fillets or incompletely penetrated butt welds are subjected to out-of-plane bending moments the stresses at the root should be calculated using a linear stress distribution through the throat (see figure 4.4.3).

(5)No allowance should be made for bearing contact on the root face in partially penetrated welded joints.

4.4.3 Adhesive bonds (see Table 5.1.5).

(1)P For lap joints failing in the bond line, the effective shear stress range $\Delta\sigma_{adh}$ shall be based on the force per unit width of the joint divided by the effective length of the lap L_{adh}, where:

L_{adh} = lap length L, where $L \leq 15$mm (see table 5.1.5)
L_{adh} = 15mm, where $L > 15$mm

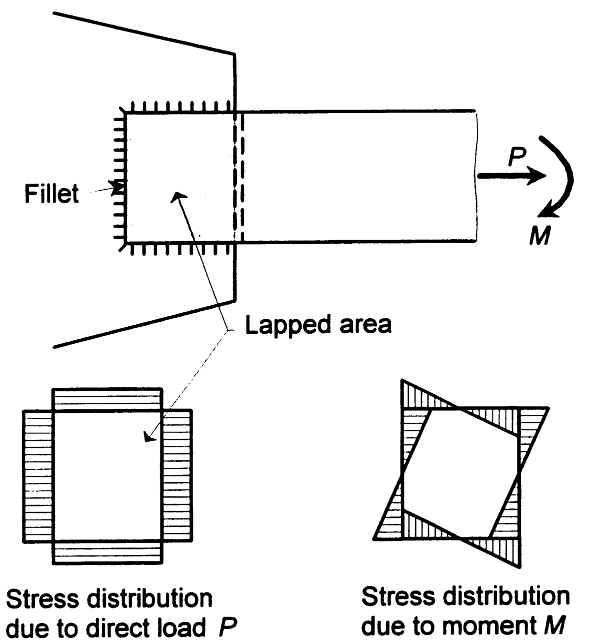


Figure.4.4.2 Stresses in lapped joints

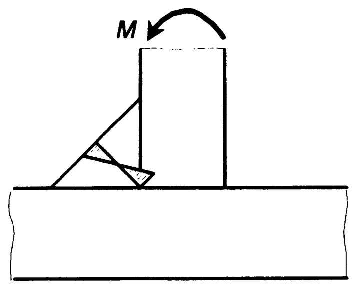


Figure 4.4.3. Stresses in root of fillet weld

4.4.4 Castings

(1)P The principal structural stress shall be obtained using finite stress analysis or strain gauging in the case of complex shapes, when standard solutions are not available.

4.5 Stress Spectra

4.5.1 Cycle counting

(1) Cycle counting is a procedure for breaking down a complex stress history into a convenient spectrum of cycles in terms of stress range $\Delta\sigma$, number of cycles n and, if necessary, R ratio (see figure 2.2.1 and 5.3). There are various methods in use.

(2) For short stress histories where simple loading events are repeated a number of times, the Reservoir method is recommended. It is easy to visualise and simple to use (see figure 4.5.1). Where long stress histories have to be used, such as those obtained from measured strains in actual structures (see Annex C) the Rain-Flow method is recommended. Both methods are suitable for computer analysis.

4.5.2 Derivation of stress spectrum

(1) The listing of cycles in descending order of $\Delta\sigma$ amplitude results in a stress spectrum. For ease of calculation it may be required to simplify a complex spectrum into fewer bands. A conservative method is to group bands together into larger groups containing the same total number of cycles, but whose amplitude is equal to that of the highest band in the group. More accurately, the weighted average of all the bands in one group can be calculated using the power m, where m is the inverse slope of the $\Delta\sigma$-N curve most likely to be used (see figure 4.5.2). The use of an arithmetic mean value will always be unconservative.

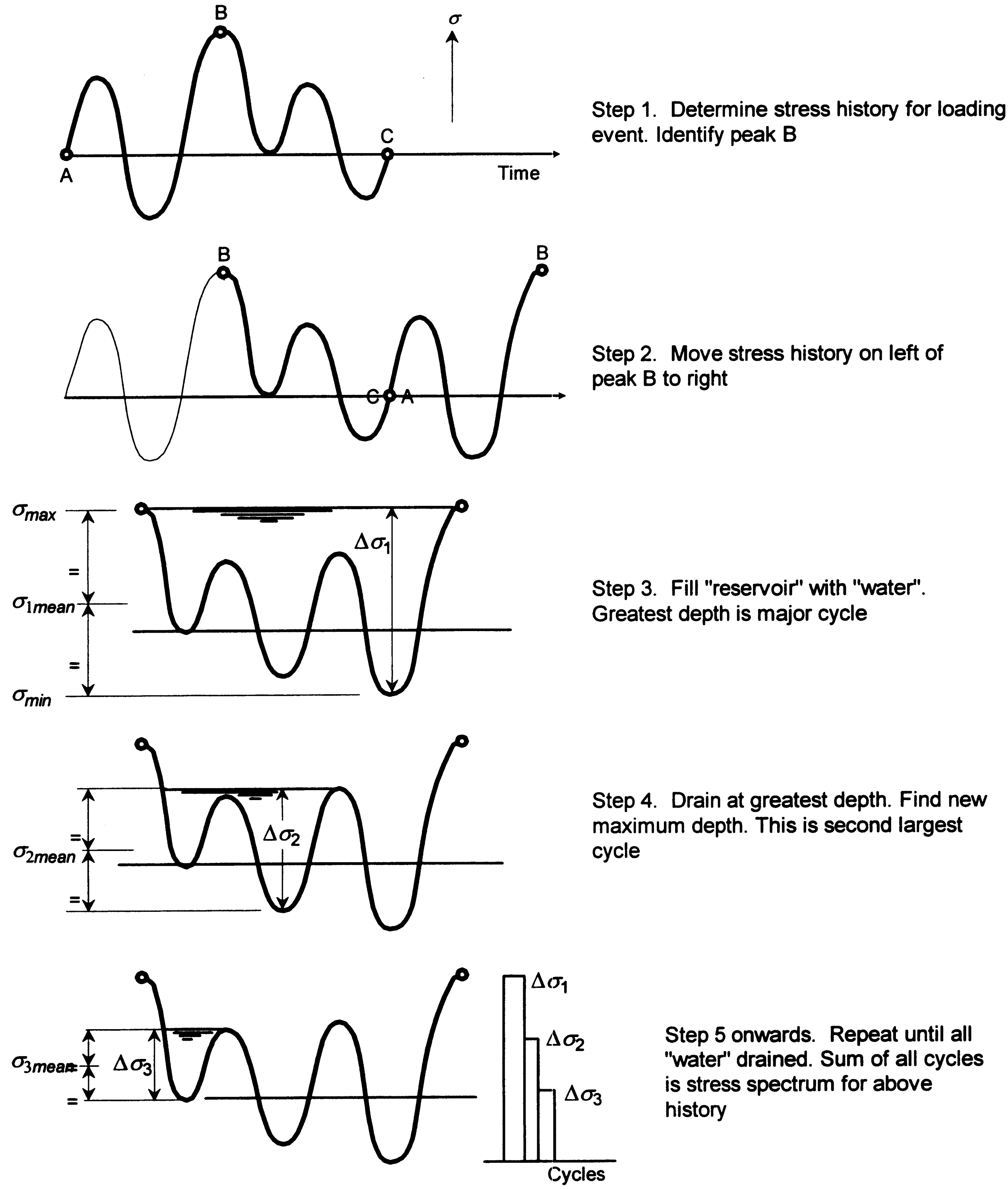
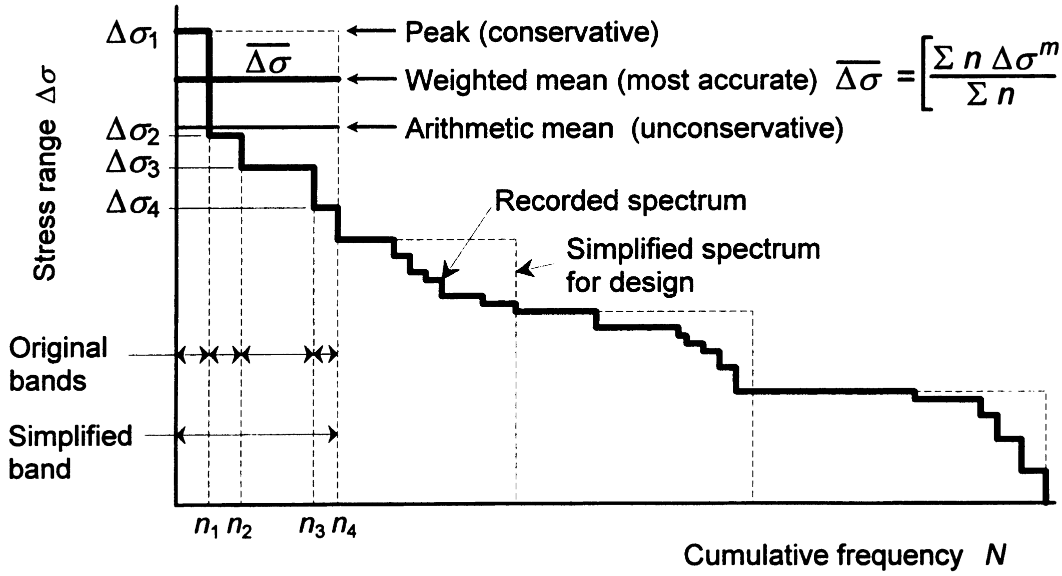


Fig.4.5.1 Reservoir cycle counting method



$$\overline{\Delta\sigma} = \left[\frac{\Sigma\, n\, \Delta\sigma^m}{\Sigma\, n}\right]^{1/m}$$

Figure 4.5.2. Simplified Stress Range Spectrum

5 Fatigue strength

5.1 Detail Categories

5.1.1 Factors affecting detail category

(1)P The fatigue strength of a detail shall take into account the following factors:

a) the direction of the fluctuating stress relative to the detail;
b) the location of the initiating crack in the detail;
c) the geometrical arrangement and relative proportion of the detail.

(2) The fatigue strength may also depend on the following:

d) the product form;
e) the material (unless welded);
f) the method of fabrication;
g) the degree of inspection after fabrication;
h) the quality level (in the case of welds and castings).

5.1.2 Detail Category tables

(1) The detail categories for more commonly used details have been divided into five basic groups, namely:

a) non-welded details in wrought and cast alloys (see table 5.1.1)
b) welded details on surface of loaded member (see tables 5.1.2(a) and 5.1.2(b))
c) welded details at end connections (see table 5.1.3)
d) mechanically fastened joints (see table 5.1.4)
e) adhesively bonded joints (see table 5.1.5)

5.2 Fatigue Strength Data

5.2.1 Classified details

(1)P The generalised form of the $\Delta\sigma$-N relationship is shown in figure 1.5.2, plotted on logarithmic scales. The design curve represents a mean minus 2 standard deviation level below the mean line through experimental data.

(2)P The basic fatigue design relationship for endurances less than 5 x 10^6 cycles is defined by the equation:

$$N_i = 2 \times 10^6 \times \left(\frac{\Delta\sigma_c}{\Delta\sigma_i} \frac{1}{\gamma_{Ff}\,\gamma_{Mf}} \right)^{m_l} \qquad (5.1)$$

where:

N_i is the predicted number of cycles to failure of a stress range $\Delta\sigma_i$
$\Delta\sigma_c$ is the reference value of fatigue strength at 2 x 10^6 cycles, depending on the category of detail;
$\Delta\sigma_i$ s the principal stress range at the detail and is constant for all cycles;
m_l is the inverse slope of the $\Delta\sigma$-N curve, depending on the detail category;
γ_{Ff} is the partial safety factor allowing for uncertainties in loading spectrum and analysis of response (see 3.4);
γ_{Mf} is the partial safety factor for uncertainties in materials and execution (see 5.2.1(3)).

(3) For normal applications where the design conforms with this Prestandard, including the manufacturing requirements of Annex D, a value of γ_{Mf}= [1,0] may be applied (but see 5.2.3(3) in the case of adhesively bonded joints).

(4) The constant amplitude fatigue limit, $\Delta\sigma_D$, occurs at 5x10^6 cycles, below which constant amplitude stress cycles are assumed to be non-damaging. However, even if occasional cycles occur above this level, they will cause propagation which, as the crack extends, will cause lower amplitude cycles to become damaging. For this reason the inverse logarithmic slope m_2 of the basic $\Delta\sigma$-N curves between 5 x 10^6 and 10^8 cycles should be changed to m_2 for general spectrum loading conditions, where $m_2 = m_l + 2$.

(5)Any stress cycles below the cut-off limit $\Delta\sigma_L$, which occurs at 10^8 cycles, should be assumed to be non-damaging.

(6) The $\Delta\sigma$-N relationship is fully described by the double number detail category $\Delta\sigma_c$ - m_l where $\Delta\sigma_c$ is an integer expressed in units of N/mm^2. Their values are given in tables 5.1.1 to 5.1.5. The $\Delta\sigma$-N curves are given in figures 5.2.1 to 5.2.5.

(7) For the purpose of defining a finite range of categories and to enable a category to be increased or decreased by a constant geometric interval, a standard range of $\Delta\sigma_c$ values is given in table 5.2.6. An increase (or decrease) of 1 category means selecting the next larger (or smaller) $\Delta\sigma_c$ value whilst leaving m_l and m_2 unchanged.

8)P The detail categories are safe for all values of mean stress (see 5.3) but do not allow for environments other than ambient (see 5.4).

9) The use of the $m_2 = m_1 + 2$ inverse slope constant may be conservative for some spectra. Where a design is critically dependent on this region and where maximum economy is sought it may be appropriate to consider using component testing (see Annex C.3.1) or applying fracture mechanics analysis (see Annex B).

(10)P The detail category values in tables 5.1.2(b) and 5.1.3 shown in brackets are attainable only with high weld quality levels which are not readily verifiable by normal non-destructive testing techniques. In order to meet the needs of quality assurance, bracketed values should only be used where special inspection procedures are applied which have been demonstrated to be capable of detecting and evaluating critical sizes of weld discontinuity which shall have been established by fracture mechanics or testing (see Annex B and C).

5.2.2 Unclassified details

(1)Details not fully covered by tables 5.1.1 to 5.1.5 should be assessed by reference to published data where available. Alternatively fatigue acceptance tests may be carried out in accordance with Annex C.3

5.2.3 Adhesively bonded joints

(1) Design of adhesive joints should consider the following:

- Peel loading should be reduced to a minimum.
- Stress concentrations should be minimised.
- Strains in the parent metal should be kept below yield.
- Chemical conversion or anodizing of the surfaces generally improves fatigue life compared to degreasing or mechanical abrasion.
- Aggressive environments usually reduce fatigue life.

(2)The reference fatigue strength of an adhesively bonded lap joint which fails in the bond line is defined by the equation:

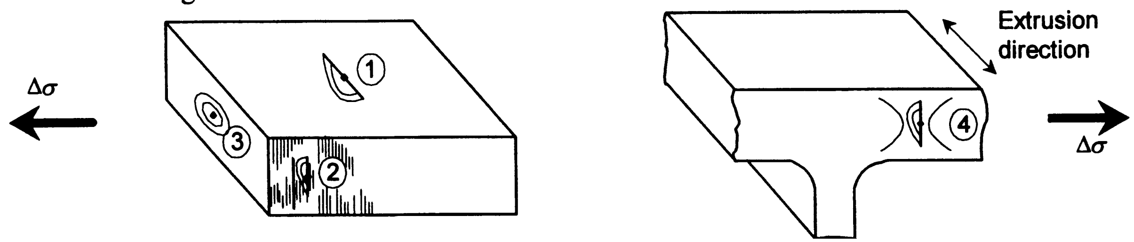
$$\Delta\sigma_c = k_{c,adh} \cdot f_{v,adh} \qquad (5.2)$$

where

$k_{c,adh}$ is the value of the adhesive joint fatigue strength factor k_{adh} at $N = 2x10^6$ cycles
$f_{v,adh}$ is the characteristic shear strength of the adhesive obtained from a standard static lap shear test (see Part 1.1 of this Prestandard).

(3)Testing under representative conditions of geometry, workmanship and environment is recommended for critical applications. Otherwise a high value of γ_{Mf} should be used.

Table 5.1.1 Detail Categories for Plain Material



Product Forms		Sheet, Plate, Simple Extruded Rod and Bar		Shaped Extrusions, Tubes, Forgings		Sheet, Plate, Solid Extrusions, Forgings		Hollow Extrusions		Castings	
Initiation Site	Reference No.	1, 2		1, 2		1, 2		2		1	3
	Location	Small surface irregularity	→		→	→	→	Extrusion seam		Surface irregularity	Internal discontinuity
Stress orientation (see 4.3.4)		PARALLEL to rolling or extrusion direction			→	NORMAL to rolling ›r extrusion direction		NORMAL to extrusion direction		-	-
Alloys		7020	as table 1.1.1 (except 7020)	7020	as table 1.1.1 (except 7020)	7020	as table 11.1 (except 7̸20)	7020	6**** series as table 1.1.1	as table 1.1.2	
Particular Requirements	Dimensional	Surfaces free of sharp corners unless parallel to stress direction				→	→	→	→	→	→
		No re-entrant corners in profile, No contact with other parts									
	Fabrication	Machining only by high speed milling cutter		Hand grinding not permitted unless parallel to stress direction				Extruded by port hole or bridge die		Casting as per Table 1.1.2. Machining permitted if by high speed milling cutter.	
	Inspection/Testing	Visual	→	→	→	→	→	Drift tests at extrusion ends		Dye Pen. Annex D	Radiography table D.3
	Quality Standard	Surface finish ($R_a < 0.5$mm)		No score marks transverse to stress direction			→	No drift test fracture along weld seam		Annex D	table D.4
Stress Analysis	Stress parameter	Principal structural stress at initiation site			→	→	→	→	→	→	→
	Stress concentrations already allowed for	Surface texture	→	→	→	→	→	→	→	→	Permitted internal porosity
Type Number		1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10
Detail Category $\Delta\sigma_c$ - m_1		**121 - 7**	**86 - 7**	**96 - 7**	**69 - 7**	**96 - 7**	**69 - 7**	**86 - 7**	**62 - 7**	**77 - 6**	**77 - 6**

Key: → requirement continues from left to right

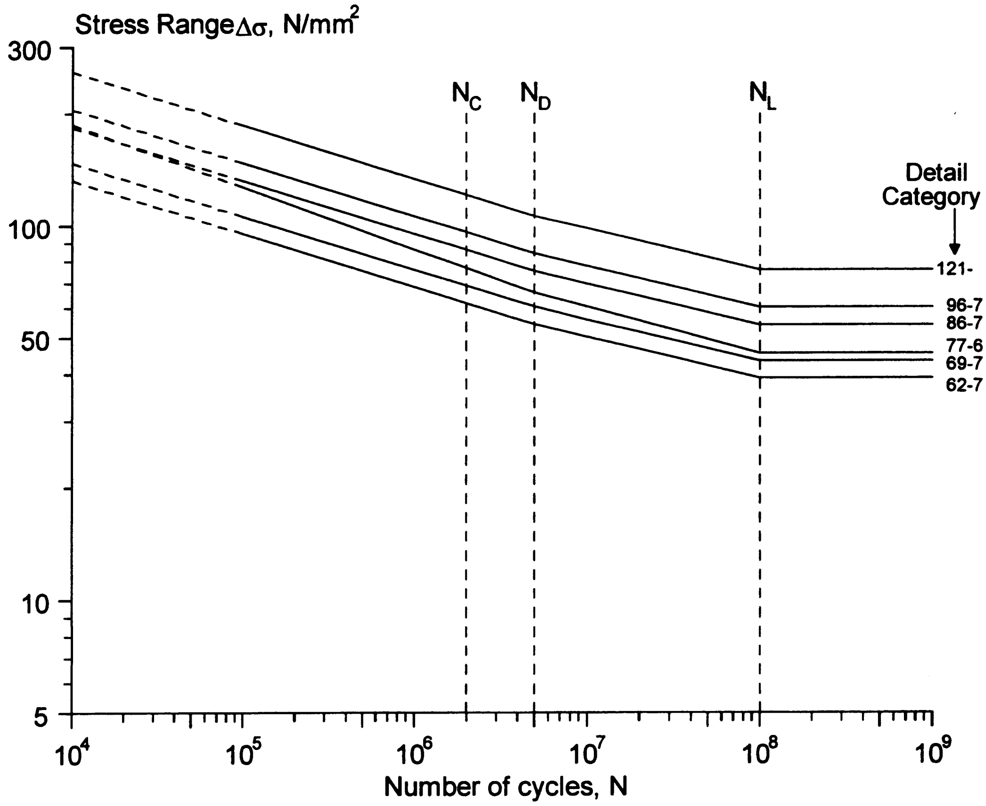
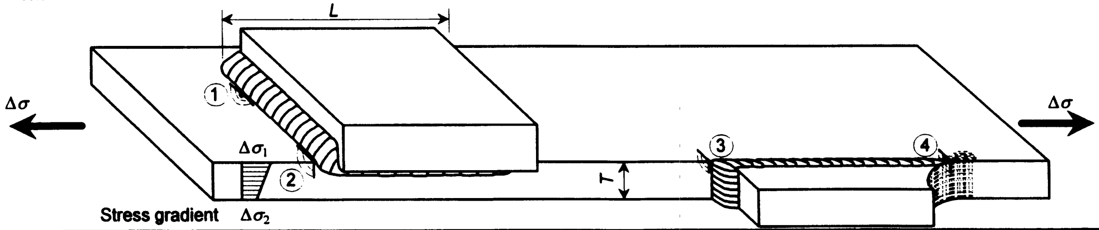


Fig. 5.2.1 Δσ-N curves for plain material

Table 5.2.1 Numerical values of Δσ (N/mm²) for plain material

Detail Category ($N = 2 \times 10^6$)		$N = 10^5$	$N_D = 5 \times 10^6$	$N_L = 10^8$
$\Delta\sigma_c$	m_1	$\Delta\sigma$	$\Delta\sigma_D$	$\Delta\sigma_L$
121	7	185,6	106,2	76,1
96	7	147,3	84,2	60,4
86	7	131,9	74,4	54,1
77	6	126,9	66,1	45,5
69	7	105,9	60,5	43,4
62	7	95,1	54,4	39,0

Table 5.1.2(a) Members with Welded Attachments - Transverse Weld Toe



Product Forms			Rolled, extruded and forged products												
Initiation site	Reference No.		1								2	3	4		
	Location		At transverse weld toe on stressed member						→	→	→	→	At longitudinal weld end		
			on surface away from edge				→	→	→	→	At corner	On edge	In ground weld toe on edge		
Stress orientation (see 4.3.4)			Normal to transverse weld toe				→	→	→	→	→	→	Parallel to weld axis		
Alloys			As table 1.1.1.		→	→	→	→	→	→	→	→	→	→	→
Particular Require- ments	Dimensional	Joint Geometry	Attachment on member surface				→	→	→	→	→	Attachment on member edge			→
			Weld on surface away from corner					→	→	→	Welded round corner	Weld on edge		→	→
		Length L(mm) > ≤	0 10	10 20	20 30	30 50	50 80	80 120	120 200	200 ¥	L and T as for Types 2.1 to 2.8	No Radius	Corner radius R (mm)		
		Thickness T (mm)	See table below			→	→	→	→	→			10<R≤20	20≤R≤40	R>40
	Fabrication										Grind undercut smooth		Grind radius in direction of Δσ*		
	Inspection/testing		As Annex D table D1			→	→	→	→	→	→	→	→	→	→
	Quality standard		As Annex D table D2			→	→	→	→	→	→	→	→	→	→
Stress Analysis	Stress Parameter		Nominal stress at initiation site				→	→	→	→	→	→	→	→	→
	Stress concentrations already allowed for		Weld profile permitted by Annex D Table D2						→	→	→	→	→	→	→
			Stiffening effect of attachment				→	→	→	→	→	→	→	→	→
Type Number			2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10	2.11	2.12	2.13
Detail Category $\Delta\sigma_c$ m_1 = 3,2 for all types		T≤4	**31**	**28**	**25**	**25**	**25**	**25**	**25**	**25**	As Types 2.1 to 2.8, but reduced by one Detail Category	**18**	**25**	**28**	**31**
		4<T≤10	**31**	**28**	**25**	**22**	**22**	**22**	**22**	**22**					
		10<T≤15	**31**	**28**	**25**	**22**	**20**	**20**	**20**	**20**					
		15<T≤25	**31**	**28**	**25**	**22**	**20**	**18**	**18**	**18**					
		25<T≤40	**31**	**28**	**25**	**22**	**20**	**18**	**16**	**16**					
		T > 40	**31**	**28**	**25**	**22**	**20**	**18**	**16**	**14**					
Adjustment for stress gradient			where $\Delta\sigma_1$ and Δ_2 are of opposite sign increase by 2 Categories where T≤15mm or 1 Category where 15<T≤40mm												

Key: * Weld toe shall be fully ground out →requirement continuous from left to right

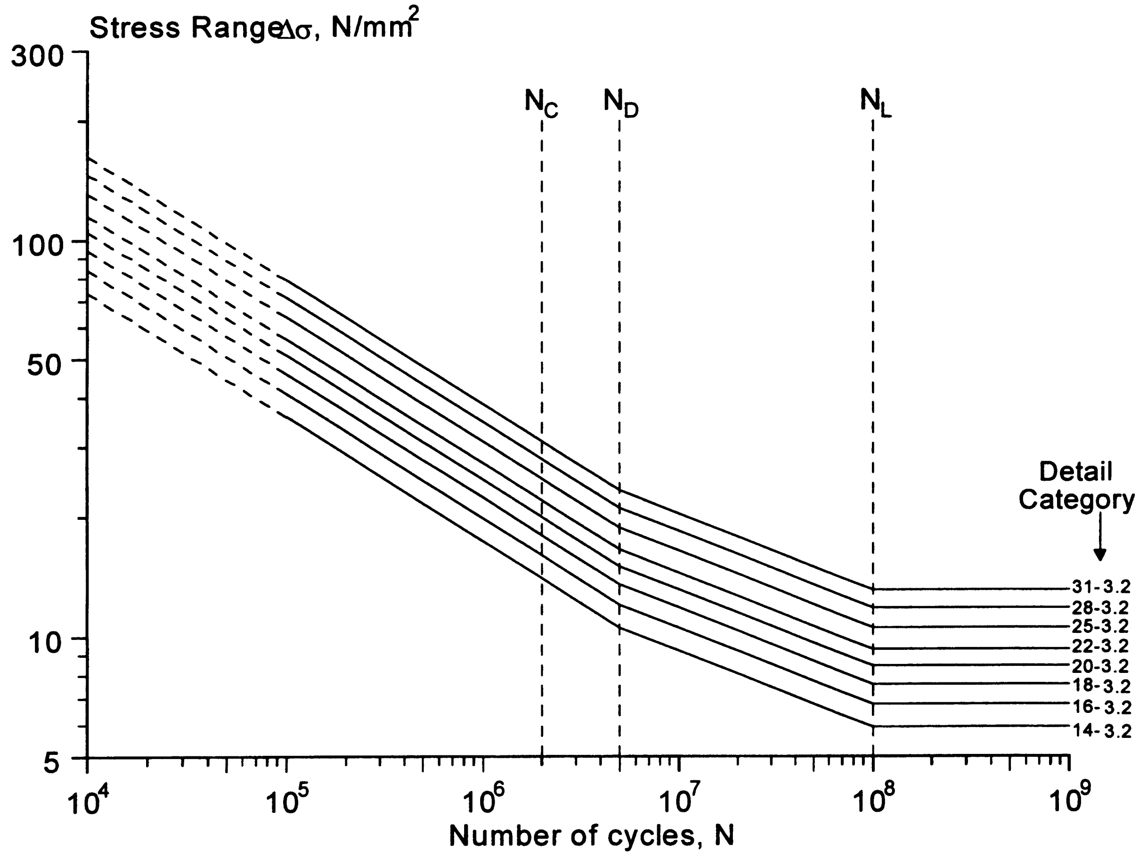
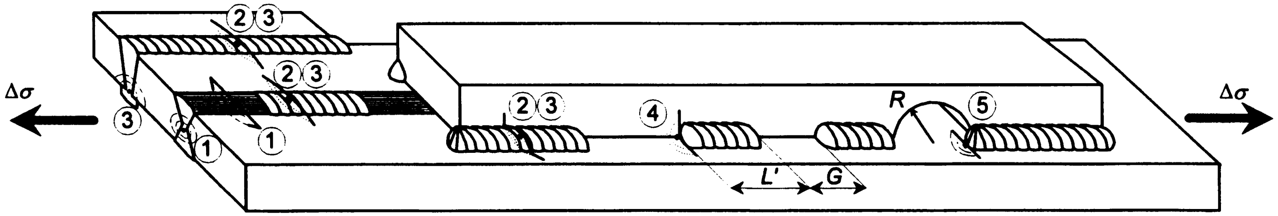


Fig. 5.2.2(a) Δσ-N curves for members with welded attachments - transverse weld toe

Table 5.2.2(a) Numerical values of Δσ (N/mm²) for members with welded attachments - transverse weld toe

Detail Category ($N = 2 \times 10^6$)		$N = 10^5$	$N_D = 5 \times 10^6$	$N_L = 10^8$
$\Delta\sigma_c$	m_1	$\Delta\sigma$	$\Delta\sigma_D$	$\Delta\sigma_L$
31	3,2	79,1	23,2	13,1
28	3,2	71,4	21,0	11,8
25	3,2	63,8	18,8	10,6
22	3,2	56,1	16,5	9,3
20	3,2	51,0	15,0	8,4
18	3,2	45,9	13,5	7,6
16	3,2	40,8	12,0	6,8
14	3,2	35,7	10,5	5,9

Table 5.1.2(b) Detail Categories for Members with Welded Attachments - Longitudinal Welds



Product Forms		Rolled, extruded and forged products				
Initiation Site	Reference No.	1	2	3	4	5
	Location	A weld discontinuity	weld ripple	Stop-start	Weld toe or crater	Weld toe or crater
Stress orientation (see 4.)		Parallel to weld axis	→	→	→	→
Alloys		As table 1.1.1.	→	→	→	→
Particular Requirements	Dimensional	Full penetration			Intermittent fillet weld	Cope hole centred on weld axis
		Double sided butt weld			$G \leq 2.5L'$	$R \leq 25mm$
	Manufacturing	Continuous automatic welding				
		Weld caps ground flush in direction of Ds				
		Any backing bars (and attachment welds) to be continuous →				
	Inspection/Testing	As Annex D Table D1	→	→	→	→
	Quality Standard	As Annex D Table D2	→	→	→	→
Stress Analysis	Stress Parameters	Nominal stress at initiation site	→	→	→	→
		Any attachment material to be included in section properties			→	→
	Stress concentrations already allowed for	Weld discontinuities permitted by Annex D Table D.1.		→	→	→
						presence of cope hole
Type Number		2.14	2.15	2.16	2.17	2.18
Detail Category $\Delta\sigma_c$-m_1		(60-4,5) **55**-4,5	**44**-4,5	**35**-4	**31**-3,5	**28**-3,5

Key: → requirement continuous from left to right ( ) Before using values in brackets see 5.2.1(10)

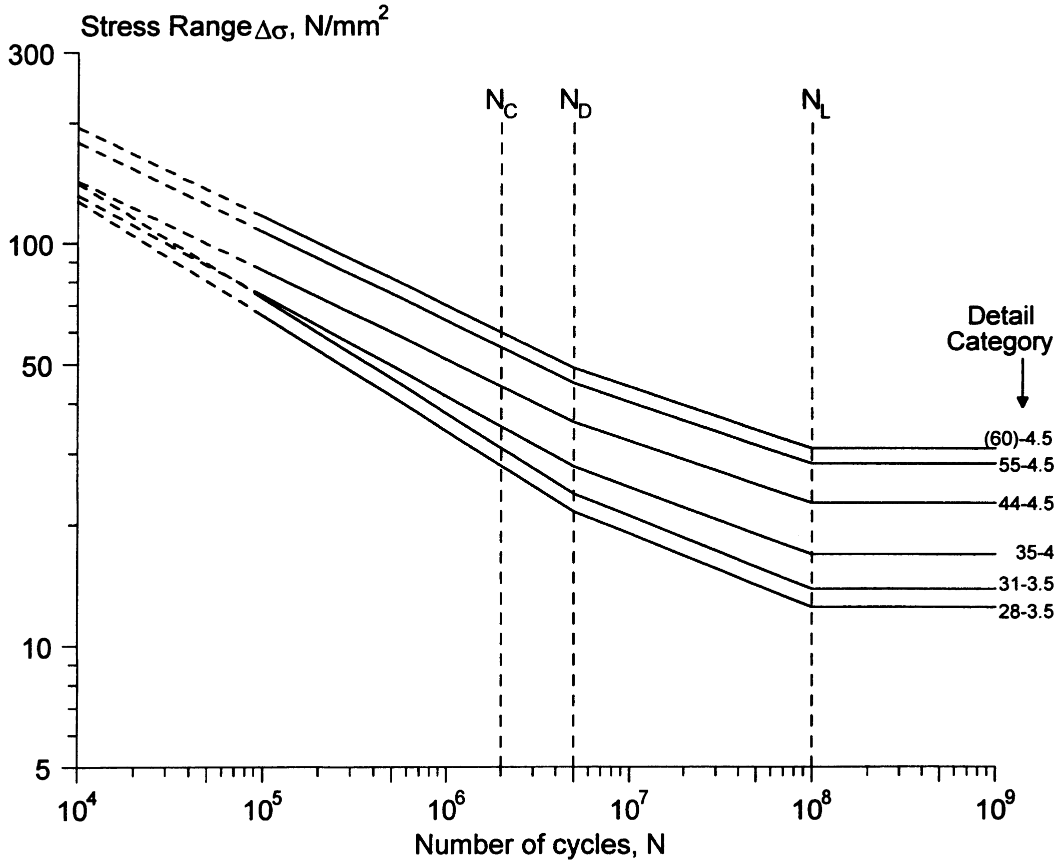
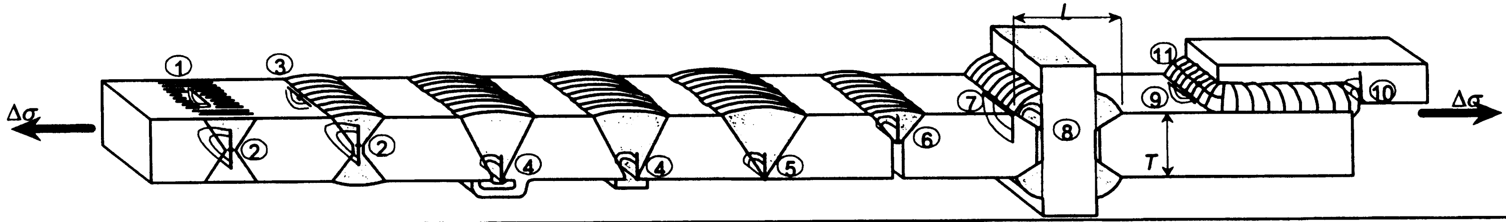


Fig. 5.2.2(b) Δσ-N curves for members with welded attachments - longitudinal welds

Table 5.2.2(b) Numerical values of Δσ (N/mm²) for members with welded attachments - longitudinal welds

Detail Category ($N = 2 \times 10^6$)		$N = 10^5$	$N_D = 5 \times 10^6$	$N_L = 10^8$
$\Delta\sigma_c$	m_1	$\Delta\sigma$	$\Delta\sigma_D$	$\Delta\sigma_L$
(60)	4,5	116,8	48,9	30,9
55	4,5	107,0	44,9	28,3
44	4,5	85,6	35,9	22,6
35	4	74,0	27,8	16,8
31	3,5	73,0	23,9	13,8
28	3,5	65,9	21,6	12,5

Table 5.1.3 Detail Categories for Welded Joints Between Members



			3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	3.10	
Product Forms			Rolled, extruded and forged products			→	→	→	→	→	→	→	Castings
Initiation sites	Reference No.		1, 2	3, 2	4	5	6	7		8	9, 10	11	as Types 3.1 to 3.10
	Locations		surface or embedded discontinuity	weld toe or embedded discontinuity	weld root	root discontinuity	unfused root	weld toe	weld toe	weld root	weld toe	weld root	
Stress orientation (see 4....)			Normal to weld axis		→	→	→	→	→	→	→	→	
Alloys			As tab 1.1.1	→	→	→	→	→	→	→	→	→	tab 1.1.2
Particular Requirements	Dimensional	Joint type	**In-line butt**	→	→	→	→	**Cruciform or Tee**		→	**Lap**	→	as Types 3.1 to 3.10
		Weld type	Butt	→	→	→	→	Butt			fillet	→	
		Preparation	Double sided	→	Single sided	→	→						
		Penetration	Full	→	→	→	partial	full	partial	→			
		Transition	Taper slope £1 in 4 at width or thickness change →				→						
	Manufacturing	Root	Ground	→	Backed	Unbacked		Ground					
		Cap	Ground flush										
		Ends	Extension plates used on ends, cut off and ground flush in direction of Δσ					→	→	→			
	Inspection/Testing		As Annex D Table D.1		→	→	→	→	→	→	→	→	
	Quality Standard		As Annex D Table D.2		→	→	→	→	→	→	→	→	
Stress Analysis	Stress parameter		Net throat + specified misalignment stress (no overfill)				→	net section		net throat	net section	net throat	
	Stress concentration effects included in Detail Category		Profile, unspecified misalignment and discontinuities permitted by Annex D Table D.2						→	→	→	→	
								Stiffening effect of transverse element			stress peaks at weld ends		
Type Number			3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	3.10	3.11to3.20
Detail Category $\Delta\sigma_c$ - m_I		Flats, solid	(55-6) **44-5**	(39-4) **35-4**	(35-4) **25-3,2**	(29-3,2) **18-3,2**	**14-3,2**	as Table 5.1.2(a) Types 2.1 to 2.9		**18-3,2**	as Types 3.6 and 3.7	**14-3,2**	as Types 3.1 to 3.10 less 1 Detail Category
		Open shapes	(44-5) **28-4**	(35-4) **28-4**									
		Hollow	NA	NA									

Key: NA = not applicable, → requirement continuous from left to right ( ) Before using values in brackets see 5.2.1(10)

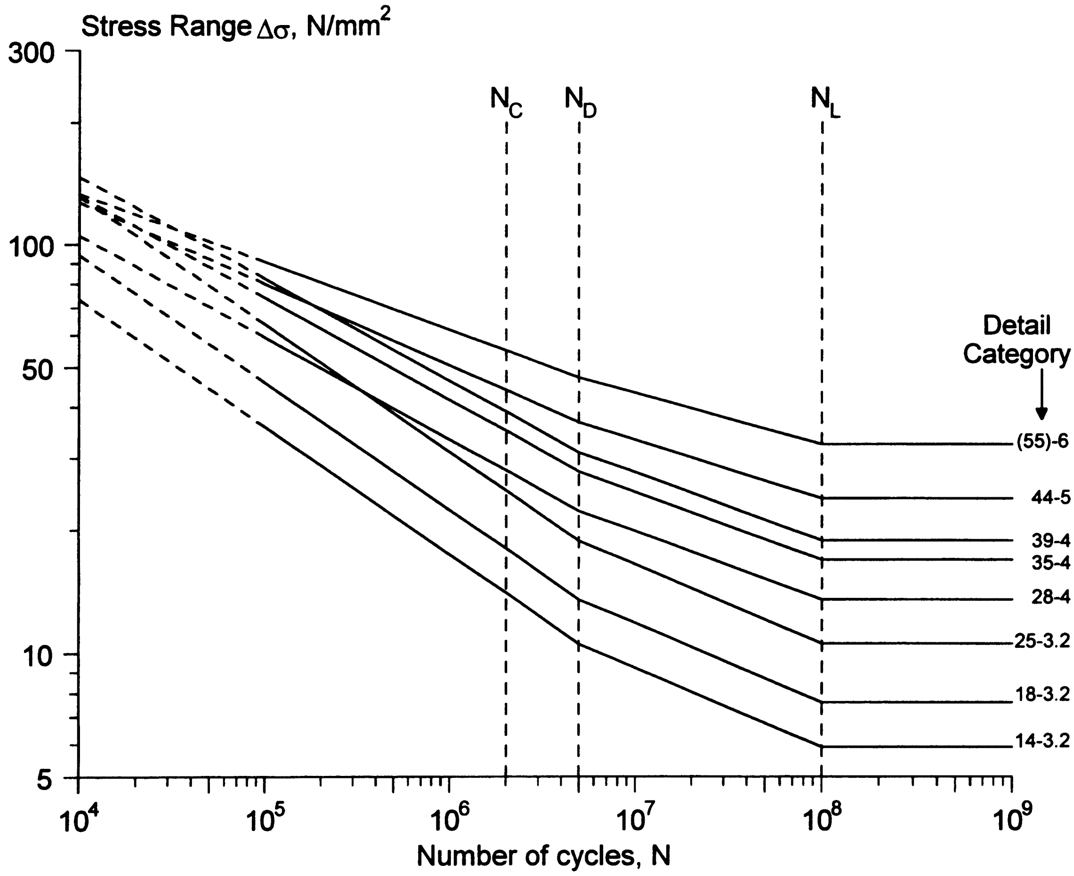
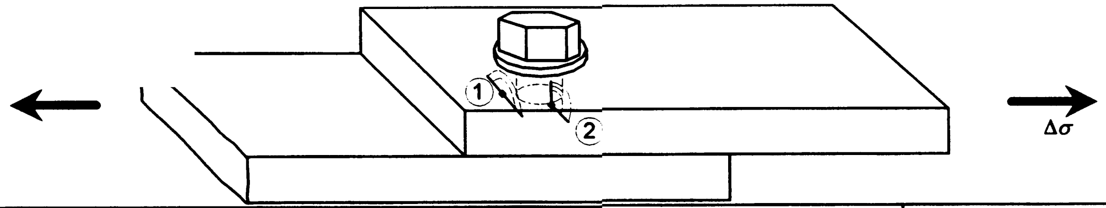


Fig. 5.2.3 Δσ-N curves for welded joints between members

Table 5.2.3 Numerical values of Δσ (N/mm²) for welded joints between members

Detail Category ($N_0 = 2 \times 10^6$)		$N = 10^5$	$N_D = 5 \times 10^6$	$N_L = 10^8$
$\Delta\sigma_c$	m_1	$\Delta\sigma$	$\Delta\sigma_D$	$\Delta\sigma_L$
(55)	6	90,6	47,2	32,5
44	5	80,1	36,6	23,9
39	4	82,5	31,0	18,8
35	4	74,0	27,8	16,8
28	4	59,2	22,3	13,5
25	3,2	63,8	18,8	10,6
18	3,2	45,9	13,5	7,6
14	3,2	35,7	10,5	5,9



Fastener Type		Preloaded (Friction Type)		Non-Preloaded (Bearing Type)	
		High strength bolt	Tensioned Rivet	Bolt	Driven Rivet
Product Forms		Rolled, extruded and forged products	→	→	→
Initiation site	Reference no.	1, (2)	1, (2)	2	2
	Location	In front of hole (sometimes at edge of hole)	→	Edge of hole	→
Stress orientation		Parallel to rolling or extrusion direction	→	→	→
Alloys		As table 1.1.1	→	→	→
Fastener Materials		Steel, $R_{p0,2}$ ³ 640 N/mm²	→	As Part 1	→
Particular Requirements	Dimensional	Lap joint with flat parallel surfaces	→	Lap joint	→
		Steel washer under bolt head and nut			
	Fabrication	Machining only by high speed milling cutter	→	→	→
		Holes drilled (with optional reaming) <u>or</u> punched (with compulsory reaming if thickness >6mm)			→
	Assembly	Degreased or shot blast faying surfaces to be in full contact with 30% pre-load in all bolts	Degreased or shot blast faying surfaces to be in full contact using temporary bolts	Holes in plies to be aligned within ± 0.5mm	
	Fastening	Bolts to be torqued to minimum of 85% of proof load	Rivet head to be swaged whilst rivet under a minimum 85% proof load	Bolts to be torqued to minimum 50% proof load unless lock nuts used	Rivets driven until faying surfaces in contact
	Inspection/Testing	Final torque/nut rotation checked after tightening complete		Final torque checked if lock nuts not used	
Stress Analysis	Stress Parameter	Nominal stress based on GROSS section properties	→	Nominal stress based on NET section properties	
	Stress concentrations already allowed for	Surface texture, fastener hole geometry, unequal load distribution between rows of bolts, eccentricity of load path in SYMMETRICAL DOUBLE COVERED lap joints only		→	→
Type Number		4.1	4.2	4.3	4.4
Detail Category $\Delta\sigma_c$ - m_1		**55 - 4**	**55 - 4**	**55 - 4**	**55 - 4**

Key → requirement continues from left to right

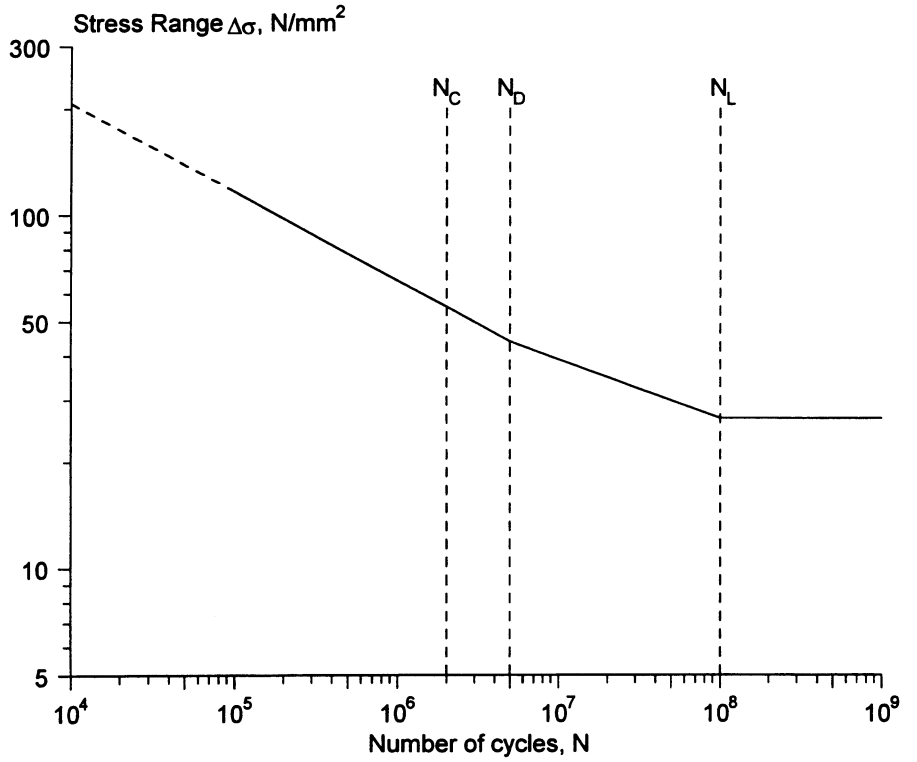
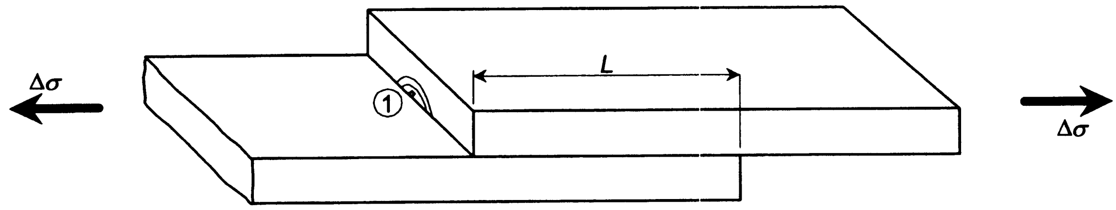


Fig. 5.2.4 Δσ-N curve for mechanically fastened joints

Table 5.2.4. Numerical values for Δσ (N/mm^2) for mechanically fastened joints

Detail Category ($N = 2 \times 10^6$)		$N = 10^5$	$N_D = 5 \times 10^6$	$N_L = 10^8$
$\Delta\sigma_c$	m_1	$\Delta\sigma$	$\Delta\sigma_D$	$\Delta\sigma_L$
55	4	116.3	43.7	26.5

Table 5.1.5 Detail Category for Adhesively Bonded Joints



Product Forms		Rolled, extruded and forged products
Initiation site	Reference No.	1
	Description	In bond line at leading edge
Stress orientation		Normal to leading edge
Alloys		As table 1.1.1
Adhesives		Single and two-part epoxies
Particular Requirements	Dimensional	Lap joint Thickness of thinner part ≤ 8mm
	Fabrication	Machining only by high speed milling cutter
	Surface Preparation	Degreasing or chromate conversion
	Assembly	Bond line thickness within tolerances specified for shear strength test
	Inspection/Testing	as Part 1-1
Stress Analysis	Stress Parameter	Average shear stress based on a effective length L_{adh} (see 4.4.3(11))
	Stress concentrations already allowed for	Stress peak at leading edge, eccentricity of load path in symmetrical double covered lap joints only
Detail Category $\Delta\sigma_c$ - m_1		0,11 f_{vadh} - 6

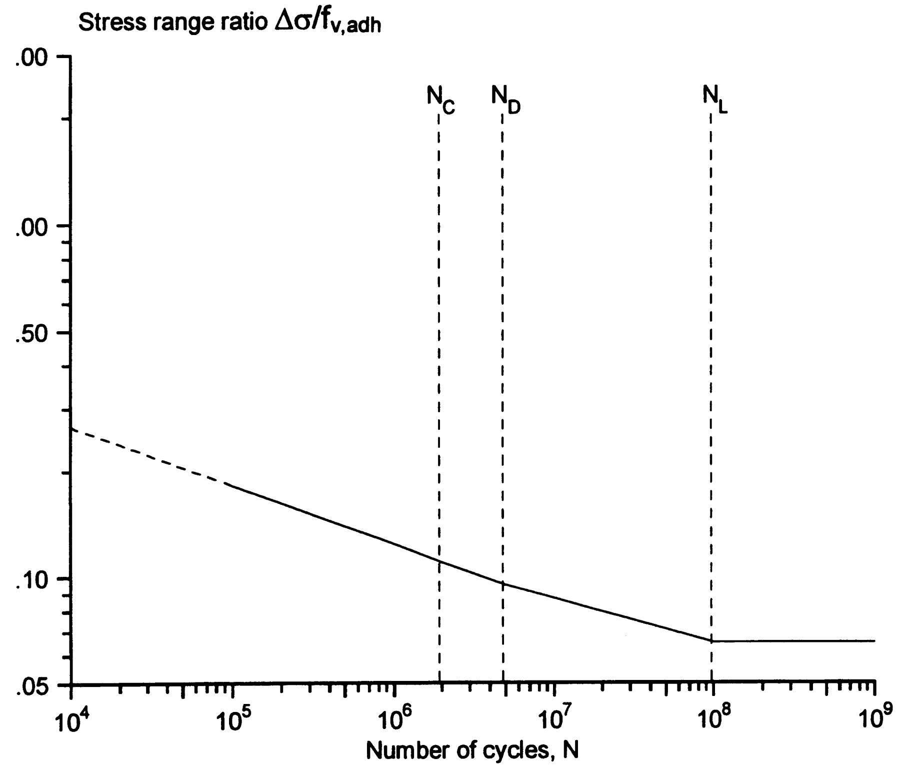


Fig. 5.2.5 $\Delta\sigma/f_{v,adh}$-N curve for adhesively bonded joints

Table 5.2.5. Numerical values for k_{adh} ($=\Delta\sigma/f_{v,adh}$) for adhesively bonded joints

Detail Category ($N = 2 \times 10^6$)		$N = 10^5$	$N_D = 5 \times 10^6$	$N_L = 10^8$
$\Delta\sigma_c/f_{v,adh}$	m_1	$\Delta\sigma/f_{v,adh}$	$\Delta\sigma_D/f_{v,adh}$	$\Delta\sigma_L/f_{v,adh}$
0.11	6	0.181	0.94	0.065

Table 5.2.6. Standard range of $\Delta\sigma_c$ values (N/mm²)

12, 14, 16, 18, 20, 22, 25, 28, 31, 35, 39, 44, 49, 55, 62, 69, 77, 86, 96, 108, 121, 135,
Note: does not apply to adhesively bonded joints

5.2.4 Hot spot stress

Values of $\Delta\sigma_c$ for hot spot stress assessment of weld toes are given in table 5.2.7.

Table 5.2.7 $\Delta\sigma_c$ -m_1 values for hot spot stress assessment

Thickness of stressed member T (mm)	$\Delta\sigma_c$ - m_1
$0 < T \leq 4$	44 -3,2
$4 < T \leq 10$	39 -3,2
$10 < T \leq 15$	35 -3,2
$15 < T \leq 25$	31 -3,2
$25 < T \leq 40$	28 -3,2
$T > 40$	25 -3,2

5.3 Effect of Mean Stress

5.3.1. General

(1) The fatigue strength data given in 5.2 refer to high tensile mean stress conditions. Where the mean stress is compressive or of low tensile value the fatigue life may be enhanced under certain conditions. See 5.3.2 to 5.3.6 and Annex G for further guidance.

5.3.2 Plain material and mechanically fastened joints

(1) Provided that the effects of tensile residual and lack of fit stresses are added to the applied stresses, the fatigue enhancement factor given in Annex G may be considered.

5.3.3 Welded joints

(1)P No allowance shall be made for mean stress in welded joints except in the following circumstances:

a) Where tests have been conducted which represent the true final state of stress (including residual and lack of fit stresses) in the structure and demonstrate a consistent increase in fatigue strength with decreasing mean stress.

b) Where improvement techniques are to be used which have been proven to result in residual compressive stresses and where the applied stress is not of such a magnitude that the compressive residual stresses will be reduced by yielding in service (see Annex E).

5.3.4 Adhesive joints

(1)P No allowance shall be made for effect of mean stress without justification by test.

5.3.5 Low endurance range

(1)P In the endurance range between 10^3 and 10^5 a check shall be made that the design stress range does not result in a maximum tensile stress that exceeds the ULS design resistance for the detail (see Part 1 of this Prestandard). This possibility is indicated by Note 2 on figure 1.5.2..

(2) For certain details higher fatigue strengths may be used for negative R ratios for $N<10^5$ cycles (see Annex F).

5.3.6 Cycle counting for R-ratio calculation

The method of obtaining the maximum, minimum and mean stress for individual cycles in a spectrum using the Reservoir counting method shall be as shown in Fig.4.5.1.

5.4 Effect of Environment

(1)P The detail category $\Delta\sigma_c$ given in Tables 5.1.1 to 5.1.5 and 5.2.2 shall be reduced in accordance with Table 5.4.1 for certain combinations of alloy and environment where the average ambient temperature during the life does not exceed 65°C.

NOTE: For marine environment the average ambient temperature during the life should not exceed 30°C.

Table 5.4.1 Number of detail categories by which $\Delta\sigma_c$ shall be reduced according to environment and alloy [1)]

Alloy			Environment							
Series	Basic Composition	Protec-tion ratings (see Part 1.1)	Rural	Industrial/Urban		Marine			Immersed	
				Moderate	Severe	Non-Industrial	Moderate	Severe	Fresh Water	Sea Water
3000[3)]	AlMnCu	A	-	-	(P)	-	-	-[5)]	-	-[5)]
5000	AlMg	A	0	0	(P)[4)]	0	0	0[5)]	0	0[5)]
5000	AlMgMn	A	0	0	(P)[4)]	0	0	0[5)]	0	1[5)]
6000	AlMgSi	B	0	0	(P)[4)]	0	0	1[5)]	0	2[5)]
7000	AlZnMg	C	0	0	(P)[4)]	0	0	2[5)]	1	3[5)]

Note 1:See Table 5.2.1. (7)
Note 2: For conditions where table 5.4.1 requires a reduction in detail category and the average temperature exceeds 30°C specialist advice should be sought.
Note 3: Data not available
Note 4: (P) very dependent on chemistry of environment. Regularly maintained protection may be required to avoid risk of local exposures which may be particularly detrimental to crack initiation.
Note 5 :The value of N_D should be increased from $5x10^6$ to 10^7 cycles.
The value of N_L should be increased from 10^8 to $2x10^8$ cycles

5.5 Improvement Techniques

(1) The fatigue strength of certain detail types shown in tables 5.1.1 to 5.1.5 may be improved by the application of special manufacturing techniques. These are generally expensive to apply and present quality control difficulties. They should not be relied upon for general design purposes, unless fatigue is particularly critical to the overall economy of the structure, in which case specialist advice should be sought. They are more commonly used to overcome existing design deficiencies.

(2) The following techniques have been used on aluminium alloys and are most effective for high cycle applications.

a) Introduction of compressive residual stresses at the location of crack initiation. This may be carried out at transverse weld toes by peening. At bolt holes the cold expansion method may be used.

(b) Reduction of stress concentration effect at the location of crack initiation. This may be carried out by grinding transverse weld toes to a smooth profile.

(3) Further information on improvement techniques is given in Annex E.

6 Quality requirements

6.1 Determination of Required Quality Level

(1)P The detail categories in tables 5.1.1 to 5.1.5 represent the maximum fatigue strength permitted by this code for the detail in question when manufactured to the quality requirements of Annex D, and shall not be exceeded without further substantiation by test (see Annex C).

(2)P The higher class details often require additional inspection and demand higher workmanship standards (see Annex D), which can have an adverse effect on the economy of manufacture. Inspection and workmanship standards shall be determined by the quality level appropriate to the particular fatigue performance requirements and not by the maximum potential fatigue resistance.

(3)P The required quality level at a detail shall be obtained by determining the lowest fatigue strength curve from where Miner's summation D_L does not exceed unity (see 2.2.2(2)g). Where stress fluctuations occur in more than one direction at a detail different class requirements may be found for each direction.

(4)P The quality level for welded joints shall be determined from table 6.1.1.

Table 6.1.1. Determination of quality level for welded joints

Lowest detail category $\Delta\sigma_c$ for which $\Delta_L \leq 1$ [1)]	Required quality level
62, 55	Fat 62
49, 44	Fat 49
39, 35	Fat 39
31, 28	Fat 31
25, 22	Fat 25
20 and below	Normal
Note 1: assuming m_1 and m_2 remain constant	

6.2 Designation of Quality Levels on Drawings

(1)P In order that inspection can be particularly concentrated on those parts of the structure which are critical for fatigue the following actions shall be taken:

a) Determine by calculation those regions of the structure where the fatigue strength requirement exceeds detail Category 20.
b) Indicate on the detailed drawings at all details in these regions the required quality level from table 6.11 and the direction of stress fluctuation as shown in figure 6.2.1.

c) Any drawing which contains a detail with a required fatigue strength greater than 20 shall have the following general note added as follows:

'Details requiring quality levels above Normal are indicated with 'Fat' number and an arrow (see ENV1999-2 Annex D)'.

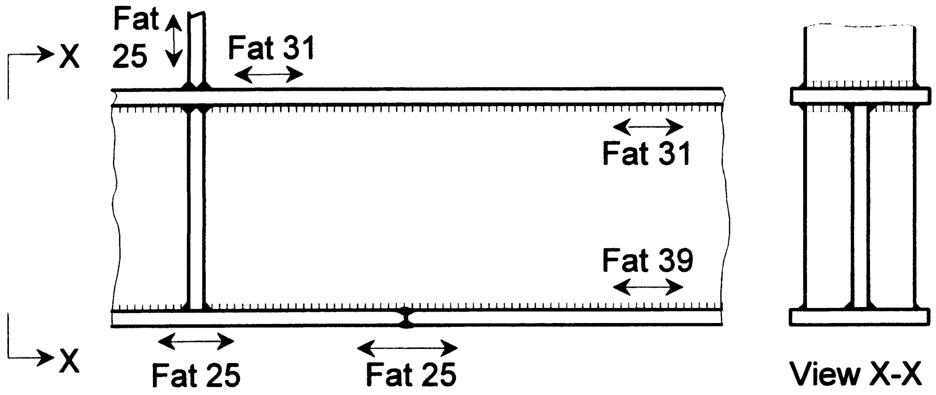


Fig.6.2.1 Method of identification of required fatigue class on drawings

(2) The same principles may be applied for denoting the required quality levels for critical areas of castings.

6.3 Fitness-for-Purpose Assessment

(1) In the event that there is a marginal non-conformity with the quality requirements in Annex D and that correction would be:

a) detrimental to the integrity of the structure, or
b) an engineering critical assessment (ECA) may be undertaken and have serious economic consequences,

the following information will be needed:

a) The static and cyclic stressing requirements at the detail concerned
b) The dimensions of the defect
c) The material properties in the region of the defect
d) Details of the environment

(2) The fatigue life can be assessed either by use of fracture mechanics (see Annex B) or by testing representative details (see Annex C).

Annex A (Informative)

Stress Analysis

A.1 Use of finite elements for fatigue analysis

A.1.1 Element types

A.1.1.1 Beam elements

(1) Beam elements are mainly used for analysis of nominal stresses in frames and similar structures. A conventional beam element for analysis of three dimensional frames has 6 degrees of freedom at each end node: three displacements and three rotations. This element can describe the torsional behaviour correctly only in cases in which the cross section is not prone to warp, or warping can occur freely. Analysis of warping stresses is impossible, when open thin-walled structures are analysed.

(2) Usually, the beam elements are rigidly connected to each other at the nodal points. Alternatively, pinned joints can also be specified. However, in many structures the joints are semi-rigid. In addition, in tubular joints the stiffness is unevenly distributed, which causes extra bending moments. Such structural features require more sophisticated modelling than the use of rigid or pinned joints.

A.1.1.2 Membrane elements

(1) Membrane elements are intended for modelling plated structures which are loaded in-plane. They cannot deal with shell bending stresses. Triangular and rectangular plate elements are suitable for solving nominal membrane stress fields in large stiffened plate structures.

A.1.1.3 Thin shell elements

(1) Finite element programs contain various types of thin shell elements. These include flat elements, single curvature elements and double curvature elements. The deformation fields are usually formulated as linear (4-noded element) or parabolic (8-noded element). In general, thin shell elements are suitable for solving the elastic structural stresses according to the theory of shells. The mid-plane stress is equal to the membrane stress, and the top and bottom surface stresses are superimposed membrane and shell bending stresses.

(2) Thin shell elements can only model the mid-planes of the plates. The actual material thickness is given as a property only for the element. There are also thin shells with tapered thickness, which are useful for modelling cast structures, for example. The most important drawback with thin shell elements is that they cannot model the real stiffness and stress distribution inside, and in the vicinity of, the weld zone of intersecting shells.

A.1.1.4 Thick shell elements

(1) Some finite element packages also include so-called thick shell elements. These allow transverse shear deformation of the shell in the thickness direction to be taking into account. Thick shell elements work better than thin shell elements in e.g. details in which the distance between adjacent shell intersections is small, giving rise to significant shear stresses.

A.1.1.5 Plane strain elements

(1) Sometimes it is useful to study the local stress fields around notches with a local 2-D model. A cross section of unit thickness can then be modelled as a two dimensional structure using plane strain elements.

A.1.2 Further guidance on use of finite elements

(1) Solid elements are needed for modelling structures with three dimensional stress and deformation fields. Curved isoparametric 20-noded elements are generally the most suitable. In welded components, they are sometimes required for modelling the intersection zone of the plates or shells.

A.2 Stress concentration factors

(1) Values of stress concentration factors and notch factors for commonly occurring geometries can be obtained from published data (see References A.4.1 and A.4.2).

(2) Typical values of K_{gt} for radiused corners in flat plate are given in Fig.A.2.1.

A.3 Hot spot stresses

(1) The hot spot stress approach is used mainly for joints in which the weld toe orientation is transverse to the fluctuating stress component, and the crack is assumed to grow from the weld toe. The approach is not suitable for joints in which the crack would grow from embedded defects or from the root of a fillet weld. Compared with the nominal stress approach, this approach is more suitable for use in the following cases:

a) there is no clearly defined nominal stress due to complicated geometric effects;
b) the structural discontinuity is not comparable with any classified details included in the design rules (nominal stress approach);
c) for the above-mentioned reasons, the finite element method is in use with shell and/or solid element modelling;
d) testing of prototype structures is performed using strain gauge measurements;
e) the offset or angular misalignments exceed any fabrication tolerances specified as being consistent with the design $\Delta\sigma$-N curves used in the nominal stress approach.

(2) For tubular nodal joints the hot spot stress range should be evaluated at sufficient locations to characterise fully the fatigue performance of each joint. For example, in the case of a tubular set-on connection at least four equally spaced points around the joint periphery will need to be considered. For any particular type of loading, e.g. axial loading this hot spot stress range is the product of the nominal stress range in the brace and the appropriate stress concentration factor (SCF).

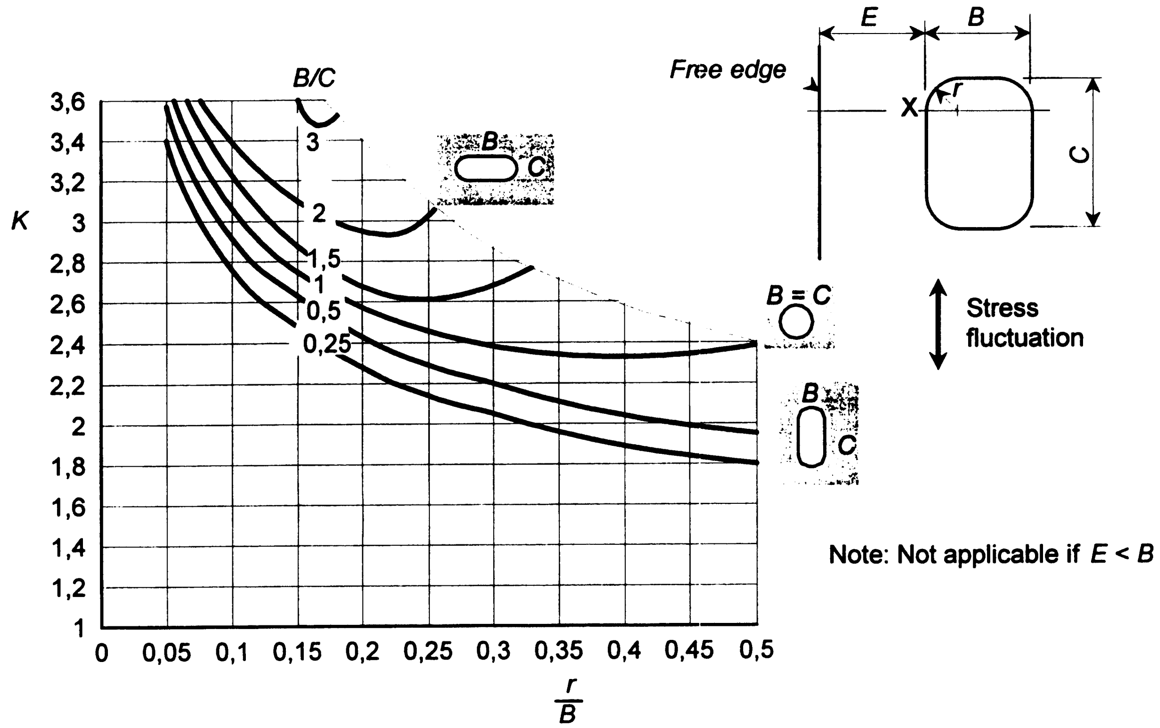
(3) The hot spot stress is defined as the greatest value of the direct stress around the brace/chord intersection of the extrapolation to the weld toe of the geometric stress distribution near the weld toe. This hot spot stress incorporates the effects of overall joint geometry, i.e. the relative sizes of brace and chord, but omits the stress concentrating influence of the weld itself, which results in a local stress distribution (see Figure A.3.1).

(4) The calculation of hot spot stress may be undertaken in a variety of ways e.g. by physical model studies, finite element analysis, or by use of semi-empirical parametric formulae. The position of the 'hot spot' in relation to the crown and saddle can be determined by the first two methods but not in all cases by parametric equations. When physical models are used, care should be taken in obtaining the geometric stress extrapolated to the weld toe as described above. When finite element calculations do not allow for any effect of weld geometry, the hot spot stress at the weld toe can be estimated from the value obtained at the brace/chord intersection. Parametric formulae should be used with caution in view of their inherent limitations; in particular they should only be used within the bounds of applicability relevant to the formula under consideration.

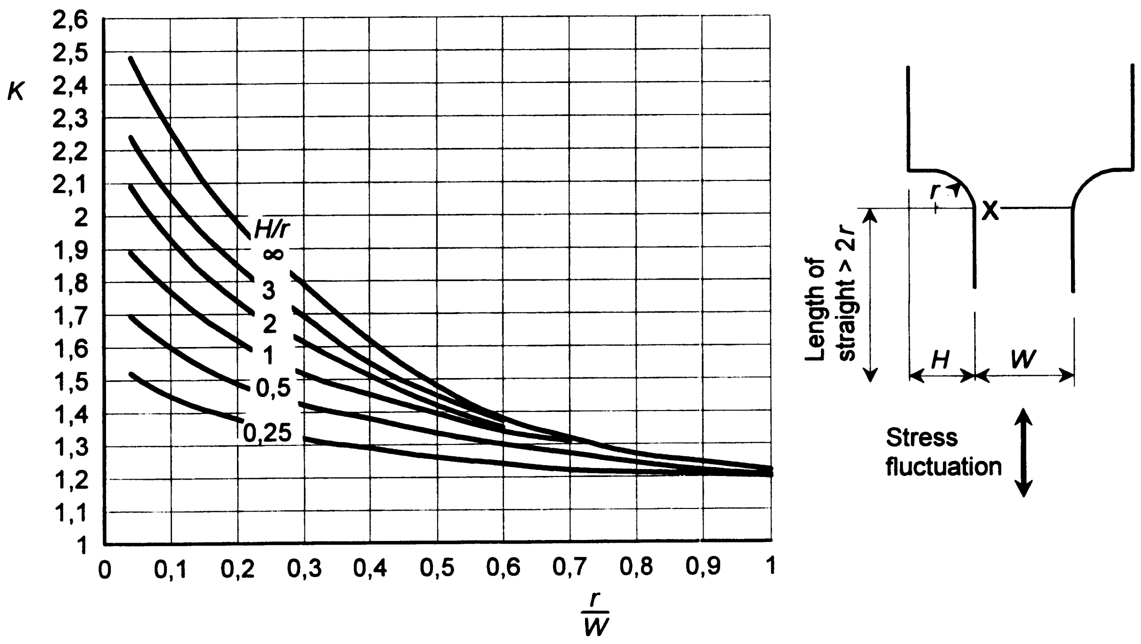
A.4 References

A.4.1 Peterson, R. E: 'Stress concentration factors' John Wiley and Sons Inc., 1974.

A.4.2 Roark, J. R. and Young, W. C: 'Formulas for stress and strain', McGraw Hill, 1973.
A.4.3 Niemi, E.: 'Stress determination for fatigue analysis of welded components', (International Institute of Welding document 1221-93), Abington Publishing, Cambridge, 1995.
A.4.4 BS7608 'Code of practice for fatigue design and assessment of steel structures',British Standards Institute 1993.
A.4.5 Hobbacher, A: 'Recommendations on fatigue of welded components', IIW Doc. XIII-1539-94/XV-845/-94.



a) Fatigue stress concentration factor for unreinforced apertures based on net stress at X



b) Fatigue stress concentration factor for reentrant corners based on net stress at X

FigA.2.1. Typical stress concentration factors from radiused corners in flat plate

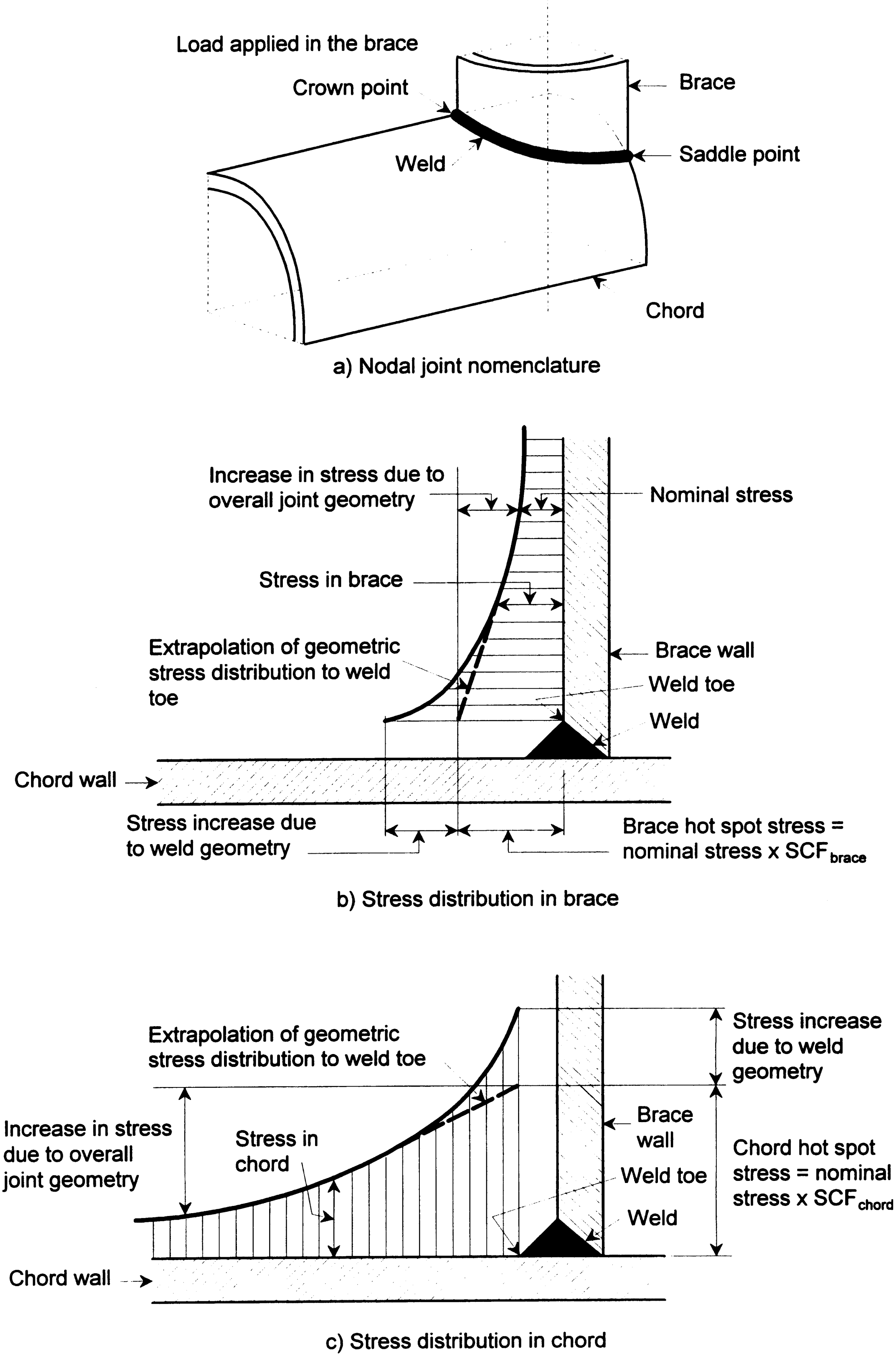


Fig.A.3.1 Example of hot spot stresses in a tubular lattice joint

Annex B [informative]:

Guidance on Assessment by fracture mechanics

B.1 Scope

(1) The objective of the annex is to provide information on the use of fracture mechanics for assessing the growth of fatigue cracks from sharp planar discontinuities. Main uses are in the assessment of:

- known flaws (including fatigue cracks found in service).
- assumed flaws (including consideration of the original joint or NDT detection limits).
- tolerance to flaws (including fitness for purpose assessment of fabrication flaws for particular service requirements).

(2) The method covers fatigue crack growth normal to the direction of principal tensile stress (Mode 1).

B.2 Principles

B.2.1 Flaw dimensions

(1) Fatigue propagation is assumed to start from a pre-existing planar flaw with a sharp crack front orientated normal to the direction of principle tensile stress fluctuation $\Delta\sigma$ at that point.

(2) The dimensions of the pre-existing flaws are shown in Figure B.2.1 depending on whether they are surface breaking or fully embedded within the material.

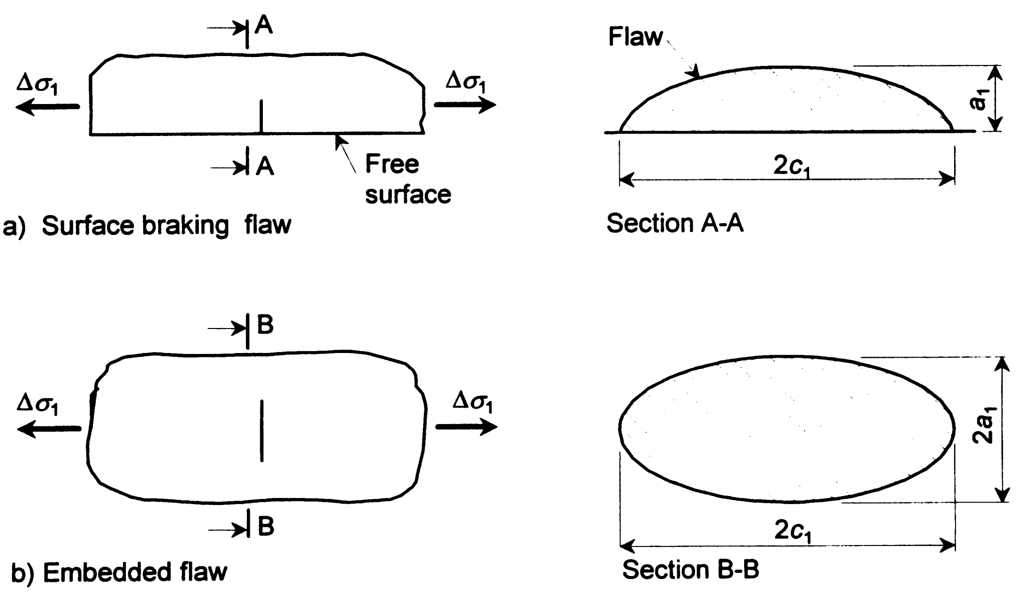


Figure B.2.1 Pre-existing planar flaws

B.2.2 Crack growth relationship

(1) Under the action of cyclic stress range $\Delta\sigma$ the crack front will move into the material according to the crack propagation law. In the direction of 'a' the rate of propagation is given by:

$$da/dN = A\,(\Delta\sigma\, a^{0,5}\, y)^m \qquad (B.1)$$

where A is the fatigue crack growth rate (FCGR) material constant
m is the crack growth rate exponent
y is the crack geometry factor depending on the crack shape, orientation and surface boundary dimensions.

NOTE: The most common units for stress intensity factors ΔK are $MPam^{0,5}$ ($Nmm^{-2}\, m^{0,5}$) and for crack growth rate da/dN is m/cycle. Data given in B.3. are only valid for these units.

(2) This can be rewritten in the form

$$da/dN = A\, \Delta K^m \qquad (B.2)$$

where ΔK is the stress intensity range and equals $\Delta\sigma\, a^{0,5}\, y$.

(3) After the application of N cycles of stress range $\Delta\sigma$ the crack will grow from dimension a_1 to dimension a_2 according to the following integration:

$$N = \int_{a_1}^{a_2} \frac{da}{A(\Delta K)^m}\, 1 \qquad (B.3)$$

(4) For the general case A, ΔK and m are dependent on 'a'.

(5) For further information on fracture mechanics techniques, particularly for welded structures, see References B.8.1 and B.8.2.

B.3 Crack growth data A and m

(1) A and m are obtained from crack growth measurements on standard notched specimens orientated in the LT, TL or ST direction (e.g. see Figure B.3.1) using standardised test methods (e.g. see Reference B.8.3). The specimen design must be one for which an accurate stress intensity factor (K) solution (i.e. the relationship between applied load and crack size 'a') is available.

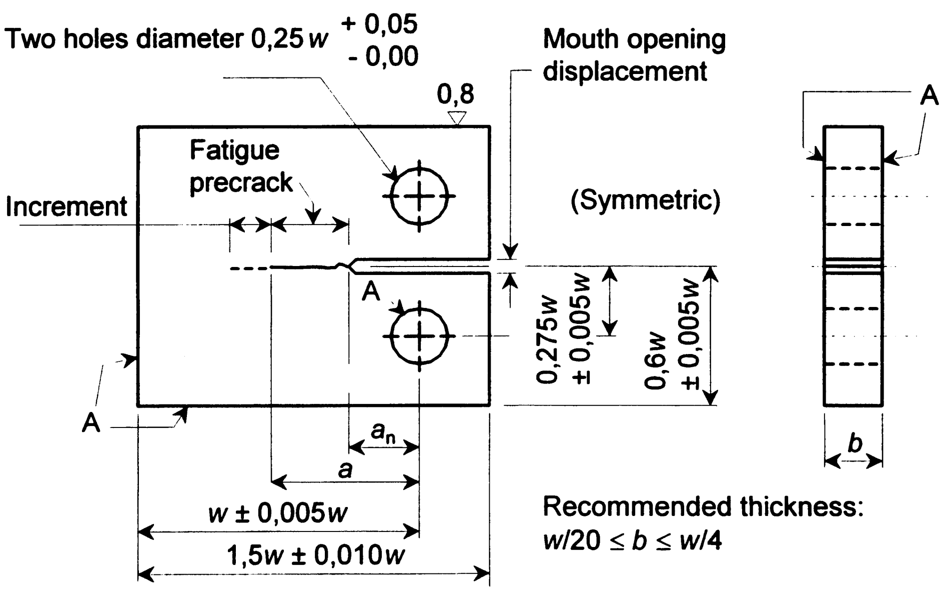


Fig.B.3.1. Typical crack growth specimen (example from ref.B.8.3)

(2) The test entails computer controlled cyclic loading of the specimen at constant applied stress intensity ratio (K_{min}/K_{max}), R, for R^c - testing conditions or at constant K_{max} for $K_{max}{}^c$ - testing conditions (see ref. B.8.7) and accurate measurement of the growth of the crack from the notch.

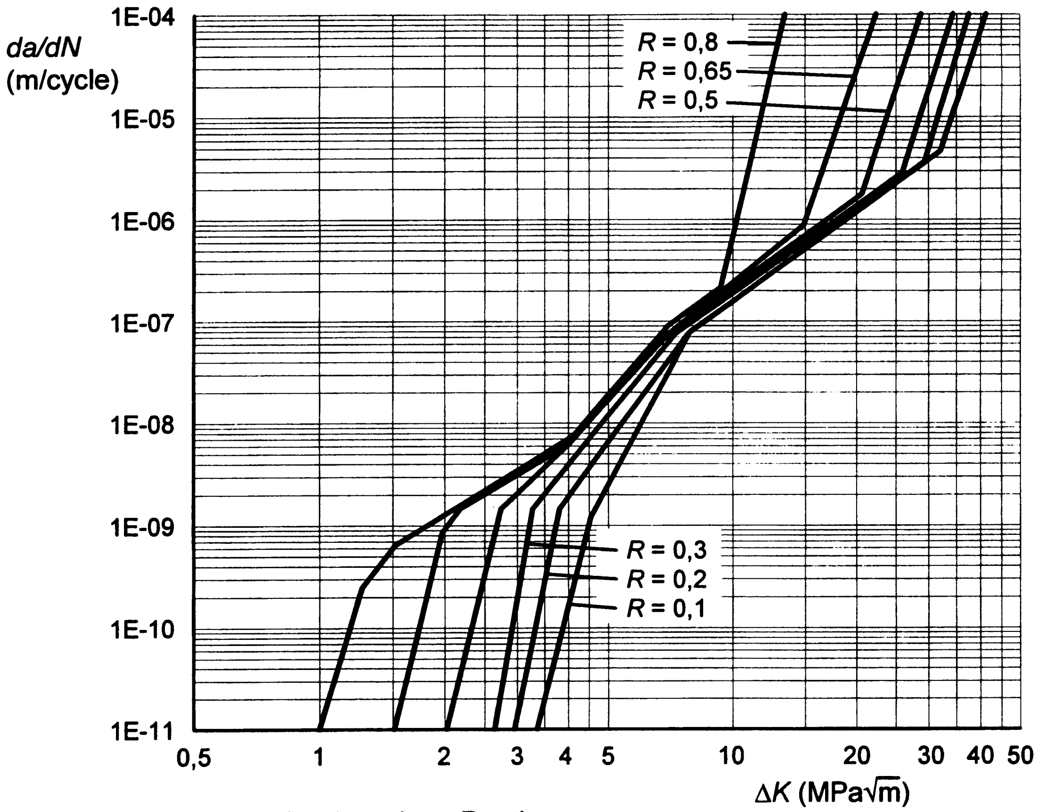
(3) If discrete values of crack length 'a' are obtained, a smooth curve is fitted to the data using the method specified in the test Standard. The crack growth rate, da/dN, at a given crack length is then calculated as the gradient of the curve at that 'a' value.

(4) The corresponding value of the stress intensity factor range, ΔK, is obtained using the appropriate K solution for the test specimen, in conjunction with the applied load range. The results da/dN versus DK are plotted using logarithmic scales.

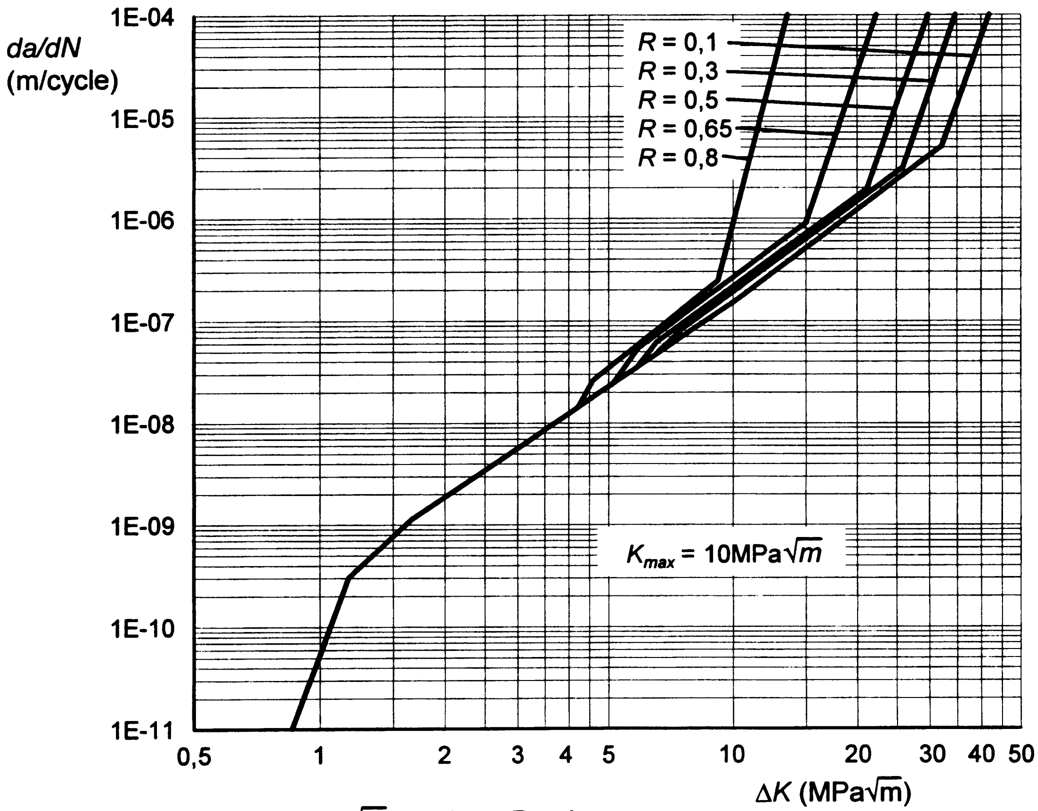
(5) For general use, crack growth curves may be required for different R values. Figure B.3.2 shows a typical set of da/dN vs ΔK curves for the aluminium extrusion alloy AA6005A-T6 (AlMgSi0.7). In Fig.B.3.2(a) the testing condition was constant ratio of stress intensity K_{min}/K_{max}, R^c, and in Fig.3.2(b) the result of a $K_{max}{}^c$ - test at a constant K_{max} of $10MPa(m)^{1/2}$ is combined with the conservative branches of the curves from Fig.B.3.2(a). This combination of the results of the R^c and the $K_{max}{}^c$ data is a conservative engineering approximation and can be used for the fatigue life prediction in case of high residual tensile stresses or short fatigue crack evaluations. The values of m and A for Fig. B.3.2. are given in tables B.3.2(a) and (b).

(6) The assumption made in ref. B.8.1, equation A4-11, that the fatigue crack propagation rates of metals are proportional to the cube of the ratio of the Young's moduli with respect to steel is used as a scale to compare the FCGR of different aluminium alloys. In Fig.B.3.3(a) the R^c-FCGR of wrought aluminium alloys of R=0.1 are plotted and in Fig.B.3.3(b) the corresponding data for R=0.8 are added. Figure B.3.4 shows the set of R^c-FCGR curves of three gravity die cast alloys at R=0.1 and R=0.8. Figure B.3.5 represents the combined data of R^c and $K_{max}{}^c$ - tests of wrought aluminium alloys for R=0.1 and R=0.8. The values of m and A of the upperbound FCGR envelopes for Figs.B.3.3 to B.3.5 are given in tables B.3.3 to B.3.5 respectively.

(7) Corrosive environments can effect A and m. Test data obtained under conditions of ambient humidity will be adequate to cover most normal atmospheric conditions.



a) R = constant (k_{min}/k_{max}) various R-ratios



b) k_{max} = constant (10MPa$\sqrt{m}$) various R-ratios

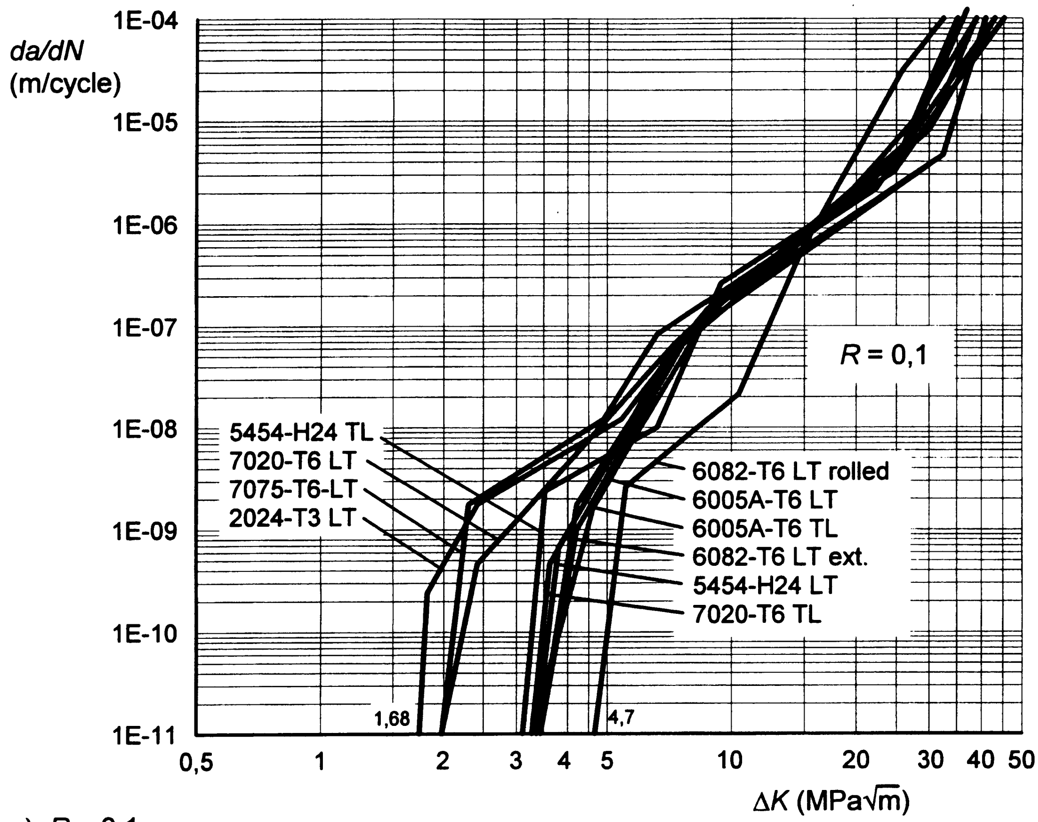
Figure B.3.2. Typical fatigue crack growth curves for aluminium alloy 6005A T6LT

Table B.3.2(a) Fatigue crack growth rate data for EN AN 6005-T6 LT, R-K_{min}/K_{max}=constant

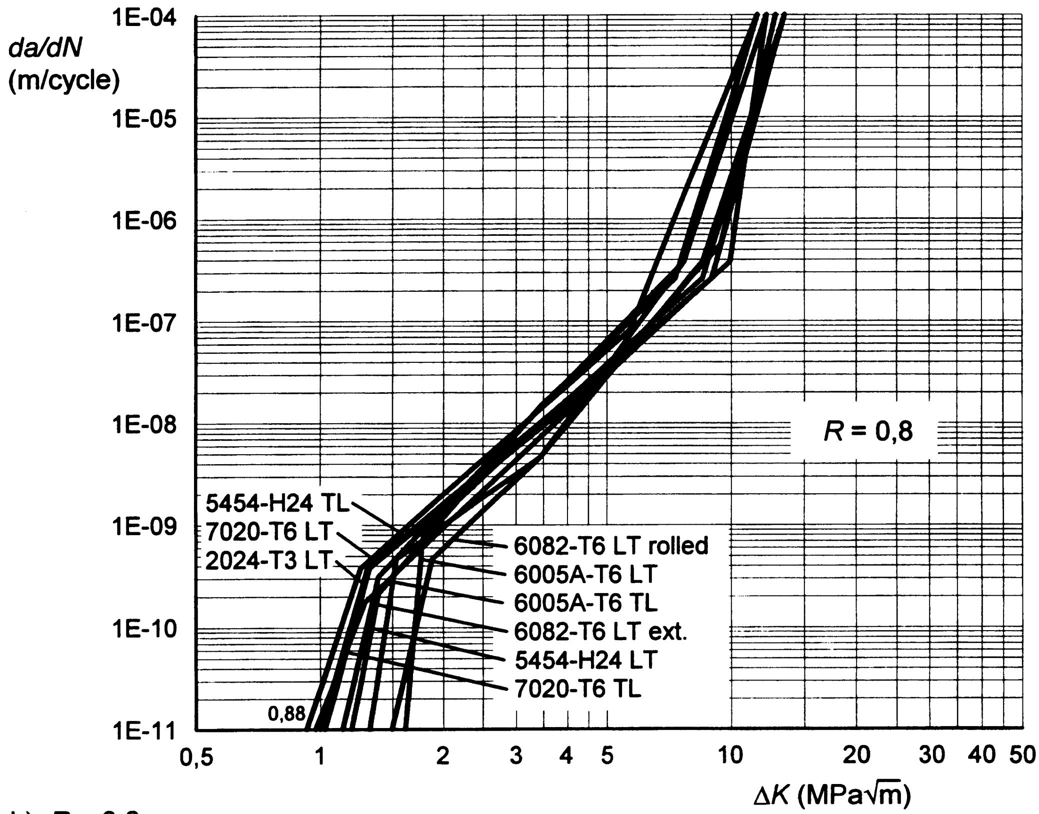
R-ratio	Stress Intensity ΔK $MPam^{0,5}$	m	A	R-ratio	Stress IntensityΔ ΔK $MPam^{0,5}$	m	A
0,100	3,30	15,00	0,1657E-18	0,500	2,00	16,29	0,1243E-15
	4,50	7,51	0,1293E-13		2,72	3,85	0,3174E-10
	8,00	2,96	0,1673E-09		4,20	4,86	0,7414E-11
	32,4	11,97	0,4100E-23		6,50	2,80	0,3406E-09
	41,61	11,97	0,4100E-23		21,00	12,23	0,1211E-21
	60,00	11,97	0,4100E-23		29,16	12,23	0,1211E-21
					42,50	12,23	0,1211E-21
0,200	2,90	18,53	0,2679E-19	0,650	1,50	16,93	0,1042E-13
	3,80	5,86	0,5949E-12		1,95	4,42	0,4418E-10
	7,50	2,92	0,2227E-09		2,20	2,38	0,2206E -09
	29,60	12,43	0,2253E-23		3,55	4,76	0,1068E-10
	37,98	12,43	0,2253E-23		6,00	3,05	0,2326E-09
	55,00	12,43	0,2253E-23		15,00	12,00	0,6084E-20
					22,17	12,00	0,6084E-20
0,300	2,60	18,67	0,1774E-18	0,800	1,00	13,03	0,9999E-11
	3,40	5,23	0,2470E-11		1,28	4,99	0,7289E-10
	7,35	2,82	0,3060E-09		1,55	2,50	0,2168E-09
	26,00	12,40	0,8411E-23		3,50	6,03	0,2611E-11
	34,49	12,40	0,8411E-23		4,60	3,11	0,2225E-09
	50,00	12,40	0,8411E-23		9,20	15,93	0,9830E-22
					13,48	15,93	0,9830E-22

Table B3.2.(b) Fatigue crack growth rate data for EN AA-6005A-T6 LT, K_{max}-100MPa(m)^{0,5} = constant

R-ratio	Stress Intensity ΔK $MPam^{0,5}$	m	A	Ratio	Stress Intensity ΔK $MPam^{0,5}$	m	A
0,100	0,85	11,09	0,6069E-10	0,500	0,85	11,09	0,6069E-10
	1,16	3,74	0,1807E-09		1,16	3,74	0,1807E-09
	1,60	2,68	0,2969E-09		1,60	2,69	0,2960E-09
	8,00	2,96	0,1673E-09		5,55	4,76	0,1081E-11
	32,40	11,97	0,4103E-23		6,50	3,05	0,2326E-09
	41,61	11,97	0,4103E-23		21,00	12,04	0,6081E-21
					29,16	12.04	0,6081E-21
0,300	0,85	11,09	0,6069E-10	0,650	0,85	11,09	0,6069E-10
	1,16	3,74	0,1807E-09		1,16	3,74	0,1807E-09
	1,60	2,71	0,2935E-09		1,60	2,69	0,2960E-09
	6,70	5,51	0,1413E-11		4,95	4,76	0,1081E-10
	7,35	2,82	0,3060E-09		6,00	3,05	0,2326E-09
	26,00	12,40	0,8421E-23		15,00	12,04	0,6081E-20
	34,49	12,40	0,8421E-23		22,17	12,04	0,6081E-20
				0,800	0,85	11,09	0,6069E-10
					1,16	3,74	0,1807E-09
					1,60	2,71	0,2927E-09
					4,15	6,01	0,2689E-11
					4,60	3,11	0,2225E-09
					9,20	15,93	0,9819E-22
					13,48	15,93	0,9819E-22

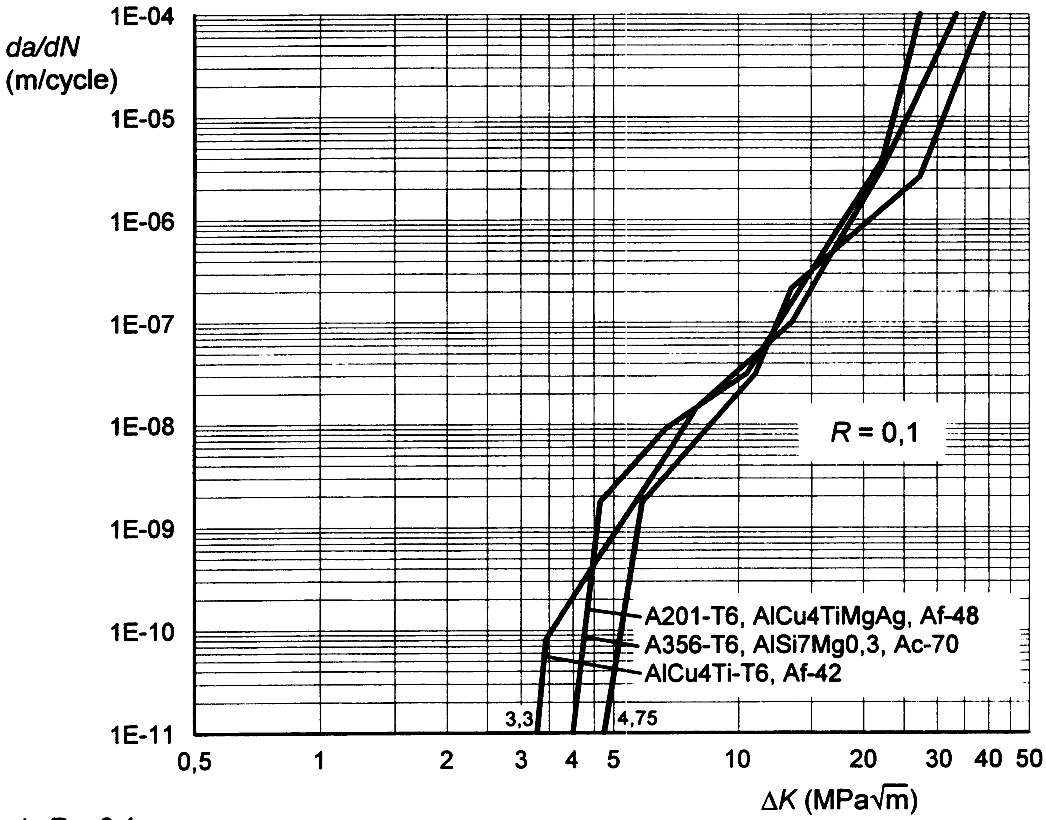


a) $R = 0{,}1$

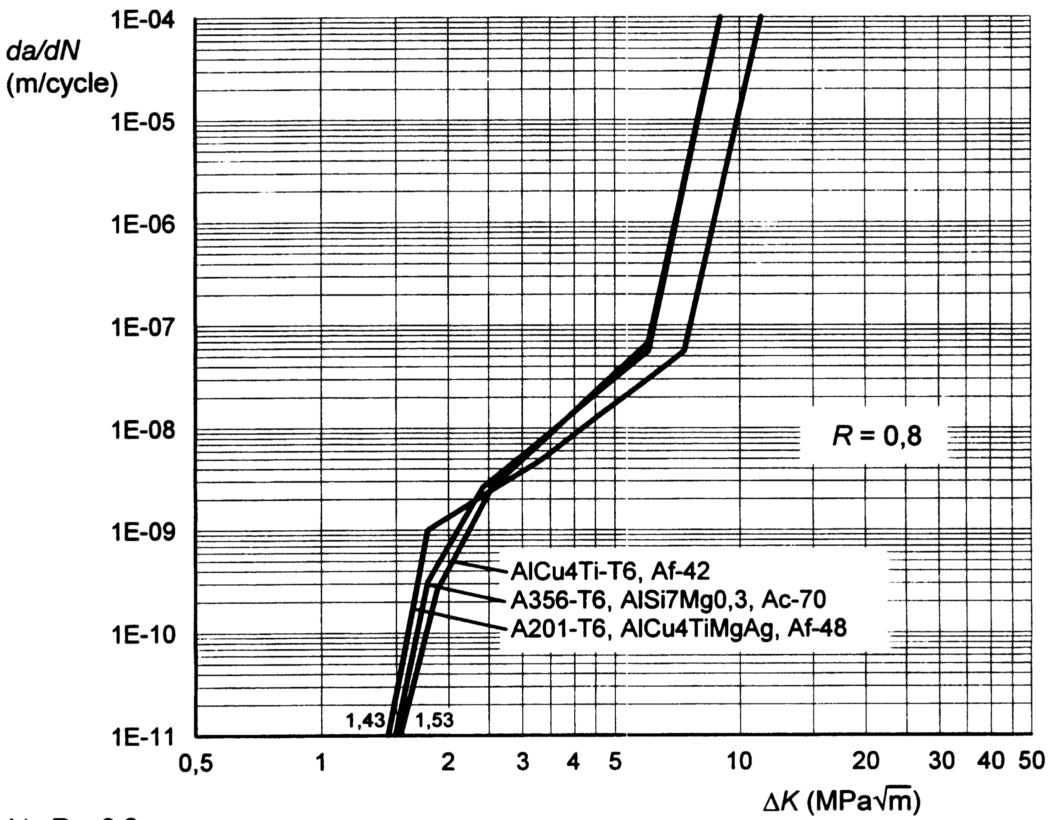


b) $R = 0{,}8$

Figure B.3.3 Typical crack growth rate curves for various wrought alloys

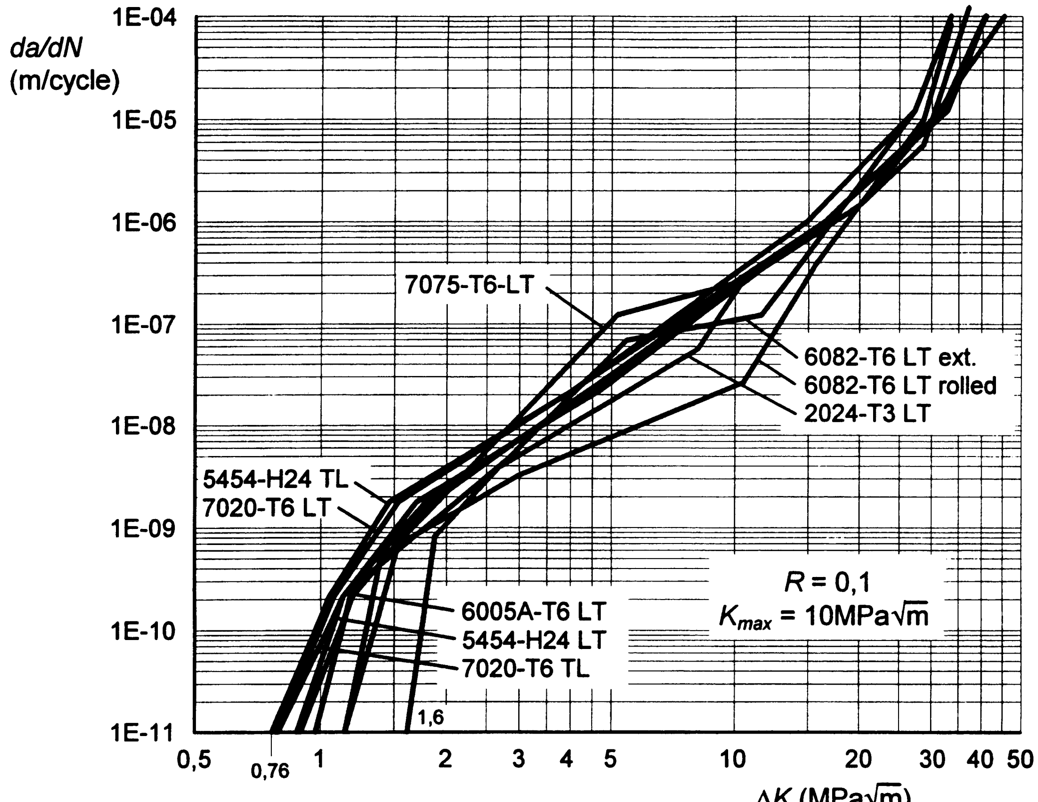


a) $R = 0,1$

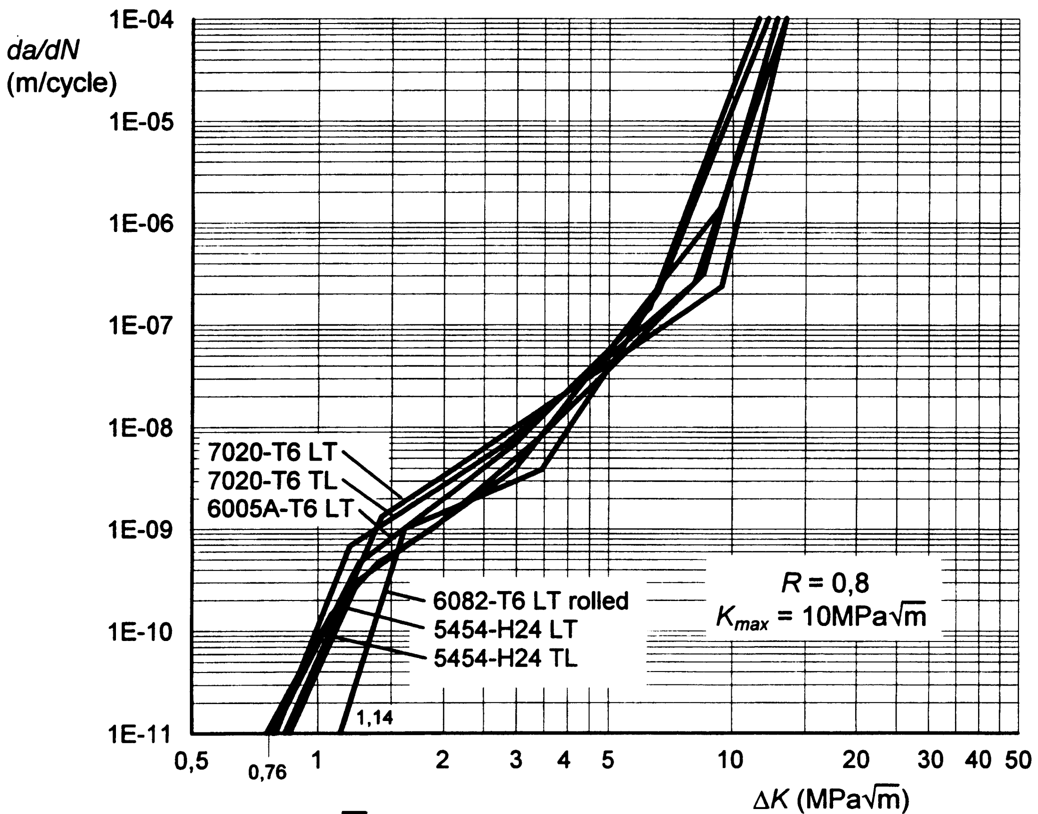


b) $R = 0,8$

Figure B.3.4. Typical fatigue crack growth curves for various cast alloys



a) $R = 0{,}1$; $k_{max} = 10\text{MPa}\sqrt{m}$



b) $R = 0{,}8$; $k_{max} = 10\text{MPa}\sqrt{m}$

Figure B.3.5 Typical fatigue crack growth curves for various wrought alloys
$(K_{max}) = 10\ \text{MPa}\sqrt{m}$

Table B3.3. Fatigue crack growth rate data for wrought alloys, $R = K_{min}/K_{max}$=constant

R-ratio	Stress Intensity ΔK MPam^{0,5}	m	A
a) 0,100	1,68	3,3	0,2541E-18
	1,89	3,4	0,4065E-10
	2,96	4,1	0,4886E-09
	4,75	6,6	0,2951E-12
	6,70	2,8	0,4838E-09
	19,51	5,9	0,4080E-13
	28,71	9,8	0,3072E-17
b) 0,800	0,87	10,43	0,4276E-10
	1,24	3,33	0,1959E-09
	2,27	2,98	0,2603E-09
	3,40	6,36	0,4155E-11
	5,44	8,34	0,1454E-12
	11,45	8,34	0,1454E-12
Note: These values are upperbound envelopes derived from the curves shown in Fig.B.3.3(a) and (b)			

Table B3.4. Fatigue crack growth rate cast alloys $R=K_{min}/K_{max}$ = constant

R-ratio	Stress Intensity ΔK MPam^{0,5}	m	A
a) 0,100	3,28	35,46	0,5102E-29
	3,45	11,01	0,7184E-16
	4,60	6,50	0,7051E-13
	8,85	3,85	0,2260E-10
	23,07	19,12	0,3475E-31
	27,30	19,12	0,3475E-31
b) 0,800	1,42	21,24	0,6086E-14
	1,76	5,47	0,4520E-10
	5,82	12,34	0,2537E-15
	8,70	12,34	0,2537E-15

Table B.3.5 Fatigue crack growth rate data for wrought alloys, K_{max}=10MPa(m)^{0,5} constant

R-ratio	Stress Intensity ΔK MPam$^{1/2}$	m	A
0,100	0,76	9,13	0,1211E-09
	1,26	2,77	0,5266E-09
	19,50	5,95	0,4190E-13
	28,71	8,79	0,3072E-17
	34,48	8,79	0,3072E-17
0,800	0,76	9,30	0,1268E-09
	1,22	2,84	0,4560E-09
	4,37	5,28	0,1243E-10
	6,76	11,02	0,2128E-15
	11,45	11,02	0,2128E-15

B.4 Geometry Function y

(1) The geometry function y is dependent on the crack dimension (shape and size), the boundary dimensions of the surface of the surrounding material and the stress pattern in the region of the crack path.

(2) This information can be obtained from finite element analyses of the detail using crack tip elements. The stress intensity for different crack lengths is calculated using the J integral procedure. Alternatively it can be calculated from the displacement or stress field around the crack tip, or the total elastic deformation energy.

(3) Published solutions for commonly used geometries (plain material and welded joints) are an alternative source of y values. Standard data are often given in terms of Y where $Y = y\pi^{-0,5}$. A typical example for a surface breaking crack in a plain plate is shown in Figure.B.4.1.a. If the crack is located at a weld toe on the plate surface then a further adjustment for the local stress concentration effect can be made using the magnification factor M_K (see Figure.B.4.1.b).

(4) The product of Y for the plain plate and M_K for the weld toe gives the variation of y as the crack grows through the thickness of the material (see Figure.B.4.1.c).

(5) For further information on published y solutions see References B.8.1, B.8.3 and B.8.5.

B.5 Integration of crack growth

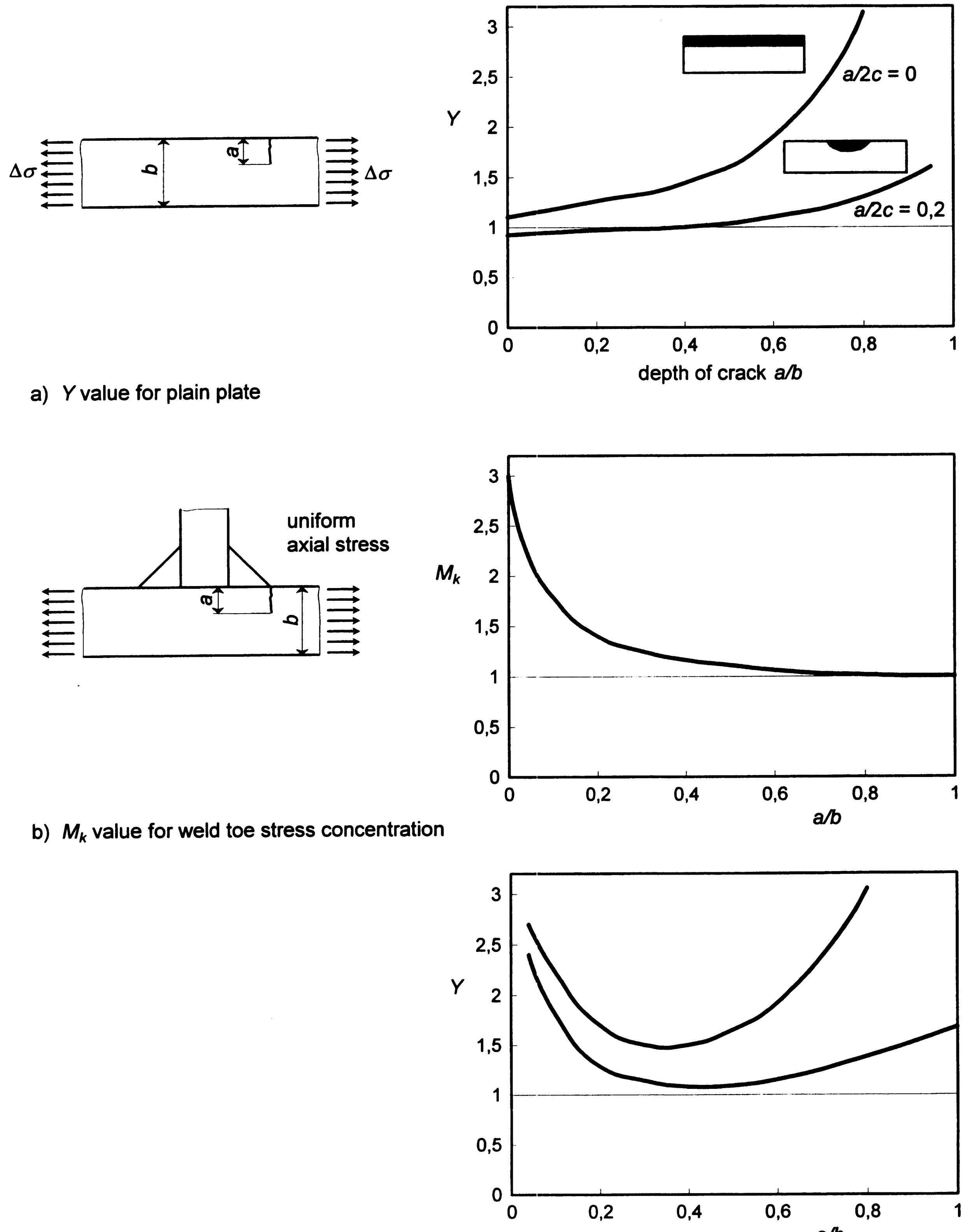
(1) For the general case of a variable amplitude stress history, a stress spectrum has to be derived (see 2.2). In practice the complete spectrum should be applied in at least 10 identical sequences with the same stress ranges and R ratios, but with one tenth of the number of cycles. The block with the greatest amplitude should be applied first in each sequence (see Figure.4.5.1). The incremental crack growth is calculated using the crack growth polygon for the appropriate R ratio, for each block of constant amplitude stress cycles.

(2)In the region of welds, unless the residual stress pattern is actually known, either a high R-ratio ($R = 0,8$) or a K_{max} constant crack growth curve should be used.

(3) The crack length 'a' is integrated on this basis over until the maximum required crack size a_2 is reached and the numbers calculated.

B.6 Assessment of maximum crack size a_2

(1) This will usually be determined on the basis of net section ductile tearing under the maximum applied tensile load with the appropriate partial factor (see Part 1 of this Prestandard). For further information on fracture toughness see References B.8.1 and B.8.2.



a) *Y* value for plain plate

b) M_k value for weld toe stress concentration

c) *Y* for welded joint

Figure B.4.1. Use of typical standard geometry solutions for y

B.7 Calculations for initial crack length, a_i, based on Annex B fatigue crack growth rate data FCGR and the fatigue reference stresses at 2 Million Cycles for a semi-circular surface crack

(1) The calibrated initial fatigue crack length, a_i, were determined for the fatigue reference stress ranges at 2 million cycles in case of (1) a uniform tension and (2) a stress gradient. The proposed conservative envelope of the fatigue crack growth curves as shown in Figs.B.3.3-B.3.5 and listed in tables B.3.3 to B.3.5 were used. The fracture mechanics model was a half disk surface crack in a 12mm thick and 200mm wide plate subjected to the two loading cases (see Fig.B.7.1).

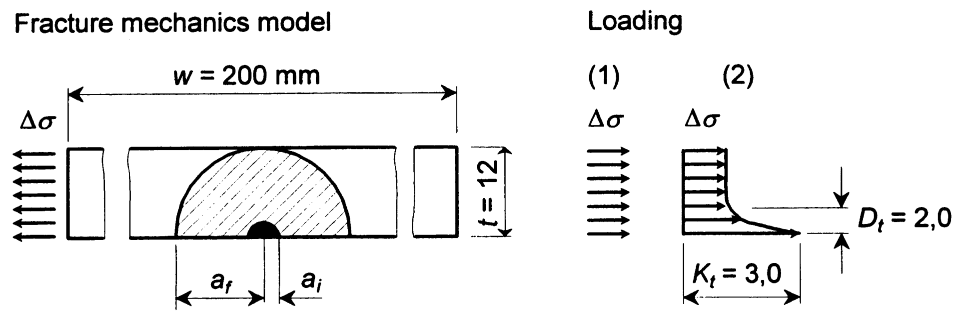


Figure B.7.1. Crack geometry and stress distributions for calculation of crack lengths for a semi-circular surface crack

(2) The two loading cases were:

Loading case 1: Uniform Tension Stress Range, $\Delta\sigma$= 80N/mm^2
(reference stress range at 2 x 10^6 cycles)

Loading case 2:Stress Gradient, K_t = 3,0, D_t = 2,0mm, $\Delta\sigma$ = 80N/mm^2
(K_t at surface 3,0 and 2.0mm below surface, 1,0, decay parabolic, DCF5)

(3) The following fatigue crack growth rate curves (FCGR) were used:

1) WAA Wrought alloy	$R = K_{min}/K_{max}$ = const.,	R = 0,1 and R = 0,8
2) WAA Wrought alloy	K_{max} = 10MPa(m)^{0,5} const.,	R = 0,1 and R = 0,8
3) Cast alloy	$R = K_{min}/K_{max}$ = const.,	R = 0,1 and R = 0,8
4) AA6005A-T6LT	$R = K_{min}/K_{max}$ = const.,	R = 0,1 and R = 0,8
5) AA6005A-T6LT	K_{max} = 10MPa(m)^{0,5} const.,	R = 0,1 and R = 0,8

(4) Fatigue crack propagation was studied in two phases:

Phase 1: Initial crack length a_i = 0,05mm, final crack length, a_f = 2,05mm
Phase 2: Initial crack length a_i = 2,0mm, final crack length, a_f = 12,mm

(5) The surface stress of three times the global stress decreases parabolically, reaches the global stress 2mm below the surface and remains constant through the rest of the thickness at the same reference stress range as in the first case. The fatigue life is equal to the fatigue crack growth from the initial crack length, a_i, to the final crack length, a_f, given by the plate thickness. The phenomenon of short crack fatigue crack propagation is approximated by using the K_{max} constant FCGR curves in the region, where the crack length is smaller than 2mm. From 2mm upwards the FCGR curves corresponding to the applied R ratio ($R=K_{min}/K_{max}$) are used. In the case of the cast aluminium alloys the K_{max} constant curves were approximated by the R = 0,8 curve of the R constant FCGR set.

(6) Tables B.7.1.(a) and (b), for wrought and cast alloys respectively, show variations in predicted maximum tolerable initial crack size as a function of fatigue reference stress range, R-ratio and stress pattern.

(7) Tables B.7.2 to B.7.5. show the variations in predicted fatigue life under a stress range of 80N/mm^2 as a function of initial crack length a_i, fatigue crack growth curve. R-ratio and stress pattern have been used.

B.8 References

B.8.1 IIW guidance on assessment of the fitness for purpose of welded structures. IIW Draft for Development doc. SST-1157-90.

B.8.2 Guidance on some methods for the derivation of acceptance levels for detects in fusion welded joints. British Standard Published Document 6493:1991.

B.8.3 Standard test method for measurement of fatigue crack growth rates, ASTM E647-93.

B.8.4 Fatigue crack propagation in aluminium, IIW Document XIII-B77-90.

B.8.5 Stress intensity factor equations for cracks in three-dimensional finite bodies. ASTM STP 791, 1983, ppI-238 - I-265.

B.8.6 Graf, U: 'Fracture mechanics parameters and procedures for the fatigue behaviour estimation of welded aluminium components', 1992.

B8.7`Simulations of short crack and other low closure loading conditions utilising contact K_{max} ΔK-decreasing fatigue crack growth procedures. ASTM STP 1149-1992, pp.197-220.

Table B.7.1. Predicted inital crack length a_i for various stress ranges at 2 x 10^6 cycles

a) Wrought aluminium alloys
Upperbound fatigue crack growth data from tables B.3.3 and B3.5.

Stress Range	Uniform Tension		K_t=3.0, Dt=2.0mm, DCF5]	
Stress intensity ratio R:	0,1	0,8	0,1	0,8
N/mm^2	mm	mm	mm	mm
16	8,57	6,68	6,28	4,06
20	6,63	4,79	4,00	1,99
25	4,82	3,00	2,19	0,266
25[1)]	-	-	0,11	0,11
31	3,22	1,42	0,44	0,07
31[1)]	-	1,42	0,051	0,051
39[1)]	1,24	0,52	0,025	0,025
49[1)]	0,30	0,26	0,014	0,014
62[1)]	0,14	0,13	0,0073	0,0073
77[1)]	0,078	0,075	-	-
96[1)]	0,042	0,042	-	-
121[1)]	0,023	0,023	-	-

Note 1: FCGR: WAA K_{max} 10MPa$(m)^{0,5}$ one single phase, i.e. FCG from a_i up to the plate thickness of 12mm

b) Cast aluminium alloys
Upperbound fatigue crack growth rate from table B.3.4.

Stress Range	Uniform Tension		K_t=3.0, Dt=2.0mm, DCF5]	
Stress intensity ratio R:	0,1	0,8	0,1	0,8
N/mm^2	mm	mm	mm	mm
16	11,99	6,46	11,99	3,33
20	11,88	4,49	11,56	1,83
25	10,99	2,97	9,09	0,391
31	8,87	1,92	5,90	0,200
39	6,51	1,17	3,32	0,1067
49	4,48	0,71	0,072	0,062
62	2,86	0,42	0,036	0,035
77[1)]	1,80	-	-	-
77	0,295	0,259	0,022	0,0219
96[1)]	1,082	-	-	-
96	0,162	0,159	-	-
121[1)]	0,621	-	-	-
121	0,096	0,095	-	-

Note 1: FCGR CAA R constant, R = 0,1, 1 single phase, ie FCG from a_i up to the plate thickness of 12mm

Table B.7.2 Fatigue life predictions based on upperbound fatigue crack growth data for wrought aluminium alloys from tables B.3.3 and B3.5

a) Uniform tension - Phase 2					
Type of FCGR:		$R=K_{min}/K_{max}$ = constant		K_{max} = 10MPa(m)^{0,5} constant	
Stress intensity ratio R:		0,1	0,8	0,1	0,8
Crack length, a_i mm	Stress intensity range, MPam^{0,5}	Fatigue life, cycles	Fatigue life, cycles	Fatigue life, cycles	Fatigue life cycles
12,00	13,88	-	-	-	-
11,00	12,97	1 428	3	1 411	2
10,00	12,03	3 172	8	3 131	6
9,00	11,08	5 347	17	5 271	15
8,00	10,12	8 123	37	7 996	40
7,00	9,16	11 749	80	11 545	110
6,00	8,20	16 614	185	16 293	336
5,00	7,25	23 258	464	22 854	1 163
4,00	6,30	33 728	1 312	32 319	4 295
3,00	5,31	61 317	3 452	46 887	12 007
2,00	4,25	149 999	16 791	71 997	33 860

b) Stress gradient - Phase 2					
Type of FCGR:		$R=K_{min}/K_{max}$ = constant		K_{max} = 10MPa(m)^{0,5} constant	
Stress intensity ratio R:		0,1	0,8	0,1	0,8
Crack length, a_i mm	Stress Intensity Range, MPam^{0,5}	Fatigue life, cycles	Fatigue life, cycles	Fatigue life, cycles	Fatigue life, cycles
12,00	15,61	-	-	-	-
10,00	14,65	2 027	2	2 009	1
9,00	14,00	3 214	3	3 184	2
8,00	13,26	4 580	6	4 535	3
7,00	12,42	6 196	10	6 130	6
6,00	11,51	8 166	17	8 070	12
5,00	10,51	10 655	31	10 516	28
4,00	98,42	13 950	64	13 745	77
3,00	8,19	18 618	158	18 303	275
2,00	6,72	26 049	547	25 524	1 590

Table B.7.3. Fatigue life predictions based on upperbound fatigue crack growth data for cast aluminium alloys from table B.3.4 and wrought alloy AA 6005A-T6 from table B.3.2(a)

a) Uniform tension - Phase 2

Type of FCGR:		CAA $R=K_{min}/K_{max}$ = constant		AA6005A $R=K_{min}/K_{max}$ = constant	
Stress intensity ratio R:		0,1	0,8	0,1	0,8
Crack length, a_i mm	Stress intensity range, $MPam^{0,5}$	Fatigue life, cycles	Fatigue life, cycles	Fatigue life, cycles	Fatigue life cycles
12,00	13,88	-	-	-	-
11,00	12,97	2'016	0	2 725	11
10,00	12,03	4'670	0	6 092	47
9,00	11,08	8'267	0	10 346	172
8,00	10,12	13'294	1	15 849	681
7,00	9,16	20'552	4	23 148	3 031
6,00	8,20	32'302	16	33 107	8 369
5,00	7,25	57'146	63	50 251	16 049
4,00	6,30	116'025	312	96 452	27 648
3,00	5,31	279'046	1'692	246 958	46 490
2,00	4,25	938'072	6'154	997 170	83 056

b) Stress gradient - Phase 2

Type of FCGR:		CAA $R=K_{min}/K_{max}$ = constant		AA6005A $R=K_{min}/K_{max}$ = constant	
Stress intensity ratio R:		0.1	0.8	0.1	0.8
Crack length, a_i mm	Stress intensity range, $MPam^{0,5}$	Fatigue life, cycles	Fatigue life, cycles	Fatigue life, cycles	Fatigue life, cycles
12,00	15,61	-	-	-	-
11,00	15,19	1 182	0	1 808	1
10,00	14,65	2 517	0	3 793	3
9,00	14,00	4 081	0	6 035	7
8,00	13,26	5 978	0	8 636	16
7,00	12,42	8 367	0	11 742	38
6,00	11,51	11 505	0	15 572	109
5,00	10,51	15 835	1	20 477	383
4,00	9,42	22 202	3	27 074	1 776
3,00	8,19	33 164	13	36 609	6 769
2,00	6,74	64 980	94	59 496	15 333

Table B.7.4. Fatigue life predictions based on upperbound fatigue crack growth data for wrought aluminium alloys from table B.3.3. and wrought alloy AA 6005A-T6 from table B.3.2.(b)

a) Uniform tension - Phase 1					
Type of FCGR:		WAA K_{max} 10MPa(m)^{0,5} const.		AA6005A K_{max} 10MPa(m)^{0,5} constant	
Stress intensity ratio R:		0,1	0,8	0,1	0,8
Crack length, a_i mm	Stress intensity range, MPam^{0,5}	Fatigue life, cycles	Fatigue life cycles	Fatigue life, cycles	Fatigue life, cycles
2,05	4,30	-	-	-	-
1,85	4,07	7 139	7 527	14 355	13 409
1,65	3,83	15 518	16 395	31 119	29 712
1,45	3,58	25 527	27 031	51 031	49 116
1,25	3,32	37 759	40 089	75 212	72 732
1,05	3,03	53 169	56 627	105 451	102 341
0,85	2,72	73 424	78 502	144 855	141 042
0,65	2,38	101 802	109 388	199 471	194 885
0,45	1,98	146 015	158 005	283 365	278 004
0,25	1,47	231 455	253 422	444 329	438 619
0,05	0,66	5 561 901	5 604 650	19 522 952	19 515 242

b) Stress Gradient - Phase 1					
Type of FCGR:		WAA K_{max} 10MPa(m)^{0,5} const.		AA6005A K_{max} 10MPa(m)^{0,5} constant	
Stress intensity ratio R:		0,1	0,8	0,1	0,8
Crack length, a_i mm	Stress itensity range, MPam^{0,5}	Fatigue life, cycles	Fatigue life cycles	Fatigue life, cycles	Fatigue life, cycles
2,05	6,82	-	-	-	-
1,85	6,70	1 905	673	3 995	2 335
1,65	6,61	3 877	1 395	8 124	4 760
1,45	6,55	5 923	2 170	12 405	7 290
1,25	6,48	8 015	2 978	16 778	9 883
1,05	6,36	10 188	3 847	21 316	12 591
0,85	6,08	12 553	4 869	26 240	15 567
0,65	5,71	15 315	6 243	31 964	19 112
0,45	5,14	18 765	8 350	39 063	23 666
0,25	4,10	24 176	13 294	50 033	31 961
0,05	1,99	42 254	32 843	85 148	66 467

Table B.7.5. Fatigue life predictions based on upperbound fatigue crack growth data for cast aluminium alloys from table B.3.4.

a) Uniform tension - Phase 1			
Stress intensity ratio R:		0,1	0,8
Crack length, a_i mm	Stress intensity range, $MPa(m)^{0,5}$	Fatigue life, cycles	Fatigue life, cycles
2,05	4,30	-	-
1,85	4,07	398 937	1 736
1,65	3,83	1 154 022	4 119
1,45	3,58	2 688 305	7 506
1,25	3,32	7 563 667	12 541
1,05	3,03	99 972 200	20 495
0,85	2,72	3,630109E+09	34 172
0,65	2,38	3,462941E+11	60 895
0,45	1,98	1,719760E+14	125 648
0,25	1,47	3,335859E+18	1 3278 202
0,05	0,66	1,680181E+30	6,315015E+12

b) Uniform tension - Phase 1			
Stress intensity ratio R:		0,1	0,8
Crack length, a_i mm	Stress intensity range, $MPa^{0,5}$	Fatigue life, cycles	Fatigue life, cycles
2,05	6,82	-	-
1,85	6,70	11 723	47
1,65	6,61	24 415	101
1,45	6,55	38 268	165
1,25	6,48	52 852	235
1,05	6,36	68 809	319
0,85	6,08	88 282	442
0,65	5,71	116 339	685
0,45	5,14	163 937	1 100
0,25	4,10	335 864	2 136
0,05	1,99	1,638740E+13	17 145

Annex C (Informative)

Testing for Fatigue Design

C.1 Derivation of loading data

C.1.1 Fixed structures subject to mechanical loading

(1) This includes structures such as bridges, crane girders and machinery supports. Existing similar structures subject to the same loading sources may be used to obtain the amplitude, phasing and frequency of the applied loads.

(2) Strain, deflection or acceleration transducers fixed to selected components which have been calibrated under known applied loads can record the force pattern over a typical working period of the structure, using analog or digital data acquisition equipment. The components should be selected in such a way that the main loading components can be independently deduced using the influence coefficients obtained from the calibration loadings.

(3) Alternatively load cells can be mounted at the interfaces between the applied load and the structure and a continuous record obtained using the same equipment.

(4) The mass, stiffness and logarithmic decrement of the test structure should be within 30% of that in the final design and the natural frequency of the modes giving rise to the greatest strain fluctuations should be within 10%. If this is not the case the loading response should be subsequently verified on a structure made to the final design.

(5) The frequency component of the load spectrum obtained from the working period should be multiplied by the ratio of the design life to the working period to obtain the final design spectrum. Allowance for growth in intensity or frequency, or statistical extrapolation from measured period to design life should also be made as required.

C.1.2 Fixed structures subject to environmental loading

(1) This includes structures such as masts, chimneys, and offshore topside structures. The methods of derivation of loading spectrum are basically the same as in C.1.1 except that the working period will generally need to be longer due to the need to obtain a representative spectrum of environmental loads such as wind and wave loads. The fatigue damage tends to be confined to a specific band in the overall loading spectrum due to effects of fluid flow induced resonance. This tends to be very specific to direction, frequency and damping. For this reason greater precision is needed in simulating both the structural properties (mass, stiffness and damping) and aerodynamic properties (cross-sectional geometry).

(2) It is recommended that the loading is subsequently verified on a structure to the final design if the original loading data are obtained from structures with a natural frequency or damping differing by more than 10%, or if the cross-sectional shape is not identical.

(3) A final design spectrum can be obtained in terms of direction, intensity and frequency of loading, suitably modified by comparing the loading data during the data collection period with the meteorological records obtained over a typical design life of the structure.

C.1.3 Moving structures

(1) This includes structures such as travelling cranes and other structures on wheels, vehicles and floating structures.

In these types of structure the geometry of the riding surface should be adequately defined in terms of shape and amplitude of undulations and frequency, as this will have a significant effect on the dynamic loading on the structure.

(2) Other loading effects such as cargo on and off loading can be measured using the principles outlined in C.1.1.

(3) Riding surfaces such as purpose-built test tracks may be used to obtain load histories for prototype designs. Load data from previous structures should be used with caution, as small differences, particularly in bogie design for example, can substantially alter the dynamic response. It is recommended that loading is verified on the final design if full scale fatigue testing is not to adopted (see C3).

C.2 Derivation of stress data

C.2.1 Component test data

(1) Where simple members occur such that the main force components in the member can be calculated or measured easily it will be suitable to test components containing the joint or detail to be analysed.

(2) A suitable specimen of identical dimensions to that used in the final design should be gauged using a convenient method such as electric resistance strain gauges, moiré fringe patterns or thermal elastic techniques. The ends of the component should be sufficiently far from the local area of interest that the local effects at the point of application of the applied loads do not affect the distribution of stress at the point. The force components and the stress gradients in the region of interest should be identical to those in the whole structure.

(3) Influence coefficients can be obtained from statically applied loads which will enable the stress pattern to be determined for any desired combination of load component. If required the coefficients can be obtained from scaled down specimens, provided the whole component is scaled equally.

C.2.2 Structure test data

(1) In certain types of structure such as shell structures the continuity of the structural material may make it impracticable to isolate components with simple applied forces. In this case stress data should be obtained from prototypes or production structures.

(2) Similar methods for measurement may be used as for component testing. For most general use it is recommended that static loads are applied as independent components so that the stresses can be combined using the individual influence coefficients for the point of interest. The loading should go through a shakedown cycle before obtaining the influence coefficient data.

C.2.3 Verification of stress history

(1) The same method as described in C.2.2. may be used to verify the stress history at a point during prototype testing under a specified loading. In this case data acquisition equipment as used in C.1.1 should be used to record either the full stress history or to perform a cycle counting operation. The latter can be used to predict life once the appropriate $\Delta\sigma$-N curve has been chosen.

(2) A further option, which may be used in the case of uncertain load histories, is to keep the cycle counting device permanently attached to the structure in service.

C.3 Derivation of endurance data

C.3.1 Component testing

(1) Whenever force spectra or stress history data are known component testing can be done to verify the design of critical parts of the structure. The component to be tested should be manufactured to exactly the same dimensions and procedures as are intended to be used in the final design. All these aspects should be fully documented before manufacture of the test component is carried out. In addition any method of non-destructive testing and the acceptance criteria should be documented, together with the inspector's report on the quality of the joints to be tested.

(2) The test specimens should be loaded in a similar manner to that described in C.1.1. Strain gauges should be used to verify that the stress fluctuations are as required. The siting of strain gauges should be such that they are recording the correct stress parameter (see 7.5). If the nominal stress is being recorded the gauge should be at least 10mm from any weld toe. Where the stress gradient is steep three gauges should be used to enable interpolation to be carried out.

(3) In order to obtain a $\Delta\sigma$-N curve for design purposes a minimum of eight identical specimens should be tested to give endurance in the range 10^4 to 10^7 cycles. Testing should be carried out with reference to the appropriate standard procedures. A mean curve should be calculated and a design curve obtained which is parallel to the mean curve in a double logarithmic diagram but not less than 2 standard deviations away nor greater than 80% of the strength value, whichever is the lower. This allows for wider variations in production than is normally expected in a single set of fatigue specimens.

(4) For damage tolerance designs a record of fatigue crack growth with cycles should be obtained.

(5) Alternatively, if the design stress history is known and variable amplitude facility is available the specimen may be tested under the unfactored stress history.

C.3.2 Full scale testing

(1) Full scale testing may be carried out under actual operating conditions, or in a testing facility with the test load components applied by hydraulic or other methods of control.

(2) The conditions for manufacturing the structure should be as for component testing in C.3.1.

(3) The loads applied should not exceed the nominal loads.

(4) Where the service loads vary in a random manner between limits they should be represented by an equivalent series of loads agreed between the supplier and the purchaser.

(5) Alternatively, the test load(s) should equal the unfactored load(s).

(6) The application of loads to the sample should reproduce exactly the application conditions expected for the structure or component in service.

(7) Testing should continue until fracture occurs or until the sample is incapable of resisting the full test load because of damage sustained.

(8) The number of applications of test load(s) to failure should be accurately counted and recorded with observations of the progressive development of cracks.

C.3.3 Acceptance

(1) The criterion for acceptance depends upon whether the structure is required to give a safe life performance or damage tolerance performance . See a and b below:

a) For acceptance of a safe life design the life to failure determined by test, adjusted to take account of the number of test results available, should not be less than the design life as defined in 2.2 as follows:

$$T_m \geq T_L \times F \quad \text{(C.1)}$$

where

T_L is the design life (in cycles)
T_m is the mean life to failure (in cycles)
F is a factor dependent upon the effective number of test results available, as defined in table C.1.

Table C.1: Fatigue test factor F

Results of tests	Number of samples tested							
	1	2	4	6	8	9	10	100
Identical samples all tested to failure. All samples failed, factors on log mean assuming population standard deviation as log 0,176	3,80	3,12	2,73	2,55	2,48	2,44	2,40	2,09
Identical samples all tested simultaneously. First sample to fail with population standard deviation assumed as log 0,176	3,80	2,67	2,01	1,75	1,60	1,54	1,54	0,91

b) Acceptance of a damage tolerance design is dependent upon the life of a crack reaching a size which could be detected by a method of inspection which can be applied in service. It also depends on the rate of growth of the crack, critical crack length considerations, and the implications for the residual safety of the structure and the costs of repair.

(2) Criteria for factoring the measured life and for acceptance will vary from one application to another and should be agreed with the engineer responsible for acceptance.

C.4 Crack growth data

Guidance on derivation of crack growth data is given in Annex B.

C.5 Reporting

(1) At the conclusion of any testing performed in accordance with this section a type test certificate should be compiled containing the following information:

a) name and address of the test house;

b) accreditation reference of the test facility (where appropriate);

c) date of test;

d) name(s) of witnesses;

e) description of sample tested, by means of:

1) reference to serial number where appropriate; or
2) reference to drawing number(s) where appropriate; or
3) description with sketches or diagrams; or
4) photographs;

f) description of load systems applied including references to other European Standards where appropriate;

g) record of load applications and measured reactions to loading, i.e. deflection, strain, life;

h) summary of loads and deformations and stress at critical acceptance points;

i) record of endurance and mode of failure;

j) record of locations of observations by reference to (e 2-4) above;

k) notes of any observed behaviour relevant to the safety or serviceability of the object under test, e.g. nature and location of cracking in fatigue test;

l) record of environmental conditions at time of testing where relevant;

m) statement of validation authority for all measuring equipment used;

n) definition of purpose or objectives of test;

o) statement of compliance or non-compliance with relevant acceptance criteria as appropriate;

p) record of names and status of persons responsible for testing and issuing of report;

q) report serial number and date of issue.

Annex D (Normative)

Inspection and Workmanship Acceptance Levels

D.1 Welded Joints

D.1.1 General

(1) These requirements are essential to ensure safe application of the design rules (see 1.4(2)P)

(2) The required quality level for each welded joint shall be obtained from the detail drawings (see 6.2).

(3) Quality levels above Normal are indicated by a 'Fat' number and an arrow.

(4) Where no 'Fat' number exists at a joint it shall be assumed that Normal quality level only is needed.

(5) Where a 'Fat' number exists at a joint, but with an arrow in one direction only, it shall be assumed that Normal quality level is needed in the other direction.

D.1.2 Control of welding quality

D.1.2.1 Quality requirements

(1) The manufacturer shall conform with the quality requirements of EN 729-2.

D.1.2.2 Welding co-ordination

(1) The welding co-ordination personnel shall have comprehensive technical knowledge in accordance with EN 719.

D.1.2.3 Welding procedures

(1) Welding procedures shall be approved in accordance with EN 288-4.

D.1.2.4 Welder approval

(1) Welders shall be approved in accordance with EN 287-2.

D.1.2.5 Welding processes

(1) Control of welding shall be in accordance with EN 1011-1 and 4.

D.1.3 Methods and extent of Inspection

(1) The methods and minimum extent of inspection shall be in accordance with Table D.1 for the purposes of final inspection of the work, unless otherwise agreed with the purchaser.

Table D.1. Methods and extent of inspection for production welds

Inspection stages	Features requiring inspection	Joint type	Orientation[4]	Weld type		Required quality level	Number of joints of each type [1) 3)] %				
Stage 1. Immediately prior to welding **Visual and dimensional inspection**	surface condition, preparation and fit-up dimensions, jigging and tacking requirements	All	All	All		All	100				
Stage 2. After completion of welding[2)] **Visual and dimensional inspection**	overall weld geometry, profile discontinuities, surface discontinuities	All	All	All		All	100				
Stage 3. After visual inspection) **Non-destructive testing**	(a) surface discontinuities (b) sub-surface discontinuities						Penetrant dye	Ultrasonic		Radiographic	
								8mm≤t <25mm	t≥25mm	t<8mm	t≥8mm
		Butt	Trans	Double sided butt		Normal	100S/S	5	20	5 DF	-
						Fat 25	100	100	100	5 DF	-
						Fat 31	100	100	100	20	-
						Fat 39	100	100	100	100	-
						Fat 49	100	100	100	100	100
				Single sided butt	unbacked	Normal	100S/S	100[5)]	100	5 DF	-
					backed	Fat 25	100	100	100	-	-
		Tee, Cruciform	Trans	Butt		Normal	100S/S	-	20	-	-
						Fat 25	100	-	100	-	-
						Fat 31	100	-	100	-	-
		Tee, Cruciform	Trans	Fillet		Normal	100S/S	-	-	-	-
						Fat 25	20	-	-	-	-
						Fat 31	100	-	-	-	-
		Lap	Trans	Fillet		Normal	100				
		All	Longl	All		Normal	100 WE	-	-	-	-
						Fat 25	100 WE	-	-	-	-
						Fat 31	100 S/S	-	-	-	-
						Fat 39	100 S/S	-	-	-	-
						Fat 49	100	-	-	-	-
						Fat 62	100	-	-	5	20

continued/ ....

Table D.1. Methods and extent of inspection for production welds (continued)

Inspection stages	Features requiring inspection	Joint type	Orientation [4]	Weld type	Required quality level	Number of joints of each type [1] [3] %
Stage 4. After non-destructive testing[5] **Destructive tests**	Ssubsurface discontinuities	Butt	Trans	Butt	Fat 39 Fat 49	% 2 (3 macrosections) 5 (3 macrosections)
			Longl	Butt	Fat 61	2 (3 macrosections)
		Tee Cruciform	Longl	Butt	Fat 49	2 (3 macrosections)
				Fillet	Fat 49	2 (3 macrosections + 2 fractures tests)

NOTE 1: Where less than 100% of the joints are to be inspected the sample should include at least one weld from each joint where a different welding procedure is required. In the case of destructive tests at least two welds from each joint should be included. In any case at the start of production the first five joints of each type should be inspected. In the event of a non-compliance with table D.2 being found a further five joints should be tested before reverting to the recommended partial inspection. Where there is no specific recommendation for non-destructive testing this is indicated with a hyphen.

NOTE 2: Where access for inspection of a joint may be eliminated by subsequent work prior to completion of all welding, that joint should be inspected before that work is carried out.

NOTE 3: W/E-within 20mm of weld end; S/S within 20mm of a stop or start; DF applies only where weld caps have to be dressed flush.

NOTE 4: Trans - transverse, Longl - longitudinal. Transverse applies to all welds whose axes are orientated at an angle greater than 45° to the longitudinal axis of the member. Welds whose angles are less than 45° are treated as longitudinal. All welds within 100mm of the connection between load-carrying members or main loading points are treated as transverse.

NOTE: Radiography may be used in place of ultrasonic inspection for detecting purposes. However, ultrasonic inspection may be required for assessment of the compliance of discontinuities with table D.2.

NOTE: Where run-off test plates are used for destructive testing they should be located so that they comply with footnote 1. Where production components are to be sampled for destructive tests, the appropriate additional number of components should be made at the time of production.

D.1.4 Quality Levels

D.1.4.1 General quality control

(1) EN 30042 - Level B shall be used as a general guide for the purpose of identifying lapses in assembly or welding control.

D.1.4.2 Final acceptance

(1) The required quality levels for final acceptance of production welds and any corrective actions shall be in accordance with Table D.2, for the purposes of avoiding unnecessary repair.

Table D.2. Acceptance levels for production welds

Feature	Parameter	Weld type	Particular conditions[1)]	Figure D.2.1 reference	Dimensions	Acceptance criteria according to required quality level [2), 3), 4)]						Corrective actions[5)]
						Normal	Fat 25	Fat 31	Fat 39	Fat 49	Fat 62	
Overall weld geometry	Location [6)]	All				D ± 10	D ± 5	D ± 5	D ± 5	D ± 5	D ± 5	E
	Weld type	All				D	D	D	D	D	D	E
	Extent (length)	All				D + 10 - 0	D + 10 - 0	D + 10	D + 10 - 0	D + 10 - 0	D + 10 - 0	E
Profile discontinuities	Actual throat thickness	All		i, ii, iii	a, ≥ a, ≤	D (50) D + 5	D D + 4	D D + 4	D D + 3	D D + 3	D D + 3	R DS
	Leg length	Fillet		i	z ≥	D (50)	D (50)	D (50)	D	D	D	R
	Toe angle (interface and interrun)	All	Trans Longl	i, ii i, ii	θ ≥ θ ≥	90° 90°	120° 90°	150° 90°	165° 90°	175° 90°	- 175°	DS/R DS/R
	Excess weld metal	Butt	Trans Longl	ii ii	h ≤ h ≤	6 6	5 6	4 5	2 4	0.5 3	- 0.5	DS DS
	Incomplete groove or concave root	Butt	Trans Longl	ii ii	h ≤ h ≤	0 (50) 0,1t	NP 0,1t	NP 0,1t	NP 0,1t	NP 0,05t	- NP	R R
	Linear misalignment	Butt All All	Trans, butt Trans, cruciform Longl	iv v iv, v	h ≤ h ≤ h ≤	D + 0.2t D + 0.4t D + 0.4t	D + 0,1t D + 0,2t D + 0,4t	D+0,05t - D+0,4t	D + 0,05t - D + 0,4t	D + 0,05t - D + 0,4t	- - D + 0,4t	E E E
Surface breaking discontinuities	Undercut[7)]	All Fillet All	Trans (not lap joint) Trans (lap joint) Long	iv, v iv iv, v	$h_1 + h_2 \le$ l≤ $h_1 + h_2 \le$ l≤ $h_1 + h_2 \le$	0,05t 25 0,03t 10 0,1t	0,05t 25 NP NP 0,1t	0,03t 10 - - 0,1t	NP NP - - 0,1t	NP NP - - 0,05t	- - - - 0,05t	R R R R R
	Lack of root penetration	S/S butt	Trans Longl	iii iii	h ≤ h ≤	D + 0,05t (50) D + 0,01t (50)	- D + 0,1t	- D + 0,1t	- D + 0,05t	- D + 0,05t	- -	R R
	Porosity	All	Trans Longl	vi vi	d ≤ Σ d ≤ d ≤ Σ d ≤	2 10 [100] 2 20 [100]	1 5 [100] 2 10 [100]	1 5 [100] 1 5 [100]	NP NP 1 5 [100]	NP NP NP NP	- - NP NP	R R R R
	Lack of fusion	All		vii	l ≤	NP	NP	NP	NP	NP	NP	R
	Cracks	All			l ≤	NP	NP	NP	NP	NP	NP	R

continued/ ....

Table D.2. Acceptance levels for production welds (continued)

Feature	Parameter	Weld type	Particular conditions[1]		Figure D.2.1 reference	Dimensions	Acceptance criteria according to required quality level [2), 3), 4)]						Corrective actions[5]
							Normal (Fat 20)	Fat 25	Fat 31	Fat 39	Fat 49	Fat 62	
Sub-surface discontinuities	Lack of fusion root penetration	Butt	All		vii, viii	h ≤	3	3	3	3	3	NP	R
			Trans	Full depth $h^1 \le 6$	vii, viii	Σ l ≤	1,5t [100]	1,5t [100]	NP	NP	NP	NP	R
						l ≤	10	5	NP	NP	NP	NP	R
						$l^1 \ge$	10	10	NP	NP	NP	NP	R
				$h^1 > 6$	vii, viii	l ≤	NL	10	5	NP	NP	NP	R
						$l^1 \ge$	NL	10	10		NP	NP	R
			Longl	Full depth $h^1 \le 6$	vii, viii	Σ l ≤	3 t [100]	1,5t [100]	1,5t [100]	1,5t [100]	1,5t [100]	NP	R
					vii, viii	l ≤	NL	NL	10	5	NP	NP	R
						$l^1 \ge$	NL	NL	NL	NL	NP	NP	R
				$h^1 > 6$	vii, viii	l ≤	NL	NL	NL	10	5	NP	R
						$l^1 \ge$	NL	NL	NL	NL	NL	NL	R
	Root gap	Fillet/ PP butt			l, v	h ≤	2 (100) 3	2	2	2	2	1	R
	Copper inclusion	All					NA	NA	NP	NP	NP	NP	R
	Solid and other inclusions	All				d ≤	NA	NA	2	1	NP	NP	R
	Porosity	All			vi, vii	d ≤ A ≤	NA	NA	2 3%	1 2%	1 1%	NP NP	R R
	Cracks	All					NP	NP	NP	NP	NP	NP	R

NOTE 1. For definition of orientation see footnote 4 in table D.1.
NOTE 2. All dimensions are in millimetres unless otherwise noted.
NOTE 3. Thickness applies to minimum member thickness at weld in question. For thicknesses greater than 20mm t is taken as 20mm. Where the permitted size h of a discontinuity is related to t the maximum permitted value is not less than 0.3mm in any case.
NOTE 4. Where more than one value is given both apply.
NOTE 5. See Note 1 in table D.1.
NOTE 6. Subject to any other locational requirements.
NOTE 7. 'lap' applies to any fillet welded attachment whose length in the longitudinal direction exceeds 50mm.
NOTE 8. Any straight line parallel to the weld axis.

Key

D Dimension specified on drawings
DS Dress smoothly
E Refer to designer
NL No limit
NP Not permitted (applies to discontinuities which are detectable by non-destructive test methods in table D.1).
PP Partial penetration
R Repair by welding to approved procedure
SS Single sided, (including butt welds in hollow sections)
( ) Length of weld, over which measurement may be averaged (in mm)
[ ] Length of weld, over which the summation is made [in mm]
NA Not normally applicable (see table D1) _Not applicable (see tables 5.1.2 and 5.1.3)
A Percentage area (of porosity) as seen on radiograph in any 100mm of weld length
l Length parallel to weld axis

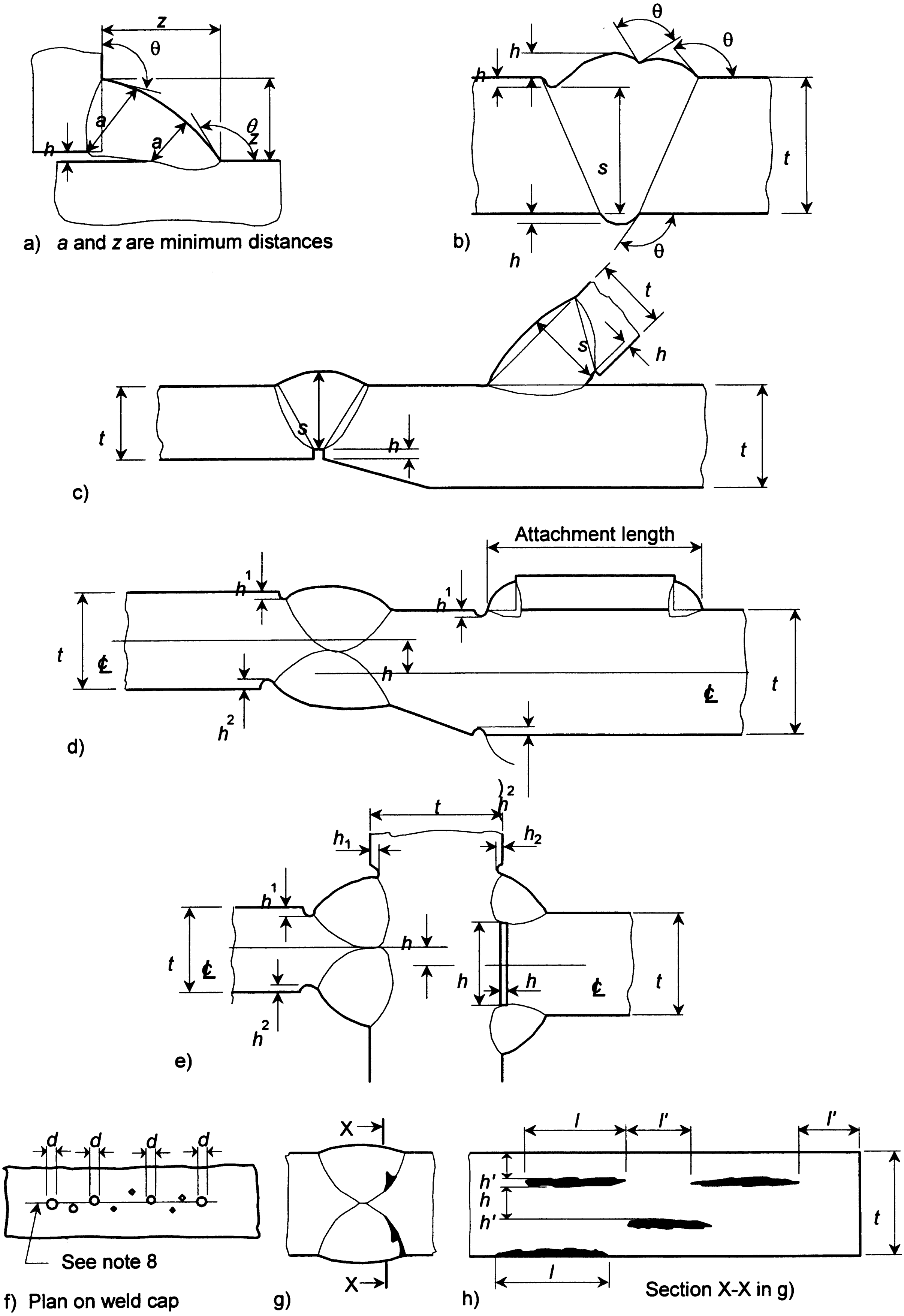


Fig.D.2.1. Dimensions of weld discontinuities

D.2 Castings

D.2.1 Methods and Extent of Inspection

(1) The methods and minimum extent of inspection shall be in accordance with table D.3 for the purposes of final inspection of the work.

Table D.3 Scope of inspection for castings

Required quality level	Type of Inspection	
	Surface	Volumetric
Normal	100% visual	-
Fat 25	100% dye penetrant	10 % Radiography
Fat 31	100% dye penetrant	100% Radiography
Fat 39	100% dye penetrant	100% Radiography
Fat 49	100% dye penetrant	100% Radiography
Fat 62	100% dye penetrant	100% Radiography
Fat 77	100% dye penetrant	100% Radiography

D.2.2 Final Acceptance

(1) The required quality levels for final acceptance of castings shall be as in table D.4.

Table D.4 Quality levels for castings

Required quality level	Type of Discontinuity	
	Cracks	Maximum pore size (mm)
Normal	Not Permitted	3,0
Fat 25	Not Permitted	2,2
Fat 31	Not Permitted	1,5
Fat 39	Not Permitted	0,9
Fat 49	Not Permitted	0,5
Fat 62	Not Permitted	0,3
Fat 77	Not Permitted	0,2

Annex E (informative)

Fatigue Strength Improvement Welds

E.1 General

(1) In cases where the fatigue cracks would initiate at the weld toe, the capacity of welded joints can be improved. In practice such methods are normally used at the most highly stressed welds or for improving welds having low strength.

(2) In cases where specified improvement techniques have been employed, an improvement of 30% for fatigue fracture at a weld toe can be obtained. The highest improvement is achieved by the combination of two methods like machining (or grinding) and hammer peening where the double improvement of the individual methods can be reached.

(3) The following methods are considered here:

- Machining or grinding
- Dressing by TIG or plasma
- Peening (shot peening, needle peening or hammer peening)

(4) For all methods the following aspects should be considered:

- A suitable work procedure must be available.

- Before applying the measures for improvement one must assure that no surface cracks are present in the critical locations. This should be done by dye penetrant or other suitable NDT methods.

- For improvement at the mid and long fatigue life region the capacity can be improved by 30% measured by stress range.

- In the short life region where the local stresses exceed the yield strength the initiation period is a small fraction (irrespective of the notch case) and the improvement is thus small. Hence, there will be no improvement in design at 10^5 cycles. (The $\Delta\sigma$-N curve is thus rotated with fixed values at 10^5).

- Potential fatigue fracture locations other than that being improved must be considered: e.g. if the weld toe area is improved, then locations like the weld throat or internal cracks (partial penetration), might be the limiting factor for the fatigue life and the usefulness of improvement methods should be considered.

- Under freely corroding conditions in water, the improvement is often lost. Methods involving compressive residual stresses (peening) are less susceptible. Corrosion protection is therefore needed if the improvement is to be achieved.

E.2 Machining or grinding

(1) Machining can be performed by a high speed rotary burr cutter and has the advantages of producing a more precise radius definition, leaving marks parallel to the stress direction and gaining access to corners. Alternatively a disk grinder may be used if access permits, see Figure E.2.1. In both cases the radius of the cutting tip or edge must be correctly chosen.

(2) To ensure the removal of intrusions etc. burr machining has to be extended to a depth of minimum 0.5mm below the bottom of any visible undercut etc., but should not exceed 2mm or 5% of the plate thickness, whichever is the less see Figure E.2.2. The slight reduction in plate thickness and corresponding increase in nominal stress is insignificant for thickness of 10mm or larger. In the case of multipass welds at least two weld toes must be treated. Care should also be taken to ensure that the required throat size is maintained.

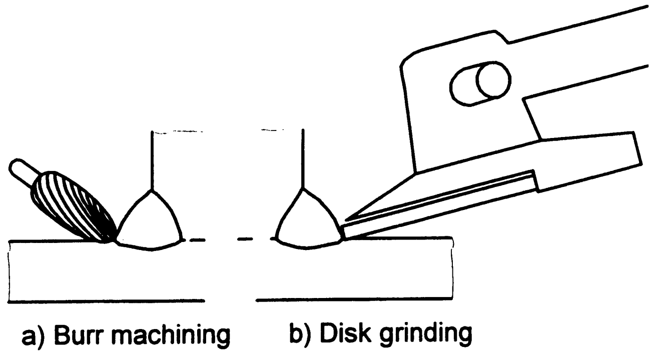


Figure E.2.1 Machining/grinding techniques

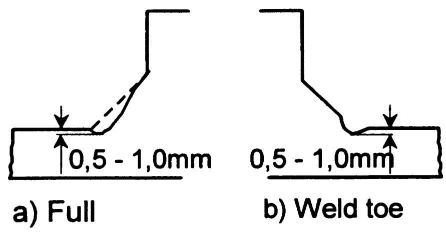


Figure E.2.2 Profile Geometries

E.3 Dressing by TIG or plasma

(1) While TIG welding is only a practical process for structures made of plates 4mm thick or less, it can be used for improving the fatigue strength in cases where the weld toe is the critical site. When re-melting the existing toe region inclusions and undercuts can be removed and the toe radius can be increased which reduces the local stress concentration factor.

(2) Standard TIG dressing equipment can be used, without the addition of any filler material. TIG dressing is sensitive to operator skills and it is important to have clean surfaces to avoid pores. Detailed procedures must be worked out.

(3) The improvement must be verified by tests.

E.4 Peening

(1) The largest benefits are normally obtained with methods where compressive residual stresses are introduced. The most common methods are hammer peening, needle peening, and shot peening. Peening is a cold working process where the impact of a tool deforms the surface plastically. The surrounding (elastic) mterial will compress the deformed volume. High compressive service loading can decrease the level of residual stress and must be taken into account when applying random loading spectra.

(2) Procedures for all peening methods must be worked out: Passes, weld toe deformation, and indentation for hammer and wire bundle peening; intensity, coverage, and Almen strip deformation for shot peening.

Annex F (informative)

Low Cycle Fatigue

F.1 Introduction

(1) Where significant damage is done by high stress ranges which are applied less than 10^5 times, the $\Delta\sigma$-N curves given in 5.2 for certain details and R-ratios may be unnecessarily conservative. The data below may be used to obtain a more accurate life prediction.

F.2 Modification to $\Delta\sigma$-N Curves

(1) For endurance between 10^3 and 10^5 cycles the fatigue design curve may be defined as:

$$N_i = \left(\frac{\Delta\sigma_c}{\Delta\sigma_1}\right) x 20^{m_o/m_1} \text{ x } 10^5 \tag{F.1}$$

where

N_i is the calculated number of cycles to failure of a stress range $\Delta\sigma_i$
Δ_c is the reference value of fatigue strength at $2{,}10^6$ cycles depending on the detail category
$\Delta\sigma_i$ is the principal stress range at the detail and is constant for all cycles
m_0 is the inverse logarithmic slope of the $\Delta\sigma$-N curve in the range 10^3 and 10^5 cycles, depending on the detail category, alloy and R-value
m_1 is the inverse logarithmic slope of the $\Delta\sigma$-N curve, depending on the detail category, see tables 5.1.1 to 5.1.5 or 5.2.1.

(2) See also 5.3.4(1).

F.3 Test Data

(1) Table F.3.1 gives values of m_0 for selected details in certain wrought alloy products which have been derived from test data.

(2) For R-ratios between R = -1 and R = 0 a linear interpolation of inverse m_0 value may be used.

(3) The R-value may be based on the applied stresses only without taking into account residual stresses.

Table F.3.1. Values of M_0

Detail Type Number	Detail Category Table	Alloys	Product Form	m_0	
				R=-1	R≥0
1,1	5.1.1	7020	Sheet and plate	5,0	m_1
1,2		6000 series	Sheet and plate	4,0	m_1
1,3		7020	Shaped extrusions	4,0	m_1
1,4		6000 series	Shaped extrusions	4,0	m_1
3,6	5.1.3	as per table 1.1.1	as per table 1.1.1	3,0	m_1
3,7				3,0	m_1
3,8				3,0	m_1
3,9				3,0	m_1
4,1	5.1.4	7020	as per table 1.1.1	3,3	m_1
4,2		7020		3,3	m_1
4,3		7020		3,3	m_1
4,4		7020		3,3	m_1

Annex G: (Informative)

Influence of R-ratio

G.1. Enhancement of fatigue strength

(1) For applied stress ratio values less than R = +0,5 the reference fatigue strength $\Delta\sigma_c$ may be enhanced by an R ratio factor f(R) where the enhanced reference fatigue strength $\Delta\sigma_{c(R)}$ at 2 x 10^6 cycles is given by:

$$\Delta\sigma_{c(R)} = f(R)\ \Delta\sigma_c \qquad \text{(G.1)}$$

(2) The value of f(R) depends on the value of R and the type of component and detail (see G.2).

(3) The fatigue strength at 10^4 cycles should not be enhanced.

(4) The basic slope $m_{1(R)}$ of the enhanced $\Delta\sigma$-N curves shall be adjusted in accordance with the values of Δ_c at 10^4 and 2 x 10^6 cycles (see fig. G.1.1.)

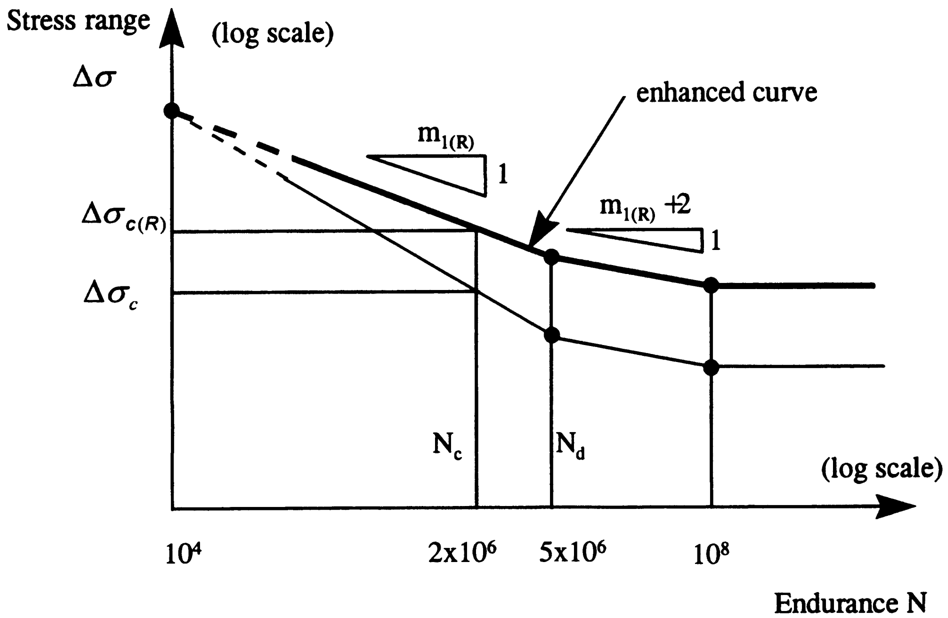


Table G.1.1. Enhancement of $\Delta\sigma$-N curve

G.2. Enhancement Cases

G.2.1. Case 1

(1) This applies to initiation sites in base material and wrought products in structural elements remote from connections. It may also be applied to structures which have been effectively stress relieved.

(2) Allowance shall be made for any pre-load or lack of fit in addition to the applied stresses.

(3) The values of f(R) are given in table G.2.1. and fig. G.2.1.

Table G.2.1. Values of f(R) for Case 1

R	f(R)
<-1	1,6
>-1 < +0,5	1,2 - 0,4R
> + 0,5	1,0

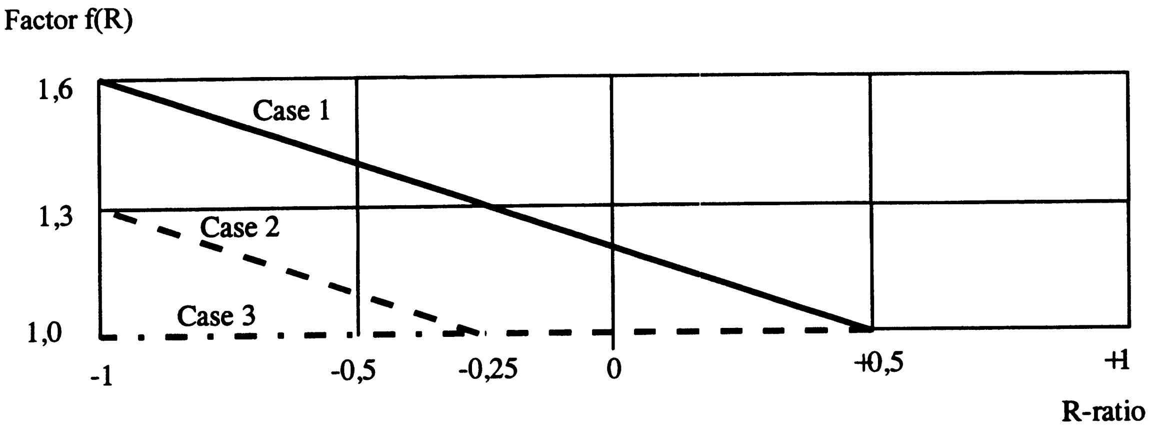


Figure G.2.1. Strength enhancement factor f(R) at 2 x10^2 cycles

G.2.2. Case 2

(1) This applies to initiation sites associated with welded or mechanically fastened connections in simple structural elements, where the residual stresses σ_{res} has been established, taking into account any pre-load or lack of fit.

(2) The effective R-ratio R_{eff} should be estimated as follows:

$$R_{eff} = (2\sigma_{res} - \Delta\sigma)/(2\sigma_{res} + \Delta\sigma)$$

where $\Delta\sigma$ is the applied stress range.

(3) The values of f(R) are given in table G.2.2. and figure G.2.1.

Table G.2.2. Values of f(R) for Case 2

R_{eff}	f(R)
< - 1	1,3
>-1 < - 0,25	0,9 - 0,4R
>-0,25	1,0

G.2.3. Case 3

(1) This applies to complex structural assemblies where control of residual strersses is not practicable.

(2) In this case f(R) should be taken as unity for all R-ratios.

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