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Welding — Methods for assessing imperfections in metallic structures

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British Standards

National foreword

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Schweißen - Verfahren zur Beurteilung von Unregelmäßigkeiten bei metallischen Bauteilen

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Foreword

This CEN Technical Report (CEN/TR 15235:2005) has been prepared by Technical Committee CEN/TC 121 “Welding”, the secretariat of which is held by DIN.

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Introduction

European provisions for assessing imperfections in metallic structures are needed to meet the requirements of industry. The technology is being applied by many industries for materials selection, design and fabrication and in-service assessment using existing methods. Engineering Critical Assessment (ECA) methods for the assessment of imperfections have received further support by the EC directive 97/23/EC concerning pressure equipment (PED) which permits such methods as an alternative to conventional methods.

The present Technical Report gives guidance to the application of BS 7910 and the European SINTAP Report. Some further documents are also mentioned.

Experience from the application should, in a few years, provide enhanced technology in the subject and eventually permit standardisation at the European level.

Conventional design procedures involve application of mathematical models such as the theory of elasticity. Actions are described by characteristics such as stress and strain. Resistance described by characteristics such as yield stress and ultimate limit stress. The designer has to assure that the resistance of the structure is adequate, using adequate safety factors, partial coefficients, etc. The mathematical models presuppose a homogenous material.

Many failure modes involve cracks. Failure may originate from a crack and/or failure may propagate (slow or fast) as a crack. Application of the conventional theory of elasticity to a structure with a crack leads to a singularity at the crack tip because the stresses approach infinity. To this should be added that a closer study of the fracture processes shows that in-homogeneities such as grain structure and even the atomic structure may influence the mode of fracture. Conventional design procedures can, for these reasons, not be applied in situations where an analysis of the significance of a crack-like imperfection is necessary and they cannot be applied for an analysis of the propagation of fatigue cracks, creep cracks, stress corrosion cracks, etc.

Alternative methods termed fracture mechanics have been developed in order to model the behaviour of structures containing cracks. Fracture mechanics interpret crack driving force and materials resistance by an alternative set of parameters such as stress intensity factor, crack tip opening displacement, etc.

Engineering critical assessments use a combination of conventional design procedures and fracture mechanics calculations, depending on the nature of the imperfection and the likely type of failure. General corrosion results for example in a reduction in cross section and may be analysed by conventional design procedures whereas propagation of fatigue cracks has to be analysed by fracture mechanics methods.

1 Scope

This Technical Report provides guidance on the selection and application of methods for assessing the significance of imperfections in all types of structures and components. The guidance is primarily tailored to welded structures and components in steel or aluminium alloys. Some of the methods may also be applied for other types of metals and for non-welded structures and components.

2 Terms and definitions

For the purposes of this Technical Report, the following definitions apply:

ECA – Engineering Critical Assessment
methods for the assessment of the significance of imperfections for the strength and usability of structures (see also clause 4)

FAD – Failure Assessment Diagram
combines the analysis of the safety against plastic instability and final fracture in a single diagram

3 Symbols and abbreviations

CDF
Crack Driving Force plot

ETM
Engineering Treatment Model

FITNET
European Fitness-for-service Network

HIDA
High Temperature Defect Assessment

SINTAP
Structural Integrity assessment procedures for European industry

The following symbols are used to characterise the local stress-strain field around the crack front. They are (usually with subscripts) used for crack driving force as well as resistance.

K
stress intensity factor

J
a line or surface integral that encloses the crack front from one crack surface to the other

CTOD
Crack Tip Opening Displacement

See the publications listed in the clause "Bibliography" (in particular references [1] and [2]) for further detail.

4 ECA principles

ECA is a designation for methods used for the assessment of the acceptability of imperfections.

Assessment of the acceptability involves consideration of:

a) Legal requirements

Legal requirements and/or provisions in the code(s) for the structure in question or contractual requirements may restrict the acceptance. Mandatory acceptance criteria, to be used for fabrication of new structures may e.g. be specified in the code or contract covering the structure.

b) Contractual requirements

The application of ECA methods should be acceptable to the parties concerned in each particular case.

c) Commercial requirements

Costs and market position may influence the benefits or disadvantages of an application

d) Requirements to fabrication.

A key consideration is maintenance of proper quality control.

5 Safety considerations

5.1 Conventional provisions for acceptance of welded structures

Standards for design and fabrication of welded structures do, as a general rule, include provisions for inspection and testing of the welded joints. The standards usually specify:

a) Acceptance levels for imperfections, normally by reference to a quality level in standards such as EN ISO 5817.

b) Methods for non-destructive testing by reference to the comprehensive system of EN standards for NDT, at least by reference to EN 12062.

c) The amount of testing (100% or examination of only a part of the welds).

d) Procedures for action when non-conformity is detected, typically requirements for repair, re-examination and some supplementary non-destructive testing.

e) Appropriate safety factors.

Conventional non-destructive testing methods involve an element of subjective judgement and the output of the testing is considered to be an evaluation and **not** a measurement (even though figures may be reported). The evaluation has two final outcomes: Accepted or not accepted.

Table 1 — Outcomes of conventional inspections

Result of inspection	**Structure**	
	Safe	*Unsafe*
Accepted	This should be the normal outcome.	Really dangerous situation where a potentially unsafe structure is accepted by mistake, neglect or inefficient inspection procedures. Usually termed customer's and society's risk. Design codes, etc. aim for reduction of this risk to very low levels for critical structures.
Not accepted	This outcome represents an expense due to unnecessary scrapping or repair in order to make the structure formally acceptable. One possible application for ECA (see below) is to document the inherent safety of the structure and thus avoid scrapping or repair. Usually termed producer's risk.	Rejection of an unsafe structure saves the customer and the society from a potential risk. However, it necessitates scrapping or repair in order to make the structure safe and it results in expenses and also a waste of resources.

Experience has shown that the system results in structures characterised by acceptable risks of failure (customer's and society's risk). The actual risk depends on the nature of the structure and on the failure mode. The acceptable risk for sudden, catastrophic failure may be of the order 10^{-6} or even lower for critical structures. The acceptable risk of having substantial fatigue cracks prior to expiration of the stipulated life time of the structure may be much higher, for example of the order 10^{-2}.

5.2 Application of ECA for new products

Application of ECA as a tool for specification of quality criteria for new structures is feasible in theory but difficult in practice. ECA shall not be invoked as an excuse for acceptance of poor workmanship.

Application of ECA involves several requirements:

a) Fracture toughness and other relevant materials data for weld metal, parent metal and heat affected zones have to be determined. This is usually performed as part of the welding procedure qualification. However, strict process control of welding operations is required in order to assure that materials data obtained during procedure testing are truly representative. If not, testing of production test plates may be required.

b) The welds have to be inspected by one or more procedures for non-destructive testing able to:

– Detect all potentially dangerous imperfections.

– Determine the type of the imperfections, at least to distinguish between planar and non-planar imperfections.

– Measure imperfection size, position and orientation.

c) All procedures for non-destructive testing have to be validated on representative samples and the inspection uncertainties determined.

d) Safety factors have to be calculated in order to counteract inspection uncertainties and other uncertainties. This may involve application of advanced probabilistic methods.

e) Acceptance criteria, extents of testing and other quality criteria have to be specified.

The common procedure for measurement of imperfections in the weldments is ultrasonic testing (UT), standardised in several European test specifications. UT requires in general a high quality of the weld metal as regards porosity and slag inclusions which may mask more serious imperfections.

The principles for evaluation of a measurement of dimensions are specified in EN ISO 14253-1. A measured value Y is associated with a measuring uncertainty U. U is usually determined from the measurement standard deviation multiplied by a safety factor. The real value may be any value in the interval Y ± U (with a confidence determined by the safety factor). For a largest acceptable imperfection A, the acceptance limit consequently becomes:

$$\mathbf{Y + U < A}$$

This illustrates the key role of the uncertainty U. The results of ECAs should only be used with a clear knowledge of the uncertainties involved in detection, sizing and identification, of imperfections. It should be noted that virtually none of the published NDT standards include provisions for the determination of uncertainties.

Specification of adequate safety factors or partial coefficients is not simple because standards for design and fabrication of structures and products rarely specify safety factors or partial coefficients for ECA. Safety considerations are covered in an annex to BS 7910, Annex K: “Reliability, partial safety factors, number of tests and reserve factors”. However, compatibility with the relevant design code can be assured with expert knowledge.

ECA may, therefore be used for new structures. One case, where the application may be most useful, is for design of fatigue loaded structures. Fatigue cracks are likely to initiate at welds in areas of high structural stress concentrations. Finite element analysis + ECA may be the only alternative to full-scale fatigue testing in such cases. Inspection uncertainties are of less importance because the safety mainly depends on visual examination of weld surface quality and in particular the occurrence of undercut in the critical areas. Non-conformity may be removed by grinding. Specification of safety factors is also comparatively simple when growth of fatigue cracks is the dominating failure mode.

Another case involves intentional introduction of “imperfections” in the welds during the design phase. Conventional codes, standards and recommendations often require butt welds to be fully penetrating. However, ECA may document that double-V butt welds with intentional central lack of penetration may be acceptable in many cases, not least when the welds mainly are exposed to bending stresses. Conventional criteria and inspection procedures may then be used for inspection of the quality of the weld metal. A supplementary examination by UT permits determination of the height of the unfused area with acceptable uncertainty

5.3 Application of ECA for assessment of nominally non-conforming structures

It is well known that the producer’s risk from non-conforming structures may be significant, and many repairs are unnecessary from a technical point of view. It is possible to use ECA in order to avoid such repair, but certain precautions are needed:

a) Deviations in welding parameters between the welding of the test plates, used for determination of fracture toughness, and the actual welds in the structure may result in the fracture toughness of the actual welds being different from the measured values. Some imperfections, in particular cracks, but also lack of penetration, lack of fusion and excessive porosity, may indicate a deviation from the qualified welding procedure. For instance, hydrogen cracks in C-Mn steel welds are caused by a combination of high hardness (low fracture toughness), high concentration of hydrogen and high residual stresses (restraint). Determination of the critical crack size on the basis of fracture toughness values obtained from the procedure tests is likely to be unsafe in such cases, and more appropriate values need to be determined.

b) All the requirements and limitations mentioned above for new structures also apply for the assessment of nominally non-conforming welds.

c) The limitations for application of UT procedures mentioned above for new structures also apply for the assessment of nominally non-conforming or repaired welds. The welds have in general to be of a high quality and the non-conformity limited to the occurrence of a single, well-defined type of imperfection. Central lack of penetration and sidewall lack of fusion are typical examples.

d) Conventional quality and inspection criteria are efficient mainly because the high costs related to non-conformity induce the manufacturers to maintain a high quality level in production. This reduces occurrence of really dangerous imperfections to a very low level. Structures, as produced, are inherently safe and inspection largely becomes a formality. Any action, which diminishes the relative costs related to non-conformity, is likely to change the balance and eventually result in manufacture of a higher proportion of structures having really dangerous imperfections. This shall be counteracted in order to avoid higher failure rates.

5.4 Application of ECA for in-service inspection

Application of fitness-for-service assessment for in-service inspection is quite common and it has far fewer complications than the application to new structures. There are two different types of application:

a) Conventional inspection procedures are known to be characterised by quite large uncertainties. A structure may easily hold imperfections, which surpass the acceptance criteria, used during the original non-destructive testing. Such imperfections may (by coincidence) be found during in-service inspection. The owner of the structure may use fitness-for-service assessment for documentation of the acceptability of these imperfections.

b) Application of ECA for assessment of crack growth, corrosion, wear and tear and other deterioration detected during in-service inspection is also a well-established practice. Provisions have, for several years, been included in a number of codes for pressurised equipment and other structures. In service inspection is facilitated by the fact that deterioration usually results in well-defined imperfections of a single type, which is often localised (e.g. fatigue cracks). This permits application of special procedures to non-destructive testing, able to give quantitative information on the size of the imperfections. The deterioration may be monitored during a number of inspections in order to follow the growth of cracks, the progress of corrosion, etc.

The following considerations are recommended:

c) The ECA may require information on fracture toughness and other materials properties. This information should be established during procedure testing. Application for in-service inspection should be taken into consideration at the design stage.

d) Fingerprint inspection should be performed on the finished structure, prior to use, in order to detect substantial imperfections originating from the fabrication but overlooked or misinterpreted during the outgoing inspection [a) above].

6 Existing ECA-procedures

6.1 BS 7910

Two publications from the British Standards Institution, namely: PD 6493:1991 "Guidance on methods for assessing the acceptability of flaws in fusion welded structures" and PD 6539:1994 "Guide to methods for the assessment of the influence of crack growth on the significance of defects in components operating at high temperatures" have been widely used. PD 6493 has been in existence for more than two decades and it has been successfully applied in many countries and industrial sectors.

The two PD publications were superseded (in December 1999) by BS 7910: "Guide on methods for assessing the acceptability of flaws in metallic structures", which was amended in 2000 and revised in 2004.

BS 7910 has been referred to by a number of European design codes such as:

– EN 13445 on unfired pressure vessels

– EN 12952 on water tube boilers

– ENV 1999 on design of aluminium structures

– EN 13480 on metallic industrial piping

BS 7910 is very comprehensive and it gives an adequate coverage of most aspects.

6.2 SINTAP (Structural integrity assessment procedures for European industry)

A comprehensive European project: Structural Integrity Assessment Procedures for European industry (SINTAP), has resulted in a report supplementing the provisions of BS 7910. The SINTAP report may be used in lieu of the sections in BS 7910 on fracture and plastic collapse. SINTAP was a Brite-Euram project Framework IV part-funded by the European Commission under its Brite-Euram framework, project number BE 95-1426. The project had a duration of three years and finished in April 1999. The consortium consisted of seventeen members from nine European countries and comprised a cross-section of industrial, safety assessment, research and academic institutions. The project was initiated in response to a number of issues pertaining to the various structural integrity methods which were reviewed early in the project: It was therefore structured into a number of tasks to address these issues, the overall objective being to derive a unified structural integrity evaluation method applicable across a wide range of European industries and which would be suitable for consideration as a CEN procedure.

The SINTAP procedure is a method for the evaluation of integrity in terms of brittle fracture, ductile tearing and plastic collapse. In its development, other procedures in use within Europe were considered: PD 6493 (now BS 7910), R6 (from the UK), and the Engineering Treatment Model (ETM, from Germany) and parts incorporated where appropriate. The underlying principles of the SINTAP method are:

a) A hierarchical structure based on quality of available data inputs.

b) Decreasing conservatism with increasing data quality.

c) Detailed guidance on determination of characteristic input values such as toughness.

d) A choice of output within the framework of a so-called Failure Assessment Diagram (FAD) or Crack Driving Force (CDF) plot.

e) Specific methods for allowing for the effect of weld strength mismatch.

f) Guidance on dealing with situations of low constraint and, for components containing fluids, Leak-Before-Break analysis.

g) Compendia of solutions for Stress Intensity Factors, Limit Load Solutions and weld residual stress profiles.

The procedure is arranged in 4 chapters:

In **chapter I**, the procedure is introduced and its scope outlined. A description of the FAD and CDF approaches is given together with guidance on interpreting results of an analysis and suggestions on the format for reporting an assessment.

Chapter II provides detailed guidance on the treatment of tensile data, determination of characteristic values of fracture toughness, imperfection characterisation and stress treatment.

Chapter III provides compendia of stress intensity factors and limit load solutions for a range of common geometry's. Residual stress distributions for a variety of welded joint configurations are given. In addition a section on guidance enables the user to determine whether any aspect of an assessment could be refined to enable a reduction in conservatism when an initial analysis has shown a particular case to be unacceptable. This will usually involve enhancement of the quality of the input data.

Finally, **chapter IV** provides details of methods, which can be used as alternatives to the standard levels described in the main text. These include the most basic 'default' method and also advanced methods, which would only be applied by the specialist user.

6.3 Other European and International developments

Methods for assessing imperfections in metallic structures have been published in several standards and recommendations. Research and experience from practical applications contribute to further developments. The following specifications may provide useful information. However, an assessment of the application of the specifications in a European context is outside the scope of the present Technical Report.

a) American Petroleum Institute API RP 579: Recommended practice for fitness-for-service. RP 579 is limited to in-service inspection and designed to support API inspection codes for pressure vessels, piping and tankage (API 510/570/653). A new API RP 571 on refining damage mechanisms will provide a link between RP 579 and API RP 580: Risk based inspection.

b) FITNET [9] is a 4-year European thematic network with the objective of developing and extending the use of fitness-for-service procedures throughout Europe. It is part-funded by the Competitive and Sustainable Growth Programme and forms part of the EU's Framework 5 research programme. Additional funding comes from the participants in the form of in-kind contributions, including information from related EU- and ECSC-funded projects. The network started in February 2002 and will run until the end of February 2006.

Flaws (such as cracks, welding defects and corrosion damage) can arise during the manufacture and/or use of metallic components. For safety-critical items such as aircraft, pipelines and pressure vessels, the failure of a single component due to the presence of a flaw can threaten human life, as well as having severe economic and environmental consequences. Other flaws may be harmless, as they will not lead to failure during the lifetime of the component. Replacement and/or repair of such flaws is economically wasteful. A fitness-for-service procedure allows flaws to be evaluated consistently and objectively, using fracture mechanics principles. Although several fitness-for-service procedures already exist (e.g. API579, BS7910, SINTAP, R6), they tend to be aimed at a particular industry sector, or a single failure mode, or are national documents. There is therefore a need for an agreed European procedure, which could ultimately become a European (CEN) standard.

The network co-ordinator is GKSS [12] in Geesthacht, Germany. Nine other organisations make up the principal contractors leading the working groups and work packages. Principal contractors include representatives of universities, industry and research and technology organisations. The remaining organisations provide in-kind contributions such as in-house procedures, case studies and industry know-how. Self-funded contributions from other organisations and individuals are also welcome.

FITNET involves currently 50 organisations from 19 countries, including participation from several of the new EU countries (Poland, Slovenia, Hungary and the Czech Republic), from Switzerland and from Japan and USA.

The network consists of a matrix of Working Groups and Work Packages, under the leadership of the network co-ordinator. The working Groups address particular fatigue modes, such as corrosion, fracture, fatigue and creep. The Work Packages cover all failure modes, and address particular stage of the network, e.g. review of state of the art, standardisation, dissemination, education. Further information is available from the project website.

c) Validation, Expansion and Standardisation of Procedures for High Temperature Defect Assessment (HIDA) is a four year (January 1996 - December 1999) project (reference BE 1702) and is partly funded by the European Commission under Brite Euram Framework IV. Thirteen partners from 7 European countries form the project consortium. The HIDA project is in particular aimed at addressing issues such as validating and expanding the database of the existing high temperature crack assessment procedures, developing new methodologies for predicting the behaviour of high temperature components and unifying and refining existing procedures with a view to making recommendations for a European Standard.

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[4] EFAM ETM 97 *Engineering Treatment Model, procedure document available through Dr. U. Zerbst, GKSS, D-21502 Geesthacht, Germany*

[5] EN ISO 14253-1 *Geometrical Product Specification (GPS) – Inspection by measurement of workpieces and measuring equipment – Part 1: Decision rules for proving conformance or non-conformance with specifications (ISO 14253-1:1998)*

[6] CEN/TS 14751 *Welding – Use of time-of-flight diffraction technique (TOFD) for examination of welds*

[7] EN ISO 5817 *Welding – Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) – Quality levels for imperfections (ISO 5817:2003)*

[8] EN 12062 *Non-destructive examination of welds – General rules for metallic materials*

[9] FITNET *www.eurofitnet.org*

[10] PD 6493:1991 *Guidance on methods for assessing the acceptability of flaws in fusion welded structures*

[11] PD 6539:1994 *Guide to methods for the assessment of the influence of crack growth on the significance of defects in components operating at high temperatures*

[12] GKSS *www.gkss.de*

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