# NEW DEVELOPMENTS IN THE IIW RECOMMENDATIONS FOR FATIGUE DESIGN AND ANALYSIS OF WELDED STRUCTURES

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**Abstract:** The recommendations of the International Institute of Welding (IIW) on fatigue of welded components and structures and on the effect of weld imperfections in respect to fatigue have been published firstly in 1996. A comprehensive recommendation was established, which embraces all current methods of verification, as e.g. component testing, nominal stress, structural stress, notch stress method as well as fracture mechanics assessment procedures. Detailed guidance for assessment of weld imperfections is also given. The safety philosophy covers the different strategies, which are used in various fields of application and gives a specified choice for the designer. The update of the recommendations was finalized in 2006. The main areas of update are the structural hot-spot stress concept, which allows now for an economic and coarser meshing in finite element analysis, the extension of the effective notch stress concept to welded aluminium structures and the numerical assessment of post weld treatments for improving the fatigue properties. It is expected that the new update will exert the same impact on design and codes as the old one.

## 1 INTRODUCTION

The recommendations of the International Institute of Welding (IIW) on fatigue of welded components and structures and on the effect of weld imperfections in respect to fatigue have been finalized after thorough discussions and published firstly in 1996. It was published in English, German, Japanese and French. This comprehensive paper described all current methods of verification, as e.g. component testing, nominal stress, structural stress, notch stress method as well as fracture mechanics assessment procedures. A detailed guidance for assessment of weld imperfections was also given. The safety philosophy covers the different strategies, which are used in various fields of application and gives a specified choice for the designer.

The update of the recommendations was finalized in 2006. It is expected that the new update will exert the same impact on design and codes as the old one. One of the reasons of the success of these new design recommendations was that it describes the fatigue behaviour and assessment very much directly without any respect to existing codes or special interests of application groups. It was assumed that the weld performs always the same way independently of the area of application, where it was built in. Different points of view originate mainly from the different histories and traditions of the various application groups. Possible different fabrication and safety requirements are also covered by the clear modular structure of the recommendations. So, different application groups may use it according to their needs and different safety strategies can be applied.

## 2 BASIC CONSIDERATIONS

Within the various concepts and assessment methods, a few elements can be recognized, which appear repeatedly in calculation procedures and codes. These elements are: Fatigue loads or actions, fatigue strength or resistance, assessment procedures and safety considerations.

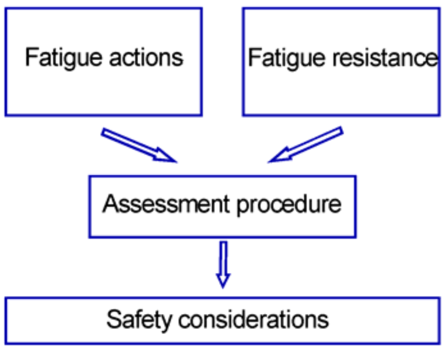



**Fig.1:** Fatigue assessment

The determination and representation of fatigue actions depend of the applied assessment concept. The representation of fatigue actions may be done by forces on the component, nominal stress in the section, structural hot-spot stress at a weld toe, notch stress at an effective weld notch or stress intensity.

The actions may be given as a direct measured graph or a list of stress peak data, as a Markov transition matrix or as a stress spectrum. The exact knowledge of the actions is one of the greatest problems and a source of many uncertainties. For many applications, only estimations of the stress history can be made. In other fields of application there are standardised load assumptions given by a code, which have to be considered. But also here, the problem is only partially solved. The fatigue design recommendations of the International Institute of Welding (IIW) [1, 2] give no regulations for the load side. It is assumed that the characteristic values of the fatigue actions have been directly determined and factored with an appropriate partial safety factor.

Some existing and approved codes give different resistance data in comparison with the IIW recommendation. When comparing, a first glance should be given to the load assumptions within this code. There are mostly specific assumptions for the very field of application, which cannot be transferred to other codes, and which ensure that the load assumptions and the resistance data within this code are in equilibrium.

The basis of the new code is a clear definition of stress types or stress parts. This definition is not only valid for fatigue, for which it was developed in IIW (Niemi), it is a universal definition. The distribution of stress through the wall of a plate usually is non-linear and so, stress parts can be separated, which are membrane, shell bending and non-linear peak stress (fig. 2). Also problems at static load in connection with a finite element analysis and established codes can be solved using this definition.

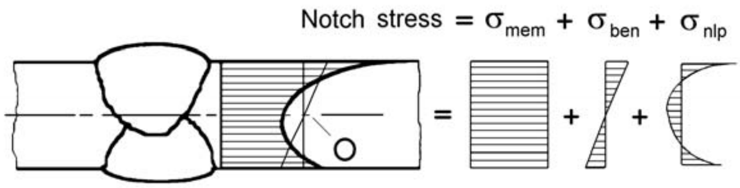



**Fig. 2:** Separation of stress parts of total notch stress (Niemi)

## 3 VERIFICATION CONCEPTS

A consistent application requires that all elements of the fatigue assessment shall correspond to each other. This correspondence may be seen in table 1.

**Tab. 1:** Consistent application of IIW recommendations

| **Type of a fatigue action** | **Information** | **Assessment** |
|---|---|---|
| Load on component | No information | Component test |
| Nominal stress | Structural detail | S-N curve of detail |
| Structural hot-spot stress | Type of weld | S-N curve of weld |
| Notch stress | Effective notch stress | S-N curve of material |
| Stress intensity at crack tip | Material parameters | Paris power law |

Because of its modular structure, the recommendations can be applied to all types of welded structures, especially where no codes exist, or where these codes are not appropriate to the specific design problem. The recommendations are also useful for bodies, which establish special application codes. They may perform further simplifications according to their needs.

### 3.1 Nominal Stress Method

The definition of nominal stress is simple at a first glance: It is average stress in a welded joint, calculated by an agreed formula. It is the basis of most codes. At a closer look, the problems emerge. Special fatigue data are needed for each structural detail. Variations within the detail in dimensions, welding procedures etc. are not covered. The consequence is that this reduction in information gives rise to the scatter. Sometimes, the nominal stress concept may become uneconomic. At establishing a code, a good compromise has to be found, which may be different in the various fields of application. The new IIW recommendations have a list of about 81 structural details.

Another problem is the possible variation of stress in the section under consideration. Macrogeometric notch effects in the vicinity of the welded joint have to be taken into account, as e.g. at cut-outs, frame edges, or unequal stress distribution by several reasons (fig. 3), but the distinction between stress concentrations which have to be considered or not is not always clear. This is especially true for tubular nodes.

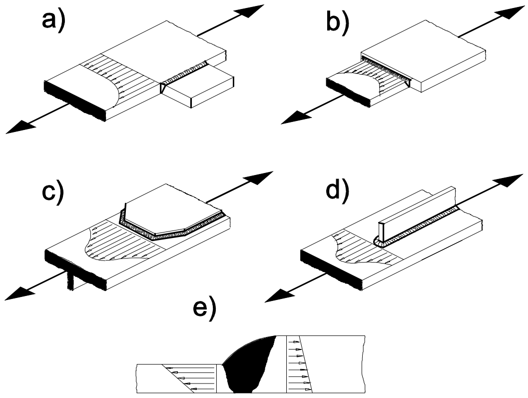



**Fig. 3:** Nominal stress vs. notch stress

Besides the numerous structural details, no details of tubular joints are regulated. These questions are discussed in a special IIW working group (SC-XV-E). Their recommendations have been recently updated and published [6].

The individual structural details are inserted into the grid of Woehler S-N curves. For normal stress and welded joints, a uniform slope of **m=3.0** was specified. The knee point was rised from $5{\cdot}10^6$ to $10^7$ cycles. New experimental results suggested this change.

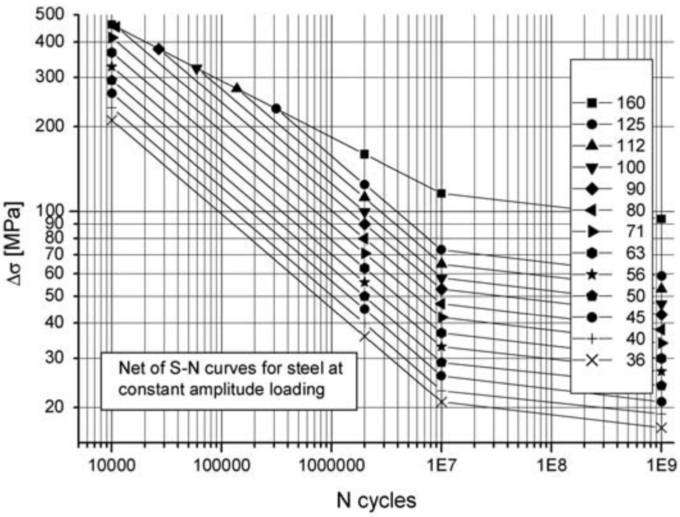
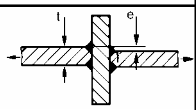



**Fig 4:** Net of S-N Woehler curves at constant amplitude

**Tab. 2:** Example of a structural detail in the catalogue of structural details

| Structural Detail | Description (St.= steel; Al.= alum.) | FAT St. | FAT Al. | Requirements and Remarks |
|---|---|---|---|---|
|  | Cruciform joint or T-joint, K-butt welds, full penetration, no lamellar tearing, misalignment e < 0.15 · t | 80 | 28 | Material of intermediate plate to be checked against susceptibility of lamellar tearing |

In traditional codes, the knee point of the S-N curve is defined as the transition to infinite life. More and more test results and failure experiences show that there is a further decline of the Woehler S-N curve beyond the knee point at higher cycles. After lengthy discussions, there was the resolution to drop the idea of a general fatigue limit. A continuous decline of the fatigue resistance of about 10% per decade was assumed. This new regulations does hardly affect structural steelwork, it is interesting for rotating machinery and vehicle components. IIW recommendations give grids of Woehler S-N curves for both cases.

Modern design offices use widely finite element methods. This method determines local or notch stresses by definition. The transition to a nominal stress is still unsolved. Local concepts are more appropriate in this case. It is a pity that several new drafts for codes do not use nor refer to local concepts.

## 3.2 Structural Hot Spot Stress Method

Structural stress comprises all notch effects of the structural detail but not the notch effect caused by the weld transition toe, i.e. membrane stress plus the linear shell bending stress, but not the non-linear stress peak (fig. 1, 5).

Structural stress is determined by a finite element analysis (FEA). Guidance is given for the selection of element types and appropriate meshing. There is a new possibility, which allows an analysis with relatively coarse elements [8]. Recommendations are also given for the positioning of strain gauges and for extrapolation onto the weld toe (fig. 5 and 6).

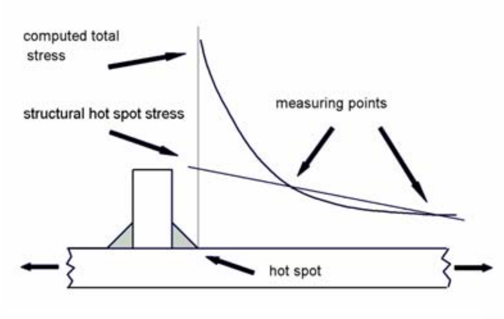



**Fig. 5:** Extrapolation to the hot spot

The final assessment is performed by a direct comparison with universal Woehler S-N curves. There are curves for butt welds and for two types of fillet welds. A S-N curve may also be derived from a reference detail of the catalogue of structural details for nominal stress assessment. Reference detail and detail under consideration should have the same element types and meshing.

The main drawback of the method is the limitation to surface crack failures and the uncertainty of extrapolation procedure. The designer has to verify in advance that the welded joint will not fail from the root or inner defects. Disregarding these limitations, the method is well established in tubular structures, shipbuilding and other areas of application. It will gain more significance in the future.

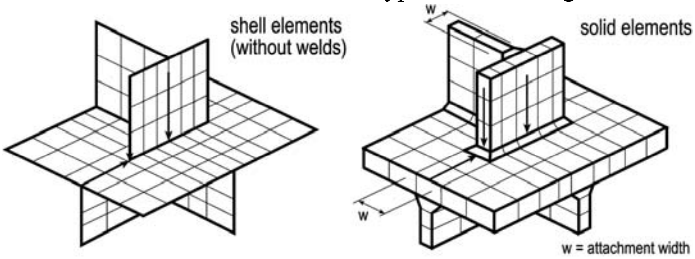



**Fig. 6:** Recommended meshing for FEA analysis

The fatigue resistance against structural stress is numerically given by different S-N curves for butt and load-carrying fillet welds.

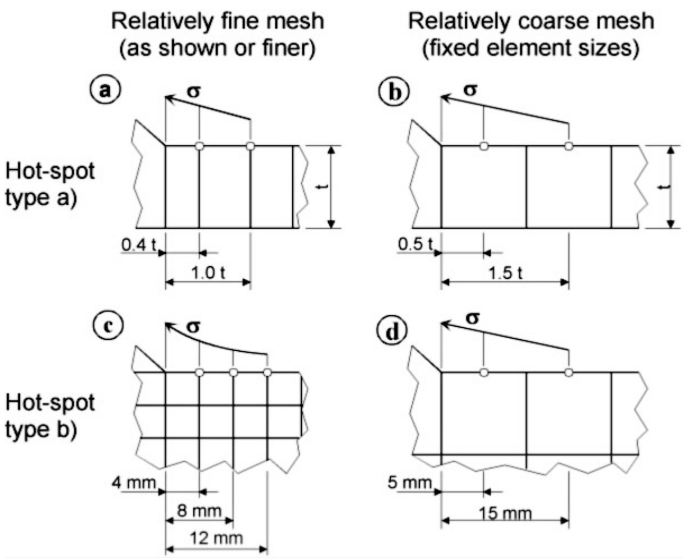



**Fig 7:** Measuring points for structural stress

## 3.3 Notch Stress Method

The usual notch stress concept of mechanical engineering cannot be applied directly to welded joints. The irregularity of the weld toe and the root configuration prevent from a normal determination of notch stress. More recent investigations have shown that the irregular notch at welded joints can be replaced by an effective notch of a radius of **1.0 mm**. The results are consistent within the scatter usually observed at welded joints and can be used as a basis for a regulation by codes, which firstly was done here. With the rising performance of computing power, a growing application of the method is expected, since the uncertainties of the determination of structural hot-spot stress are not existent.

The effective notch stress may be determined by finite element or boundary element analysis. The assessment is then done by the use of a single universal Woehler S-N curve. Thus the weld toe and the root can be assessed.

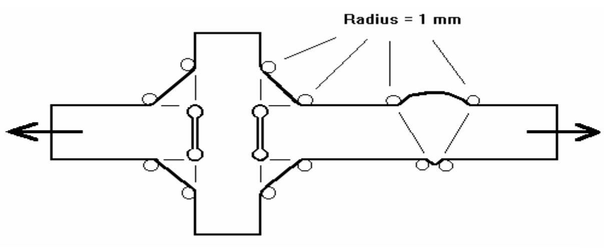



**Fig. 8:** Effective radius

From the logic of the procedure, only a universal Woehler S-N resistance curve is given.

Earlier, the S-N curve of steel was given by FAT 225. Recent investigations have shown that the method can also be applied to aluminium. The resistance Woehler S-N curve here is FAT 72.

## 3.4 Fracture Mechanics Method

The fracture mechanics concept is useful for assessment of cracks or crack-like imperfections. The simplicity and clearness of the theory has been in contrast to the difficulty of practical application. The knowledge of the notch stress in the vicinity of the crack is required, as membrane, shell bending and non-linear peak stress. Furthermore, a formula for the determination of the stress intensity factor (SIF) is required. The latter problem has been solved satisfactorily. So, the fatigue life can be determined by integrating the Paris power law.

$$\frac{da}{dN} = C_0 \cdot \Delta K^m \quad for \quad \Delta K > K_{th} \quad where \quad K = \sigma \cdot \sqrt{\pi \cdot a} \cdot Y(a) \cdot M_k(a)$$

Parametric formulae for the determination of the SIF have been developed for a multitude of structural details. They are based on the well established formulae for cracks in plates under membrane and shell bending stress.

An additional function $\mathbf{M_k}$ considers the non-linear stress peak and the special geometrical conditions of the different structural details and joint types. Here, the IIW recommendations give formulae and refer to selected literature. Today it is possible to determine the function $\mathbf{M_k(a)}$ by a single finite element run from the distribution of the stress concentration factor $\mathbf{k_{t,\,nlp}}$ in thickness direction.

$$M_k(a) = \frac{2}{\pi} \cdot \int_{x=0}^{x=a} \frac{k_{t,nlp}(x)}{\sqrt{a^2 - x^2}} \cdot dx$$

The numerical integration of the Paris power law and the determination of the $\mathbf{M_k}$ –values can be easily performed by modern computers. So, parametric formulae are no more necessary besides the well known standard solutions of the different crack types. If a proper initial crack depth was chosen e.g. 0.15 mm, the fatigue behaviour of welded joints can be simulated and thus predicted. It can be used for a normal fatigue assessment. The resistance against crack propagation under the load of cyclic stress intensity can be given as the material parameters of the Paris power law of crack propagation.

**Tab. 3:** Resistance against crack propagation (Paris power law)

| Material | $C_0$ | m | $K_{th}$ [N· mm$^{-3/2}$] |
|---|---|---|---|
| Steel | 5.0 E-13 | 3.0 | 190 - 144· R, not lower than 62 N· mm$^{-3/2}$ |
| Aluminium | 4.0 E-11 | 3.0 | 63 - 48· R, not lower than 21 N· mm$^{-3/2}$ |

The rising computing power, the widespread use of FEA methods and the simplicity of the method will make fracture mechanics a wider used tool for fatigue assessment of welded joints in the near future. This is especially true for thick-walled components and at complicated shapes.

## 3.5 Component Testing

The simplest and safest way to assess a component for fatigue is to test it. The problem is that the loads in service and in test should be equal as far as possible. Mostly load spectra are used to control the test loading. Statistical verification is done by well established mathematical procedures. Because of scatter of the cloud of data, there are basically two ways to ensure safety of a component: Firstly to draw a worst case line under the cloud and use it for design, or secondly to make an estimate of the mean, design for that and subsequently to test the component (fig. 9).

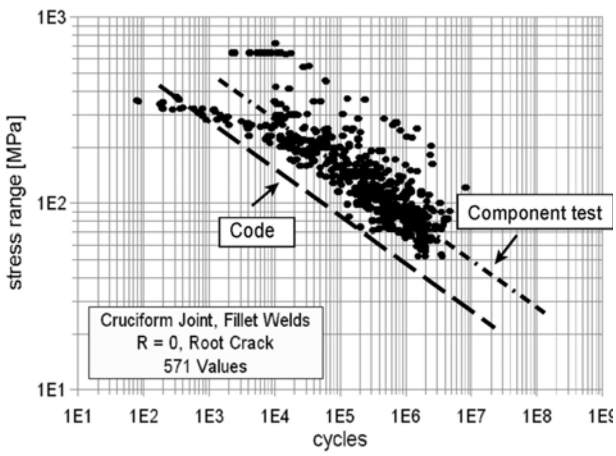



**Fig. 9:** Scatter of experimental data

The second procedure gives a better usage of the material, but it is expensive. It is appropriate in aircraft and vehicle engineering, where weight is governing the considerations. If verification by test was planned or mandatory, 40% to 50% higher stresses may be used in the design stage.

## 4. MODIFICATIONS BY VARIOUS EFFECTS

The effect of residual stress is covered by the fatigue resistance values given. If a stress relieving annealing was done or if there were other reasons for assuming a low residual stress level, a bonus factor on the fatigue resistance values may be used.

The effect of wall thickness is considered by different exponents, by which the wall thickness reduction has to be calculated. The effect of high temperatures is in proportion to the decrease of the elasticity modulus of the material at higher temperatures.

## 5. IMPROVEMENT TECHNIQUES

The fatigue strength can be improved by different methods of post-weld treatments. That is already known and is also applied at large series production. Here, the fatigue strength has to be verified by test. The new update of the IIW recommendations have a real novelty, a calculative verification of fatigue at post weld treatments. Existing data have been re-evaluated, they have been completed by round robin tests and finally they have been processed in order to establish a code for application [9].

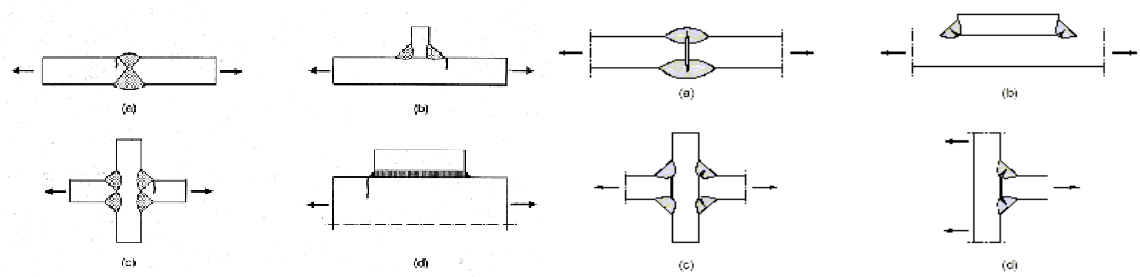


**Fig. 10:** Suitable for improvement Not suitable for improvement

The methods can be divided into three groups: Improvement of shape, improvement of residual stress conditions and improvement of surface geometry. The IIW recommendations specify the improvement of the weld toe by burr grinding, by TIG dressing and by hammer and needle peening. It has to be borne in mind that only such welds can be improved, at which the possible crack at the weld toe is governing. It must be always checked, if not another spot of a possible crack initiation could become dominant and governing for the fatigue assessment.

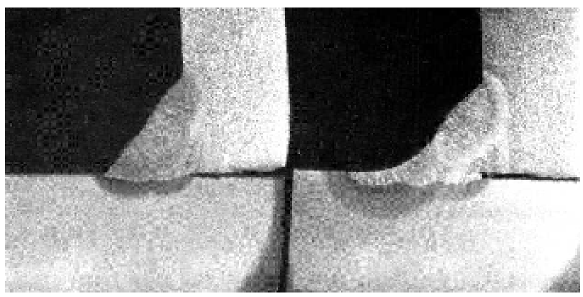


**Fig. 11:** Improved toe by TIG dressing

The improvement methods considered in the IIW recommendations are grinding of the toe, TIG dressing of the toe, hammer and needle peening. The tables, which give the improvement factors for the different methods specify only a minimum value of the improving effect. It can be used immediately without further experimental verification. If higher improvements are needed, it has to be verified by test.

## 6. WELD IMPERFECTIONS

ISO 5817 distinguishes between 26 different types of weld imperfections, as e.g. cracks, porosity, worm holes, inclusions, lack of penetration, lack of fusion, lack of fit, undercut, excessive weld overfill, insufficient weld throat, root overfill, misalignment, weld sag, incomplete root, cold lap, arc strike, sputter etc. For each of these imperfections, the allowable extent is tabulated for the different quality levels **B, C** and **D**.

This standard has a congenital defect. It is an adoption of the old German standard DIN 8563, which was established as a standard for communication between the welders and the inspectors. The classification criterion was the difficulty, the expenses or the efforts to fabricate or to inspect by NDT. It was not fatigue strength. So by the nature, ISO 5817 cannot be applied directly to fatigue problems, it is inconsistent in respect to fatigue properties and needs application guidance. Most codes specify a general quality level according to ISO 5817 and give additional regulations.

In this situation, the IIW recommendations have extended the scope of usual fatigue design codes by describing the fatigue properties of joints containing weld imperfections. Users or writers of special application codes may use it in order to establish adequate regulations for their specific purpose.

**Tab. 4:** Categorization and assessment procedure for weld imperfections

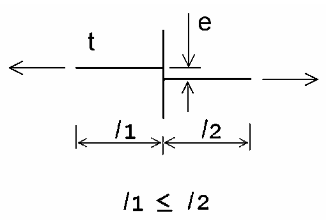
| Effect of imperfection | | Type of imperfection | Assessment |
|---|---|---|---|
| Rise of general stress level | | Misalignment | Formulae for effective stress concentration |
| Local notch effect | additive | Weld shape imperfections, undercut | Tables given |
| | competitive | Porosity and inclusions not near the surface | Tables given |
| Cracklike imperfection | | Cracks, lack of fusion and penetration, all types of imperfections other than given here | Fracture mechanics |

After inspection and detection of a weld imperfection, the first step of the assessment procedure is to determine the type and the effect of the imperfection as given here. If a weld imperfection cannot be clearly associated to a type or an effect of imperfections listed here, it is recommended that it is assumed to be crack-like. Before assessing the imperfections with respect to fatigue, it should be verified if the conditions apply for competitive or additive notches. The fatigue resistance tables are valid for non-coinciding imperfections. It is important to ensure that there is no interaction between multiple weld imperfections, be it from the same or different type. Combined porosity or inclusions shall be treated as a single large one. The defect interaction criteria given for the assessment of cracks also apply for adjacent inclusions. Worm holes are assessed as slag inclusions.

## 6.1 Misalignment

Misalignment in axially loaded joints leads to an increase of stress in the welded joint due to the occurrence of secondary shell bending stresses. The resulting stress is calculated by stress analysis or by using the formulae for the stress magnification factor $\mathbf{k_m}$ .

**Tab. 5:** Examples of formulae for assessment of misalignment

| Axial misalignment of cruciform joints (toe cracks) | |
|---|---|
|   | $$k_m = \lambda \cdot \frac{e \cdot l_1}{t \cdot (l_1 + l_2)}$$ λ is dependent on restraint. $l_1 \leq l_2$ |
| λ varies from **λ=3** (fully restrained) to **λ=6** (un-restraint). For unrestrained remotely loaded joints assume: $\mathbf{l_1=l_2}$ and **λ=6** | |

Secondary shell bending stresses do not occur in continuous welds longitudinally loaded or in joints loaded in pure bending, and so misalignment will not reduce the fatigue resistance. However, misalignment in components, e.g. beams, subject to overall bending may cause secondary bending stresses in parts of the component, where the through thickness stress gradient is small, e.g. in a flange of a beam, where the stress is effectively axial. Such cases should be assessed.

Some allowance for misalignment is already included in the tables of classified structural details. In particular, the data for transverse butt welds are directly applicable for misalignment which results in an increase of stress up to 30%, while for the cruciform joints the increase can be up to 45% .

## 6.2 Undercut

The basis for the assessment of undercut is the ratio **u/t**, i.e. depth of undercut to plate thickness. Though undercut is an additive notch, it is already considered to a limited extent in the tables of fatigue resistance of classified structural details. Undercut does not reduce fatigue resistance of welds which are only longitudinally loaded.

**Tab. 6:** Acceptance levels for weld toe undercut in steel

| Fatigue class | Allowable undercut u/t | |
|---|---|---|
| | butt welds | fillet welds |
| 100 | 0.025 | not applicable |
| 90 | 0.05 | not applicable |
| 80 | 0.075 | 0.05 |
| 71 | 0.10 | 0.075 |
| 63 | 0.10 | 0.10 |
| 56 and lower | 0.10 | 0.10 |

Notes:
a) undercut deeper than 1 mm assessed like a crack
b) the table is valid for plate thicknesses from 10 to 20 mm

## 3.4 Porosity and Inclusions

Embedded volumetric discontinuities, such as porosity and inclusions, are considered as competitive weld imperfections which can provide alternative sites for fatigue crack initiation than those covered by the fatigue resistance tables of classified details.

**Tab. 7:** Acceptance levels for porosity and inclusions in welds in steel

| Fatigue class | Max. length of an inclusion in mm | | Limits of porosity in % of area * ** |
|---|---|---|---|
| | as-welded | stress relieved + | |
| 100 | 1.5 | 7.5 | 3 |
| 90 | 2.5 | 19 | 3 |
| 80 | 4 | 58 | 3 |
| 71 | 10 | no limit | 5 |
| 63 | 35 | no limit | 5 |
| 56 and lower | no limit | no limit | 5 |

* Area of radiograph
** Max pore diameter or width of inclusion < than 1/4 thickness or 6 mm
\+ Stress relieved by post weld heat treatment

## 6.4 Crack-like Imperfections

Planar discontinuities, cracks or crack-like defects are identified by non-destructive testing and inspection. NDT indications are idealized as elliptical cracks for which the stress intensity factor is calculated.

A simplified procedure has been developed which is based on the integration of the crack propagation law from an initial defect size $\mathbf{a_i}$ to defect size of 0.75% of wall thickness. This cracked component has a lower Woehler S-N curve of which the fatigue class can be calculated. In the tables e.g. in table 8, the stress ranges at $2*10^6$ cycles corresponding to the definition of the fatigue classes (FAT) of classified structural details are shown. The tables have been calculated using the correction functions and the weld joint local geometry correction given in ref. 10.

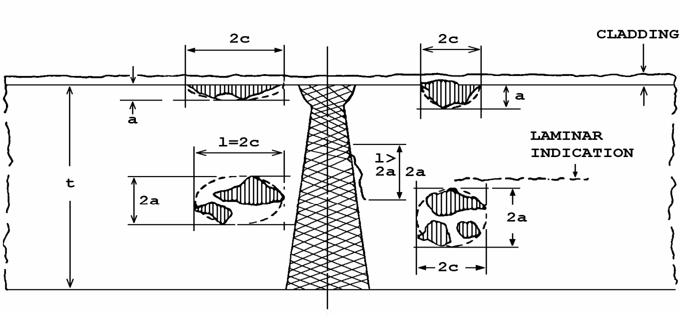



**Fig. 12:** Transfer of NDT indications into ellipses

The real problem in non-destructive testing is the determination of the dimensions of a crack or a crack-like imperfection. These dimensions are needed for calculative assessment. It is hoped that in the near future imaging procedures will be available, by which these dimensions are directly visible. This point is important, because all fracture mechanics procedures are sensitive to the location and dimensions of the initial flaw.

**Table 8:** Example of a table of fatigue classes of welds containing cracks

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Surface cracks at fillet weld toes | | | | | | | | | | | | | | | | |
| $a_i$ | short surface crack not at edge, fillet welds l/t=2.5 a/c=.5 | | | | | | | | | | | | | | | |
| 25.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | 23 | 35 |
| 20.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 21 | 24 | 29 | 38 |
| 16.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 18 | 23 | 27 | 30 | 34 | 42 |
| 12.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21 | 27 | 32 | 35 | 37 | 40 | 45 |
| 10.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 27 | 33 | 36 | 39 | 41 | 43 | 47 |
| 8.0 | 0 | 0 | 0 | 0 | 0 | 0 | 18 | 24 | 28 | 34 | 39 | 41 | 43 | 45 | 47 | 49 |
| 6.0 | 0 | 0 | 0 | 0 | 0 | 23 | 30 | 34 | 37 | 42 | 45 | 47 | 48 | 49 | 51 | 52 |
| 5.0 | 0 | 0 | 0 | 0 | 22 | 31 | 36 | 39 | 42 | 46 | 48 | 50 | 51 | 52 | 53 | 53 |
| 4.0 | 0 | 0 | 0 | 20 | 32 | 38 | 42 | 45 | 47 | 50 | 52 | 54 | 54 | 55 | 55 | 55 |
| 3.0 | 0 | 0 | 26 | 33 | 42 | 47 | 50 | 52 | 53 | 55 | 57 | 58 | 58 | 58 | 58 | 57 |
| 2.0 | 22 | 36 | 43 | 48 | 53 | 56 | 58 | 60 | 61 | 62 | 62 | 62 | 62 | 62 | 62 | 59 |
| 1.0 | 53 | 60 | 63 | 66 | 68 | 69 | 70 | 70 | 70 | 70 | 69 | 69 | 68 | 67 | 66 | 62 |
| 0.5 | 74 | 76 | 78 | 78 | 79 | 78 | 78 | 77 | 77 | 76 | 74 | 73 | 72 | 71 | 69 | 64 |
| 0.2 | 92 | 91 | 91 | 90 | 88 | 86 | 85 | 84 | 83 | 81 | 79 | 77 | 75 | 74 | 72 | 65 |
| t = | 3 | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 20 | 25 | 30 | 35 | 40 | 50 | 100 |

## 6.7 Summary of the Effect of Weld Imperfections

Since the cohesion between ISO 5817 quality levels and fatigue properties is not consistent over the types of irregularities, different tables and diagrams have been developed for guidance. Figure 13 shows the fatigue properties of butt welds of steel for the different levels. It can be easily seen, that for some types of imperfections could be relaxed and others must be tightened for a required level of fatigue resistance. A low fatigue class of FAT 10 indicates that this type of imperfection is not allowed. It can be seen that for a butt weld of FAT 90 porosity is over-penalized, but slag inclusions in as-welded welds are underestimated.

A shop normally can produce only one level of quality. Different specified levels at different welds are hardly to be managed and could spoil the overall quality considerations of the staff. On the other side, the full quality is not always needed and unnecessary repair work will be done. A possible solution could be that the designer indicates in the drawing the required fatigue class for each weld. So, a deviation in shop can be immediately assessed and reasonable remedies can be started, if necessary. This can be achieved by the help of tables or diagrams as figure 13.

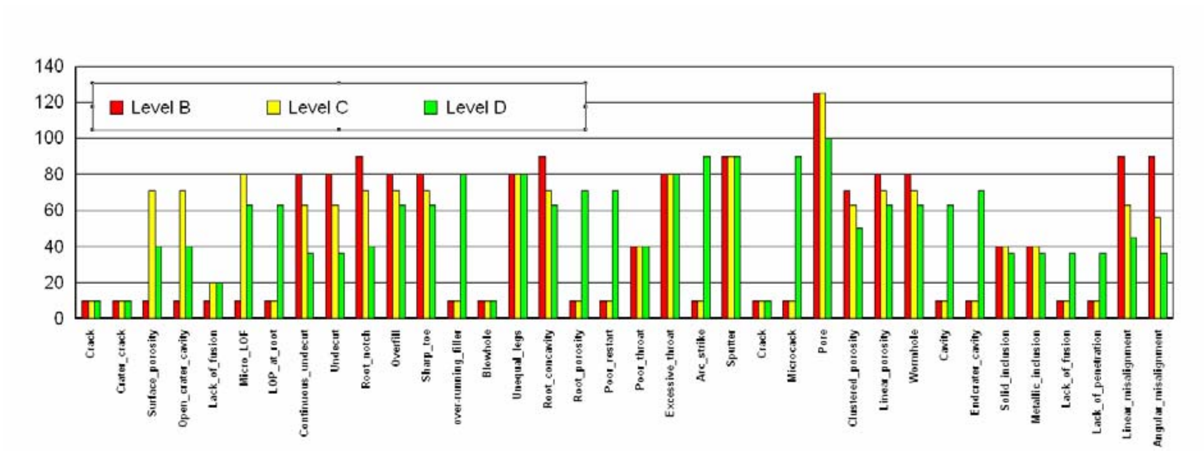



**Fig. 13:** Fatigue properties of weld imperfections and ISO 5817 quality levels at butt welds

# 7. CUMULATIVE FATIGUE

## 7.1 Palmgren-Miner rule

The actual stress history may be measured and stored in a computer database and later be used for component testing. For calculative fatigue life assessment, this history must be compressed in a way, that it can be used for the calculations. The most widely introduced counting algorithm is the so called rainflow or reservoir counting method. There are computer programs available, which do the computational work.

The result of this compression is a Markov transition matrix or just a spectrum of the load frequency histogram. The example shows a spectrum of a Gaussian distribution which is also used for standardizing purposes. The presentation of the spectrum may be as a continuous spectrum or as a sequence of blocks. The calculation of cumulative damage is done in most codes by linear summation of partial damages according to Palmgren (1922) and Miner (1945), colloquially by the Miner rule. The idea is that each load cycle or block causes a damage Di, which can be calculated fron the SN curve. If the sum of all partial damages reaches unity, then the calculated life is exhausted.

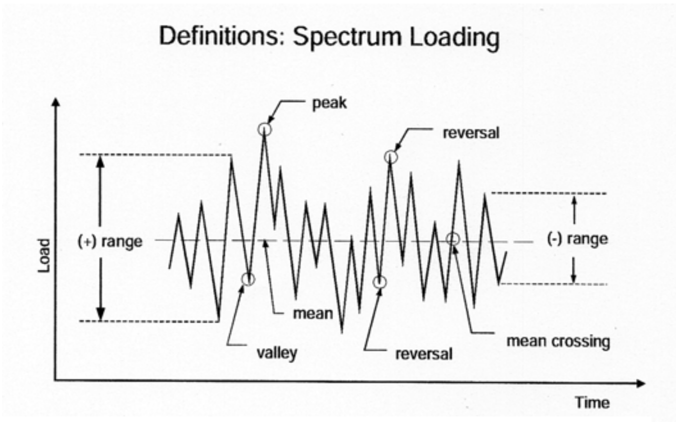



**Fig. 14:** Actual load history

Original rule : Partial damage: **Di = ni / Ni**
failure at: **ΣDi = 1**

In order to verify this idea, damage calculations and the belonging experimental fatigue lives have been collected and plotted into a Gaussian probability diagram (fig. 16). It can be seen that the damage sum is not unity! The mean value is around 0.3. So, the IIW recommendations have specified:

IIW recommendation: **ΣDi < 0.5**

Despite of this experimental fact, most codes stick to a damage sum of unity. It is hoped to cover the difference in the safety margins, which might be questionable in certain cases.

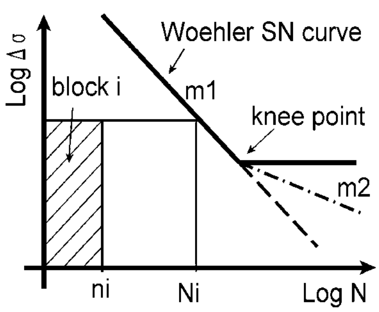



**Fig. 15:** SN curve for damage summation

Sometimes it might be convenient to determine an equivalent constant amplitude stress range $\Delta\sigma_{eq,S}$ which can be directly compared with the constant amplitude resistance S-N curve. It is calculated as:

$$\Delta\sigma_{eq,S,d} = \sqrt[m_1]{\frac{1}{D} \cdot \frac{\Sigma(n_i \cdot \Delta\sigma_{i,S,d}^{m_1}) + \Delta\sigma_{L,d}^{(m_1-m_2)} \cdot \Sigma(n_j \cdot \Delta\sigma_{j,S,d}^{m_2})}{\Sigma n_i + \Sigma n_j}}$$

Where:

| | |
|---|---|
| D | specified Miner sum |
| $\Delta\sigma_{eq,S,d}$ | design value of characteristic equivalent stress (loads) |
| $m_1$ | slope above the knee point of the SN curve |
| $m_2$ | slope below the knee point of the SN curve |
| $\Delta\sigma_{i,S,d}$ | design values of stress (loads) above the kneepoint |
| $\Delta\sigma_{j,S,d}$ | design values of stress (loads) below the knee point |
| $\Delta\sigma_{L,d}$ | design value of stress (resistance) at the knee point |
| $n_i$ | number of cycles belonging to $\Delta\sigma_i$ |
| $n_j$ | number of cycles belonging to $\Delta\sigma_j$ |

The constant decline of the knee point of the S-N curve during the process of fatigue makes stress cycles, initially under the fatigue limit, more and more effective. This requires an adjustment of the S-N curves. For this reason, the grid of S-N curve was modified according to Haibach. Figure 17 shows the net of the adjused Woehler S-N curves.

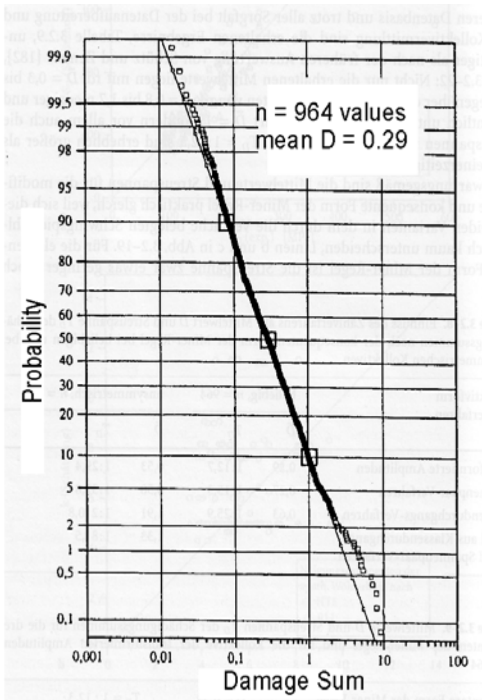



**Fig. 16:** Experimental damage sums

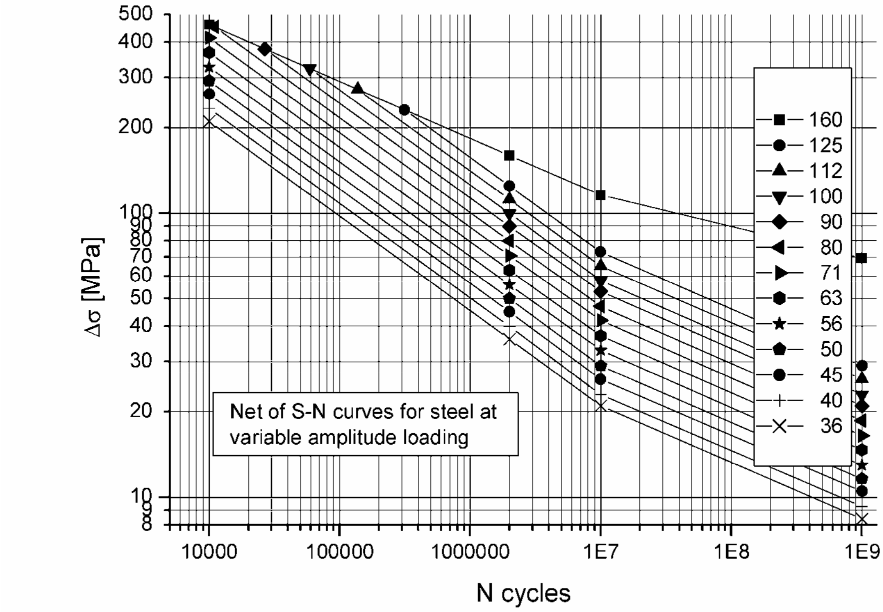



**Fig. 17:** Modified net of SN curves for variable amplitude loading

### 7.2 Multiaxial stress

The assessment of multi-axial stress in fatigue is still in discussion. For proportional loads in phase, i.e. normal and shear stress vary proportionally in phase, the proposals of Gough and Pollard are preferred. For non-proportional loading out of phase, the scientific discussion has not yet ended. IIW recommendations have introduced regulations, which cover the most recent experiments and so, can be regarded as state of art and science. Almost all other codes give neither regulations nor recommendations at this point.

**Table 9:** Damage sums **D** or comparison values **CV** in IIW Recommendations

| Type of load | Phase of stresses | Verification procedure | Miner-sum D or comparison value CV | |
|---|---|---|---|---|
| Constant amplitude | proportional | verification of maximum principal stress or $\left(\frac{\Delta\sigma_{S,d}}{\Delta\sigma_{R,d}}\right)^2 + \left(\frac{\Delta\tau_{S,d}}{\Delta\tau_{R,d}}\right)^2 \leq CV$ | CV=1.0 | |
| | non-proportional | $\left(\frac{\Delta\sigma_{S,d}}{\Delta\sigma_{R,d}}\right)^2 + \left(\frac{\Delta\tau_{S,d}}{\Delta\tau_{R,d}}\right)^2 \leq CV$ | steel | CV=0.5 |
| | | | aluminium | CV=1.0 |
| Variable amplitude | proportional | Verification of maximum principal stress and Miner sum D, or $\left(\frac{\Delta\sigma_{eq,S,d}}{\Delta\sigma_{R,d}}\right)^2 + \left(\frac{\Delta\tau_{eq,S,d}}{\Delta\tau_{R,d}}\right)^2 \leq CV$ | D=0.5<br>CV = 1.0 | |
| | non-proportional | $\left(\frac{\Delta\sigma_{eq,S,d}}{\Delta\sigma_{R,d}}\right)^2 + \left(\frac{\Delta\tau_{eq,S,d}}{\Delta\tau_{R,d}}\right)^2 \leq CV$ | steel | D=0.5<br>CV=0.5 |
| | | | aluminium | D=0.5<br>CV=1.0 |

*Note: For fluctuating mean stress, a Palmgren-Miner sum of D=0.2 is recommended.*

## 8. CONCLUSIVE REMARKS

The update of the recommendations was finalized in 2006. It had the influx of ideas and knowledge of leading experts and laboratories in the world from a wide range of fields of applications. It is expected that the new document will have the same the same influence on design codes as the old one.

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