Aalto University
School of Engineering

MEC-E8006 Fatigue of Structures

Lecture 10: Fatigue of welds

Course contents

Week		Description
43	**Lecture 1-2**	**Fatigue phenomenon and fatigue design principles**
	Assignment 1	Fatigue Damage process, design principle and Rainflow counting – dl after week 43
44	**Lecture 3-4**	**Stress-based fatigue assessment**
	Assignment 2	Fatigue life estimation using stress-based approach – dl after week 44
45	**Lecture 5-6**	**Strain-based fatigue assessment**
	Assignment 3	Fatigue crack initiation life by strain-based approach – dl after week 46
46	**Lectures 7-8**	**Fracture mechanics -based assessment**
	Assignment 4	Fatigue crack propagation life by fracture mechanics – dl after week 46
47	**Lectures 9-10**	**Fatigue assessment of welded structures and residual stress effect**
	Assignment 5	Fatigue life estimation of welded joint – dl after week 48
48	**Lecture 11-12**	**Multiaxial fatigue and statistic of fatigue testing**
	Assignment 6	Fatigue life estimation for multiaxial loading and statistical analysis – dl after week 48
49	**Exam**	**Course exam**
	Project work	Delivery of final project (optional) – dl on week 50

Assignment are delivered in pdf format using MyCourse and the following naming ***AssignmentNumber_FirstName_Surname.pdf.***

Learning outcomes

After the lecture, you

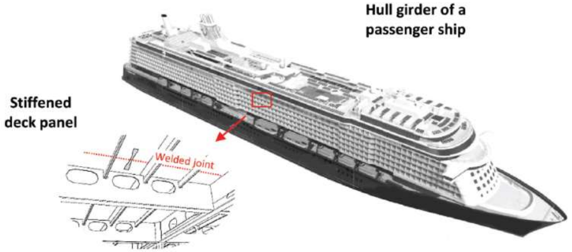
- *understand* fatigue phenomena in welded structures
- *know* the main influencing factors for fatigue strength of welded structural
- *can apply* the common methods for fatigue strength assessment of welded structures

Contents

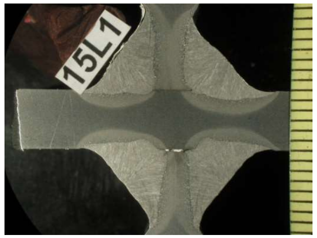
- Fatigue of welded structures
- Main influencing factors for welded joints
- Fatigue assessment of welded structures
- Fatigue approaches for welded structures
- Recent developments

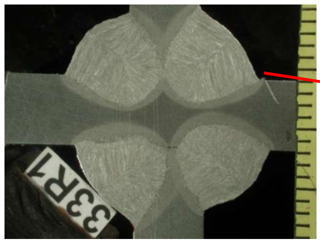
Fatigue of welded structures

Complex structural geometry



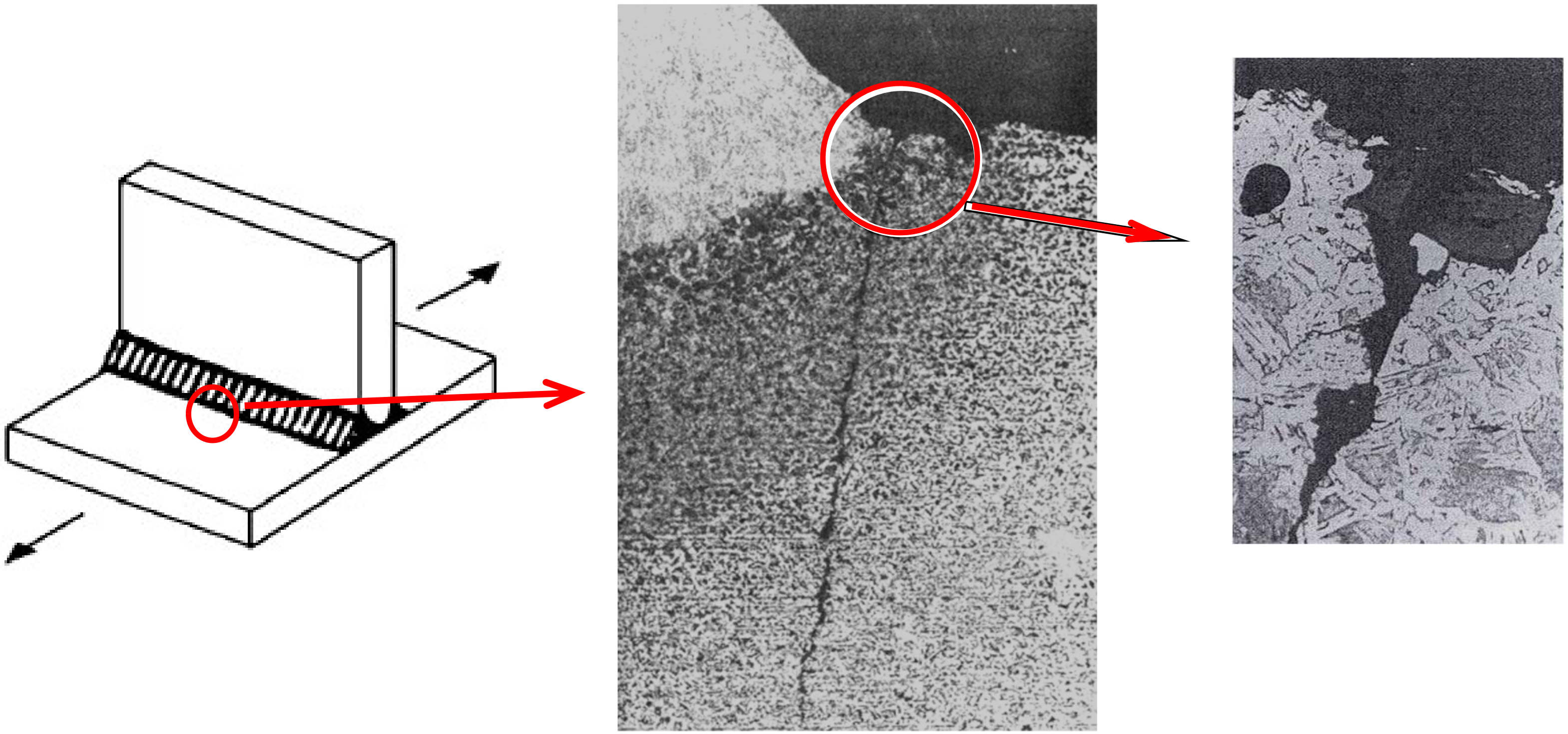
Variation of local geometry





Arbitrary micro geometry

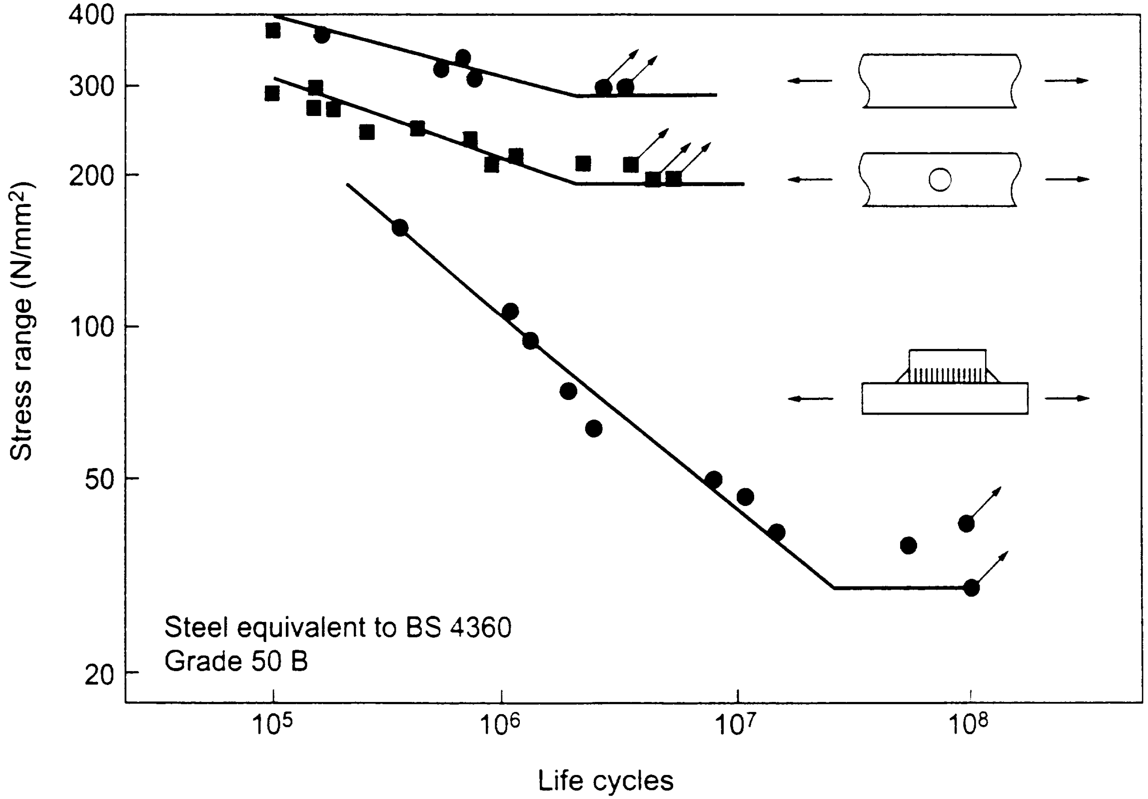
Fatigue of welded structures



Sharp undercuts and inclusions

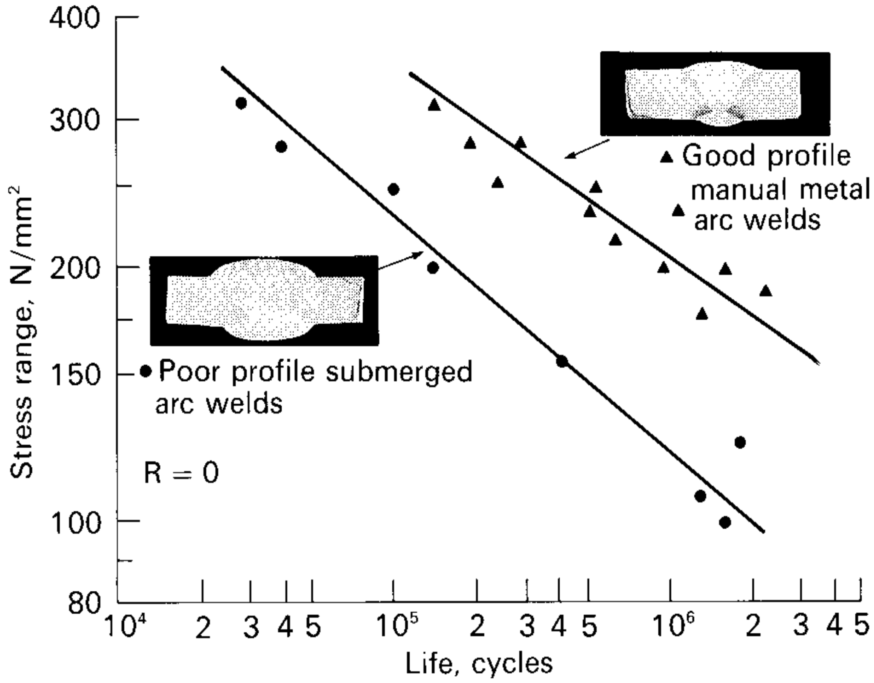
Fatigue of welded structures

Welds have much lower strength that the base materials due to ***early crack initiation***



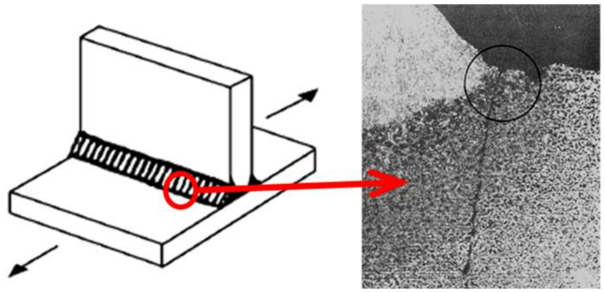
Fatigue of welded structures

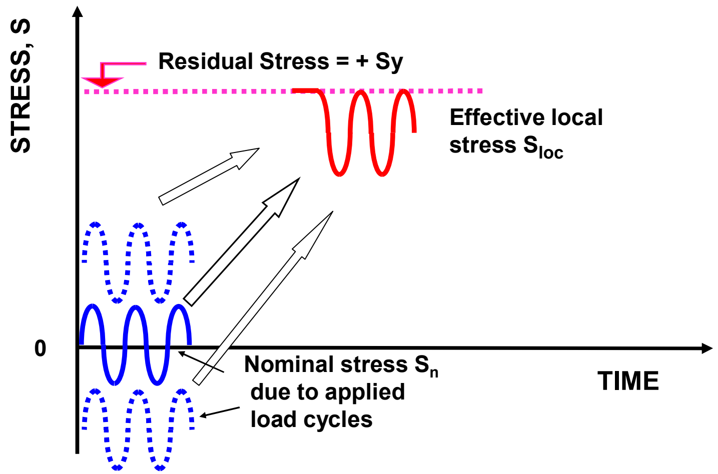
Welds have stress concentrations



Fatigue of welded structures

- **Stress concentrations reduce fatigue strength**
  - welds have both structural and local stress concentrations
- **Tensile mean stresses reduce fatigue strength**
  - welds have high residual stresses that act as mean stresses
- **Material strength affects crack initiation but not crack growth**
  - weld fatigue is usually dominated by crack growth

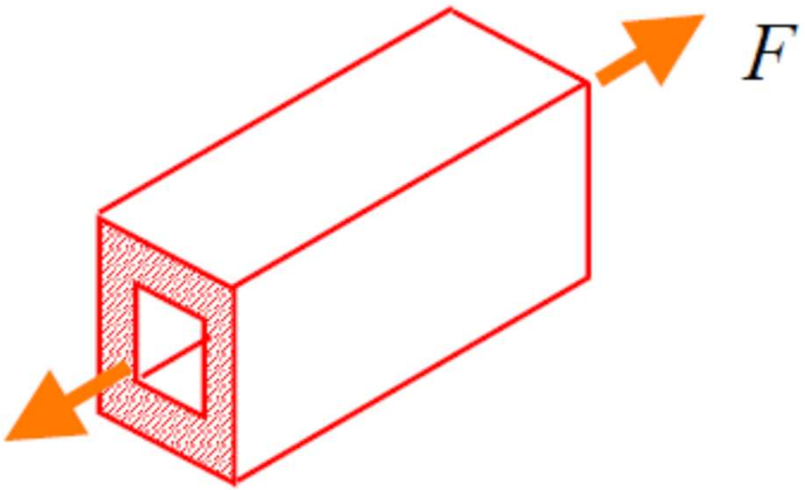




Fatigue of welded structures

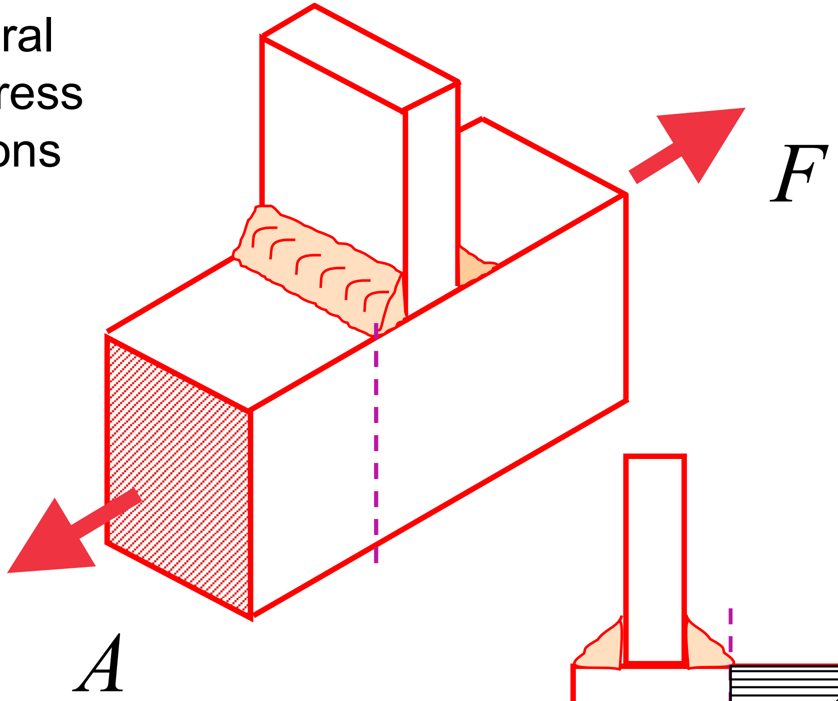
For simple geometries stress is easy to define, but in the case of welded joint geometry becomes more complex…

$$\sigma = \frac{F}{A}$$

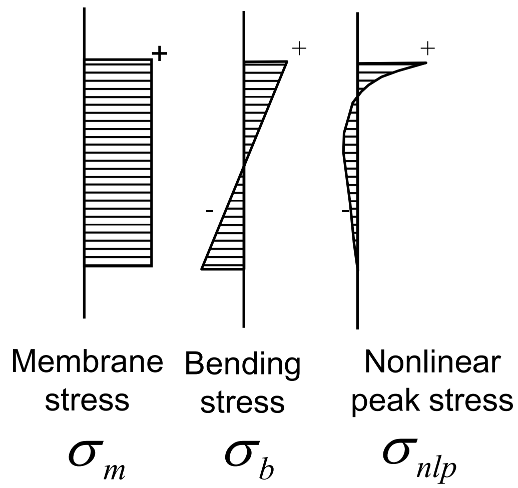


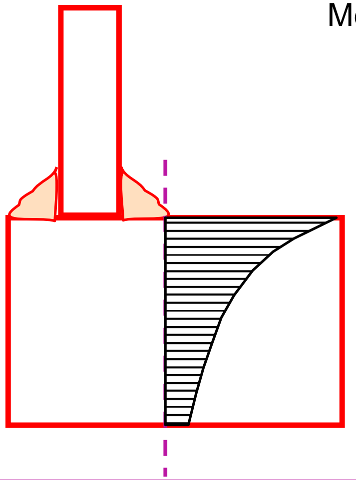
Fatigue of welded structures

Welds cause both structural and local stress concentrations



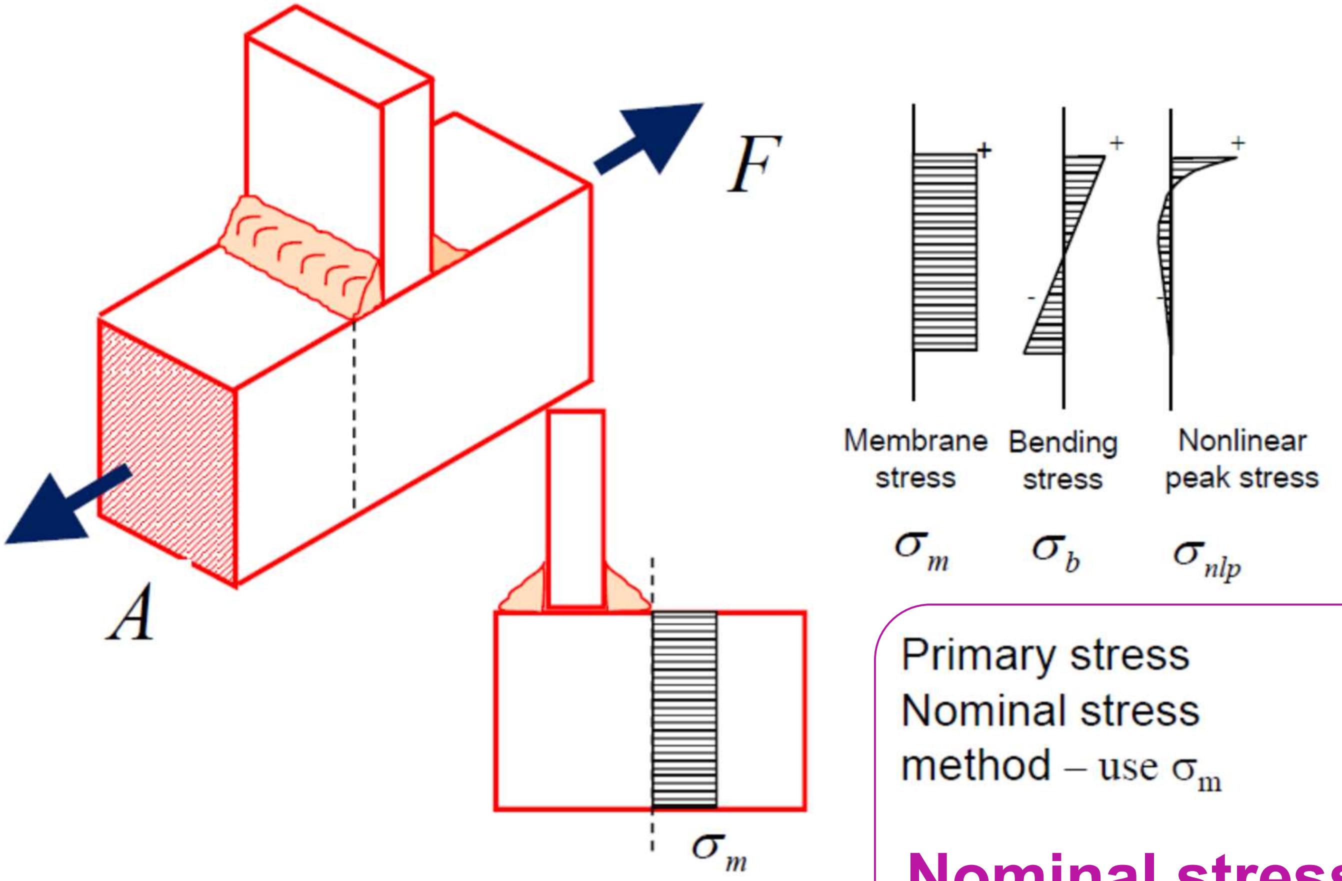
$$\sigma_m = \frac{F}{A}$$





$$\sigma_m + \sigma_b + \sigma_{nlp}$$

Fatigue of welded structures



Primary stress
Nominal stress
method – use σ_m

Nominal stress

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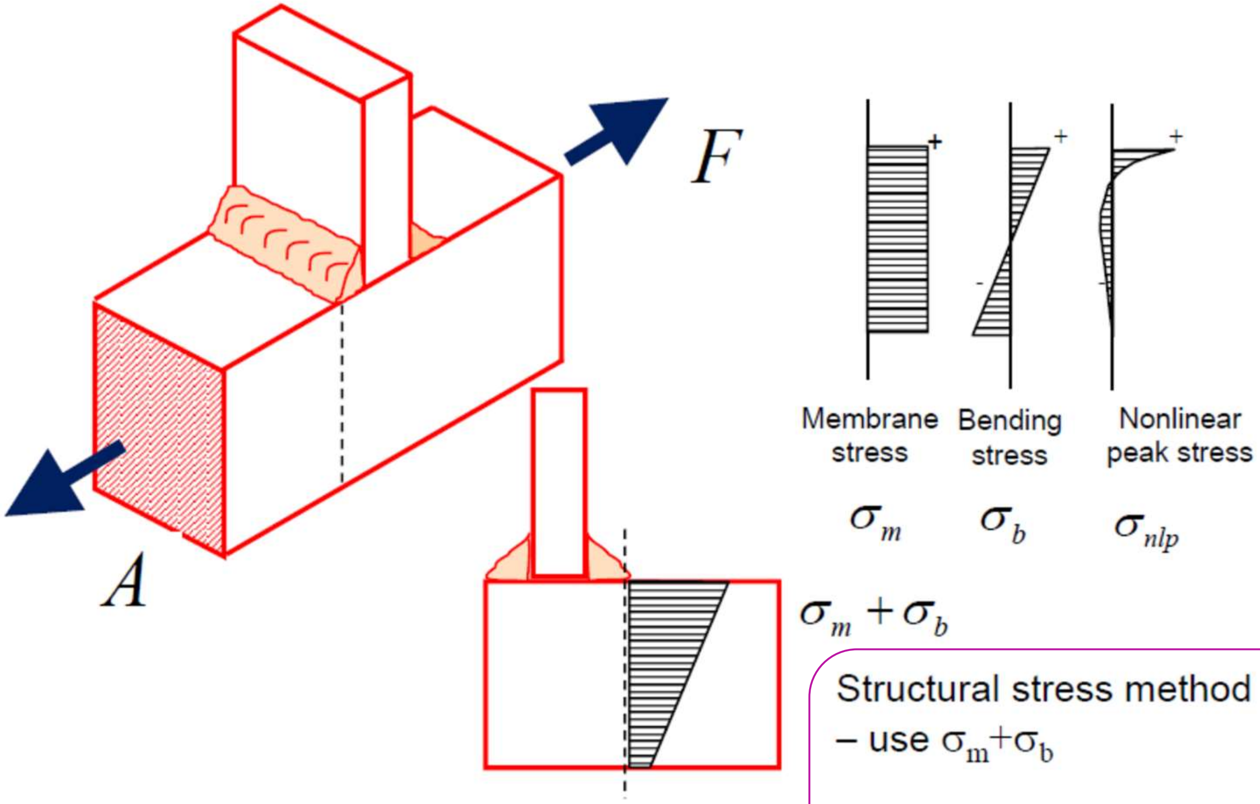
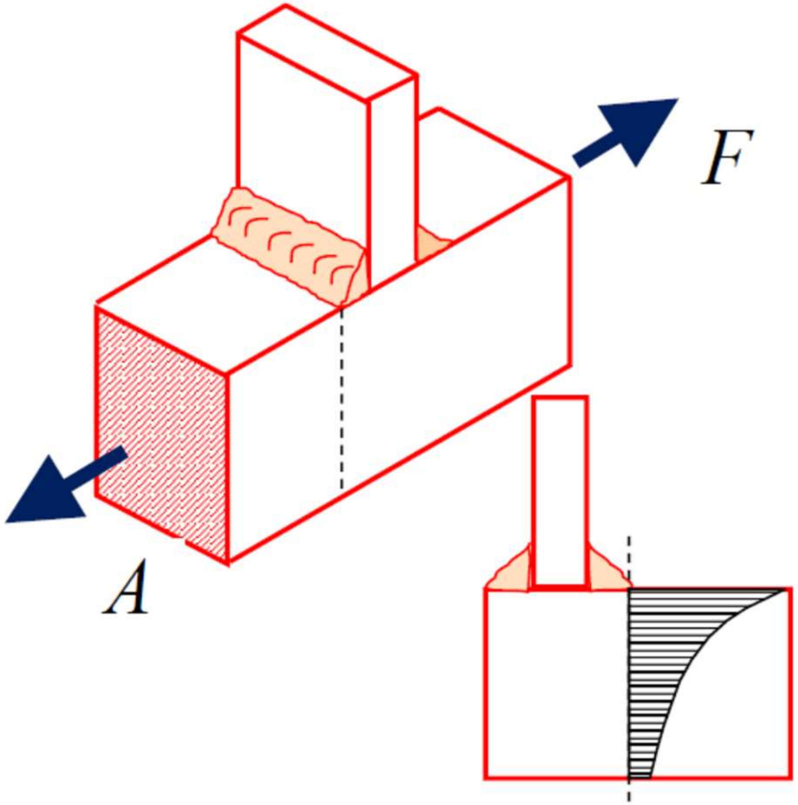
Fatigue of welded structures

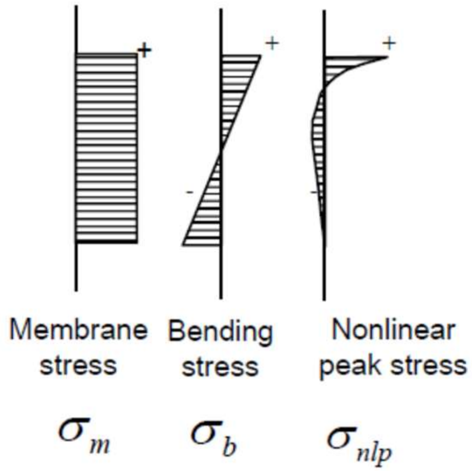


Structural stress method
– use $\sigma_m + \sigma_b$

Structural stress

Fatigue of welded structures





$\sigma_m + \sigma_b + \sigma_{nlp}$

"total stress" is difficult to use in design

Notch stress

Fatigue assessment of welded structures

Response | **Strength**

Fatigue actions → Assessment procedure ← Fatigue resistance

Assessment procedure

Life prediction

Fatigue assessment of welded structures

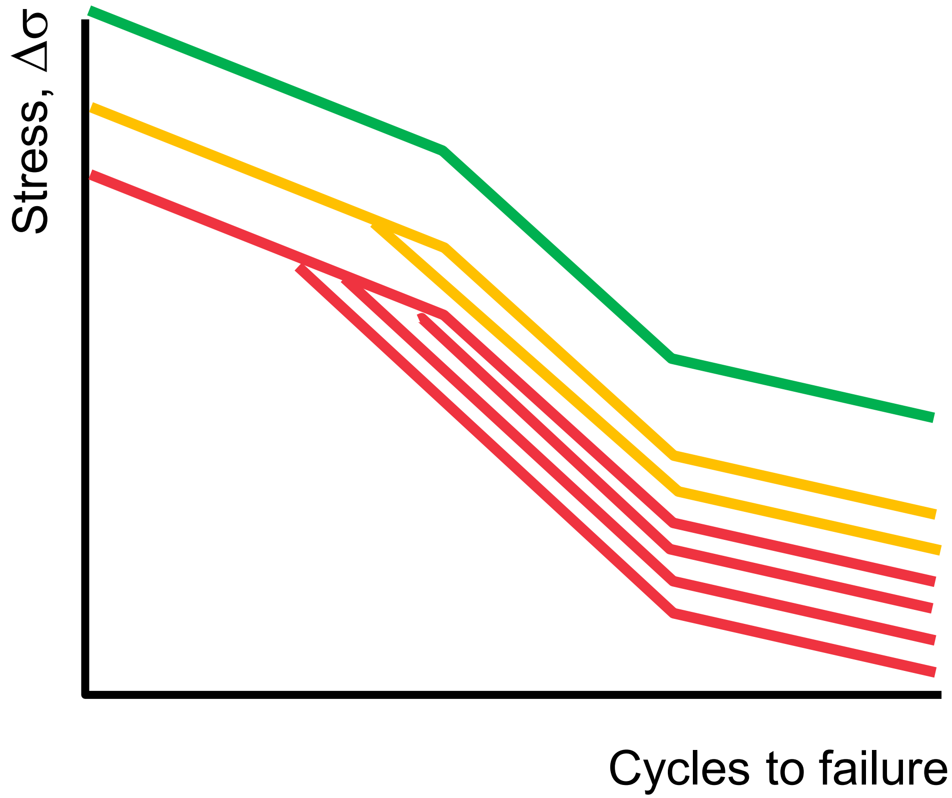
Fatigue approach

Nominal stress:
Many $\Delta\sigma$-N lines
depending of weld type

Structural stress:
Two $\Delta\sigma$-N lines
depending of weld type

Notch stress:
One $\Delta\sigma$-N line for all
welds

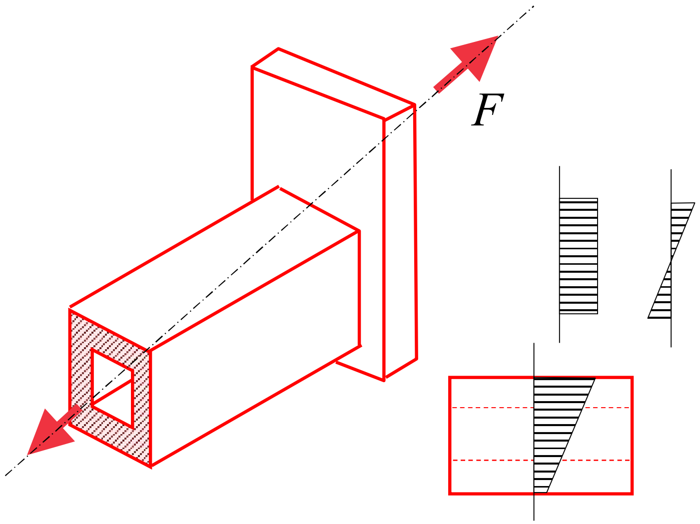
Fatigue resistance

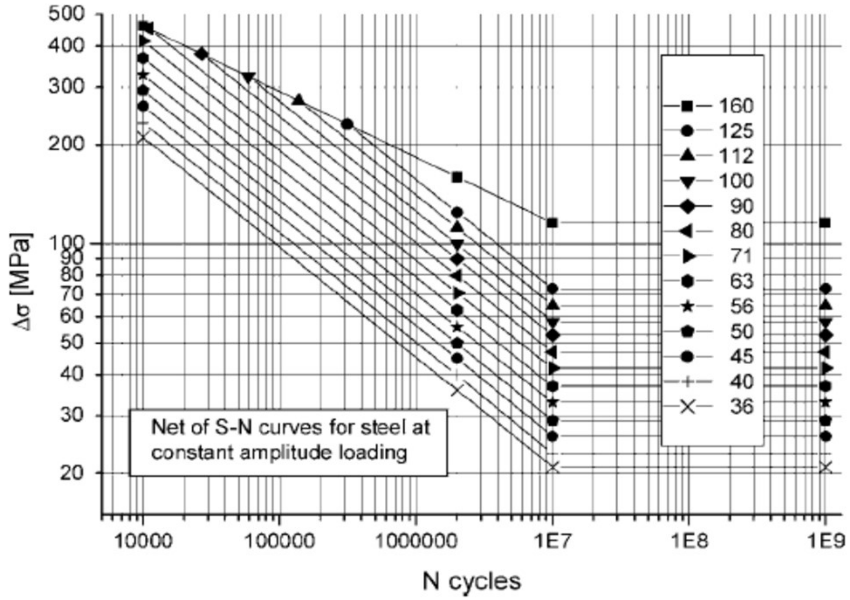


Nominal Stress Approach

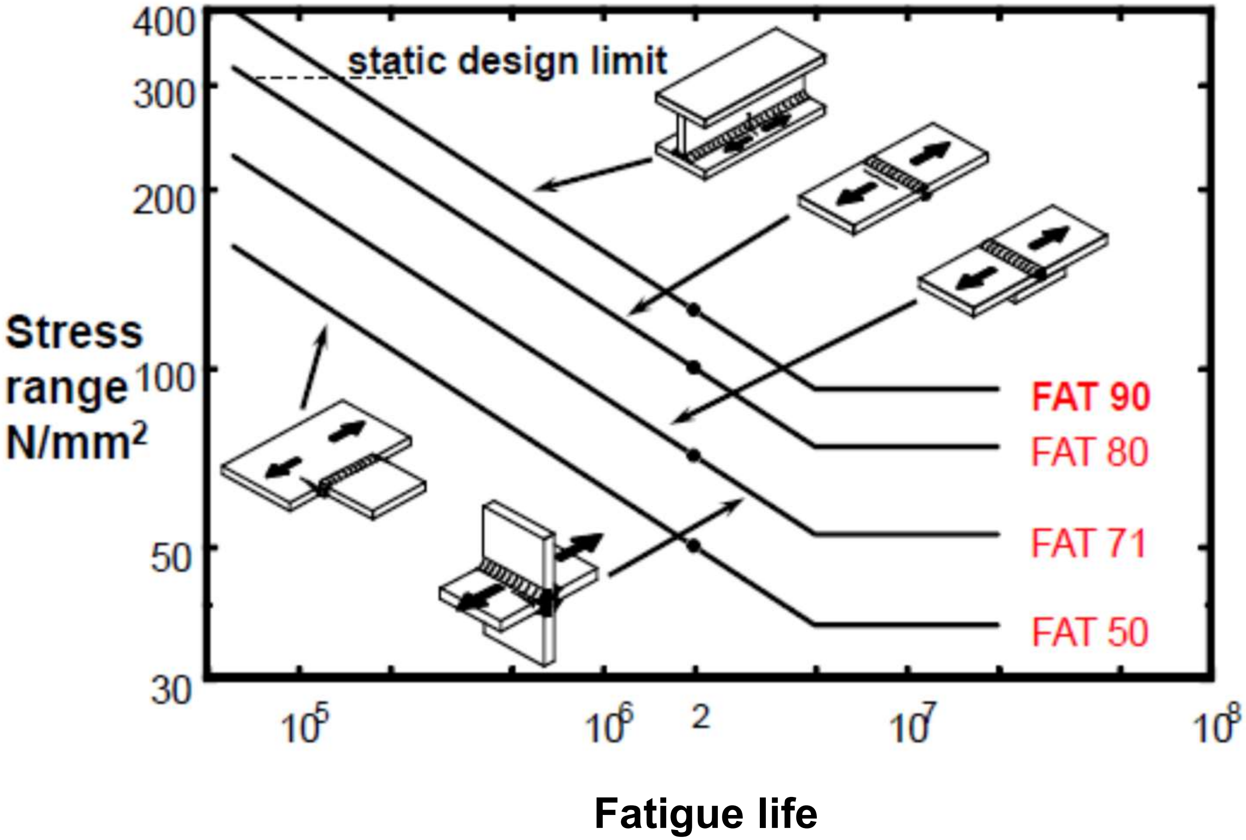
$$\sigma = \frac{F}{A} + \frac{My}{I}$$

Nominal stress:
Many Δσ-N lines
depending of weld type





Nominal Stress Approach



Nominal Stress Approach

- FAT class gives the allowable stress at $2x10^6$ cycles to failure
- For shorter lives use $N(\Delta\sigma)^m = C$, where C is the fatigue capacity.
- Therefore, for any class $2x10^6(FAT)^3 = C$

FAT	C
100	$2.00x10^{12}$
90	$1.46x10^{12}$
80	$1.02x10^{12}$
...	

Nominal Stress Approach

Compute stresses

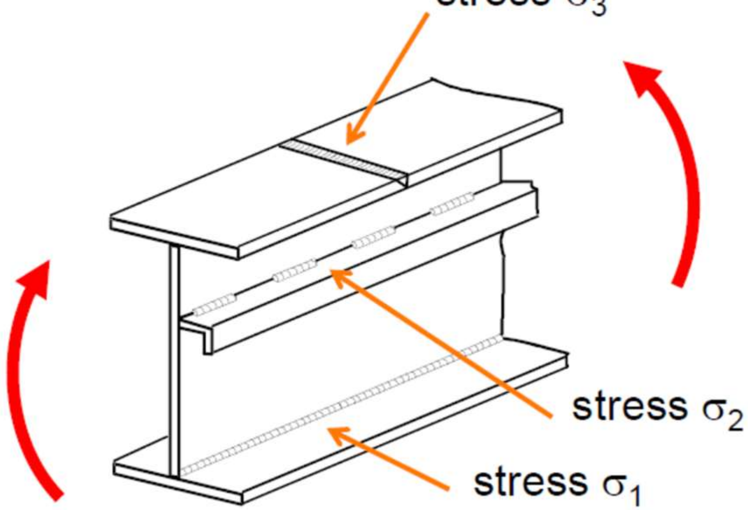


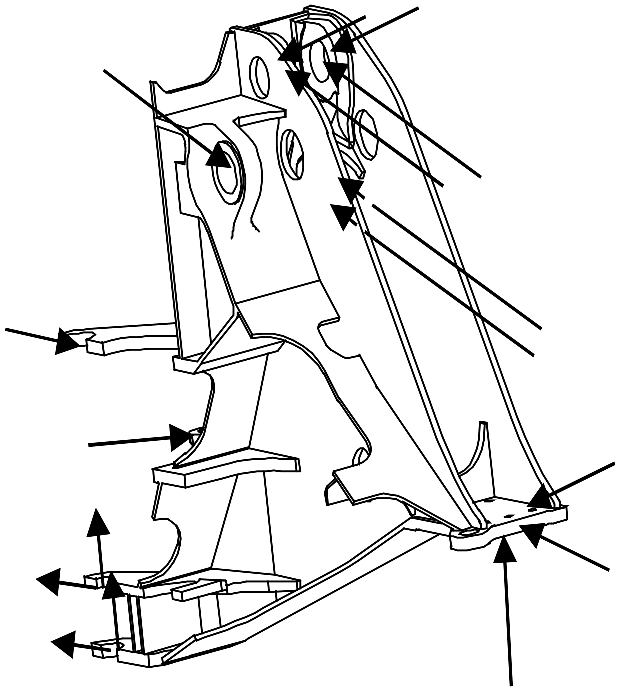
Plate edge

121		Machine gas cut or sheared material with subsequent dressing, no cracks by inspection, no visible imperfections $m = 3$	140

Flange weld

211		Transverse loaded butt weld (X-groove or V-groove) ground flush to plate, 100% NDT	112
212		Transverse butt weld made in shop in flat position, weld reinforcement $< 0.1 \cdot$ thickness	90
213		Transverse butt weld not satisfying conditions of 212, NDT Al.: Butt weld with toe angle $\leq 50°$ Butt welds with toe angle $> 50°$	80

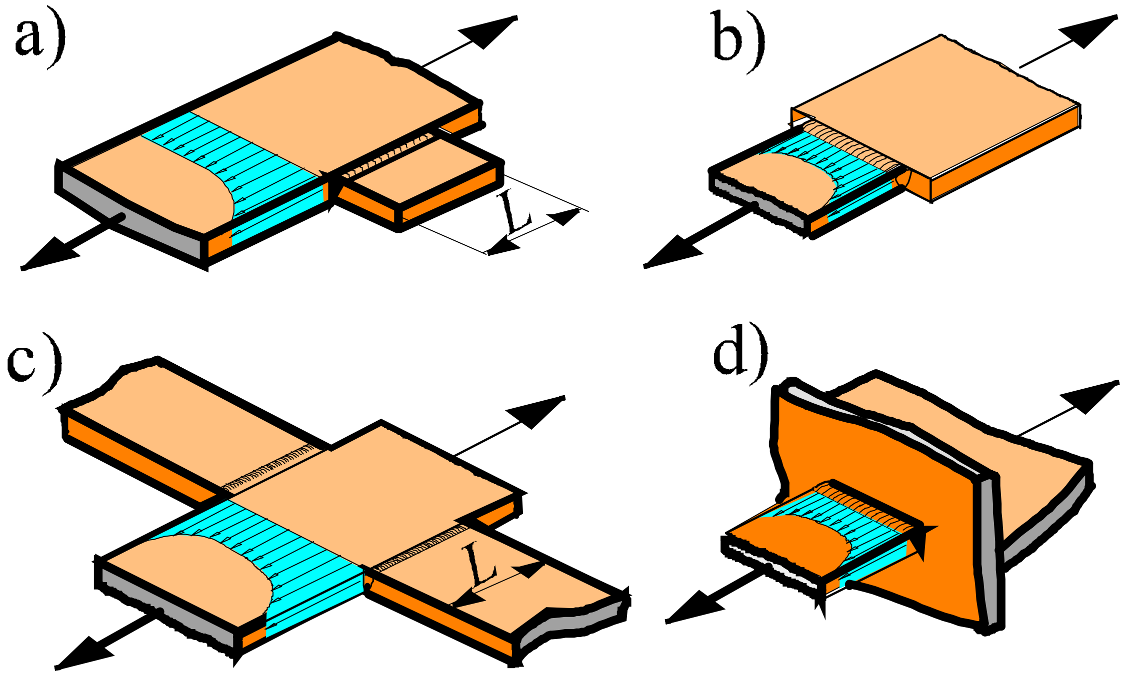
Structural Stress approach



- In many structures nominal stress is not possible to define
- Weld details do not always ”look like” the categorized details
- Finite Element Analysis is often a basic tool for designers

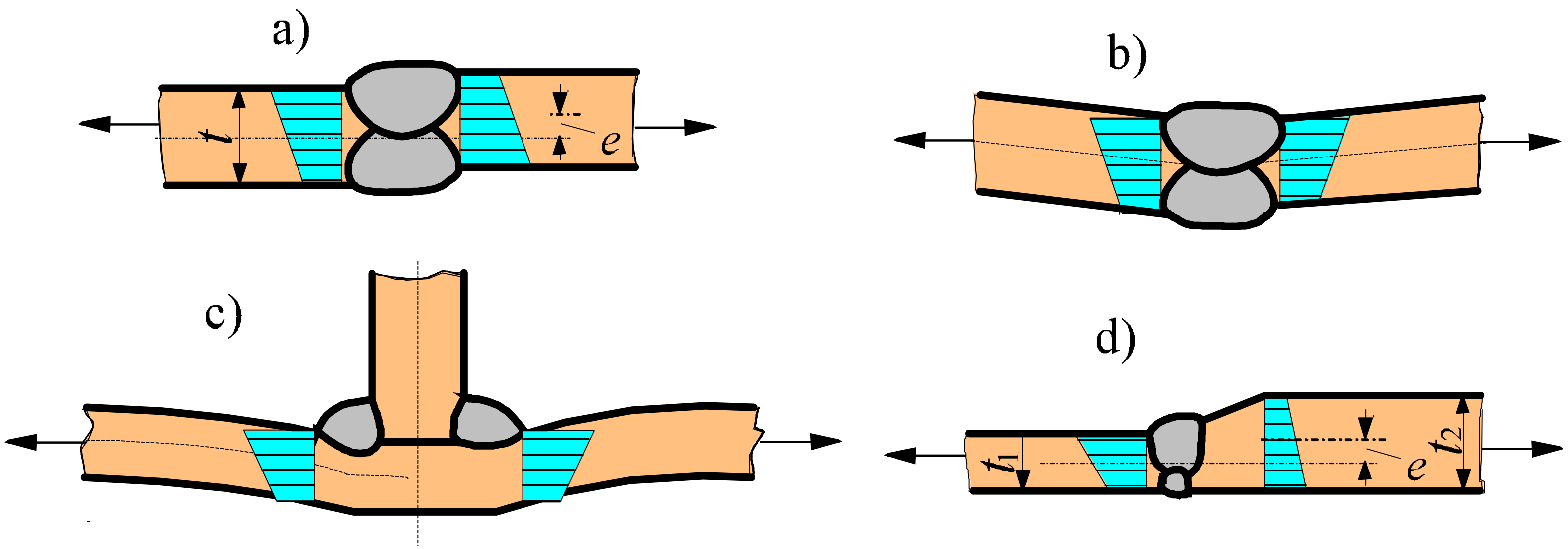
Structural Stress approach

Welded join has structural stress concentrations



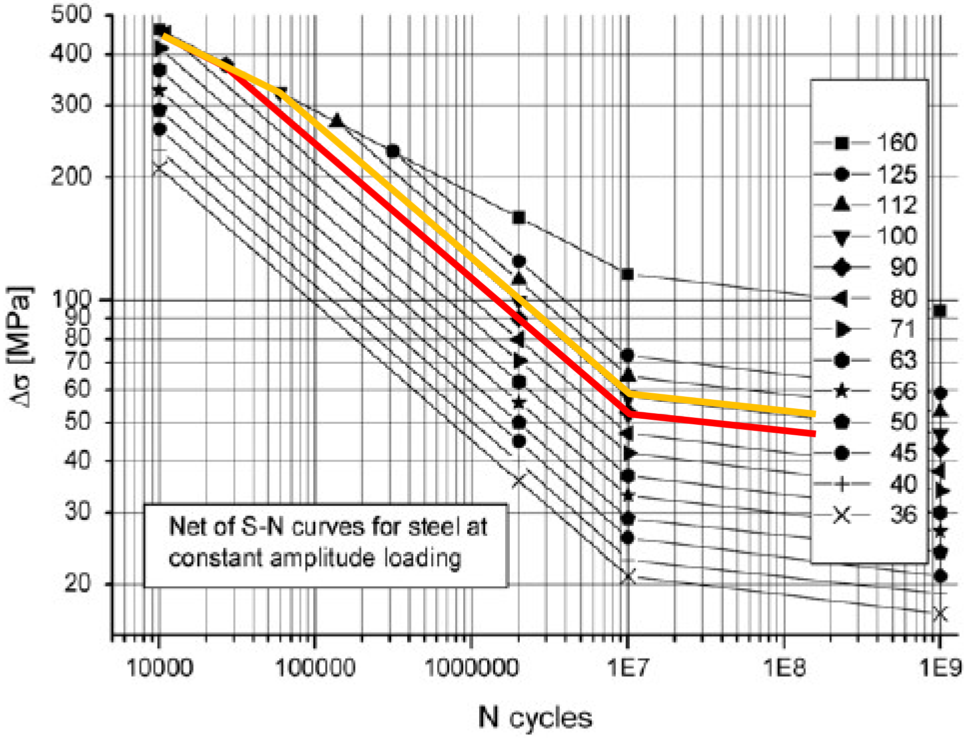
Structural Stress approach

Welded joint has stress concentrations due to misalignment



Source: Niemi, E., *Designers guide for hot spot fatigue analysis,* IIW document XIII-WG3-06-00, 2000

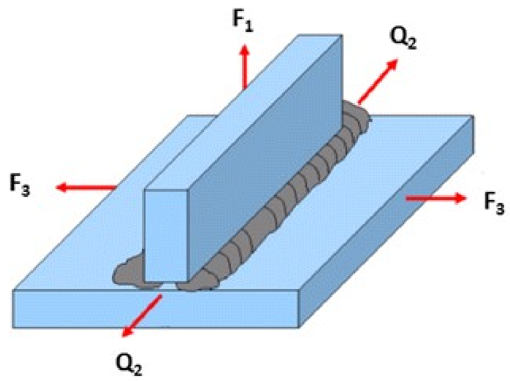
Structural Stress approach



Two $\Delta\sigma$-N lines depending of weld type

FAT 90 load carrying

FAT 100 non-load carrying

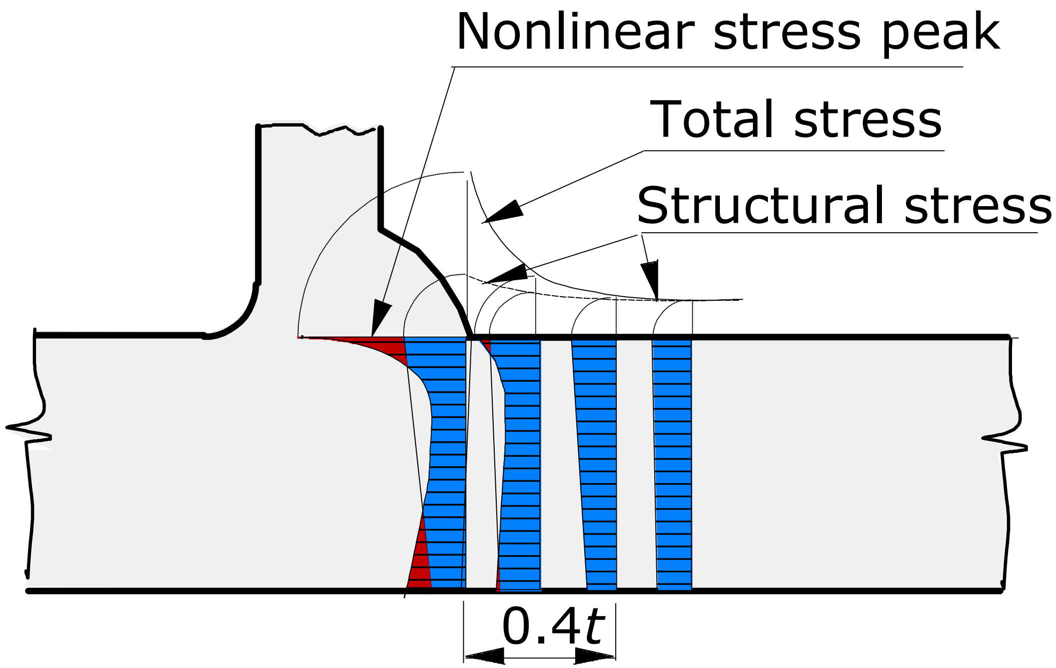


F1= load carrying

F3= non-load carrying

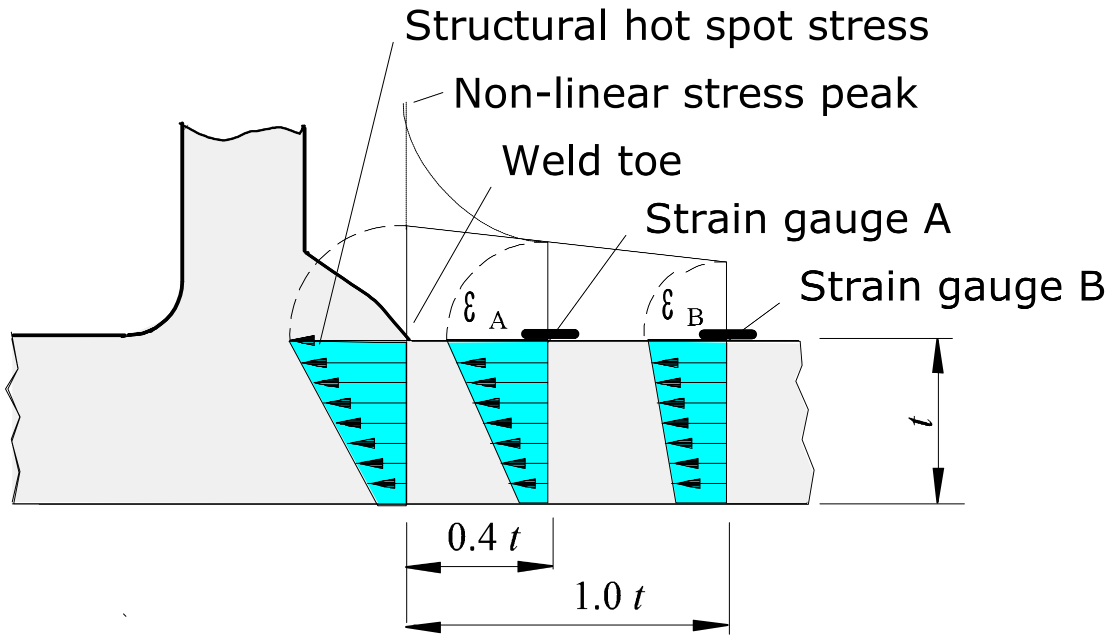
Structural Stress approach

Hot spot stress, i.e. the structural stress at the location of expected fatigue crack initiation, is applied



Structural stress

Stress extrapolation to weld toe using fixed distance gages



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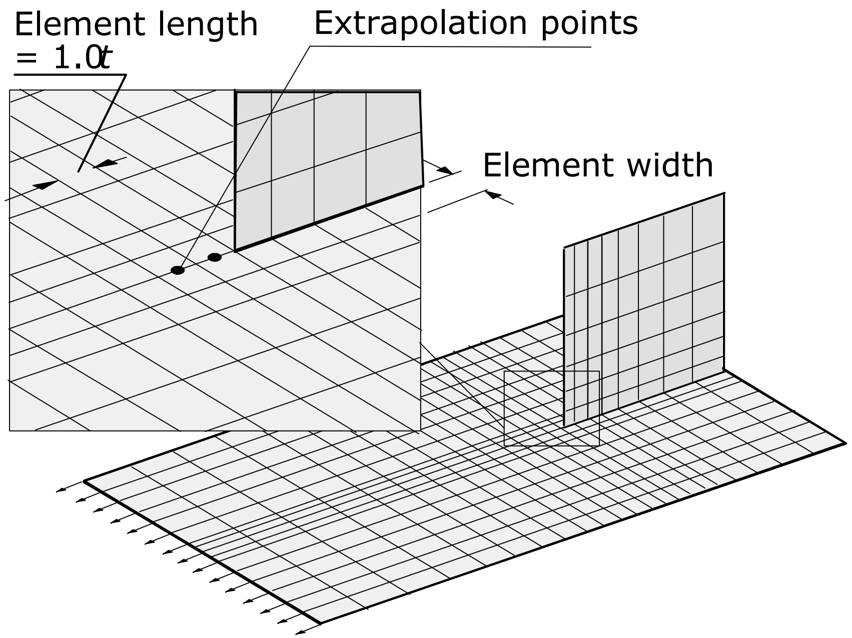
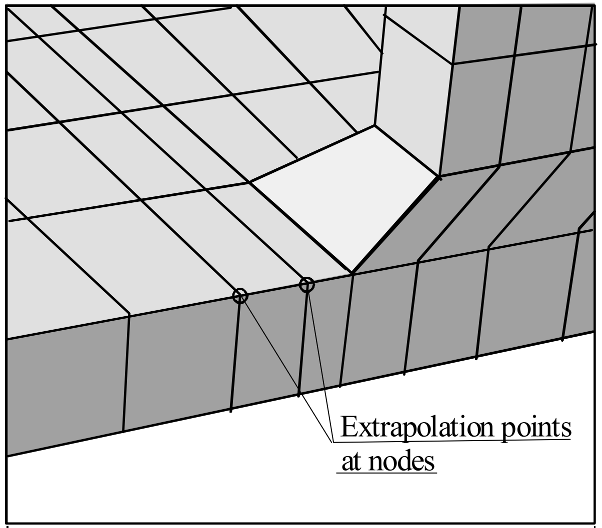
Model examples

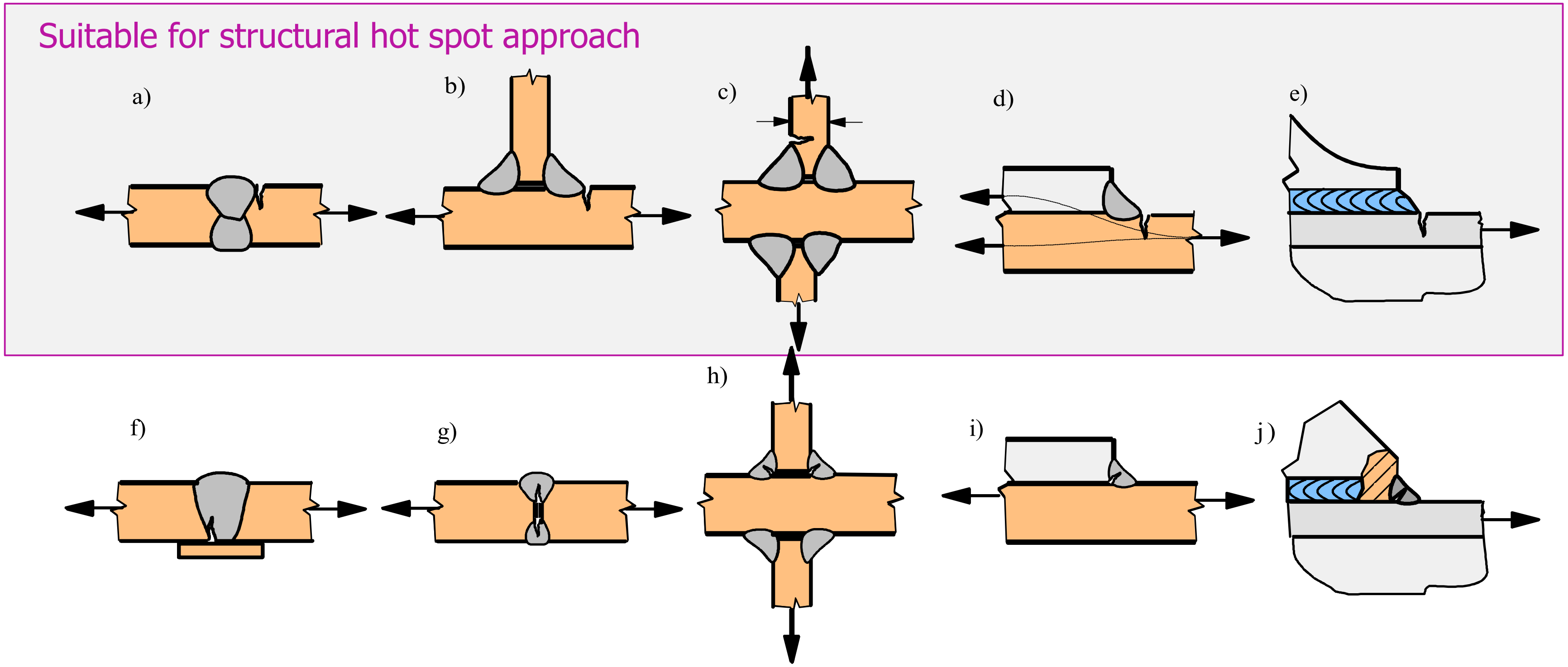




Shell elements

Solid elements

Structural Stress approach

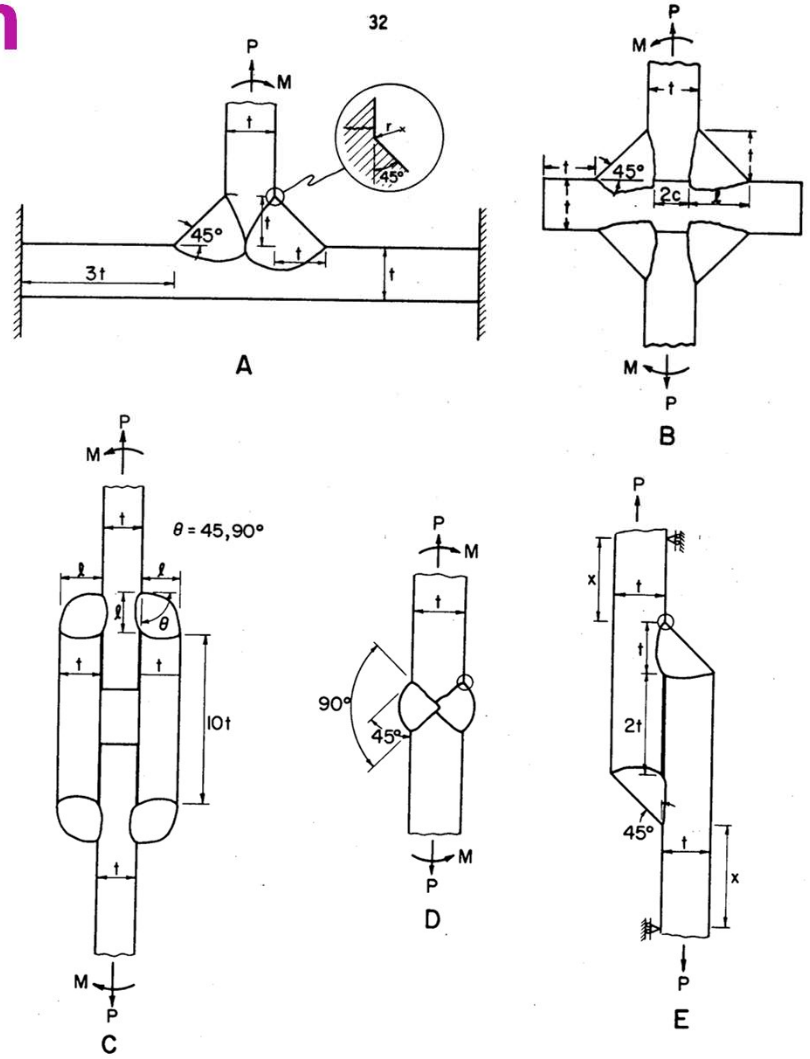


Structural Stress approach is not applicable for the cases (case f-j), where cracks grow from the root side of the weld

Notch stress approach

- Notch stress method aims to calculate the fatigue effective stress at notch tip

- Tedious, but flexible method for fatigue assessment of details such as weld profiles etc.



Notch stress approach

$$K_t = 1 + \alpha\sqrt{t/\rho}$$

Lawrence equation

as ρ decreases, K_t increases

t = plate thickness
ρ= weld toe radius
α = geometry constant related to structural stress concentration

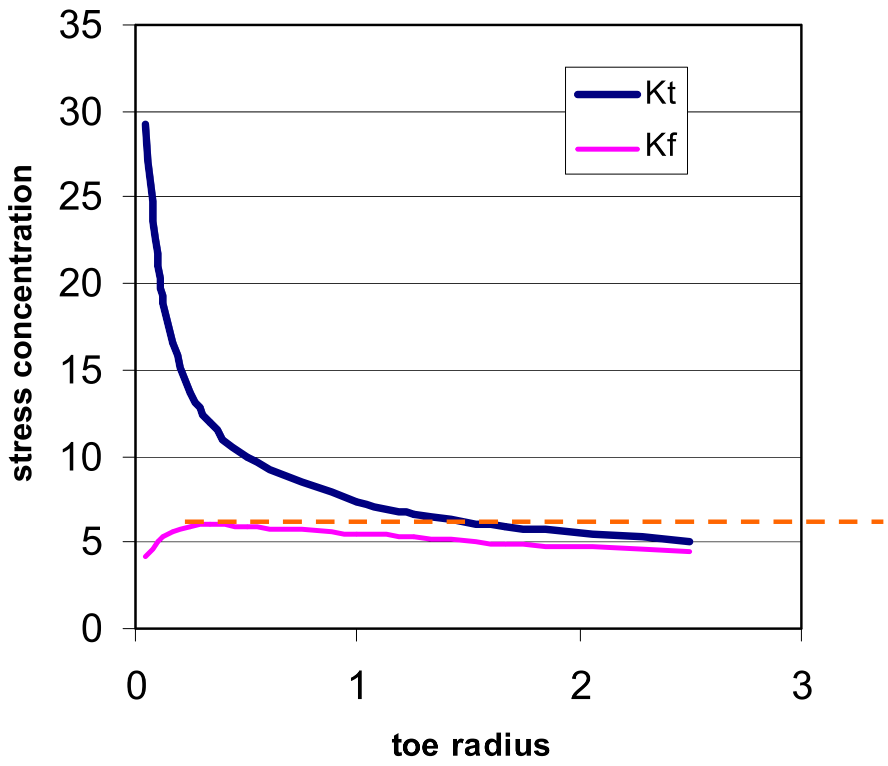
$$K_f = 1 + \frac{(K_t - 1)}{\left(1 + a/\rho\right)}$$

Petersen equation

as ρ decreases, K_f decreases (constant K_t)

$$a = 10^{\left(\frac{(\sigma_U - 134\ )}{586}\right)}$$

Notch stress approach



Lawrence - worst case notch theory

- Toe radius corresponding the maximum of K_f is used

Notch stress approach

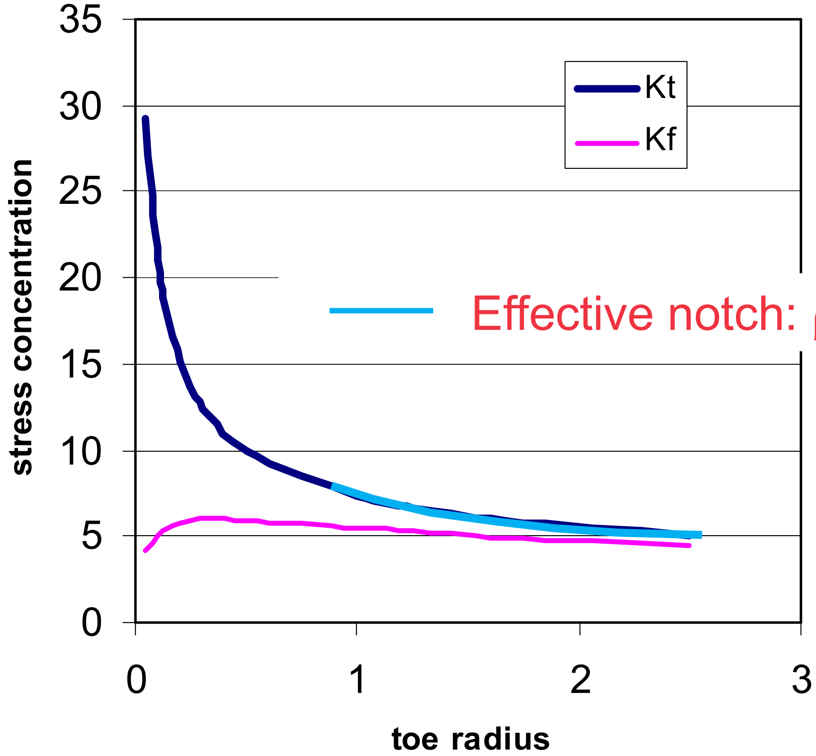
Neuber microstructural support length theory and
Radaj notch rounding approach

ρ_f = effective notch radius

ρ^* = 0.4 mm
material constant
(365 MPa)

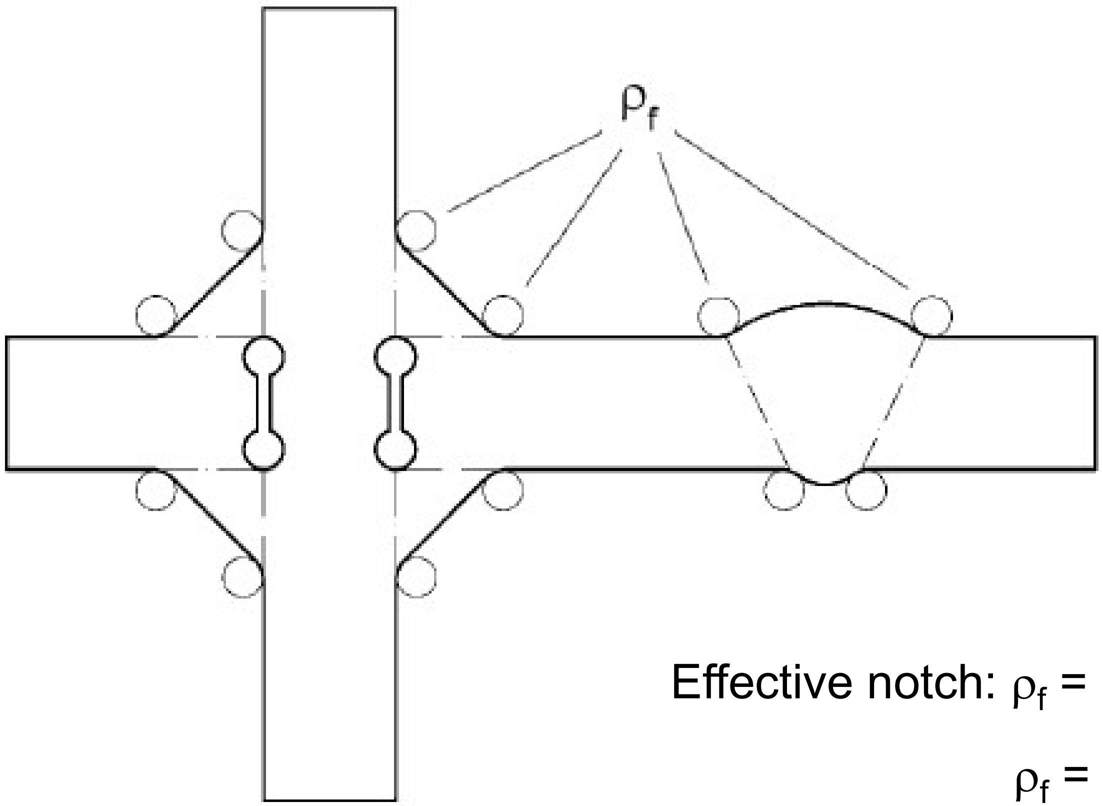
s = 2.5
plane strain multiaxial constant

ρ= actual notch radius
(default 0.0 mm)



Effective notch: $\rho_f = \rho + s\rho^*$

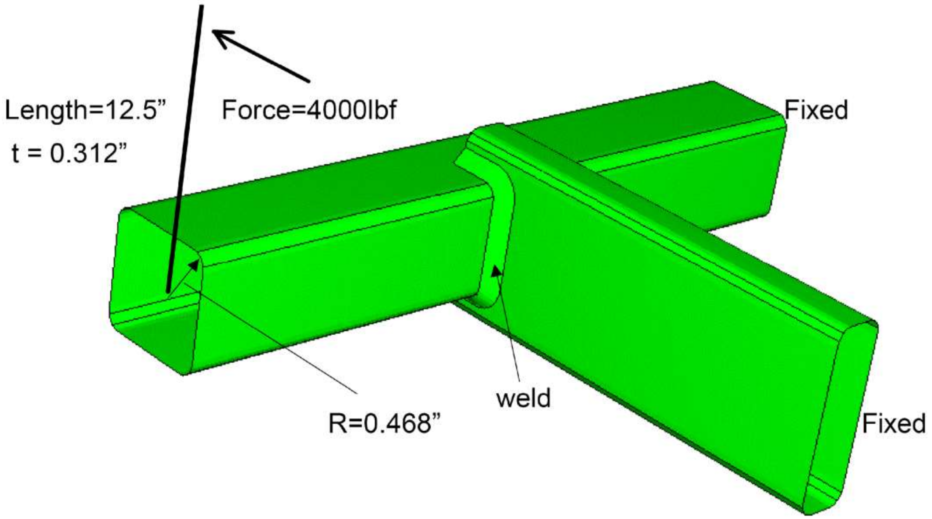
Notch stress approach

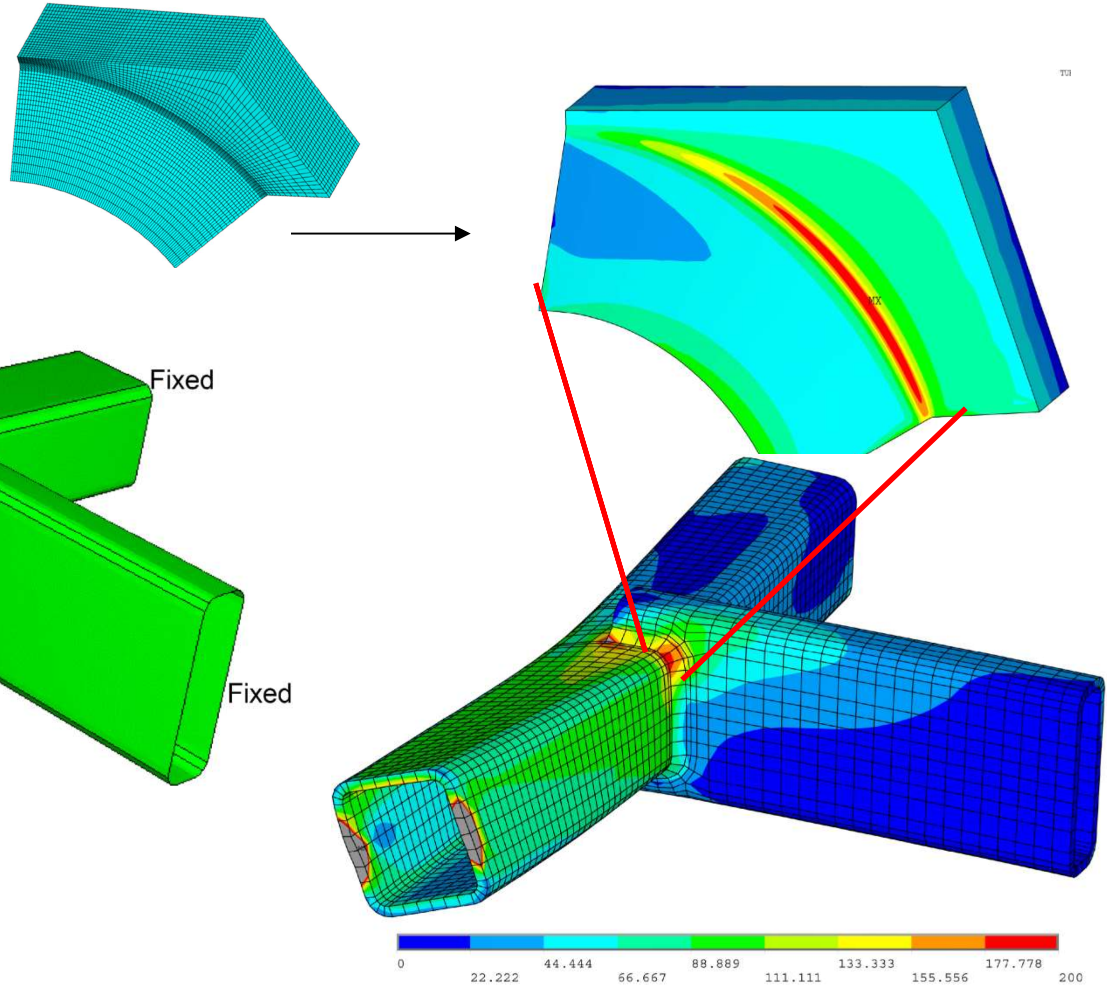


Effective notch: $\rho_f = \rho + s\rho^*$

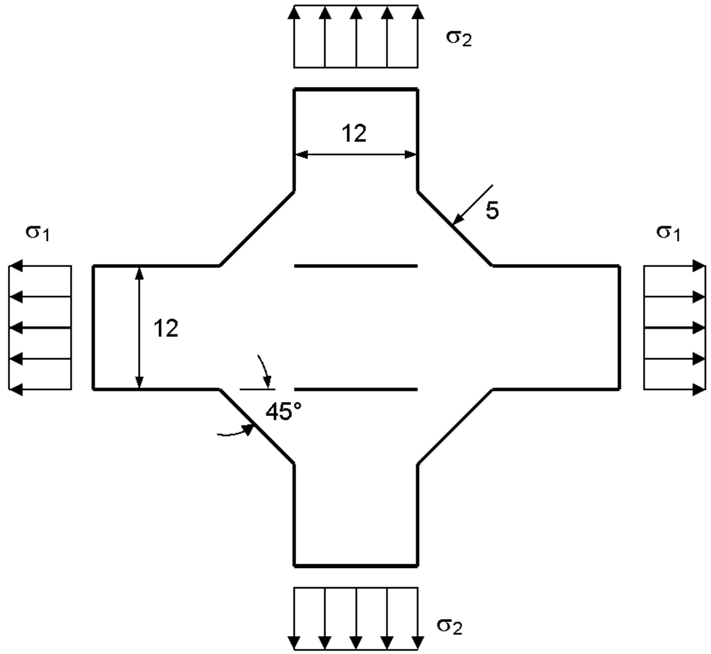
$\rho_f = 1$ mm

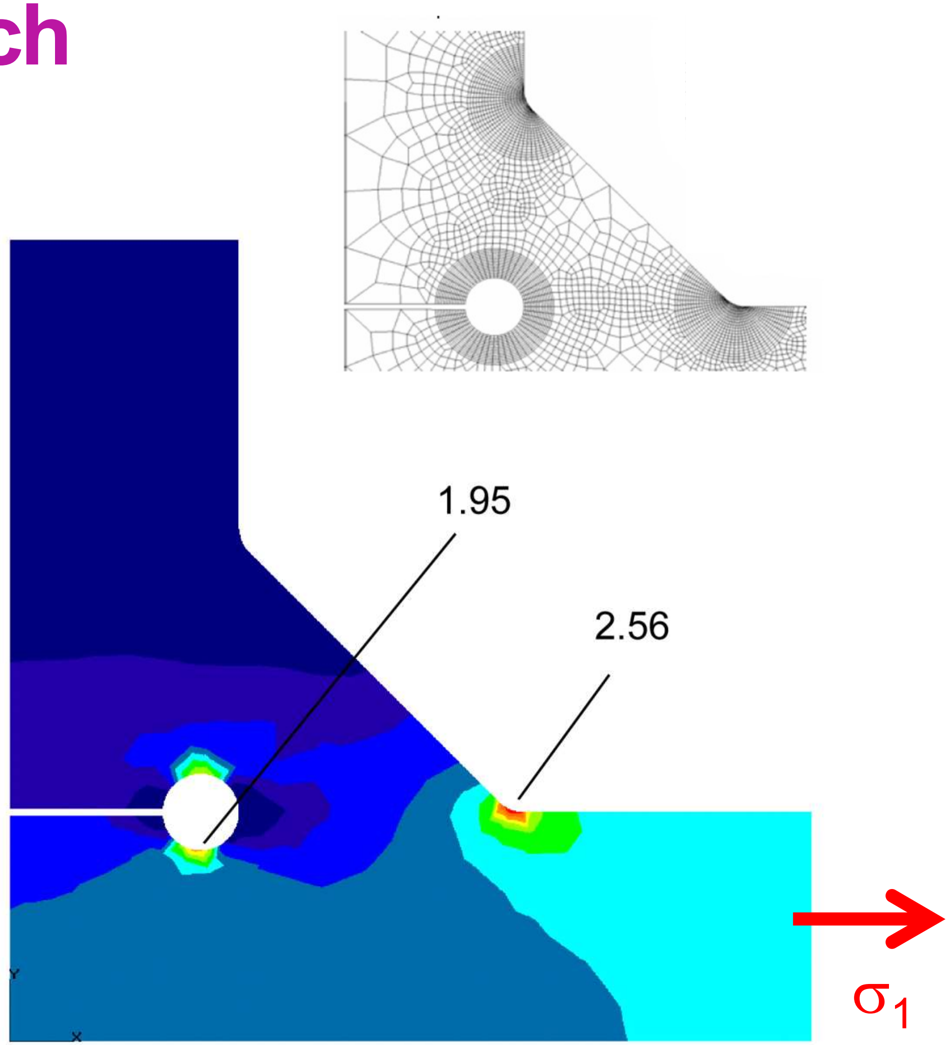
Notch stress approach



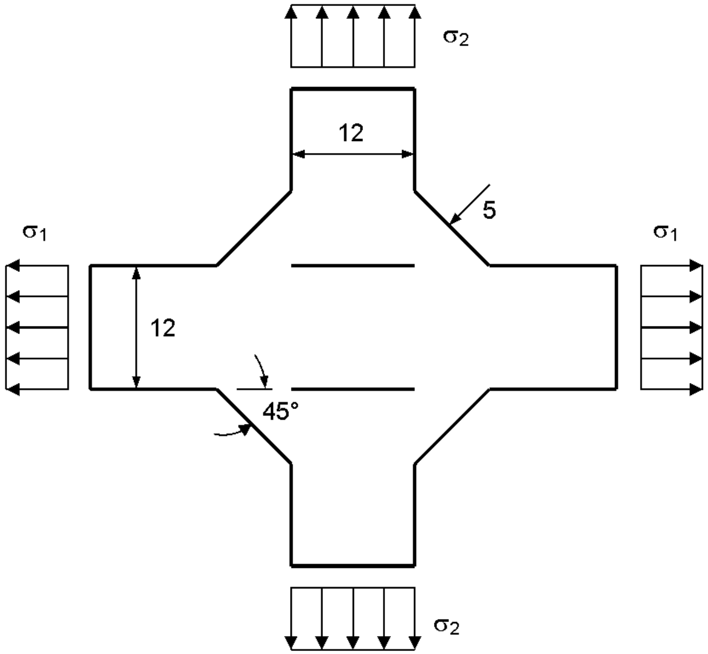


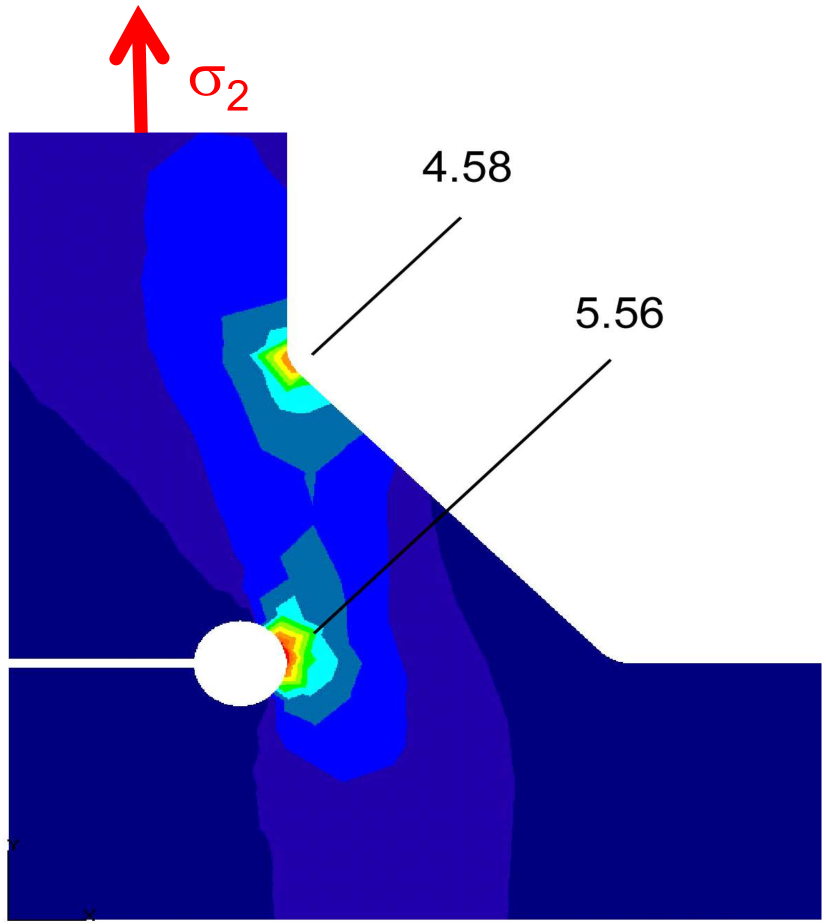
Notch stress approach



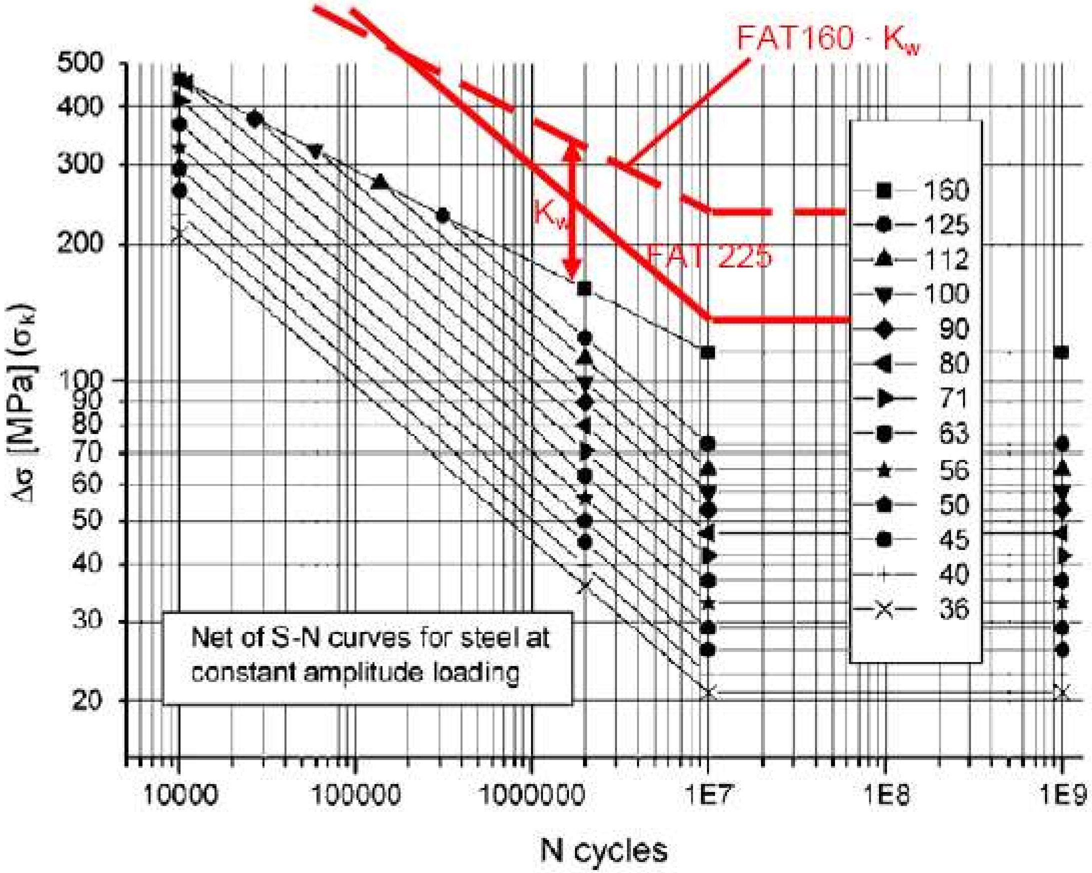


Notch stress approach





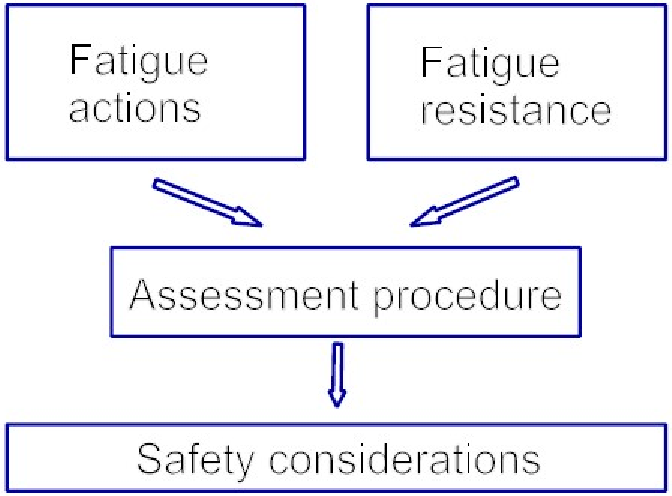
Notch stress approach



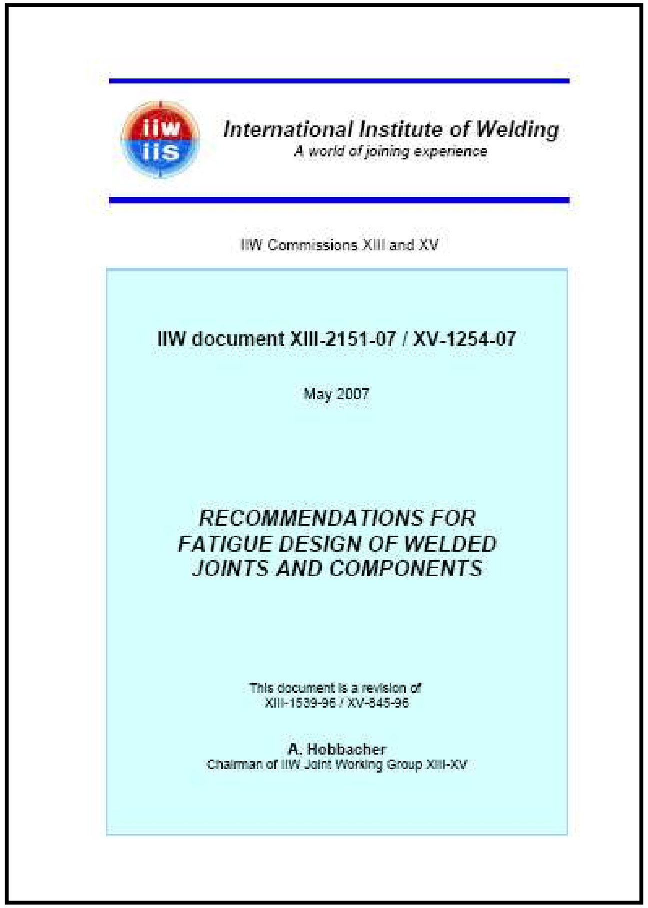
Effective stress based on FAT 225

- Constant slope 3
- Fatigue limit at $1 \text{x} 10^7$ cycles (constant amplitude)
- Bi-linear curve for variable amplitude loading

Fatigue assessment of welded structures



Type of fatigue action	Assessment procedure	Information of resistance
Nominal stress	S-N curve based assessment	Resistance of the structural detail
Structural stress		Resistance of the weld type
Notch stress		Uniform resistance curve of the material
Crack stress intensity	Paris power law	Material parameters for resistance against crack propagation
Load on component	Service testing	no information, tests required


International Institute of Welding
A world of joining experience

IIW Commissions XIII and XV

IIW document XIII-2151-07 / XV-1254-07

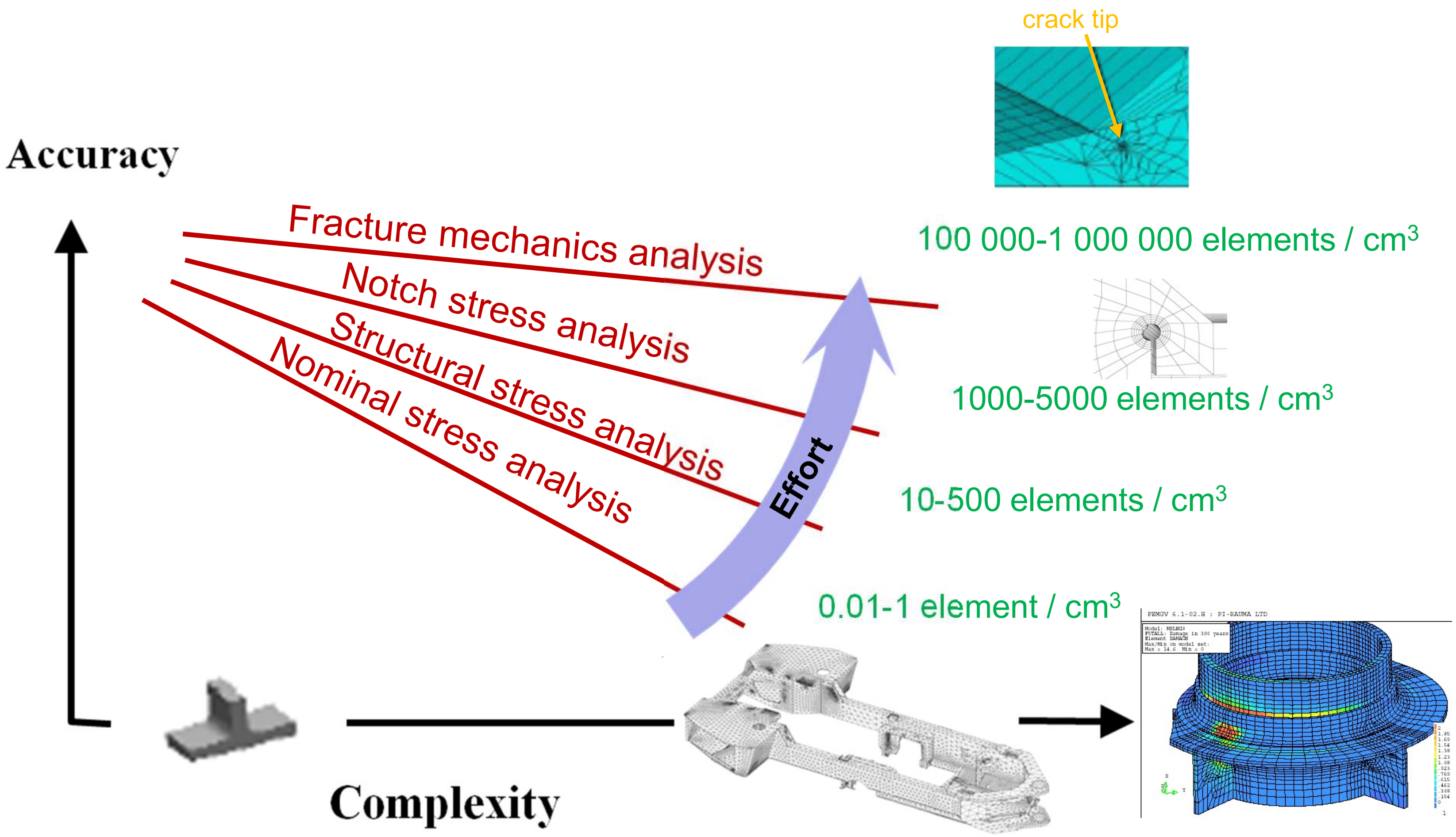
May 2007

RECOMMENDATIONS FOR FATIGUE DESIGN OF WELDED JOINTS AND COMPONENTS

This document is a revision of XIII-1539-96 / XV-845-96

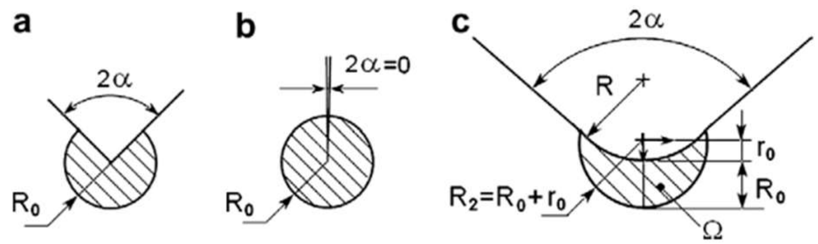
A. Hobbacher
Chairman of IIW Joint Working Group XIII-XV

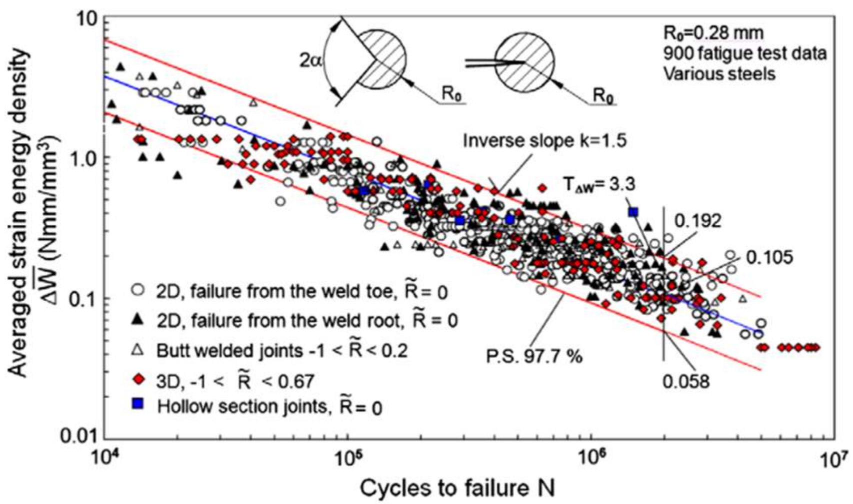
Fatigue assessment of welded structures



SED approach

- Instead on stress, local strain energy density (SED) is used
- Averaged value ΔW is calculated over "volume/area" R_0
- Local strain energy density approach aim to characterize in a single scatter band all the geometries





F. Berto, P. Lazzarin,A review of the volume-based strain energy density approach applied to V-notches and welded structures, Theoretical and Applied Fracture Mechanics, 2009, 52:183-194

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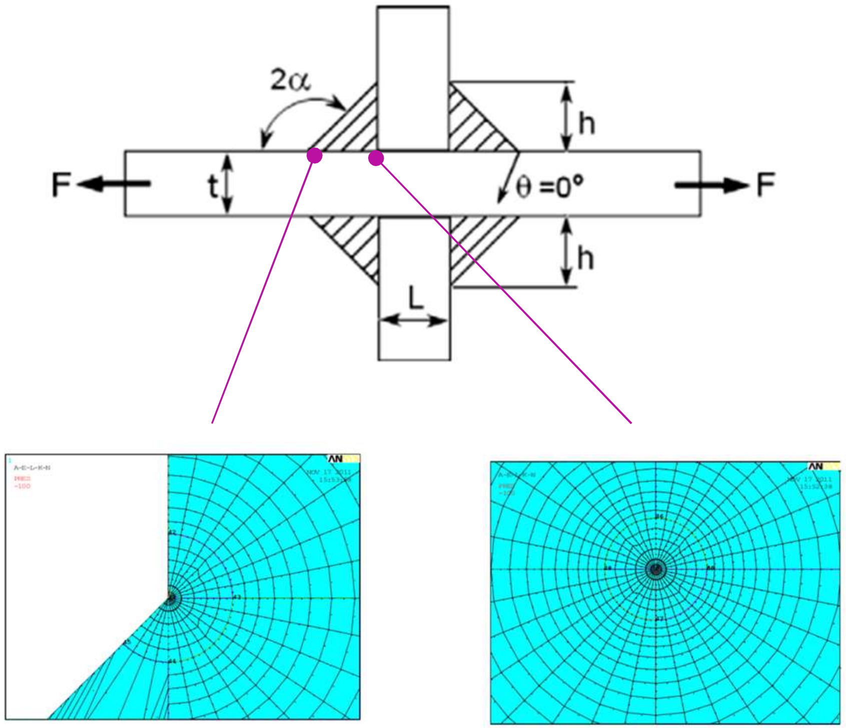

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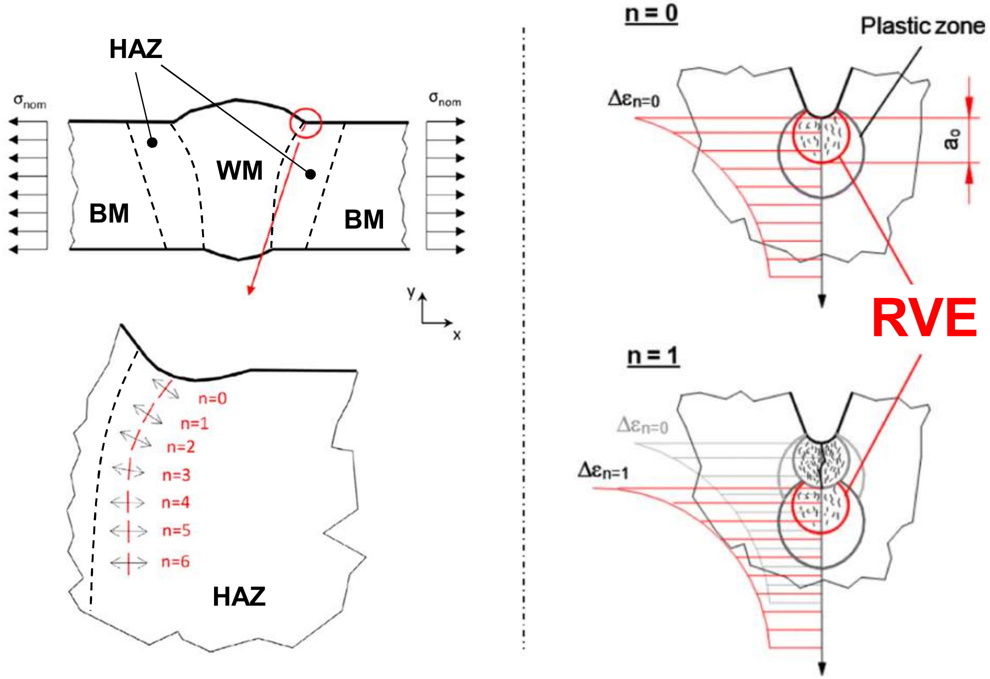
Strain-based crack growth approach

- The fatigue life from crack nucleation until final failure modelled as a repeated crack initiation process
- Coffin-Manson model (strain-based approach) is applied for representative volume element (RVE)
- The size of (RVE) is defined based on relationship between the material strength and microstructure



H. Remes, P. Gallo, J. Jelovica, J. Romanoff, P. Lehto, Fatigue strength modelling of high-performing welded joints, International Journal of Fatigue, 2020, 135

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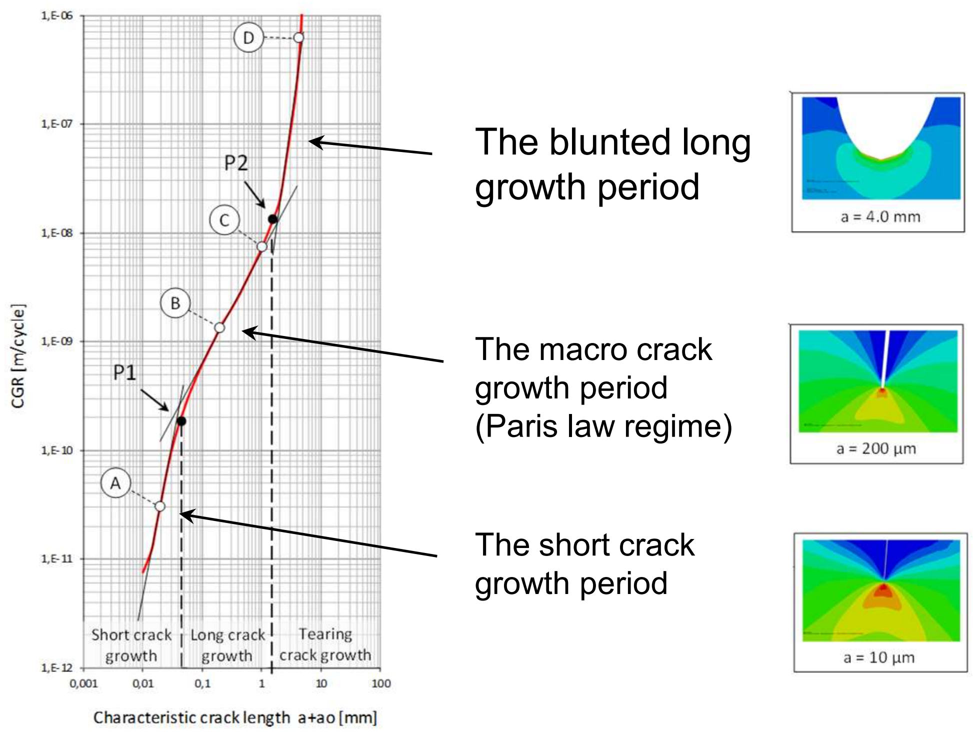
Simulated fatigue crack growth rates



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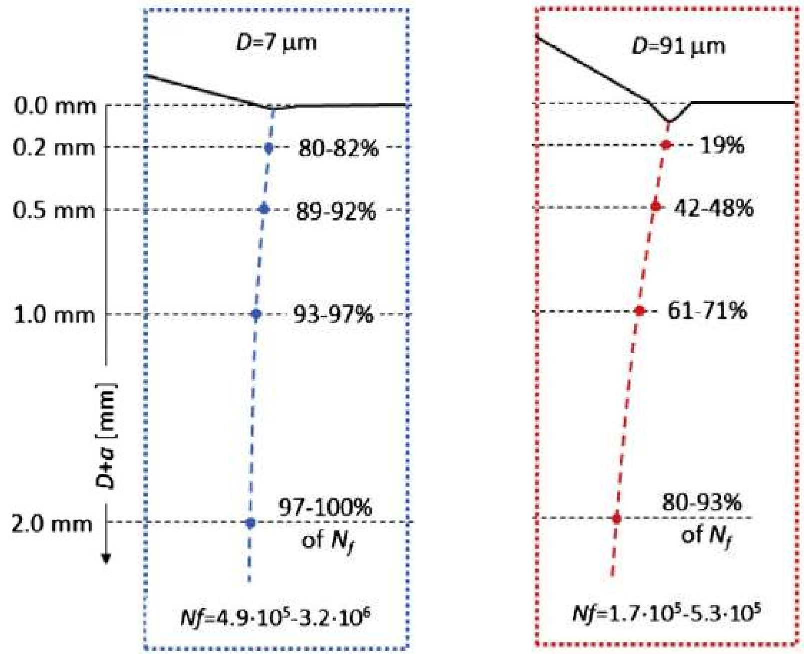
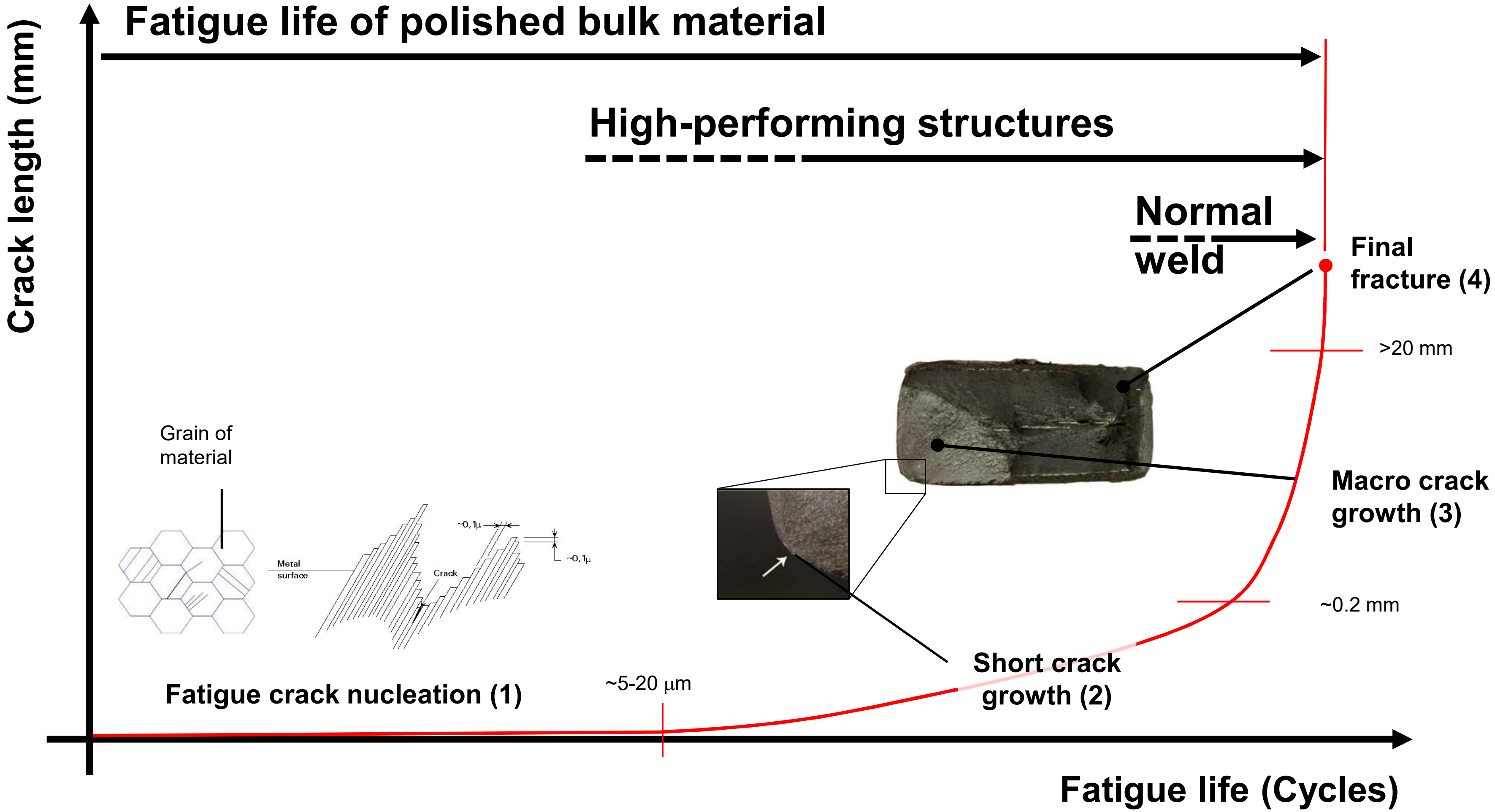
Crack growth time between different crack length in comparison to the total fatigue life



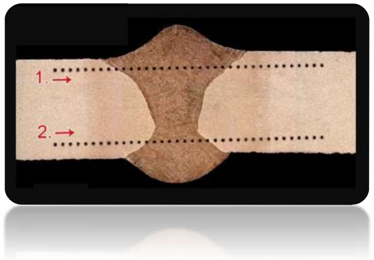
H. Remes, P. Gallo, J. Jelovica, J. Romanoff, P. Lehto, Fatigue strength modelling of high-performing welded joints, International Journal of Fatigue, 2020, 135

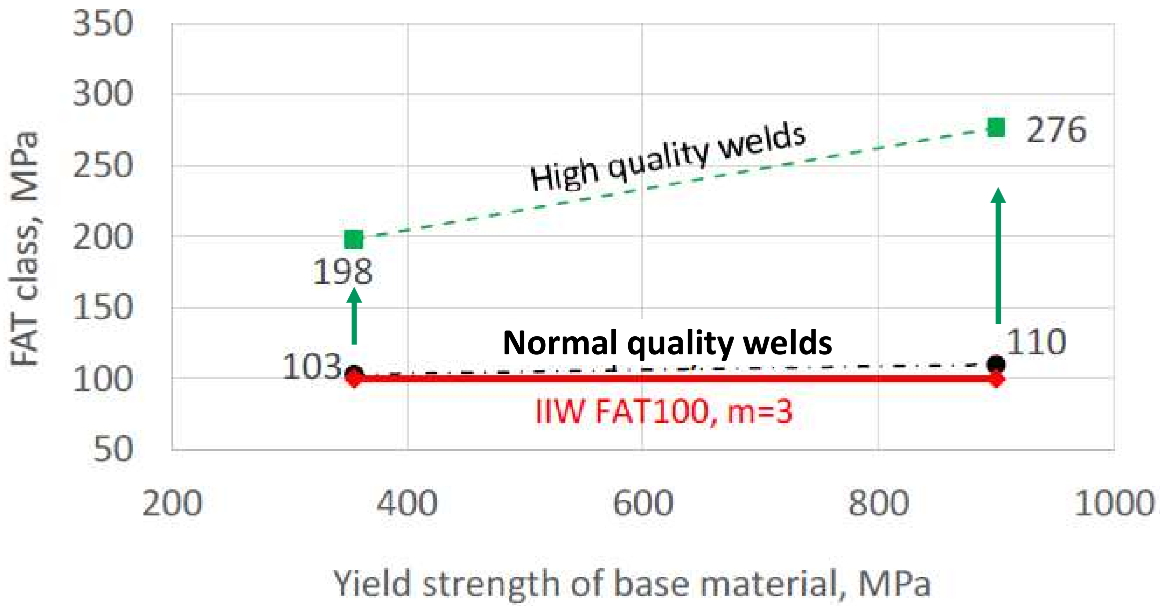
Fatigue of high-performing structures



Example: High-quality butt-welded joint

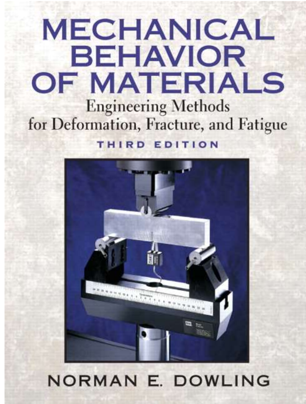
- Smooth weld geometry and small defect size result in significant fatigue strength improvements, increasing as a function of yield strength





Lillemäe, I; H. Remes, H; Liinalampi, S; Antti Itävuo, A. Influence of weld quality on the fatigue strength of thin normal and high strength steel butt joints, Welding in the World, 2016; 60:731–740.

Readings – Course material



Course book

Mechanical Behavior of Materials Engineering Methods for Deformation, Fracture, and Fatigue, Norman E. Dowling

- Section 10.8.4

Additional papers and reports given in MyCourses webpages

- Metal Fatigue in Engineering Book: Chapter 12 – Fatigue weldments
- D. Radaj, C.M. Sonsino, W. Fricke, Recent developments in local concepts of fatigue assessment of welded joints, International Journal of Fatigue, 2009, 31:2-11,
- H. Remes, P. Gallo, J. Jelovica, J. Romanoff, P. Lehto, Fatigue strength modelling of high-performing welded joints, International Journal of Fatigue, 2020, 135
- F. Berto, P. Lazzarin, A review of the volume-based strain energy density approach applied to V-notches and welded structures, Theoretical and Applied Fracture Mechanics, 2009, 52:183-194