Local (Structural) Stress Based Fatigue Design

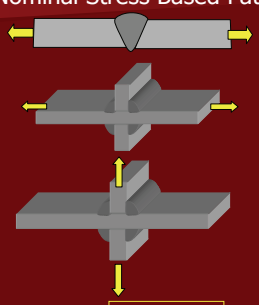
Department of Civil Engineering
Tokyo Institute of Technology

Contents

- Brief Review of Nominal Stress Based Fatigue Design
- Structural Stress Based Fatigue Design
  -Fatigue Assessment of Welded Joints-
- Stress Analysis Method for Root Cracks
  -Effective Notch Stress-

Fatigue Design

- Nominal Stress Based Fatigue Design (Review)



Butt Welded Joints:
JSSC-Category D

Non-Load Carrying
Cruciform Joints:
JSSC-Category E

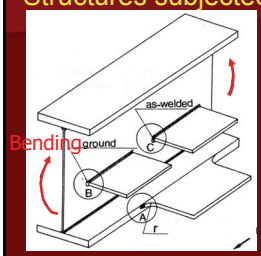
Load Carrying
Cruciform Joints:
JSSC-Category F(toe), H(root)

Joint Types

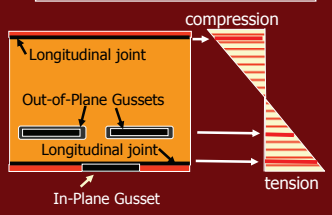
Strength Category

Nominal Stress Ranges

Structures subjected to loads



Nominal Stress Distribution at Section

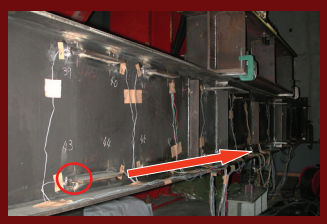


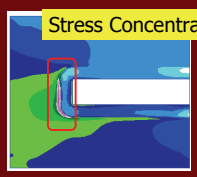
Nominal stress and nominal stress range are commonly used in actual fatigue design of steel bridges

Fatigue Design

- **Structural Stress Based Fatigue Design**

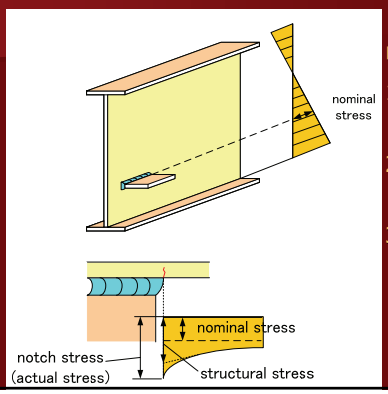
Structural Hot-spot Stress Approach
Define the fatigue strengths directly
By the local stress at crack initiation points





Stress Distribution

Fatigue stress on a gusset



- stress
1. nominal stress
2. structural hot spot stress
3. notch stress concentration due to weld bead

Type of Stress for Fatigue Assessment

Type	Stress raisers	Stress determined	Assessment procedure	
A	General analysis of sectional forces using beam theory, no stress raiser considered	Gross average stress from sectional forces	not applicable for fatigue analysis, only component testing	Beam model
B	A + macrogeometrical effects due to the design of the component, but excluding stress risers due to the welded joint itself.	Range of nominal stress (also modified or local nominal stress)	Nominal stress approach	Shell model
C	A + B + structural discontinuities due to the structural detail of the welded joint, but excluding the notch effect of the weld toe transition	Range of hot-spot structural stress	hot-spot structural stress approach	Shell or Solid model
D	A + B + C + notch stress concentration due to the weld bead notches a) actual notch stress b) effective notch stress	Range of elastic notch stress (total stress)	a) Fracture mechanics approach b) effective notch stress approach	Solid detailed FEM model with bead

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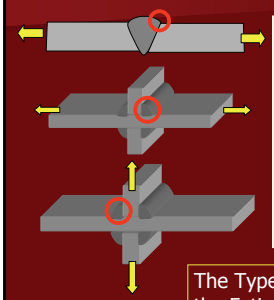
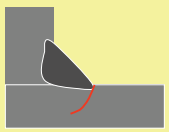
Structural Stress (Hot Spot Stress) approach





Local Stresses control the fatigue phenomenon in any types of joints.

The Types of Joints don't affect the Fatigue Strengths Defined by Structural Hot-Spot Stress Approach

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The Structural Hot-Spot Stress Approach

The Structural Hot-Spot Stress Approach is recommended for welded joints where there is no clearly defined nominal stress due to complicated geometric effects, and where the structural discontinuity is not comparable to a classified structural detail

- due to complicated geometry
- due to structural discontinuities
- due to complicated plate deformation

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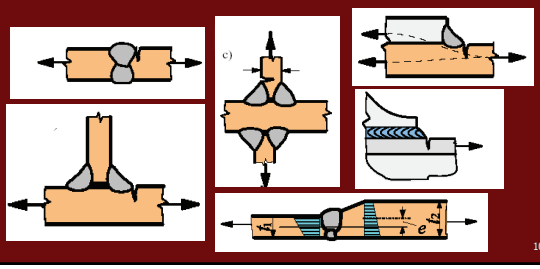
applicability of the hot spot stress to the weld toe

- where there is no clearly defined nominal stress due to complicated geometric effects
- where the structural discontinuity is not comparable to a classified structural detail



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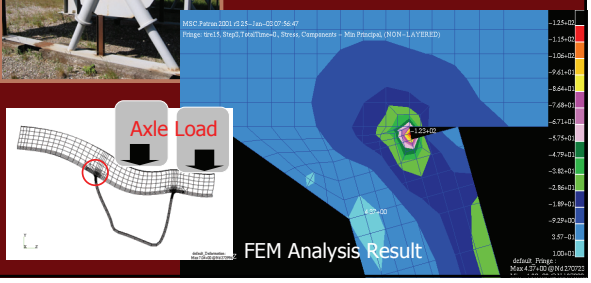
Applicability of Hot Spot Stress

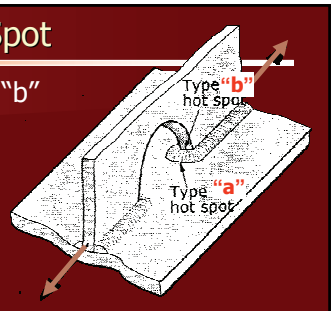
Complicated Geometry

In case of Orthotropic Steel Deck Bridges



2 Types of Hot Spot

2 Types: "a" and "b"



Type	Description	Determination
a	Structural hot spot stress transverse to weld toe on plate surface	Special FEA procedure or measurement and extrapolation
b	Structural hot spot stress transverse to weld toe at plate edge	Special FEA procedure or measurement and extrapolation

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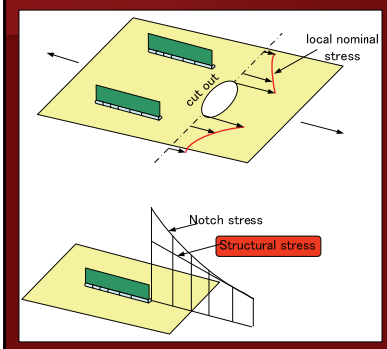
Definition of The Structural Hot-Spot Stress



Local nominal stress includes

- The effects of macro-geometric features of the component
- stress fields in the vicinity of concentrated loads
- significant shell bending stress

Structural Hot Spot Stress

- includes all stress raising effects of a structural detail excluding all stress concentrations due to the local weld profile.
- non-linear peak stress caused by the local notch is excluded

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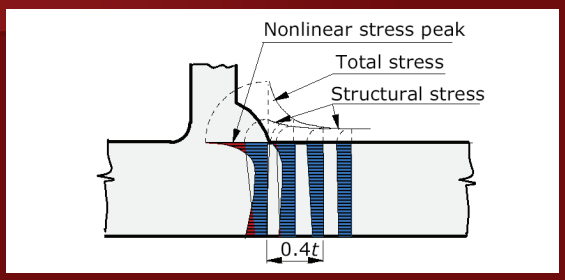
Definition of The Structural Hot-Spot Stress



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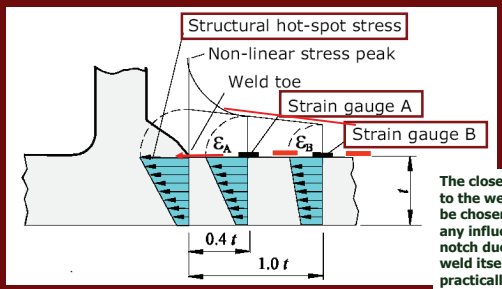
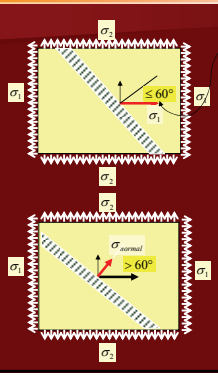
The Estimation Method of The Structural Hot-Spot Stress by Measuring Strain



Linear Extrapolation

The closest position to the weld toe must be chosen to avoid any influence of the notch due to the weld itself. This is practically the case at a distance of 0.4t from the weld toe.

Dependency on Angle : principal or normal



the principal stress which is approximately in line with the perpendicular to the weld toe

$$\sigma_{HotSpot} = \sigma_1$$

$$\sigma_{HotSpot} = \sigma_{normal}$$

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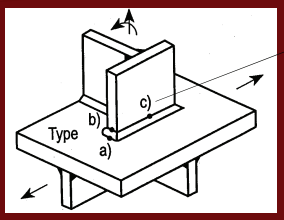
Hot Spot Stresses in Complex Welded Structures

Types of Weld Toes



Type a) : On the Plate Surface at the End of an Attachment
Type b) : At the Plate Edge at the End of an Attachment
Type c) : Along the Weld of an Attachment

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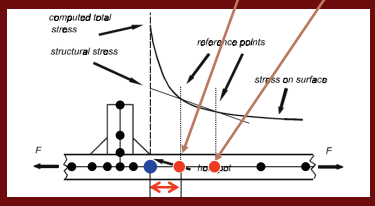
Element length

Reference points for subsequent extrapolation.

→ Determination of Element Lengths

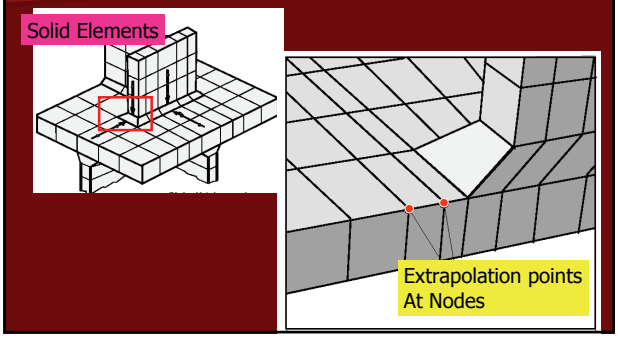
Avoiding stress singularity → Evaluation of stress at First and Second Nodes



Element Lengths

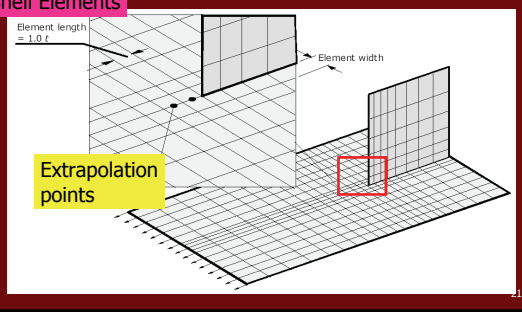
FEM Modeling for Structural Hot-Spot Stress Evaluation(1)

Solid Elements

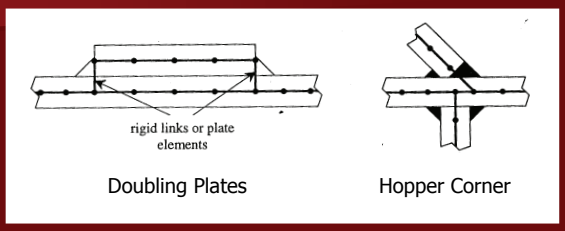


FEM Modeling for Structural Hot-Spot Stress Evaluation(2)

Shell Elements

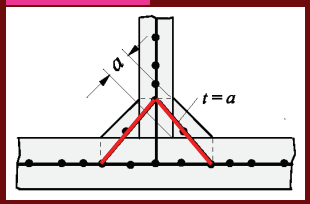


Modeling of Offsets in Shell Models

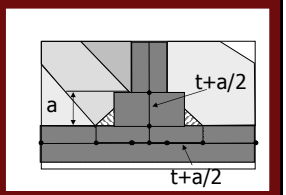


Recommended Techniques for Modeling of Welds

Shell Elements



Method I:
Inclined Shell Elements



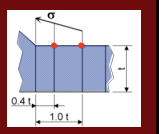
Method II:
Thickness Changes

International Institute of Welding (IIW)

Reference points for type "a" hot spots

Related to shell thickness t

1. Fine mesh (element length<0.4t):
   1. By Two Reference Points: 0.4t & 1.0t

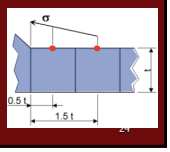


$$\sigma_{hs} = 1.67\sigma_{0.4t} - 0.67\sigma_{1.0t}$$

   2. By Three Reference Points: 0.4t, 0.9t & 1.4t

$$\sigma_{hs} = 2.52\sigma_{0.4t} - 2.24\sigma_{0.9t} + 0.72\sigma_{1.4t}$$

2. Coarse mesh: 0.5t & 1.5t
   Element length=1.0t with higher-order Elements



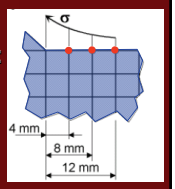
$$\sigma_{hs} = 1.50\sigma_{0.5t} - 0.50\sigma_{1.5t}$$

Reference points for type "b" hot spots

Given by absolute distance

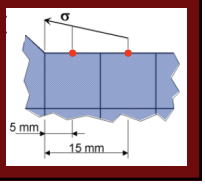
1. Fine mesh (element length< 4mm): 4, 8 & 12 mm

$$\sigma_{hs} = 3\sigma_{4mm} - 3\sigma_{8mm} + \sigma_{12mm}$$



2. Coarse mesh: 5 & 15 mm
   Element length=10mm
   with higher-order Elements

$$\sigma_{hs} = 1.5\sigma_{5mm} - 0.5\sigma_{15mm}$$



Recommended meshing and extrapolation

Type of model and weld toe		Relatively coase models		Relatively fine models	
		Type a	Type b	Type a	Type b
Element size	Shells	t x t max t x w/2*)	10 x 10 mm	≤0.4 t x t or ≤0.4 t x w/2	≤ 4 x 4 mm
	Solids	t x t max t x w	10 x 10 mm	≤0.4 t x t or ≤0.4 t x w/2	≤ 4 x 4 mm
Extrapo-lation points	Shells	0.5 t and 1.5 t mid-side points**)	5 and 15 mm mid-side points	0.4 t and 1.0 t nodal points	4, 8 and 12 mm nodal points
	Solids	0.5 and 1.5 t surface center	5 and 15 mm surface center	0.4 t and 1.0 t nodal points	4, 8 and 12 mm nodal points

*) w = longitudinal attachment thickness + 2 weld leg lenths
**) surface center at transverse welds, if the weld below the plate is not modelled (see left

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Hot Spot S-N Curves

No	Structural detail	Description	Requirements	FAT Steel	FAT Alu.
1		Butt joint	As welded, NDT	100	40
2		Cruciform or T-joint with full penetration K-butt welds	K-butt welds, no lamellar tearing	100	40
3		Non load-carrying fillet welds	Transverse non-load carry-ing attachment, not thicker than main plate, as welded	100	40
4		Bracket ends, ends of longitudinal stif-feners	Fillet welds welded around or not, as welded	100	40
5		Cover plate ends and similar joints	As welded	100	40
6		Cruciform joints with load-carrying fillet welds	Fillet welds, as welded	90	36

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Hot Spot S-N Curves

No	Structural detail	Description	Requirements	FAT Steel	FAT Alu.
7		Lap joint with load carrying fillt welds	Fillet welds, as welded	90	36
8	L ≤ 100 mm	Type "b" joint with short attachment	Fillet or full penetration weld, as welded	100	40
9	L > 100 mm	Type "b" joint with long attachment	Fillet or full penetration weld, as welded	90	36

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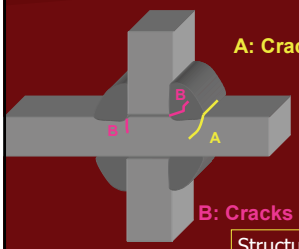
The Target Cracks of Structural Hot-Spot Stress Approach



A: Cracks Initiated from the Weld Toe

Structural Stress Approach
Can be Applied

B: Cracks Initiated from the Roots

Structural Stress Approach
Cannot be Applied

Different Approach is Needed

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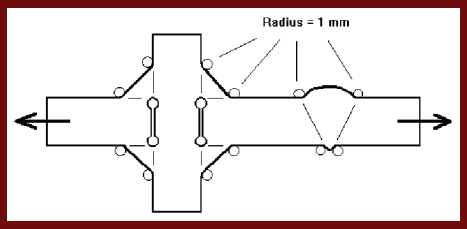
Stress Evaluation by the Effective Notch Stress

Effective notch stress is the total stress at the root of a notch, obtained assuming linear-elastic material behavior. The real weld outline is replaced by an effective one. Effective notch root radius of r=1mm has been verified to give consistent results.



If the Toe is Finished, the radius = 2mm

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Effective Notch Fatigue Resistance

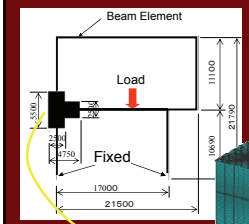
- The method is restricted to assessment of naturally formed weld toes and roots.
- The method is well suited to the comparison of alternative weld geometries.
- In case where a mean geometrical notch root radius can be defined, this radius plus 1mm may be used in the effective notch stress analysis.

Tab. {3.4}-1: Effective notch fatigue resistance for steel

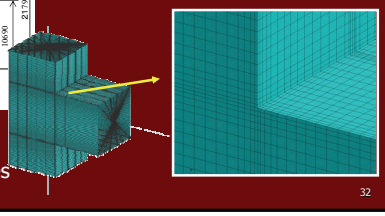
No.	Quality of weld notch	Description	FAT
1	Effective notch radius equalling **1 mm** replacing weld toe and weld root notch	Notch as-welded, normal welding quality m=3	225

IIW fatigue recommendation

An Example of Application of the Effective Notch Stress –Beam-to-Column Connections-



- Analysis Code: ABAQUS
- Min Element Size: 11.5mm (T/2)
- Number of Nodes: 91,278
- Number of Element: 90,200



Full Scaled Structures

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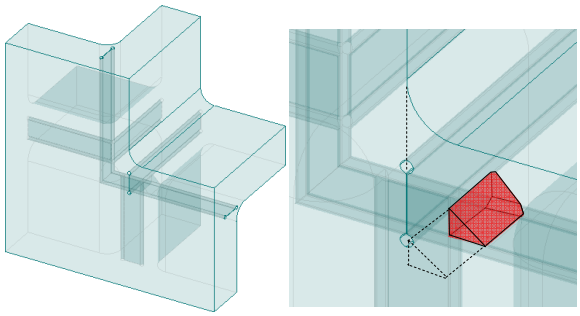
Model of Delta zone



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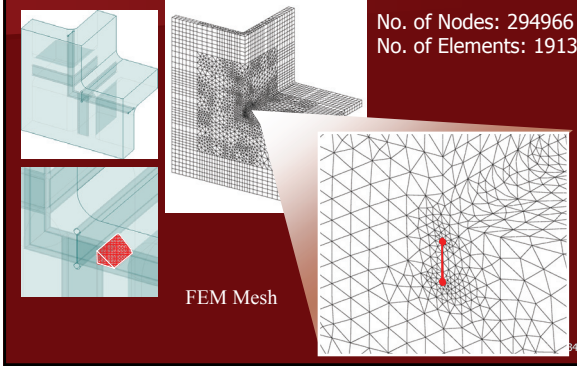
Detailed Solid Models



No. of Nodes: 294966
No. of Elements: 191382

FEM Mesh

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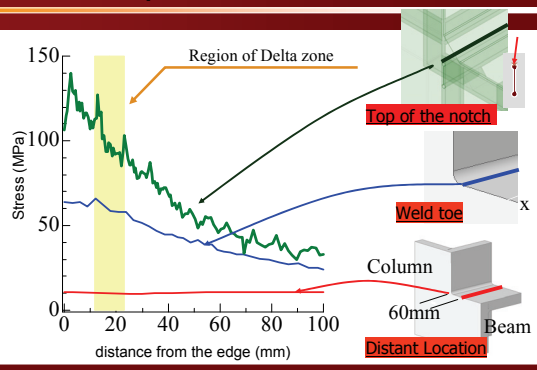
The Analysis Result



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