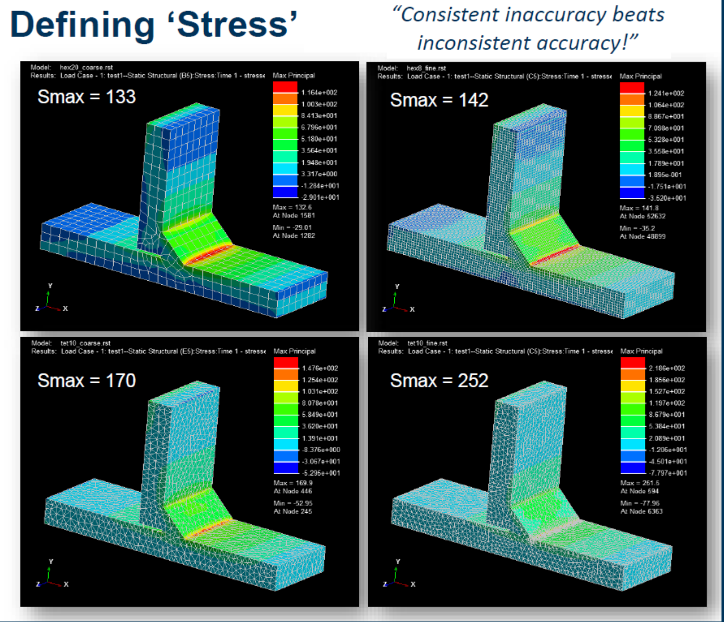
Virtual Seminar Series – Tuesday 2, 9, 16 November



Introducing Fatigue Testing and Fatigue Simulation of Structural Joints

Presented by Dr. Andrew Halfpenny
Director of Technology
Prenscia (HBK)

Tuesday, November 2, 2021

Introducing Fatigue Testing and Fatigue Simulation of Structural Joints

Abstract

A wide range of joints are used to assemble structures including welds, rivets, bolts, adhesives, between similar and dis-similar materials - metals, polymers and composites. These joints distribute load into or through the structure, and when these loads vary during operational use they introduce fatigue cycling at and close to the joint. The local geometry detail at the joint acts as a stress raiser reducing the fatigue strength at the joint. Any evaluation of the durability of the structure must therefore place a high priority on a fatigue assessment of the joints.

This presentation introduces fatigue of joints from their fatigue testing and supporting finite element analyses, through to their application in fatigue simulation analysis. Examples include welded joints (thin, thick, spot, seam, etc), brazed joints, bolted joints, adhesive joints, and self-piercing-rivet joints.

About the presenter, Dr. Andrew Halfpenny, Chief Technologist, Prenscia (HBK)

Dr. Halfpenny has a PhD in Mechanical Engineering from University College London (UCL) and a Masters' in Civil and Structural Engineering. With over 25 years of experience in structural dynamics, vibration, fatigue and fracture, he has introduced many new technologies to the industry including: FE-based vibration fatigue analysis, crack growth simulation and accelerated vibration testing. He holds a European patent for the 'Damage monitoring tag' and developed the new vibration standard used for qualifying UK military helicopters.

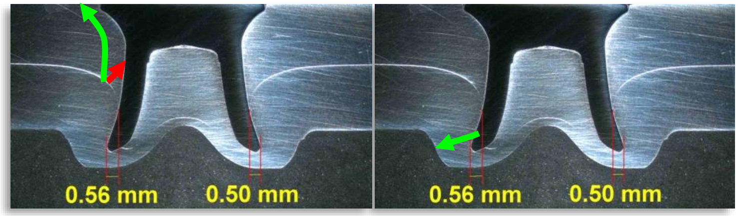
He has worked in consultancy with customers across the UK, Europe, Americas and the Far East, and has written publications on Fatigue, Digital Signal Processing and Structural Health Monitoring. He sits on the NAFEMS committee for Dynamic Testing and is a guest lecturer on structural dynamics with The University of Sheffield.

Introducing:
Fatigue Testing and Simulation of Structural Joints

Dr Andrew Halfpenny

Director of Technology – nCode Products

Agenda



JLR research on SPRs

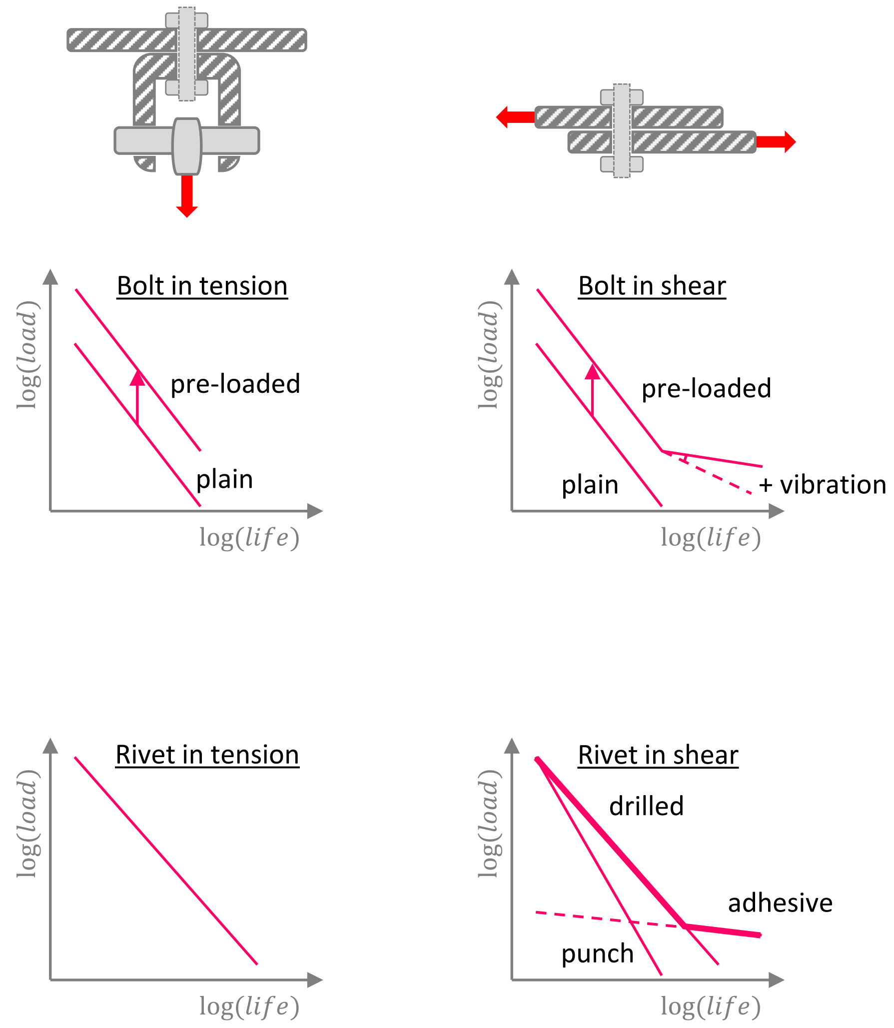
1. Joint Classification
   - Discrete (Fasteners) & Continuous (Welds & bonding)
   - Sketching SN curves & understanding their shape
2. Design Methods
   - Safety Factor vs. SN Curve vs. Fracture Mechanics
3. Fatigue Testing & Characterisation
   - Measuring Load vs. Life curves
   - Transforming Load vs. Life to 'Stress' vs. Life
4. In search of a Robust 'Stress' Parameter
   - Local vs. Nominal vs. Hot-spot Stresses
   - Stress (*Continuous*) vs. Load (*Discrete*) Recovery
5. Conclusion

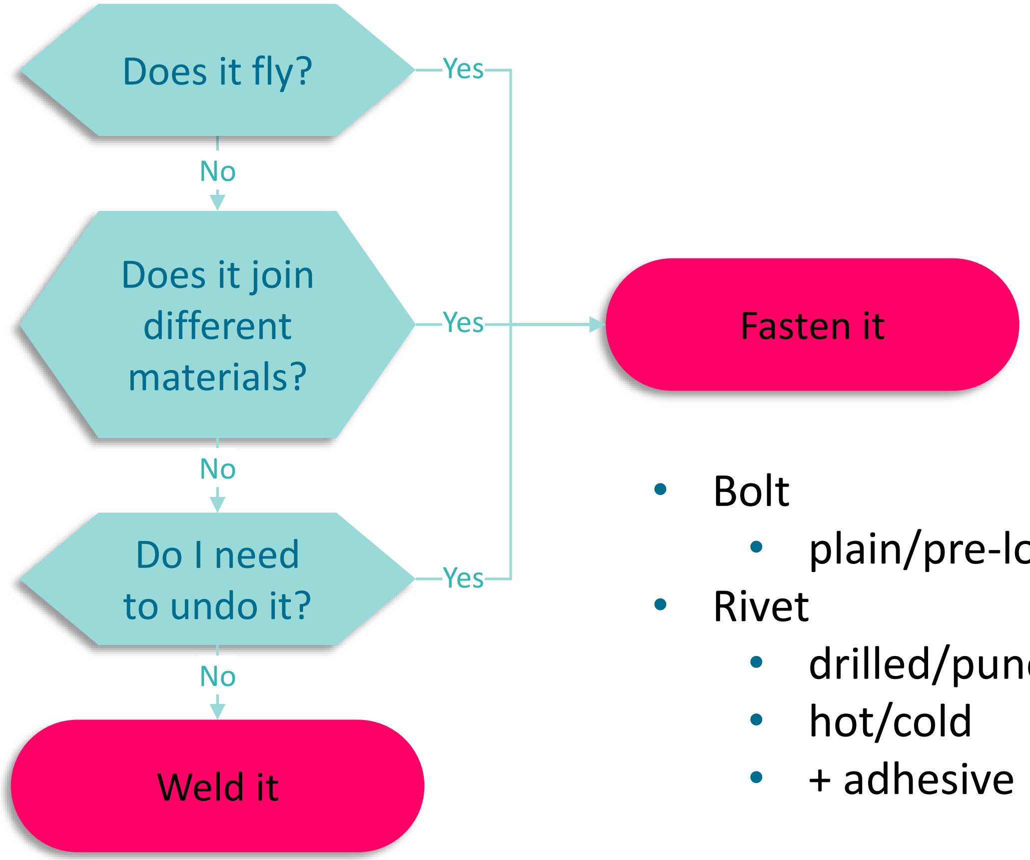
Hyundai RM15 Concept

HBK HOTTINGER BRÜEL & KJÆR

UNRESTRICTED

The olden days





- Bolt
  - plain/pre-loaded
- Rivet
  - drilled/punch
  - hot/cold
  - + adhesive

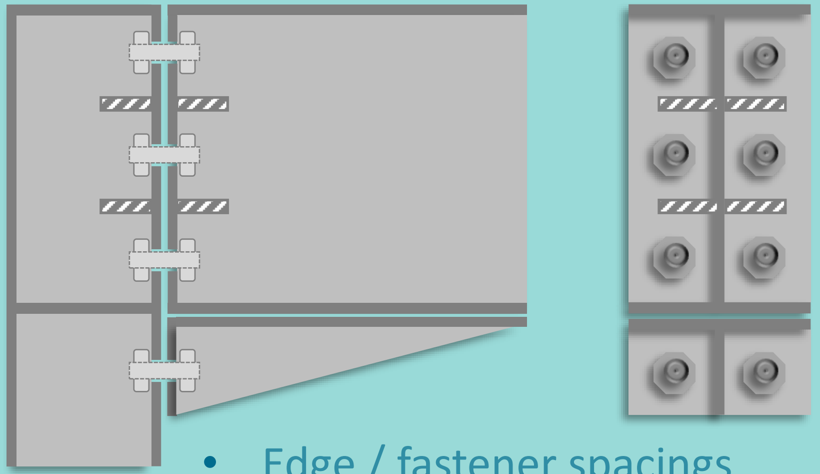
Shape of SN curve depends on the failure modes

- **Load type**: *axial vs. shear*
- **Secondary effects**: *mean stress & surface finish*
- **Additional load paths**: *additional friction*
- **Alternative failure modes**: *fastener/sheet (in shear or bearing)*

The olden days

Good practice:

Ensures a consistent failure mode by avoiding suboptimal failures



- Edge / fastener spacings
- Fastener vs. sheet thickness ratios
- Bearing stiffeners
- Butt straps
- etc…

Does it fly? — Yes → Fasten it; No ↓

Does it join different materials? — Yes → Fasten it; No ↓

Do I need to undo it? — Yes → Fasten it; No ↓

Weld it

Fasten it

- Bolt
  - plain/pre-loaded
- Rivet
  - drilled/punch
  - hot/cold
  - + adhesive

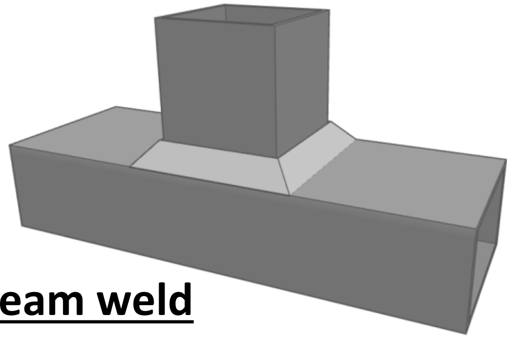
Shape of SN curve depends on the failure modes

- **Load type**: *axial vs. shear*
- **Secondary effects**: *mean stress & surface finish*
- **Additional load paths**: *additional friction*
- **Alternative failure modes**: *fastener/sheet (in shear or bearing)*

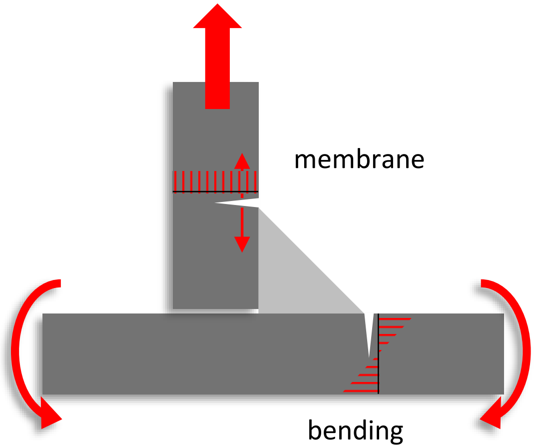
HBK HOTTINGER BRÜEL & KJÆR

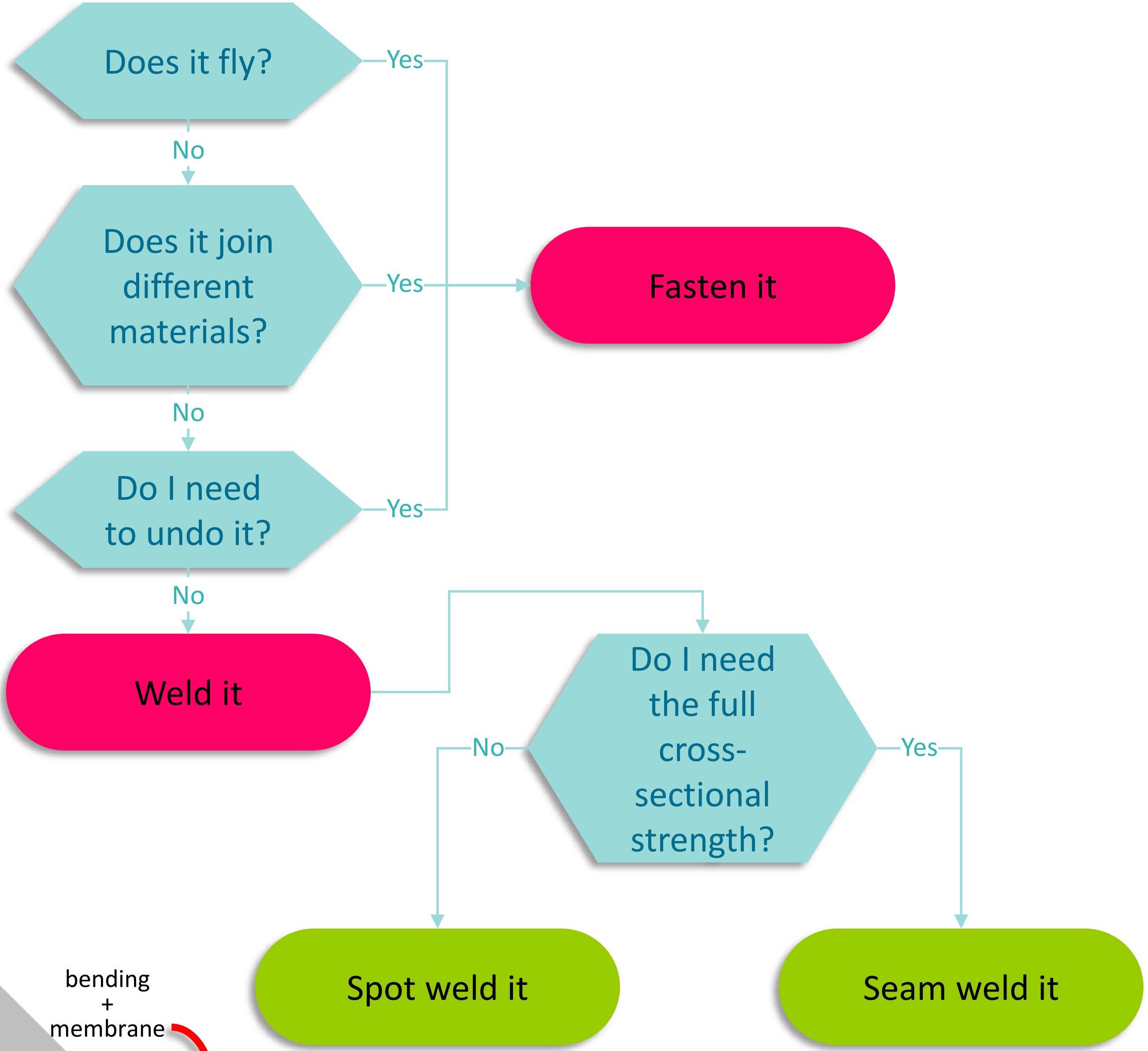
UNRESTRICTED

The olden days

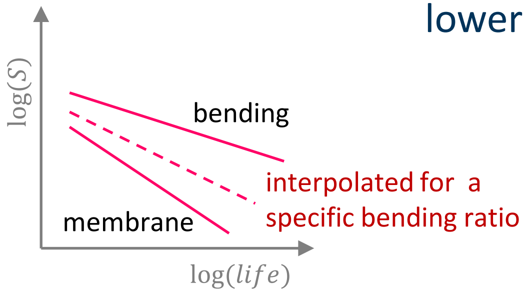


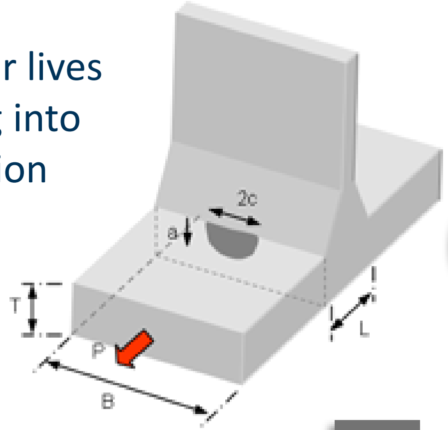
Seam weld



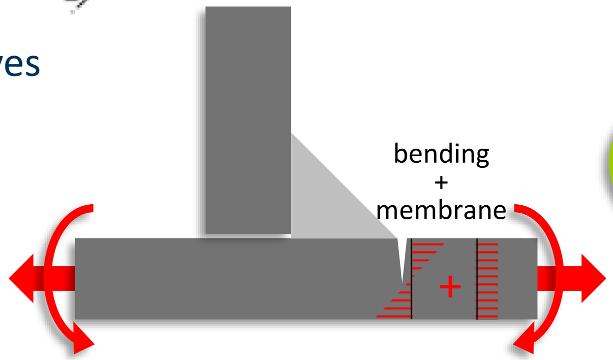


Bending = longer lives
∵ crack growing into lower stress region

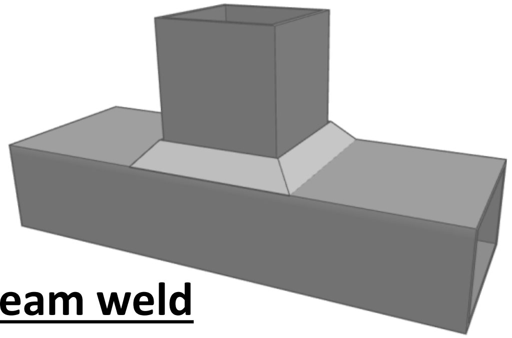




Membrane = shorter lives
∵ crack growing into uniform stress region

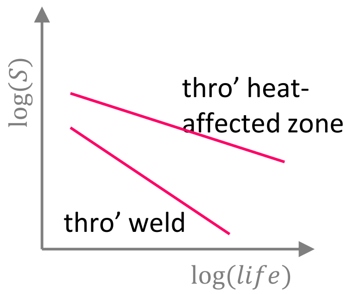


The olden days

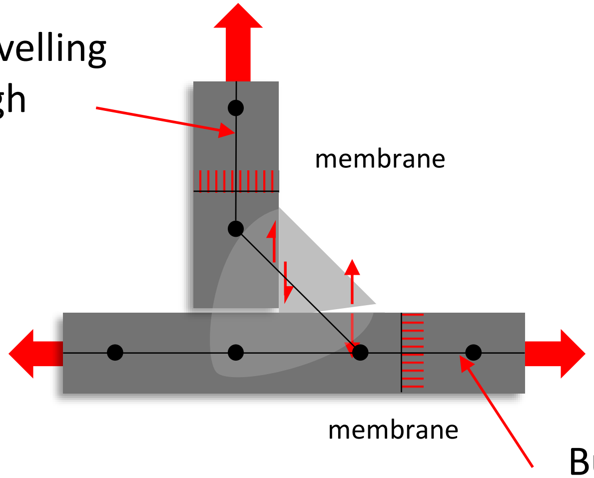


Seam weld

Load travelling thro' weld

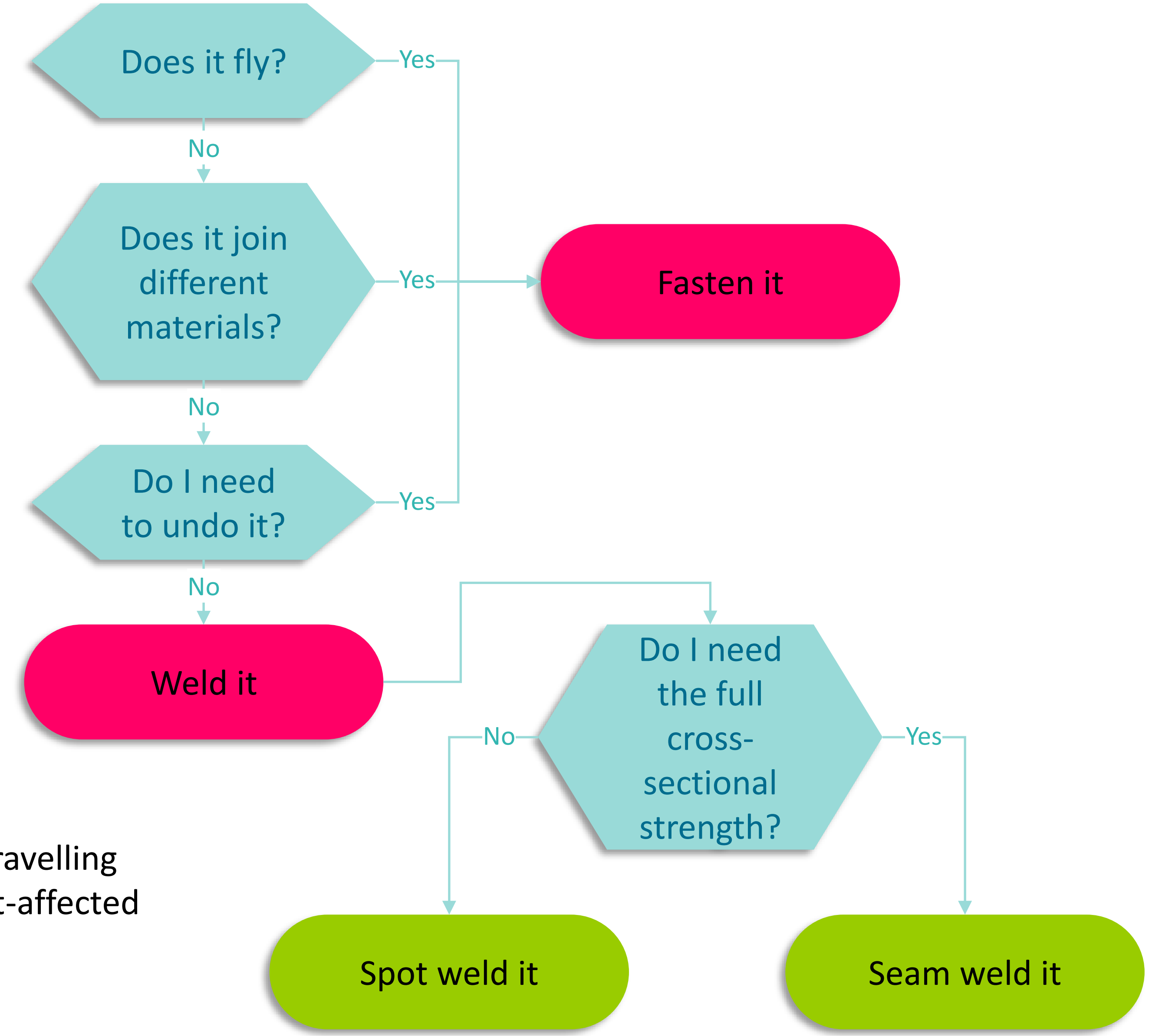


This load is travelling entirely through the weld



But this load is travelling through the heat-affected zone

We model this explicitly in FEA and capture the worst-case in the SN curve (load travelling entirely through the weld)

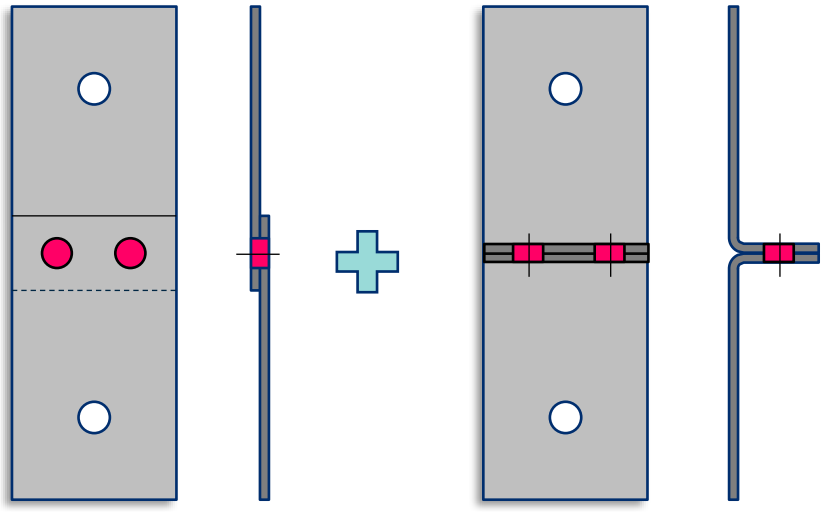


HBK HOTTINGER BRÜEL & KJÆR

UNRESTRICTED

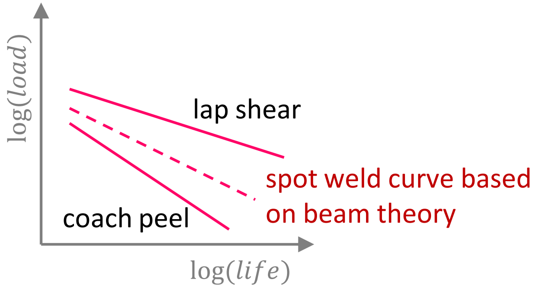
The olden days

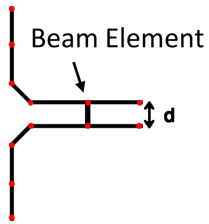
Spot weld



Lap shear joint

Coach peel joint





Equations to calculate structural stresses in the sheet

$$\Delta S(\theta) = -\sigma(F_x)\cos\theta - \sigma(F_y)\sin\theta + \sigma(F_x) + \sigma(M_x)\sin\theta + \sigma(M_y)\cos\theta$$

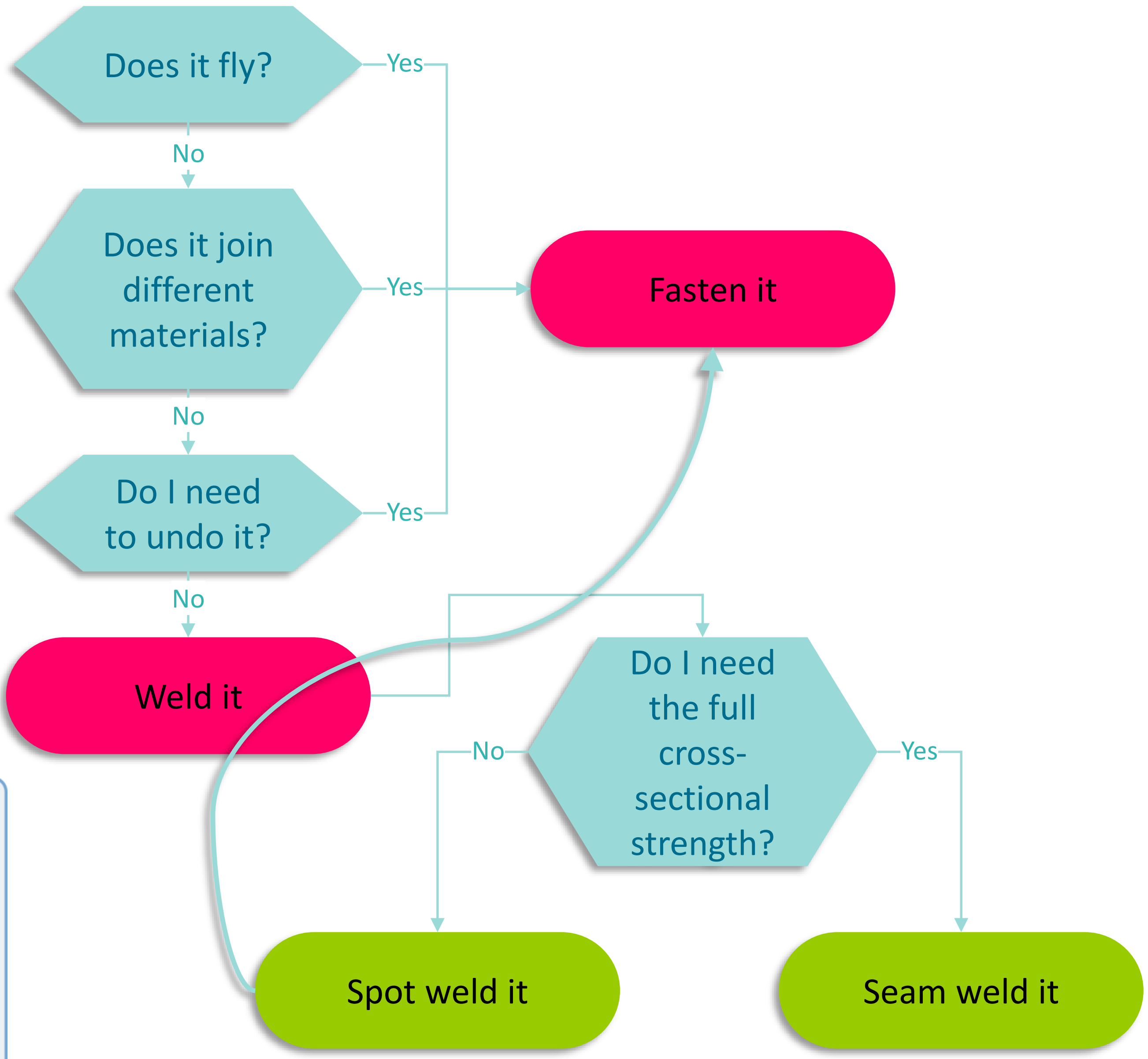
$$\sigma(F_x) = d^{DEFXY} \cdot t^{TEFXY} \frac{F_x}{\pi d t}$$

$$\sigma(F_y) = d^{DEFXY} \cdot t^{TEFXY} \frac{F_y}{\pi d t}$$

$$\sigma(F_z) = SFFZ \cdot d^{DEFZ} \cdot t^{TEFZ} \frac{1.744 F_z}{t^2}$$

$$\sigma(M_x) = SFMXY \cdot d^{DEMXY} \cdot t^{TEMXY} \frac{1.872 M_x}{d t^2}$$

$$\sigma(M_Y) = SFMXY \cdot d^{DEMXY} \cdot t^{TEMXY} \frac{1.872 M_Y}{d t^2}$$



HBK HOTTINGER BRÜEL & KJÆR

UNRESTRICTED

Summary so far – *Discrete vs. Continuous Joints*

Discrete

Fasten it

- Bolt
  - plain/pre-loaded
- Rivet
  - drilled/punch
  - hot/cold
  - + adhesive (hybrid joints)
  - pop rivets
  - self-piercing rivets (SPRs)

Discrete or Continuous

- Spot welds
- Adhesives joints (current method)
- Other mechanical fastenings

Weld it

Continuous

- Seam welds
  - butt welds
  - fillet welds
- Adhesive (bonded) joints
  - metals
  - composites
  - dissimilar materials

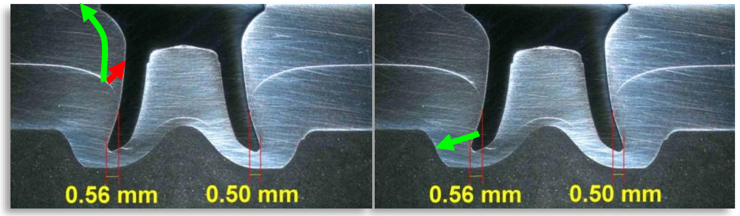
Olden days
New stuff

Shape of SN curve depends on the failure modes

- **Load type**: *axial vs. shear or membrane vs. bending*
- **Secondary effects**: *mean stress & surface finish (+ thickness effects)*
- **Additional load paths**: *additional friction (hybrid joints)*
- **Alternative failure modes**: *fastener / sheet or sheet / nugget*

HBK HOTTINGER BRÜEL & KJÆR

Agenda

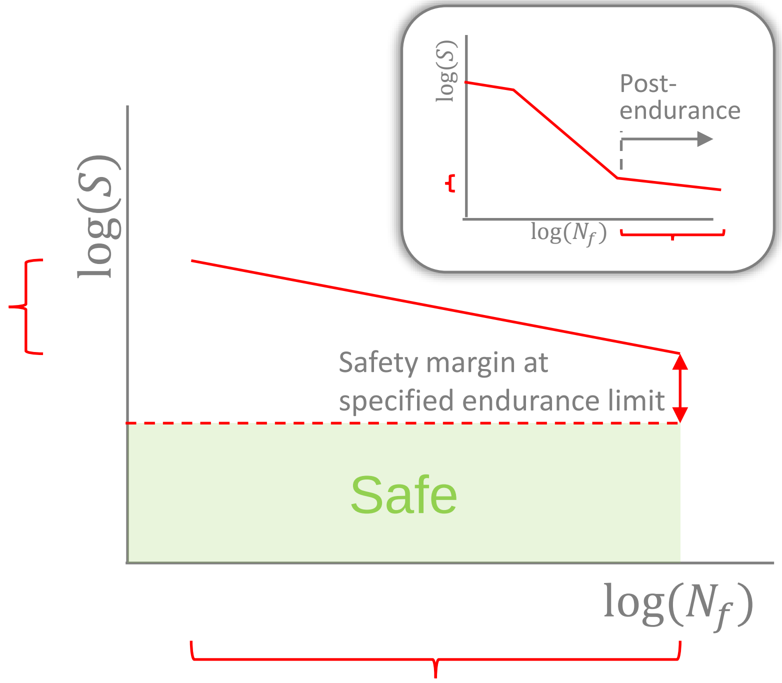


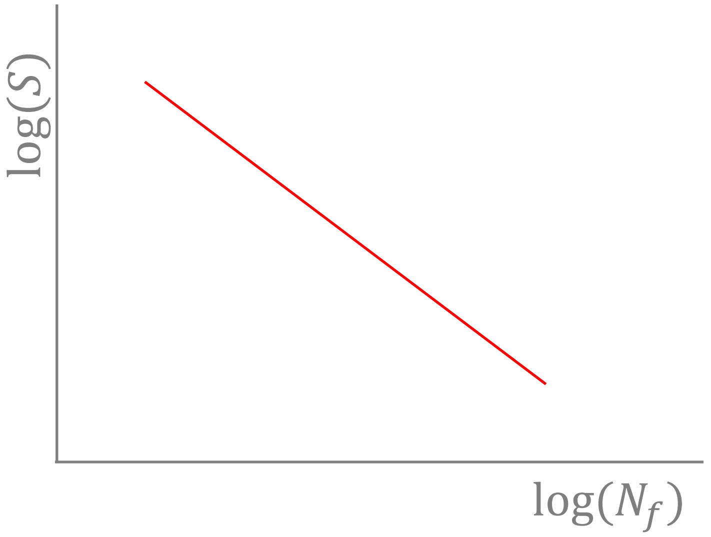
JLR research on SPRs

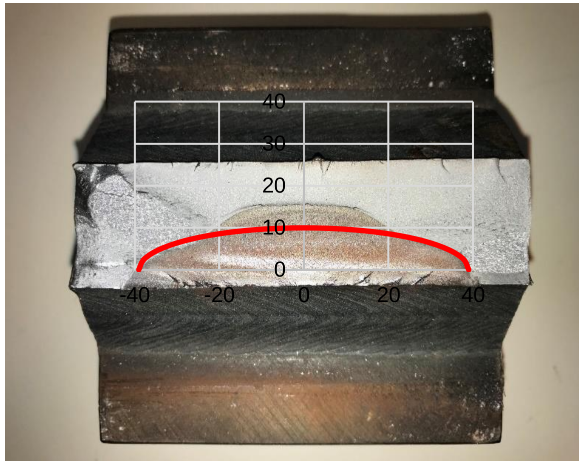
1. Joint Classification
    - Discrete (Fasteners) & Continuous (Welds & bonding)
    - Sketching SN curves & understanding their shape
2. Design Methods
    - Safety Factor vs. SN Curve vs. Fracture Mechanics
3. Fatigue Testing & Characterisation
    - Measuring Load vs. Life curves
    - Transforming Load vs. Life to ‘Stress’ vs. Life
4. In search of a Robust ‘Stress’ Parameter
    - Local vs. Nominal vs. Hot-spot Stresses
    - Stress (*Continuous*) vs. Load (*Discrete*) Recovery
5. Conclusion

Hyundai RM15 Concept

Safety factor *vs.* SN *vs.* Crack growth modelling







WholeLife

Safety factor approach

- Use when SN curve is flat
- Much better resolution in stress than life
- Ideal for traditional adhesive joints (brittle behaviour)
- Ideal if there's post-endurance behaviour (very high-cycle)

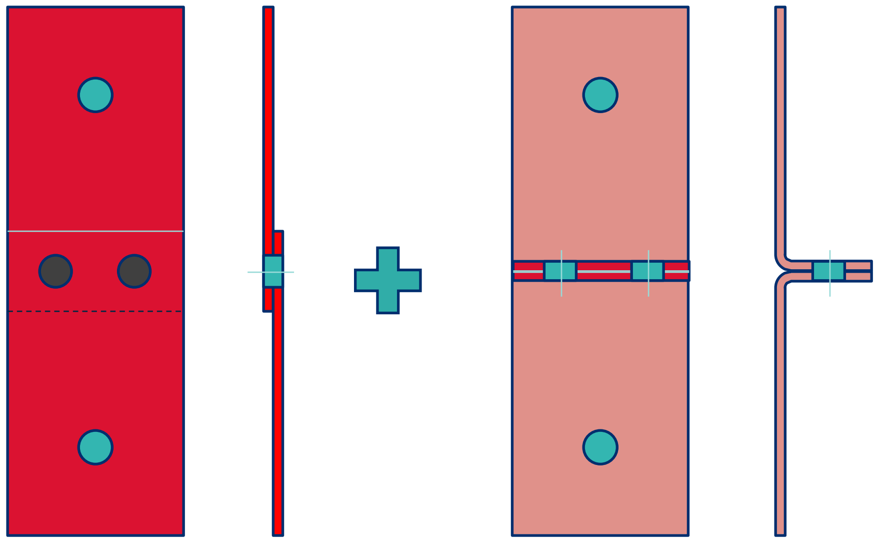
SN approach

- Use when SN curve is steep
- Good resolution in life and stress, but life is more intuitive for durability/reliability targets
- Ideal for joints in metals and composites
- Ideal for some modern adhesives (ductile behaviour)

Fracture mechanics approach

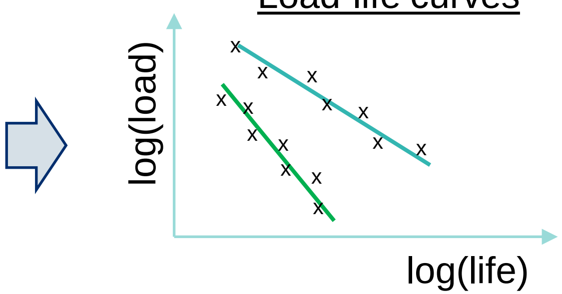
- Use when there's significant crack growth through a complex stress field
- Life based on crack growth modelling is the most accurate
- Ideal for 'designed welds' (i.e. dressed, stress relieved, built-up)
- Ideal for damage tolerant structures

Fatigue testing and characterization (curve-fitting)



Lap shear test coupons
(predominantly membrane)

Coach peel test coupons
(predominantly bending)



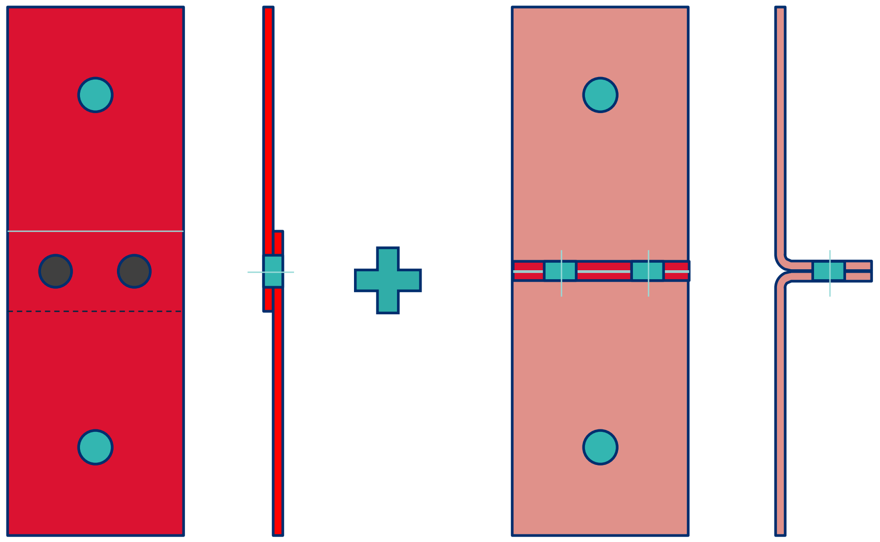
But we need 'Stress' – life curves!

How to get them?

Specimen joints must be as close as possible to production

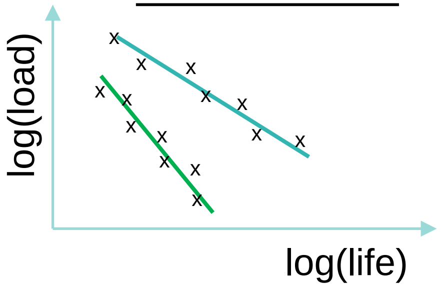
- Similar geometries (butt, fillet weld, etc)
- Similar penetration for welds
- Similar production quality
- Similar material thicknesses *(may derive an explicit factor)*
- etc.

Fatigue testing and characterization (curve-fitting)



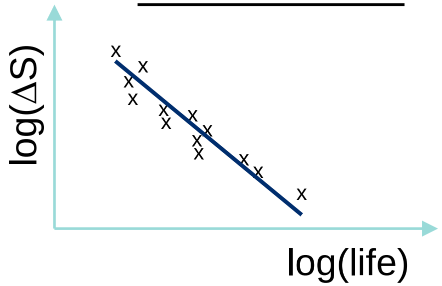
Lap shear test coupons
(predominantly membrane)

Coach peel test coupons
(predominantly bending)

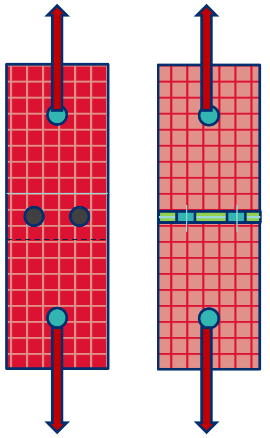


The final conundrum:

What is 'Stress'



Use the same FE meshing, analysis methods & stress recovery methods as the customer



FEA analysis

Equations to calculate structural stresses in the sheet

$$\Delta S(\theta) = -\sigma(F_x)\cos\theta - \sigma(F_y)\sin\theta + \sigma(F_z) + \sigma(M_x)\sin\theta + \sigma(M_y)\cos\theta$$

$$\sigma(F_x) = d^{DEFXY} \cdot t^{TEFXY} \frac{F_x}{\pi d t}$$

$$\sigma(F_y) = d^{DEFXY} \cdot t^{TEFXY} \frac{F_y}{\pi d t}$$

$$\sigma(F_z) = SFFZ \cdot d^{DEFZ} \cdot t^{TEFZ} \frac{1.744 F_z}{t^2}$$

$$\sigma(M_x) = SFMXY \cdot d^{DEMXY} \cdot t^{TEMXY} \frac{1.872 M_x}{d t^2}$$

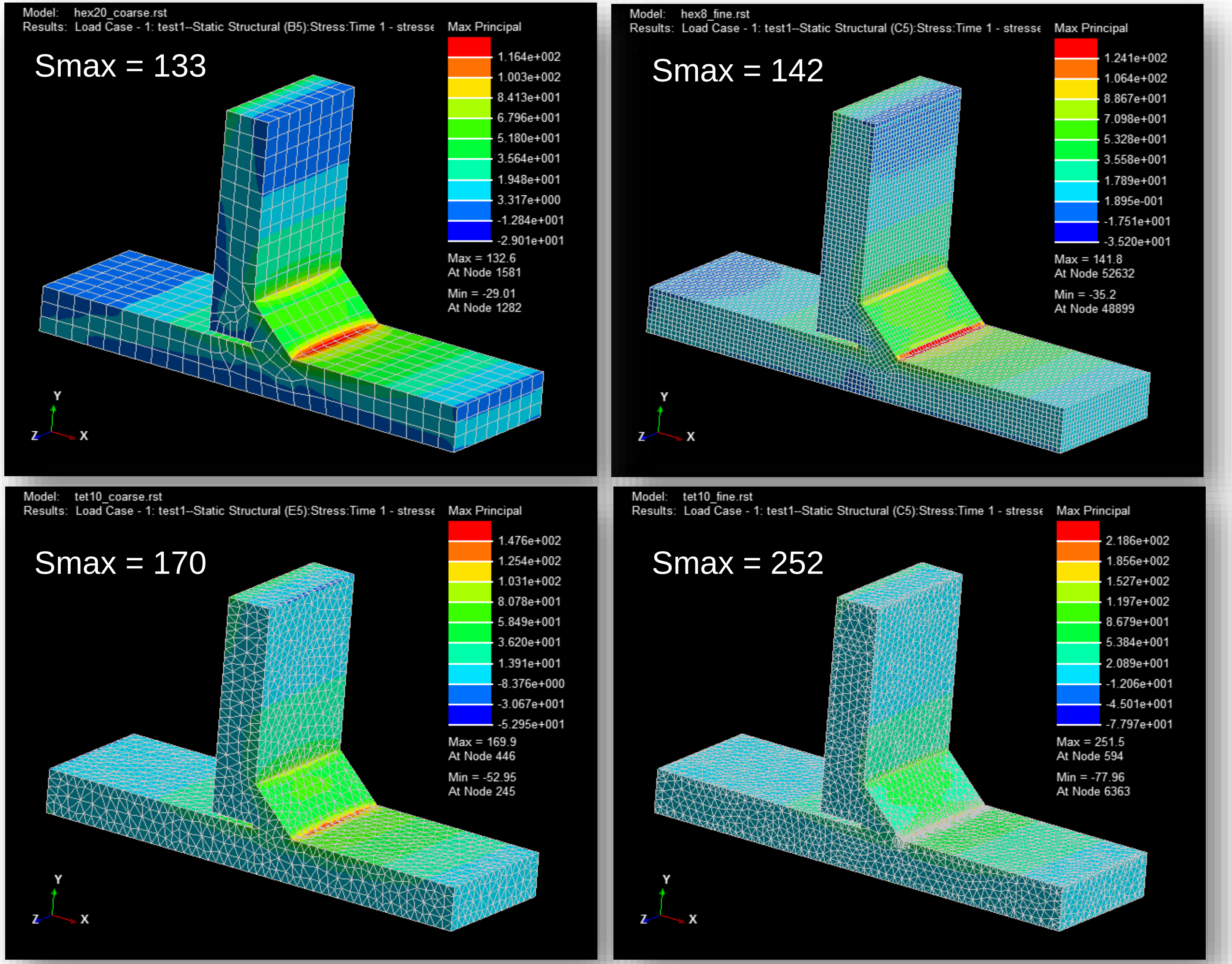
$$\sigma(M_y) = SFMXY \cdot d^{DEMXY} \cdot t^{TEMXY} \frac{1.872 M_y}{d t^2}$$

Optimizer

Component	Factor	Diameter Exponent	Thickness Exponent
FX, FY	SFFXY = 1.0	DEFXY = 0.0	TEFXY = 0.0
MX, MY	SFMXY = 0.6	DEMXY = 0.0	TEMXY = 0.5
FZ	SFFZ = 0.6	DEFZ = 0.0	TEFZ = 0.5

HBK HOTTINGER BRÜEL & KJÆR

Defining 'Stress' – *Local stress* vs. *Nominal stress* vs. *Hotspot stress*



<u>Requirements for the 'Stress' parameter</u>

- Robust estimate of 'stress' consistent with:
  - avoiding mesh singularities
  - uncertainties in surface quality/finish
  - uncertainties in residual stresses
  - joint-joint statistical variability
  - natural scatter of fatigue test results

- 'Stress' parameter must be **consistent** between structure mesh and coupon mesh (i.e. same mesh guidelines)

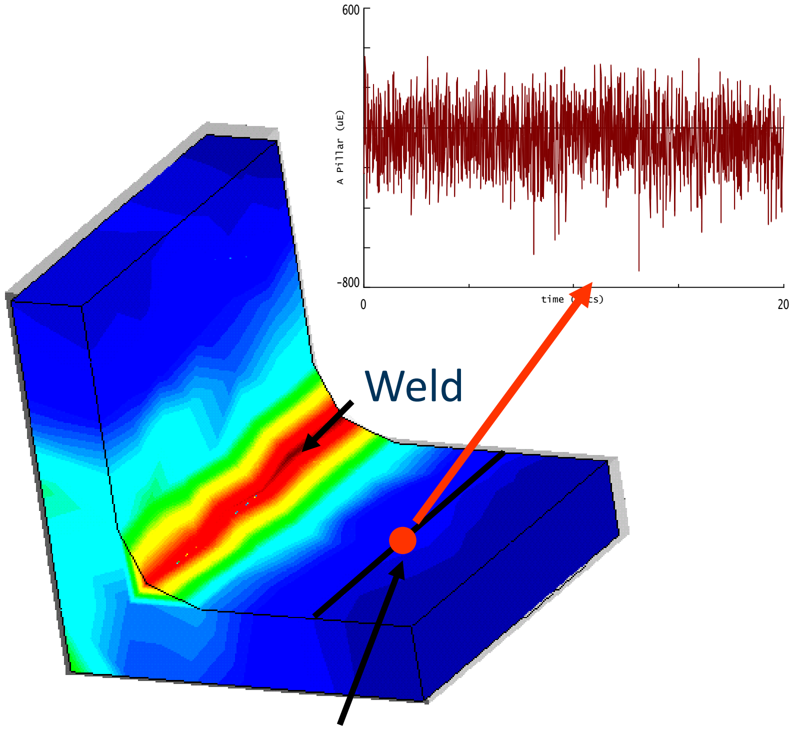
"Consistent inaccuracy beats inconsistent accuracy!"

Examples showing how critical stress changes with mesh

HOTTINGER BRÜEL & KJÆR

Defining ‘Stress’ – *Local stress* vs. *Nominal stress* vs. *Hotspot stress*

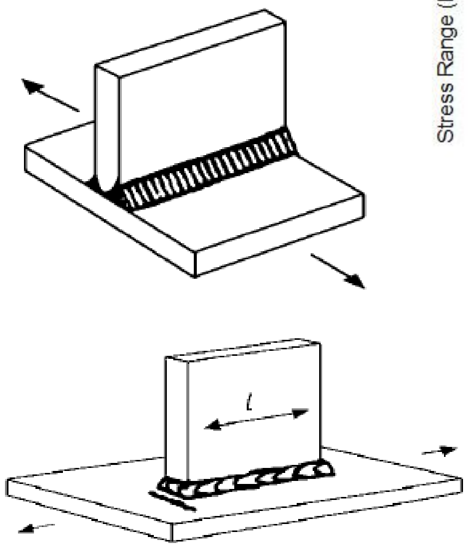
‘Stress’ definition

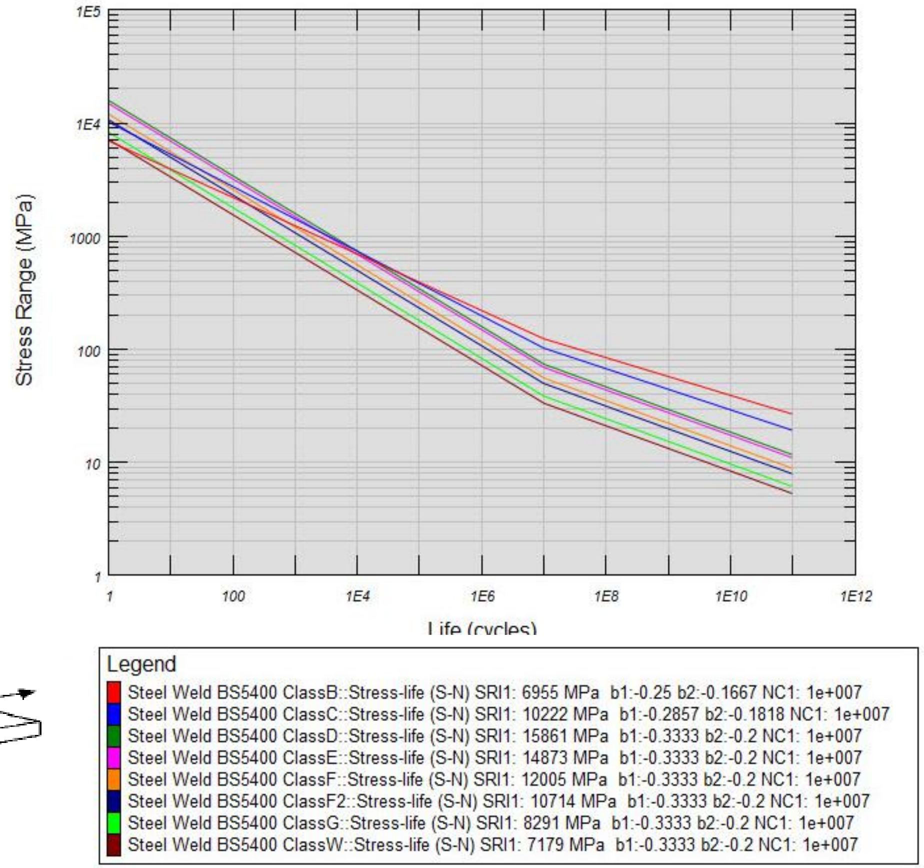


Position strain gauge at least 1 gauge length from root to reduce stress averaging

‘Stress’ vs. life relationship

- Maintain a consistent definition of ‘stress’





- Choosing a weld class or classes for the joint considering:
  - Joint geometry (butt, fillet, etc.)
  - Loading direction and mode
  - Failure location to be considered
  - Type of weld (full penetration etc.)

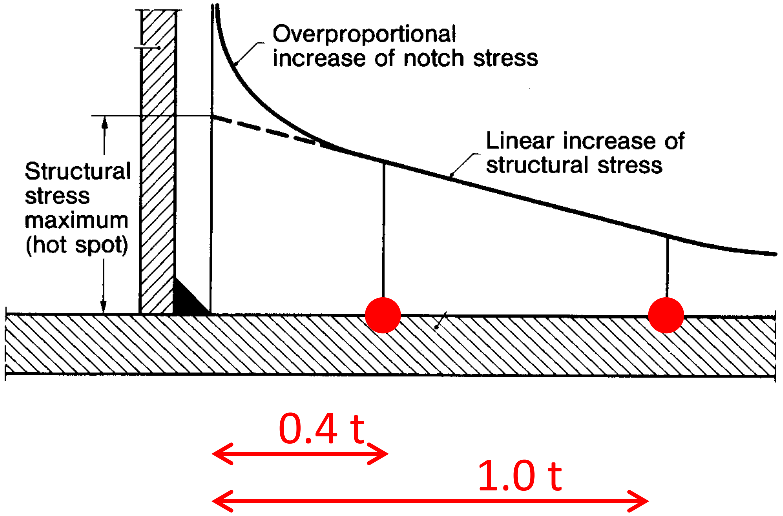
Very constraining!

BSI, IIW, Eurocode

HBK HOTTINGER BRÜEL & KJÆR

Defining ‘Stress’ – *Local stress* vs. *Nominal stress* vs. *Hotspot stress*

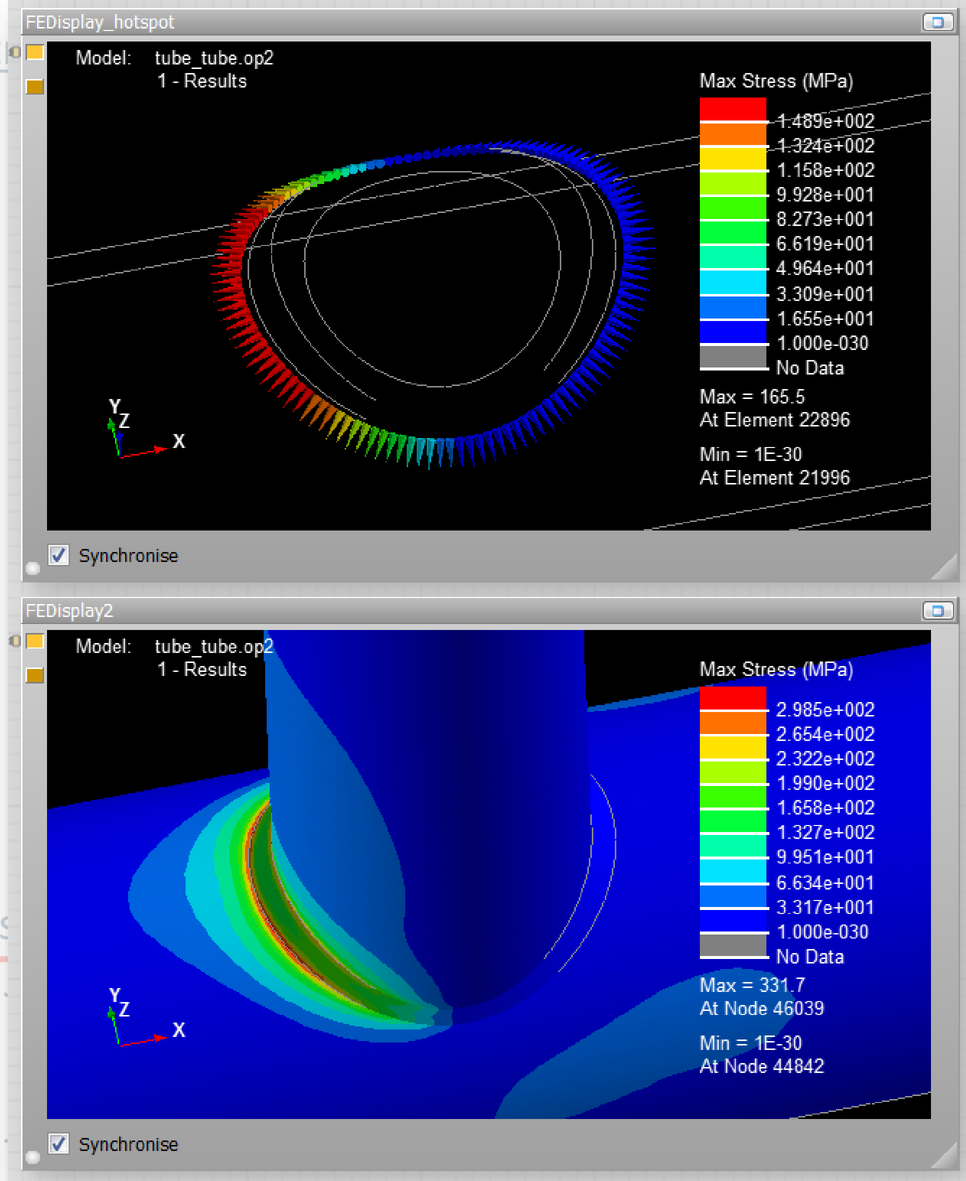
‘Stress’ definition



Surface Stress Extrapolation

‘Surface Hotspot stress’

- mitigates constraints
  - ratio of thickness (IIW type a)
  - actual distance (IIW type b)
  - linear & parabolic extrapolations
- so DesignLife can be compatible with standard weld SN curves

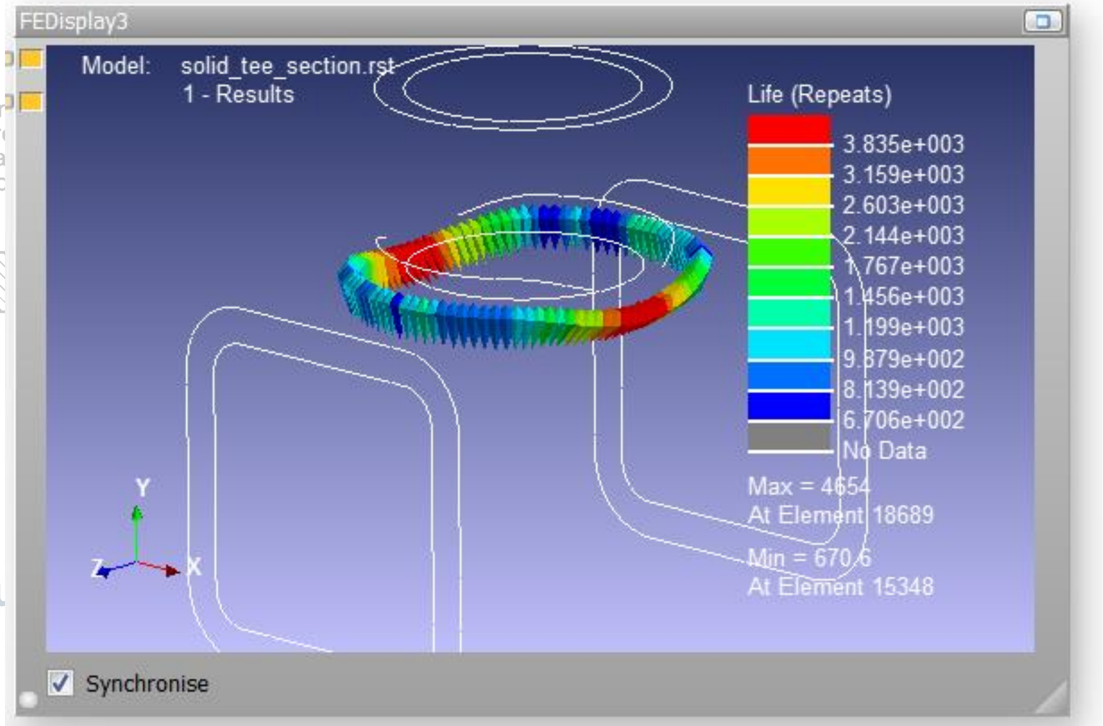


HBK HOTTINGER BRÜEL & KJÆR

UNRESTRICTED

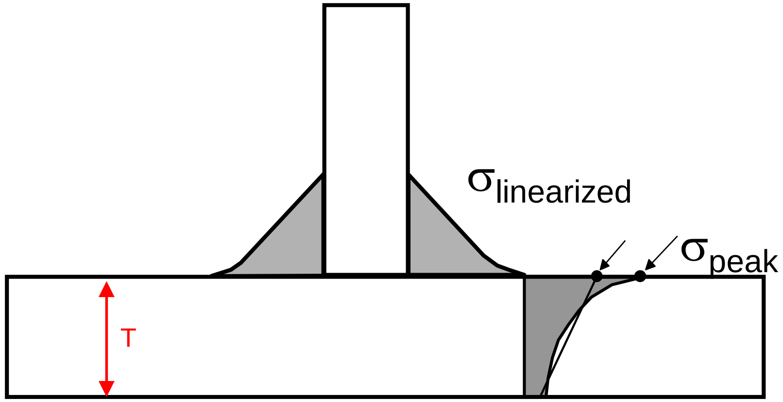
Defining 'Stress' – *Local stress vs. Nominal stress vs. Hotspot stress*

'Stress' definition



- actual distance (IIW type b)
- linear & parabolic extrapolations
- so DesignLife can be compatible with standard weld SN curves

Alternative 'Hotspot Stress' definition



Through-thickness Stress Extrapolation

'Through-thickness Hotspot stress'

- eliminates impact of mesh singularities

$$\sigma_{linearized} = \sigma_m + \sigma_b = \frac{P}{A} + \frac{MT}{2I}$$

- different to 'Surface Hotspot Stress' so needs different SN curve (consistency)

HBK HOTTINGER BRÜEL & KJÆR

Defining 'Stress' – *through a fastener*

Spot welds & fasteners (rivets, SPRs, bolts, etc.)

Method 1 – continuous 'stress' recovery method

- As previous slides (e.g. treat spot weld as a small seam weld)

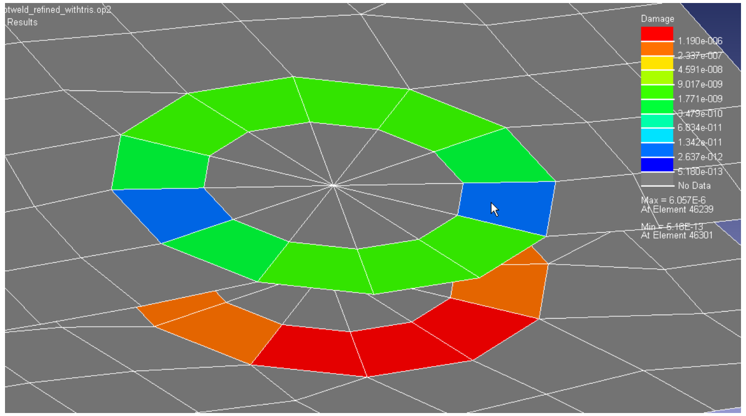
Method 2 – discrete load/displacement recovery method

Pros.

- Ideal for course mesh models (load transfer)
- load/displacement is converted to 'stress' using an engineering model external to FEA
- Reduced dependency on FEA package[1]
- Many opportunities for stress model improvements (e.g. thickness corrections, multiple failure modes, critical plane analysis, etc.)

Cons.

- Multiple non-standard meshing methods
- Complexity of meshing (e.g. need for concentric meshes, etc.)
- Issues with over-stiffening of meshes
- Different methods on different FEA packages[1]

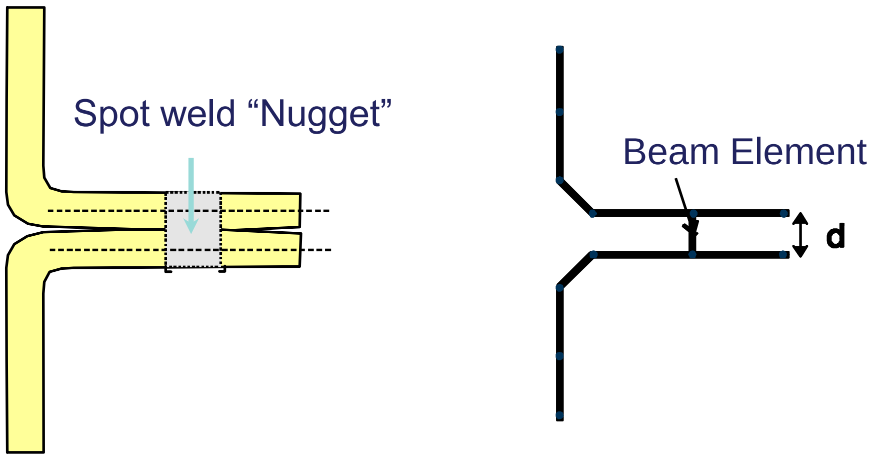


HOTTINGER BRÜEL & KJÆR

UNRESTRICTED

Defining ‘Stress’ – *through a fastener*

Spot welds & fasteners (rivets, SPRs, bolts, etc.)



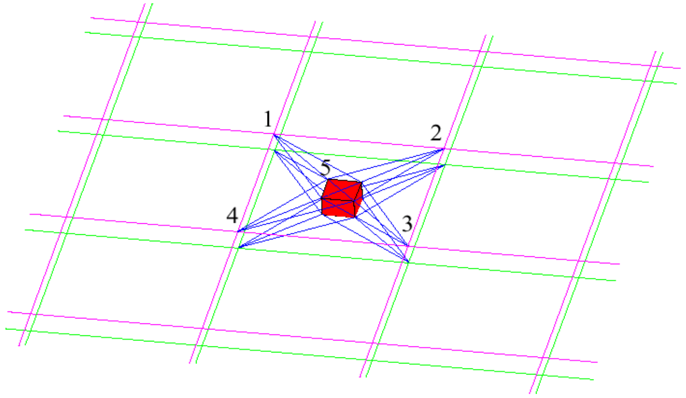
Method 1 – **continuous** ‘stress’ recovery method

- As previous slides (e.g. treat spot weld as a small seam weld)

Method 2 – **discrete** load/displacement recovery method

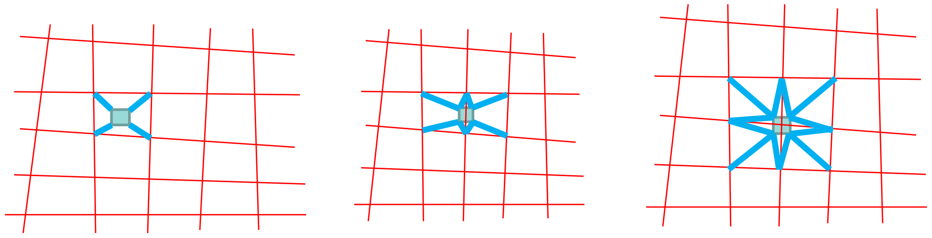
<u>*Pros.*</u>

- Ideal for course mesh models (load transfer)
- load/displacement is converted to ‘stress’ using an engineering model external to FEA
- Reduced dependency on FEA package[1]
- Many opportunities for stress model improvements (e.g. thickness corrections, multiple failure modes, critical plane analysis, etc.)



<u>*Cons.*</u>

- Multiple non-standard meshing methods
- Complexity of meshing (e.g. need for concentric meshes, etc.)
- Issues with over-stiffening of meshes
- Different methods on different FEA packages[1]



Defining ‘Stress’ – *through a fastener*

Calculation of engineering stresses in a sheet based on forces $F_x, F_y, F_z, M_x, M_y, M_z$ obtained from the fastener reaction loads:

$$\left.\begin{aligned}\sigma_{F_x} &= \\ \sigma_{F_y} &= \end{aligned}\right\} \frac{F_{xy}}{\pi d s}\left(S_{F_{xy}}\right)\left(d^{D_{F_{xy}}}\right)\left(s^{T_{F_{xy}}}\right)$$

$$\sigma_{F_z} = 1.744\frac{F_z}{s^2}\left(S_{F_z}\right)\left(d^{D_{F_z}}\right)\left(s^{T_{F_z}}\right)$$

$$\left.\begin{aligned}\sigma_{M_x} &= \\ \sigma_{M_y} &= \end{aligned}\right\} 1.872\frac{M_{xy}}{d s^2}\left(S_{M_{xy}}\right)\left(d^{D_{M_{xy}}}\right)\left(s^{T_{M_{xy}}}\right)$$

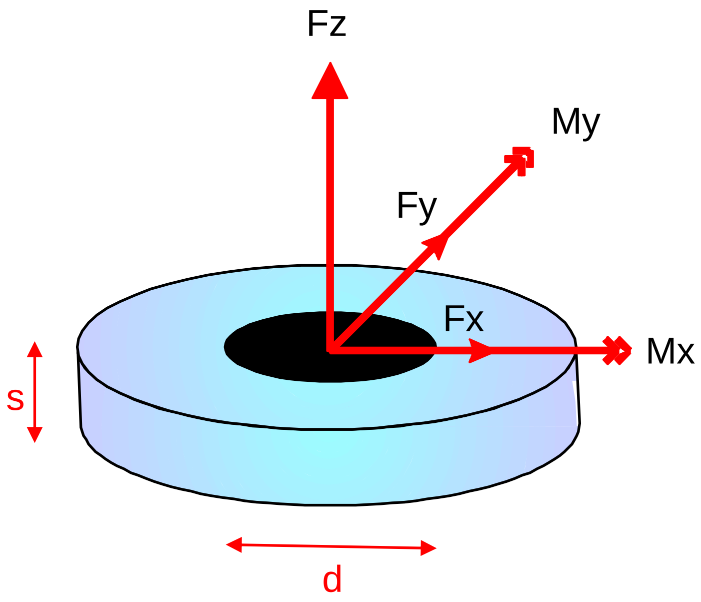
$$\sigma_{M_z} = \frac{2}{\pi s d^2}$$

Table 1: Transform coefficients used for steel sheets:

Component	Factor	Diameter exponent	Thickness exponent
F_x, F_y	$S_{F_{xy}} = 1.0$	$D_{F_{xy}} = 0$	$T_{F_{xy}} = 0$
M_x, M_y	$S_{M_{xy}} = 0.6$	$D_{M_{xy}} = 0$	$T_{M_{xy}} = 0.5$
F_z	$S_{F_z} = 0.6$	$D_{F_z} = 0$	$T_{F_z} = 0.5$

Table 2: Transform coefficients used for aluminium sheets:

Component	Factor	Diameter exponent	Thickness exponent
F_x, F_y	$S_{F_{xy}} = 0.4$	$D_{F_{xy}} = 0.5$	$T_{F_{xy}} = -0.25$
M_x, M_y	$S_{M_{xy}} = 0.4$	$D_{M_{xy}} = 0.5$	$T_{M_{xy}} = -0.25$
F_z	$S_{F_z} = 1.0$	$D_{F_z} = 0$	$T_{F_z} = 1.0$



Engineering ‘stress’ model for Spotweld fastener

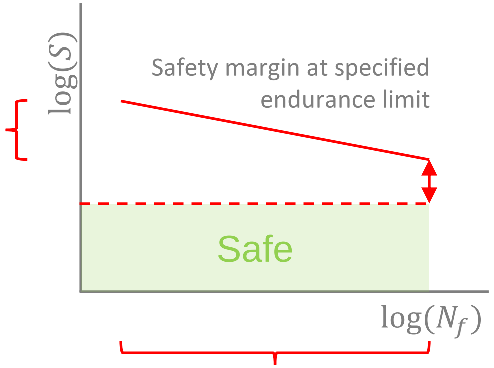
- Critical-plane calculation
- Correction factors available for relative scale, diameter and thickness
- Additional calculation for ‘nugget’ failure
- Additional calculation for 3-sheet joints

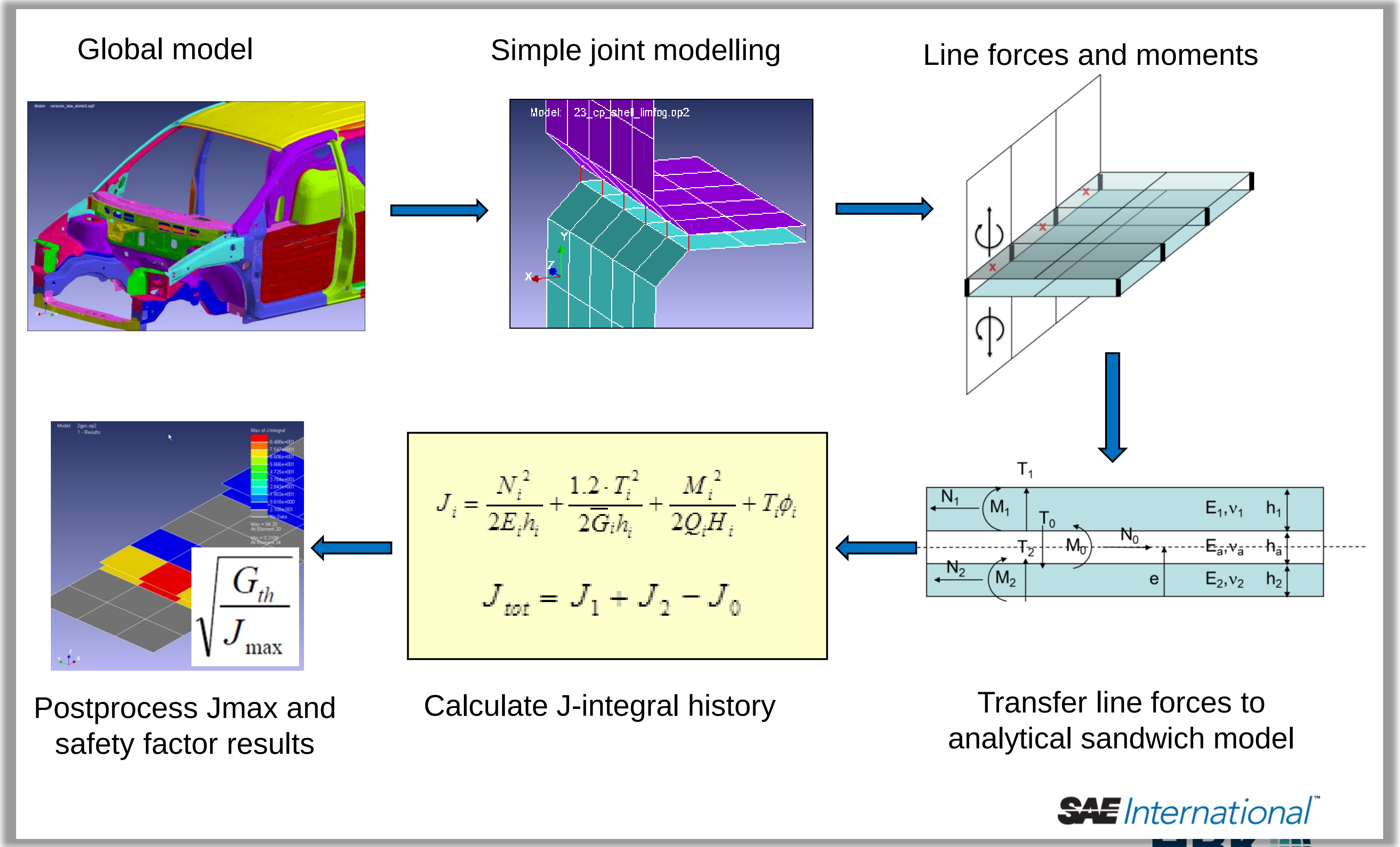
This versatile model has also been used for other fasteners (e.g. bolts, rivets and SPRs)
But DesignLife also allows user-defined models

HBK
HOTTINGER BRÜEL & KJÆR

Defining 'Stress' – *through an adhesive bond – current approach*

This method recovers edge loads from an adhesive bond using beam elements and calculates the J integral for use as a safety factor analysis against J_{1c}





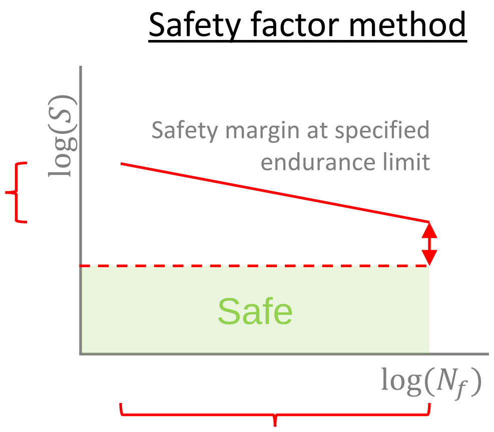
HBK HOTTINGER BRÜEL & KJÆR

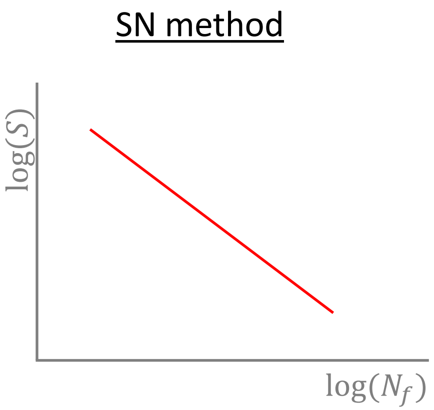
UNRESTRICTED

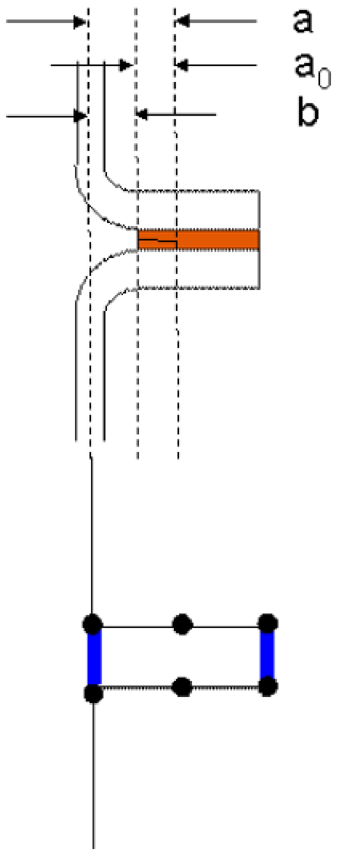
Defining 'Stress' – *through an adhesive bond – future approach*

Future work:

- FEA packages now offer adhesive elements so the need for beam elements (& concentric meshes) is removed
- Many newer adhesives behave in a ductile manner so an SN method is preferred over the safety factor
- Adhesive bonds fail through fracture ∴ research fracture mechanics approach

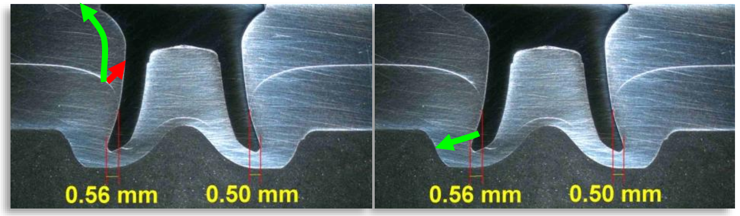






HBK HOTTINGER BRÜEL & KJÆR

Agenda



JLR research on SPRs

1. Joint Classification
    - Discrete (Fasteners) & Continuous (Welds & bonding)
    - Sketching SN curves & understanding their shape
2. Design Methods
    - Safety Factor vs. SN Curve vs. Fracture Mechanics
3. Fatigue Testing & Characterisation
    - Measuring Load vs. Life curves
    - Transforming Load vs. Life to ‘Stress’ vs. Life
4. In search of a Robust ‘Stress’ Parameter
    - Local vs. Nominal vs. Hot-spot Stresses
    - Stress (*Continuous*) vs. Load (*Discrete*) Recovery
5. Conclusion

Hyundai RM15 Concept

HBK HOTTINGER BRÜEL & KJÆR

UNRESTRICTED

Conclusion – *Discrete* vs. *Continuous Joints*

Discrete

Fasten it

- Bolt
  - plain/pre-loaded
- Rivet
  - drilled/punch
  - hot/cold
  - + adhesive (hybrid joints)
  - pop rivets
  - self-piercing rivets (SPRs)

Discrete or Continuous

- Spot welds
- Adhesives joints (current method)
- Other mechanical fastenings

Weld it

Continuous

- Seam welds
  - butt welds
  - fillet welds
  - spot welds
- Adhesive (bonded) joints
  - metals
  - composites
  - dissimilar materials

Olden days
New stuff

'Stress' parameter (load/displacement recovery)

- Load-transfer mesh
- Convert 'Load' to 'engineering stress'
- Versatile method already included in DesignLife, but also user-programmable

'Stress' parameter (mesh insensitive stress recovery)

- Local vs. Nominal vs. Hot spot stresses (surface / through-thickness)
- Same mesh guidelines / analysis methods for fatigue curve fitting as in component design

"Consistent inaccuracy beats inconsistent accuracy!"

HBK HOTTINGER BRÜEL & KJÆR

Q & A

HOTTINGER BRÜEL & KJÆR

Thank You

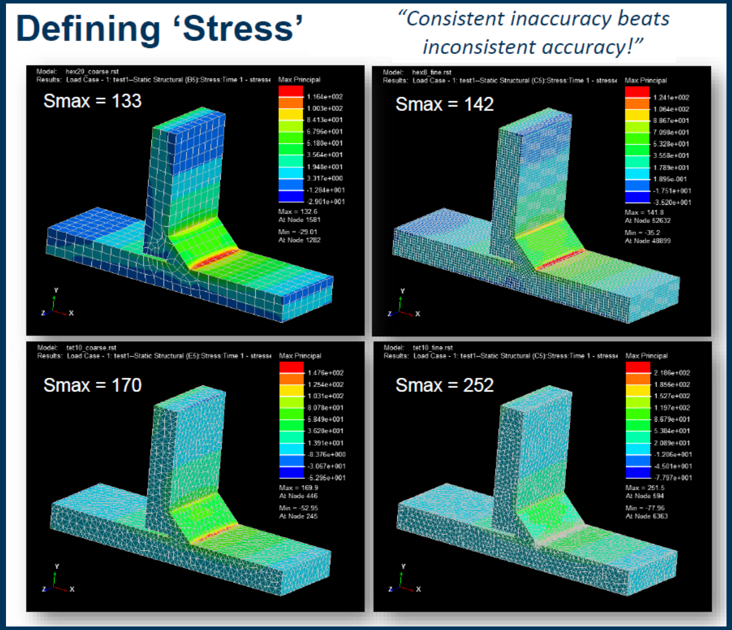
Dr Andrew Halfpenny | Director of Technology – nCode Products

andrew.halfpenny@hbkworld.com

Q&A

- (no questions)

Virtual Seminar Series – Tuesday 2, 9, 16 November



Introducing Fatigue Testing and Fatigue Simulation of Structural Joints

Presented by Dr. Andrew Halfpenny
Director of Technology
Prenscia (HBK)

Tuesday, November 2, 2021