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Calculating Fatigue in Welded Structures

EIS 24th Jan 2018

nCode

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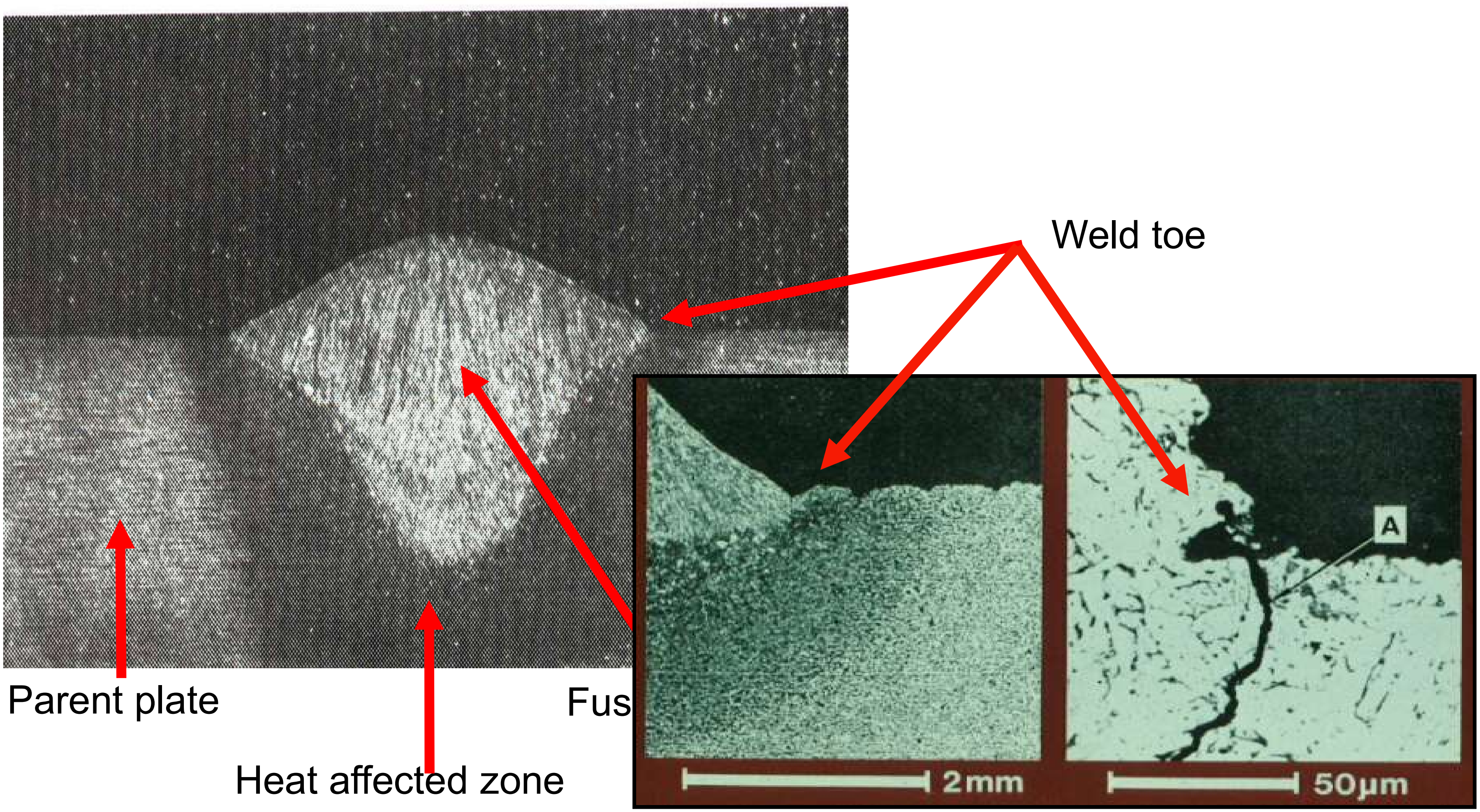
Agenda – EIS 24th Jan 2018

- Brief background to fatigue analysis of welded structures
    - What is a weld?
- Thin wall vs thick walled structures
    - Standard approaches e.g. BS7608 & Eurocode
        - FE / hand-calc / strain gauges
    - “Volvo” method based on shell elements (FE)
- Methods of stress recovery for weld fatigue analysis
    - Stress Recovery vs SN fatigue curves
    - Fatigue Limits & Thresholds
- Fracture Mechanics – Crack Growth

Background

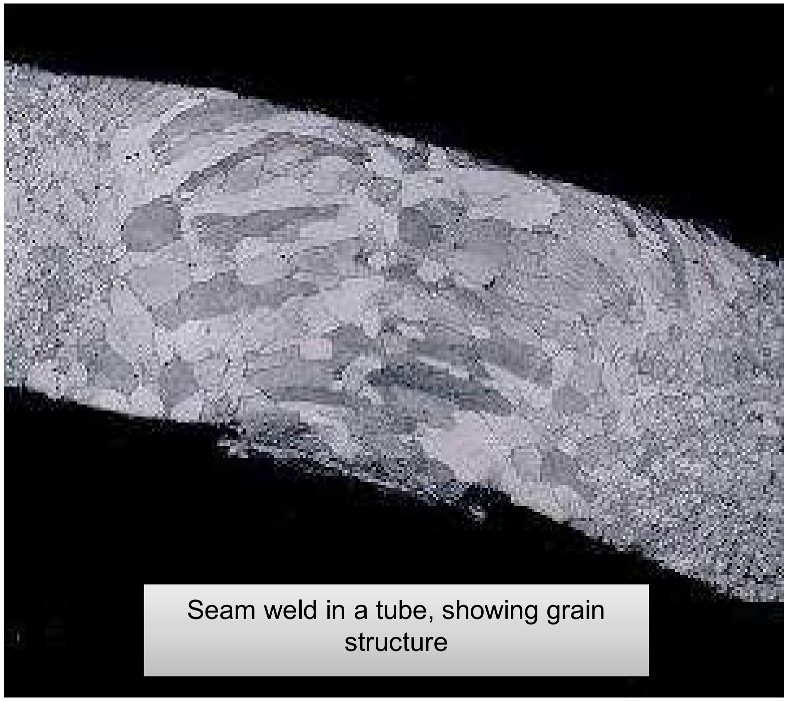
Fatigue analysis of welded structures

Effect of Welding on Durability



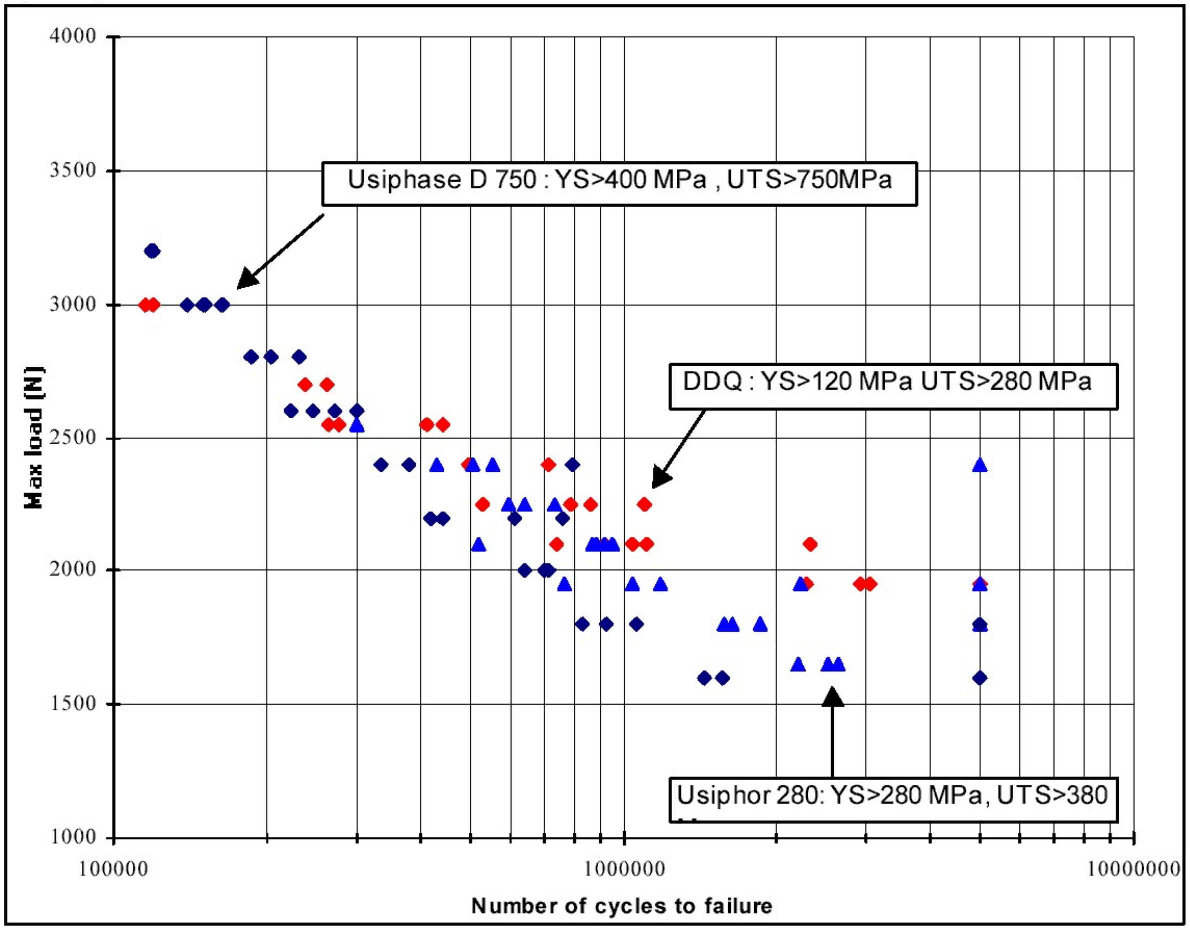
Observations on fatigue of welds

- The fatigue properties of a welded joint are completely different from those of the parent metal because of:
  - Fairly sharp and poorly-controlled geometric features
  - Defects such as slag inclusions
  - Residual stresses
  - Heat-affected zone
  - Modified grain structure
- Fatigue properties of welds in a range of steels have much less variation than in the parent metal
- Fatigue of welded joints is mainly about crack growth – hence well predicted by LEFM



Seam weld in a tube, showing grain structure

Effect of Welding on Fatigue Properties – Spot Welds



Spot weld Load-Life curves

When steels of widely differing grades are welded, the resulting S-N curves tend to fall within a single scatter band

SAE 2006-1- 0978
Bonnen, et al

UTS > 1300 MPa

Effect of Welding on Fatigue Properties – Seam Welds

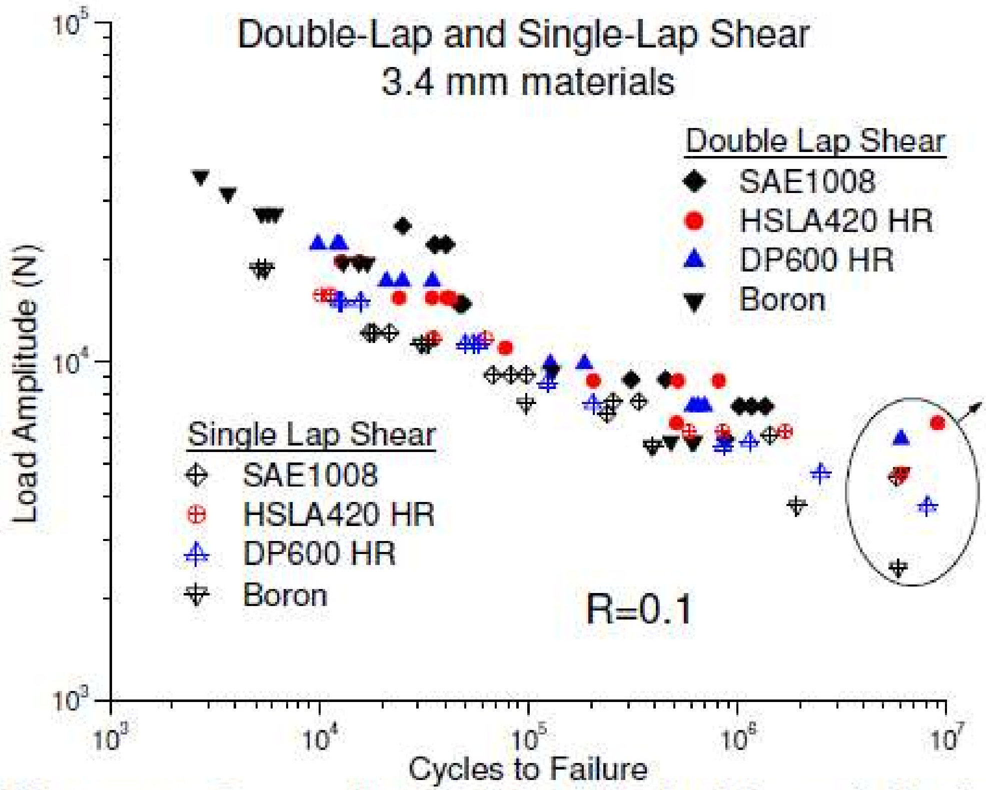


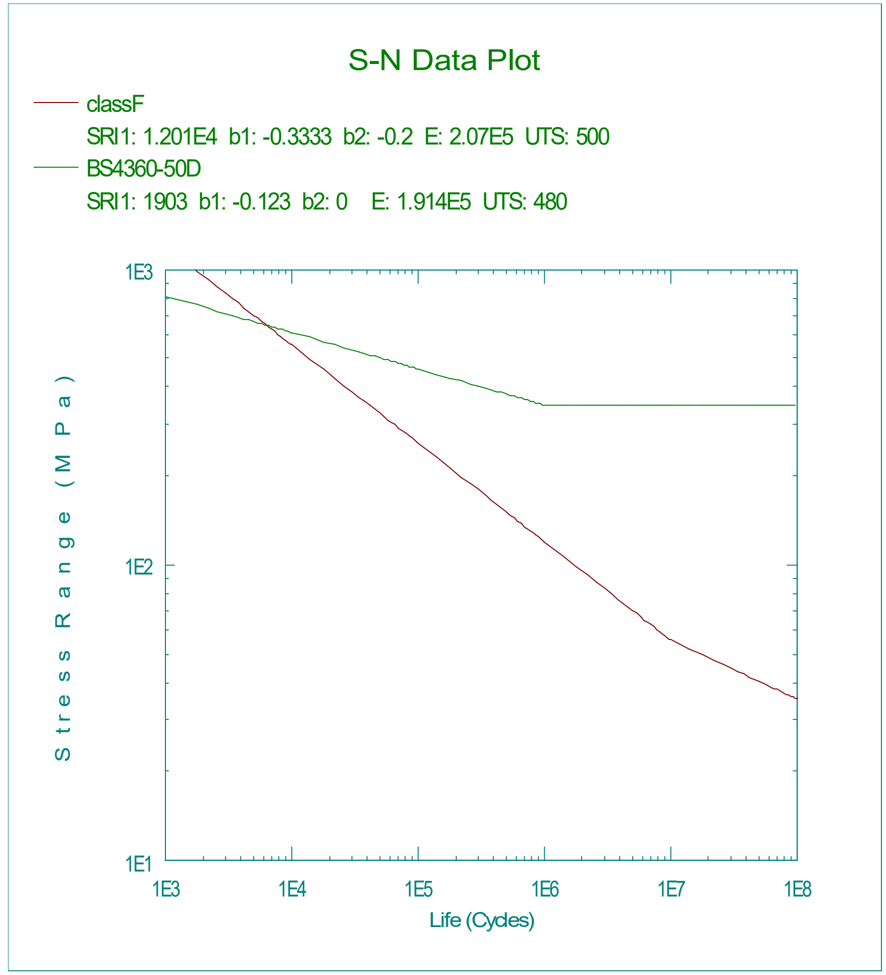
Figure 17. Comparison of 3.4mm double and single lap-shear specimen R=0.1 fatigue performance.

When steels of widely differing grades are welded, the resulting S-N curves tend to fall within a single scatter band

SAE 2009-01-0257
Bonnen, et al

General comments and issues

- Welds naturally coincide with geometric features, changes in section etc
- The fatigue strength of welded joints is in general much less than that of the "parent plate"
- Even in well-designed welded structures, the welds are the most likely failure locations



- Standards usually try to be generic, encompassing a wealth of knowledge from a committee of experts
- Steel welds
  - BS7608 1993 & 2014 (see also BS5400)
  - Eurocode 3
- Aluminium
  - BS8118
  - Eurocode 9
- IIW – International Institute of Welding (steel & aluminium)
  - IIW-1823-07 ex XIII-2151r4-07/XV-1254r4-07
- DNV GL (wind turbines and off-shore)
  - DNVGL-RP-C203 "Recommended Practice"

BRITISH STANDARD BS 7608:2014+A1:2015

Use of this document

As a guide, this British Standard takes the form of guidance and recommendations. It should not be quoted as if it were a specification or a code of practice and claims of compliance cannot be made to it.

Presentational conventions

The guidance in this standard is presented in roman (i.e. upright) type. Any recommendations are expressed in sentences in which the principal auxiliary verb is "should".

Commentary, explanation and general informative material is presented in smaller italic type, and does not constitute a normative element.

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Standards – stress definitions and SN curves

- Basic process
- Compare the real weld with sketches and descriptions
  - Eg BS7608 (p29)- select “class”
  - Use stress definition
- Use SN curve of that class at that stress (p61)
- Update in 2014, FE hot-spots usually fall into class D
  - Can choose nominal or hot-spot

- IIW similar concept, different definitions (p9, 19, 23), different curves. (p75)

- Some definitions from BS7608 (p11~13)
- Fatigue failure: through section cracking or sufficiently large to cause…… failure
- Nominal stress: in the absence of a discontinuity
  - *IIW: A stress in a component, resolved using general theories e.g. beam theory.*
- Structural stress: surface stress, linear distribution across a section
  - Includes attachments / excludes weld toe notches
  - *IIW: A stress resolved to take into account a structural discontinuity (p 19)*
- Hot-spot stress: structural stress at a wed toe or weld end
- SN curve slope transition: point beyond which it is extrapolated

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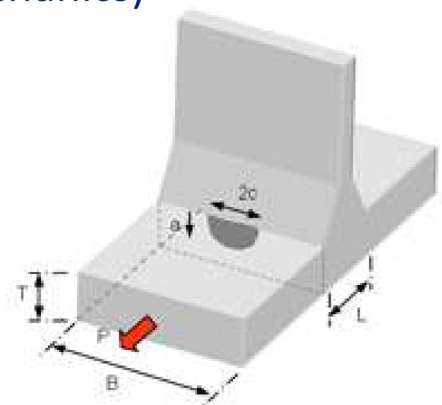
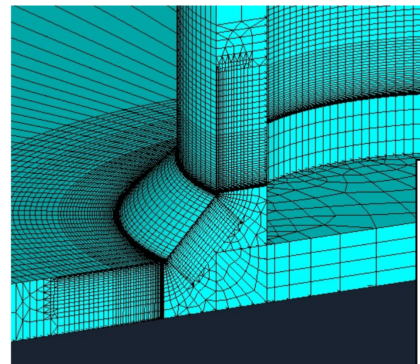
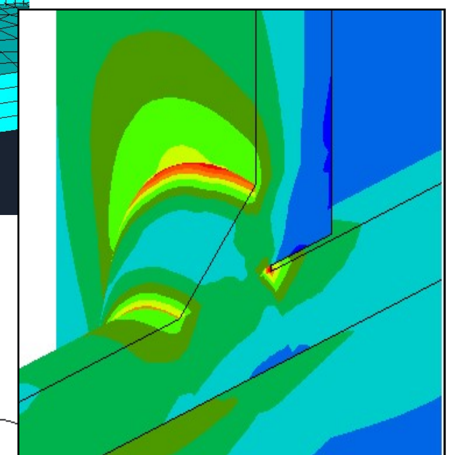
LEFM (fracture mechanics)

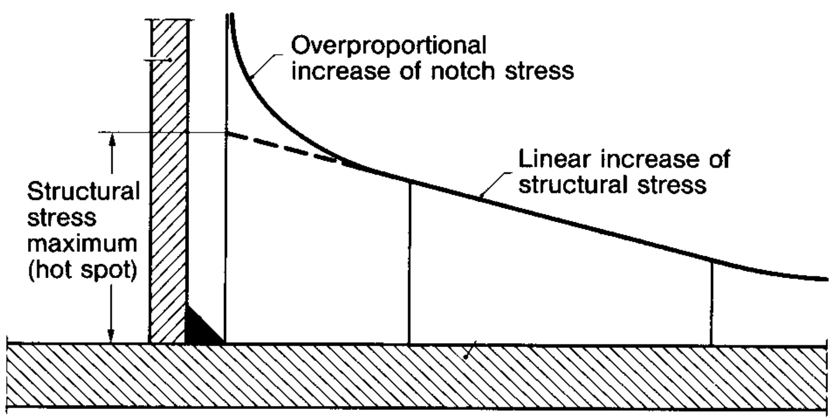


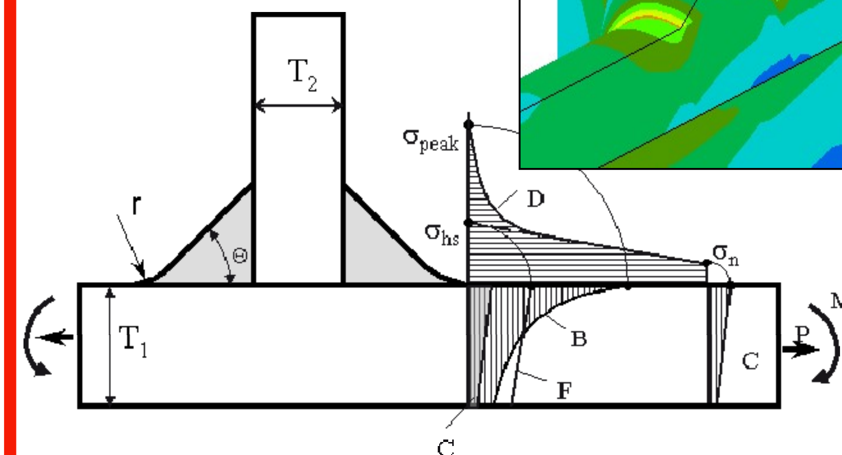


Local approach



Structural hot spot stress





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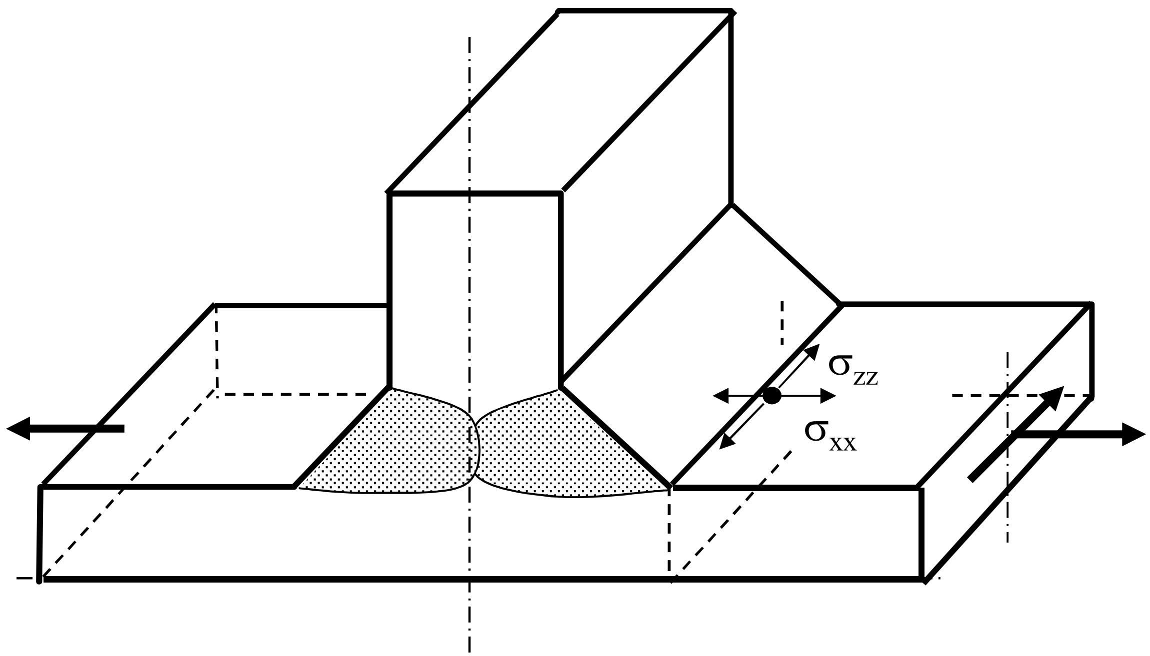
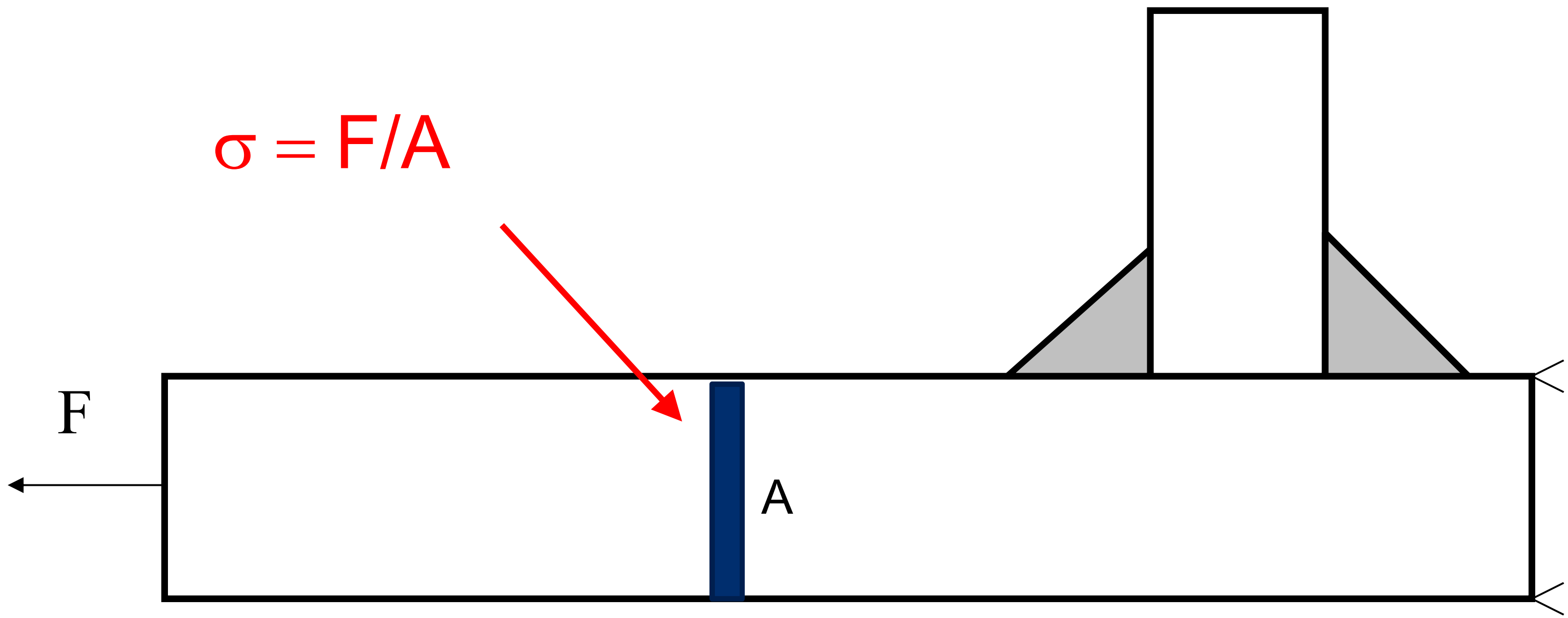
Weld as a Component

Need force, stress or strain measure that corresponds to fatigue damage



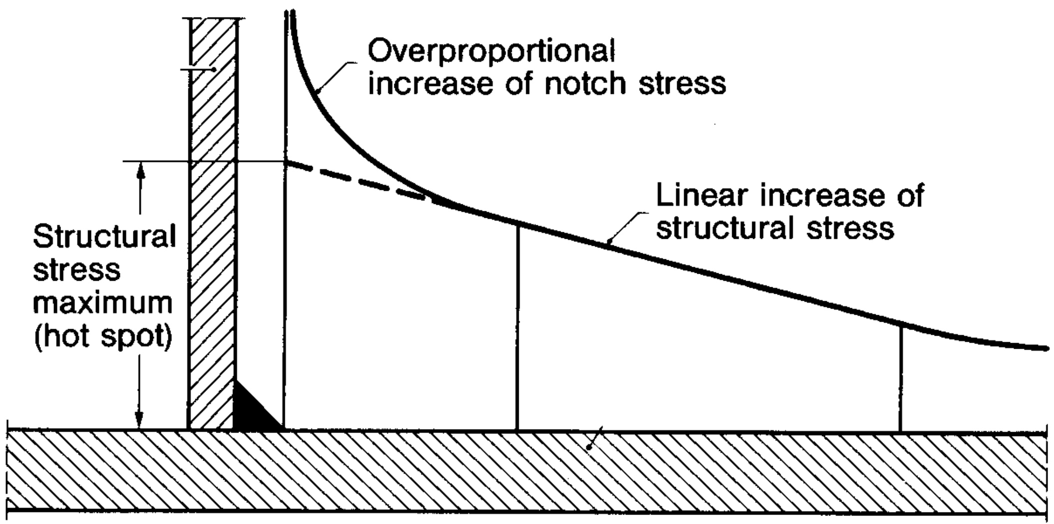
"Nominal Stress"

The stress away from the stress raiser at the weld toe. Typically defined as the stress at predetermined location – may be tricky to define



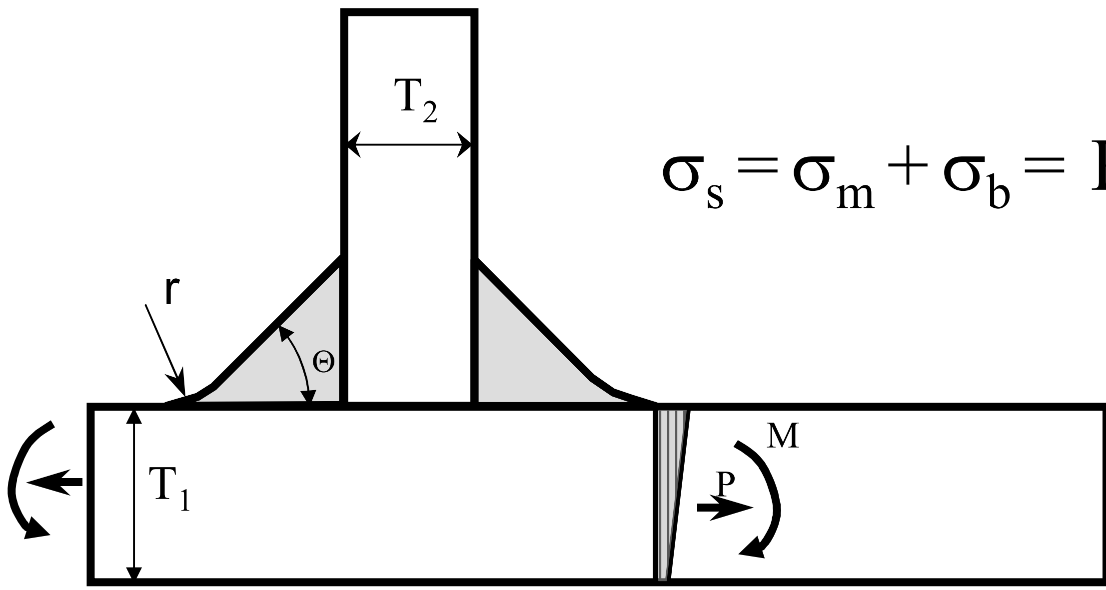
"Hot Spot Stress" by extrapolation

The stress at the weld toe obtained by the linear extrapolation of the stress distribution in the neighborhood of the weld but being far enough not to be affected by the local features of the weld



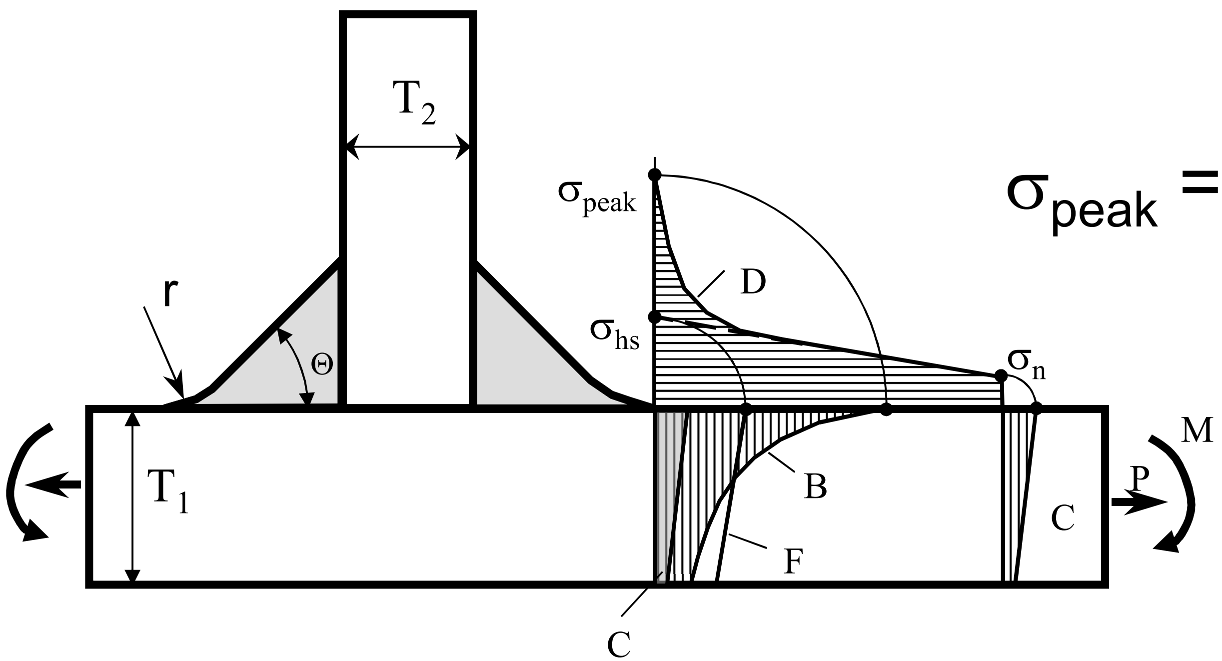
"Structural Stress" (structural hot-spot stress)

A stress resulting from the factoring of the forces and moments in the analyzed cross section by its section properties



$$\sigma_s = \sigma_m + \sigma_b = P/A + My/I$$

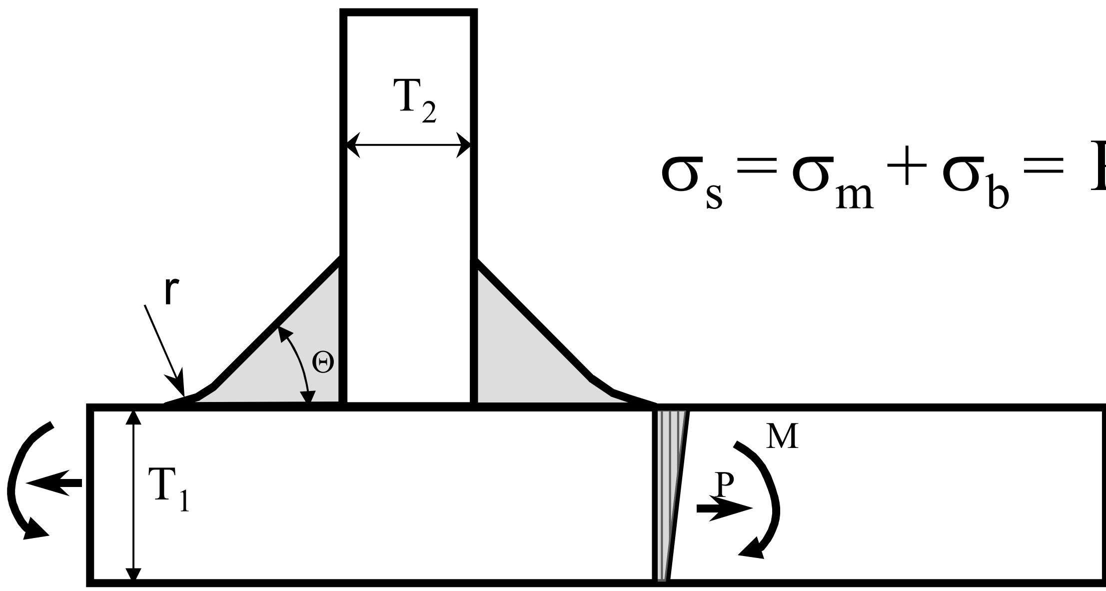
The stress at the weld toe including the local geometry effects.



$$\sigma_{peak} = K_t{}^{*}\sigma_{hs}$$

Examples of structural hot-spot stress approach

- BS7608 (formerly BS5400 Pt 10)……….. 1993 vs 2014
- Eurocode 3
- BS 8118 & Eurocode 9
- ASME Pressure Vessel Code
- Battelle
- “Volvo” method



$$\sigma_s = \sigma_m + \sigma_b = P/A + My/I$$

- **BS7608:1993 – (Similar to Eurocode, AWS)**
  - Code of practice for fatigue design and assessment of steel structures
  - Based closely on BS5400: Pt 10: 1980 (Code of practice for fatigue design of steel, concrete and composite bridges)
  - Applicable to:
    - wrought structural steel of yield strength < 700 MPa
    - plates, welds, bolted and riveted joints
    - in air and seawater
    - sub creep regime
  - Similar technique for welds in Al alloys in BS8118

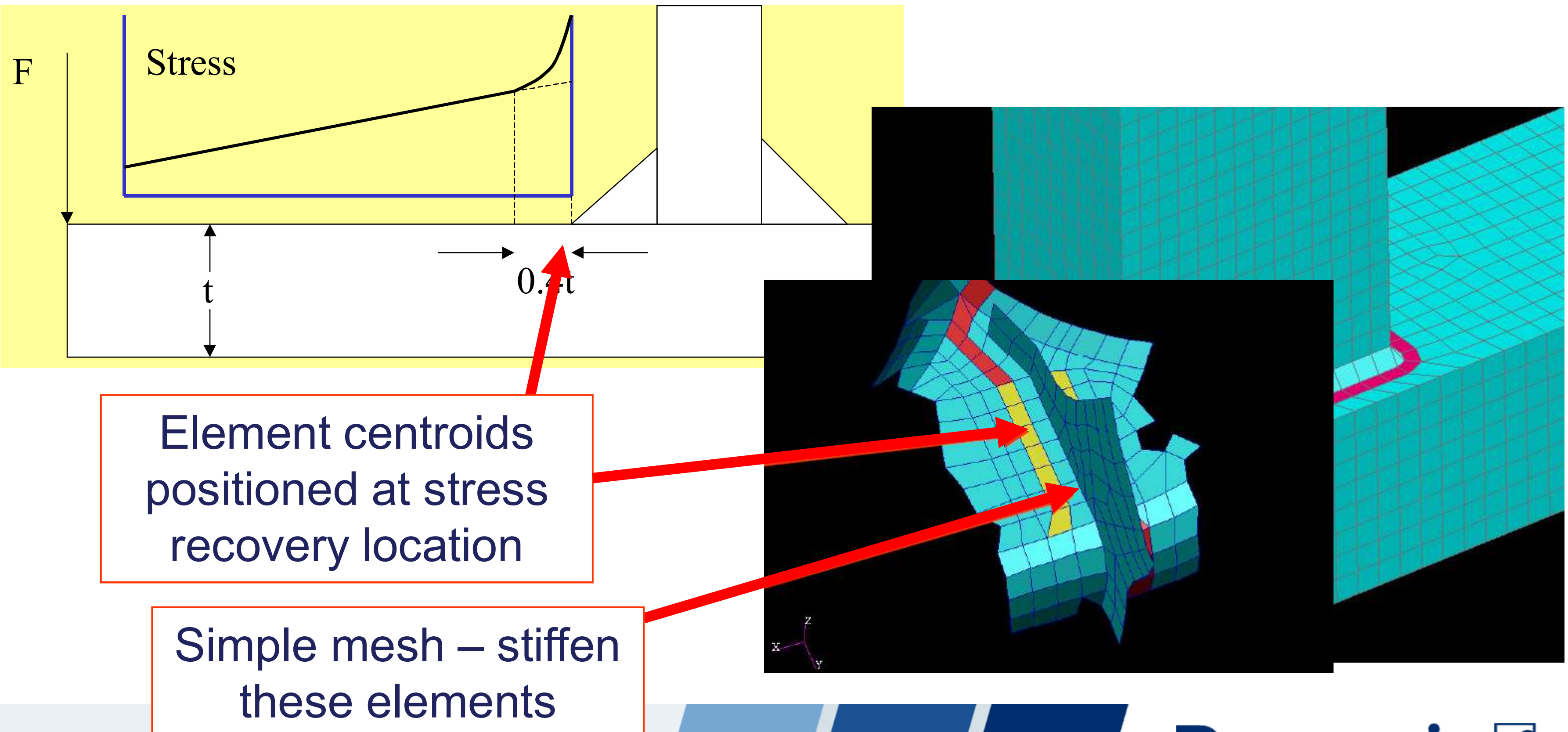
  - More recent edition (2014) aimed to be better suited to FE use
    - 200 MPa < UTS < 900 MPa

Different features of structural hot-spot stress methods

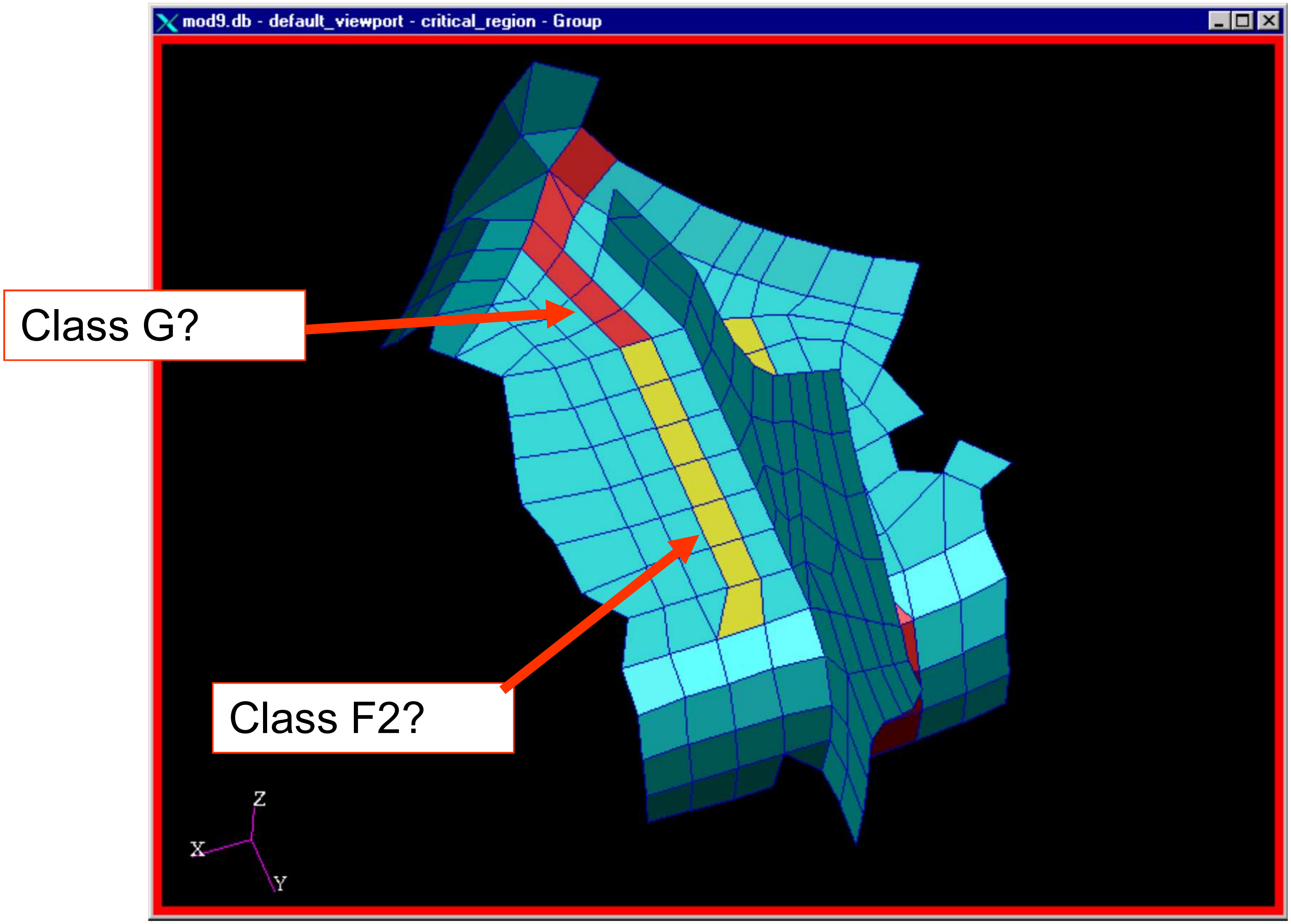
- FE modelling guidelines (no panaceas)
- Weld classification
- Stress recovery methods
- Damage parameter definition
  - Direct stress / critical plane / Principal Stress
- SN curve definition
- Mean stress effect
  - Not forgetting residuals (post treatment)
- Size/thickness effect
- Bending effect
- Failure modes
- Multiaxial loadings

Modelling strategy and stress recovery

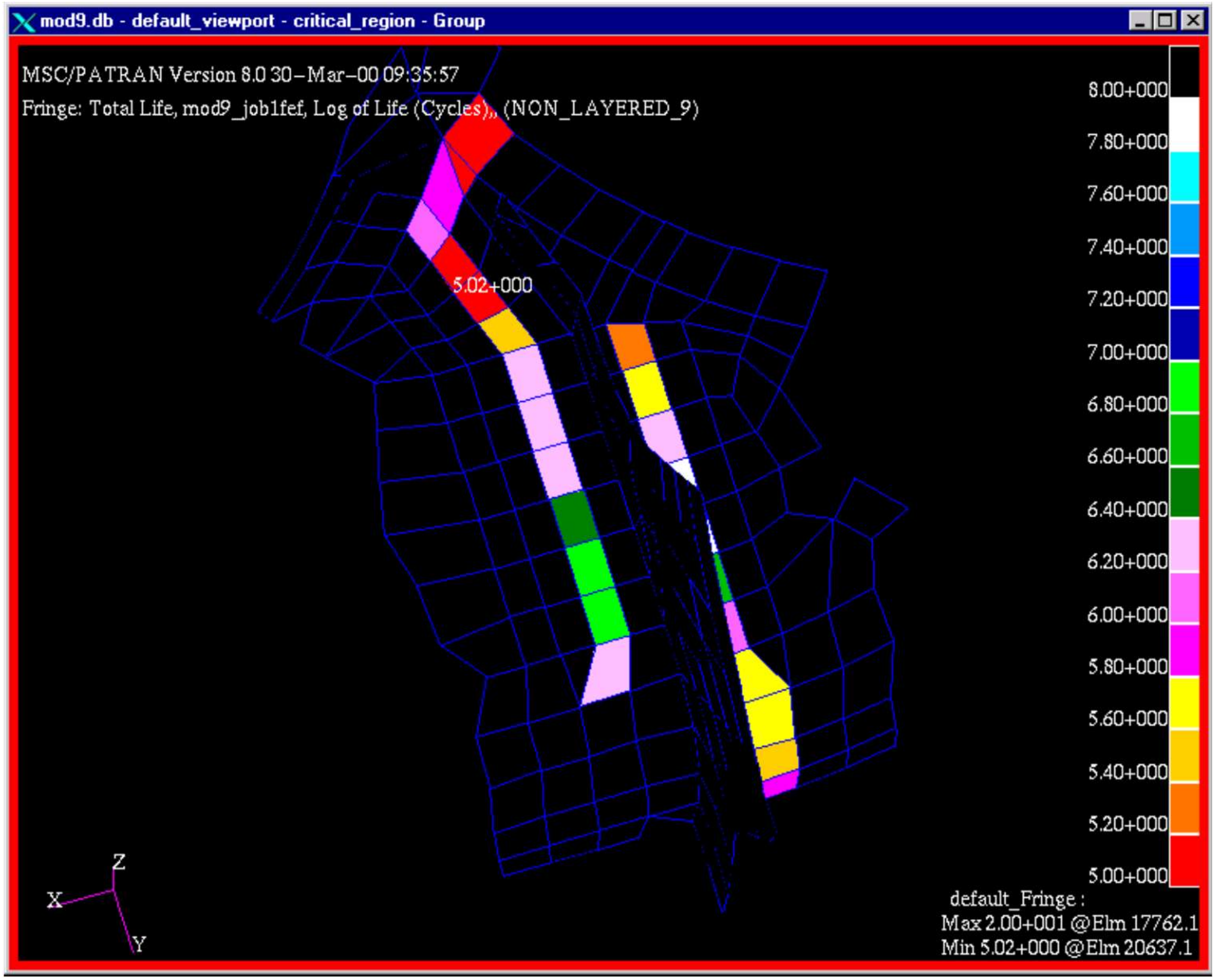
- Read weld class to determine required stress location
  - Nominal stress in plate or structural hot-spot stress at weld toe
  - Mesh with row of nodes or element centroids at desired stress recovery points
  - Create groups or element sets for processing
  - Usually based on largest principal stress



Weld classification

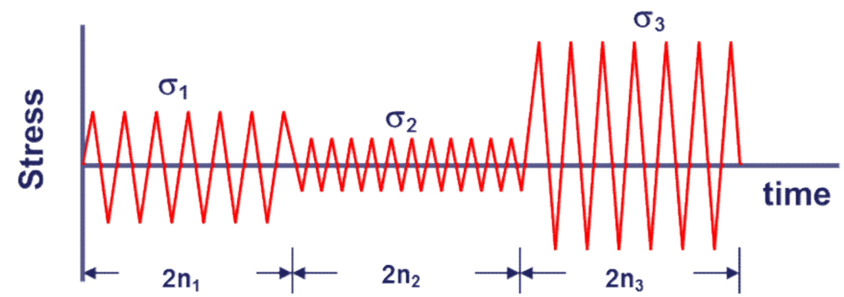


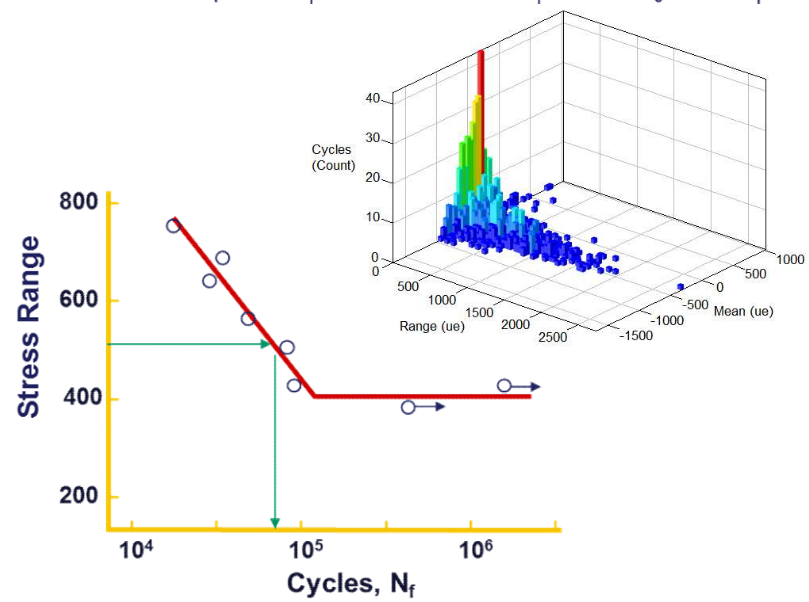
Life prediction results

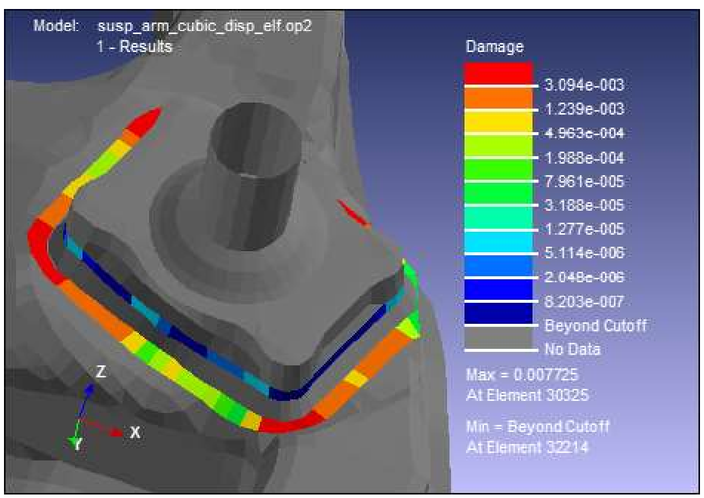


Fatigue calculation process

- Assemble stress history at selected locations in usual way
- Rainflow cycle counting
- Linear damage accumulation
- Usually no mean stress correction
- Postprocess results on FE model



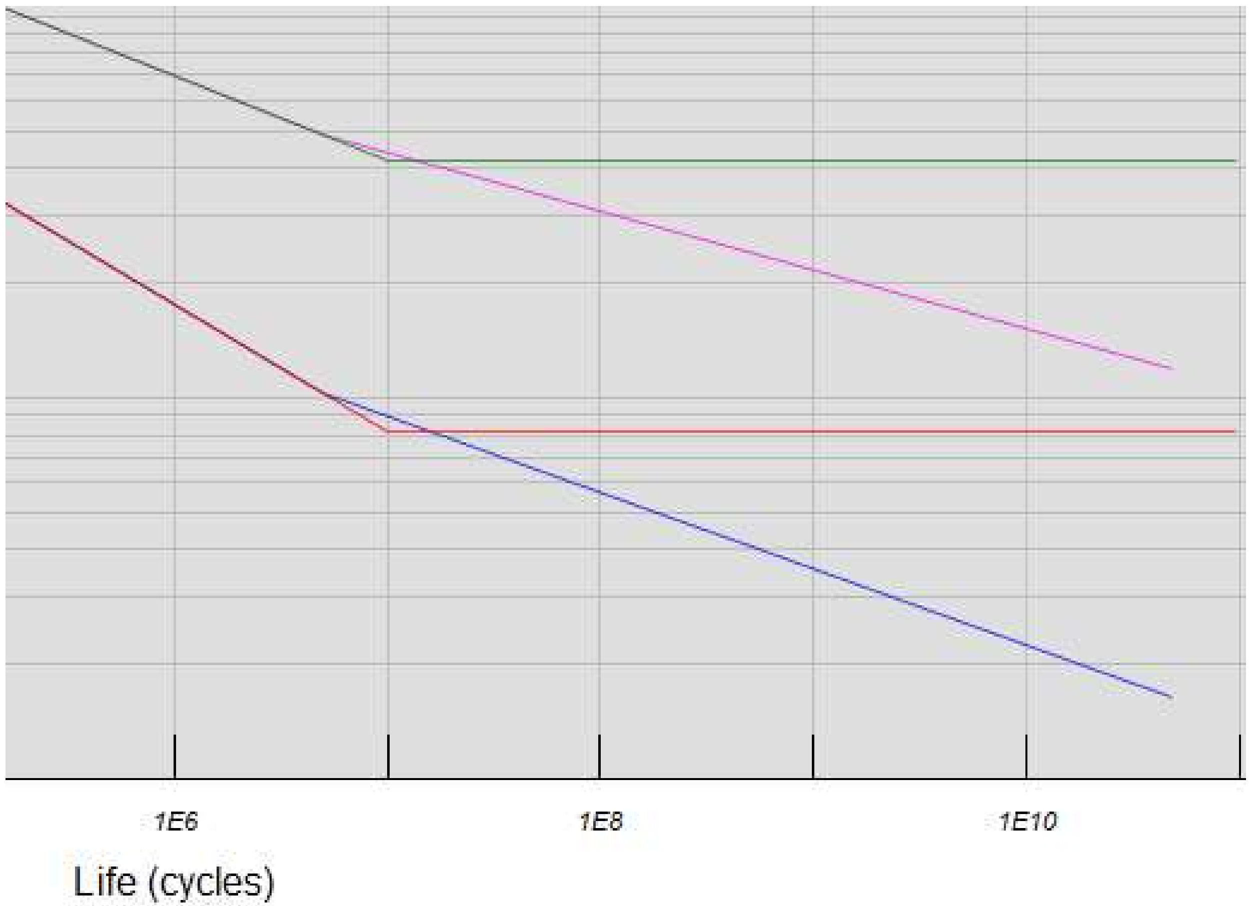




$$\sum_{i=1}^{m} \frac{n_i}{N_{fi}} \geq 1$$

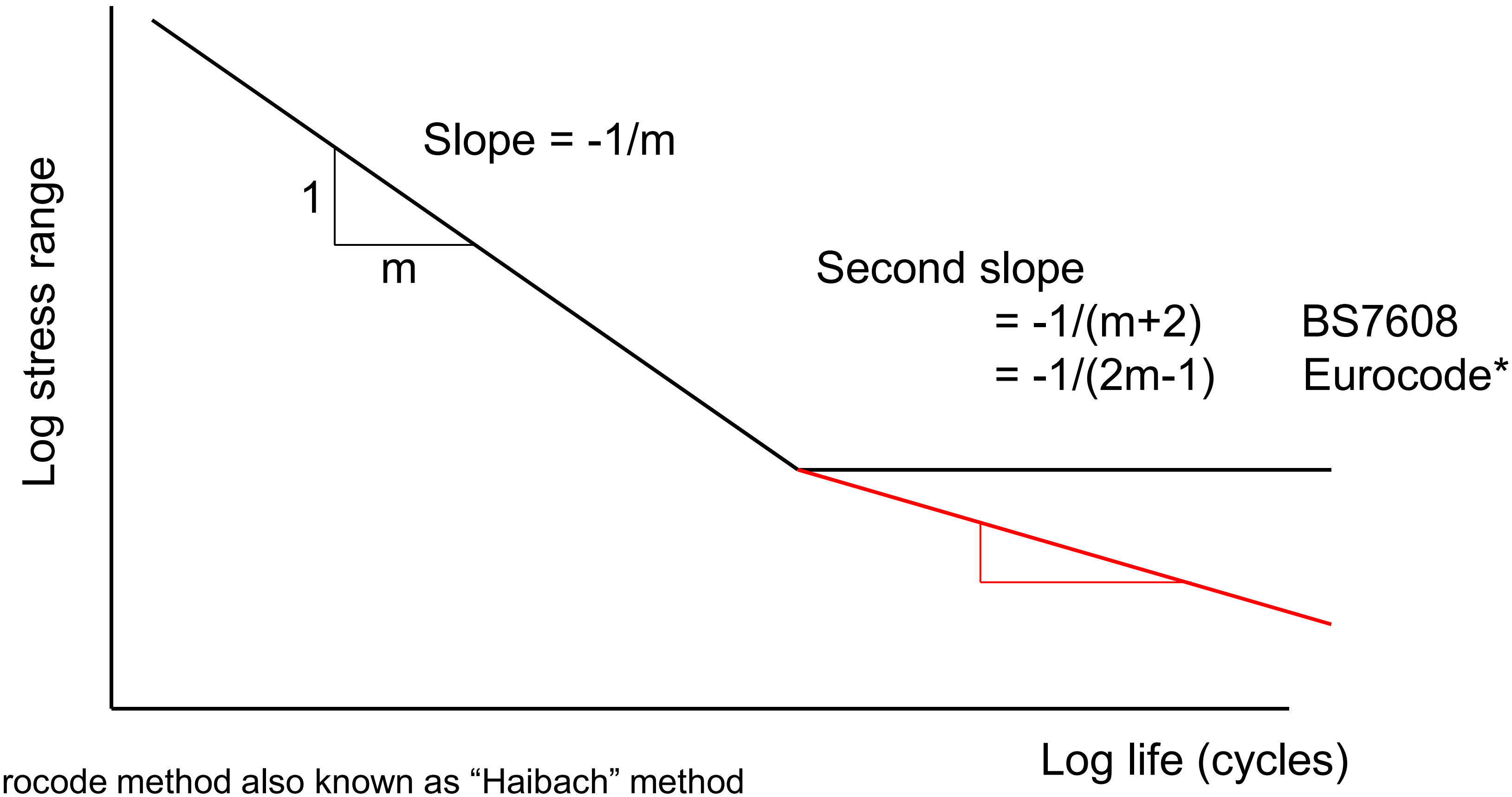
Welds and fatigue thresholds

- Fatigue thresholds (limits) should not be relied upon
- Small cycles below limit become significant under variable amplitude loading. Similar effects under corrosive conditions (sea water)



Small cycle correction

- Both codes include a fatigue limit (at 10 million cycles in BS7608)
- If all cycles are below fatigue limit, no damage is predicted
- If even one cycle in loading history is above fatigue limit, the limit is replaced by a reduced slope – smaller cycles become damaging



*Eurocode method also known as "Haibach" method

Welded aluminium structures – BS8118

- BS8118 is a design code for Al structures
- It includes a short section on fatigue, which is closely based on BS7608/BS5400:Pt10
- Classification system is very similar
- S-N curves are very similar, except that the fatigue strength is reduced by a factor of 3 (the ratio ESteel/EAl)
- Note different transition life and treatment of fatigue limit

Summary – BS7608 and Eurocode

- Standard approaches based on weld classification and design curves
- Developed primarily for plate/beam type structures
- Developed primarily for heavy structures
- May be over conservative for thin sheet structures (TWI study suggests sheet correction might be extrapolated to 2 mm)
- Require some engineering judgement to apply to many situations
- Limitations:
  - Range of geometries based on typical civil and other large engineering structures
  - May need some imagination and judgement to apply to, say, automotive components
  - Limited to cases where the damaging principal stresses are not varying in orientation by more than 45 degrees over time (check using multiaxial assessment)

BS7608 and Eurocode – mean life & scatter

- SN curves contain scatter
  - Typical curve is 50% +/- scatter
  - Engineer chooses the required certainty for the task
  - Do you want a conservative design calculation?
  - Do you want calculations that agree with test?
- Not all standards do this – they vary
- BS7608 (2014) shows 50% mean and defines scatter
  - "Standard basic design SN curves" should be "minus two standard deviations of log N" (nominal probability of failure 2.3)
- Eurocode 3 (2005) does not provide mean data and scatter. Curves factored down – so harder to compare with test results
  - "75% confidence level of 95% probability of survival for log N, taking into account the standard deviation and the sample size and the residual stress effects".

Conclusion - standards

- Standards are useful when the structure in question is similar to the one in the standard
  - Defined with historic experience & methods
- Not easy to apply to non-standard shapes
- Generally assumes simplified loading – especially direction, which is not always realistic
- Does not help with ***innovation***

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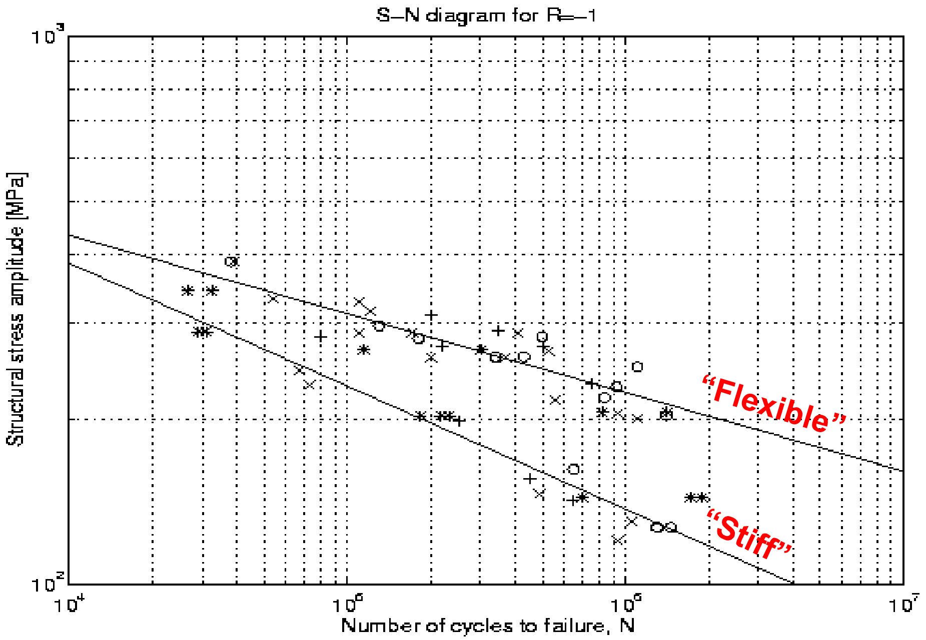
Conclusion – general analysis methods

- Nearly all weld analysis methods rely on
  - Representative stress (or force)
  - SN curve related to representative stress
- Methods reply on good SN curves
  - Must represent a typical manufactured joint
  - Manufactured joint depends on process as well as geometric shape (eg preparation) and loading direction
- Representative stress extraction needs to be repeatable and reliable

S-N curve determination

- Different specimen geometries are tested
- FE-models must be built to calculate stress
- Results fall on 2 curves depending on the nature of the joint loading



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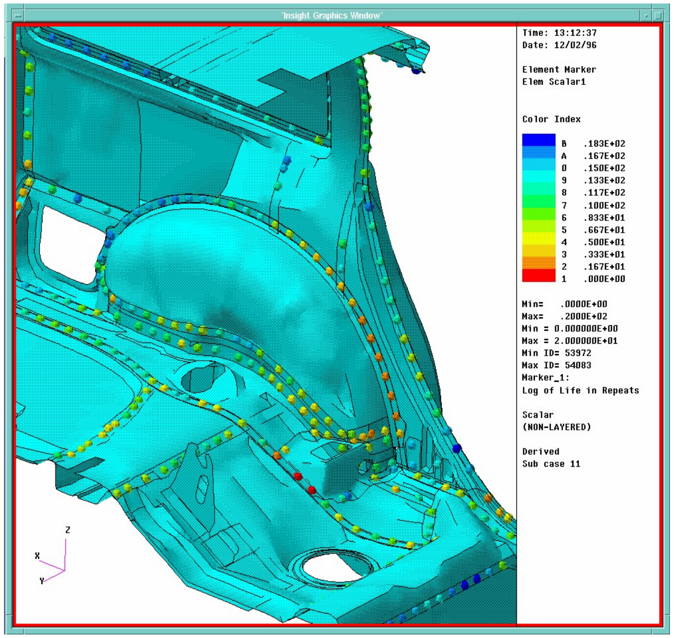
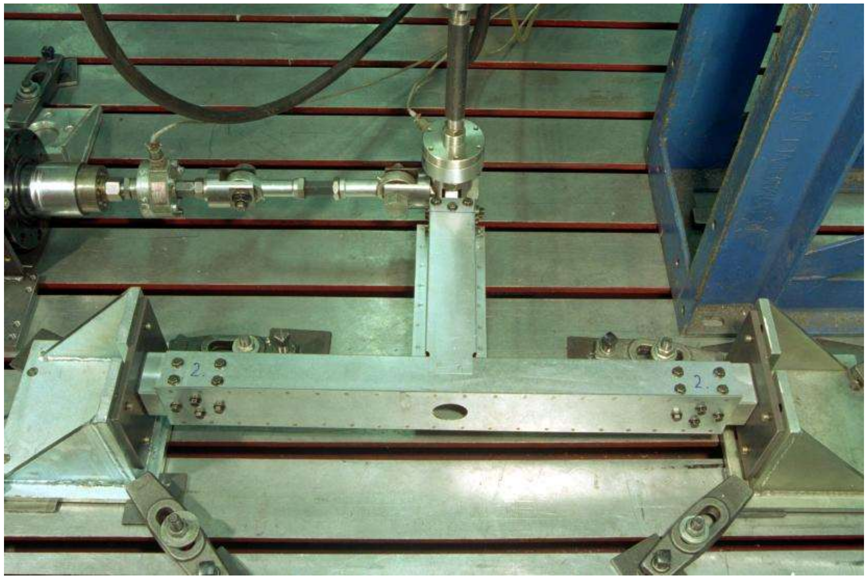
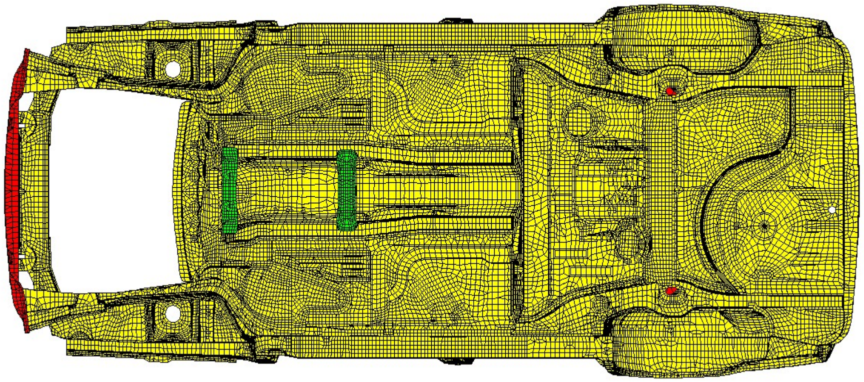
Case Studies

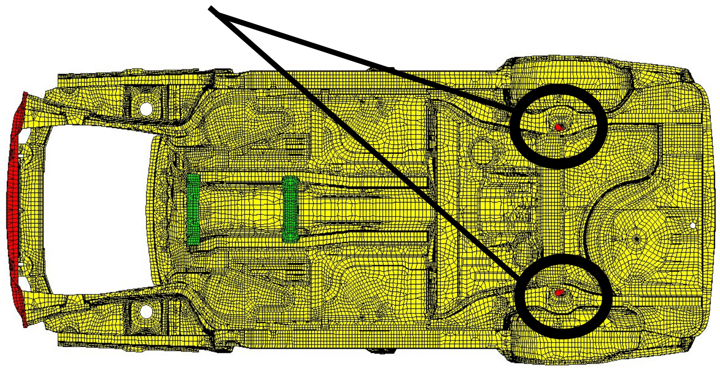






Volvo S-80

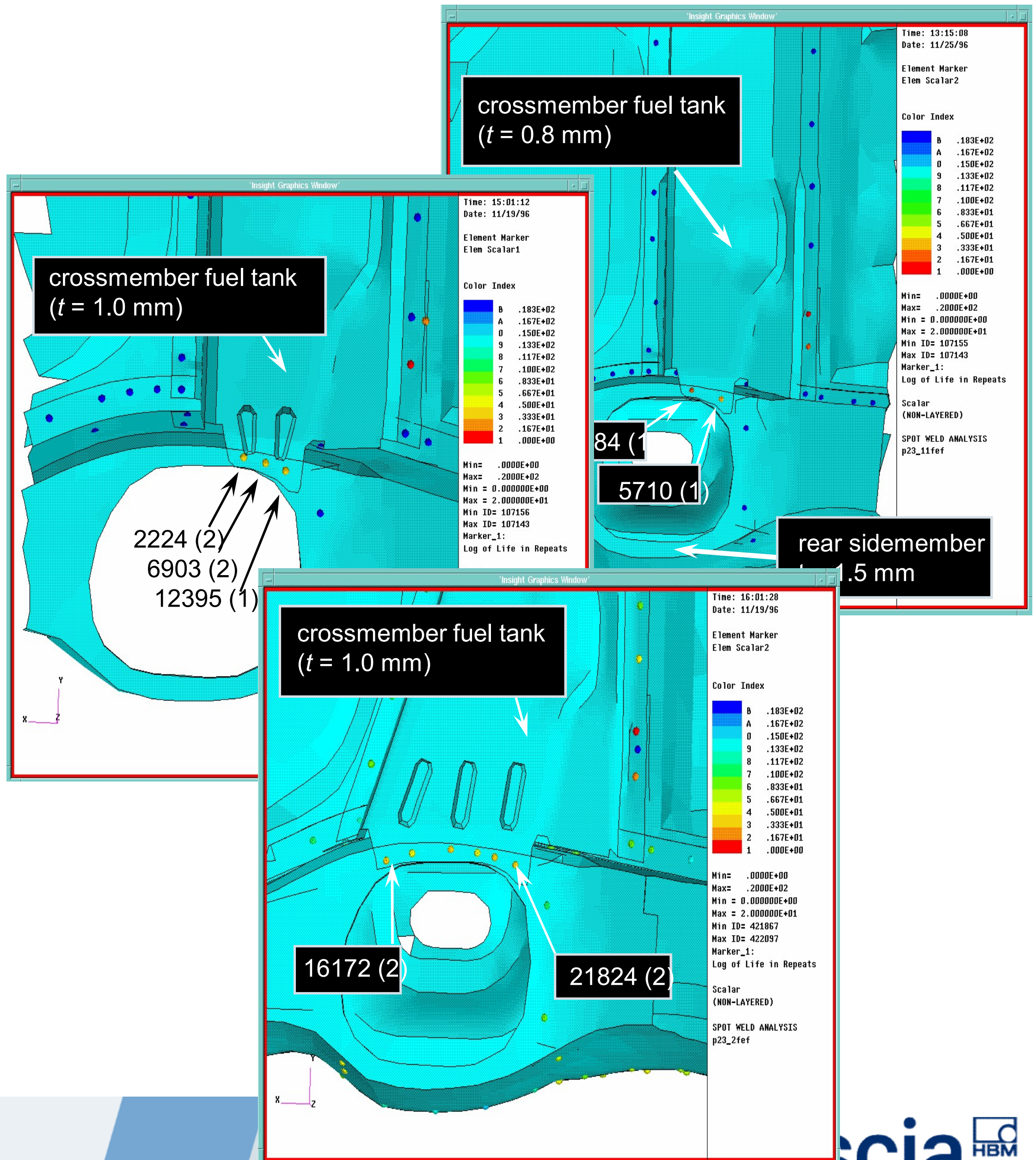
Mission: Increase fatigue life



- Analytical Life Prediction
  - Case study covers the first 3 design iterations
  - Loads from physical spring and damper measurements made on proving ground
- Physical Testing
  - Lab based simulation of the equivalent proving ground event
  - Target Life is 12000 repeats of loading event

Volvo S-80

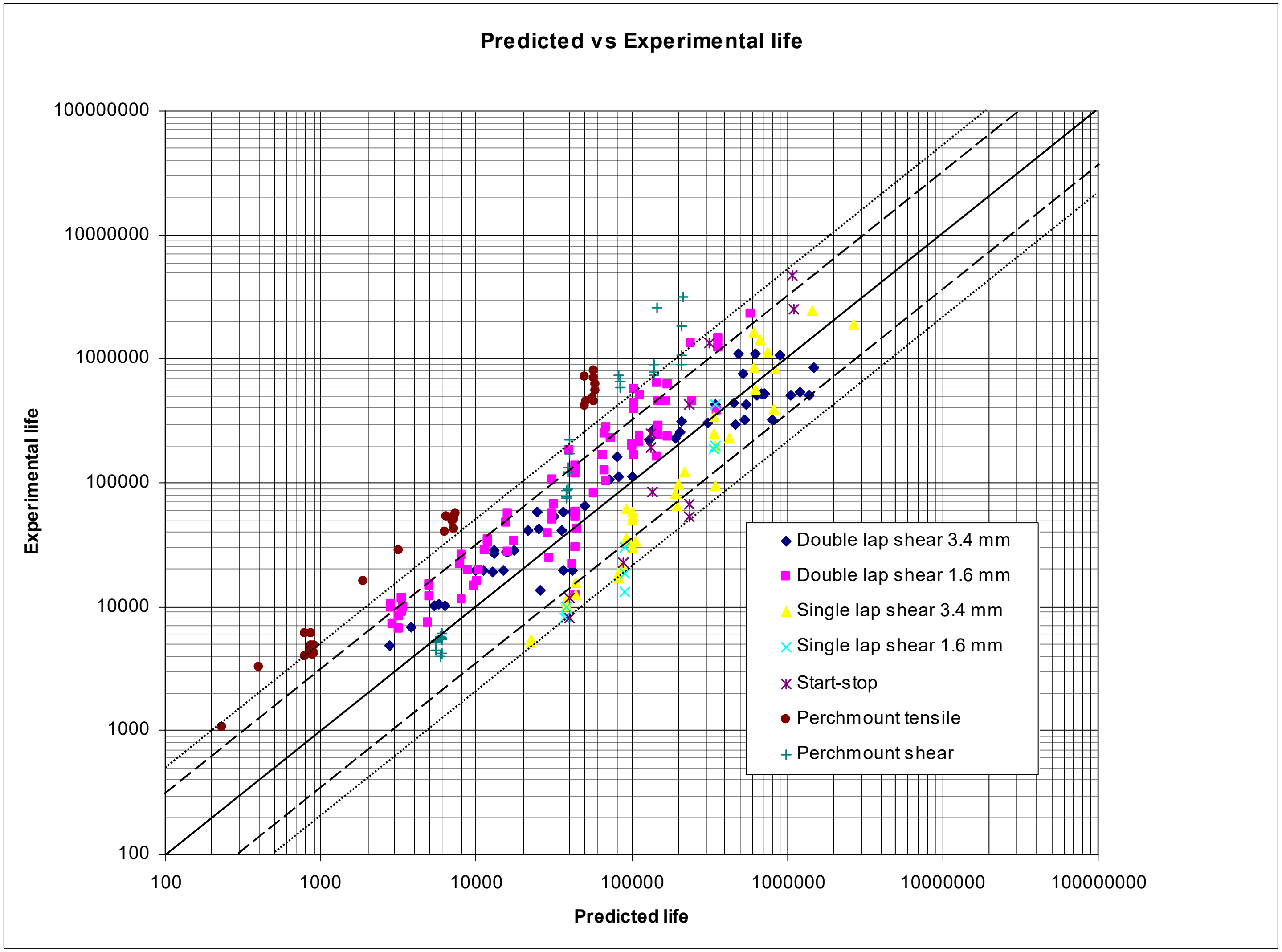
- Results of analysis matched test very closely through 3 design iterations, predicting:
  - failed spotwelds
  - life
  - crack location
- Results gave confidence in method



Volvo S-80 Bi-Fuel Version Development

- Floor pan of Volvo S-80 was extensively modified to accommodate an extra gas tank for the bi-fuel version
- ADAMS based loads from previous S-80 used, with some modifications
- Durability was analysed and optimised virtually before manufacture of final prototype
- Structure verified on shake-rig test
- No fatigue failures on floor pan

Summary – prediction vs experiment



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Thank You!

Robert Cawte
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