TWI

World Centre for Materials Joining Technology

CCOPPS

Fatigue of Welded Pressure Vessels

CCOPPS Webinar

Wednesday 21st May 2008

15:00 – 16:00 BST

Steve Maddox

The Welding Institute (TWI)

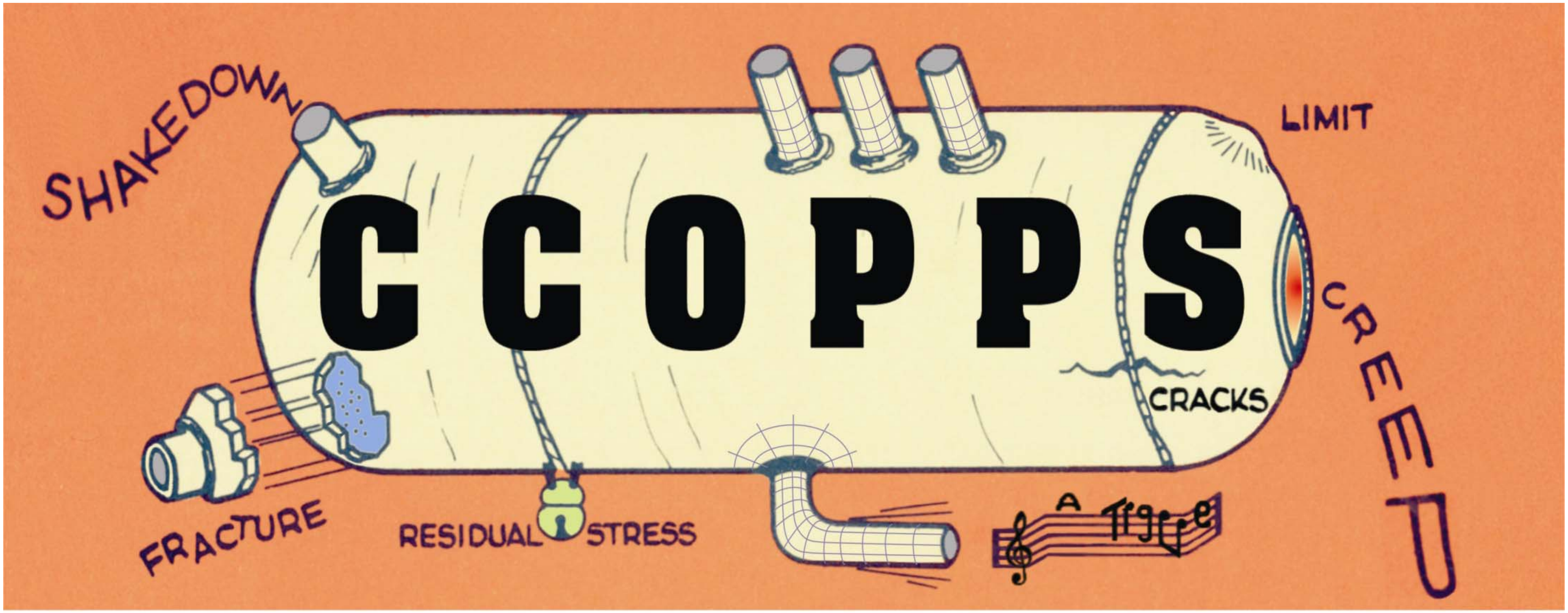
Jim Wood

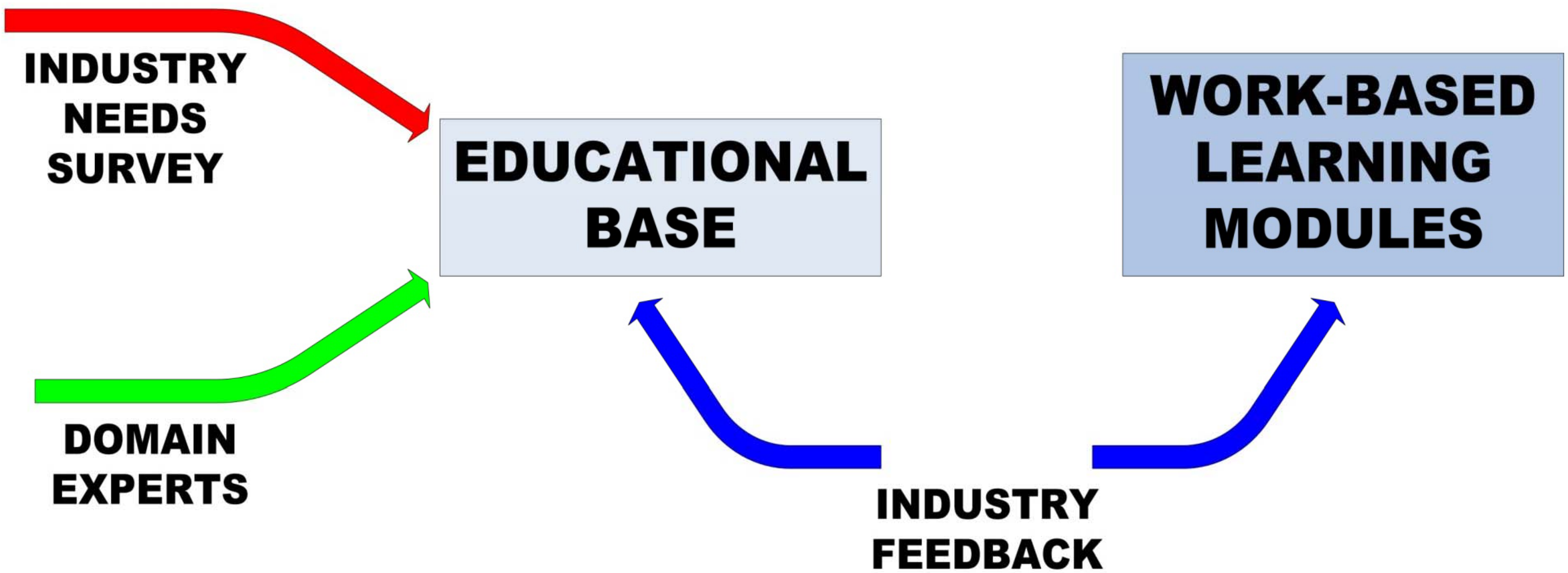
University of Strathclyde

University of Strathclyde · cetim · Universität Stuttgart · Warsaw University of Technology · NAFEMS · Education and Culture Leonardo da Vinci European Training for the UK

Agenda

- **Introduction and Relevant CCOPPS Activity**
  Jim Wood
- **Fatigue of Welded Pressure Vessels**
  Steve Maddox
- **Q&A Session**
  Steve Maddox & Jim Wood
- **Closing Remarks**
  Jim Wood

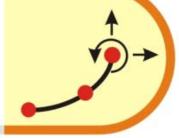

SHAKEDOWN
LIMIT
CCOPPS
CREEP
CRACKS
FRACTURE
RESIDUAL STRESS


INDUSTRY NEEDS SURVEY
EDUCATIONAL BASE
WORK-BASED LEARNING MODULES
DOMAIN EXPERTS
INDUSTRY FEEDBACK

Industry Needs Survey

- ***Findings relevant to this webinar:***
  - *FEA use is increasing as is complexity of models*
  - *Interfacing with codes of practice seen as issue*
  - *Happy with facilities in commercial codes in general (exception is weld modelling and assessment + automation of the analysis process)*
  - *Non-European Codes are used often by most respondents.*
- ***Preliminary report available for download from http://www.ccopps.eu/***

Beams Membranes
Plates and Shells



Buckling
and
Instability

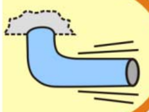
Code of Practice
Philosophy and
Application

Composites

Creep and
Time-Dependency

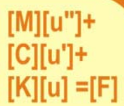
Design
by
Analysis

Dynamics
and
Vibration



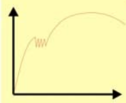
Fatique

FEA of
Pressure Systems
and Components



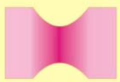
Flaw Assessment
in
Pressure Components

Mechanics, Elasticity
and
Strength of Materials



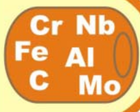
Nonlinear
Geometric Effects
and Contact

Plasticity and
Shakedown

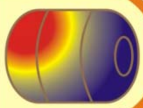


Pressure System
Components
and Fabrication

Pressure Vessel
Materials



Thermo-Mechanical
Behaviour



Category & Code Number	STATEMENT OF LEARNING OUTCOME (click for Threshold and Comprehensive performance interpretations)	Standard or Advanced and EQF Level	Resource Reference
Knowledge			
FATkn8	Sketch typical butt and fillet welds, highlighting features detrimental to fatigue performance.	S,7	
Comprehension			
DBAco19	Explain why the assessment of Shakedown and Fatigue is often carried out using elastic analysis.	A,7	
FATco7	Discuss the observed relationship between endurance limit and static tensile strength for steels and explain why this relationship does not hold for welded steels.	S,7	
FATco17	Discuss the significance of the choice of equivalent stress used in the fatigue assessment of welded joints	A,7	
FATco28	Describe the approximations inherent in a plate/shell idealisation of welded joints and how these could influence fatigue assessment.	A,7	
Application			
FATap7	Use hot spot stress techniques (extrapolation and/or linearization) to determine structural stresses for fatigue assessment.	S,7	
DBAap9	Carry out a Fatigue design check.	S,7	
Analysis			
FATan1	Assess the results from fatigue analyses and determine whether they satisfy the requirements of a Code of Practice.	S,7	
Synthesis			
FATsy5	Specify appropriate idealisation(s) for welds, which are consistent with the objectives of fatigue analyses and available computing resources.	A,7	
Evaluation			
FATev4	Assess the need for Ratcheting and Shakedown assessment.	A,7	

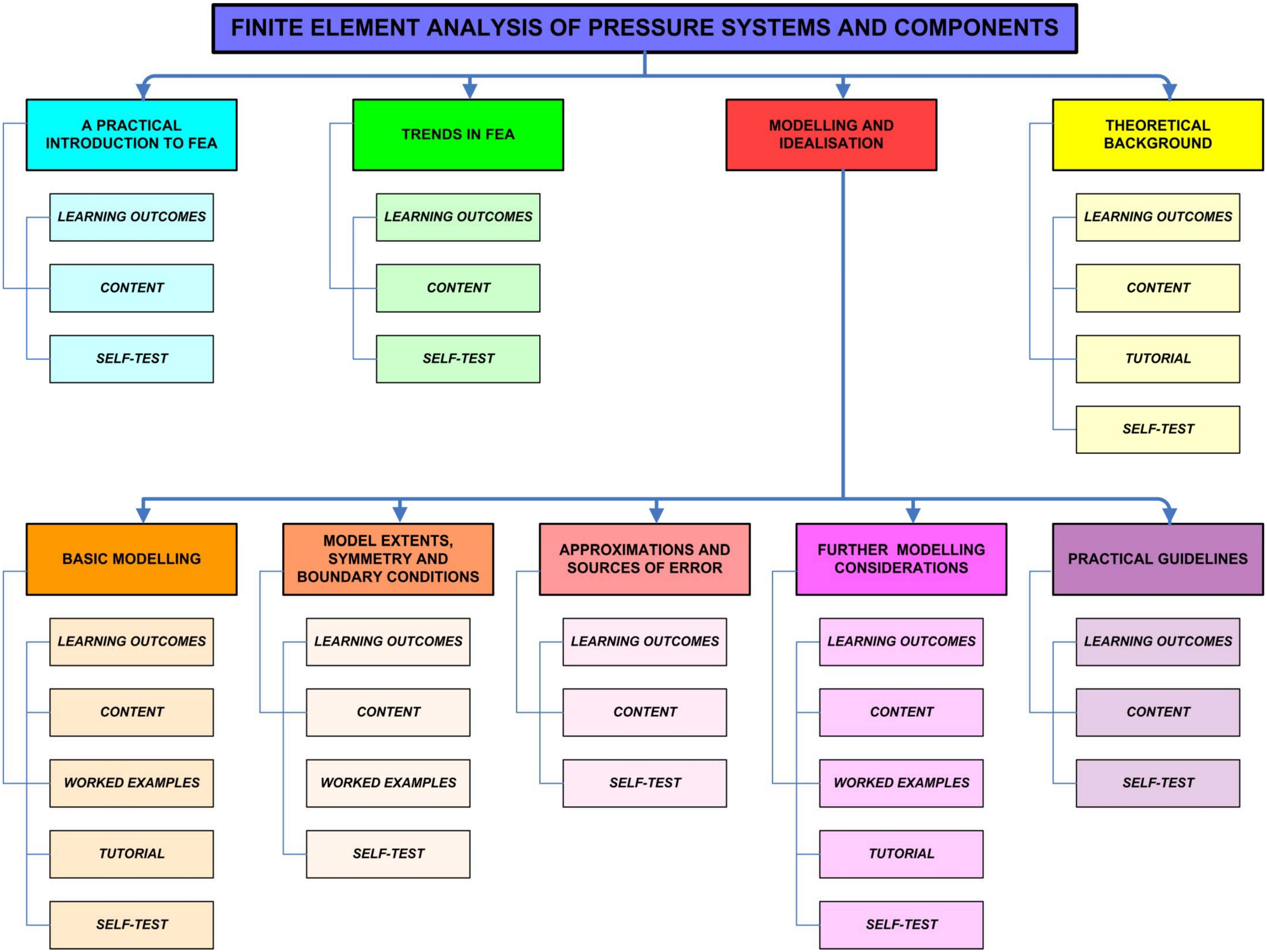
COMPETENCE CODE	RESOURCE REFERENCE	STANDARD LEVEL	ADVANCED LEVEL	EQF LEVEL
BMPSan1	***BMPSref8***	X		7

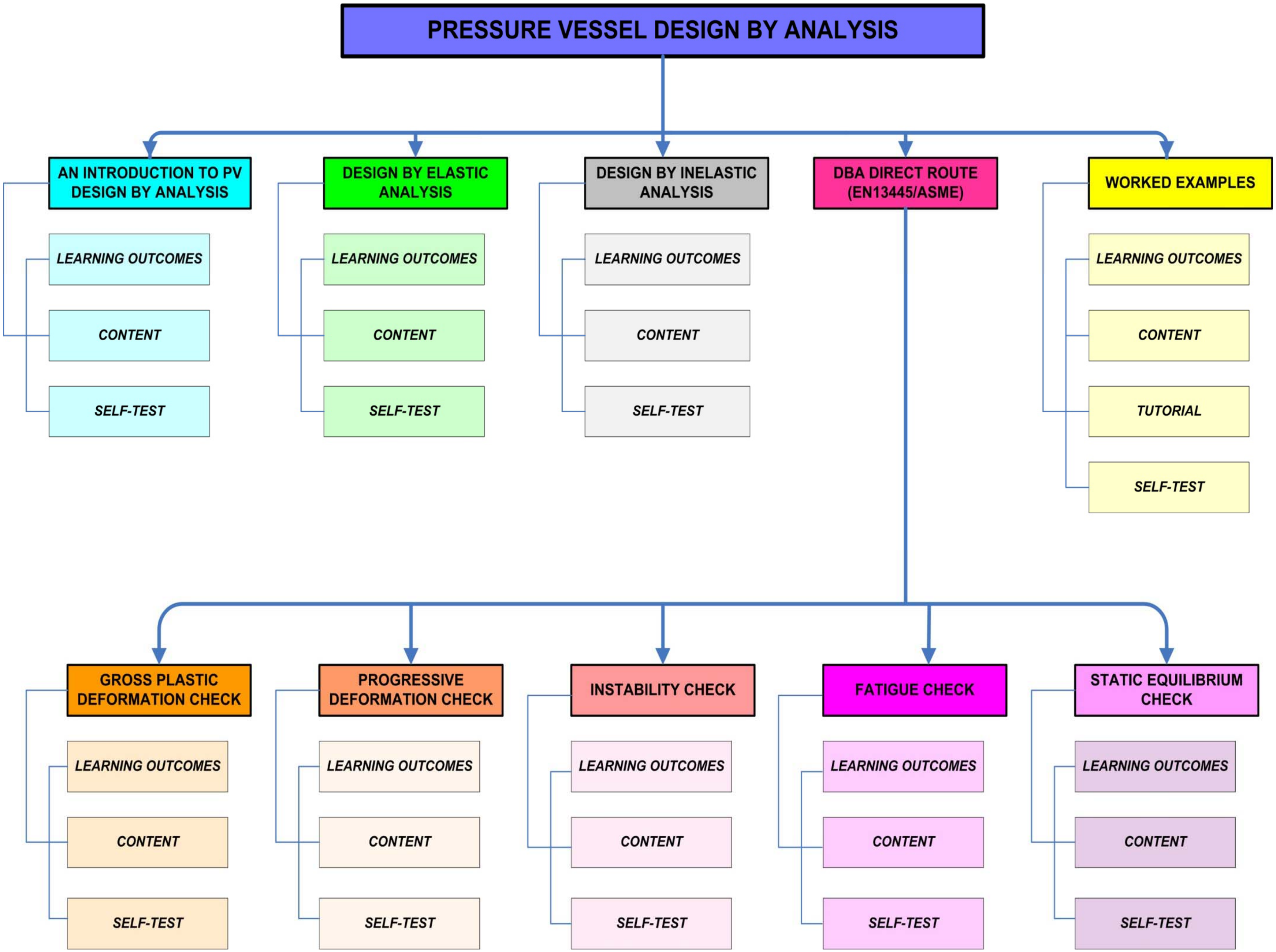
1. COMPETENCE STATEMENT *(Complete achievement record for 1,2 or 3)*	ACHIEVED	
	Formally	Informally
Analyse requirements for finite element models of industrial components using beam, membrane, plate and shell elements and determine whether the basic assumptions inherent in the element formulations are valid.		
	ATTESTING SIGNATURE	

2. MINIMUM THRESHOLD INTERPRETATION	ACHIEVED	
	Formally	Informally
Limited ability to analyse problems from industry sector and to make correct engineering judgement whether assumptions inherent in beam, membrane, plate and shell element formulations are applicable. Limited ability to explain decisions. Relies largely on established procedures within organisation or published guidelines.		
	ATTESTING SIGNATURE	

3. COMPREHENSIVE THRESHOLD INTERPRETATION	ACHIEVED	
	Formally	Informally
Ability to independently analyse a comprehensive range of problems from industry sector and to make correct engineering judgement whether assumptions inherent in beam, membrane, plate and shell element formulations are applicable. Significance of such assumptions is clearly explained.		X
	ATTESTING SIGNATURE	

NAME	DATE
JOE BLOGGS	24^{th} February 2008


FINITE ELEMENT ANALYSIS OF PRESSURE SYSTEMS AND COMPONENTS
A PRACTICAL INTRODUCTION TO FEA
LEARNING OUTCOMES
CONTENT
SELF-TEST
TRENDS IN FEA
LEARNING OUTCOMES
CONTENT
SELF-TEST
MODELLING AND IDEALISATION
THEORETICAL BACKGROUND
LEARNING OUTCOMES
CONTENT
TUTORIAL
SELF-TEST
BASIC MODELLING
LEARNING OUTCOMES
CONTENT
WORKED EXAMPLES
TUTORIAL
SELF-TEST
MODEL EXTENTS, SYMMETRY AND BOUNDARY CONDITIONS
LEARNING OUTCOMES
CONTENT
WORKED EXAMPLES
SELF-TEST
APPROXIMATIONS AND SOURCES OF ERROR
LEARNING OUTCOMES
CONTENT
SELF-TEST
FURTHER MODELLING CONSIDERATIONS
LEARNING OUTCOMES
CONTENT
WORKED EXAMPLES
TUTORIAL
SELF-TEST
PRACTICAL GUIDELINES
LEARNING OUTCOMES
CONTENT
SELF-TEST


PRESSURE VESSEL DESIGN BY ANALYSIS
AN INTRODUCTION TO PV DESIGN BY ANALYSIS
LEARNING OUTCOMES
CONTENT
SELF-TEST
DESIGN BY ELASTIC ANALYSIS
LEARNING OUTCOMES
CONTENT
SELF-TEST
DESIGN BY INELASTIC ANALYSIS
LEARNING OUTCOMES
CONTENT
SELF-TEST
DBA DIRECT ROUTE (EN13445/ASME)
WORKED EXAMPLES
LEARNING OUTCOMES
CONTENT
TUTORIAL
SELF-TEST
GROSS PLASTIC DEFORMATION CHECK
LEARNING OUTCOMES
CONTENT
SELF-TEST
PROGRESSIVE DEFORMATION CHECK
LEARNING OUTCOMES
CONTENT
SELF-TEST
INSTABILITY CHECK
LEARNING OUTCOMES
CONTENT
SELF-TEST
FATIGUE CHECK
LEARNING OUTCOMES
CONTENT
SELF-TEST
STATIC EQUILIBRIUM CHECK
LEARNING OUTCOMES
CONTENT
SELF-TEST

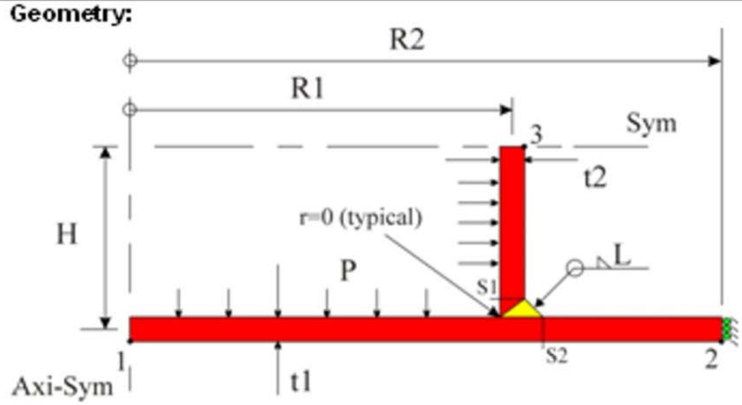
Number:	**Title:**	**Date:**
CCOPPS_WM1	Weld Modelling.	10th February 2008

Statement of Purpose:

The main purpose of this worked example is to identify the limitations of modelling practices currently in use, using plate/shell elements, for adequate representation of the stiffness and stresses in large fabrications containing welded intersections that exhibit a slope discontinuity in shell/plate mid-surfaces.

The stresses and deflections in the fabricated detail shown are to be determined using common industrial modelling practices. Target solution quantities required for deflection and stresses have been specified. Assessment of the stresses obtained, is not included in this example.

Geometry:



R1 = 650 mm; R2 = 1000 mm
H = 300 mm; t1 = 20mm
t2 = 15 mm; L = 15mm (leg length)
Neglect self-weight; 45 degree full penetration fillet

Analysis Type(s):

Linear material, static, small displacement.

Material:

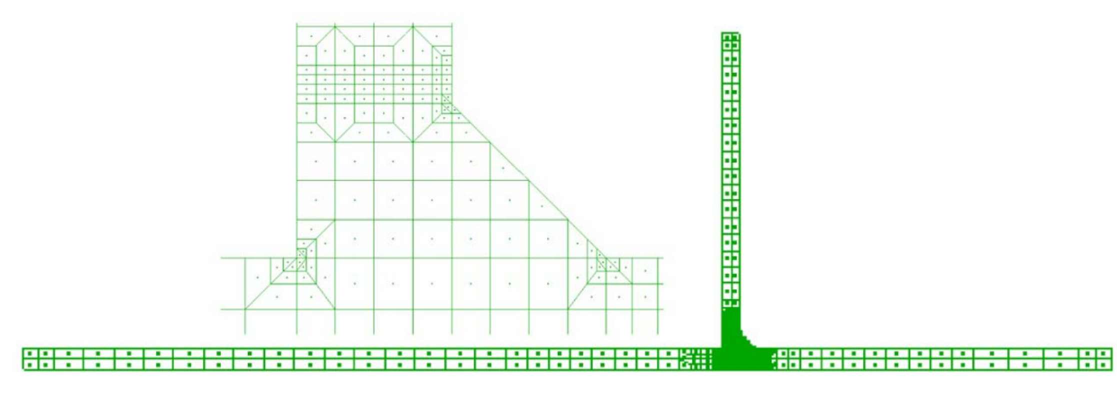
EN10025 S355 JR steel (old BS 4360 Grade 50B) in the as-rolled, as-welded condition. Young's Modulus = 200000 N/mm^2; Poisson's Ratio = 0.3; Minimum Yield Strength = 355 N/mm^2 for $t<16$mm (345 for $16<t<40$); Fatigue strength (stress range) for plain plate = 280 N/mm^2 with a 2.3% (2SD) probability of failure. Tensile Strength 560 N/mm^2.

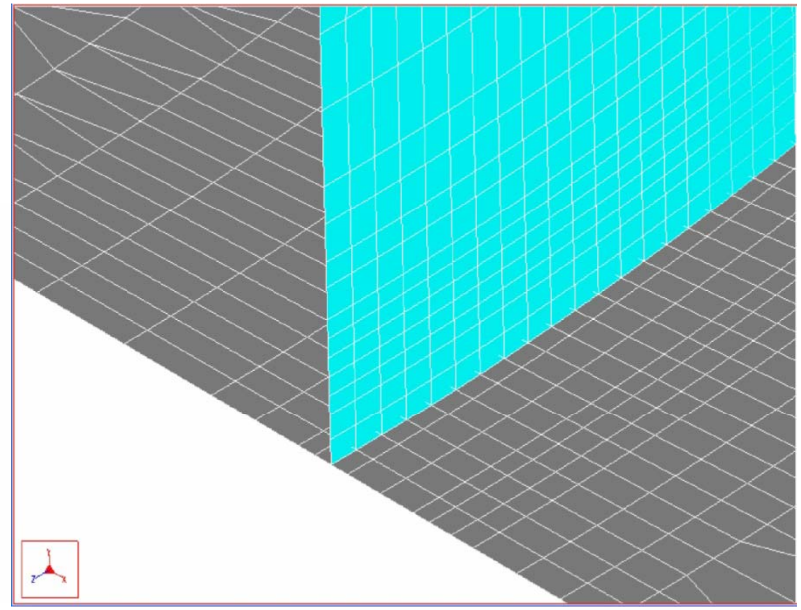
Loading:

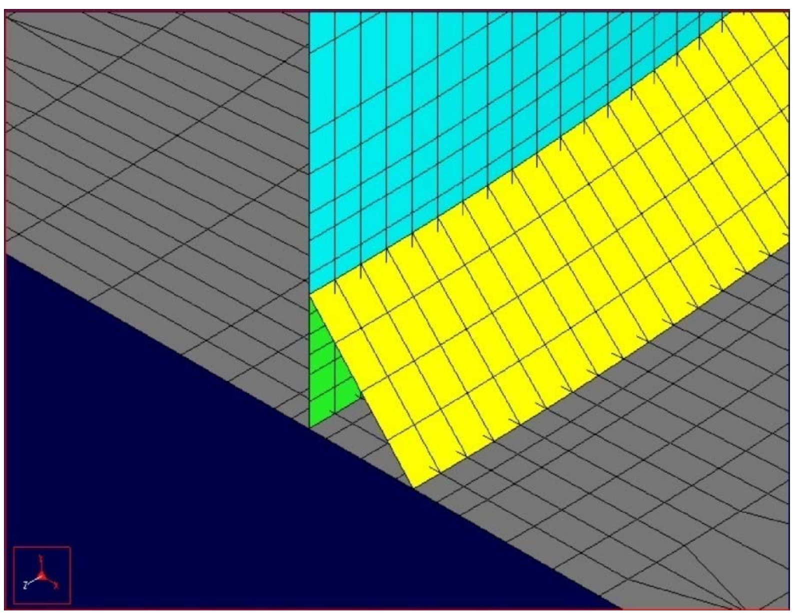
Internal pressure P = 0.2 N/mm^2 @ 2x10e6 cycles (0 ... P ... 0).

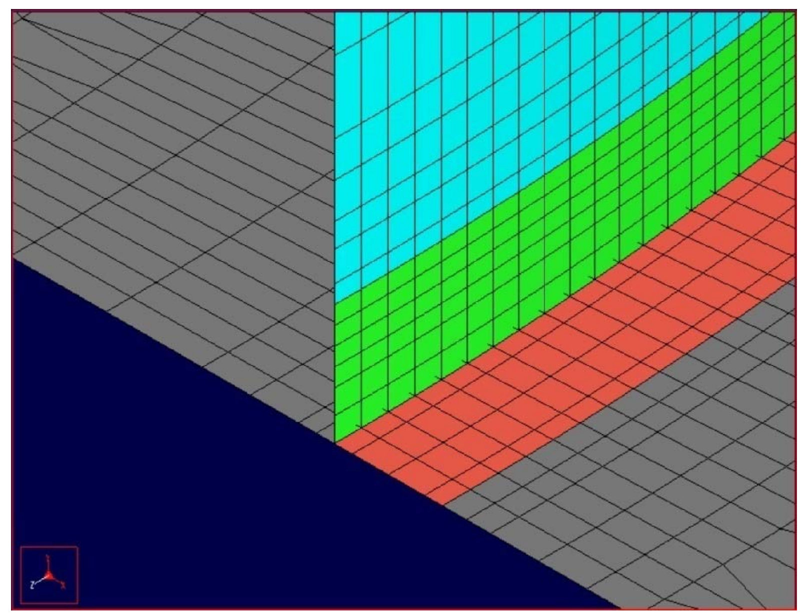
Boundary Conditions:

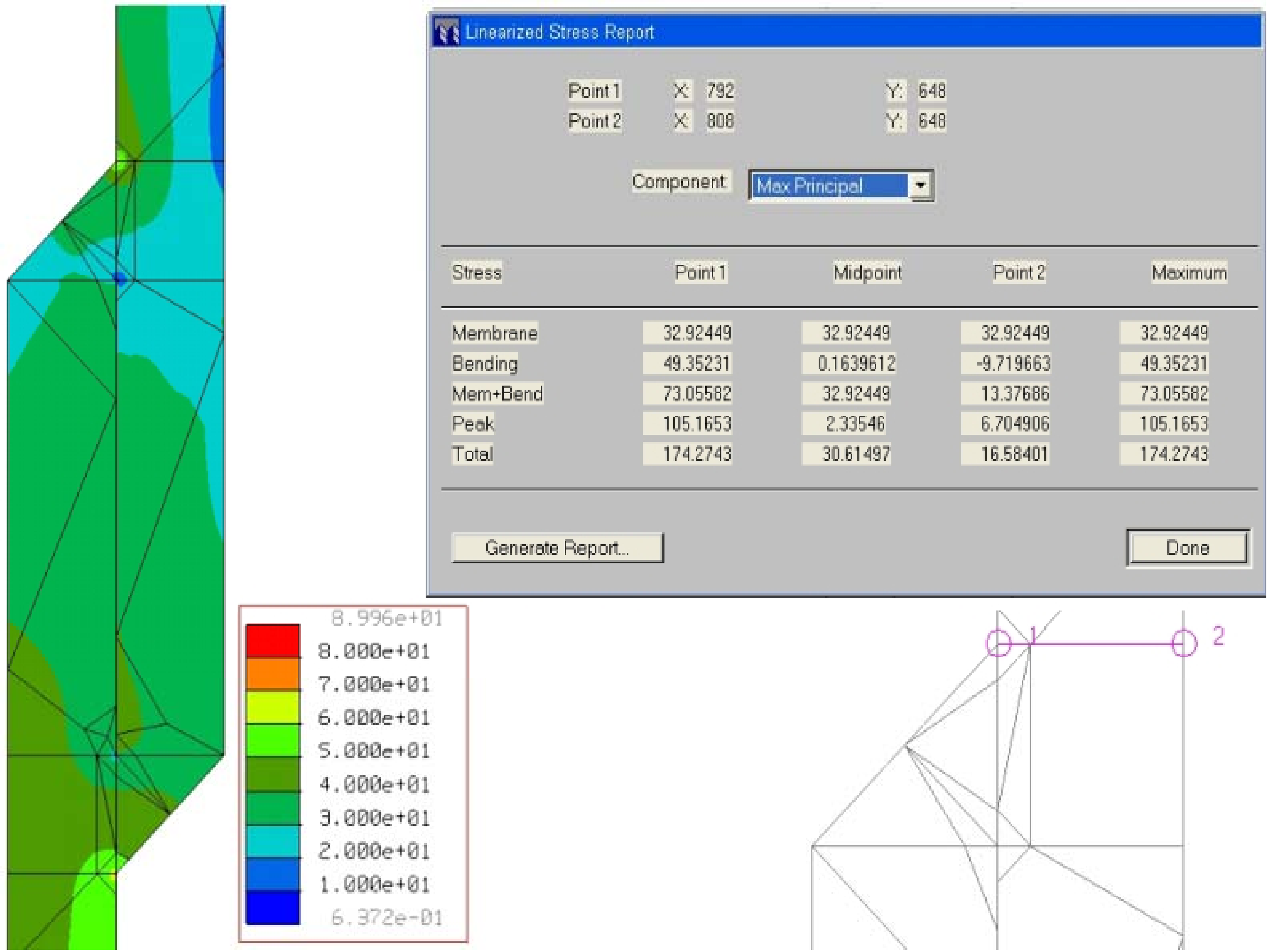
See figure above.









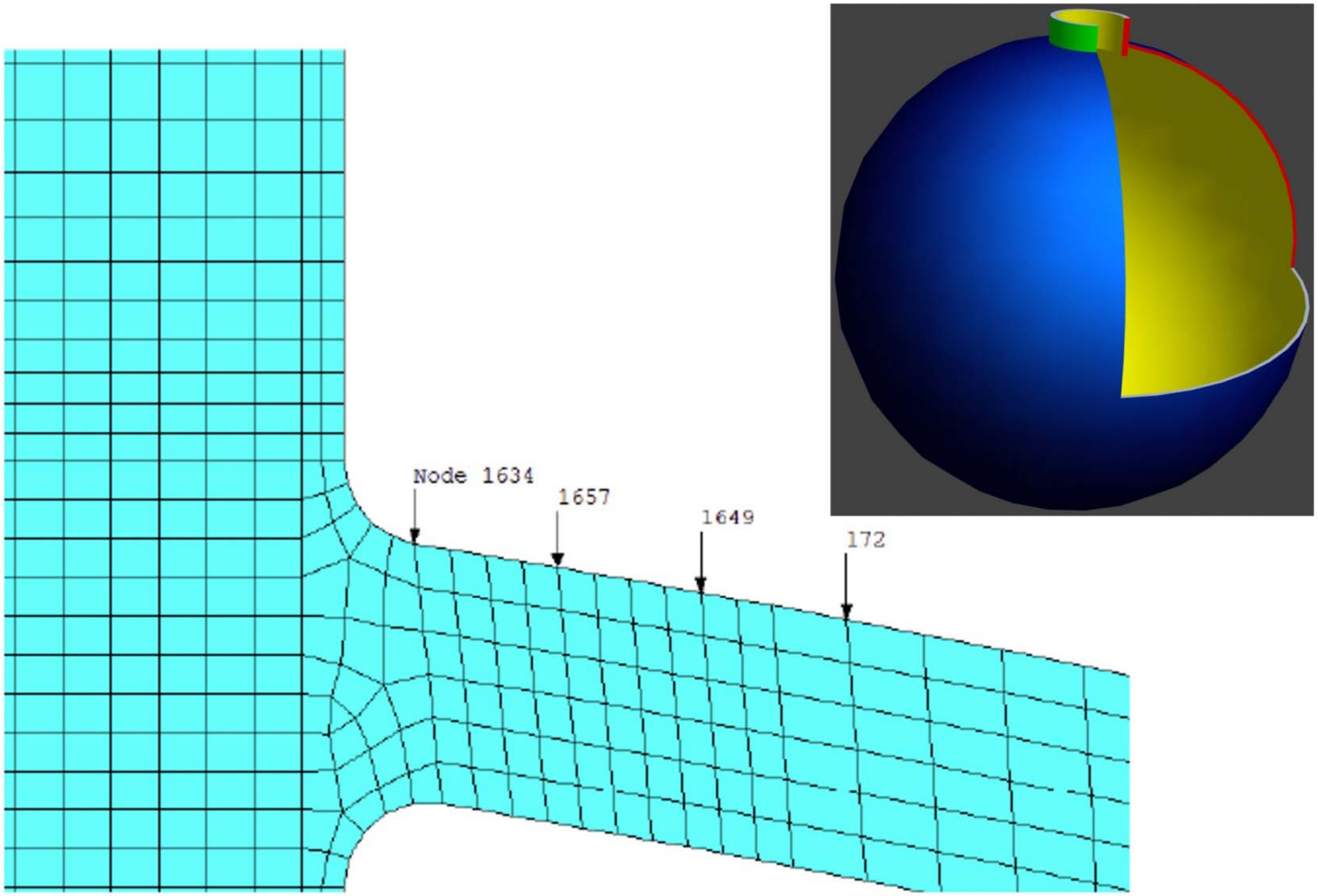

8.996e+01
8.000e+01
7.000e+01
6.000e+01
5.000e+01
4.000e+01
3.000e+01
2.000e+01
1.000e+01
6.372e-01
Linearized Stress Report
Point 1 X: 792 Y: 648
Point 2 X: 808 Y: 648
Component Max Principal
Stress Point 1 Midpoint Point 2 Maximum
Membrane 32.92449 32.92449 32.92449 32.92449
Bending 49.35231 0.1639612 -9.719663 49.35231
Mem+Bend 73.05582 32.92449 13.37686 73.05582
Peak 105.1653 2.33546 6.704906 105.1653
Total 174.2743 30.61497 16.58401 174.2743
Generate Report...
Done
1
2

Stress range

For welded regions structural stress ranges are used. The analysis is performed at location 2 - see above.

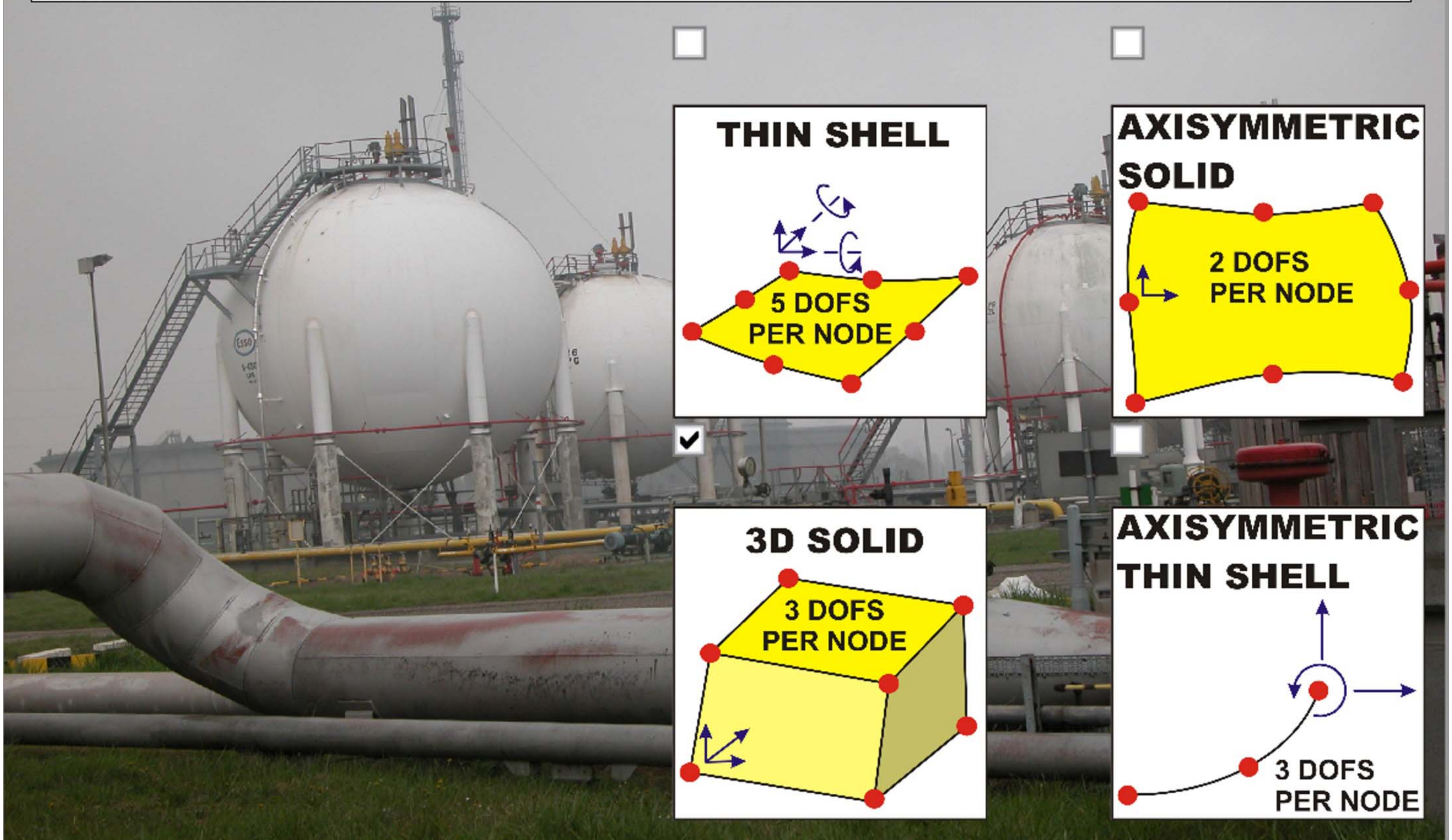
- The stresses for the calculation of the structural stress range are obtained by quadratic extrapolation at the investigated hot spot.

The structural equivalent stress range is calculated using the procedure described in EN13445-3 clause18 (for structural principal stresses direction remain constant).



Node points for quadratic extrapolation of structural principal stresses at the welded location 2

Which is the best element to determine the hot-spot stresses at the intersections of the multi-mitred pipe bend?



Check Answer | Explanation | Yes that is correct.

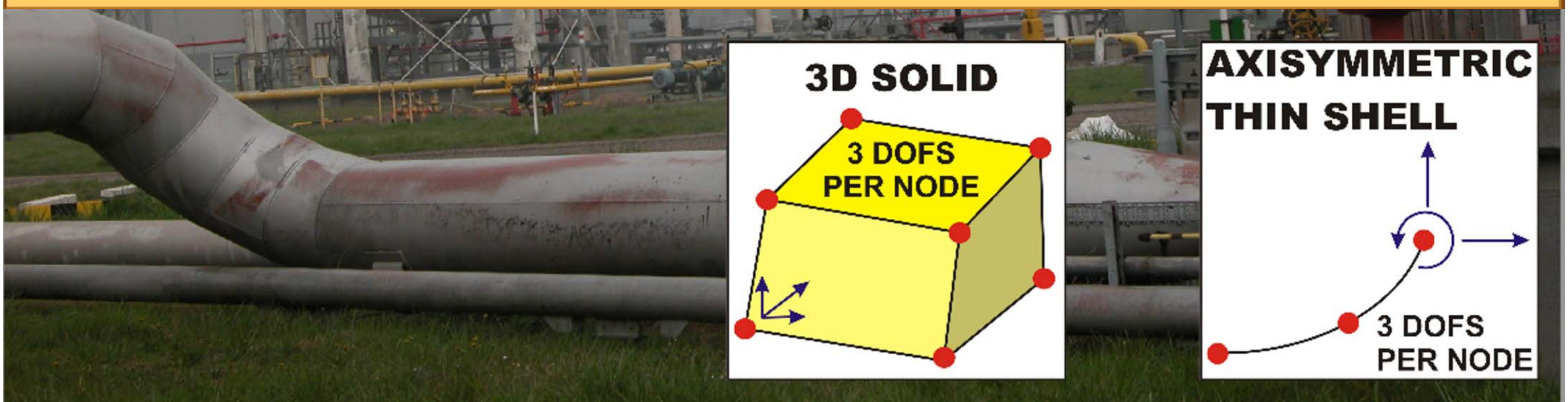
Which is the best element to determine the hot-spot stresses at the intersections of the multi-mitred pipe bend?

Answer:

3D Solid

Explanation:

The multi-mitre geometry is clearly not axisymmetric. While hot-spot stresses can be obtained from thin-shell elements, a 3D solid representation would allow both surface extrapolation and through-thickness linearization techniques to be used. This type of idealization would avoid the inherent approximations of thin shell theory and would also allow the actual weld-profile and any toe grinding to be modeled as well if necessary. Given today's typical computing resources, such a level of idealizations is perfectly feasible.



Check Answer

Explanation

Yes that is correct.

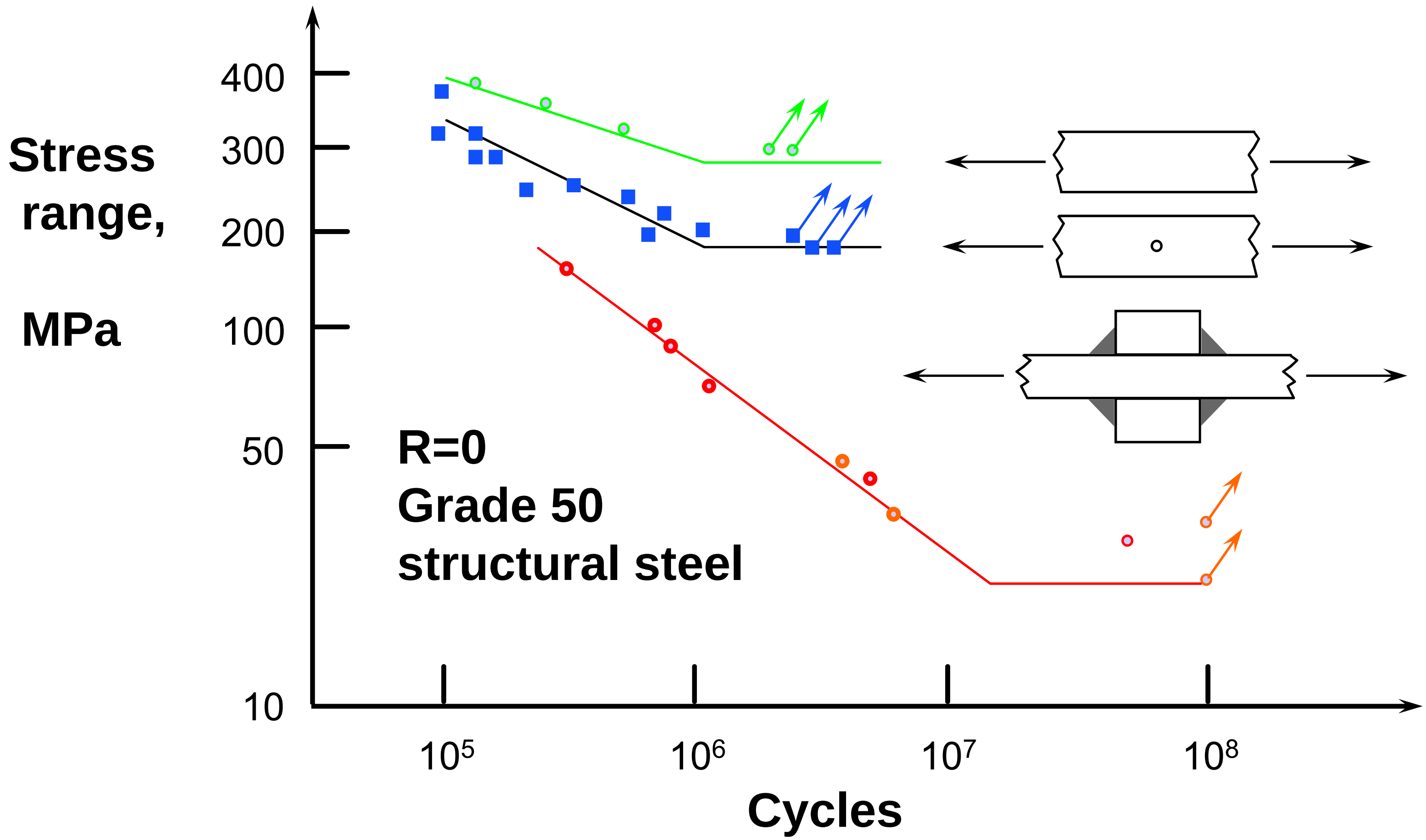
Agenda

- **Introduction and Relevant CCOPPS Activity**
  Jim Wood
- **Fatigue of Welded Pressure Vessels**
  Steve Maddox
- **Q&A Session**
  Steve Maddox & Jim Wood
- **Closing Remarks**
  Jim Wood

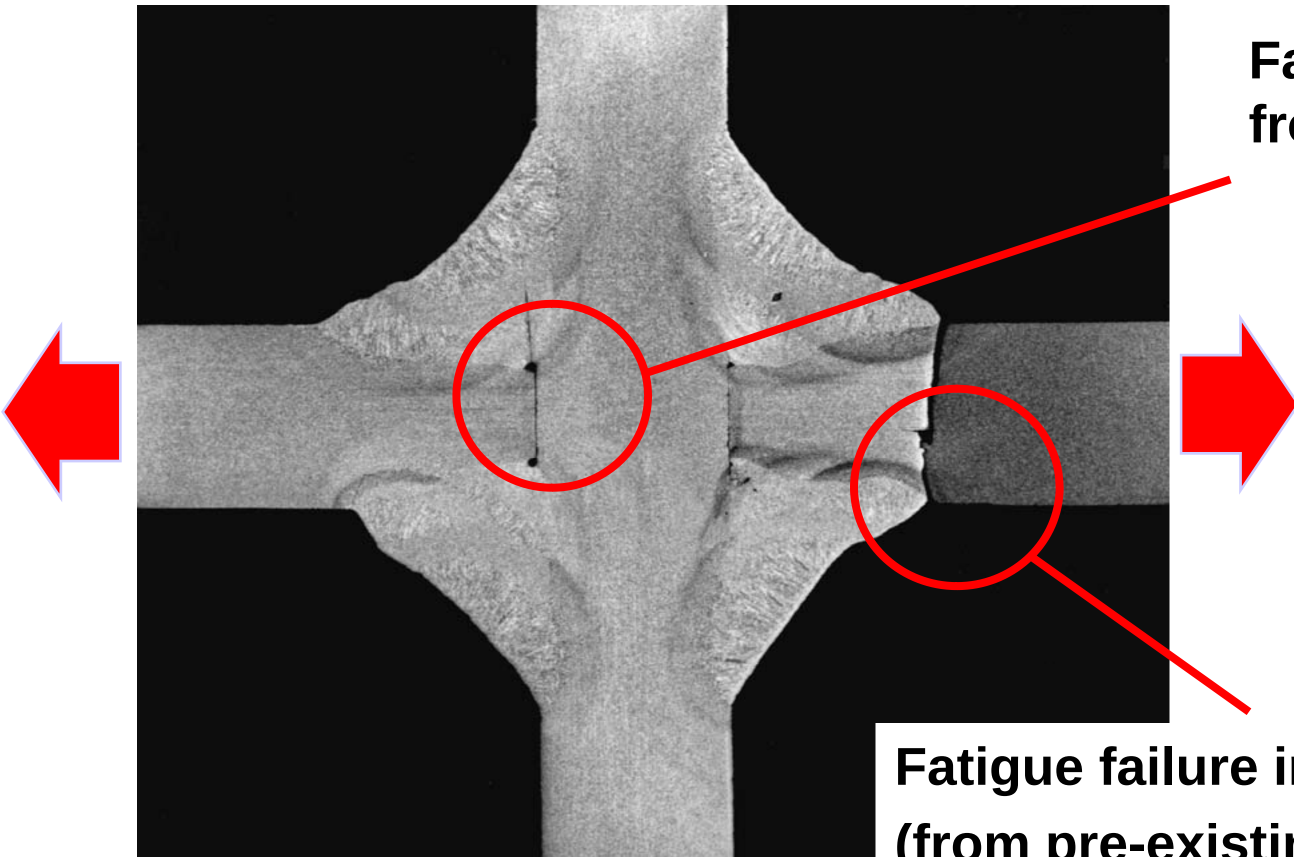
Fatigue design of welded pressure vessels

- BS PD 5500 Annex C, EN 13445-3 and ASME VIII, Division 2 (new structural stress approach)
- Fatigue failure in pressure vessels
- Fatigue design data
- Stresses used in fatigue design
- Detailed fatigue assessment
  - use of design curves
  - classification of weld details
  - stress concentrations
  - fatigue life improvement
- Simplified assessment methods
- Fatigue assessment of welding imperfections
- Future needs

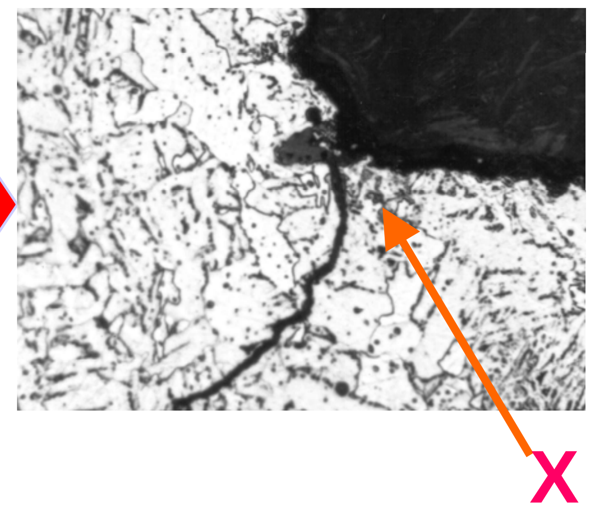
Effect of welding on fatigue resistance



Fatigue cracking in a welded joint



Fatigue cracking from weld root



Fatigue failure in plate at toe
(from pre-existing sharp flaw at X)

Key features of welds and welded joints

- Sharp section changes - High SCF
- Local discontinuities - Crack initiation sites
- High tensile residual stresses - Maximum mean stress effect, compressive stresses damaging

Consequences:

- Relatively <u>low</u> fatigue strength,
- <u>dominated</u> by fatigue crack growth
- and <u>controlled</u> by full applied stress range.
- Fatigue life <u>not increased</u> by use of higher strength material

Fatigue failure in pressure vessels

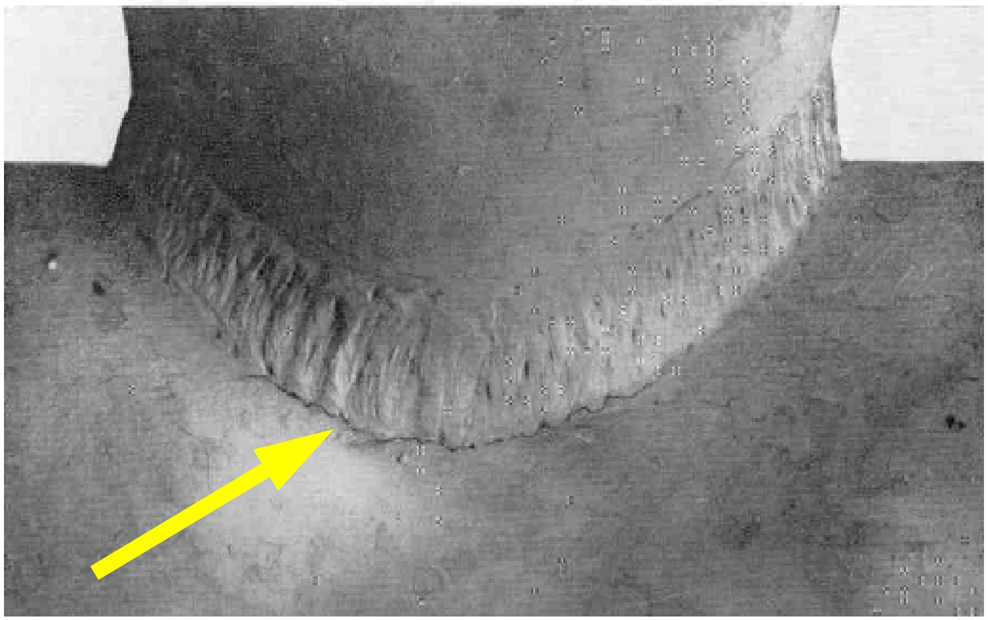
Fatigue loading

- Pressure fluctuations
- Temperature changes
- Temperature differentials
- External mechanical loading
- Vibration

Sources of stress concentration and hence fatigue cracking

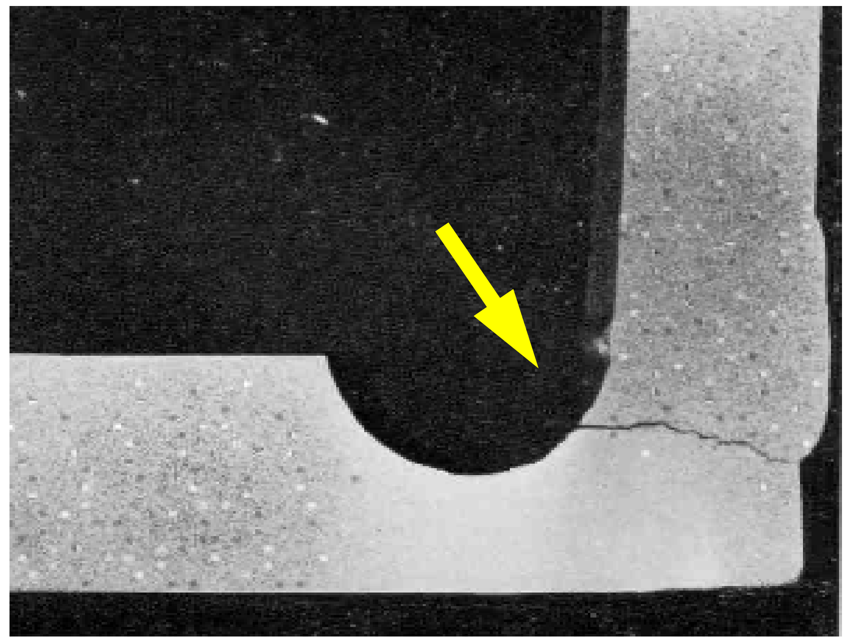
- Joints (welds, bolts)
- Geometric discontinuities (openings, nozzles, ends, supports)
- Temporary attachments

Fatigue failure from weld details



Fatigue cracking from nozzle weld toe

Fatigue cracking from inside of butt weld between a cylindrical shell and a flat end



Fatigue design process

Compare number of repetitions (n_i) of stress range Sr_i which vessel or part of vessel must withstand in its service life with the number (N_i) withstood by representative specimens at same stress in fatigue tests, such that:

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + etc = \Sigma \frac{n_i}{N_i} \leq 1.0$$

***N* values obtained from relevant design S-N curves**

Basis of fatigue design data and assessment method for welded joints

- BS PD 5500 and EN 13445 adapted from nominal stress-based fatigue rules for welded structures (bridges, offshore structures, etc)
- Thus, grid of S-N curves each applicable to one or more particular weld detail, chosen on the basis of a classification system
- In general, curves related to structural stress range
- For potential fatigue failure from weld toe, structural stress range at toe (hot-spot structural stress range) may be used
- New ASME VIII uses only hot-spot structural stress calculated in a specific way and converted to a fracture mechanics–based parameter called the 'Equivalent structural stress range parameter'

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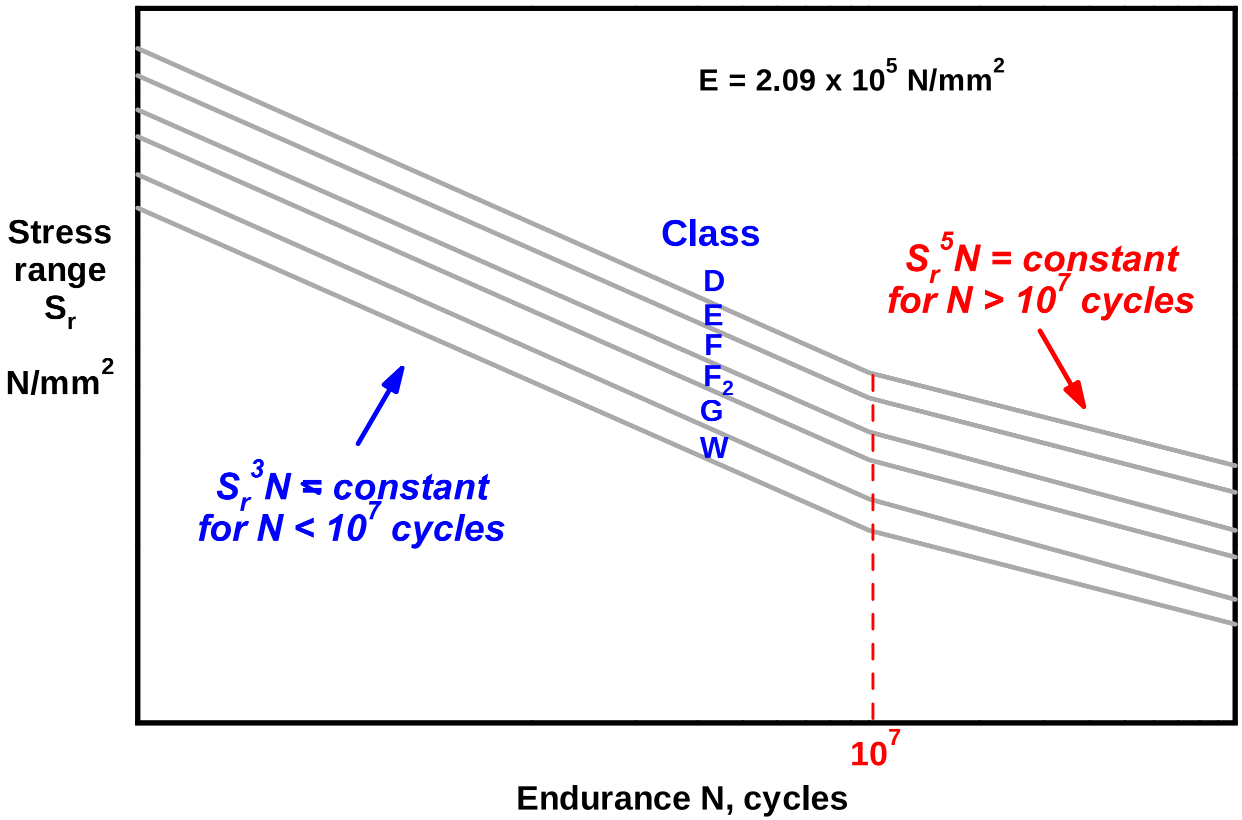
Fatigue design curves for weld details in BS PD 5500 and other UK Standards



- Applicable to any of metals covered by PD 5500, on basis of relative E values
- For thickness $e > e_{ref}$, where e_{ref} =22mm, allowable stress

$$= S_r \cdot \left(\frac{e_{ref}}{e}\right)^{0.25}$$

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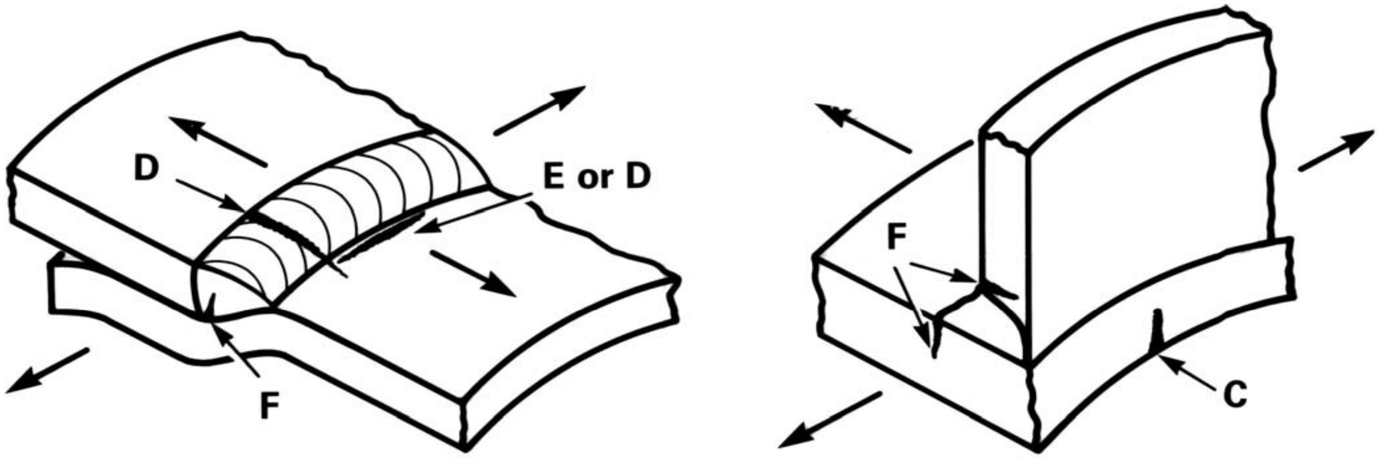
Weld detail classification in BS PD 5500



Classification depends on:

- welded joint geometry
- direction of loading
- crack initiation site
- methods of manufacture and inspection

Stresses used in BS PD 5500 for fatigue design

- Structural (primary + secondary) stress range
- Principal stress (not stress intensity) used directly
- Nominal stress for simple details (e.g. attachments, seam welds)
- Nominal stress x SCF for structural details, or
- Hot-spot structural stress at any weld toe (Higher design curve than those used with nominal stress)
- Net section of load-carrying fillet welds

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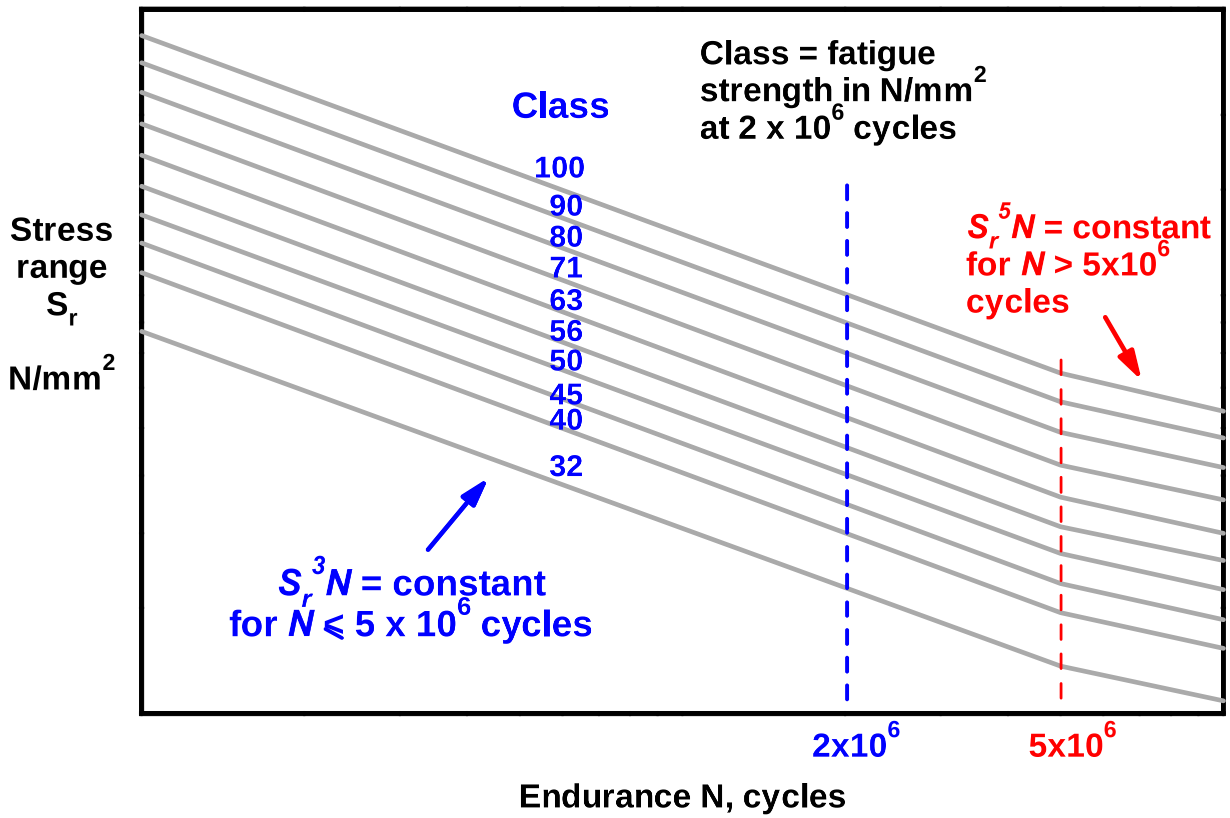
Fatigue design S-N curves for weld details in EN 13445



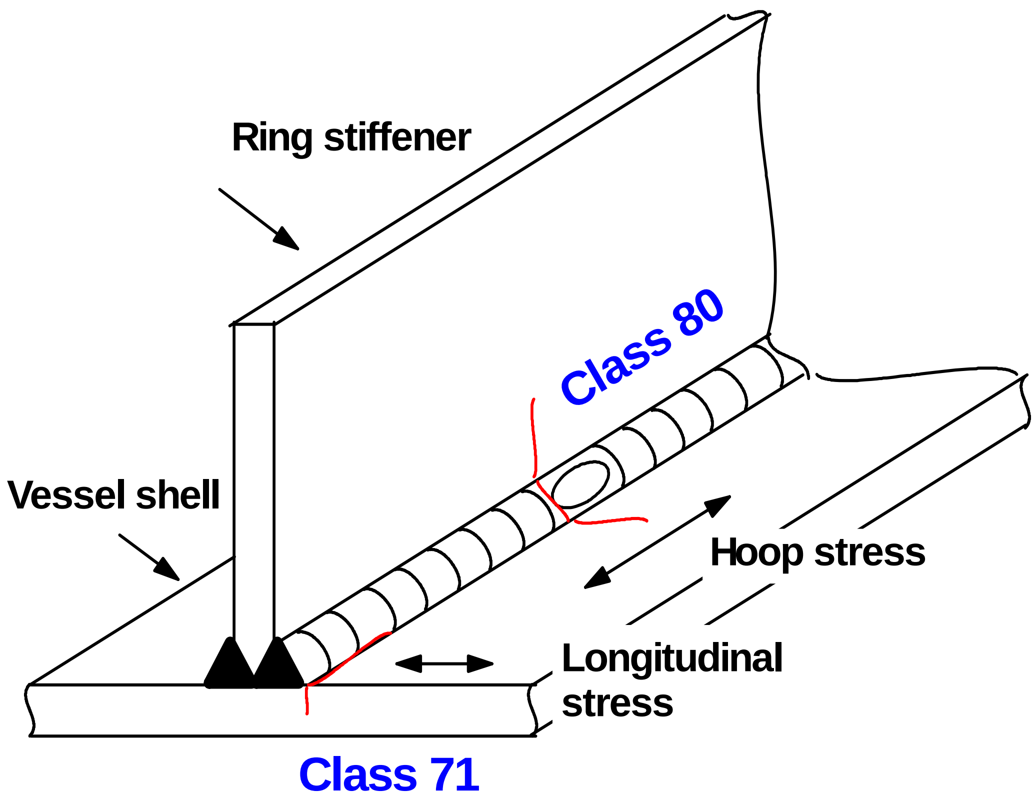
- Currently applicable only to steel
- For thickness e > 25mm, allowable stress

$$= S_r \cdot \left(\frac{25mm}{e}\right)^{0.25}$$

Stresses used in EN 13445 for fatigue design

- Structural (primary + secondary) stress range
- Option to use principal or equivalent stress range
- Nominal stress for simple details (e.g. attachments, seam welds)
- Structural stress at any weld toe (Hot-spot stress)
- Net section of load-carrying fillet welds

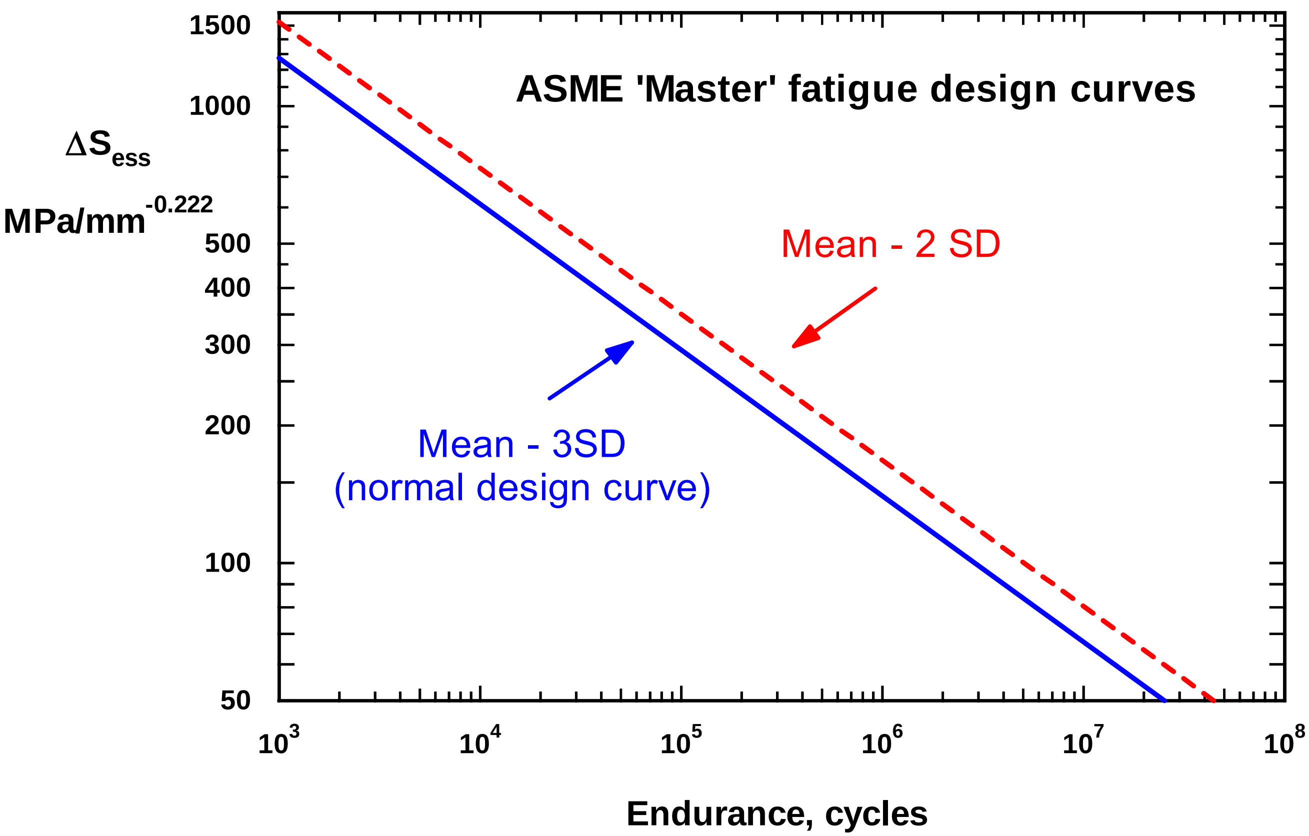
Weld detail classification in EN 13445



EN 13445 offers choice of using equivalent stress or principal stress. Since equivalent stress has no direction, a consequence is that the lowest detail Class must be assumed.

Thus, the joint shown would be designed as Class 71.

Fatigue design curves from ASME VIII



- Applicable to any of metals covered by ASME on basis of relative E values
- Stress parameter depends on plate thickness, membrane/bending stress ratio and applied stress ratio (**Not** units of stress)
- No other thickness correction required

Basis of fatigue design curves

- Regression analysis of S-N data obtained from tests on actual welded joints
- ≈2.5% probability of failure (mean – 2 standard deviations of log N [SD]):-

  BS PD 5500 design curves; included in ASME.
- ≈ 0.1% probability curves (mean - 3SD):-

  BS PD 5500 simplified design methods; all EN 13445 design curves for weld details; generally required for ASME

Application of design curves for weld details

- No effect of applied mean stress in PD 5500 and EN 13445; mean stress correction in ASME
- No effect of material tensile strength
- No effect of welding process
- May need to be reduced to allow for corrosive environment; no specific guidance in BS PD 5500 or EN 13445 but penalty factors specified in ASME

Stresses used in ASME VIII Div. 2 for fatigue design of welded joints

- Structural (primary + secondary) stress range based on through-thickness stress distribution obtained by numerical analysis
- Structural equivalent stress range parameter (a function of material's fatigue crack propagation properties *(m*=3.6), applied structural stress range (Δσ), material thickness *(t)*, membrane to bending stress ratio and applied stress ratio):

$$\Delta S_{ess} = \frac{\Delta\sigma}{t_{ess}^{\frac{2-m}{2m}} . I^{\frac{1}{m}} . f_M}$$

Generalized stress parameter (Maddox, 1974)

$$da/dN = C(\Delta K)^m, \quad \Delta K = Y\Delta\sigma\sqrt{\pi a}, \; Y = f(a/t \;\&\; \text{crack front shape } a/2c)$$

$$\therefore \int_{a_i/t}^{a_f/t} \frac{d(a/t)}{\left(Y\sqrt{\frac{\pi a}{t}}\right)^m} = I = C\,\Delta\sigma^m\, t^{\left(\frac{m}{2}-1\right)} N$$

$$\text{i.e} \left[\Delta\sigma\left(\frac{t^{\left(\frac{m}{2}-1\right)}}{I}\right)^{1/m}\right]^m .N = 1/C = \text{constant}$$

$$\text{or} \qquad \left(\Delta\sigma^*\right)^m .N = \text{a constant},$$

$$\text{where} \quad \text{'Generalized stress parameter'}\; \Delta\sigma^* = \Delta\sigma\left(\frac{t^{m/2-1}}{I}\right)^{\frac{1}{m}}$$

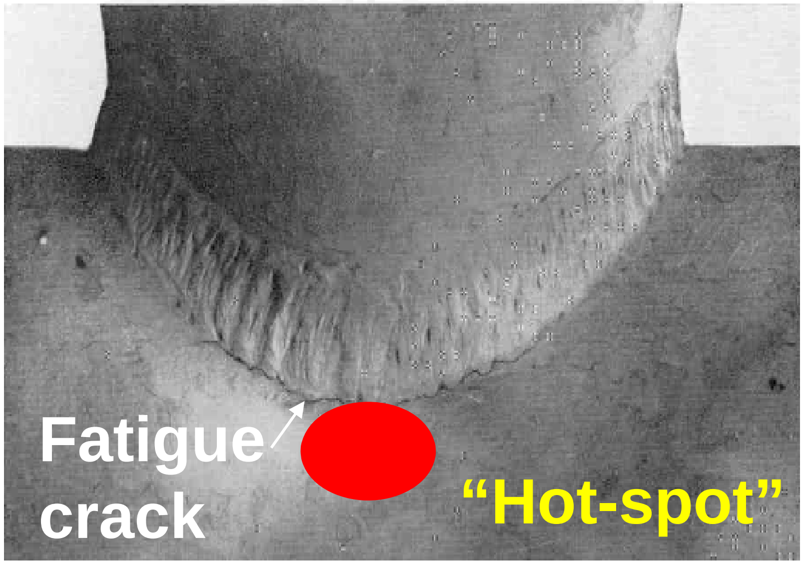
$$\text{or} \quad \Delta\sigma^* = \frac{\Delta\sigma}{t^{\frac{2-m}{2m}}.I^{\frac{1}{m}}} \quad (\text{cf}: \text{ASME } \Delta S_{ess})$$

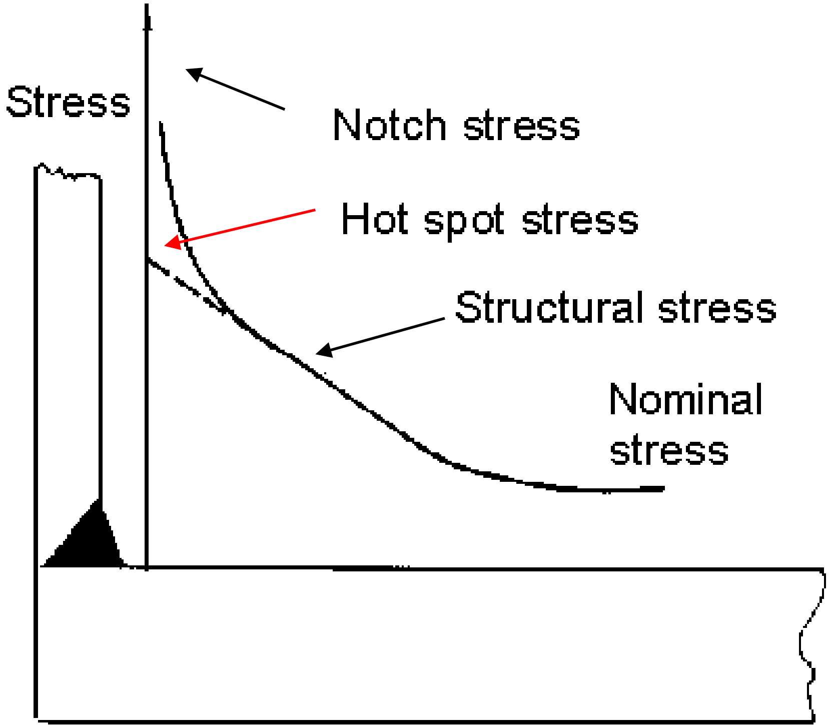
ASME Equivalent structural stress range parameter ΔS_{ess}

Based on:

- Structural stress (presumably assumed to allow for SCF factor M_k normally applied to stress intensity factor)
- Fatigue life mainly growth of a pre-existing crack
- Implicit assumptions made about initial flaw size and shape
- Specific fatigue crack growth rate relationship

Hot-spot structural stress approach

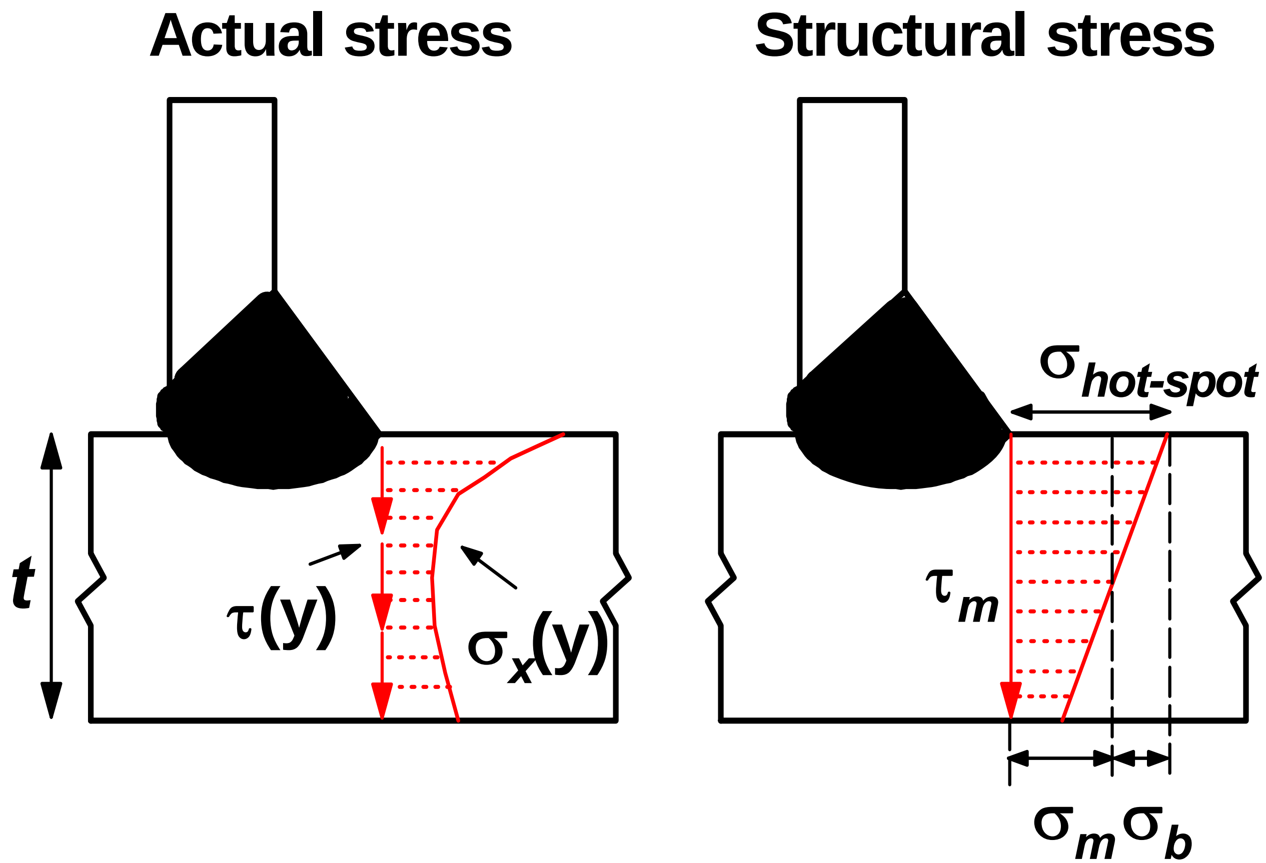




Hot-spot stress = structural stress at weld toe.

It includes all stress concentrating effects except the local notch effect of the weld toe.

Hot-spot structural stress from through-thickness stress distribution



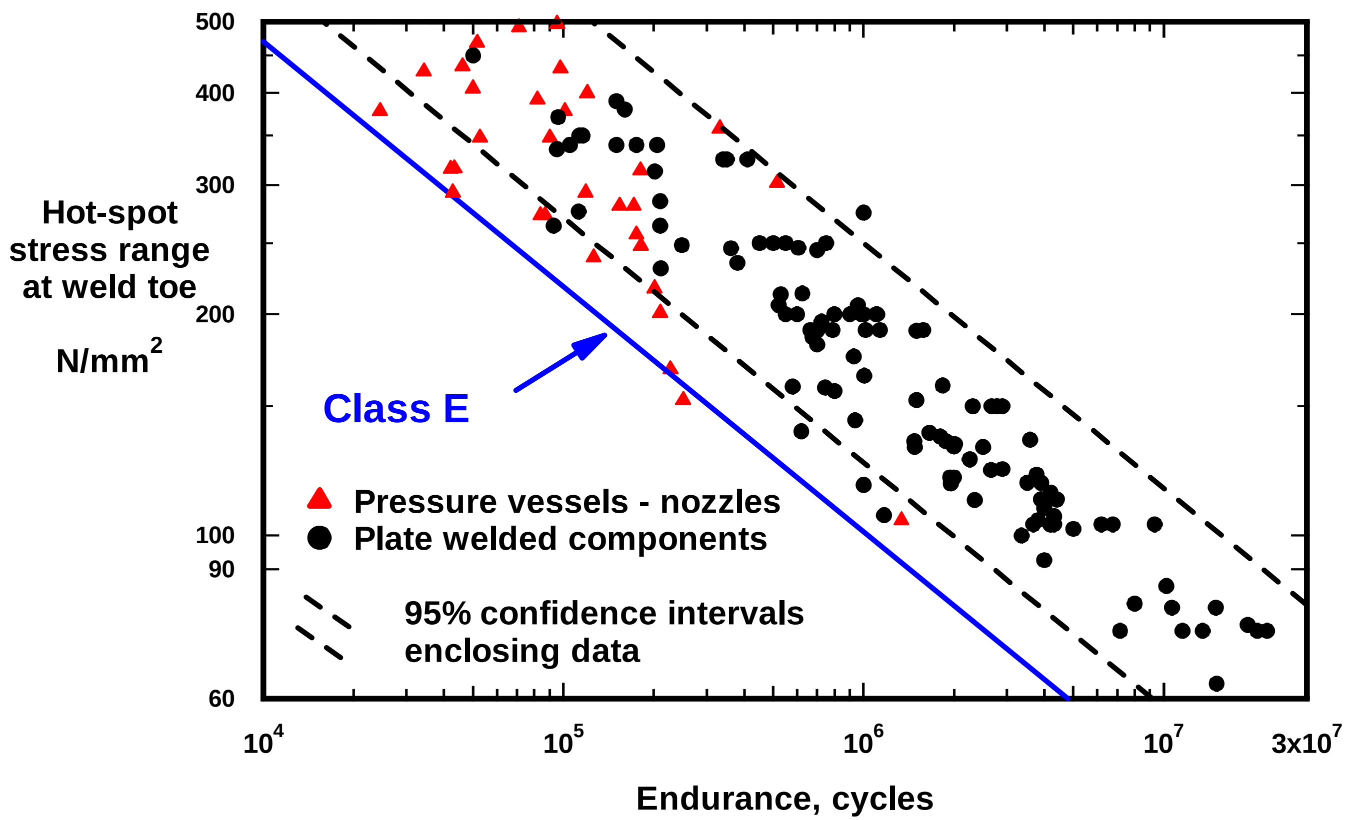
Methods for calculating the hot-spot structural stress

- Using surface stresses (e.g. measured):
  Surface stress extrapolation (SSE)
- Using through-thickness stress distribution (e.g. from numerical analysis):
  - Through-thickness integration (TTI)
  - Nodal forces (NF) method

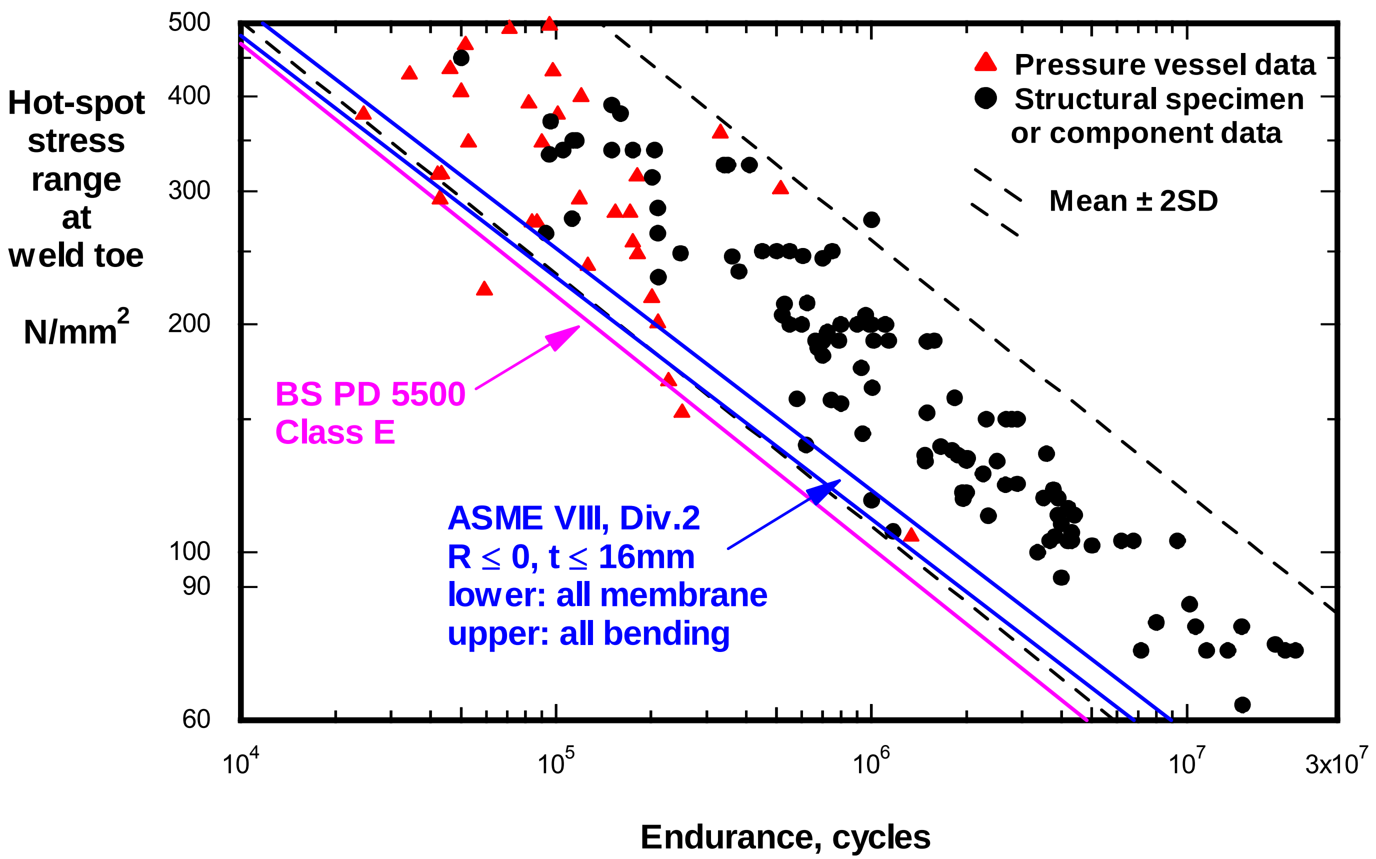
Hot-spot stress developments in British Standards

- Current TWI joint-industry project aims to produce guidance on hot-spot structural stress approach for inclusion in British Standard fatigue design rules (initially BS 7608)
- Comparison of the three methods of calculating hot-spot stress (SSE, TTI and NF) from FEA
- Solid and shell elements, examination of sensitivity to mesh size
- Case studies on range of structural components
- All methods mesh sensitive but mesh sensitivity least for simple welded joints in plates under unidirectional loading
- Findings so far indicate that nodal force method most mesh sensitive of the three when applied to structural component
- Mesh insensitivity of the ASME method may be for a restricted set of possible mesh types and weld meshing options.

Fatigue data expressed in terms of hot-spot stress range (SSE method)



Comparison with mean – 2SD S-N curves derived from ASME VIII



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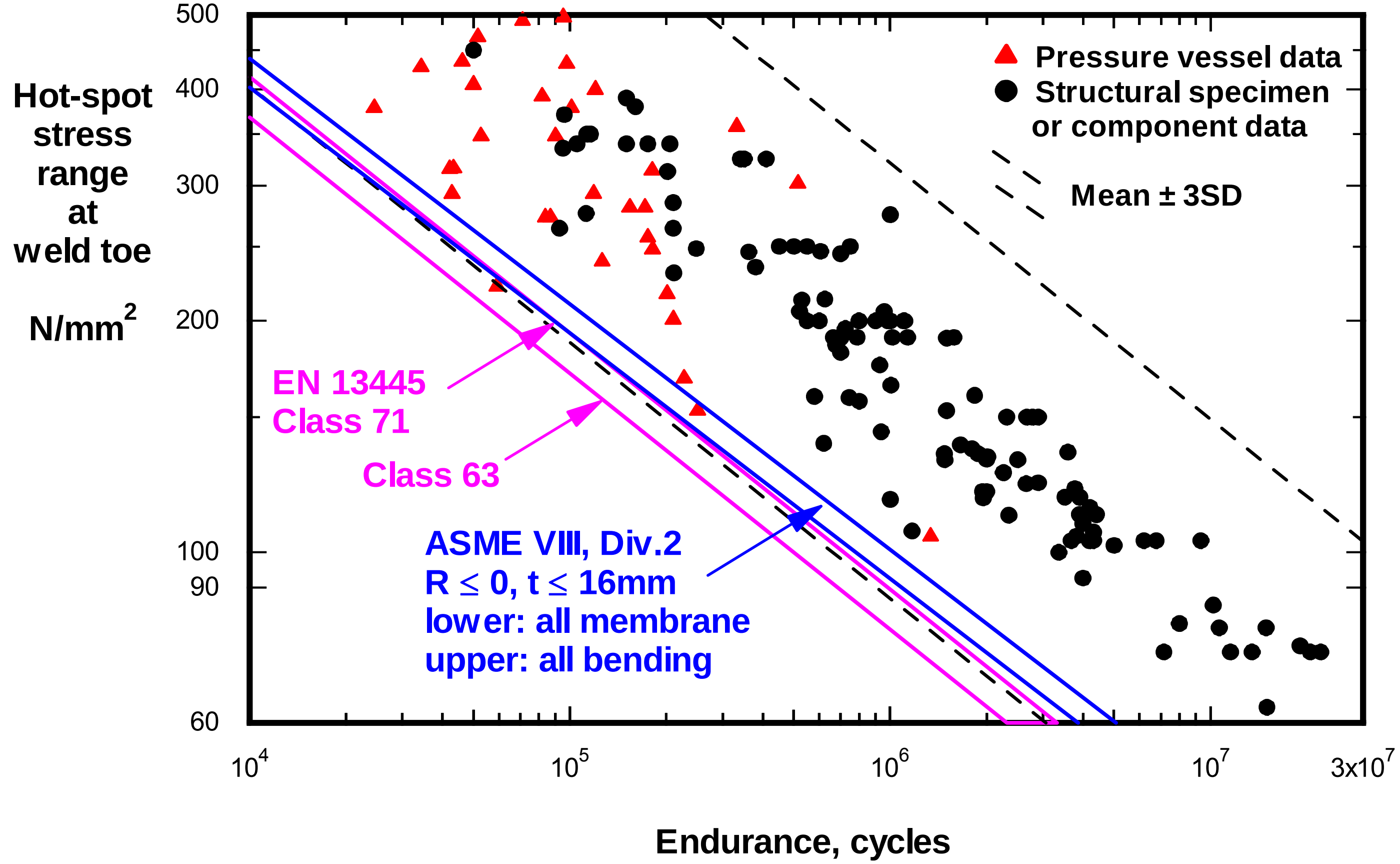
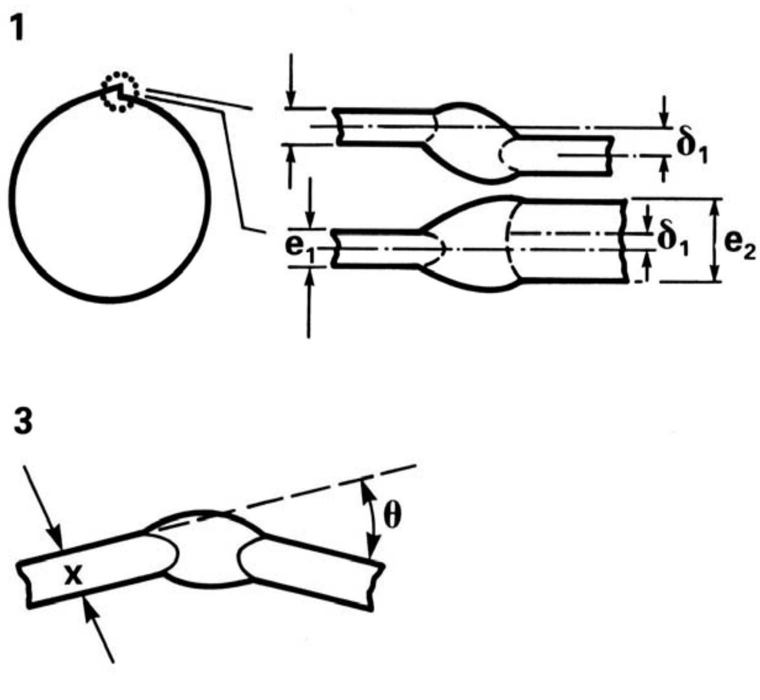
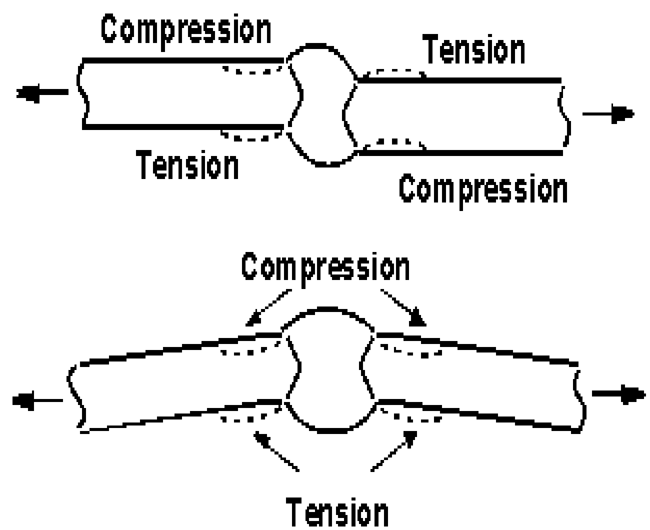
Comparison with mean – 3SD S-N curves derived from ASME VIII



Misalignment as a source of stress concentration

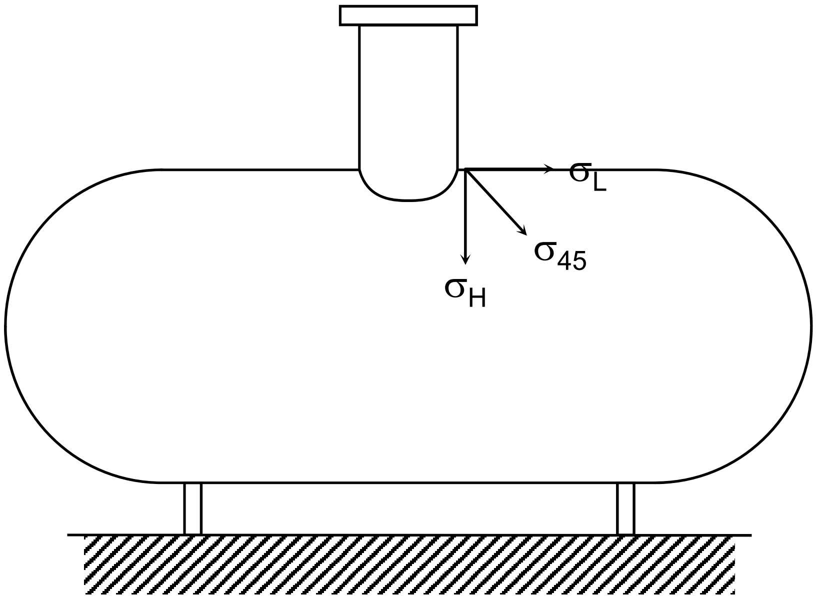




Bending stresses due to misalignment

Same guidance on calculation of SCF is given in PD5500 and EN 13445

Treatment of weld details subject to combined or multi-axial loading



$\Delta\sigma_L$ = Maximum change in σ_L

$\Delta\sigma_H$ = Maximum change in σ_H

$\Delta\sigma_{45}$ = Maximum change in σ_{H45}

Principal stresses then calculated from $\Delta\sigma_L$, $\Delta\sigma_H$, and $\Delta\sigma_{45}$

Same approach in PD5500 and EN 13445. Current research should provide better method for out-of-phase loading.

ASME treatment of weld details subject to multi-axial loading

$$\Delta S_{ess} = \frac{1}{F(\delta)}\left[\left(\frac{\Delta\sigma}{t_{ess}^{\frac{2-m}{2m}} . I^{\frac{1}{m}} . f_M}\right)^2 + 3\left(\frac{\Delta\lambda}{t_{ess}^{\frac{2-m}{2m}} . I^{\frac{1}{m}}}\right)^2\right]^{0.5}$$

Where:

For in-phase loading (principal stress directions remain constant throughout loading cycle), F(δ) = 1

while

For out-of-phase loading (principal stress directions change during loading cycle), F(δ) = function of applied normal and shear stresses and out-of-phase angle, or conservative value of 1/√2

Elastic-plastic (E-P) conditions

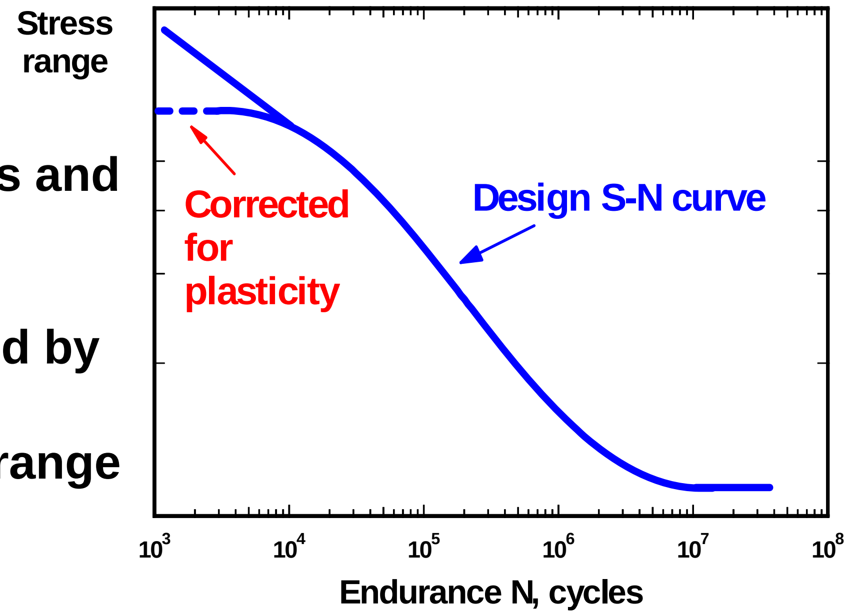
BS PD 5500 & EN 13445:

For stress ranges > twice yield:

E-P strain obtained directly from analysis and converted to stress

or

Stresses from design S-N curves reduced by factor that depends on load source (mechanical or thermal) and stress range / yield.



ASME VIII, Div. 2:

For every case:

E-P strain obtained directly from analysis (Neuber's rule & material's cyclic stress-strain properties) and converted to stress range

Fatigue life improvement methods

- BS PD 5500 and EN 13445 allow weld toe grinding and corresponding increase in design classification
- ASME VIII accepts weld toe grinding, TIG dressing or hammer peening. Equivalent structural stress parameter design curves increased accordingly, with greatest benefit in high-cycle regime

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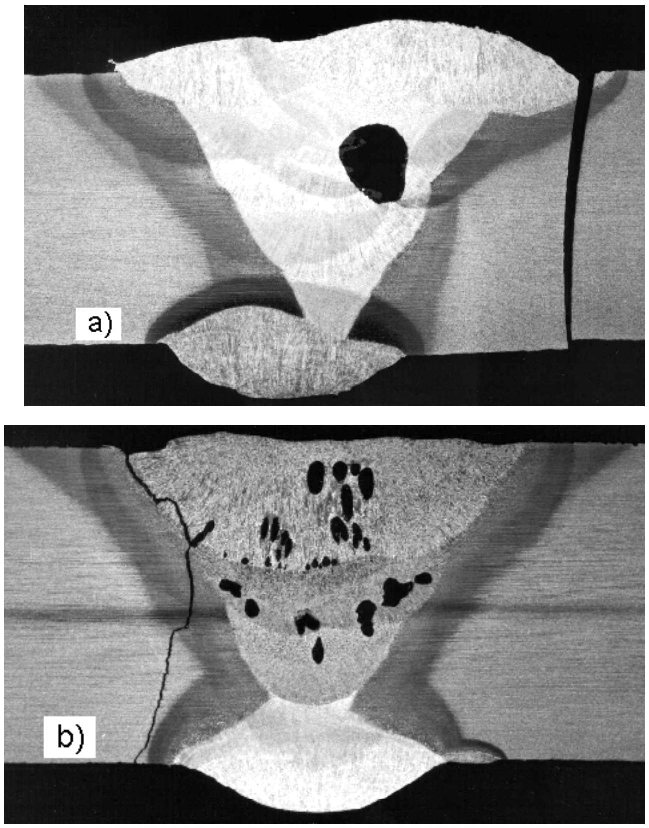
Assessment of welding flaws



Guidance given in BS PD 5500 and EN 13445 on flaw assessment based on fitness-for-purpose:

- Reference to BS 7910
- Specific recommendations on:

1. Planar flaws not acceptable
2. Buried flaws - inclusions, porosity;
3. Deviations from design shape - misalignment, peaking, ovality.

ASME seems to accept planar flaws since equivalent structural stress parameter can be calculated for cracks up to 10% of section thickness

Fatigue design of pressure vessels - future needs

- Parametric hot-spot SCFs for pressure vessel details
- Elastic-plastic fatigue
- Effect of environment (corrosive, elevated temperature, hydrogen)
- Closer link between design and fabrication quality
- Experimental methods for design (draft for EN 13445 now available)

Thank you for your attention

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- **Introduction and Relevant CCOPPS Activity**
  Jim Wood
- **Fatigue of Welded Pressure Vessels**
  Steve Maddox
- **Q&A Session**
  Steve Maddox & Jim Wood
- **Closing Remarks**
  Jim Wood

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