Creep-fatigue life assessment of high-temperature weldments using the linear matching method

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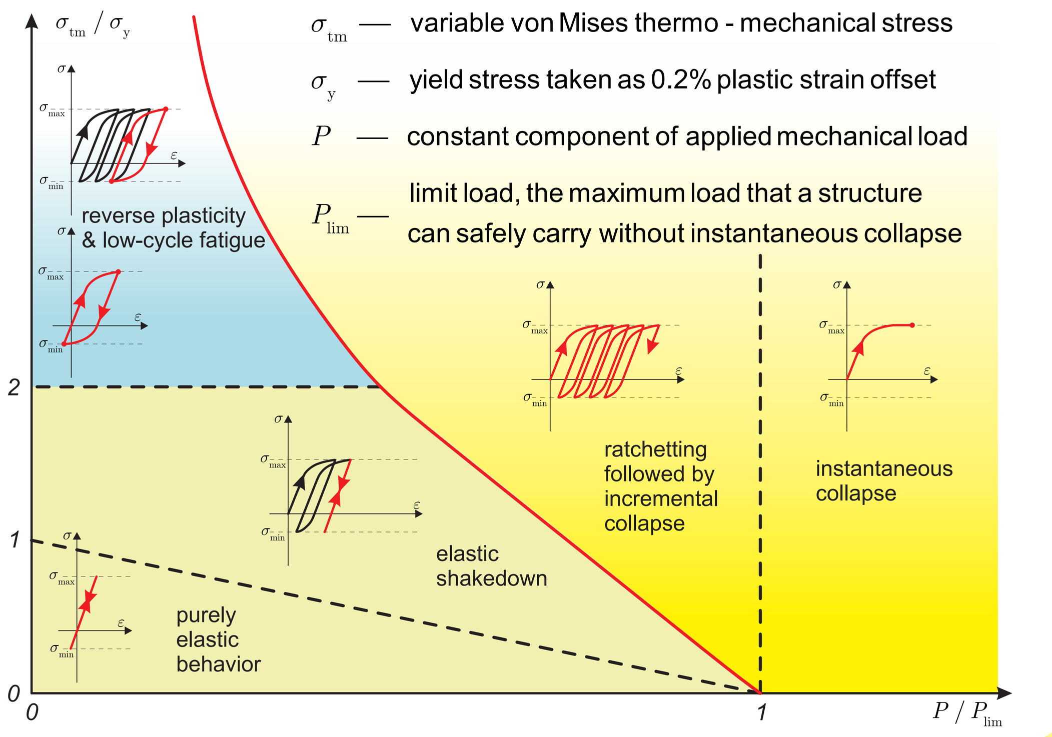
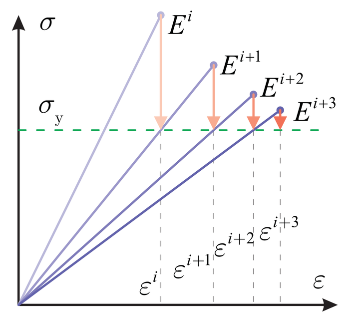
1. Theoretical Background and the Linear Matching Method

1.1 Bree diagram with responses to cyclic loading[1]



1.2 Fundamentals of the Linear Matching Method[2]

- belongs to the group of modified elastic modulus methods;
- has the character of a non-linear programming method;
- with each step involves the solution of a linear problem;
- each solution satisfies the condition of force equilibrium;
- non-linear constitutive equations are imposed sequentially;
- strain rate histories give rise to equilibrium residual stress fields;
- solution is the minimum of a functional of the strain rate history;
- generates inelastic solutions for the stabilized cyclic state;
- compatible with standard finite element codes, e.g. ABAQUS.



Alternatives to the LMM:

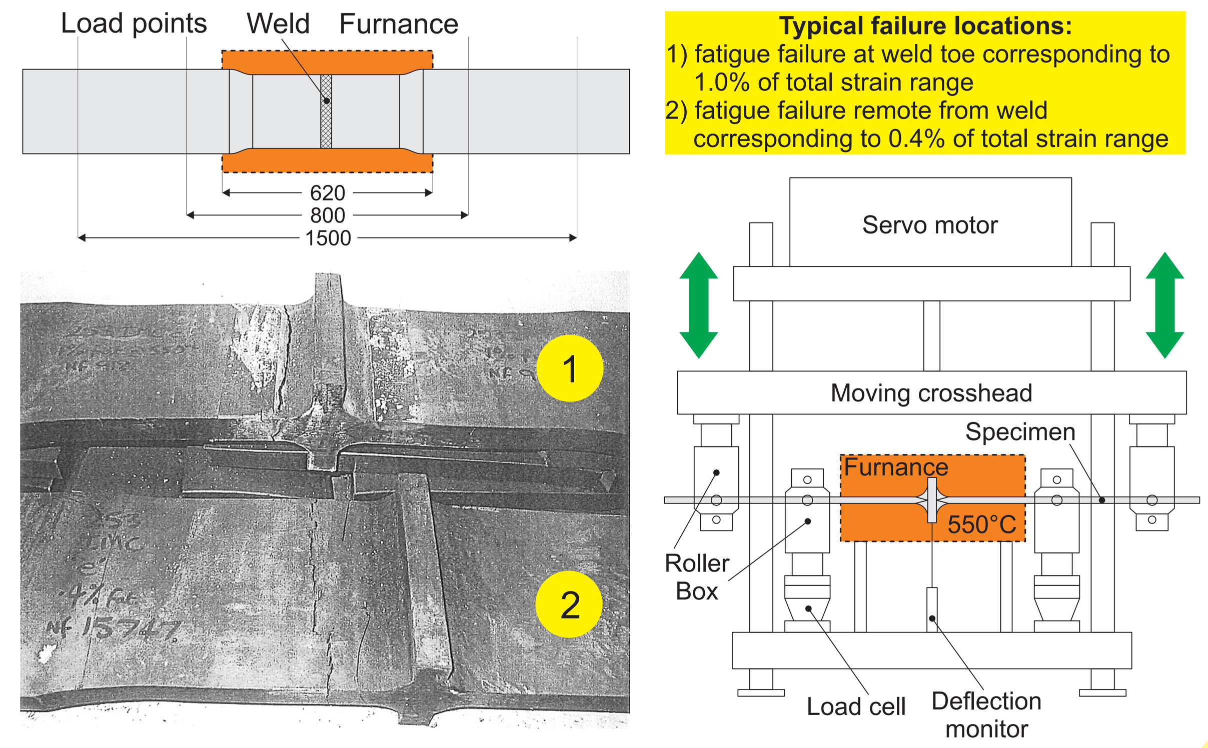
- Life Assessment Methods and Design Codes – R5 Procedure, ASME N47 and RCC-MR (1980's – today) based on Neuber's Rule
- Conventional incremental (transient) FEA
- Direct Cyclic Analysis (DCA) implemented into ABAQUS
- Direct Methods using Static or Kinematic Bounding Theorem (Koiter, 1960)

Development of the LMM framework:

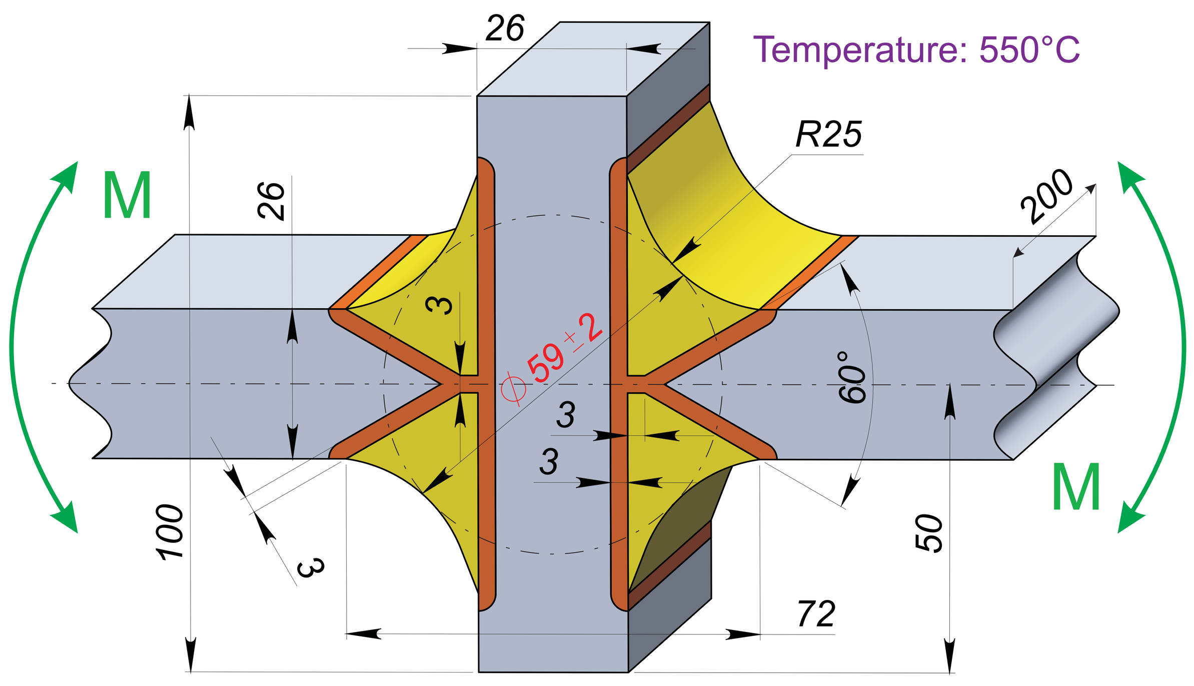
- Modified Modulus Method (MMM) for limit load analysis (Ponter, early 1990's)
- MMM modified for elastic shakedown analysis (Ponter & Carter, 1997)
- MEM implemented as ABAQUS UMATs (Ponter & Engelhardt, 2000)
- Linear Matching Method (LMM) implemented in ABAQUS for reverse plasticity (global shakedown) & ratchet boundary evaluation (Ponter & Chen, 2001)
- LMM further developed to evaluate R5 related parameters (Ponter & Chen, 2005)

2. Testing & modelling of cruciform weldment

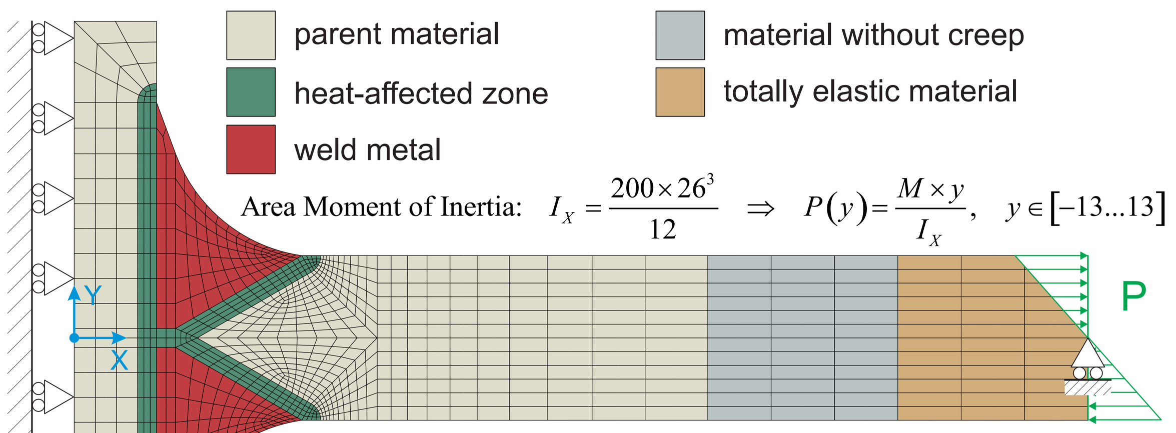
2.1 Experimental facility and specimen with typical failures[3]



2.2 Dimensions (mm) of the cruciform weldment specimen[3]



2.3 Parameters of the FE-model



Area Moment of Inertia: $I_x = \dfrac{200\times 26^3}{12} \Rightarrow P(y) = \dfrac{M\times y}{I_x}, \quad y\in[-13\ldots13]$

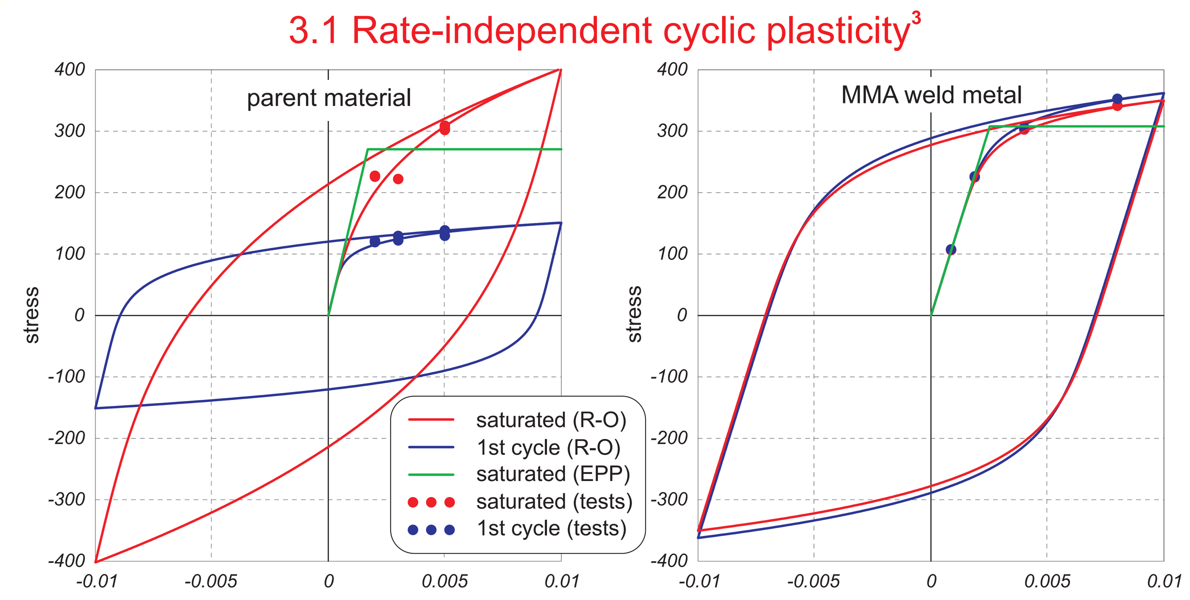
1) 977 CPE8R finite elements: 8-node biquadratic plane strain quadrilaterals with reduced integration

2) 3 variants of dwell period - pure fatigue, 1 hour, 5 hours

3) 5 variants of reverse bending moment M corresponding to $\Delta\varepsilon$ equal to 1.0%, 0.6%, 0.4%, 0.3% and 0.25% of total strain

3. Properties of the steel AISI type 316N(L) at 550°

3.1 Rate-independent cyclic plasticity[3]

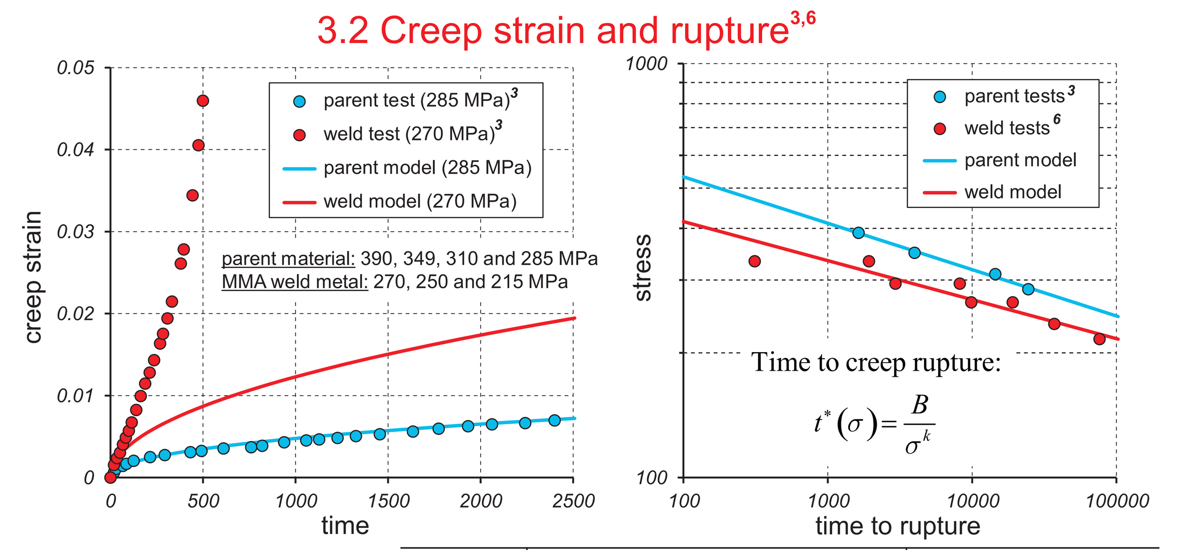


Deformation plasticity (Ramberg-Osgood model):

$$\frac{\Delta\varepsilon_{\rm tot}}{2} = \frac{\Delta\sigma}{2\bar{E}} + \left(\frac{\Delta\sigma}{2B}\right)^{1/\beta}, \quad \bar{E} = \frac{3E}{2(1+\nu)}$$

Zone	E (MPa)	B (MPa)	β	σ_y (MPa)
Parent	160000	1741.96	0.29960	270.662
Weld	122000	578.99	0.10162	307.894
HAZ	154000	1632.31	0.25304	338.731

3.2 Creep strain and rupture[3,6]



Time to creep rupture: $t^*(\sigma) = \dfrac{B}{\sigma^k}$

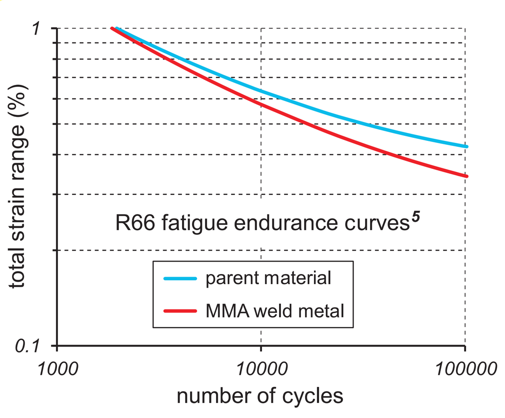
Time-hardening power-law:

$$\dot{\varepsilon}^{cr} = A\,\sigma^n t^m$$

$$\varepsilon^{cr} = \frac{A}{m+1}\sigma^n t^{m+1}$$

Zone	Primary creep strain			Time to creep rupture	
	A (MPa^{-n}h^{-m-1})	n	m	B (MPa^k h)	k
Parent	6.604E-19	5.769	-0.55	2.172E+26	8.927
Weld	6.597E-23	7.596	-0.5	5.993E+29	10.61
HAZ	6.600E-21	6.683	-0.525	1.291E+28	9.768

3.3 Low-cycle fatigue endurance[5]



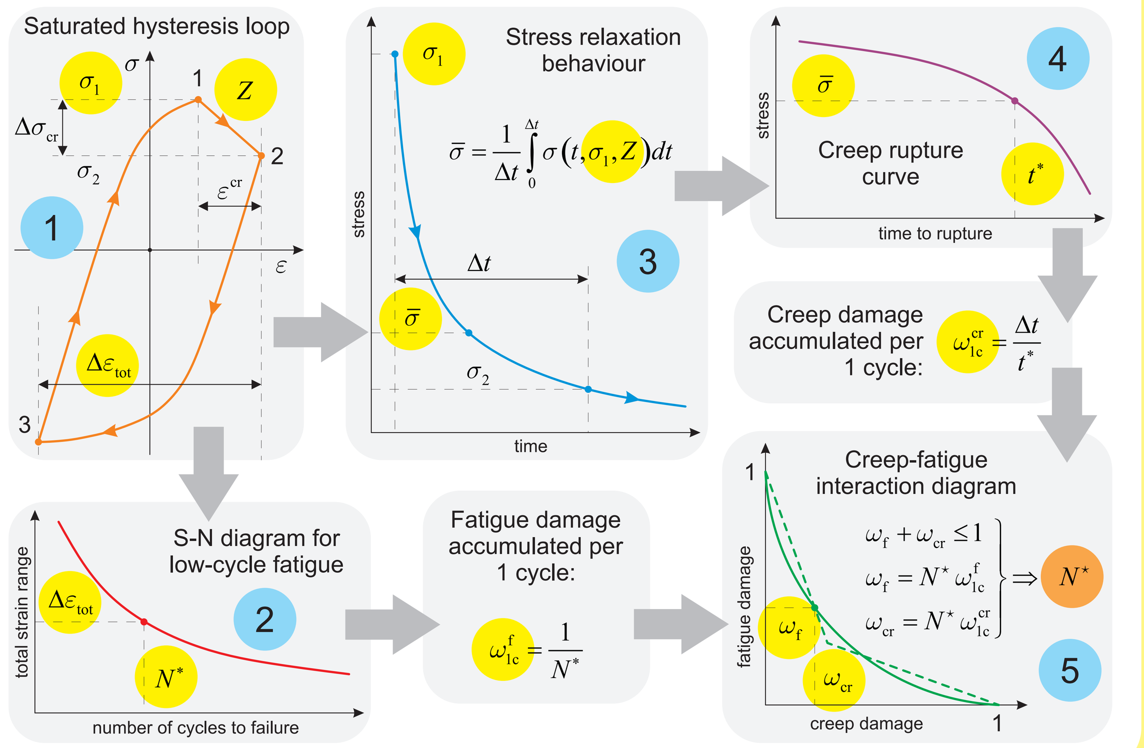
$$\log(\Delta\varepsilon^{\rm tot}) = m_0 + m_1\log(N^*) + m_2\log(N^*)^2 \quad \text{and}$$

$$\log(\Delta\varepsilon^{\rm tot}) = m_0 + m_1\log(N^*) + m_2\log(N^*)^2 + m_3\log(N^*)^3$$

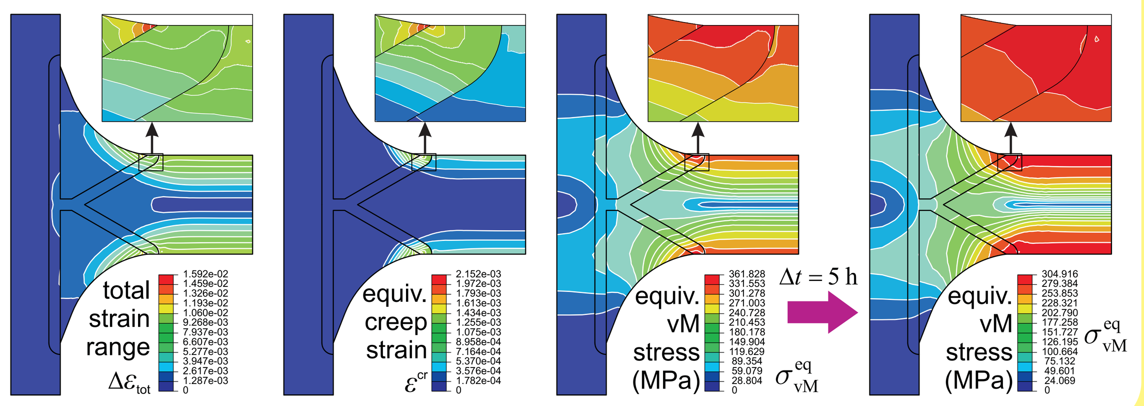
Zone	Quadratic		Cubic	
	parent	MMA weld	parent	MMA weld
m_0	1.73339	1.85169	2.40906	1.93432
m_1	-0.72959	-0.76094	-1.25128	-0.82500
m_2	0.06170	0.05951	0.19399	0.07585
m_3	—	—	-0.01102	-0.00137

4. Creep-Fatigue Evaluation Procedure

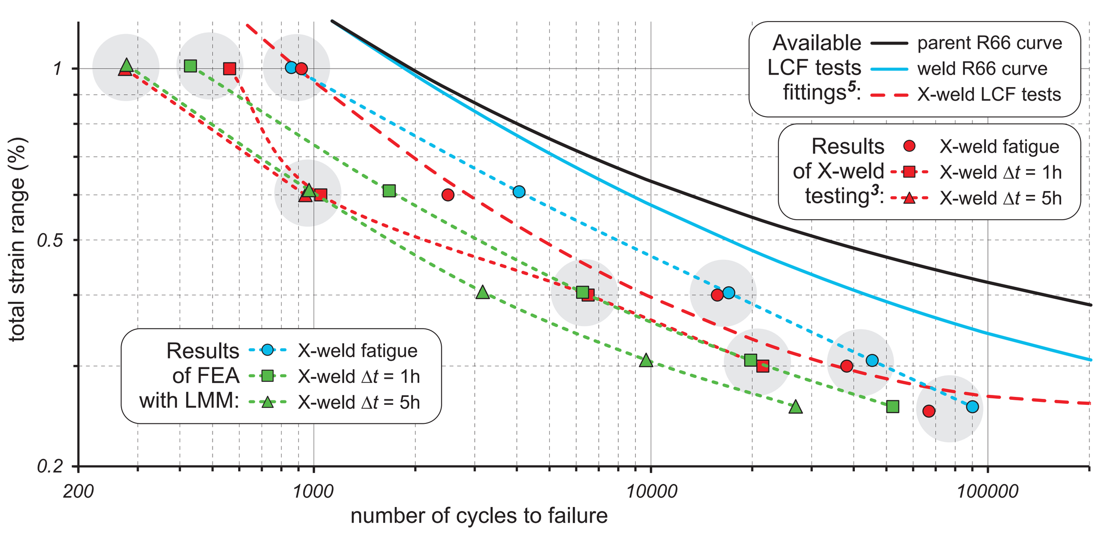
4.1 Creep-fatigue evaluation procedure with time fraction rule[4]



4.2 FEA/LMM results corresponding to $\Delta\varepsilon_{\rm tot}$ = 1% and Δt = 5h



4.3 Creep-fatigue evaluation results of the cruciform weldment



$\Delta\varepsilon^{\rm tot}$, %	Δt = 0 h				Δt = 1 h				Δt = 5 h			
	FEA/LMM		experiments[3]		FEA/LMM		experiments[3]		FEA/LMM		experiments[3]	
	N^*	failure	N^*	failure	N^*	failure	N^*	failure	N^*	failure	N^*	failure
1.0	857	T	918	T	430	T	562	U	278	T	275	P
0.6	4062	T	2499	U	1673	T	1048	U	967	T	943	W
0.4	17025	T	15747	P	6270	T	6512	U	3168	T	—	—
0.3	45374	W	38127	P	19776	T	21488	W	9679	T	—	—
0.25	90056	W	66847	P	52221	T	—	—	26901	T	—	—

(U) Specimen failed at the undercut close to the weld toe in the parent plate
(T) Specimen failed at the weld toe propagating through the HAZ
(P) Specimen failed in parent plate remote from weld
(W) Specimen failed in weld metal

5. Analysis of the Obtained Results

5.1 Analytical functions for cycles to failure and residual life

$\tilde{M} = \dfrac{\Delta M_{\rm var}}{\Delta M_{\rm sh}}$ (normalized moment)	Δt, dwell time (hours)								
	0	0.5	1	2	5	10	100	1000	10000
1.470528	857	500	430	362	278	223	95	33	8
1.153799	4062	2037	1673	1339	967	746	307	122	42
0.925507	17025	7963	6270	4756	3168	2294	799	308	121
0.777426	45374	24952	19776	14931	9679	6755	1963	635	230
0.691045	90056	63964	52221	40511	26901	18869	5116	1415	434

$$\log(N^*) = a(\Delta t)\tilde{M}^{-b(\Delta t)} \quad \Rightarrow \quad L^* = N^*\left[\frac{\Delta t}{365\cdot 24} + \frac{2\,\Delta\varepsilon_{\rm tot}(\tilde{M})}{\dot{\varepsilon}\,(365\cdot 24\cdot 60\cdot 60)}\right],$$

where Δt - dependent parameters:

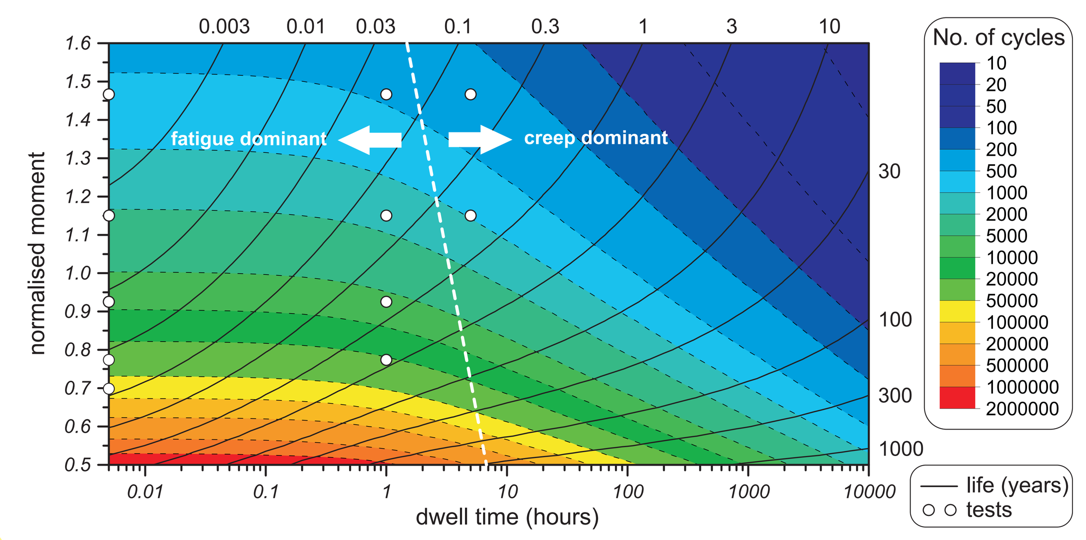
$a(\Delta t) = a_1\log(\Delta t+1) + a_2$

$b(\Delta t) = b_1\log(\Delta t+1) + b_2$

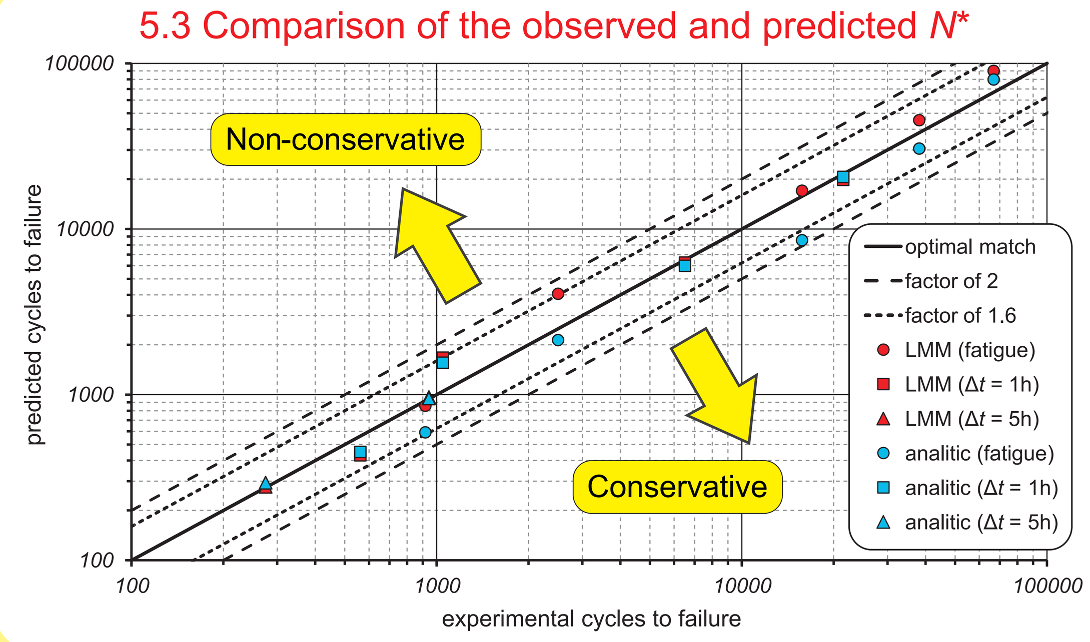
a_1	a_2	b_1	b_2
−0.4921	3.708929	0.0255	0.754959

$\Delta\varepsilon_{\rm tot}(\tilde{M}) = p_1\tilde{M} + p_2\tilde{M}^{p_3}$ with $p_1 = 0.2817,\ p_2 = 0.17649,\ p_3 = 3.11051$

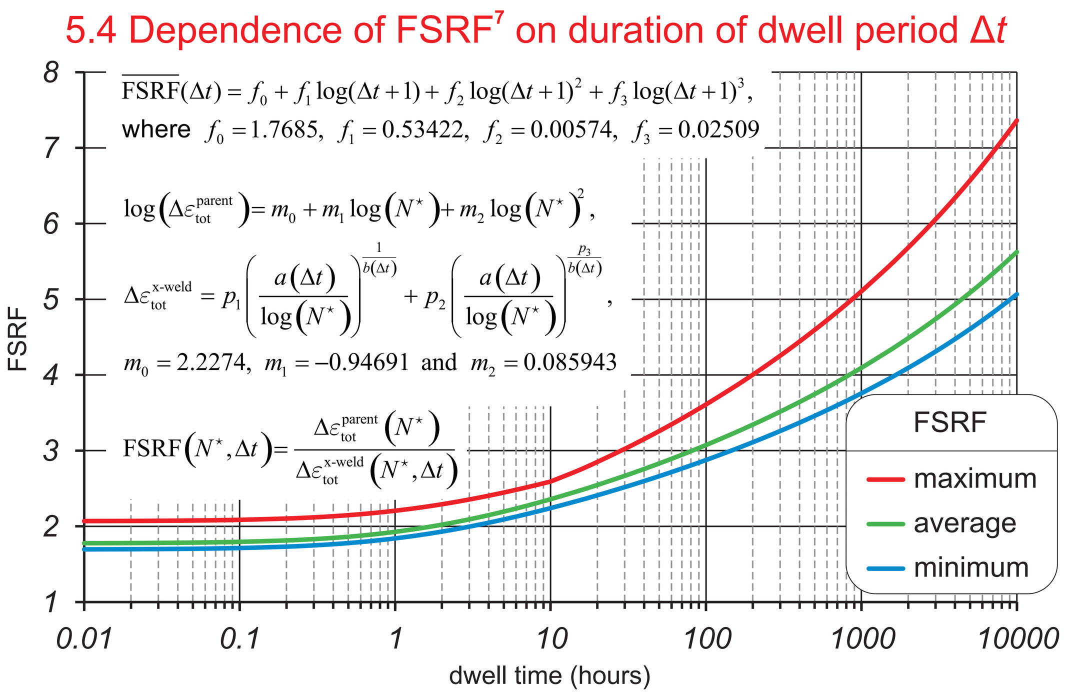
5.2 Design contour plot for creep-fatigue durability



5.3 Comparison of the observed and predicted N^*



5.4 Dependence of FSRF[7] on duration of dwell period Δt



$$\overline{\rm FSRF}(\Delta t) = f_0 + f_1\log(\Delta t+1) + f_2\log(\Delta t+1)^2 + f_3\log(\Delta t+1)^3,$$

where $f_0 = 1.7685,\ f_1 = 0.53422,\ f_2 = 0.00574,\ f_3 = 0.02509$

$$\log\left(\Delta\varepsilon_{\rm tot}^{\rm parent}\right) = m_0 + m_1\log(N^*) + m_2\log(N^*)^2,$$

$$\Delta\varepsilon_{\rm tot}^{\rm x\text{-}weld} = p_1\left(\frac{a(\Delta t)}{\log(N^*)}\right)^{\frac{1}{b(\Delta t)}} + p_2\left(\frac{a(\Delta t)}{\log(N^*)}\right)^{\frac{p_3}{b(\Delta t)}},$$

$m_0 = 2.2274,\ m_1 = -0.94691$ and $m_2 = 0.085943$

$${\rm FSRF}(N^*,\Delta t) = \frac{\Delta\varepsilon_{\rm tot}^{\rm parent}(N^*)}{\Delta\varepsilon_{\rm tot}^{\rm x\text{-}weld}(N^*,\Delta t)}$$

6. Conclusions

1) The series of **creep-fatigue analyses** have been implemented with LMM using:
   - Ramberg-Osgood material model and corresponding constants to describe plastic strains under saturated cyclic conditions;
   - power-law model in "time hardening" form and corresponding constants to describe creep strains during primary creep stage.
2) The amount of damage per cycle caused by **creep-fatigue interaction** is estimated using:
   - experimentally defined relation for number of cycles to fatigue failure (N^*) dependent on numerically defined total strain range for the fatigue damage (ω^f);
   - experimentally defined relation for time to creep rupture (t^*) dependent on the average stress during dwell period for the creep damage (ω^{cr});
   - the average stress during dwell period is defined as a mean value of analytical function for stress during relaxation dependent on elastic follow-up factor (Z), initial stress and time.
3) A non-linear **creep-fatigue diagram** is used to define the total damage caused by both creep and fatigue, which can't exceed one ($\omega^f + \omega^{cr} \le 1$). Basing upon this interaction, the number of cycles to creep-fatigue failure (N^*) is defined.
4) Comparison of the observed and predicted cycles to failure with creep-fatigue FEA/LMM for 3 types of experiments shows, that simulation of 9 of total available 11 cases is very close to optimal match. Simulation of other 2 cases produces non-conservative results with factor of difference equal to **1.6**, which is even better than the factor acceptable for engineering analysis equal to **2**.
5) Sets of creep-fatigue FEA/LMM results analysis corresponding to 0, 0.5, 1, 2, 5 and 10 hours are fitted by analytical function and used for contour plot of cycles to failure (N^*) depending on dwell period and normalized moment intended for design application.
6) Further research will be devoted to parametric studies of the influence of variation of weldment geometrical parameters on the number of cycles to failure (N^*) and formulation of a mathematical relation to describe the corresponding dependence.

Acknowledgements

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EPSRC Engineering and Physical Sciences Research Council
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