Mixed mode rolling contact fatigue crack growth in flash-butt welds of curved tracks

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- Numerical study on RCF
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Introduction

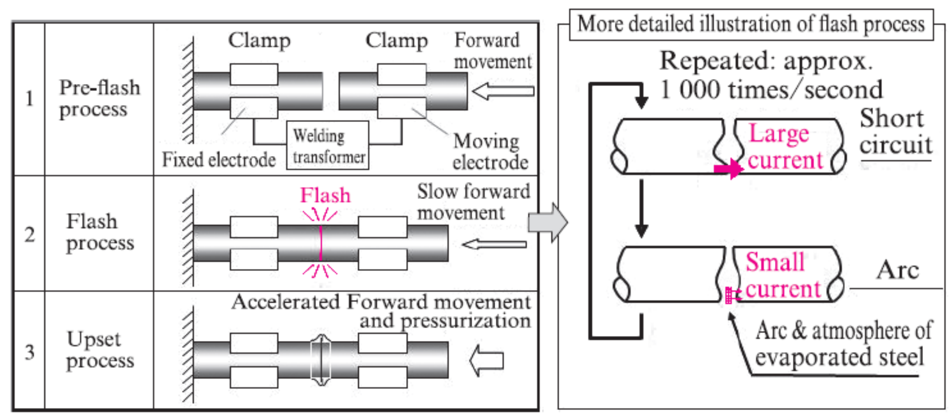
Flash-butt welding:

- Widely found in Australian heavy-haul railways
- Produces smooth and continuous rail surface to reduce dynamic loadings

Compare with Aluminothermic welding:

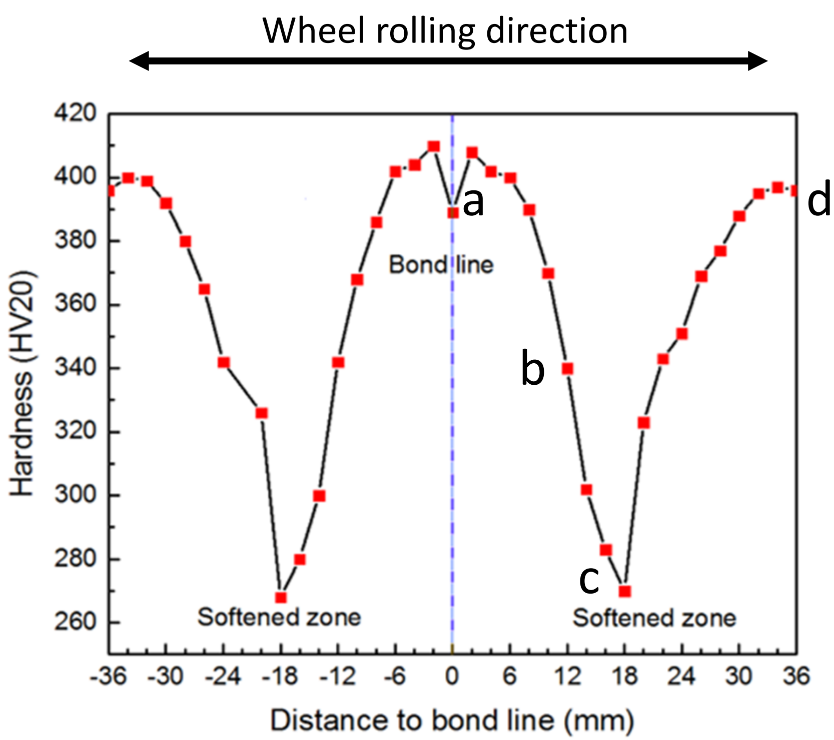
- Shorter heating time; less thermal input
- No external material
- Narrower HAZ; Less strength loss

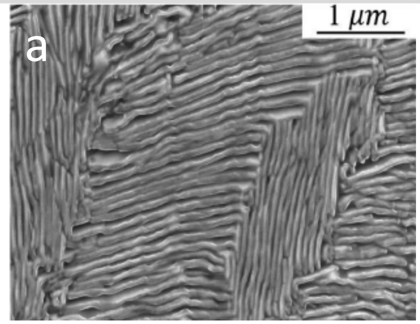
Main procedures of flash-butt welding



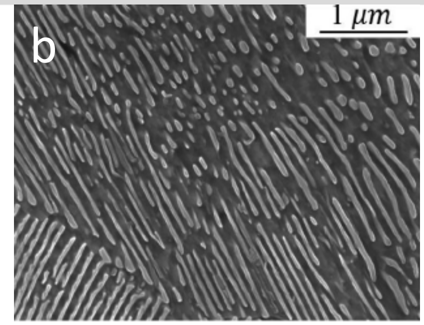
Fujii M. et al., *JFE Technical Report*, 2015

Variation of microstructure in HAZ of flash-butt weld

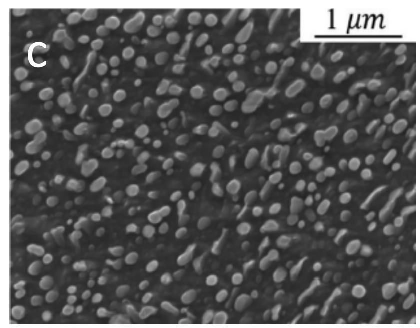




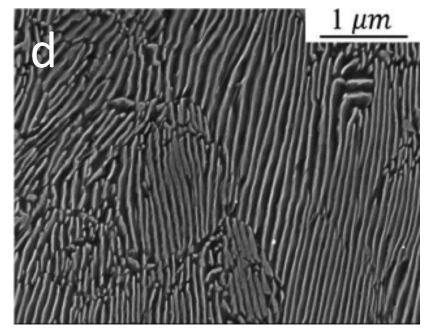
3mm to bond line
Re-austenitised zone



13mm to bond line
Partially-spheroidised zone



18mm to bond line
Spheroidised zone



100mm to bond line
Parent rail

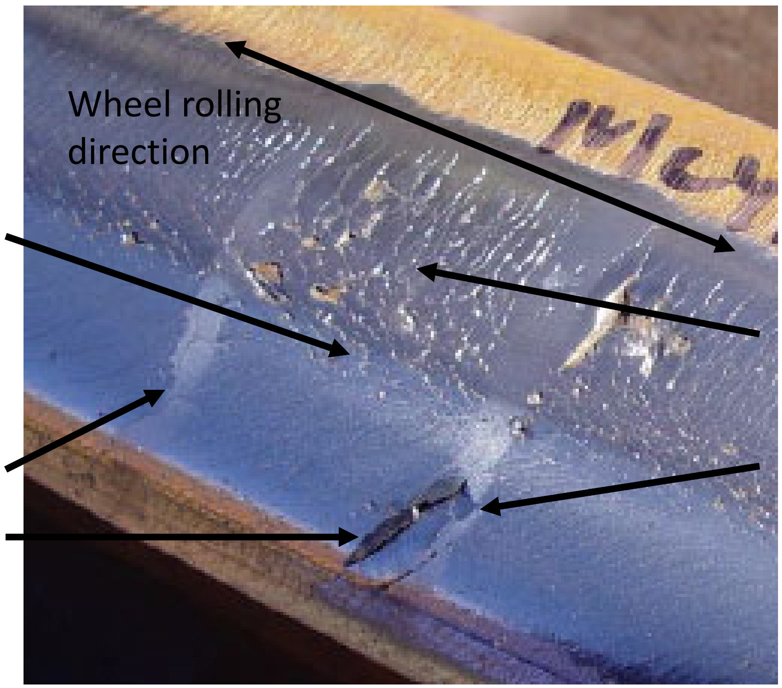
Su H. et al., *International Journal of Mechanical Sciences*, 2020

RCF damages in Australian heavy-haul railways

RCF cracks in flash-butt weld

Bond line region

Softened zone



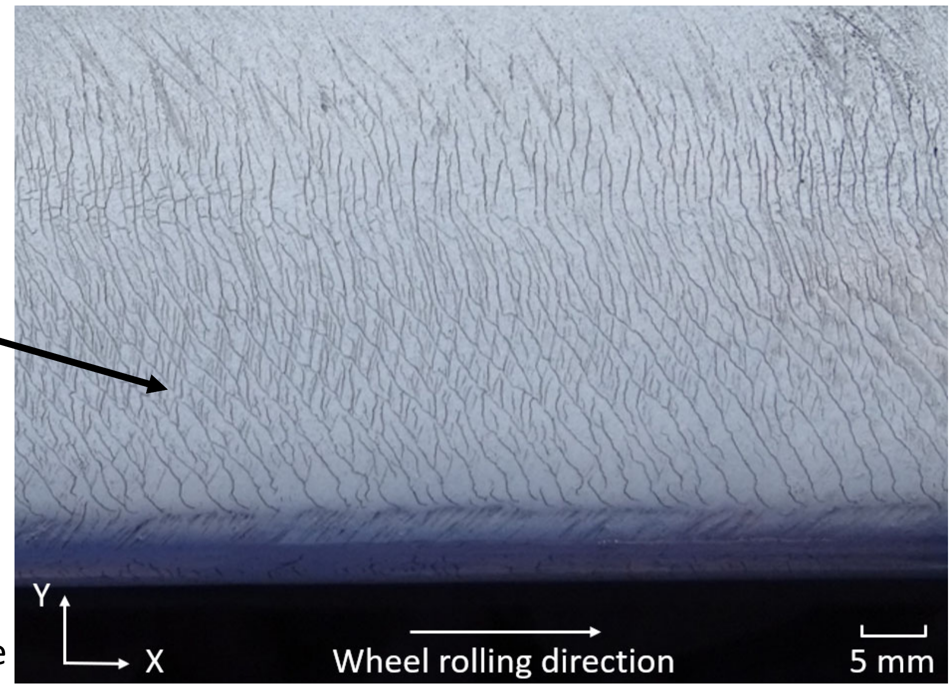
Field side

Cracking network

Spalling

Gauge side

RCF cracks in curved track



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Mutton P. et al., *Wear*, 2016

Overall research aim

Applying damage tolerance method to predict RCF surface crack growth in softened zone of rail welds of curved tracks

Obtain in-service stress intensity factors histories

- MBD and FE analysis

Obtain material fatigue crack growth data

- da/dN versus ΔK_{eq}
- Crack growth deflection

Non-destructive inspection

- Identify pre-service and in-service crack sizes

→

Crack growth life

Critical crack size

Inspection interval

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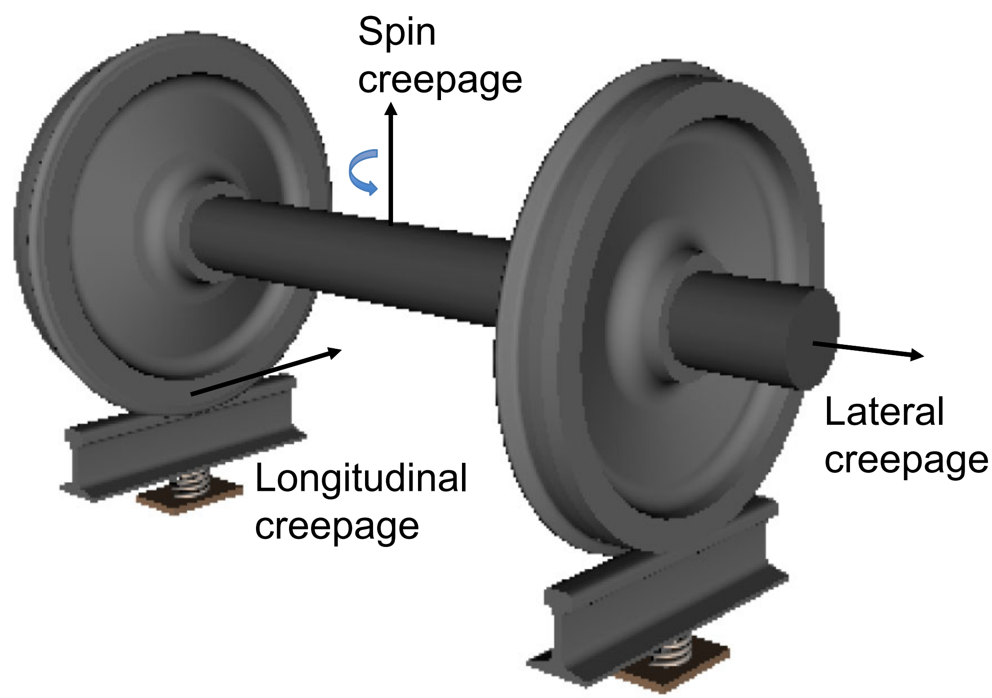
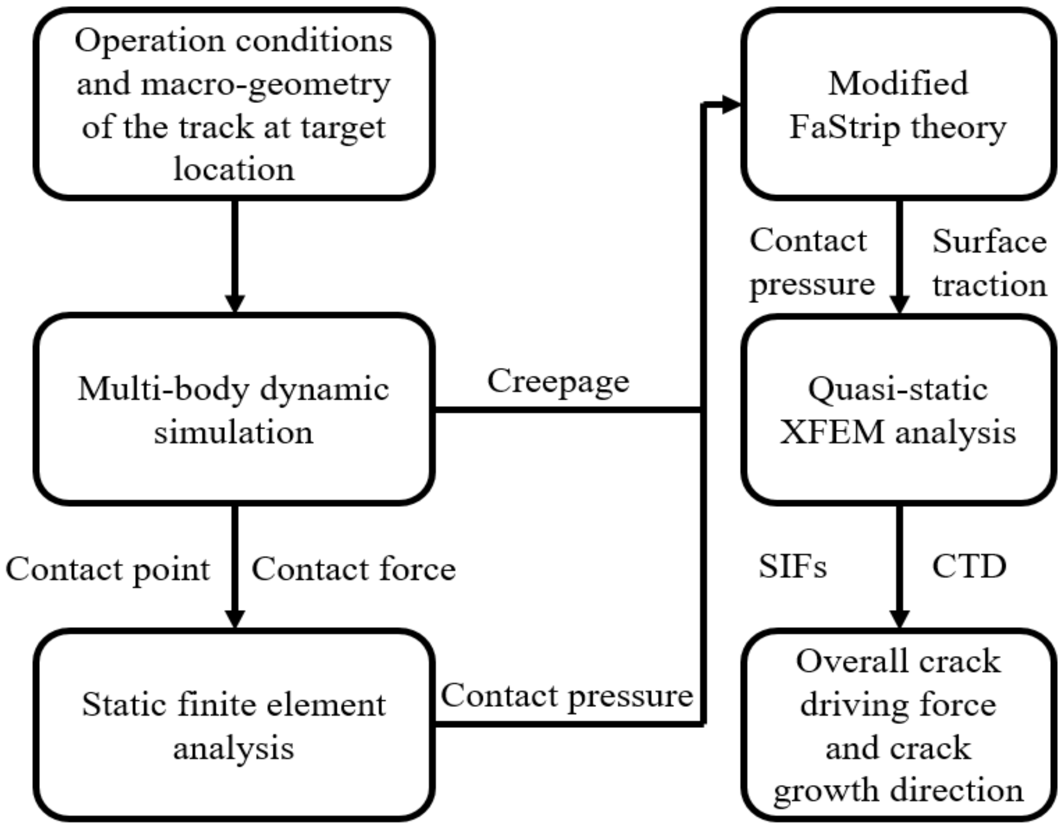
Numerical study on RCF

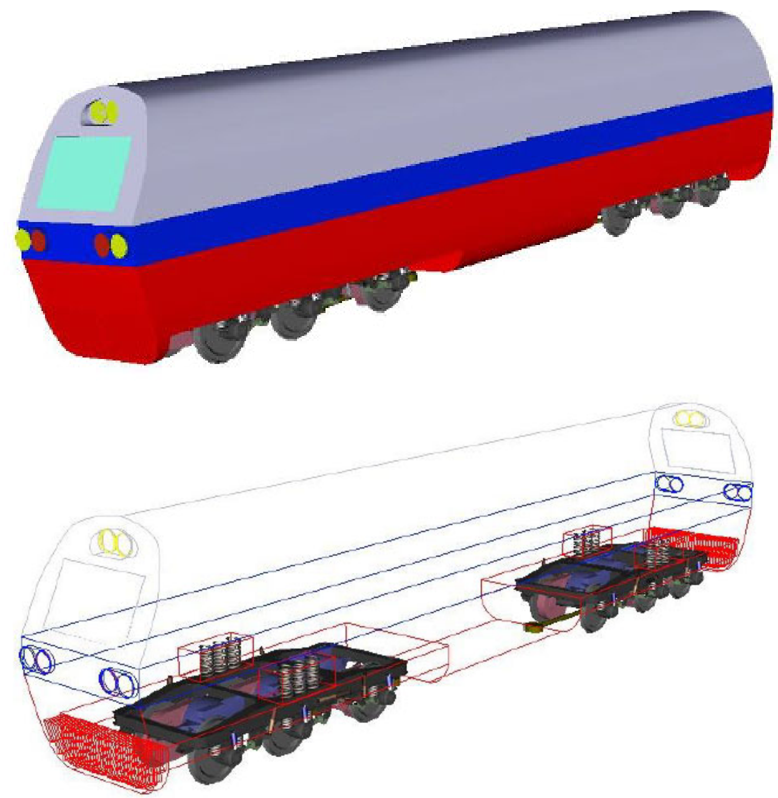
Objectives of numerical study

- Existing studies only reflected the traction distribution under elastic contacts and various **longitudinal creepages.**
- Creepage: wheel slips in **longitudinal**, **lateral** and **spin** directions; Highly sensitive to track curvatures.
- Verify and quantify the influence of all the **three creepages** on the rolling contact fatigue crack growth driving force



Methodology





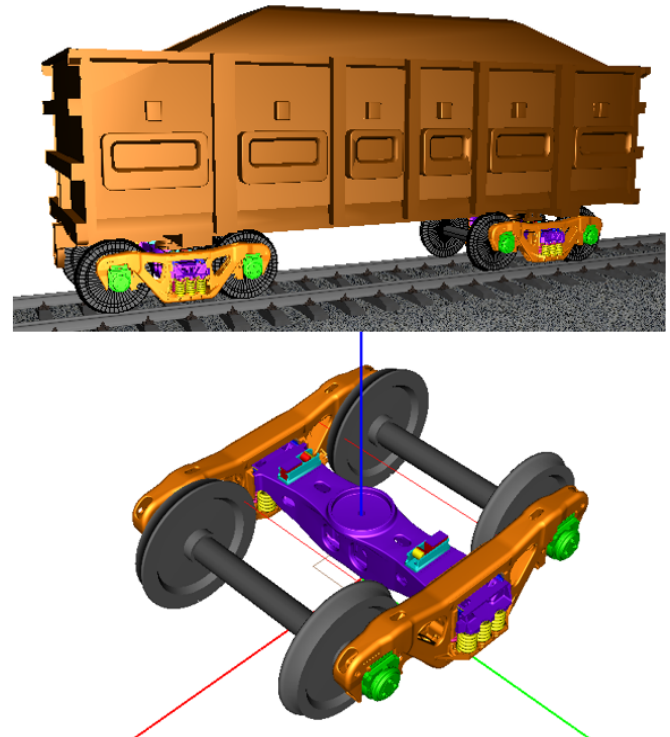
Locomotive from software Universal Mechanism

Multi-body dynamic simulation

Curve Radius (m)	1000
Superelevation (mm)	35
Gradient (%)	-0.15
Top of Rail Friction Coefficient	0.5
Rail Gauge Face Friction Coefficient	0.5
Vehicle Speed (km/h)	70
Wheel/Rail Contact Angle (Deg)	8.36
Lateral Contact Location on Rail (mm)	8.80
Total Wheel Lateral Force (kN)	-3.04
Total Wheel Vertical Force (kN)	204.57
Longitudinal, lateral and spin creepage: v_x, v_y, φ	

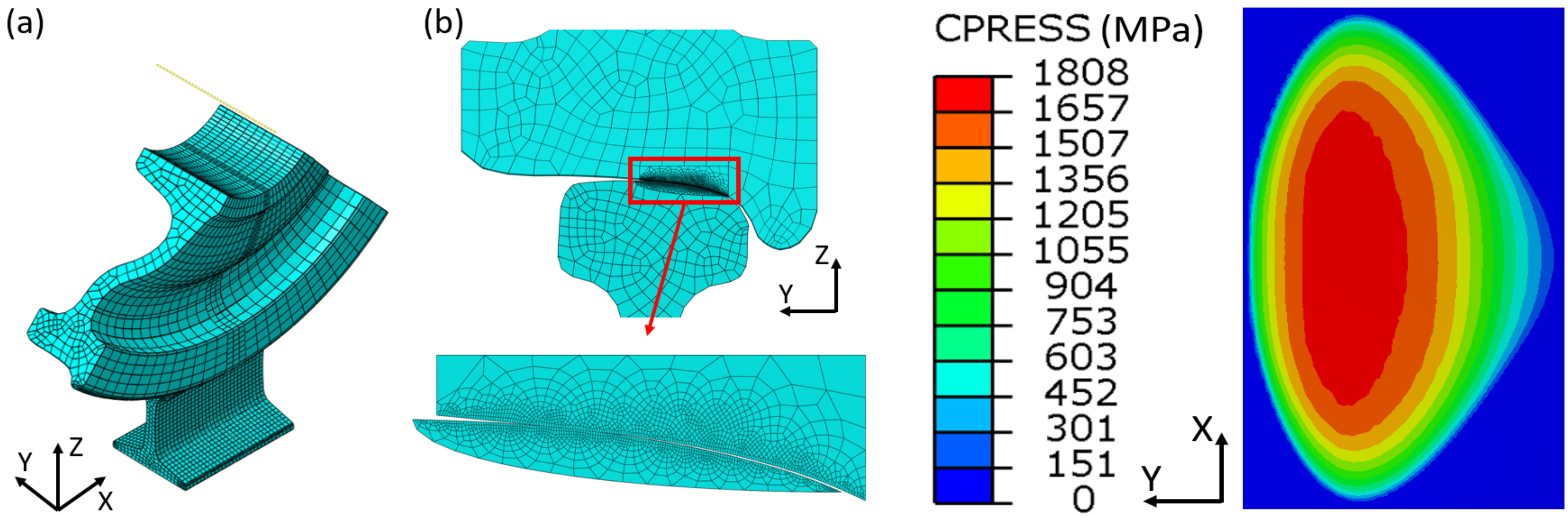
Input parameters obtained from target location

Output Results



Standard iron ore wagon with a typical three-piece 'ride control' type bogie.

Static finite element analysis



Traction distributions based on creepages

Traction distribution in slip zone:

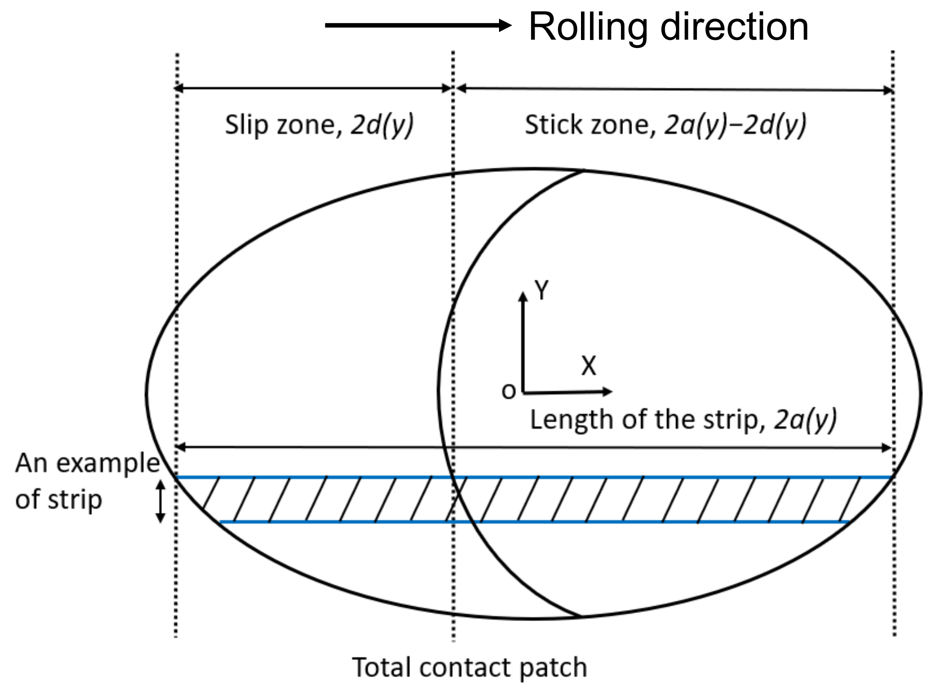
$$Q_x(x,y) = -\frac{q_{xf}(x,y)}{q_{tf}(x,y)} \cdot \mu \cdot [P(x,y)]$$

$$Q_y(x,y) = -\frac{q_{yf}(x,y)}{q_{tf}(x,y)} \cdot \mu \cdot [P(x,y)]$$

Traction distribution in stick zone:

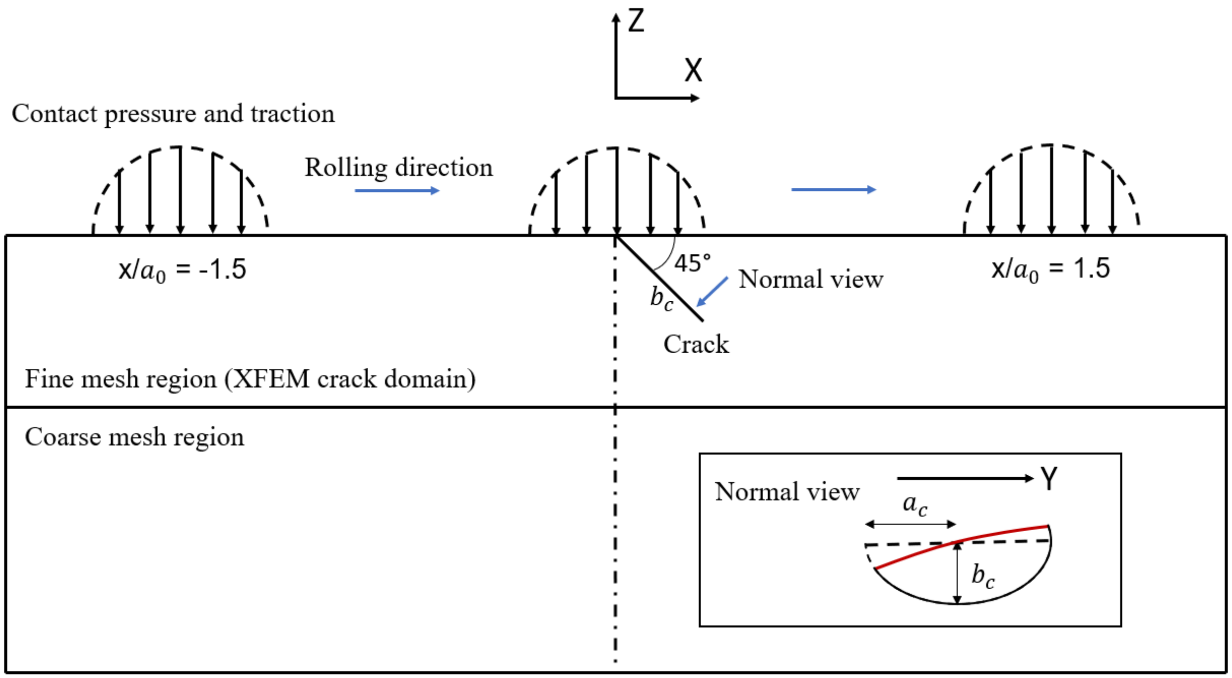
$$Q_x(x,y) = -\mu \cdot k \cdot \left[P(x,y) - P\left(\frac{a(y)\cdot(x-d(y))}{a(y)-d(y)}, y\right) \cdot \frac{a(y)-d(y)}{a(y)}\right]$$

$$Q_y(x,y) = -\mu \cdot \left[\lambda \cdot P(x,y) - \lambda' \cdot P\left(\frac{a(y)\cdot(x-d(y))}{a(y)-d(y)}, y\right) \cdot \frac{a(y)-d(y)}{a(y)}\right]$$

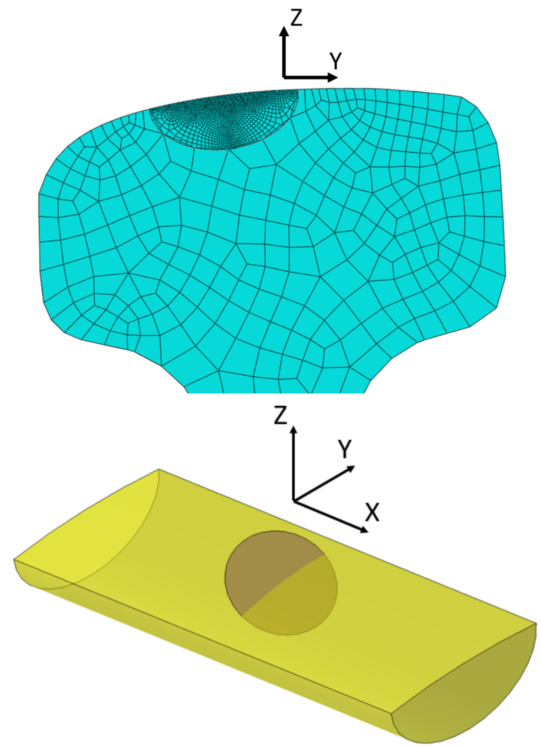


An example of strip in the modified FaStrip algorithm

Quasi-static finite element analysis



loadings for one complete wheel passage over a 3D surface crack



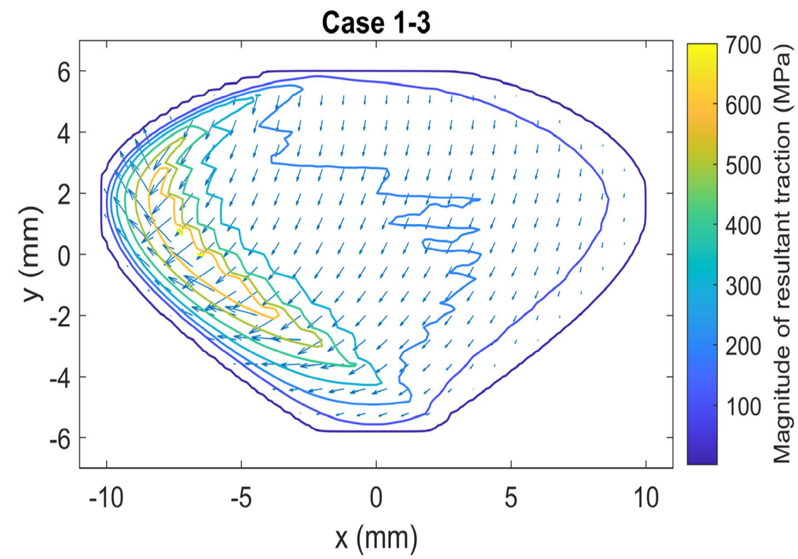
Fine mesh region (0.2mm) with embedded crack

Studied cases

Case No.	v_x	v_y	φ (rad/mm)	μ	a_c (mm)	b_c (mm)
1	-0.0015	-0.000578	-0.000215	0.5	2	1.6
2	-0.0015	-0.000578	-0.000215	0.5	5	4
3	-0.0015	-0.000578	-0.000215	0.5	8	6.4
4	-0.001	0	0	0.3	8	6.4
5	-0.001	-0.001	0	0.3	8	6.4
6	-0.001	-0.001	-0.0001	0.3	8	6.4
7	-0.002	-0.001	-0.0001	0.3	8	6.4
8	-0.003	-0.001	-0.0001	0.3	8	6.4
9	-0.004	-0.001	-0.0001	0.3	8	6.4
10	-0.005	-0.001	-0.0001	0.3	8	6.4
11	-0.001	-0.002	-0.0001	0.3	8	6.4
12	-0.001	-0.003	-0.0001	0.3	8	6.4
13	-0.001	-0.004	-0.0001	0.3	8	6.4
14	-0.001	-0.005	-0.0001	0.3	8	6.4
15	-0.001	-0.001	-0.0003	0.3	8	6.4
16	-0.001	-0.001	-0.0005	0.3	8	6.4
17	-0.001	-0.001	-0.0007	0.3	8	6.4

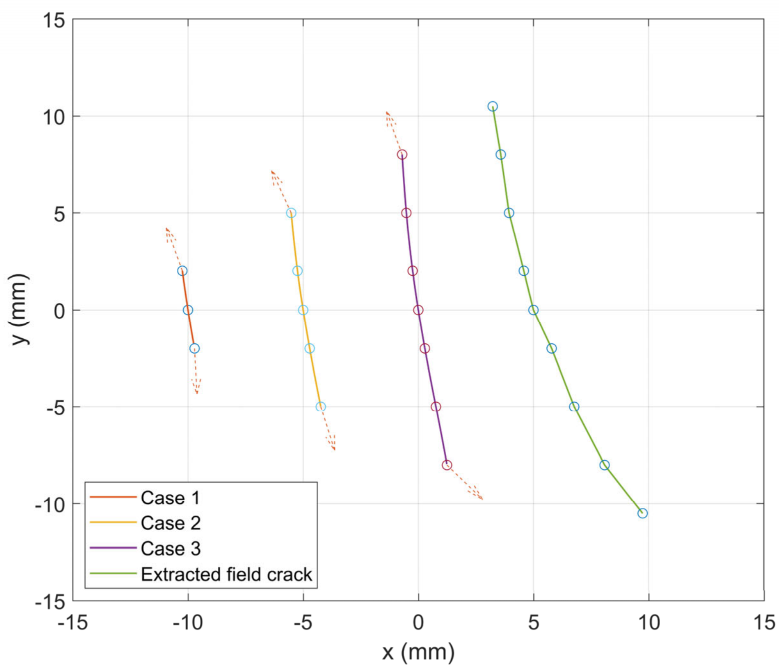
From target location (cases 1–3)

Artificial cases (cases 4–17)



Traction distribution of case 1-3

Results - Surface crack growth direction prediction using VCTD criterion

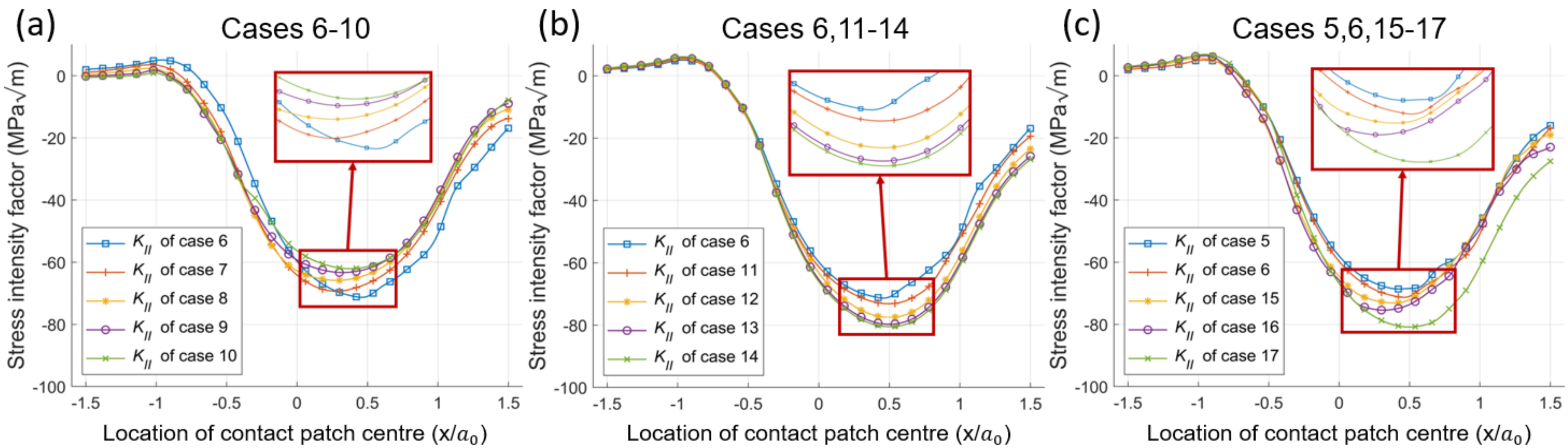


Angle name	Predicted crack growth angle (º)	Measured average deflection angle (º)	Standard deviation of measured angles (º)	Difference between predicted and measured angle (º)
$\alpha_{y=-2}$	2.5	18.1	9.4	-15.6
$\alpha_{y=2}$	17	11.9	9.7	+5.1
$\alpha_{y=-5}$	14.9	23.7	12.7	-8.8
$\alpha_{y=5}$	21	6.7	10.7	-14.3
$\alpha_{y=-8}$	41.1	33.4	11.5	-7.7
$\alpha_{y=8}$	16.5	7.9	10	-8.6

Crack growth direction prediction at target location

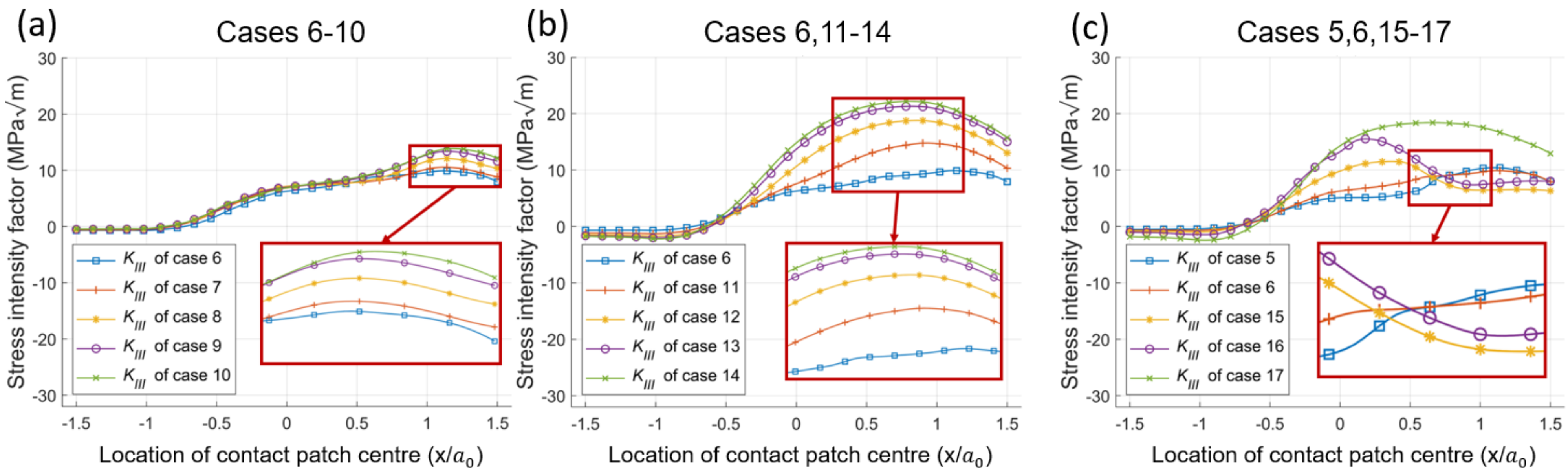
Results - Stress intensity factors histories at crack tip

a) Longitudinal creepage on K_{II}. b) lateral creepage on K_{II}. c) spin creepage on K_{II}.



Results - Stress intensity factors histories at crack tip

a) Longitudinal creepage on $\mathrm{K}_{\mathrm{III}}$. b) lateral creepage on $\mathrm{K}_{\mathrm{III}}$. c) spin creepage on $\mathrm{K}_{\mathrm{III}}$.



Experiment study on RCF

Objectives of experiment study

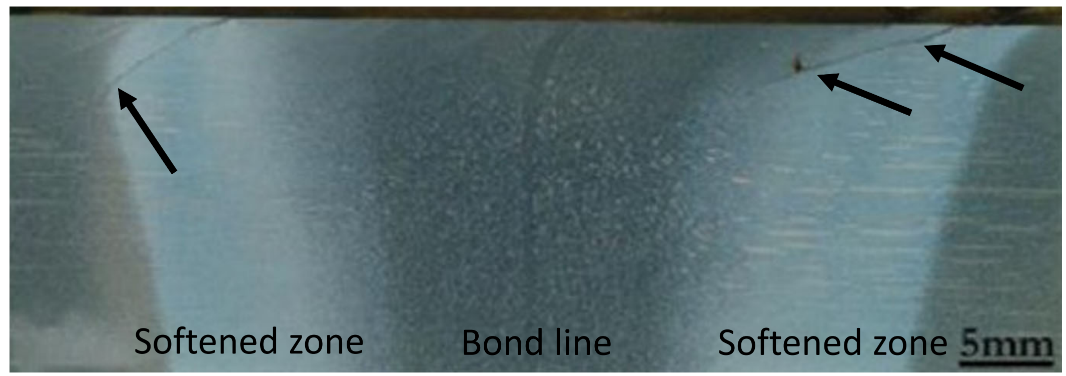
Crack growth rate data under a range of mode mixity ($\Delta K_{II}/\Delta K_I$)

RCF crack growths are often under:

- Shear stresses due to contact loadings
- Friction force between crack faces
- Crack opening force due to entrapped pressurised fluid
- Crack opening force due to roughness of crack faces

Crack growth deflection behaviour due to:

- Mode mixity
- Variation of microstructures



Cross section view of a flash-butt weld with RCF cracks after etching

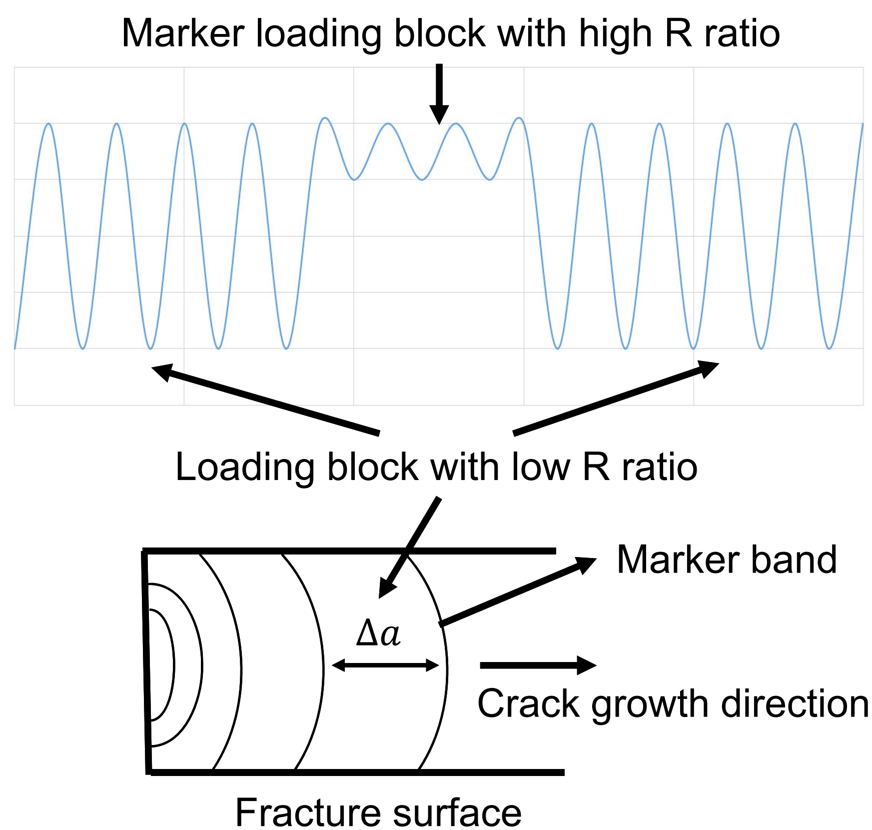
Methodology -- Marker band method

Marker band method:

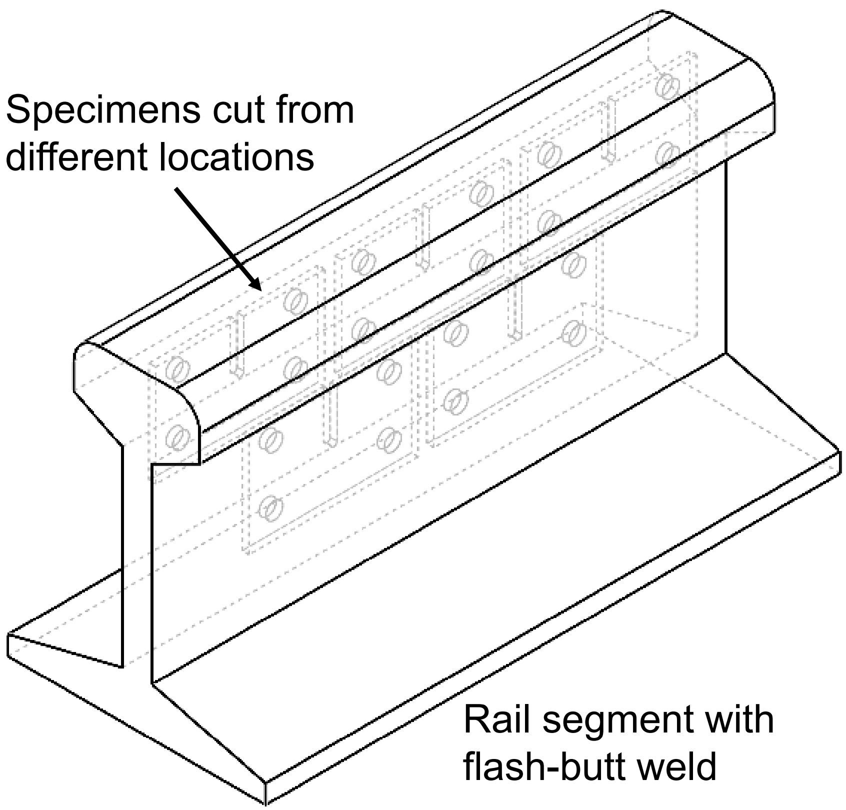
- Widely applied in fatigue testing of aerospace materials: aluminum and titanium alloys
- Alternating loading blocks with different R ratios
- Quantitative fractography

Advantages of marker band method comparing with ASTM E647:

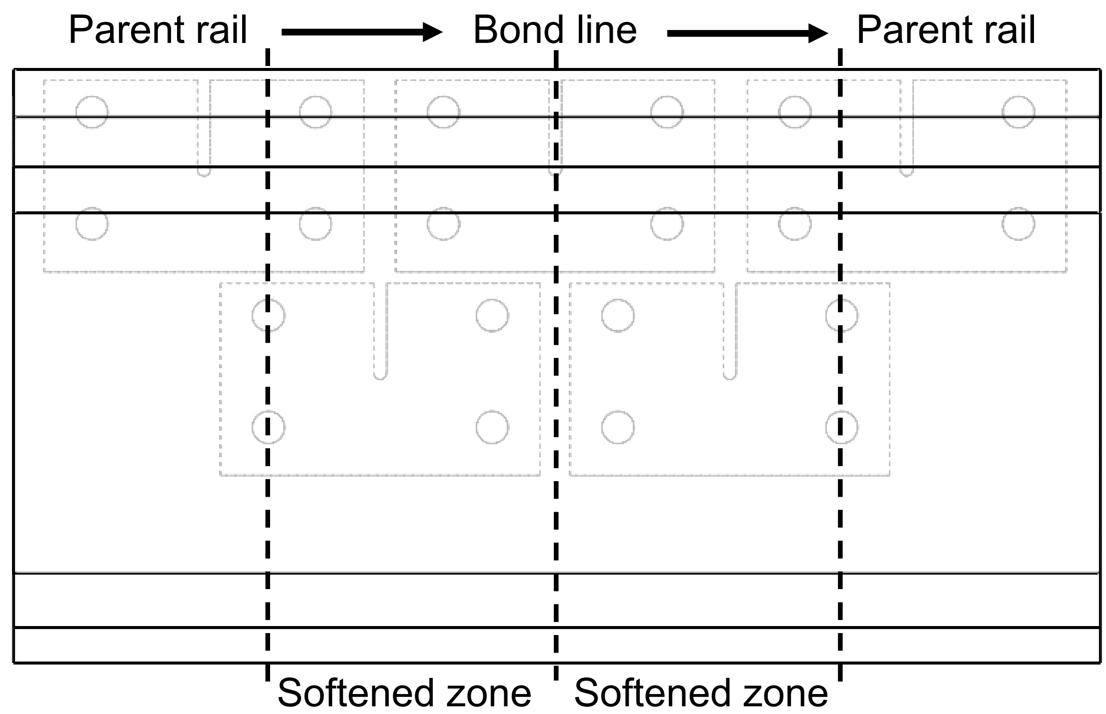
- No size/geometry requirement
- Data from short crack growth stage
- Compatibility with mixed mode tests
- Accurate determination of both crack growth distances and ΔK



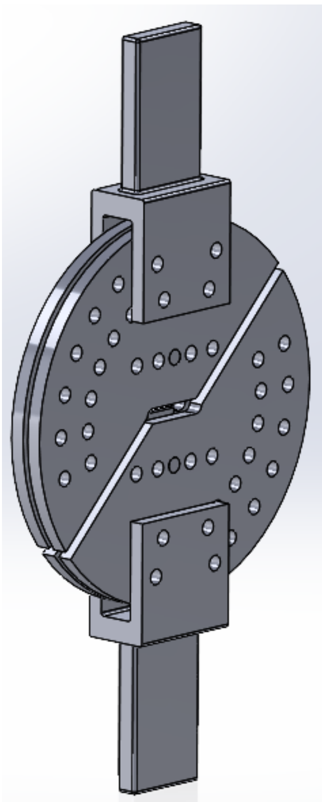
Methodology -- Extraction of specimens

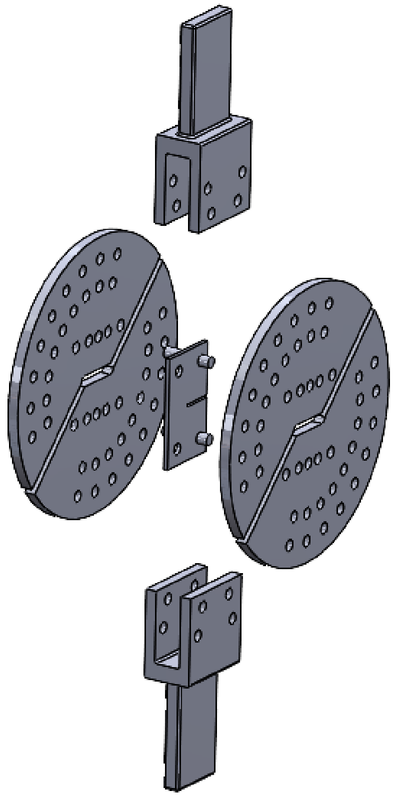


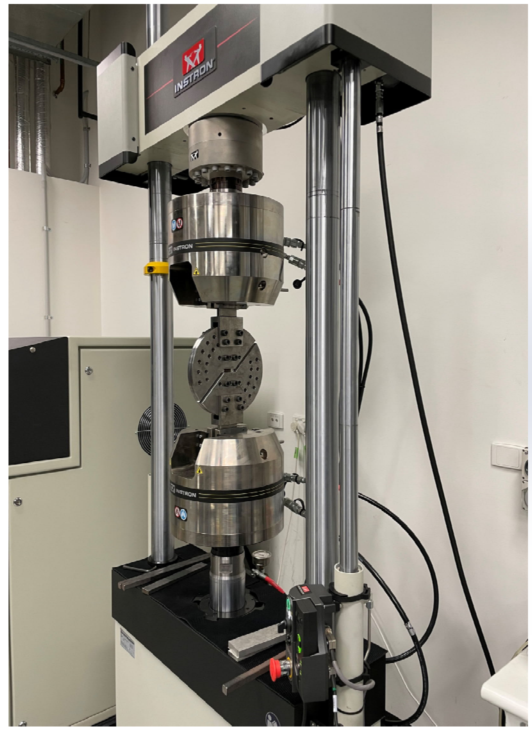
The range of cutting locations



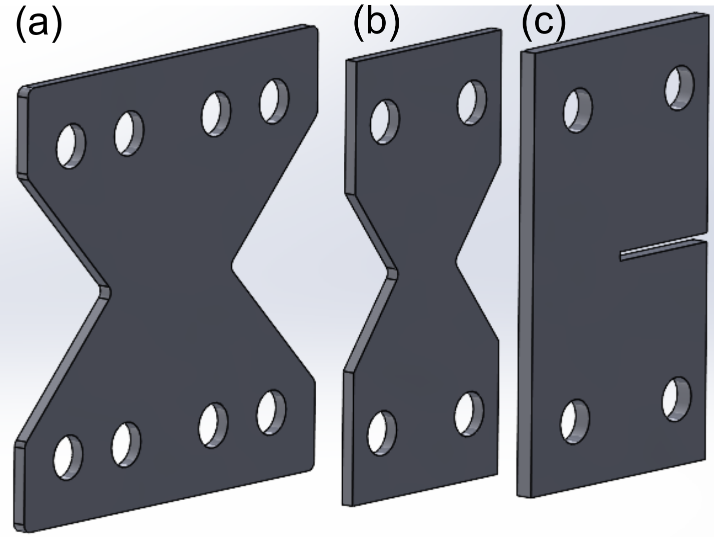
Methodology -- Testing rig & specimen designs







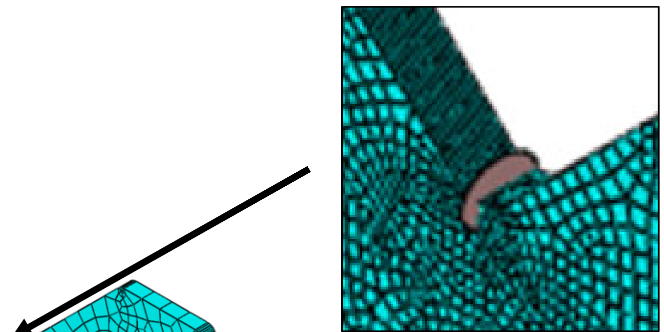
Specimen designs:

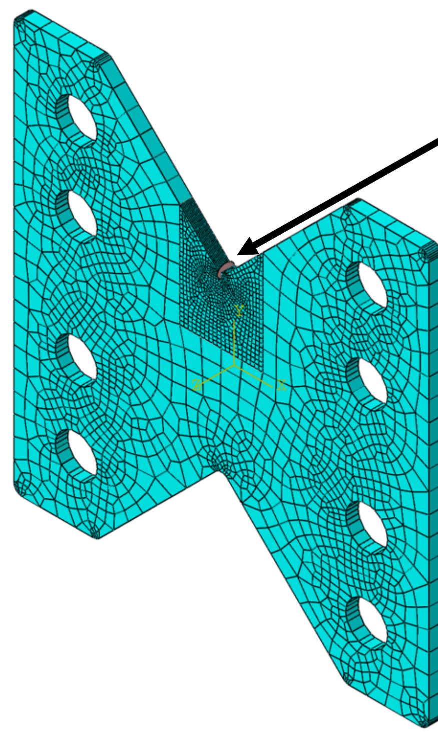


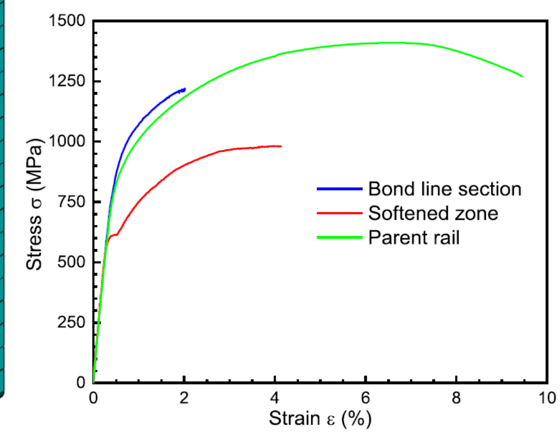
Methodology -- ΔK Calculation

Extended Finite Element Method (XFEM)

- Crack geometry represented by an inserted planar shell part
- Material inhomogeneity reflected by different mechanical properties
- Capability of simulating irregular crack geometry and crack front
- No stringent requirement of element type and mesh size







Su H. et al., *International Journal of Mechanical Sciences*, 2020

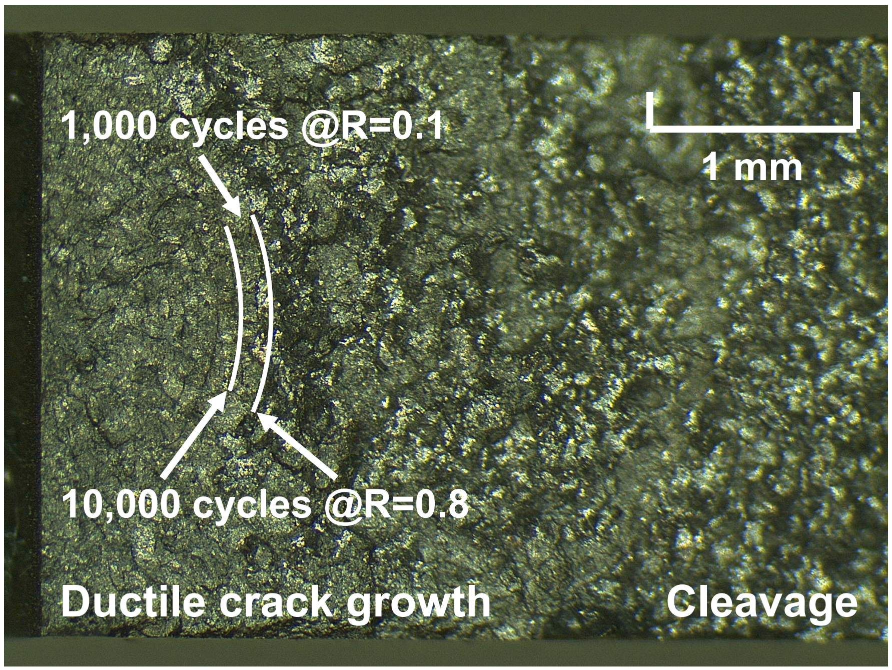
Preliminary results -- Details of some successful tests

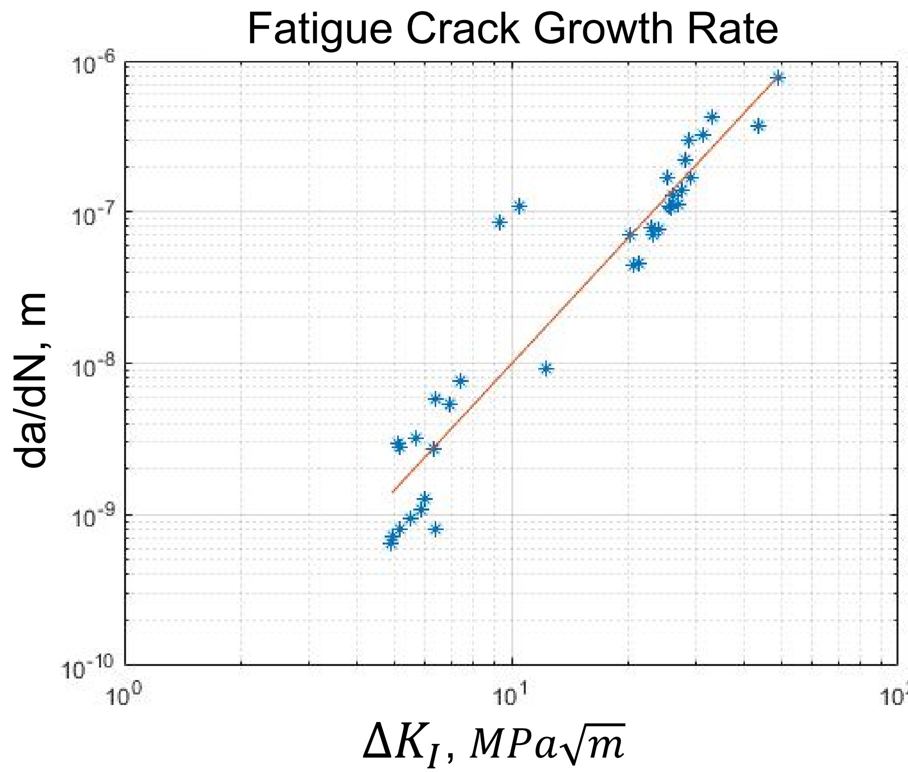
Specimen No.	Specimen design	Location of specimen	Max. Loading/kN	Loading angle	High R ratio	Low R ratio	No. of cycle in high R block	No. of cycle in low R block	No. of cycle till break
1	Design a	PR	30kN	0º	0.8	0.1	10,000	1,000&5,000	810,000
2	Design a	PR	30kN	0º	0.8	0.1	10,000	1,000	584,000
3	Design b	PR	15kN	0º	0.8	0.1	10,000	1,000	755,000
4	Design b	PR	20kN	0º	0.8	0.1	10,000	1,000	700,000
5	Design b	PR	20kN	0º	0.8	0.1	10,000	600	890,000
6	Design b	PR	20kN	0º	0.8	0.1	12,000	600	781,000
7	Design a	PR	30kN	30º	0.8	0.1	10,000	1,000	320,000
8	Design a	PR	15-20-25kN	30º	0.8	0.1	10,000	1,000	2,520,000
9	Design c	BL	10kN	0º, 45º	0.8	0.1	10,000	1,000	800,000
10	Design c	3mm to BL	10kN	0º, 45º	0.8	0.1	10,000	1,000	650,000

PR: Parent rail BL: Bond line

Preliminary results -- Results from mode I tests in parent rail

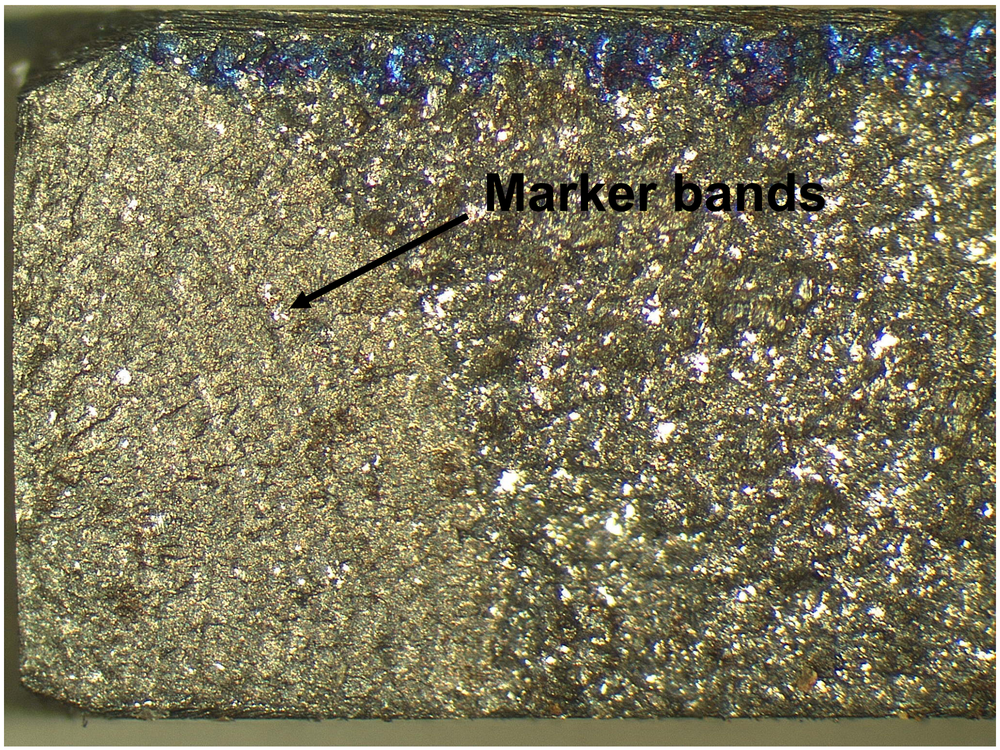
Marker bands on a fractured rail steel specimen from mode I fatigue test

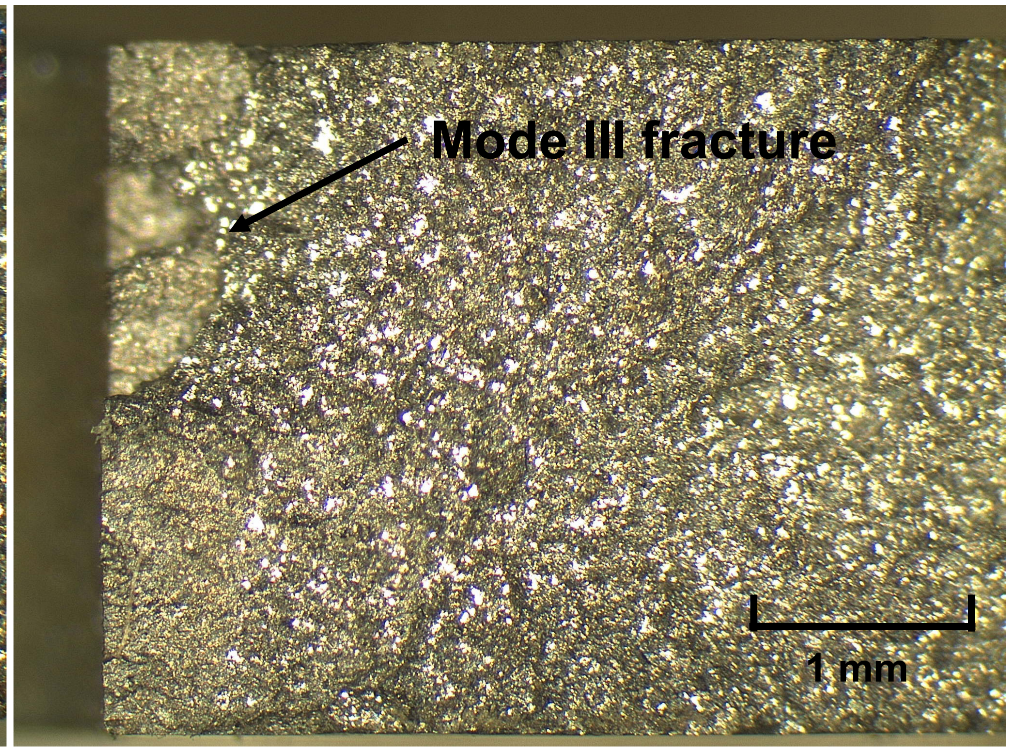




Preliminary results -- Results from mixed mode tests in parent rail

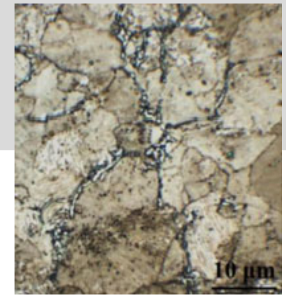
Loading angle of 30º and 45º

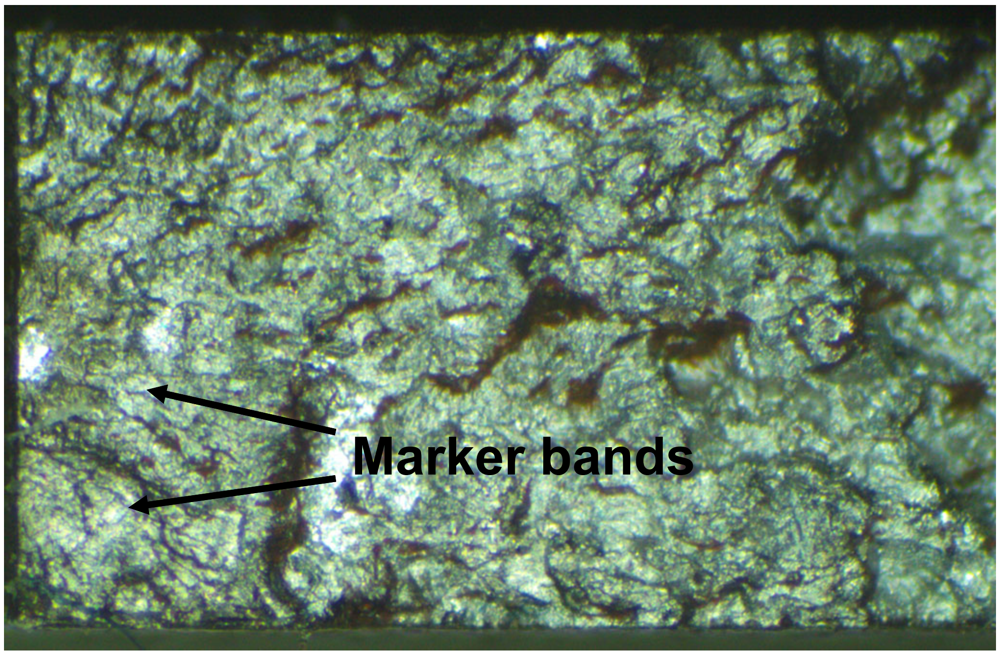


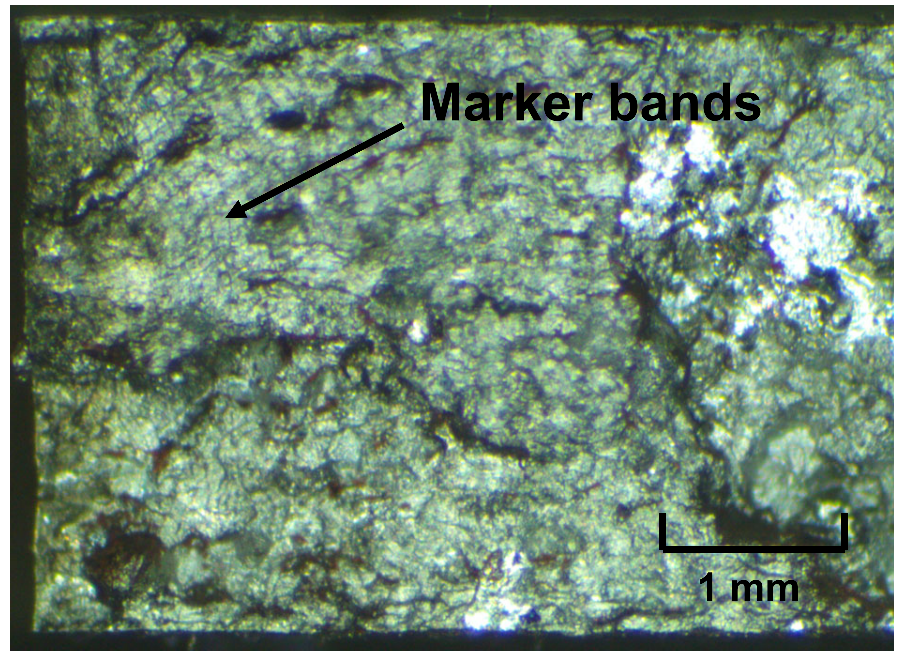


Preliminary results -- Results from tests near bond line

Effect of existing defects and grain boundary cementite







Summary

From numerical work:

- The creepages in curved tracks have significant influence on the phase and magnitude of stress intensity factors histories.
- Creepages, especially spin creepage, should be considered in RCF crack growth prediction.

From experiment work:

- The results proved the applicability of marker band method in obtaining mixed mode crack growth data in flash-butt welds.

However, there are still many challenges:

- The visibility of marker bands when crack length is smaller than 0.2mm and when loading angle is larger than 45º.
- How to minimise the influences of existing defects and grain boundary cementite due to welding process on the visibility of marker bands?

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Thank you.