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Characterization of Fatigue Behaviour, from Material Science to Civil Engineering Applications

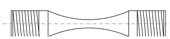
OptiBri-Workshop

"Design Guidelines for Optimal Use of HSS in Bridges"

3rd May 2017

Chantal Bouffioux

Outline

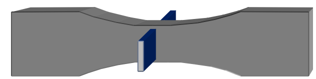


Small samples

Static & fatigue tests

Material behaviour

- Static
- Fatigue (small size)



Large welded plates

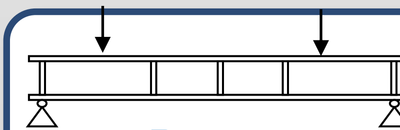
Fatigue tests
Residual stress

Effect of:

- size & machining
- welding
- post-treatments

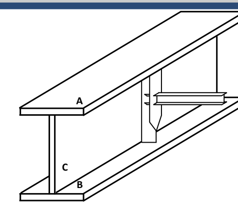
Fatigue behaviour

Future applications



Beams

- Size effect
- Laws validation

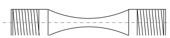


Critical bridge detail

- interest of HSS

Outline

Small samples



Static & fatigue tests

Material behaviour

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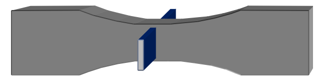
- Fatigue (small size)

Large welded plates



Fatigue tests
Residual stress

Effect of:

- size & machining
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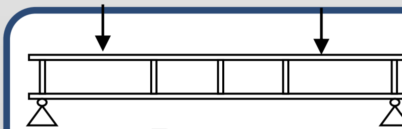
- post-treatments

Fatigue behaviour

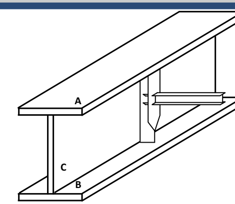
Future applications

Beams



- Size effect
- Laws validation

Critical bridge detail



- interest of HSS

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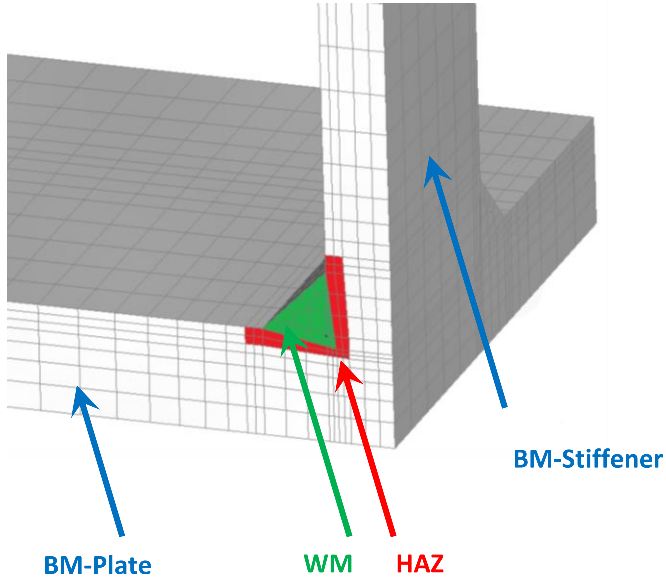
Small samples

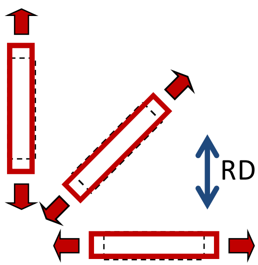
- **4 materials:**
  - Base Material: BM **(HSS - S690QL)**
  - Heat Affected Zone:
    - HAZ1 (25 mm thick)
    - HAZ2 (40 mm thick)
  - Welded Metal: WM

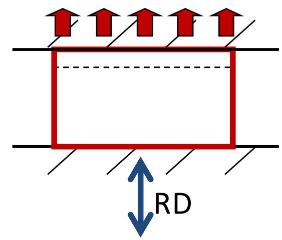


Small samples

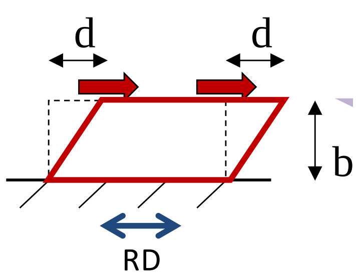
- **Static tests:**

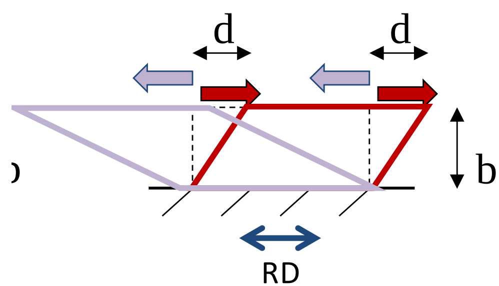
Tensile test **or** **Large tensile test**





+ Shear test **+ Bauschinger shear test**





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Small samples

- **Static behavior – material laws & parameters :**

Elastic part: Hooke's law: E, ν

Plastic part: Hill's law (Hill48):

$$F_{HILL}(\underline{\sigma}) = \frac{1}{2}\left[H(\sigma_{xx} - \sigma_{yy})^2 + G(\sigma_{xx} - \sigma_{zz})^2 + F(\sigma_{yy} - \sigma_{zz})^2 + 2N(\sigma_{xy}{}^2 + \sigma_{xz}{}^2 + \sigma_{yz}{}^2)\right] - \sigma_F^2 = 0$$

Isotropic hardening: Voce formulation:

$$\sigma_F = \sigma_0 + K(1 - exp(-n.\varepsilon^{pl}))$$

Back-stress (kinematic hardening): Armstrong-Frederick's equation:

$$\underline{\dot{X}} = C_X(X_{sat}\underline{\dot{\varepsilon}^{pl}} - \bar{\dot{\varepsilon}}^{pl}.\underline{X})$$

E & **ν:** defined by tensile tests

F, G, H: defined by tensile tests in 3 directions (RD, TD, 45°)

N, σ_0, K, n, C_x, X_{sat}: defined by Optim

Small samples

- **Static behavior – material data (inverse method):**
  - **BM**: hardening fully kinematic
  - **HAZ1 ≈ HAZ2**: same static behaviour
  - **WM**

For fatigue tests: $\sigma_{u,eng} = F_i / A_0$

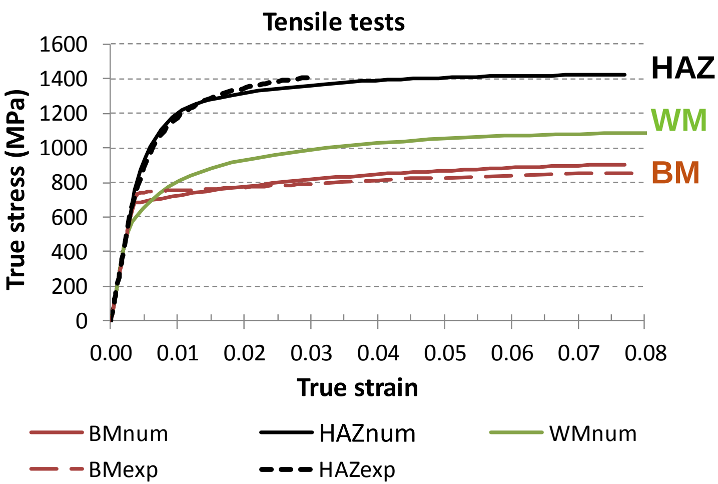
For FEM: $\sigma_{u,true} = F_i / A_i$

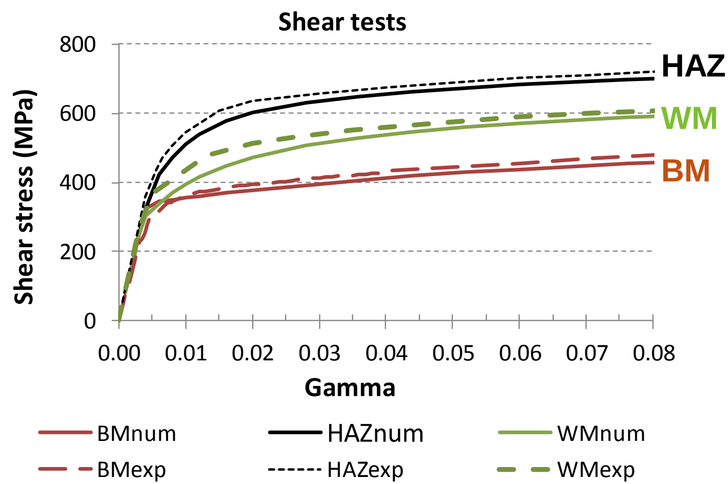
	Ultimate tensile strength (Mpa)	
	$\sigma_{u,eng}$	$\sigma_{u,true}$
BM (S690QL)	838	905
HAZ1, HAZ2	1338	1424
WM	1008	1101

Data for Hooke, Hill, Voce and Armstrong-Frederick laws (units: MPa, s)											
	Elast. data		Yield locus				Isotropic hardening			Kinematic hardening	
Material	E	ν	F	G	H	*N=L=M*	*K*	σ_0	*n*	C_X	X_{sat}
BM (S690QL)	210 116	0.3	1	1	1	*3.9*	*0*	*674*	*0*	*31.9*	*167*
HAZ1, HAZ2	210 000	0.3	1	1	1	*4.45*	*371*	*827*	*511*	*52.5*	*152*
WM	210 000	0.3	1	1	1	*3.2*	*241*	*531*	*285*	*42.6*	*218*

Small samples

- **Static behavior – comparison of material behavior:**





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Small samples

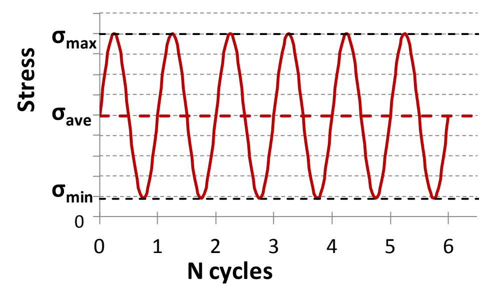
- **Fatigue tests:**
  - On vibrophore
  - Axial loading
  - Frequency: 100 – 150 Hz

    (→ correction factor)

$R = \sigma_{min} / \sigma_{max}$ = 0.1 or 0.2 or …

Material	Smooth	Notch
BM (S690QL)	4 R	3 geom.
HAZ1	1 R	1 geom.
HAZ2	2 R	1 geom.
WM	2 R	1 geom.

Vibrophore



Small samples

- **Fatigue behavior – material laws & parameters :**

Multiaxial Lemaître Chaboche fatigue model

$$\frac{\partial D}{\partial N} \begin{cases} = 0 & \text{if } f_D < 0 \\ = \left[1-(1-D)^{\beta+1}\right]^{\alpha} \left(\frac{\tilde{A}_{II}}{M}\right)^{\beta} & \text{if } f_D \geq 0 \end{cases}$$

$$f_D = A_{II} - A_{II}^{*}$$

$$A_{II} = \frac{1}{2}\sqrt{\frac{3}{2}\left(\hat{\sigma}_{ijmax} - \hat{\sigma}_{ijmin}\right)\left(\hat{\sigma}_{ijmax} - \hat{\sigma}_{ijmin}\right)} \quad \text{with } \hat{\sigma}_{ij} = \sigma_{ij} - \sum_k \frac{1}{3}\sigma_{kk}$$

$$A_{II}^{*} = \sigma_{l0}\left(1 - 3.b.\sigma_{Hm}\right) \quad \text{(Sines' criterion)}$$

$$\tilde{A}_{II} = \frac{A_{II}}{1-D}$$

$$M = M_0\left(1 - 3.b.\sigma_{Hm}\right)$$

$$\alpha = 1 - a\left\langle \frac{A_{II} - A_{II}^{*}}{\sigma_u - \sigma_{eqmax}} \right\rangle$$

$$\sigma_{Hm} = \frac{1}{3}\left[\frac{1}{T}\int_T \mathrm{Tr}\left(\underline{\underline{\sigma}}(t)\right) dt\right]$$

D:	damage val., 0: sound material, 1: rupture
N:	number of cycle
A_{II}:	2nd invar. of amplit. deviator of σ tensor
A_{II}^{*}:	fatigue limit
f_D:	damage yield locus
σ_{Hm}:	mean hydrostatic stress
σ_{eqmax}:	maximum Von Mises stress per cycle
<x>	= x if x > 0 else = 0
$b = 1/\sigma_u$	
σ_u:	ultimate tensile stress
σ_{l0}:	endurance limit= fatigue limit at null σ_{mean}
a, M0, β:	other material data to define

Small samples

- **Fatigue behavior – material laws & parameters :**

Volume averaged stress gradient method

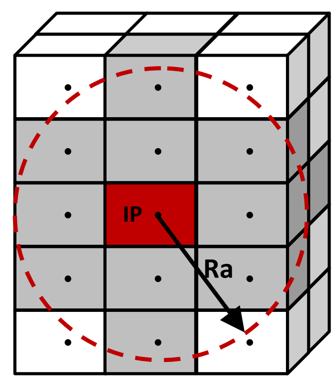
For each element, variables χ_{ip}: replaced by an average value of all the elements with their integration point inside the circle with a radius Ra

$$\overline{\chi_{ip}} = \frac{1}{V} \cdot \sum_{i=1}^{Nelem} \chi_{ip,i} . V_i$$

$$\chi_{ip} = \{A_{II}, \sigma_{eqmax}, \sigma_{Hm}\}$$

$$V = \sum_{i=1}^{Nelem} V_i$$

A_{II}:	2nd invar. of amplit. deviator of σ tensor
σ_{eqmax}:	maximum Von Mises stress per cycle
σ_{Hm}:	mean hydrostatic stress
Ra:	material data to define



Small samples

- **Fatigue behavior – material data (inverse modelling):**

HAZ1 ≈ HAZ2: same fatigue behavior

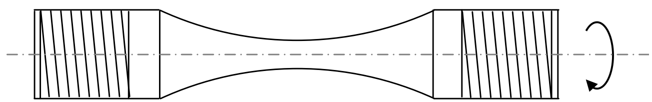
Material	σ_U (Mpa)	σ_{l0} (Mpa)	b	β	a	M0	Ra (mm)	a*(M0$^{-\beta)}$
BM	905.0	580.0	1.10 E-03	0.17	1	5.385 E+30	0.06	5.966E-06
HAZ1, HAZ2	1424.0	428.4	7.02E-04	2.094	1	4.410E+05	0.00	1.516E-12
WM	1101.0	319.4	9.08E-04	0.161	1	7.245E+32	0.00	5.182E-06

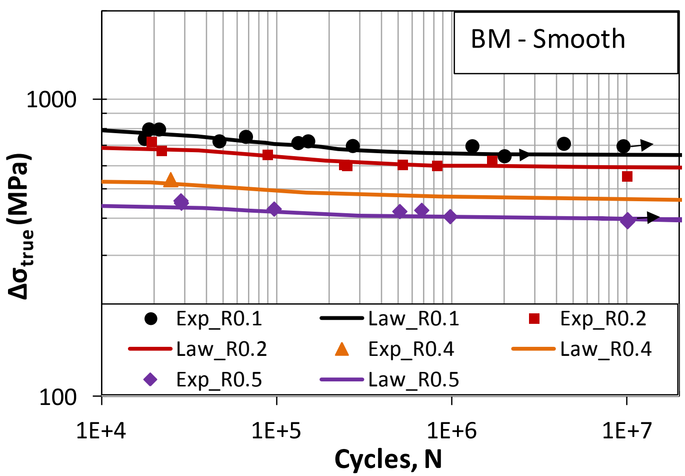
Small samples

- **Fatigue behavior – comparison experiments & fatigue law:**

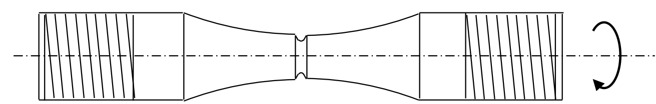
Base material (BM)

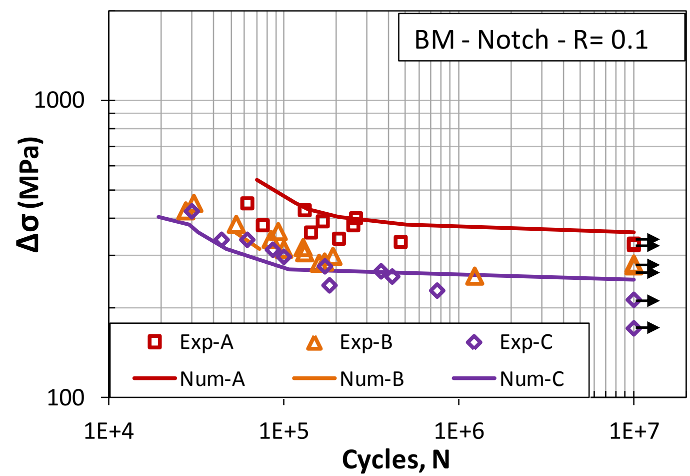
Smooth samples, 4 R





Notched samples, 3 geom.



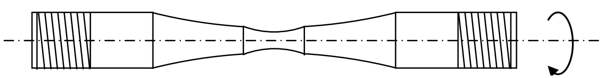


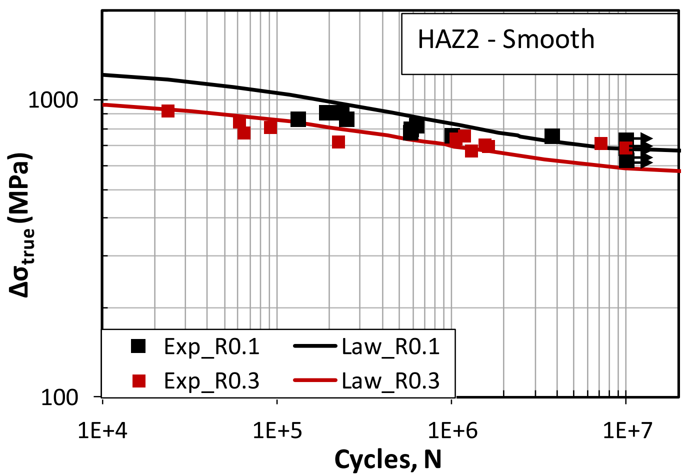
Small samples

- **Fatigue behavior – comparison experiments & fatigue law:**

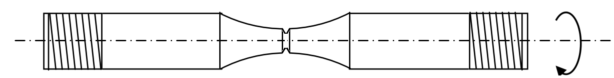
Heat affected zone (HAZ) with HAZ1 ≈ HAZ2

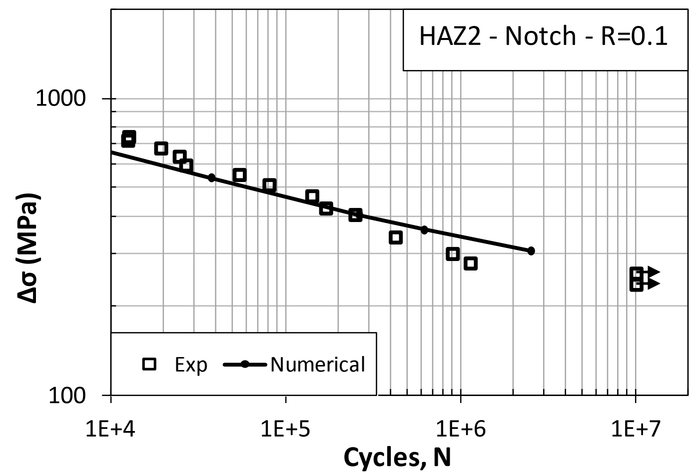
Smooth samples, 2 R





Notched samples, 1 geom.



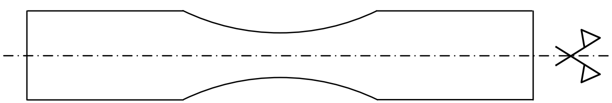


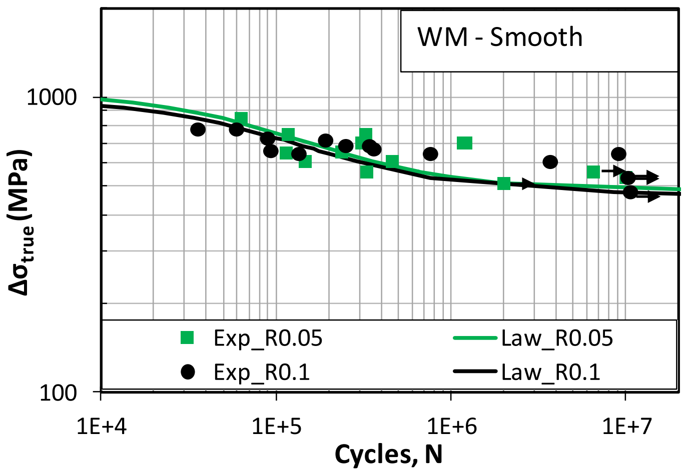
Small samples

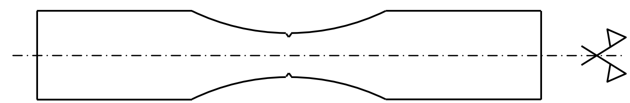
- **Fatigue behavior – comparison experiments & fatigue law:**

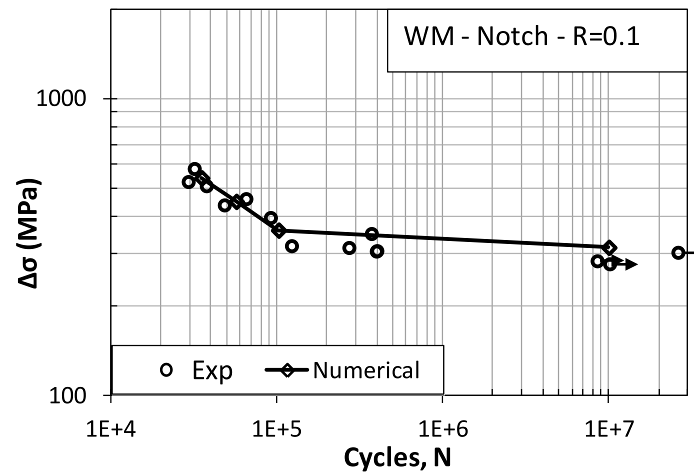
Weld metal (WM)

Smooth samples, 2 R	Notched samples, 1 geom.









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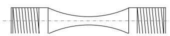
Research Fund for Coal & Steel

Outline

Small samples

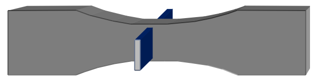


Static & fatigue tests

Material behaviour

- Static
- Fatigue (small size)

Large welded plates



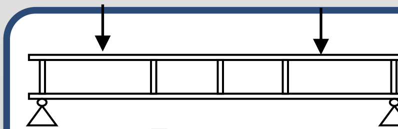
Fatigue tests
Residual stress

Effect of:

- size & machining
- welding
- post-treatments

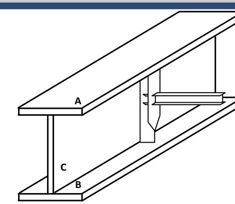
Fatigue behaviour

Future applications



Beams

- Size effect
- Laws validation



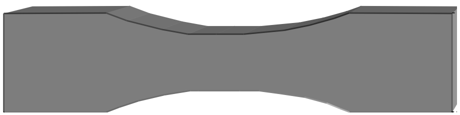
Critical bridge detail

- interest of HSS

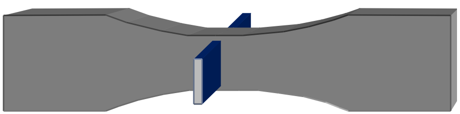
Large welded plates

- **Fatigue tests on plates (length= 1070 mm):**

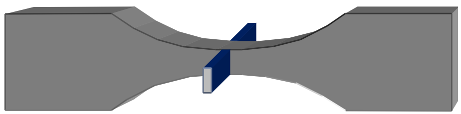
Plate



Edge distance



No edge distance



Case	Post-treatment	plate thickness (mm)	Stiffener thickness (mm)	Stiffener length (mm)	distance to edge	stress ratio R
Plate	No weld	25	-	-	-	0.1
A (ref case)	PIT	25	15	60	✓	0.1, 0.3, 0.5
B	PIT	15	15	60	✓	0.1
E	PIT	25	15	60	no	0.1
H	PIT	40	15	60	no	0.1
C	TIG remelting	15	15	60	✓	0.1
D	TIG remelting	25	15	60	✓	0.1
F	TIG remelting	25	15	40	✓	0.1
G	TIG remelting	15	6	60	✓	0.1
I	No post-treatment	15	15	60	✓	0.1

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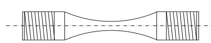
Large welded plates

- **Fatigue behavior – material data (inverse modelling):**

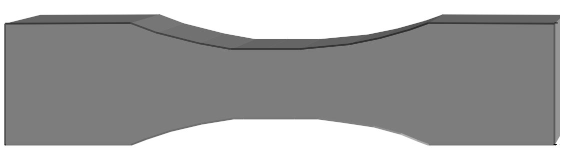
Material	σ_U (Mpa)	σ_{l0} (Mpa)	b	β	a	M0	Ra (mm)	a*(M0$^{-\beta}$)
BM-SS	905.0	**580.0**	1.10 E-03	0.17	1	5.385 E+30	0.06	5.966E-06
BM-plate	905.0	**203.0**	1.10 E-03	0.17	1	5.385 E+30	0.06	5.966E-06

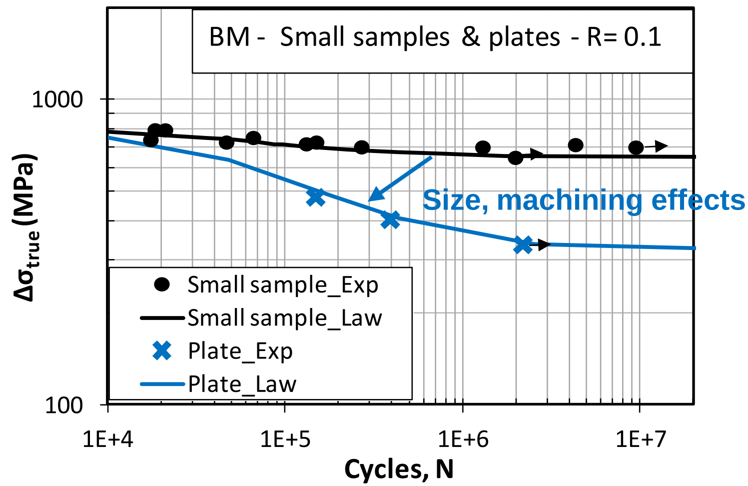
σ_{l0} = endurance limit= fatigue limit at null σ_{mean}

Small samples, Ra= 0.8 µm, length: 96 mm



Plates, as produced, length: 1070 mm





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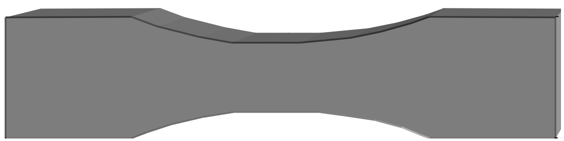
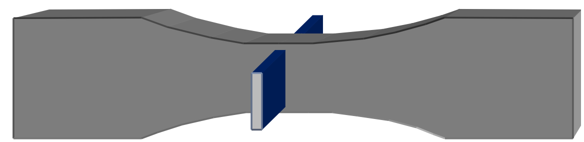
Large welded plates

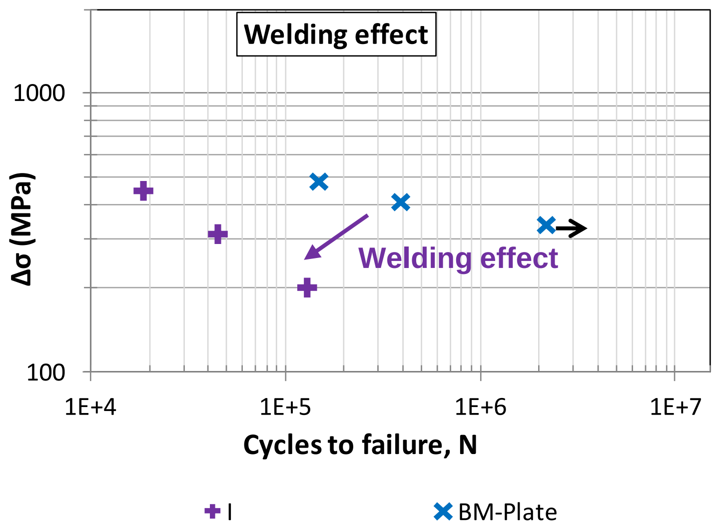
- **Fatigue tests: welding effect**

Plates



Welded plates

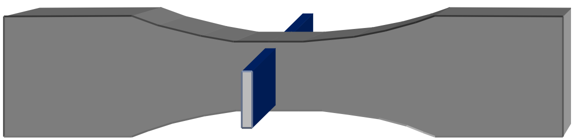


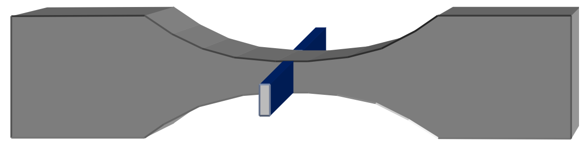


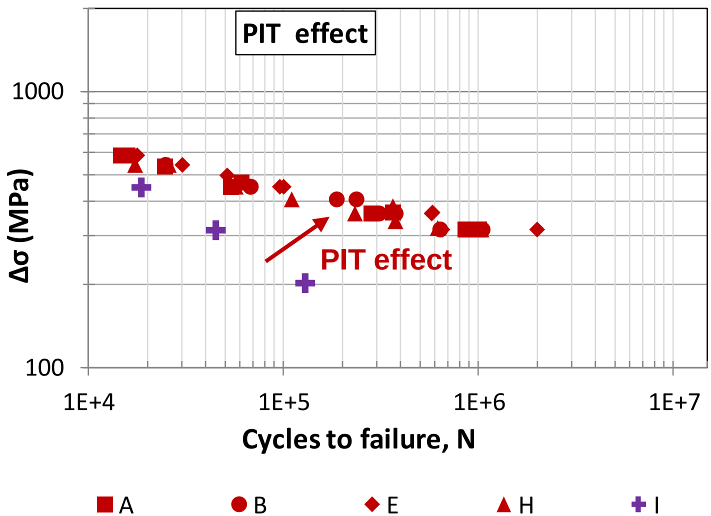
Large welded plates

- **Fatigue tests: PIT post-treatment effect**

Welded plates	Welded plates + PIT, ≠ geom.







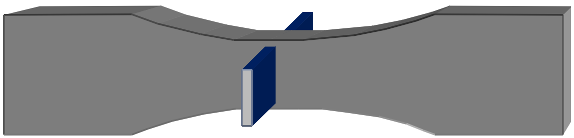
PIT: 4 cases

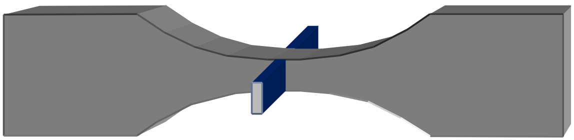
low effect of geometry

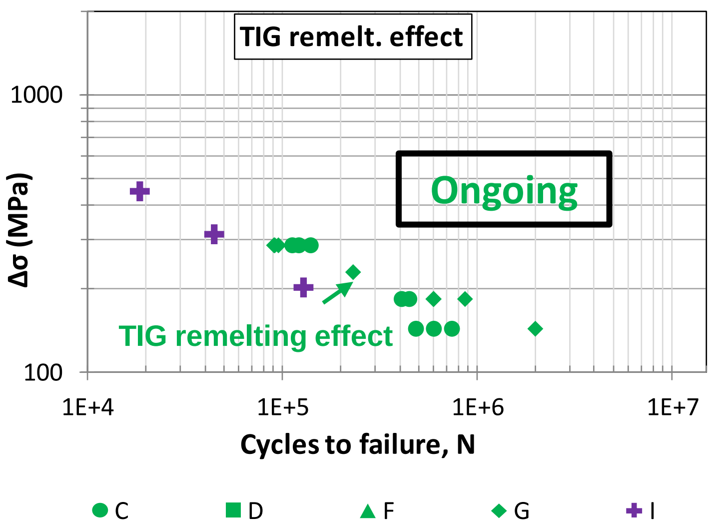
Large welded plates

- **Fatigue tests: TIG remelting post-treatment effect**

Welded plates	Weld. plates + TIG rem. , ≠ geom.





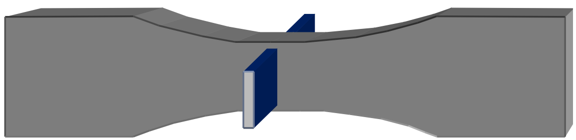


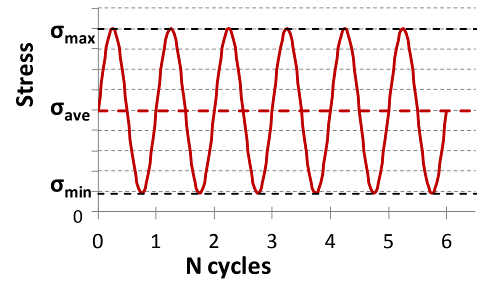
Large welded plates

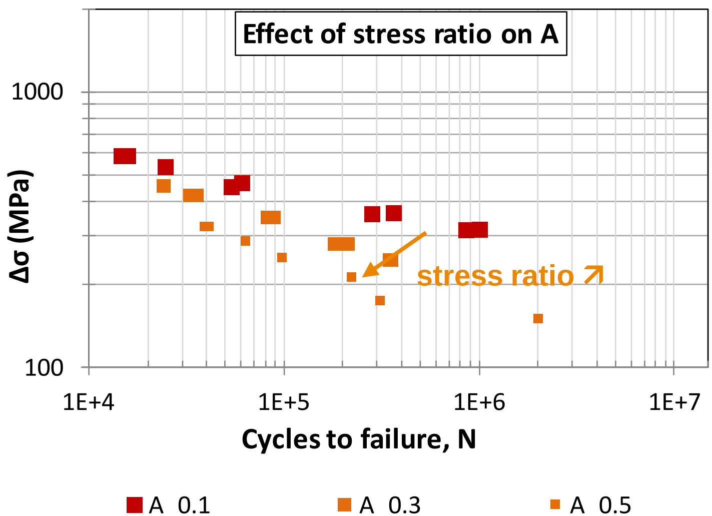
- **Fatigue tests: Stress ratio effect**

$R = \sigma_{min} / \sigma_{max} = 0.1$ or 0.3 or 0.5

Welded plates + PIT

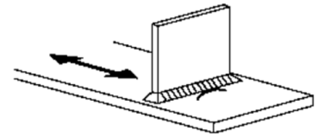






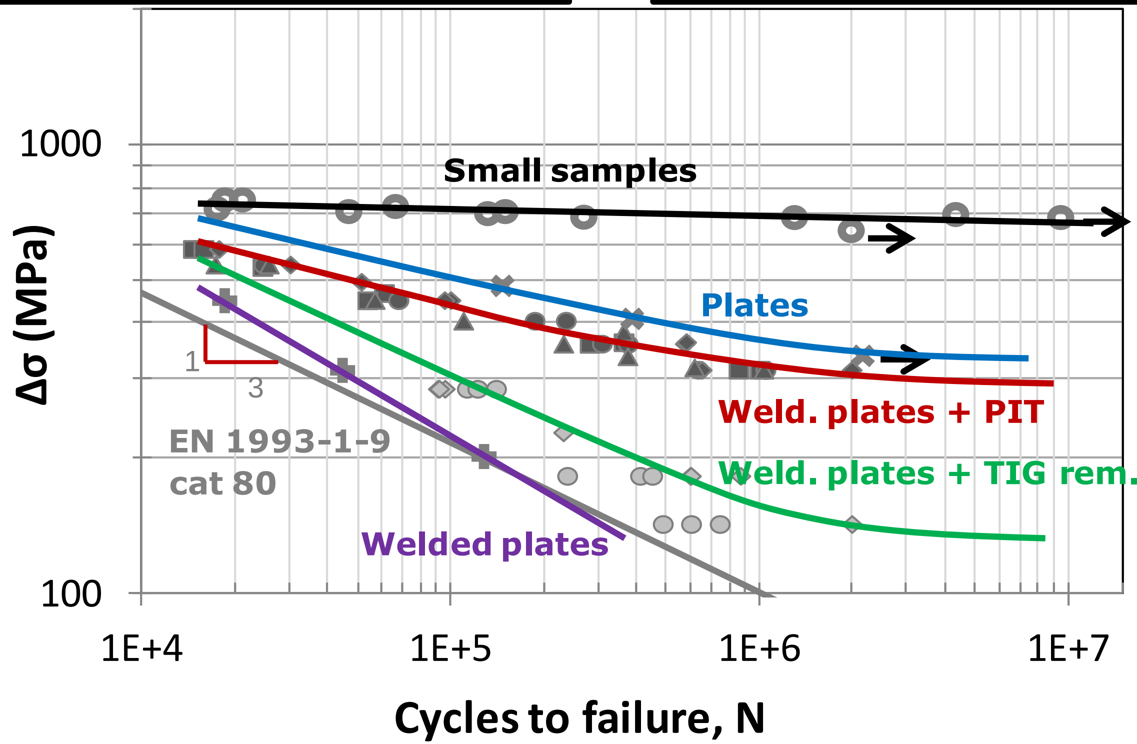
Large welded plates

- **Fatigue tests**



Summary, all cases, R= 0.1

EN 1993-1-9, $\Delta\sigma c$ = 80 MPa



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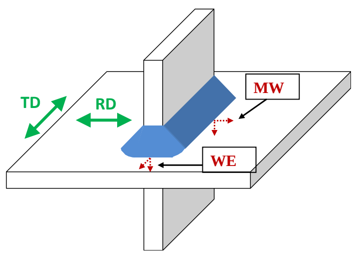
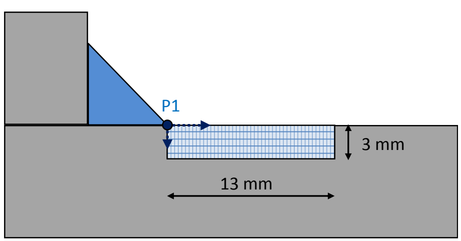
Large welded plates

- **Residual stress measurement**

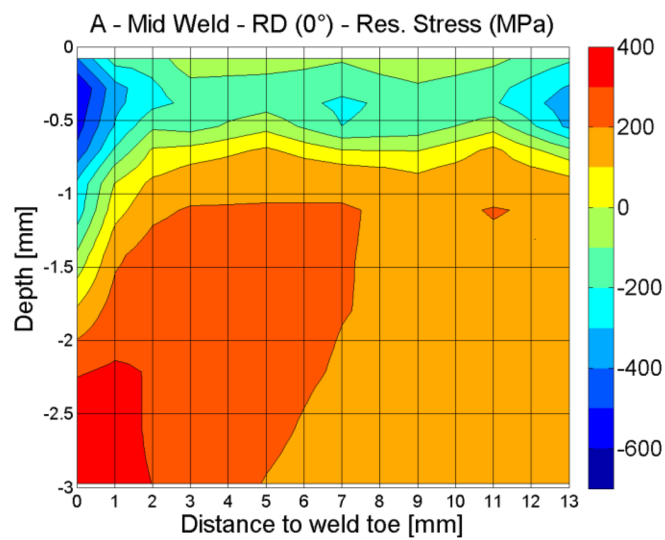
Several cases:
- **3 geometries**
- **3 cases: PIT, TIG remelting, no post-treat.**
- **Mid-weld (MW), weld edge (WE), RD, TD**
- **X-ray, neutron diffraction**

Welding & post-treatment effects:
- **up to depth ≈ 3-4 mm**
- **up to weld toe distance ≈ 6-7 mm**





Ex: ref. case: A, with post-treatment (X-ray)

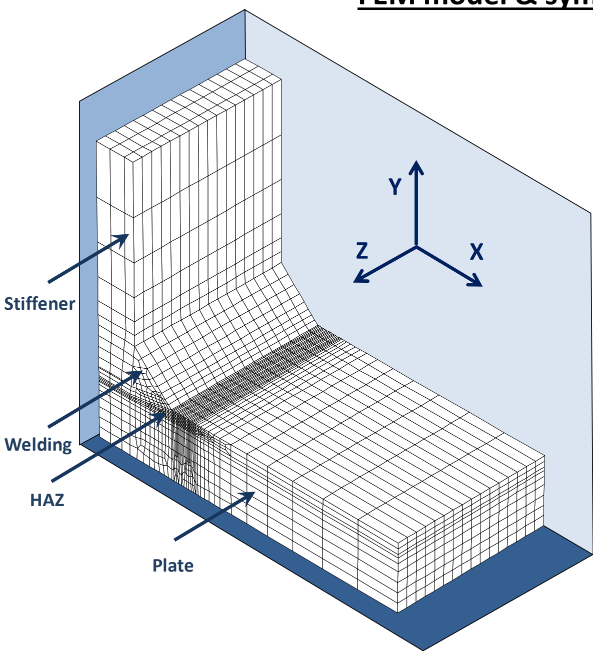


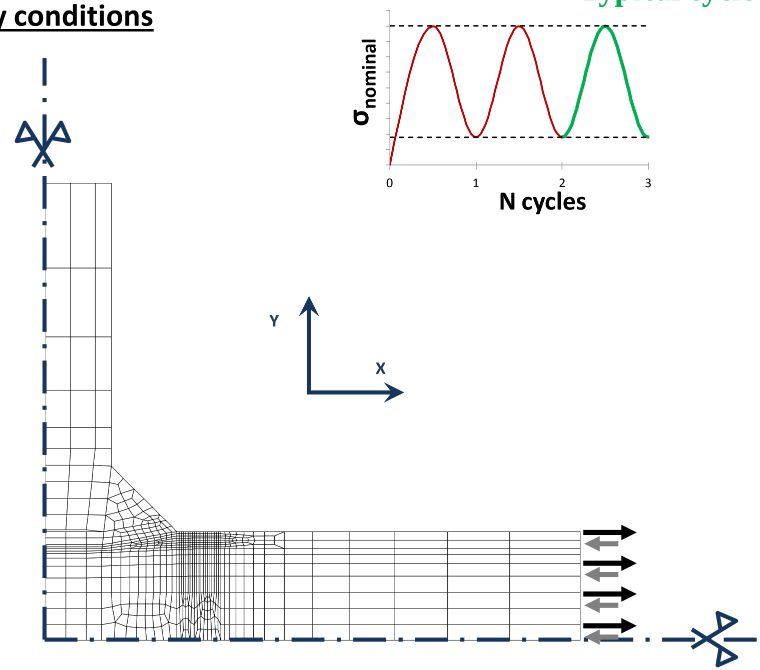
Large welded plates

- ## Fatigue - numerical analysis

FEM model & symmetry conditions

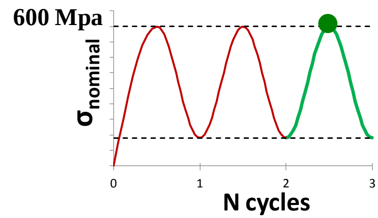
Typical cycle





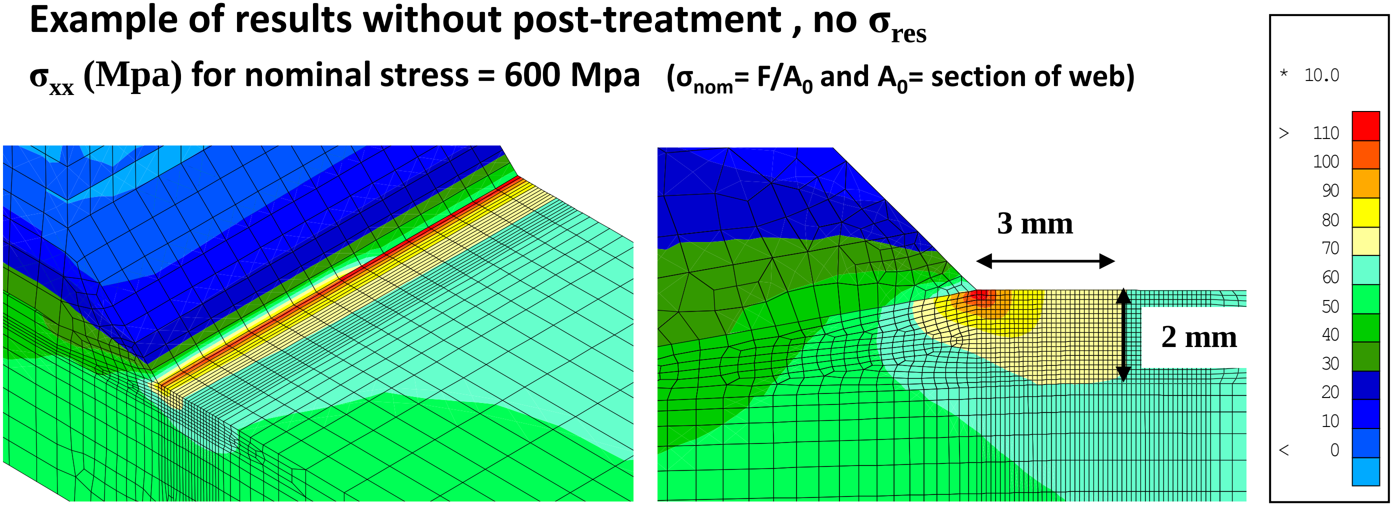
Large welded plates

- **Fatigue - numerical analysis**



Example of results without post-treatment , no σ_{res}

σ_{xx} (Mpa) for nominal stress = 600 Mpa (σ_{nom}= F/A_0 and A_0= section of web)



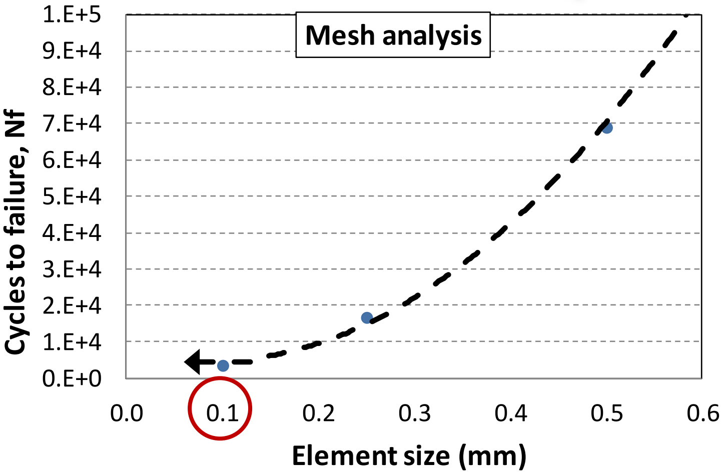
<u>Stress concentration at weld toe:</u>

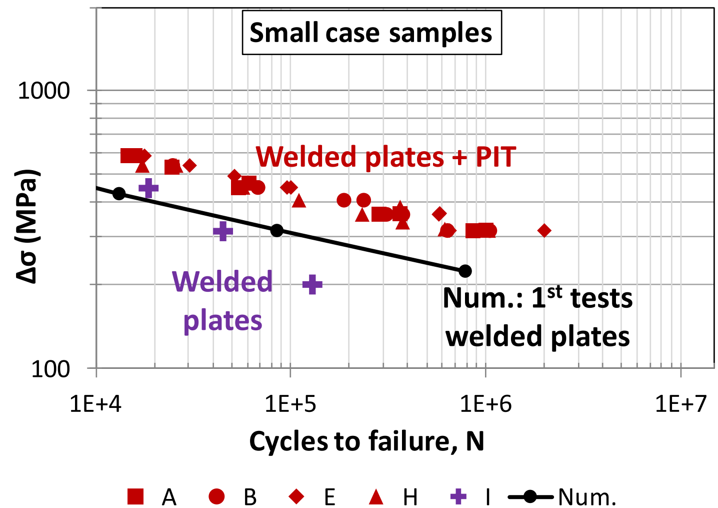
- **up to depth ≈ 2 mm (in HAZ)**
- **up to weld toe distance ≈ 3 mm**

Large welded plates

- ## Fatigue - numerical analysis

1. **Mesh analysis ➡ element size at weld toe: 0.1 mm (results not mesh dependent)**
2. **For several stress ranges and a specified stress ratio (here: 0.1):**
   - **Numerical analysis ➡ Stress distribution ➡ number of cycle at rupture**





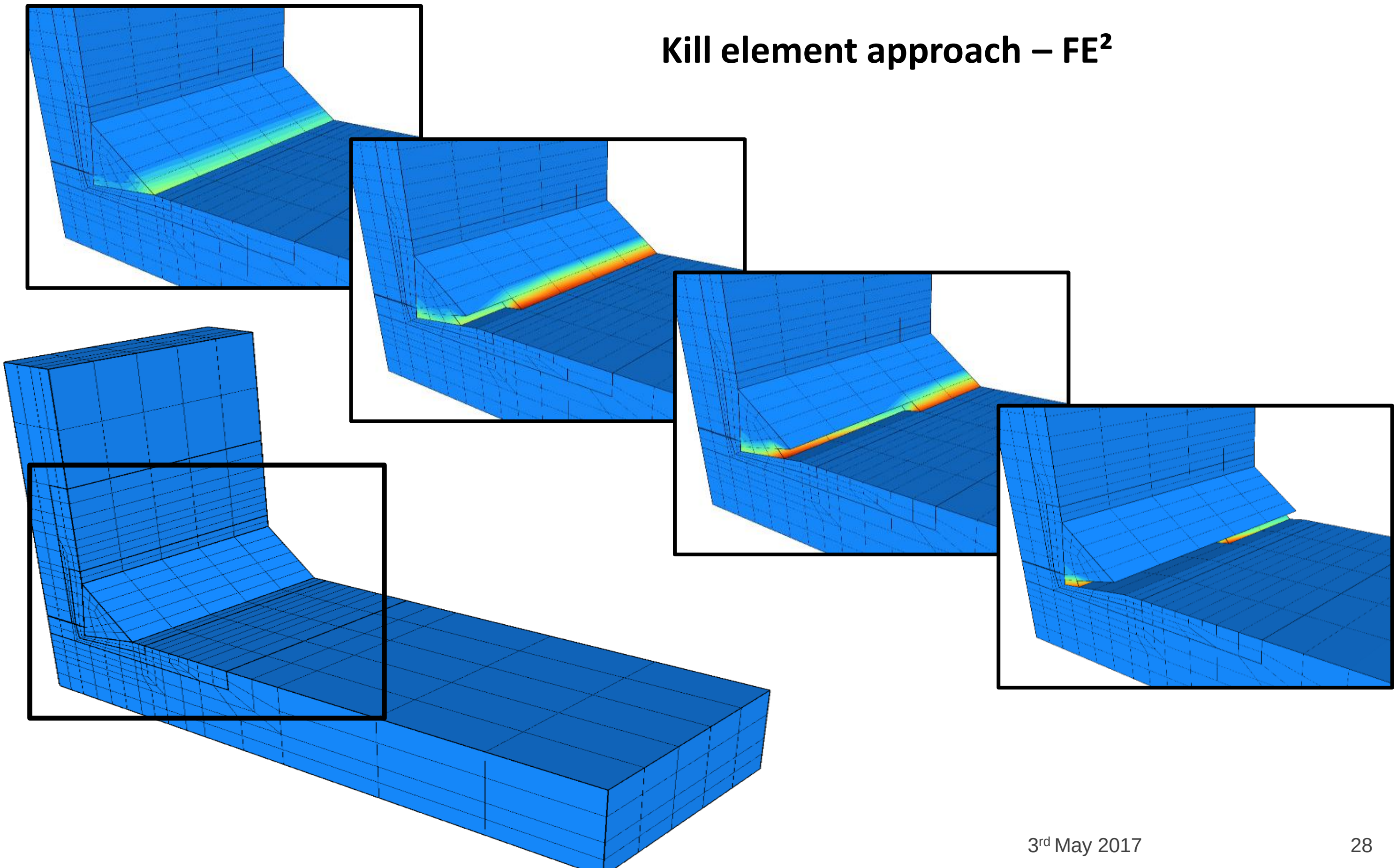
Next steps:

- **to add σ_{res} to model (welding + post-treatment)**
- **to improve fatigue mat. data of HAZ (σ_{l0})**
- **to study beams and critical bridge detail**

Large welded plates

- **Fatigue - numerical analysis, crack propagation**

Kill element approach – FE²



Summary & conclusions

Important test campaign has been done to prepare numerical fatigue study of bridge details:

- **Static tests / Fatigue tests** on small samples ➡ **Static behaviour / Fatigue behaviour (small size)** BM, HAZ, WM
- **Fatigue tests on large welded plates** ➡ **Effects of size, surface roughness, welding, geometry, post-treatments**
- **Residual stresses measurements** ➡ **Effect of post-treatments for num. analysis**
- **Mesh analysis** ➡ **welded plates: elem. size at weld toe: 0.1 mm**
- **Crack propagation** ➡ **deep analysis of fatigue study**

➡ **Positive effect in fatigue life is shown on welded plates**

Fatigue characterisation almost ready for analysis on critical bridge detail

Thank you for your attention!

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