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IACM Special Interest Conference

Numerical assessment of the influence of cutting operations on the fatigue strength of metals

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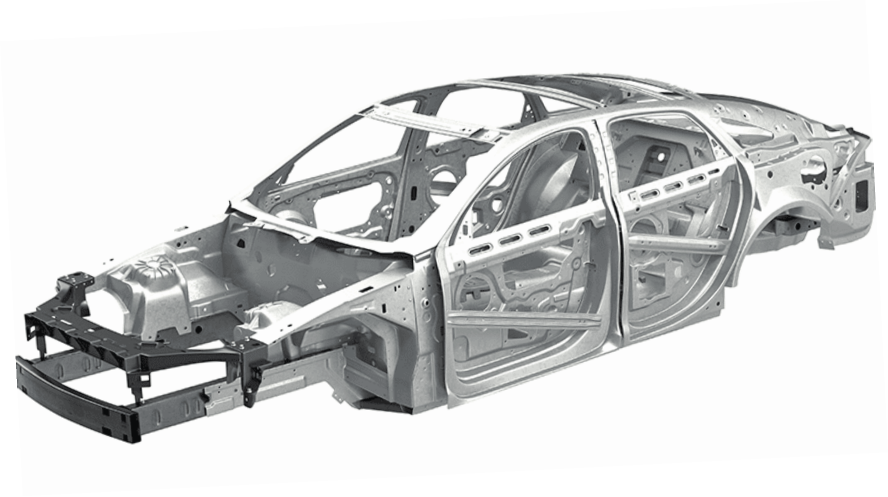
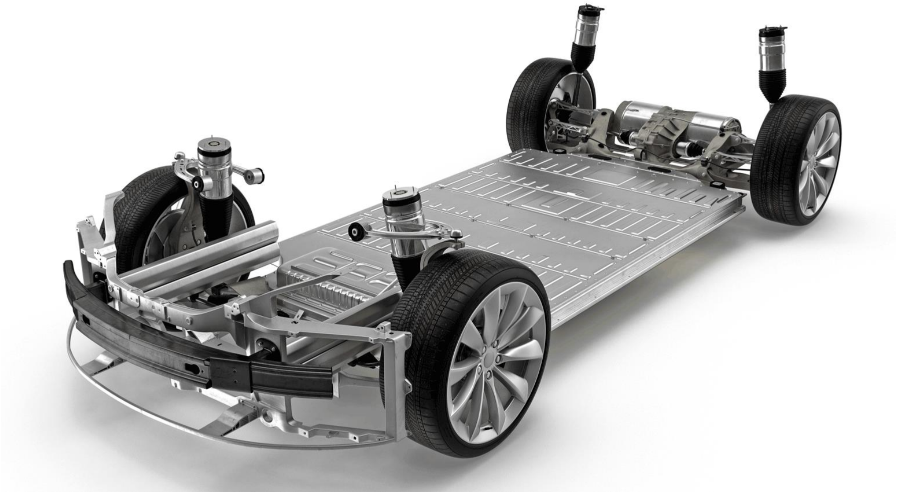
Barcelona, 5th of September 2023

Motivation

- Automotive sector continuously seeks the design of lightweight solutions to increase market competitiveness and mitigate environmental impacts
- Material selection represents a key factor in the design process: *high strength steels*, *stainless steels* and *Al-alloys* are the most used grades for the fabrication of metallic parts
- Body in White (BiW) and chassis areas with major potential for mass reduction: ≈ 40% and 25% of the vehicle total weight*

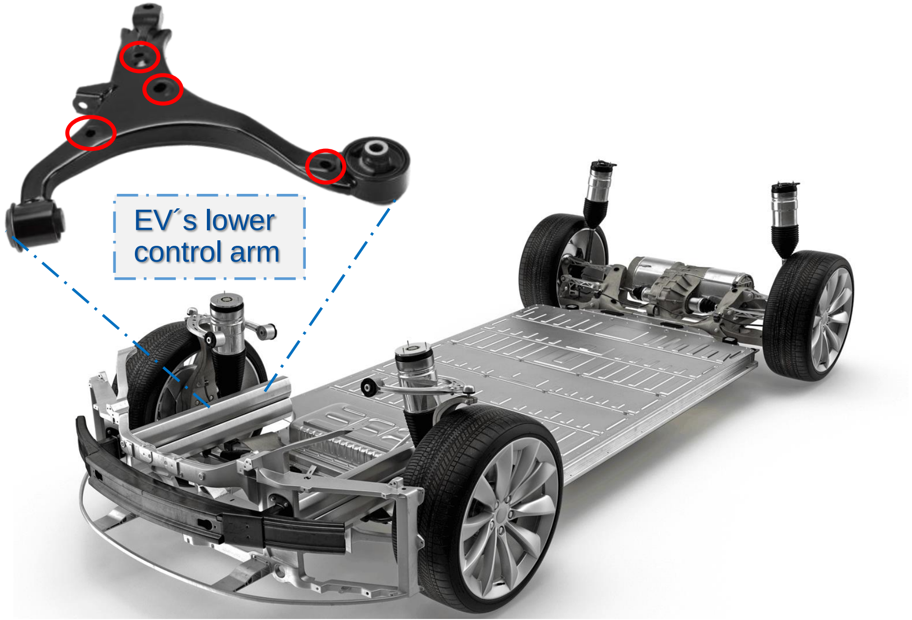


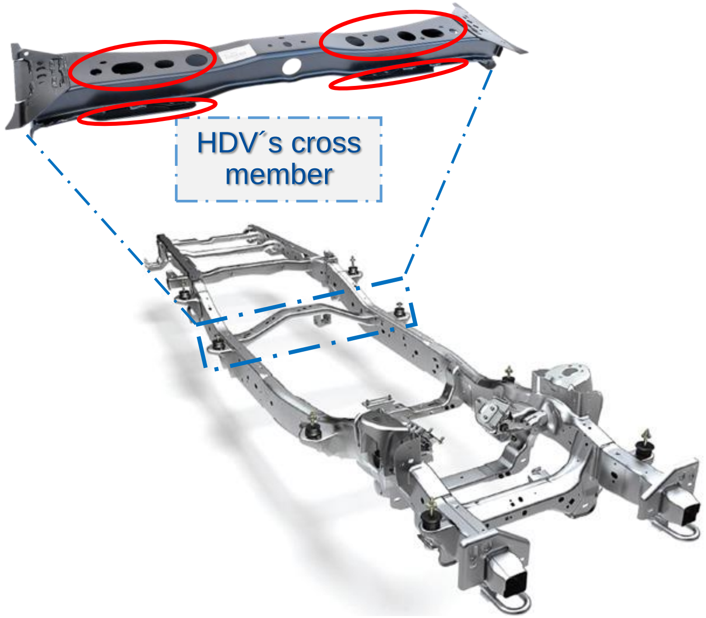


*M. Goede. ***SuperLIGHT-Car project - An integrated research approach for lightweight car body innovation***. In Proceedings of the International Conference On Innovative Developments For Lightweight Vehicles Structures, pp.25 – 38, Wolfsburg, Germany, 2009.

Motivation

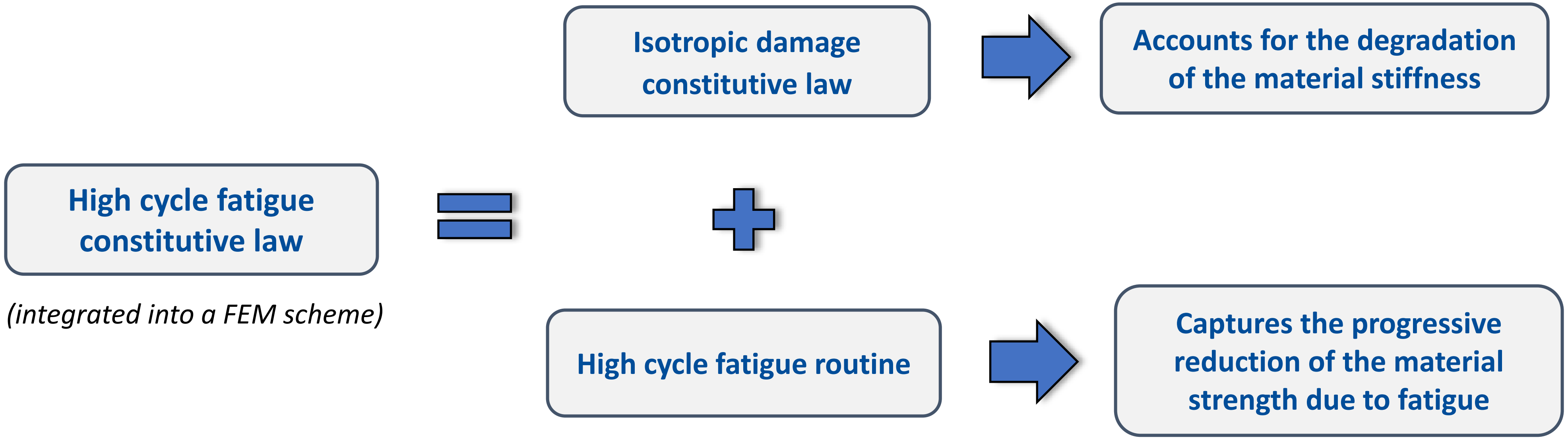
- Application on chassis parts conditioned to material fatigue properties (particularly in the high cycle domain)
- Chassis parts usually manufactured through shear cutting (punching, trimming, blanking, etc.), forming and welding operations due the combination of production rate and cost-efficiency
- Material fatigue behavior may be considerably affected by these operations





HCF constitutive model

- High cycle fatigue constitutive law proposed by Oller et al.*
    - Isotropic damage model
    - Introduction of a fatigue reduction factor accounting for the effects cyclic load



High cycle fatigue constitutive law

(integrated into a FEM scheme)

=

Isotropic damage constitutive law → **Accounts for the degradation of the material stiffness**

+

High cycle fatigue routine → **Captures the progressive reduction of the material strength due to fatigue**

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*S. Oller, O. Salomón and E. Oñate. ***A continuum mechanics model for mechanical fatigue analysis***. Comput Mater Sci 2005;32(2):175-95, doi: 10.1016/j.commatsci.2004.08.001.

HCF constitutive model

High cycle fatigue constitutive law = **Isotropic damage constitutive law*** + **High cycle fatigue routine**

- *Helmholtz free energy*

$$\psi(\boldsymbol{\varepsilon}, d) = \frac{1}{2}(1-d)\left(\boldsymbol{\varepsilon} : \mathbb{C}_{\mathbf{0}} : \boldsymbol{\varepsilon} + \boldsymbol{\sigma}_0^{ini} : \boldsymbol{\varepsilon}\right)$$

d - damage variable
$d \in [0,1]$

- *Cauchy stress tensor*

$$\Big\downarrow \ \frac{\partial \psi}{\partial \boldsymbol{\varepsilon}}(\boldsymbol{\varepsilon}, d)$$

$$\boldsymbol{\sigma} = (1-d)\left(\mathbb{C}_{\mathbf{0}} : \boldsymbol{\varepsilon} + \boldsymbol{\sigma}_0^{ini}\right) = \left[\mathbb{C}_{\mathbf{0}} : \boldsymbol{\varepsilon} + \boldsymbol{\sigma}_0^{ini}\right] - \left[d\left(\mathbb{C}_{\mathbf{0}} : \boldsymbol{\varepsilon} + \boldsymbol{\sigma}_0^{ini}\right)\right] = \boldsymbol{\sigma}_{\mathbf{0}} - \boldsymbol{\sigma}_{\boldsymbol{i}}$$

$\boldsymbol{\sigma}_0$ - *effective stress*
$\boldsymbol{\sigma}_i$ - *inelastic stress*

- *Damage threshold function*

$$\mathbb{F}(f(\boldsymbol{\sigma}_0), K_0) = f(\boldsymbol{\sigma}_0) - K_0 \leq 0, \ f(\boldsymbol{\sigma}_0) = \begin{cases} f(\boldsymbol{\sigma}_0)^+, \ \dot{d} \geq 0 \text{ if } r(\boldsymbol{\sigma}_{\mathbf{0}}) \geq 0.5 \\ f(\boldsymbol{\sigma}_0)^-, \dot{d} = 0 \quad \text{otherwise} \end{cases}, \ r(\boldsymbol{\sigma}_{\mathbf{0}}) = \frac{\sum_{i=1}^{3}\langle \boldsymbol{\sigma}_i \rangle}{\sum_{i=1}^{3}|\boldsymbol{\sigma}_i|}$$

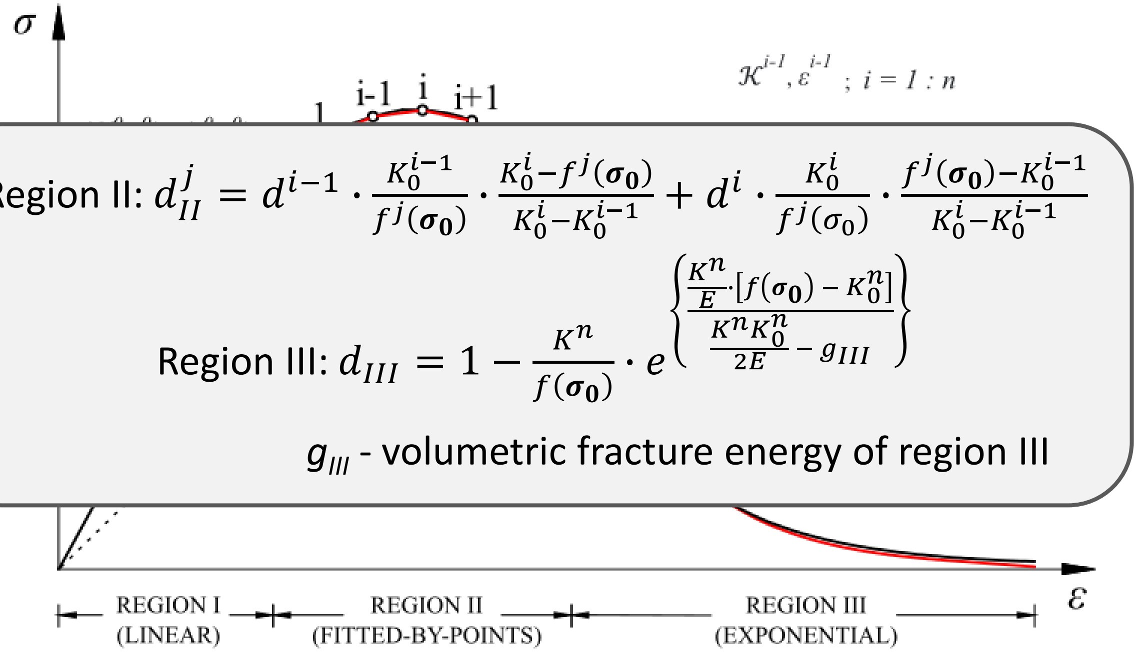
$f(\boldsymbol{\sigma}_0)$ - stress norm
K_0 - damage threshold
*$r(\boldsymbol{\sigma}_0)$ – weight factor**

*J. Oliver, M. Cervera, S. Oller, and J. Lubliner, ***Isotropic damage models and smeared crack analysis of concrete***, In Second International Conference on Computer Aided Analysis and Design of Concrete Structures, volume 2, pages 945-958, 1990.

HCF constitutive model

High cycle fatigue constitutive law = **Isotropic damage constitutive law*** + **High cycle fatigue routine**

Hardening-softening stress-strain curve for damage



Region II: $d_{II}^{j} = d^{i-1} \cdot \frac{K_0^{i-1}}{f^j(\boldsymbol{\sigma_0})} \cdot \frac{K_0^i - f^j(\boldsymbol{\sigma_0})}{K_0^i - K_0^{i-1}} + d^i \cdot \frac{K_0^i}{f^j(\sigma_0)} \cdot \frac{f^j(\boldsymbol{\sigma_0}) - K_0^{i-1}}{K_0^i - K_0^{i-1}}$

Region III: $d_{III} = 1 - \frac{K^n}{f(\boldsymbol{\sigma_0})} \cdot e^{\left\{\frac{\frac{K^n}{E} \cdot [f(\boldsymbol{\sigma_0}) - K_0^n]}{\frac{K^n K_0^n}{2E} - g_{III}}\right\}}$

g_{III} - volumetric fracture energy of region III

*S. Parareda, D. Casellas, A. Lara, and A. Mateo, ***Fatigue resistance evaluation of high Mn-TWIP steel through damage mechanics: A new method based on stiffness evolution***, Int. J. Fatigue, vol. 156, no. November 2021, p. 106643, 2022, doi: 10.1016/j.ijfatigue.2021.106643.

HCF constitutive model

High cycle fatigue constitutive law = **Isotropic damage constitutive law** + **High cycle fatigue routine***

- *Modified damage threshold function to account for HCF*

$$\mathbb{F}(\boldsymbol{\sigma}_0, d, \boldsymbol{\gamma}) = \frac{f(\boldsymbol{\sigma}_0)}{\boxed{f_{red}(\boldsymbol{\gamma})}} - K_0 \leq 0$$

$\boldsymbol{\gamma}$ – *Set of arguments of* f_{red}

- *Fatigue reduction factor,* $\boldsymbol{f_{red}}(\boldsymbol{\gamma})$
  - ✓ Irreversible factor, $f_{red} \in (0,1] \mid f_{red}(N_c = 0) = 1$
  - ✓ Amplifies the stress norm reducing the maximum admissible stress
  - ✓ Formulated through Wöhler curves for material points under subcritical stress levels
  - ✓ Rapid decaying exponential function for "low life" material points

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*S. Oller, O. Salomón and E. Oñate, ***A continuum mechanics model for mechanical fatigue analysis***, Comput. Mater. Sci. 32(2) (2005) 175-195, doi: 10.1016/j.commatsci.2004.08.001.

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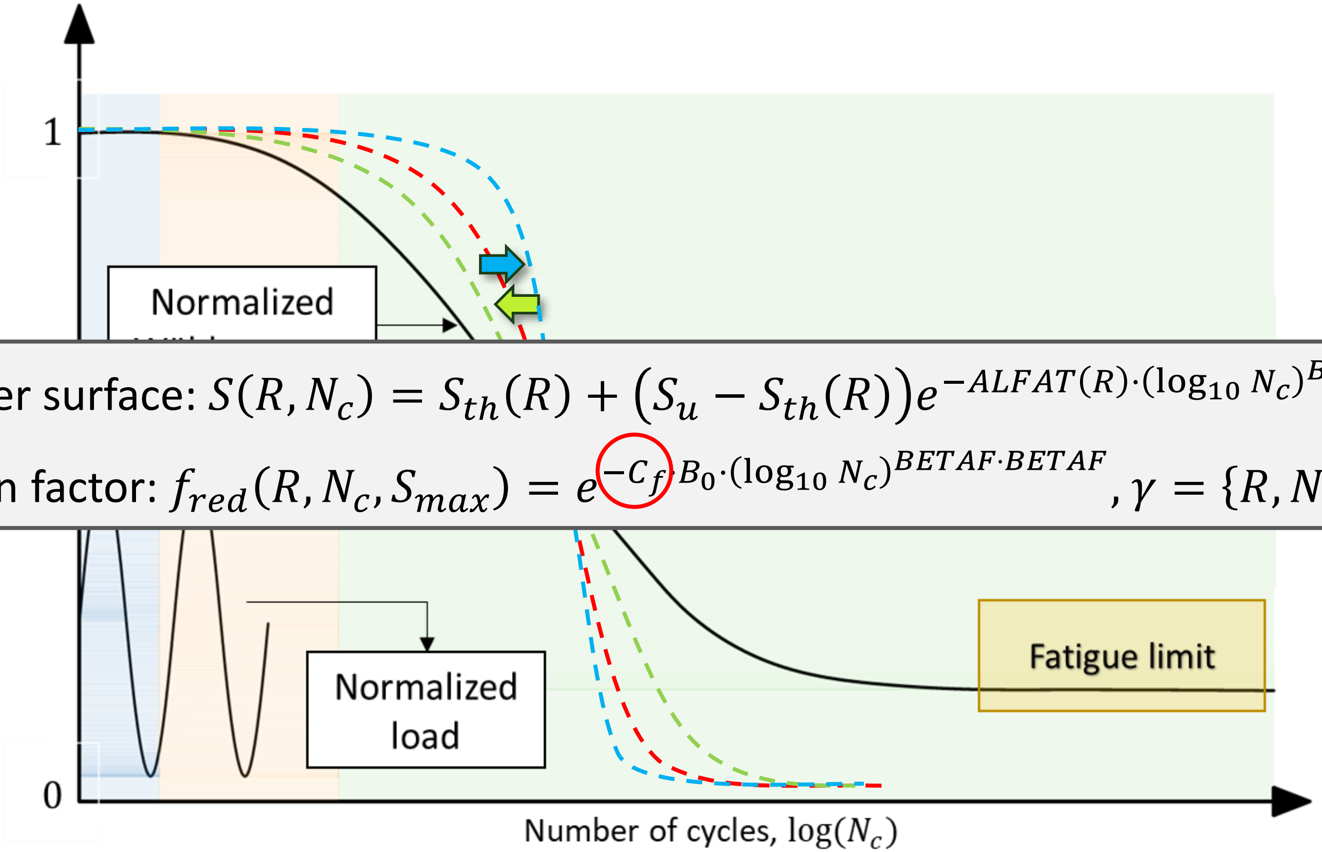

Wöhler surface: $S(R,N_c) = S_{th}(R) + \left(S_u - S_{th}(R)\right)e^{-ALFAT(R)\cdot(\log_{10} N_c)^{BETAF}}$

Reduction factor: $f_{red}(R,N_c,S_{max}) = e^{-C_f\cdot B_0\cdot(\log_{10} N_c)^{BETAF\cdot BETAF}}, \gamma = \{R, N_c, S_{max}\}$

*S. Oller, O. Salomón and E. Oñate, ***A continuum mechanics model for mechanical fatigue analysis***, Comput. Mater. Sci. 32(2) (2005) 175-195, doi: 10.1016/j.commatsci.2004.08.001.

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Reduction factor: $f_{red}(R,N_c,S_{max}) = e^{-C_f\cdot B_0\cdot(\log_{10} N_c)^{BETAF\cdot BETAF}}$

$$\underline{S_{th}(R)} = \begin{cases} \underline{S_e{}^*} + (S_u - \underline{S_e{}^*})\cdot(0{,}5 + 0{,}5\cdot R)^{\boxed{STH\ R1}} & \text{for } |R| \le 1 \\ \underline{S_e{}^*} + (S_u - \underline{S_e{}^*})\cdot(0{,}5 + 0{,}5/R)^{\boxed{STH\ R2}} & \text{for } |R| > 1 \end{cases}$$

S_{th} - fatigue limit
S_e* - modified fatigue limit at R =-1
S_u - ultimate strength

$$\underline{ALFAT(R)} = \begin{cases} \boxed{ALFAF} + (0{,}5 + 0{,}5\cdot R)\cdot\boxed{\mathrm{AUX\ R1}} & \text{for } |R| \le 1 \\ \boxed{ALFAF} - (0{,}5 + 0{,}5/R)\cdot\boxed{\mathrm{AUX\ R2}} & \text{for } |R| > 1 \end{cases}$$

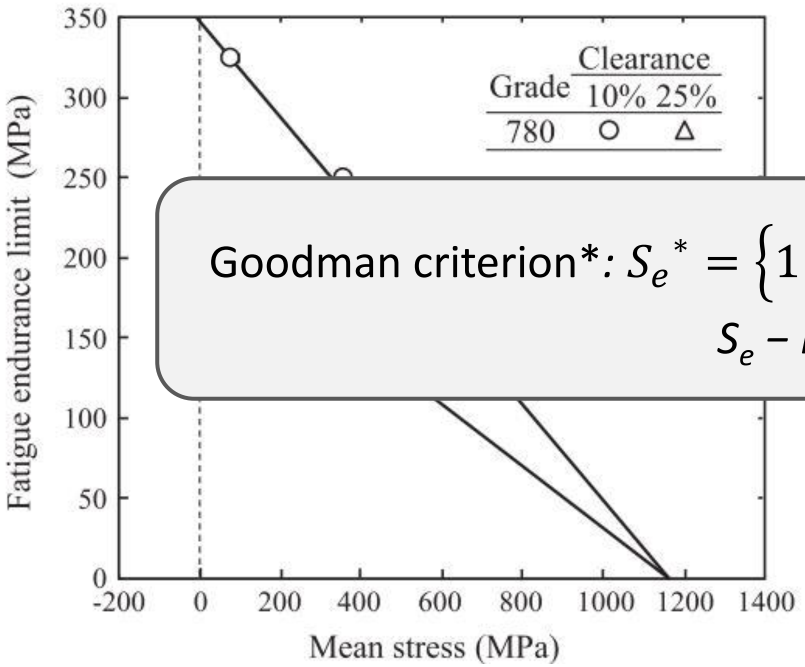
- *Fatigue model parameters:* $\underline{ALFAF, BETAF, STH\ R1, STH\ R2, AUX\ R1, AUX\ R2}$
  - ✓ Calibrated through curve fitting procedure
  - ✓ S-N experimental data for 2 stress ratios R required for the calibration

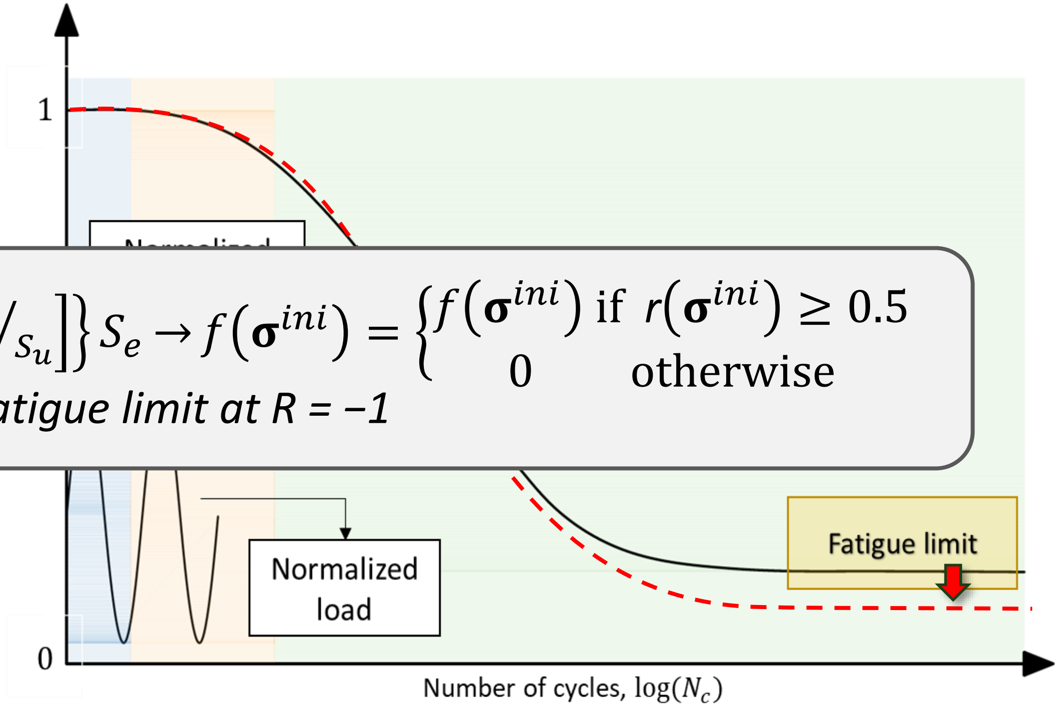
*S. Oller, O. Salomón and E. Oñate, ***A continuum mechanics model for mechanical fatigue analysis***, Comput. Mater. Sci. 32(2) (2005) 175-195, doi: 10.1016/j.commatsci.2004.08.001.

HCF constitutive model

High cycle fatigue constitutive law = **Isotropic damage constitutive law** + **High cycle fatigue routine***

- *Influence of residual stress in the fatigue limit*





Goodman criterion*: $S_e^{\,*} = \left\{1 - \left[{}^{f(\boldsymbol{\sigma}^{ini})}\!/_{S_u} \right]\right\} S_e \rightarrow f(\boldsymbol{\sigma}^{ini}) = \begin{cases} f(\boldsymbol{\sigma}^{ini}) & \text{if } r(\boldsymbol{\sigma}^{ini}) \geq 0.5 \\ 0 & \text{otherwise} \end{cases}$

S_e – nominal fatigue limit at R = −1

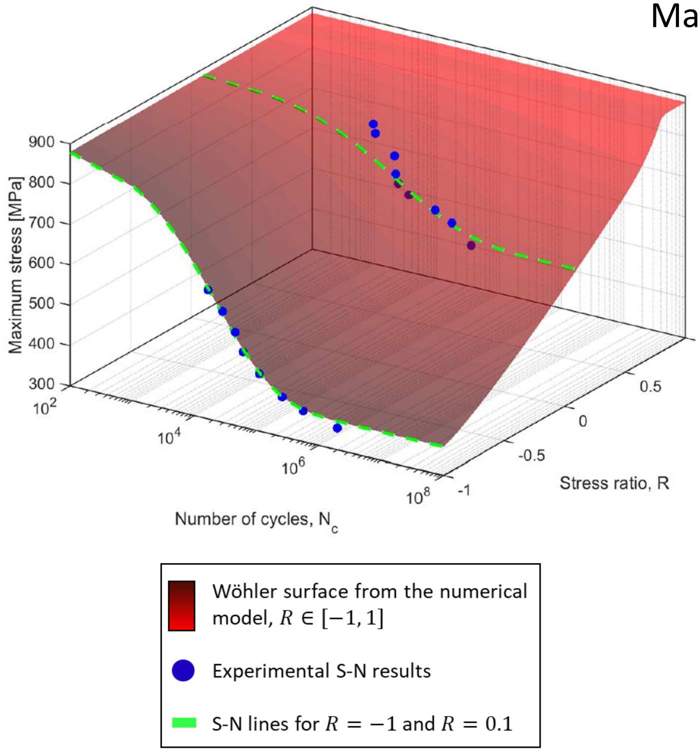
*T. Shiozaki, Y. Tamai and T. Urabe, ***Effect of residual stresses on fatigue strength of high strength steel sheets with punched holes***, Int. J. Fatigue, 80:324–331, 2015. doi: 10.1016/j.ijfatigue.2015.06.018

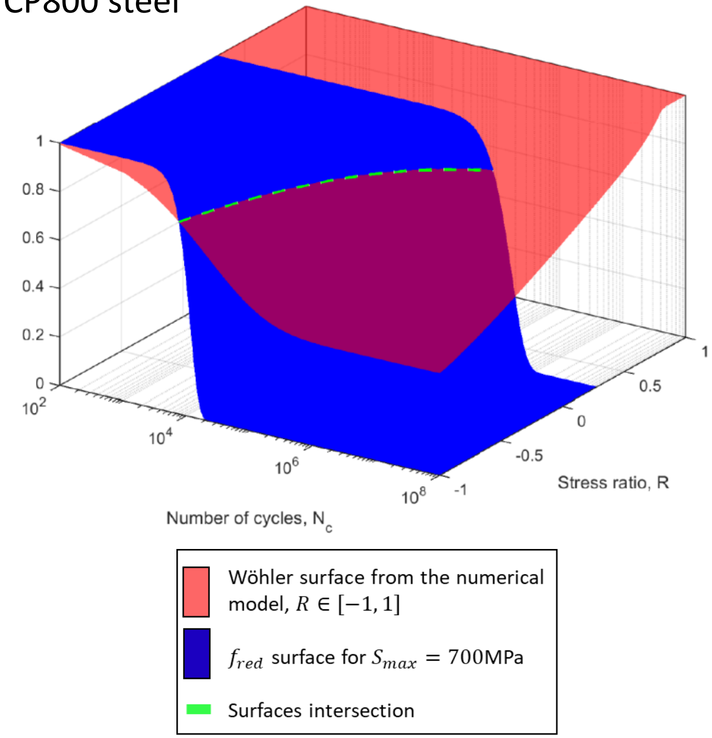
HCF constitutive model

High cycle fatigue constitutive law = **Isotropic damage constitutive law** + **High cycle fatigue routine***

- *Graphical representation of the Whöler surface together with the* f_{red} *surface for* $S_{\max} = 700\ MPa$.

Material: CP800 steel





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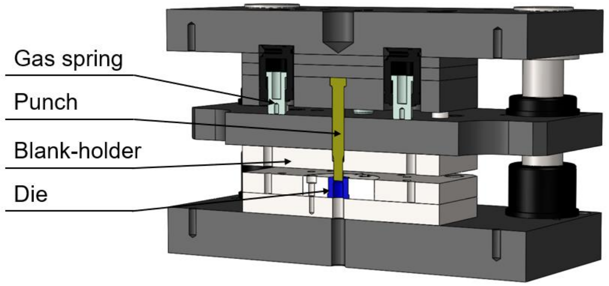
*S. Oller, O. Salomón, E. Oñate, ***A continuum mechanics model for mechanical fatigue analysis***, Comput. Mater. Sci. 32(2) (2005) 175-195, doi: 10.1016/j.commatsci.2004.08.001.

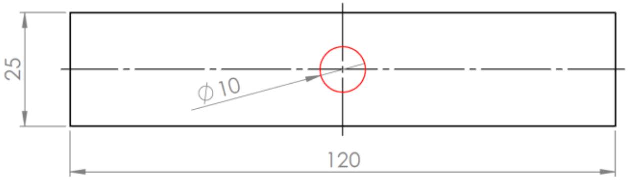
Fatigue test of punched specimens

- Reproduction of the fatigue test on small scale specimens

Punching operation

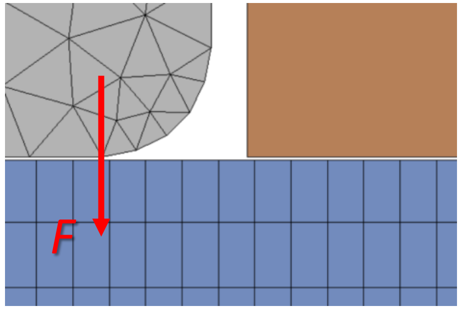


Specimen geometry



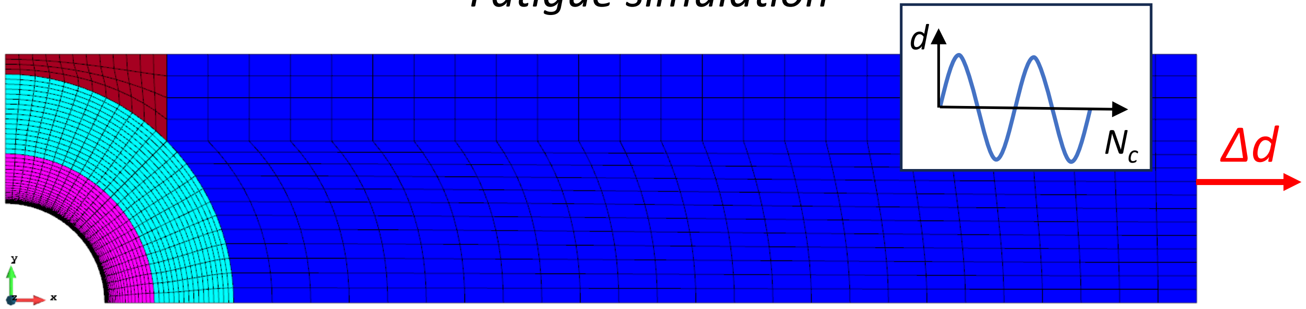
Fatigue test

Punching simulation



Data transfer

Fatigue simulation



Sym. plane 1

Sym. plane 2

Fatigue test of punched specimens

- Punching simulation
  - Axisymmetric model
  - Power law as flow-curve

Only one uniaxial tensile curve and another force-displacement one from punching experiment are need to calibrate the model for wide range of cutting clearances!

$$\boldsymbol{\sigma} = A + B\bar{\boldsymbol{\varepsilon}}_p^n$$

σ, ε_p – True stress and plastic strain

A, B, n – Constants calibrated through experimental stress-strain data

  - Failure criterion based on GISSMOS damage model

$$\dot{\boldsymbol{D}} = \frac{2\sqrt{D}}{\bar{\boldsymbol{\varepsilon}}_f(\eta,\cancel{L},k)}\dot{\boldsymbol{\varepsilon}}_p$$

Nearly zero for shear cutting processes

D – Damage

$\bar{\boldsymbol{\varepsilon}}_f$ – Equivalent strain to fracture

$\dot{\boldsymbol{\varepsilon}}_p$ – Plastic strain increment

η – Stress triaxiality

L – Lode angle parameter

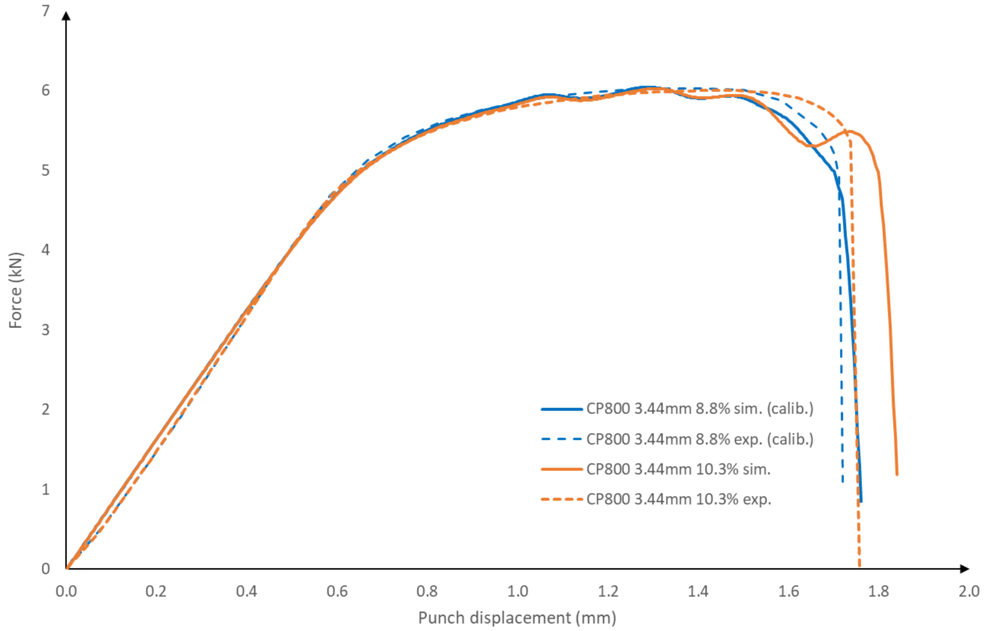
k – set of constant to be calibrated force-displacement curves of punching experiments

Fatigue test of punched specimens

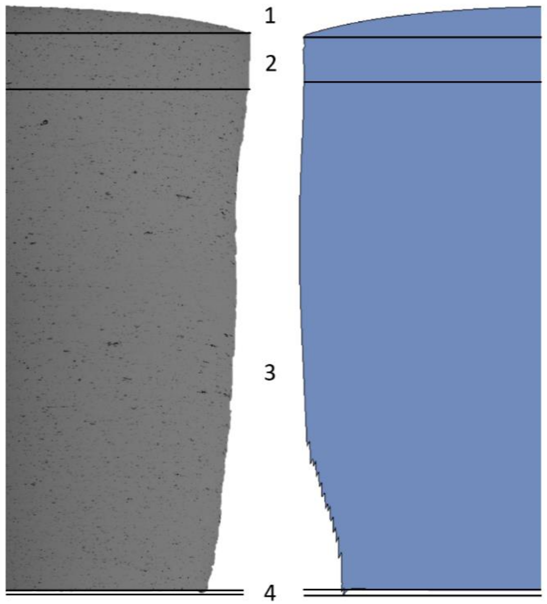
- Punching simulation

Model calibration and validation

Force-displacement response



Cut edge morphology



Experiment *Simulation*

Cut edge zones

Up to 1 - Rollover

1 to 2 – Burnish

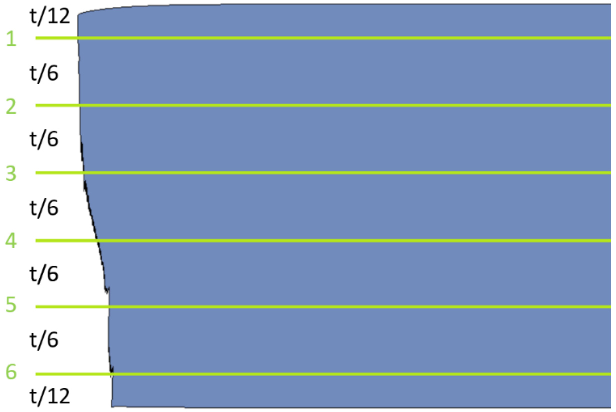
2 to 3 - Fracture

From 4 on - Burr

Fatigue test of punched specimens

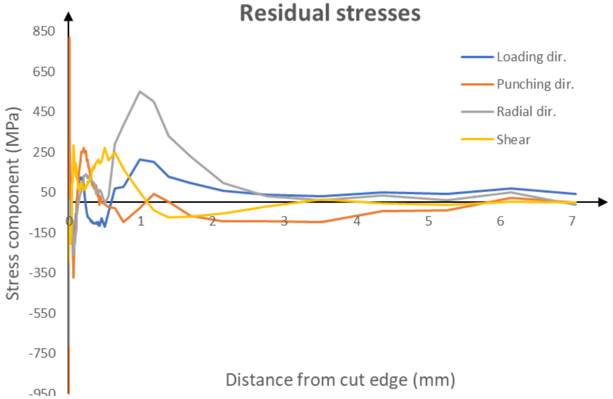
- Punching simulation
  - Data transfer between models
  - Residual stresses as dominant factor on the specimen fatigue resistance*

Punching result



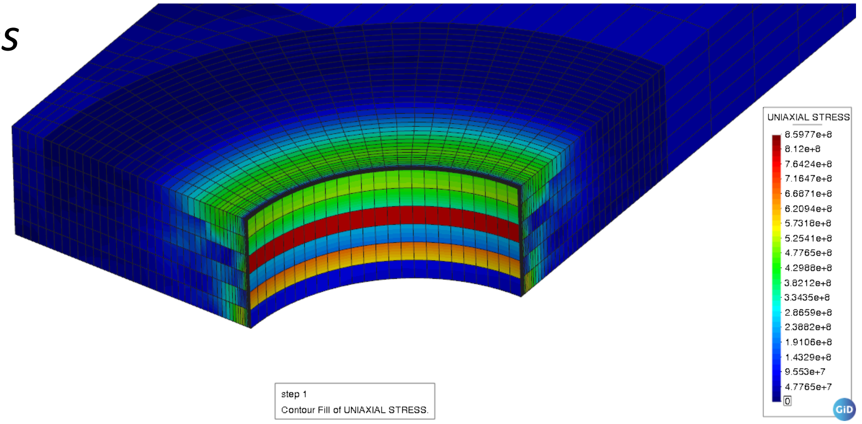
Residual stresses

Stress profiles



Initial stresses

Fatigue model initial state



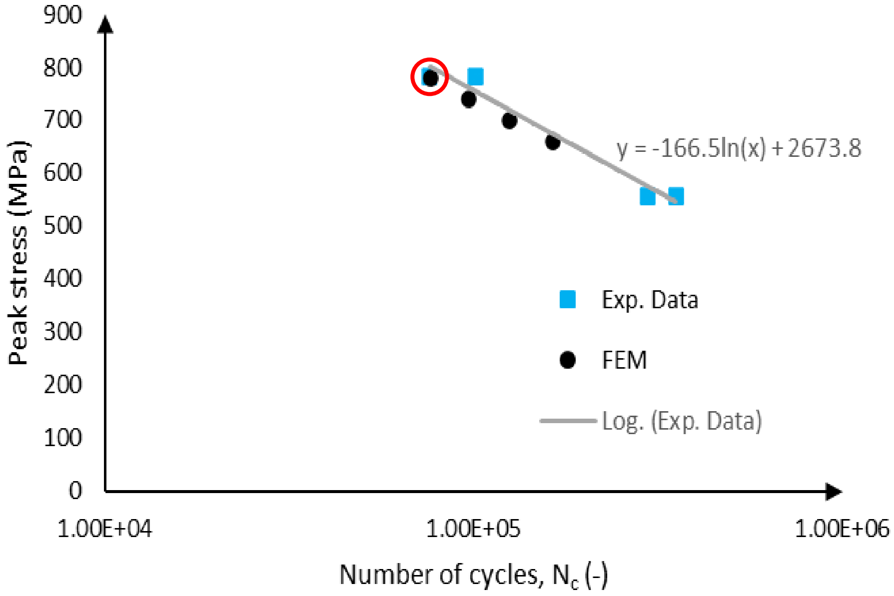
H. Dehmani, C. Brugger, T. Palin-Luc, C. Mareau, S. Koechlin, ***High cycle fatigue strength assessment methodology considering punching effects***, Procedia Engineering 213, 691-698 (2018) doi: 10.1016/J.PROENG.2018.02.065

Representative results

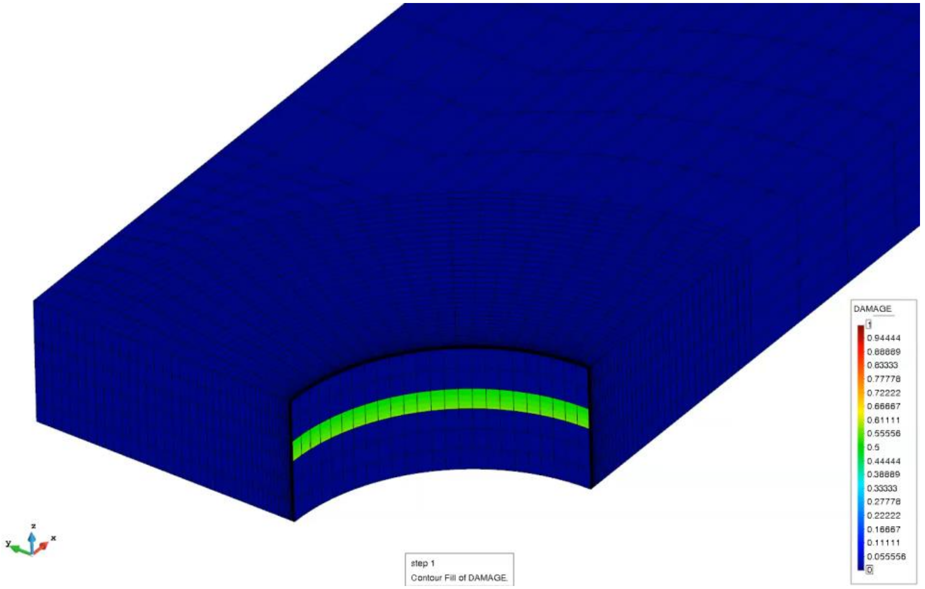
- S-N curve reproduction

Material: CP800 steel

S-N curve (R = 0.1)



Damage contour animation
(peak stress 781 MPa)

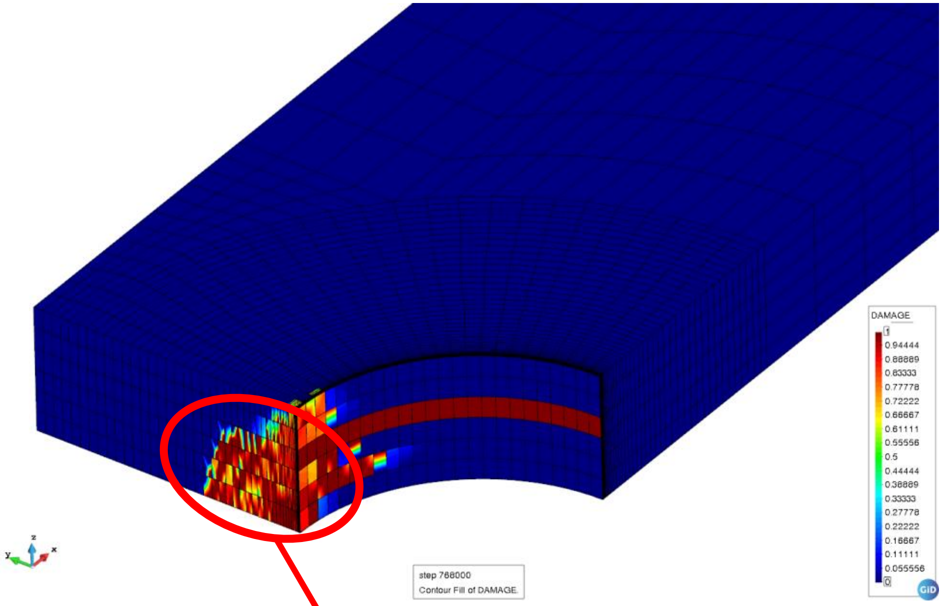


Representative results

- Failure mode

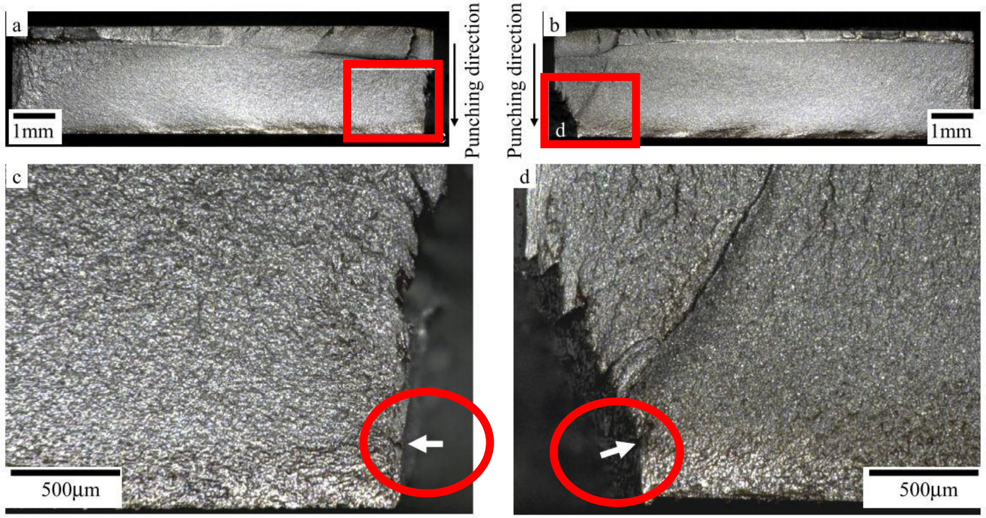
Material: CP800 steel

FEM prediction



Damage concentrated in the <u>burr</u> and <u>fracture</u> zones

Experimental observations*



*T. Shiozaki, Y. Tamai and T. Urabe, ***Effect of residual stresses on fatigue strength of high strength steel sheets with punched holes***, Int. J. Fatigue, 80:324–331, 2015.
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Concluding remarks

- A sequential punching-high cycle fatigue numerical scheme is presented to predict the influence of shear cutting operations on the fatigue strength of metals
- Residual stresses resulting from the punching simulations are used to set the initial state of the high cycle fatigue model
- Results obtained for the fatigue life span of punched specimens are in good agreement with the experimental observations
- The proposed scheme was capable of capturing the main features of the failure mode commonly observed in the fatigue test of this nature

Acknowledgements

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The work has been also supported by **the Spanish Government program** FPU17/04196.

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Thank you very much for your attention!