RUPTURE OF MATERIALS AND STRUCTURES

Mechanisms and modelling VS. industrial applications

MECAMAT, AUSSOIS 2019

René BILLARDON — Safran Landing Systems

OUTLINE

- **Industrial environment**
    - ☐ Structures, systems, loadings
    - ☐ Certification procedures
    - ☐ High strength metallic materials
    - ☐ Prediction of the rupture of a structure under monotonic loading
- **Application to structures made of High Strength steels**
    - ☐ Constitutive model and ductile damage model
    - ☐ Prediction of the rupture
        - Local material rupture
        - Global instability
- **Other typical applications**
- **Some conclusions**

1

INDUSTRIAL ENVIRONMENT

AERONAUTICAL SYSTEMS

- Engines

- Landing Gears, Wheels & Brakes
- Systems and Equipment

CERTIFICATION PROCEDURES

Different strength requirements – Static (monotonic) loading

- **Landing Gear, Wheels & Brakes, Systems and Equipment**
  - **Fatigue loads**
  - **Limit loads**: maximal loads expected in service
    - No detrimental permanent deformation of the structure
  - **Ultimate loads**: each limit load case multiplied by a safety factor of 1.5
    - No rupture
- **Engines**
  - **Fatigue loads**
  - **A few limit loads** expected in service
  - **A few ultimate loading cases** due to particular adverse conditions
    - e.g. Fan Blade Out, turbine over-speed

CERTIFICATION PROCEDURES

Different strength requirements – Fatigue loading

- **Safe life approach**
  - ☐ No (detectable) crack in the structure in service
- **Damage tolerant approach**
  - ☐ To cope with anomalies occurring in-service or/and during maintenance operations
  - ☐ To assess the fatigue life of non Critical Structural Elements
  - ☐ Regular inspections so that the residual strength of the structure is capable of the limit loads

CERTIFICATION PROCEDURES

Different requirements – Tests and analyses

- **Landing Gear**
  - ☐ Certification by Type Certificate Holder (aircraft manufacturer) **by analysis supported by tests**
    - Hundreds of non-proportional load cases
- **Wheels & Brakes**
  - ☐ Qualification and Technical Standard Order **by tests supported by analyses**
  - ☐ Certification by Type Certificate Holder (aircraft manufacturer) **after flight tests**
- **Systems and Equipment**
  - ☐ All components certified **by tests supported by analyses** except for Critical Structural Elements (e.g. retraction actuator)
  - ☐ Integrated systems certified **by tests and analyses** mainly at aircraft level
- **Engines**
  - ☐ Certification **by analysis supported by tests**

CERTIFICATION PROCEDURES

Analysis vs. tests

- **Analyses**
  - ❑ To deal with numerous complex load cases
  - ❑ To deal with the scatter of material properties and the scatter of parts geometry
- **Tests**
  - ❑ Tests at different scales to support analysis methods
  - ❑ Full scale –detail or complete- tests to certify a particular system
- **Past experience**
  - ❑ Positive lessons learnt from in-service systems
    validate the methods that were used for their design
    whatever their theoretical background
  - ❑ Authorities strongly support the use of “classical” methods

CERTIFICATION PROCEDURES

Analysis vs. tests

- **A need for new analysis methods and tools**
  - ☐ To introduce new designs and new materials
  - ☐ To take best benefit of 3D analysis tools
  - ☐ To better control conservatisms to be decreased because of weight reductions
- **New analysis tools must not lead to a regression**
  when applied to a system that has been already certified
- **Models used to better understand mechanisms**
  vs. models to design structures

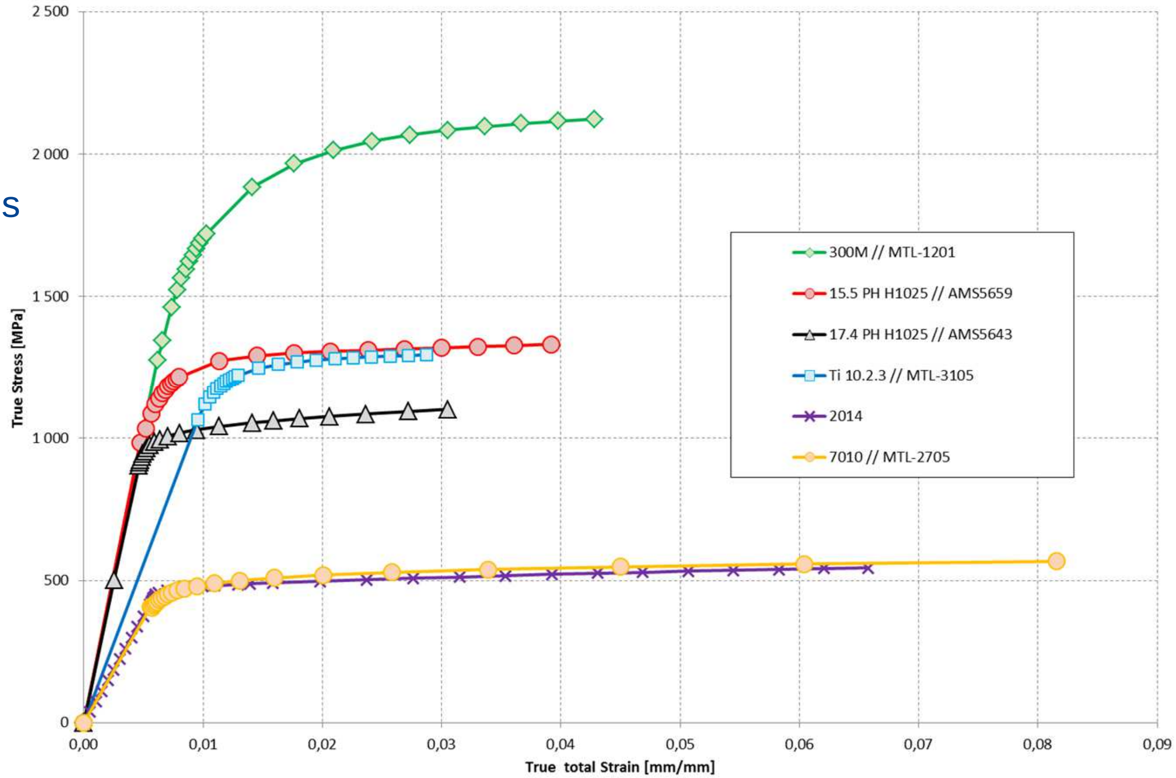
MATERIALS

High strength materials

- **Tensile tests**
  - ☐ Typical

    true stress-strain curves

    up to UTS



MATERIALS

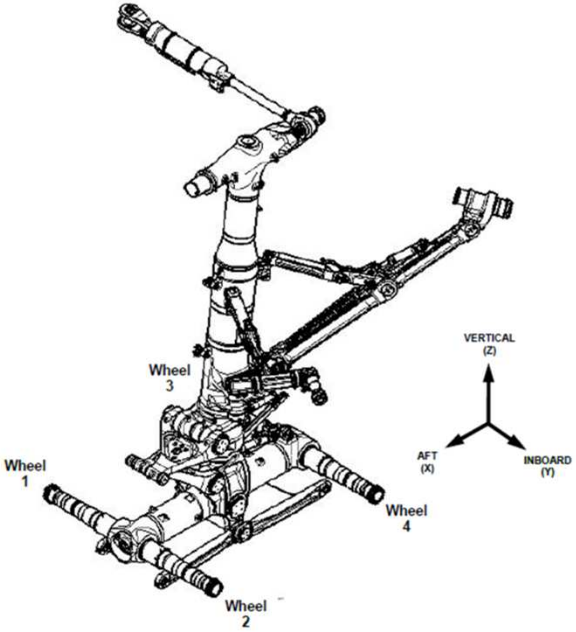
High strength materials

- **High yield stresses**
  - Large elastic strains
- **Low Hardening**
  - *UTS / YS < 1.x*
- **Different forms of ductility depending on the materials**
  - For several materials: small strain to UTS e_u
  - No correlation between e_u and Elongation or Reduction of Area
- **Toughness**
  - For several materials: small

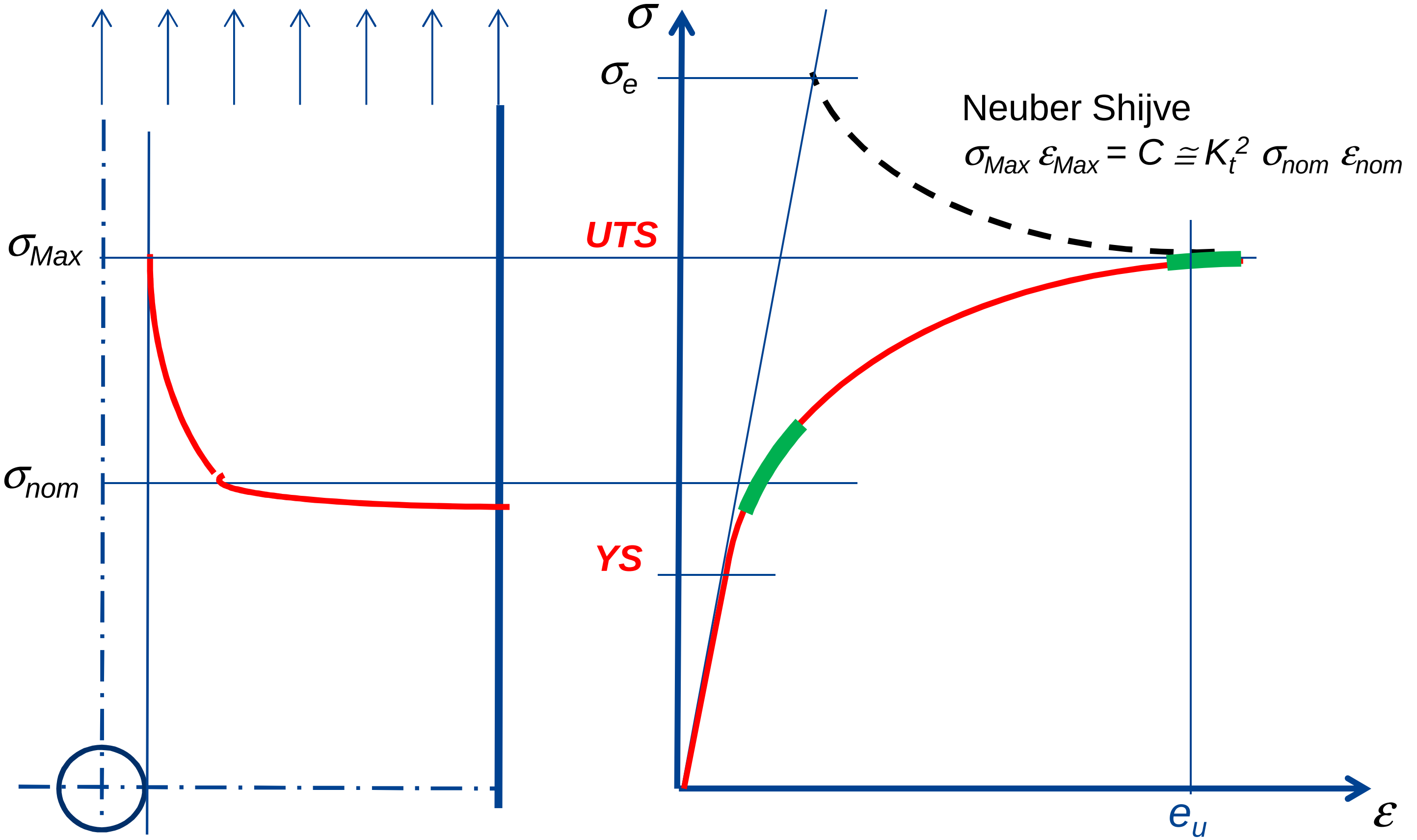
STANDARD STATIC ANALYSIS

General approach

- **Specifications**
  - Loading cases
- **Structural analysis**
  - Inputs:
    - Geometry
    - Boundary Conditions, loads
    - Material strain behaviour
- **Strength assessment**
  - Material rupture criterion
  - Geometrical instability



STANDARD STATIC ANALYSIS – SIMPLE APPLICATION



Neuber Shijve

$\sigma_{Max}\,\varepsilon_{Max} = C \cong K_t^2\,\sigma_{nom}\,\varepsilon_{nom}$

2

APPLICATION TO STRUCTURES MADE OF HIGH STRENGTH STEELS

Ductile rupture criterion for ML340 steel (from C. Defaisse PhD 2018)

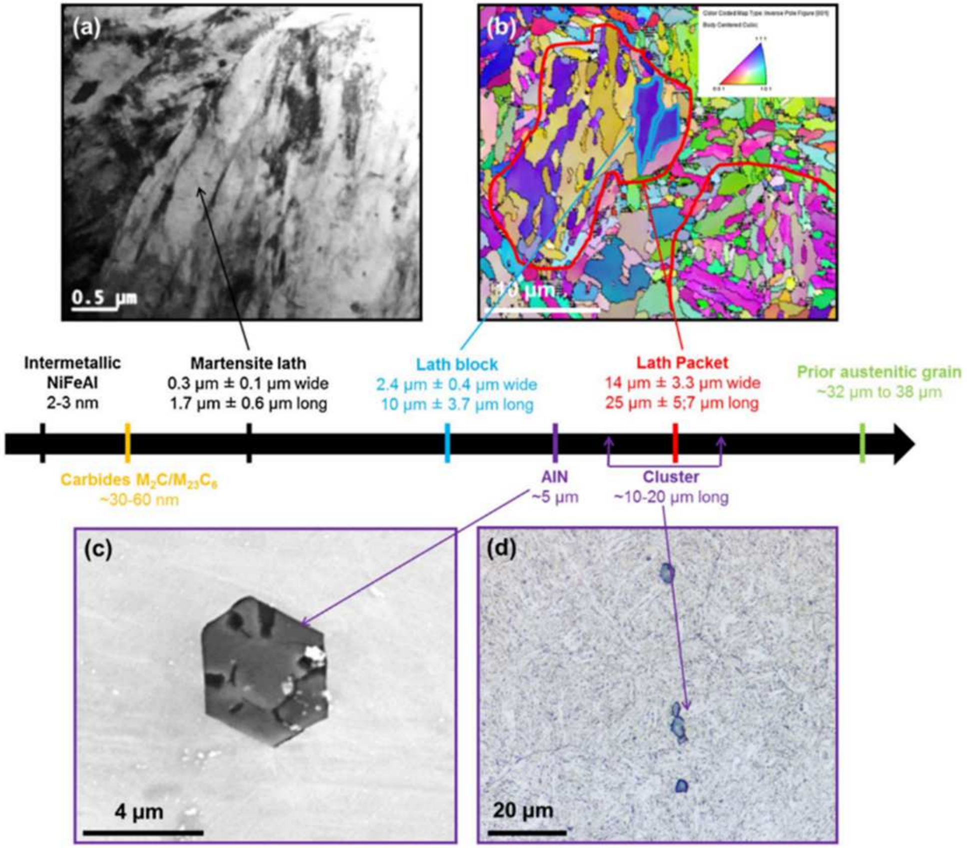
ML340 steel

- **Complex microstructure**
  - ☐ Typical composition (wt%)

Fe	C	Ni	Cr	Mo	Al	Co	V
Base	0.23	13.	3.3	1.5	1.5	5.8	0.25

(from Aubert & Duval 2015)

  - ☐ Martensite + 1wt% austenite
  - ☐ Carbides and intermetallics (<1µm)
  - ☐ AlN inclusions



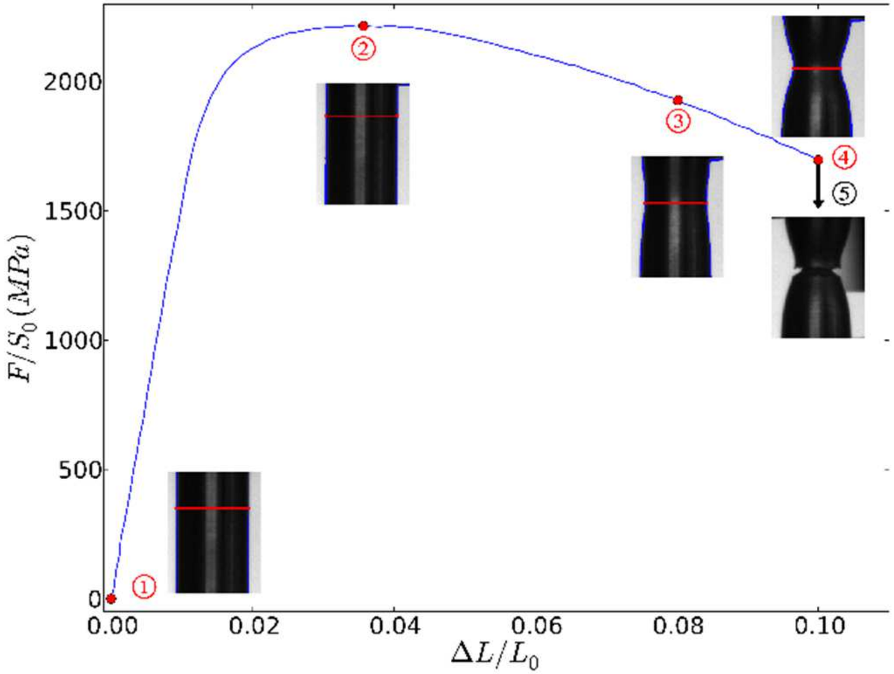
Ductile rupture criterion for ML340 steel (from C. Defaisse PhD 2018)

ML340 steel

- **Very high strength**

Material	UTS (MPa)	YS (Mpa)
Maraging 250	1758	1724
300M	1979	1682
ML340	2200	1900

- **Low ductility**
  - ☐ Strain to UTS $e_u = 3\%$
  - ☐ *Red. of A* = *40%*

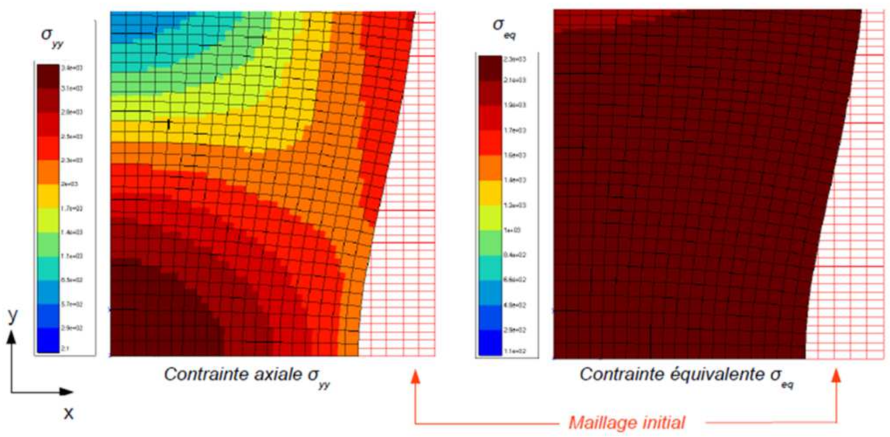


Ductile rupture criterion for ML340 steel (from C. Defaisse PhD 2018)

ML340 steel

- **Elastoplastic stress-strain behaviour**
  - ☐ von Mises criterion, isotropic hardening
  - ☐ Inverse identification using necking geometry

$$\langle \sigma_{yy} \rangle_S \neq \sigma_{eq}$$



Ductile rupture criterion for ML340 steel (from C. Defaisse PhD 2018)

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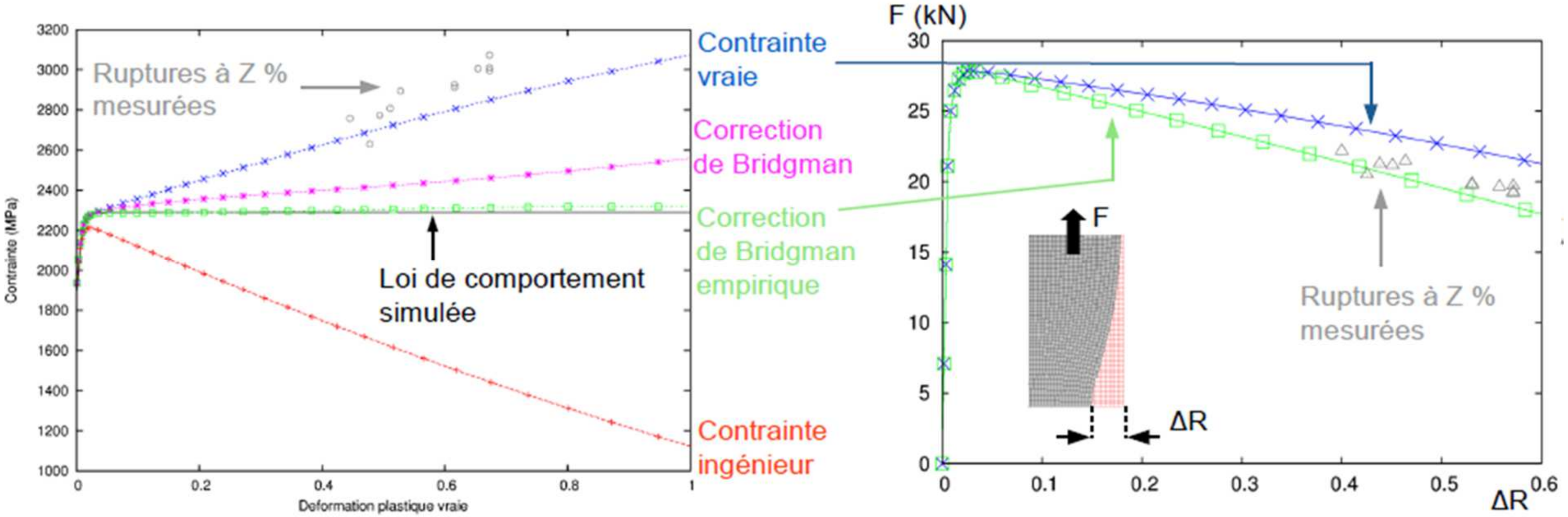
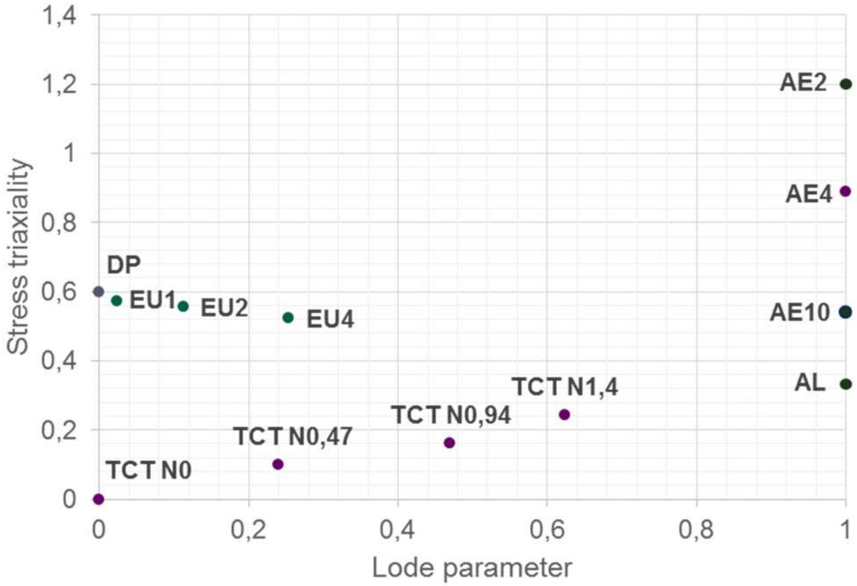


Ductile rupture criterion for ML340 steel (from C. Defaisse PhD 2018)

ML340 steel

- **Ductile damage model**
  - ❑ Experimental campaign
    - TCT: tension-compression-torsion
    - DP: plane deformation
    - AL: standard tension
    - AE: cylindrical notched tension
    - EU: plane notched tension
  - ❑ Model proposed

$$D = \int_0^p \Big(\underbrace{a e^{-bT}}_{\text{Rice \& Tracey}} + \underbrace{c\big(1 - |L|^d\big)}_{\text{Lode correction}} \Big) \, \mathrm{d}\bar{\varepsilon}$$

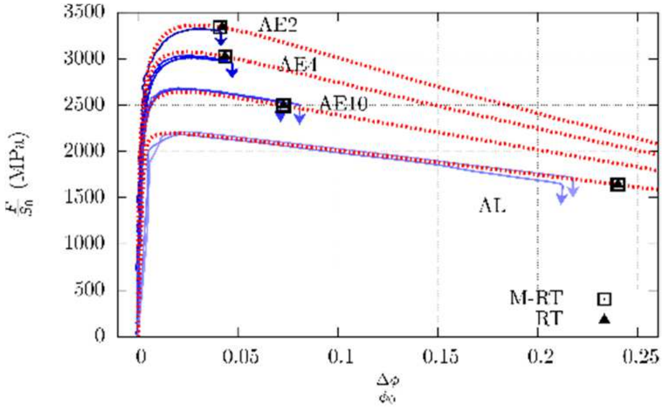


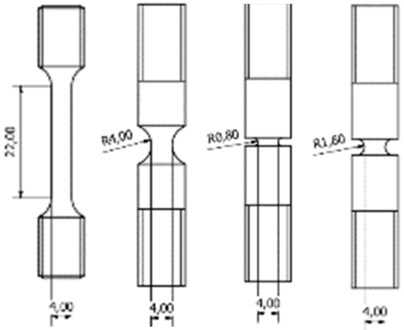
SAFRAN

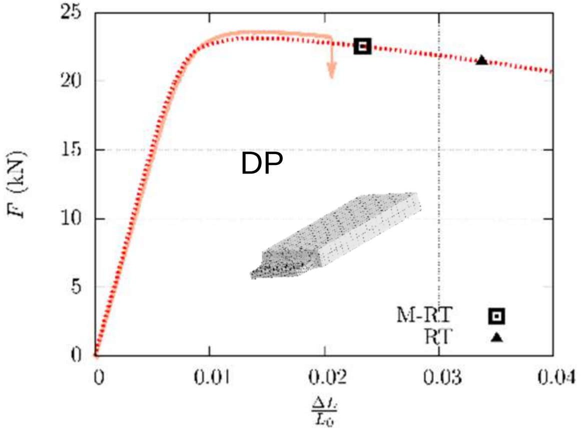
Ductile rupture criterion for ML340 steel (from C. Defaisse PhD 2018)

ML340 steel

- **Numerical simulation of all tests and inverse identification of damage model**
  - Cylindrical notched tension (AE) and Plane tension (DP)





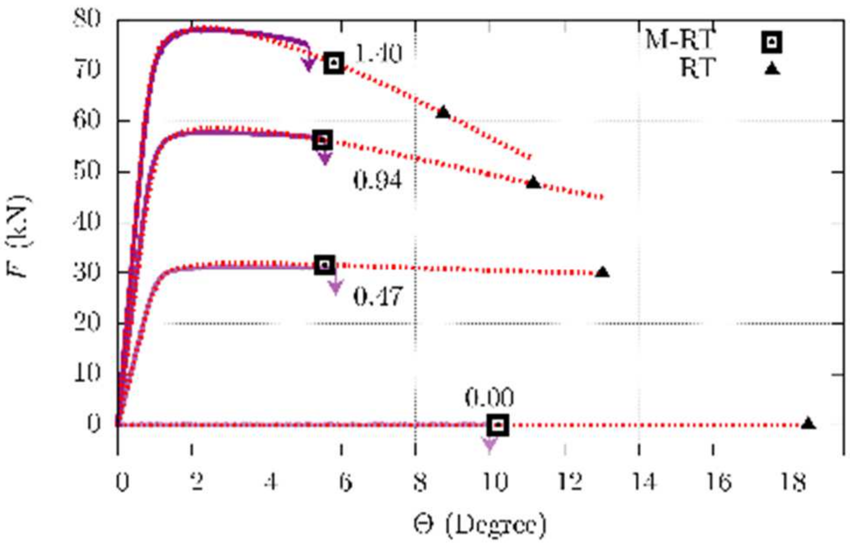


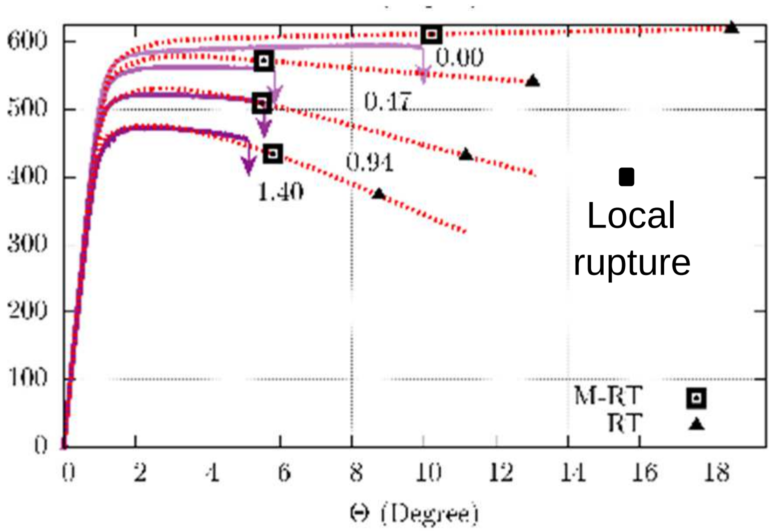
■ Local rupture

Ductile rupture criterion for ML340 steel (from C. Defaisse PhD 2018)

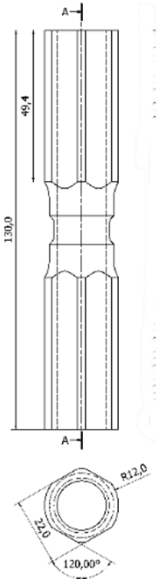
ML340 steel

- **Numerical simulation of all tests and inverse identification of damage model**
  - ❑ Tension-Compression-Torsion





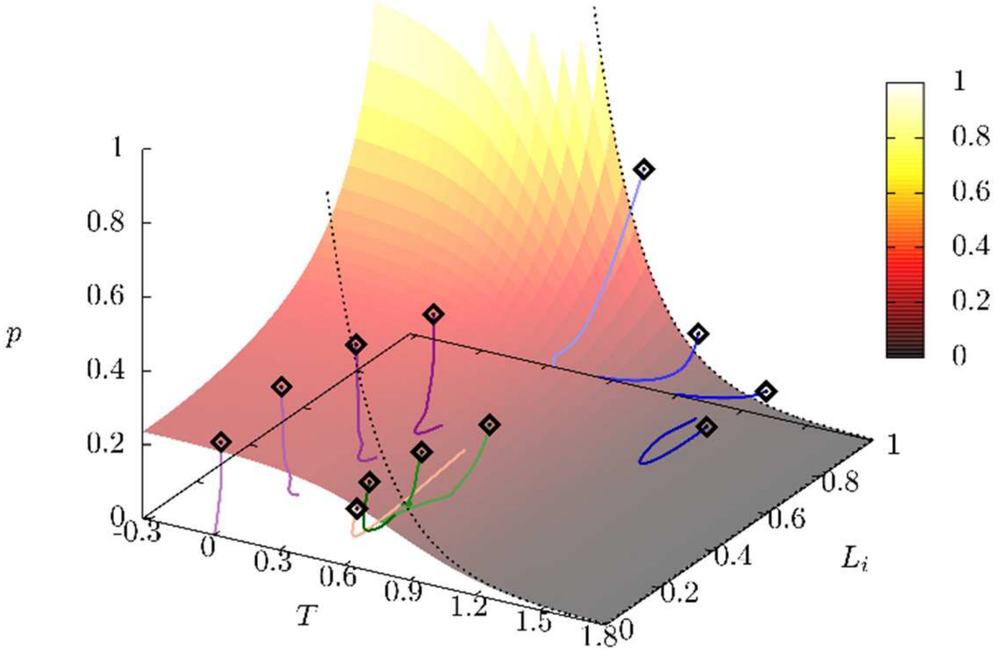
■ Local rupture



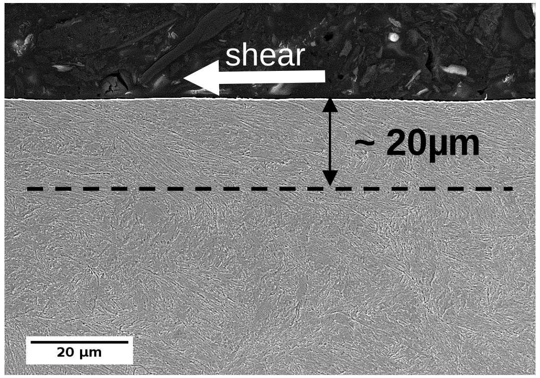
Ductile rupture criterion for ML340 steel (from C. Defaisse PhD 2018)

ML340 steel

- **Identified damage model**



❑ But… at which scale?



Fracture surface of a torsion coupon

TORSION MODULUS OF RUPTURE – TMoR ALLOWABLE

“Classical” approach to size tubes submitted to torsion loading

- **Typical curve (from MMPDS)**
  - ☐ Different failure mechanisms
  - ☐ Analytical model (Lee & Ades, 1957)
    - Material failure

      Shear stress criterion
      - “Identified” as UTS / √3
      - Through the whole thickness of the tube
    - Buckling analysis

      Deformation theory

      Minimization of the total potential energy

      No local buckling

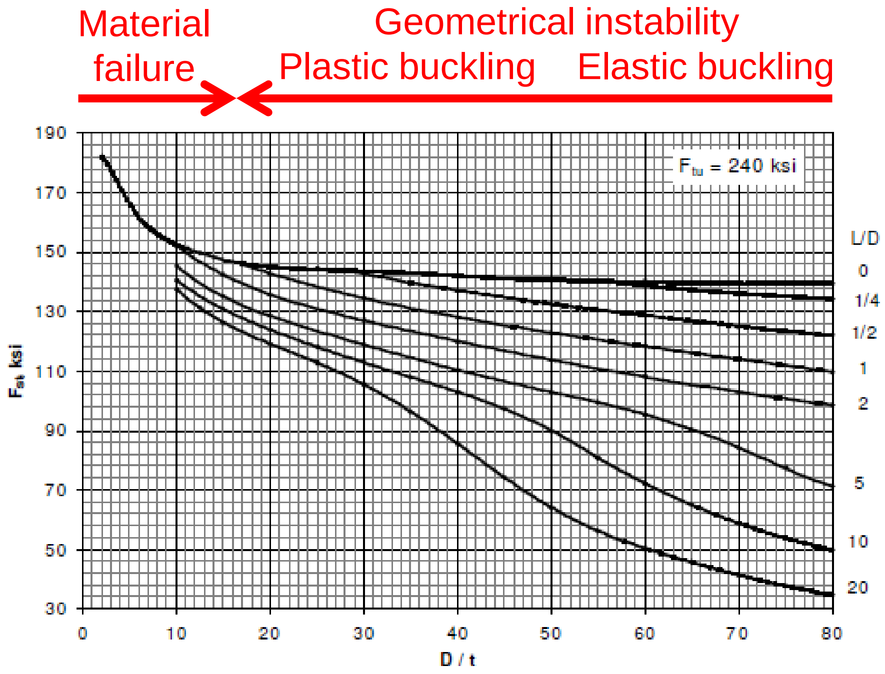


Figure 2.8.3.2(i). Torsional modulus of rupture - plain carbon steels, F_{tu} = 240 ksi.

TMoR ALLOWABLE – NUMERICAL PREDICTIONS (from M. Al Kotob PhD 2019)

Competition between local and global instabilities

- **Approaches**
  - ☐ Material failure by strain localization
    - Loss of ellipticity : Rice criterion
  - ☐ Hill loss of stability analysis
  - ☐ Finite strain formalism
  - ☐ von Mises criterion
  - ☐ Isotropic hardening

Material failure

Geometrical instability

Plastic buckling

Elastic buckling

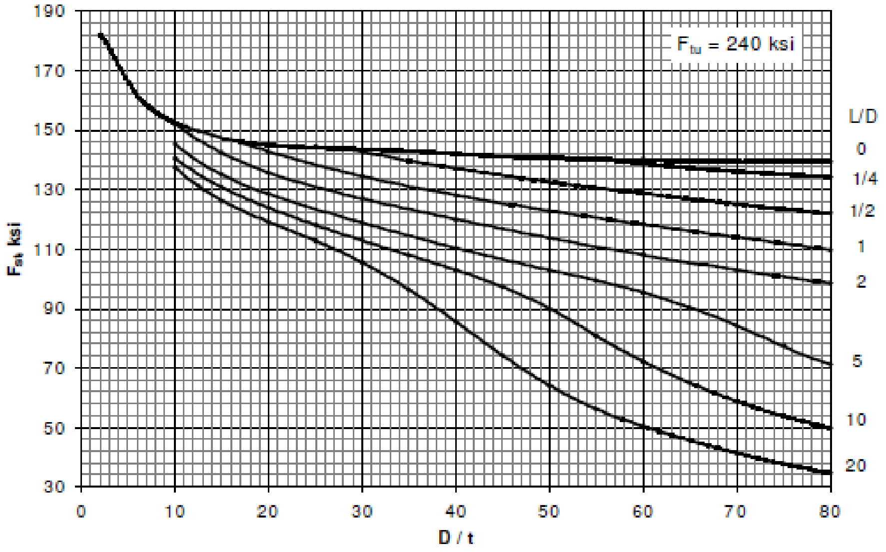
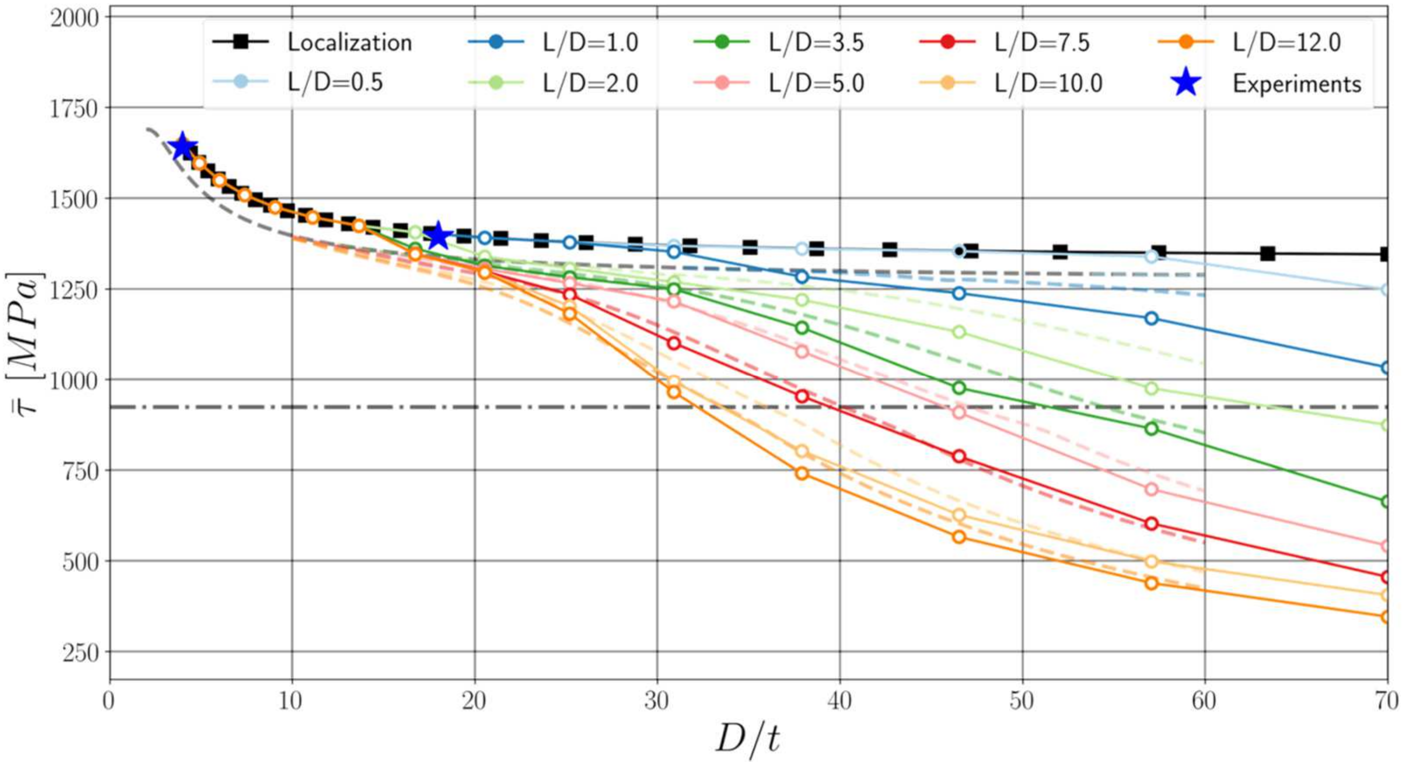


Figure 2.8.3.2(i). Torsional modulus of rupture - plain carbon steels, F_{tu} = 240 ksi.

TMoR ALLOWABLE – NUMERICAL PREDICTIONS (from M. Al Kotob PhD 2019)

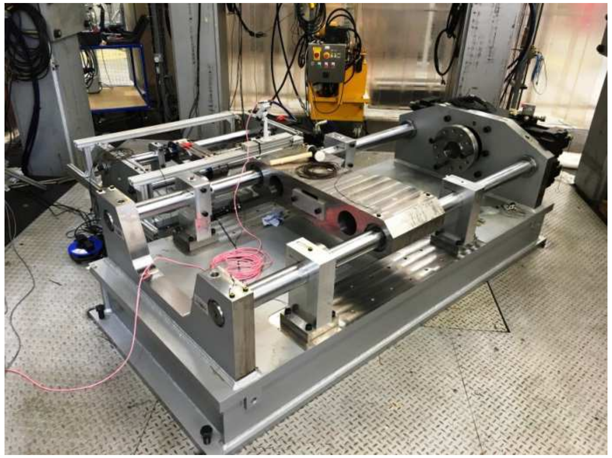
Comparison with test results for ML340 steel

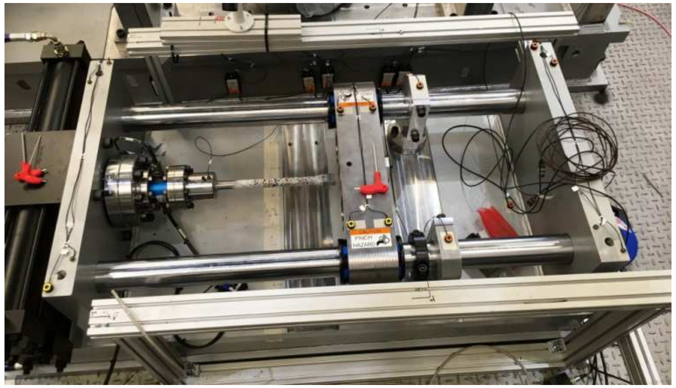


TMoR ALLOWABLE – EXPERIMENTAL RESULTS

Test rigs at TestEng lab Safran Landing Systems Gloucester

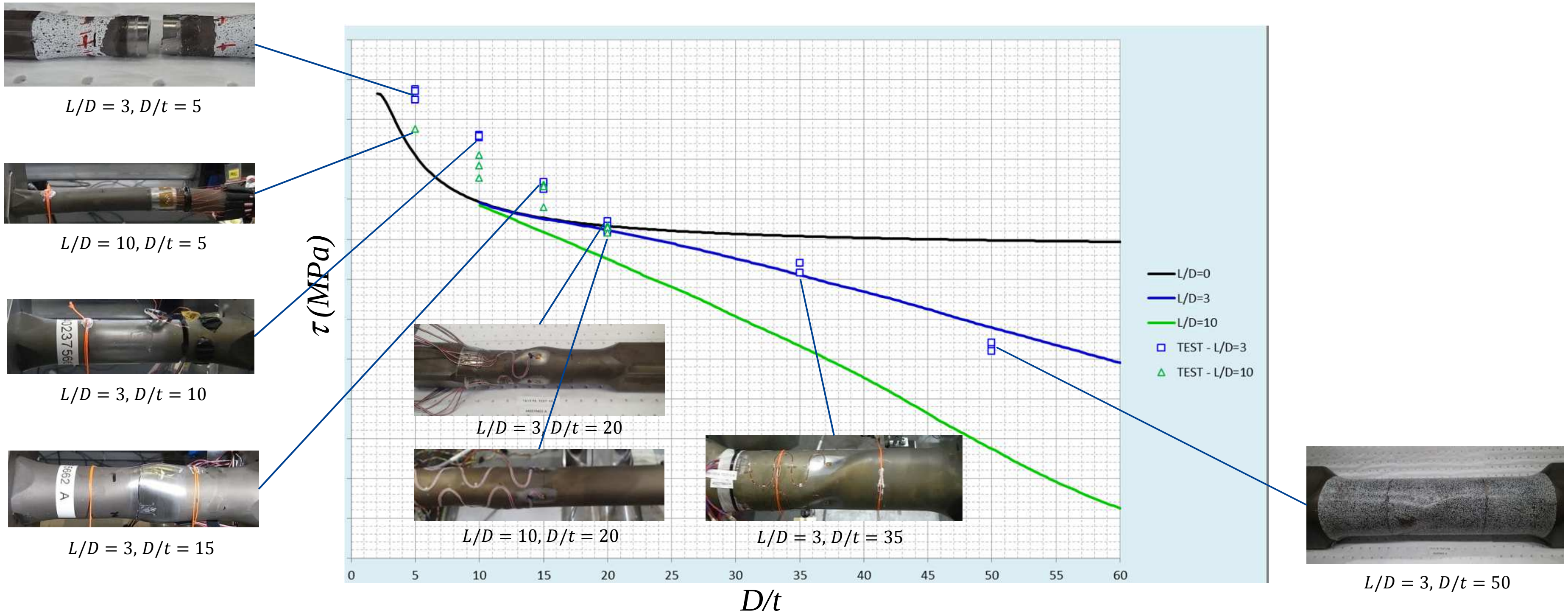
- **First experimental campaign on 300M martensitic steel**
  - ☐ 3 specimens for each size (*L/D*, *D/t*)
  - ☐ Torque, rotation, strain gauges, DIC on specimens, optical markers on test rig





TMoR ALLOWABLE – EXPERIMENTAL RESULTS

Comparison of test results for 300M steel with Lee & Ades predictions (from N. Antoni)


$L/D = 3, D/t = 5$

$L/D = 10, D/t = 5$

$L/D = 3, D/t = 10$

$L/D = 3, D/t = 15$

$L/D = 3, D/t = 20$

$L/D = 10, D/t = 20$

$L/D = 3, D/t = 35$

$L/D = 3, D/t = 50$

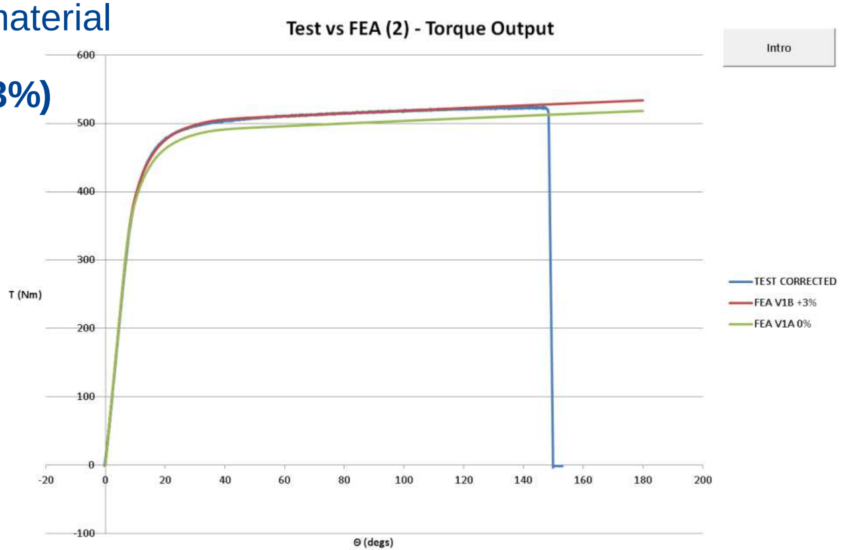
TMoR ALLOWABLE – FINITE ELEMENT SIMULATIONS

Comparison with test results for 300M steel for stable structures

- **Constitutive model**
  - ❑ von Mises criterion
  - ❑ Isotropic hardening
  - ❑ Identification from coupons cut from the same material
- **Systematic error on predicted global response (~3%)**
  - ❑ Constitutive model to be revisited
    - Kinematic hardening to be added?
    - Yield criterion to be refined

      Hosford, Hill, 3rd invariant,…?
  - ❑ Further material tests in progress

$L/D = 3, D/t = 5$



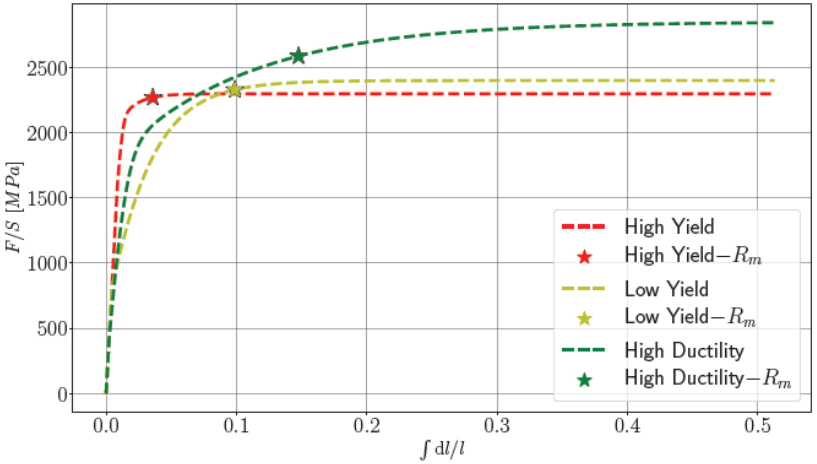
TMoR ALLOWABLE – FINITE ELEMENT SIMULATIONS

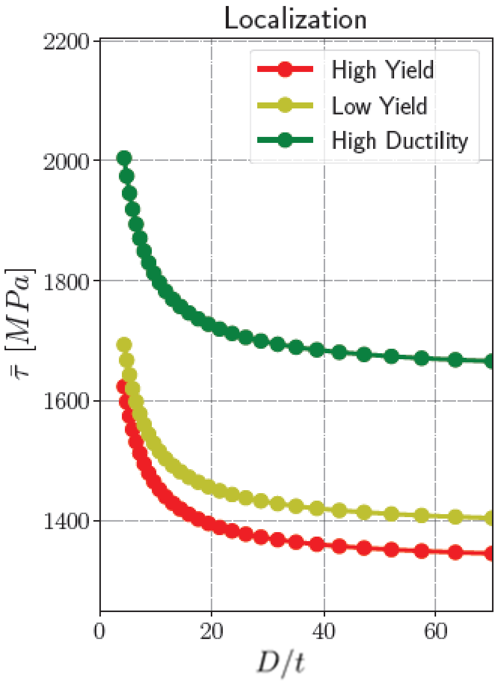
Comparison with test results for 300M steel for geometrical instabilities

- **Geometry of the specimens**
  - Small geometrical imperfections measured on each specimens
    - In general different for the 3 specimens of the same geometry
  - No obvious relationship between instability onset and instability mode
- **Sensitivity of the predicted global response**
  - No obvious relationship between geometrical imperfections and the predicted instability mode
  - Further investigations on the influence of Boundary Conditions in progress

TMoR ALLOWABLE – NUMERICAL PREDICTIONS (from M. Al Kotob PhD 2019)

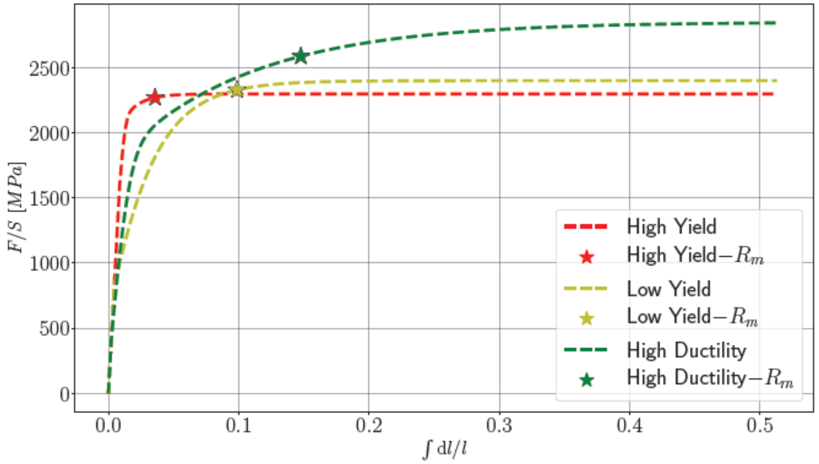
Sensitivity to material hardening – Prediction of strain localization

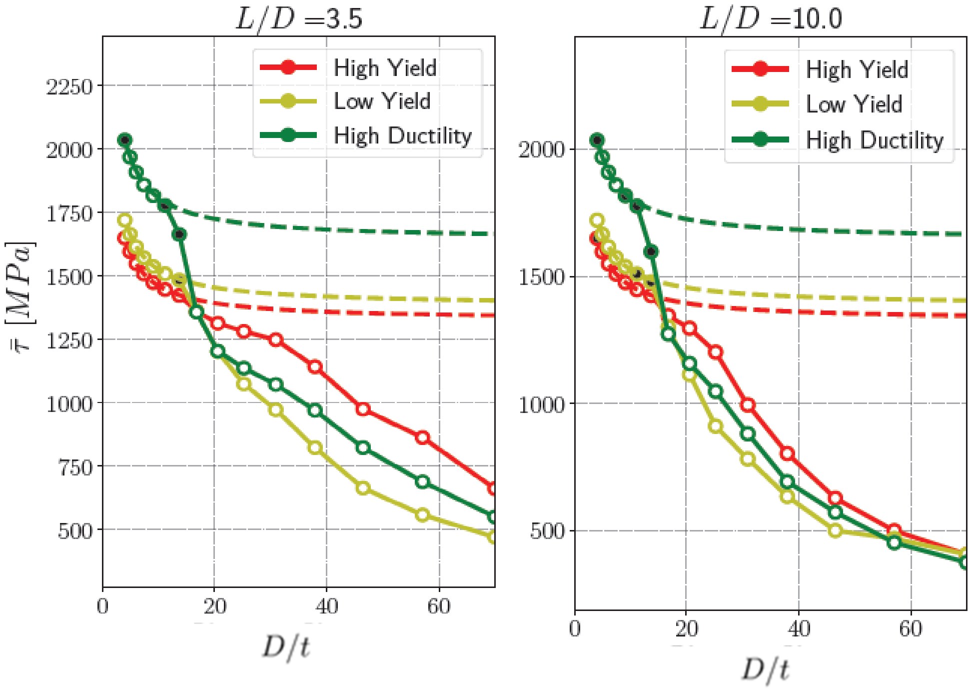




TMoR ALLOWABLE – NUMERICAL PREDICTIONS (from M. Al Kotob PhD 2019)

Sensitivity to material hardening – Prediction of geometrical instabilities





TMoR ALLOWABLE – NUMERICAL PREDICTIONS (from M. Al Kotob PhD 2019)

Sensitivity to Boundary Conditions – Prediction of geometrical instabilities *(L/D = 0.5)*

Flat/Fixed

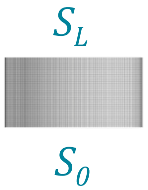
$$\begin{cases} \Delta \underline{\boldsymbol{u}} \cdot \underline{\boldsymbol{e}}_y = 0 & \forall \underline{\boldsymbol{X}} \in S_0 \\ \Delta \underline{\boldsymbol{u}} = \underline{\boldsymbol{0}} & \forall \underline{\boldsymbol{X}} \in S_L \end{cases}$$

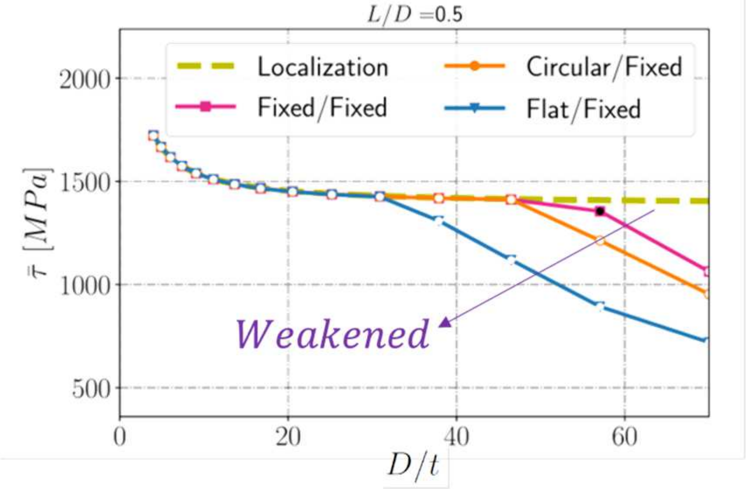
Circular/Fixed:

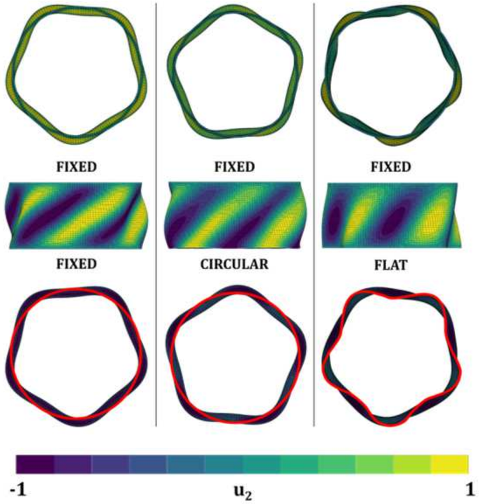
$$\begin{cases} \Delta \underline{\boldsymbol{u}} \cdot \underline{\boldsymbol{e}}_r = 0 & \forall \underline{\boldsymbol{X}} \in S_0 \\ \Delta \underline{\boldsymbol{u}} = \underline{\boldsymbol{0}} & \forall \underline{\boldsymbol{X}} \in S_L \end{cases}$$

Fixed/Fixed

$$\begin{cases} \Delta \underline{\boldsymbol{u}} = \underline{\boldsymbol{0}} & \forall \underline{\boldsymbol{X}} \in S_0 \\ \Delta \underline{\boldsymbol{u}} = \underline{\boldsymbol{0}} & \forall \underline{\boldsymbol{X}} \in S_L \end{cases}$$







TMoR ALLOWABLE – NUMERICAL PREDICTIONS (from M. Al Kotob PhD 2019)

Sensitivity to Boundary Conditions – Prediction of geometrical instabilities *(L/D = 12)*

Flat/Fixed

$$\begin{cases} \Delta \underline{\boldsymbol{u}} \cdot \underline{\boldsymbol{e}}_y = 0 & \forall \underline{\boldsymbol{X}} \in S_0 \\ \Delta \underline{\boldsymbol{u}} = \underline{\boldsymbol{0}} & \forall \underline{\boldsymbol{X}} \in S_L \end{cases}$$

Circular/Fixed:

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Fixed/Fixed

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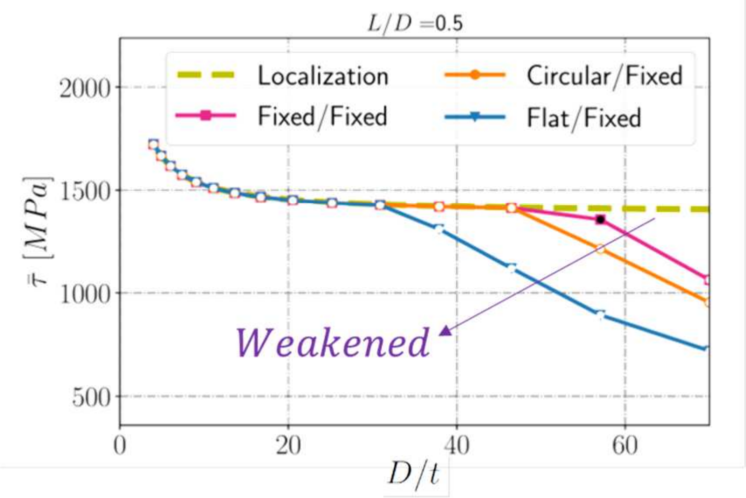
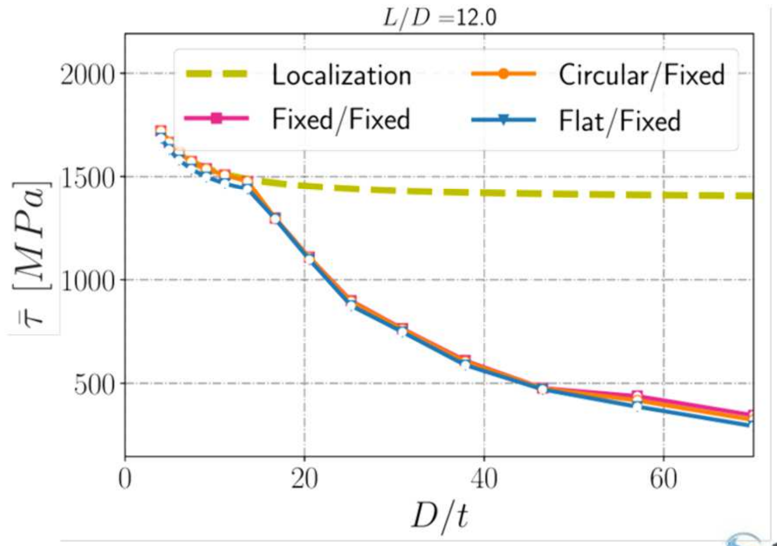




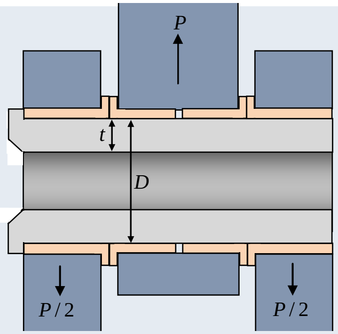
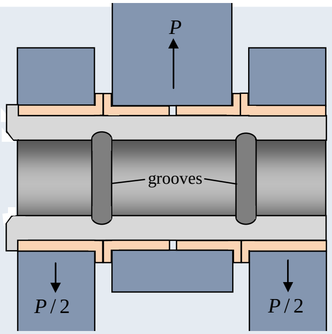
3

OTHER APPLICATIONS

FUSE PINS

Design and analysis

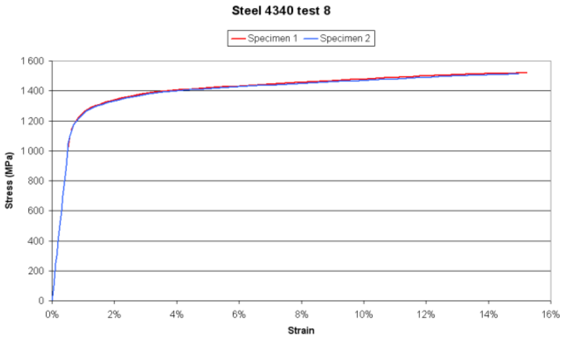
- **Designed to provide a safe and controlled separation of the landing gear from the aircraft**
  - ☐ Special care to fatigue life assessment

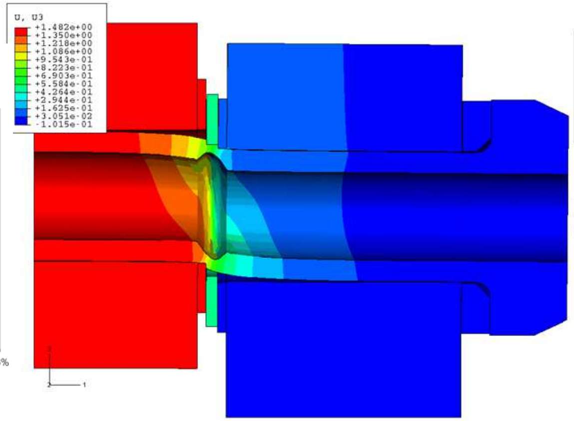
	Slick fuse pins	Groove fuse pins
Design type		
Static strength	**Cons**: Initiation << Total rupture Shear Fracture criterion: $\frac{P}{2S} = F_{su} = K_r F_{tu}$ Requires low D/t ratio	**Pros**: Initiation ≈ Total rupture Shear Fracture criterion: $\frac{P}{2S} = \frac{1}{\sqrt{3}} F_{tu}$
Fatigue	**Pros**: higher fatigue strength	**Cons**: high stress concentration area unfavourable against fatigue and stress corrosion

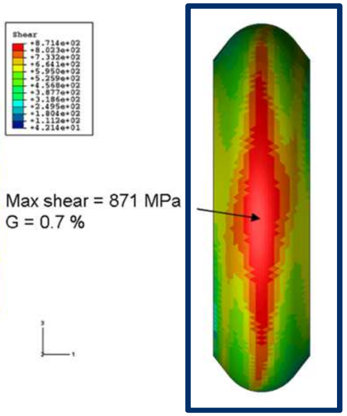
FUSE PINS

Design and analysis

- **Analysis supported by test**
  - ❑ Rupture at a load slightly larger that the ultimate load
  - ❑ Shear design curves derived from dedicated tests
    - Fine tuning of the geometry to meet strength requirement and material variability





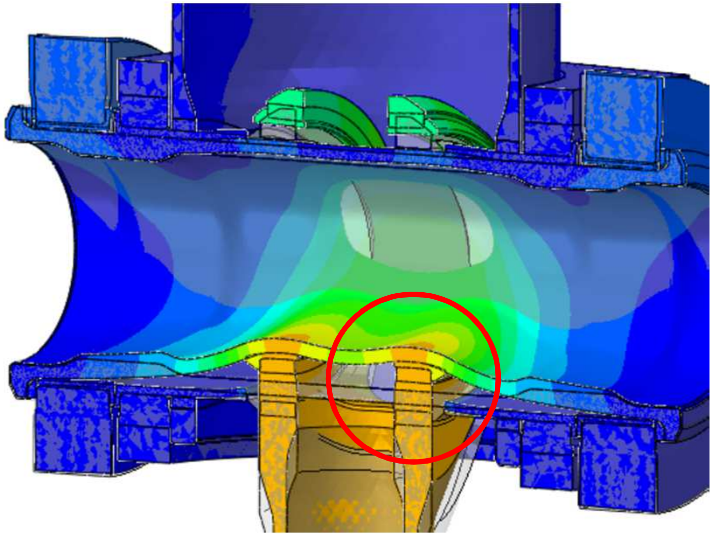


Max shear = 871 MPa
G = 0.7 %

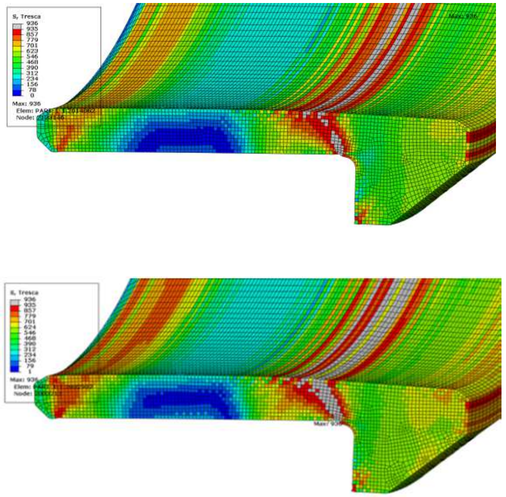
BUSH SUBJECTED TO EXTREME LOAD

Design and analysis

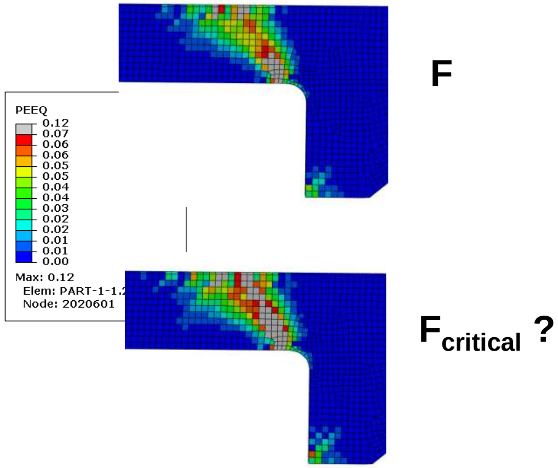
- **Prediction of the load leading to the fracture of the bronze bush**



☐ Tresca stress



☐ Cumulated plastic strain



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CONCLUSIONS

CONCLUSIONS

More efforts are needed on local rupture criteria

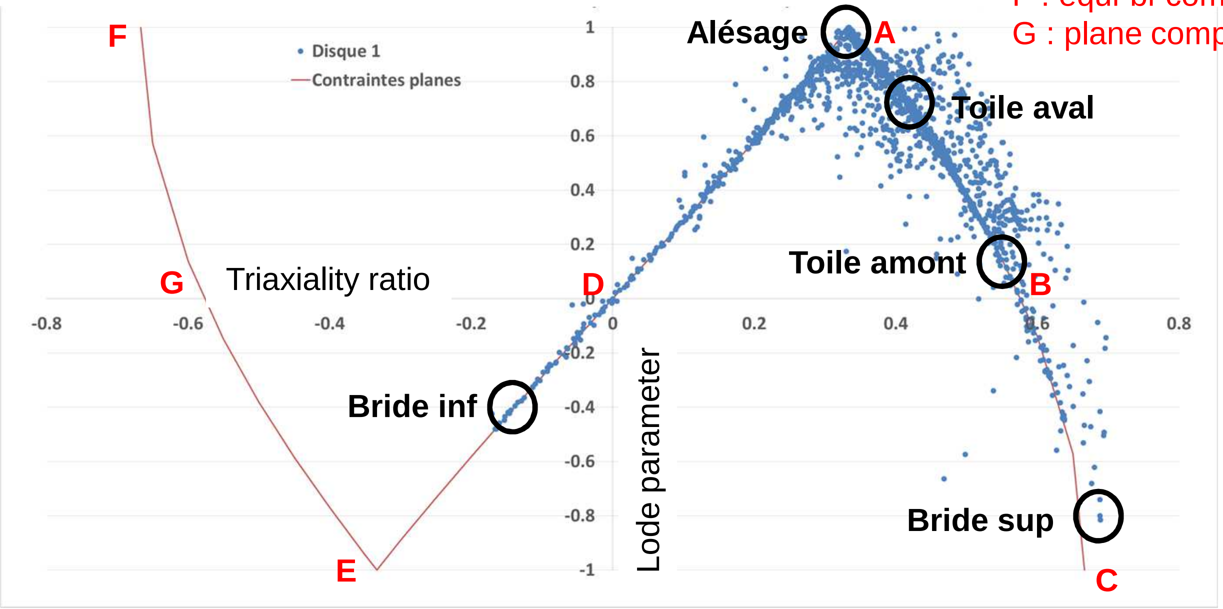
- **Rupture initiation in contact zones**
  - ☐ Lugs, assemblies
- **Validation for different materials and loadings**
  - ☐ Effect of the stress-strain behaviour
  - ☐ Effect of stress 3rd invariant
    - Shear + positive or negative stress 1st invariant
  - ☐ Complex multiaxial non-proportional loadings
    - Complex tests to be designed

CONCLUSIONS

More efforts are needed on local rupture criteria

- **Complex stress fields**

A : uniaxial tension
B : plane tension
C : equi-bi-tension
D : pure shear
E : uniaxial compression
F : equi-bi-compression
G : plane compression

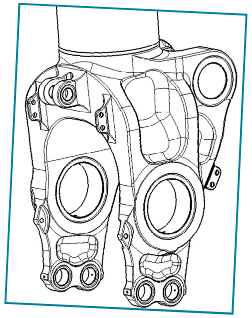


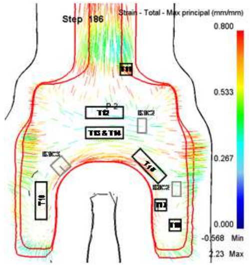
CONCLUSIONS

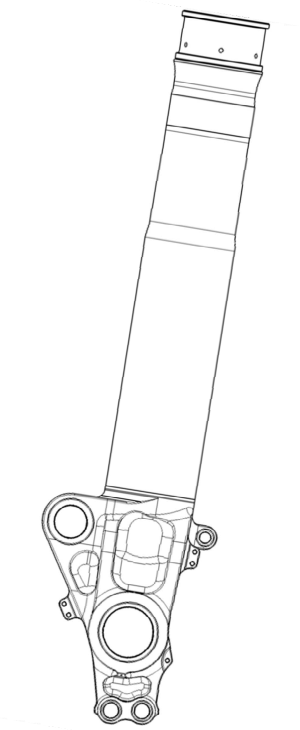
More efforts are needed on local rupture criteria

- **How to cope with the variability of material properties?**
  - ☐ Anisotropy
  - ☐ Isotropic and kinematic hardening
  - ☐ Behaviour post-localization,…

  → via numerical sensitivity analyses with validated tools?







CONCLUSIONS

More efforts are needed on global instability analyses

- **How to cope with the variability of key factors?**
  - ☐ Variability of material behaviour post-localization
  - ☐ Variability of components geometry
  - ☐ Uncertainty on Boundary Conditions

    → via numerical sensitivity analyses with validated tools?

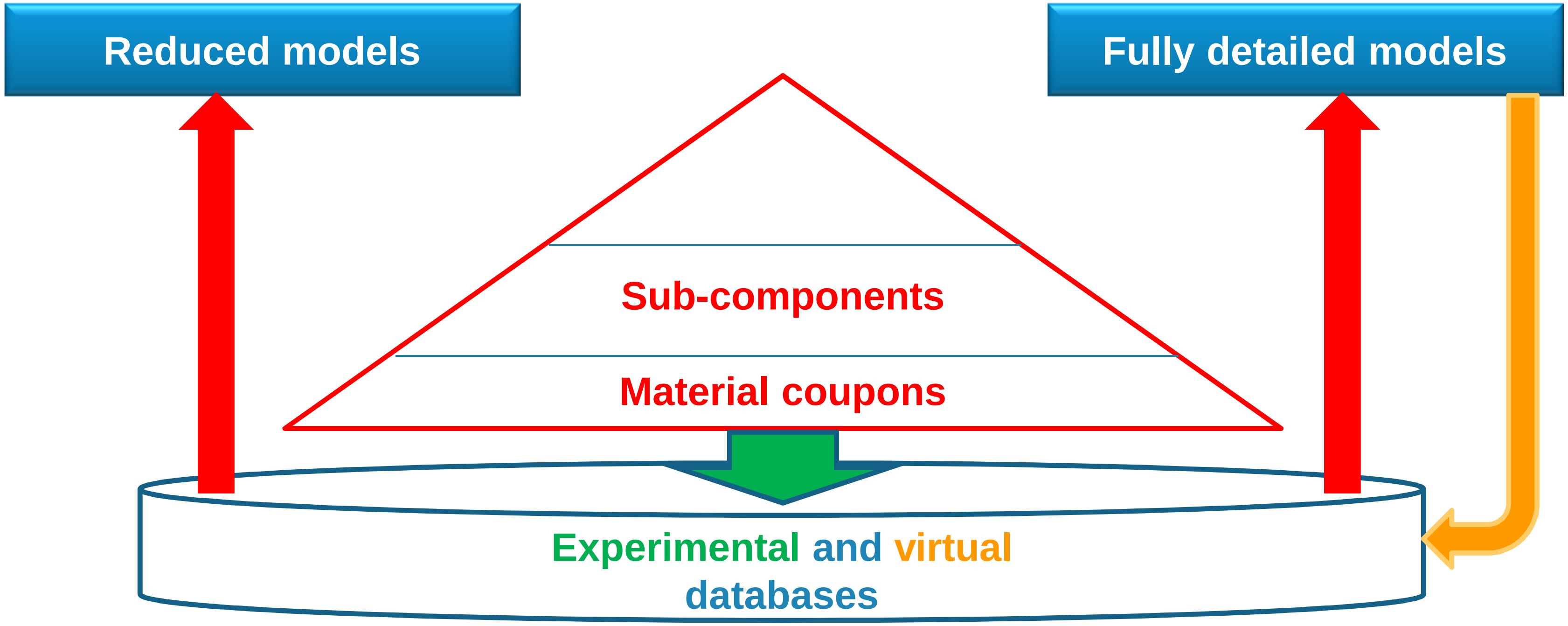
CONCLUSIONS

Design allowables

- **Requirements for certification by analysis supported by tests**
  - ☐ Material allowables: material standard properties
  - ☐ Design allowables: strength of particular features (lugs, tubes,…)
- **Tests to support analysis methods**
  - ☐ Good knowledge of mean values and scatter of material and design allowables
    - To validate analysis methods at different scales
    - To substitute some tests at sub-component level by numerical simulations
    - To derive Reserve Factors taking account of material variability
- **Mature and documented analysis methods supported by tests at sub-components scale**
  - ☐ To decrease the number and the complexity of full-scale tests

CONCLUSIONS

Testing pyramid



Reduced models

Fully detailed models

Sub-components

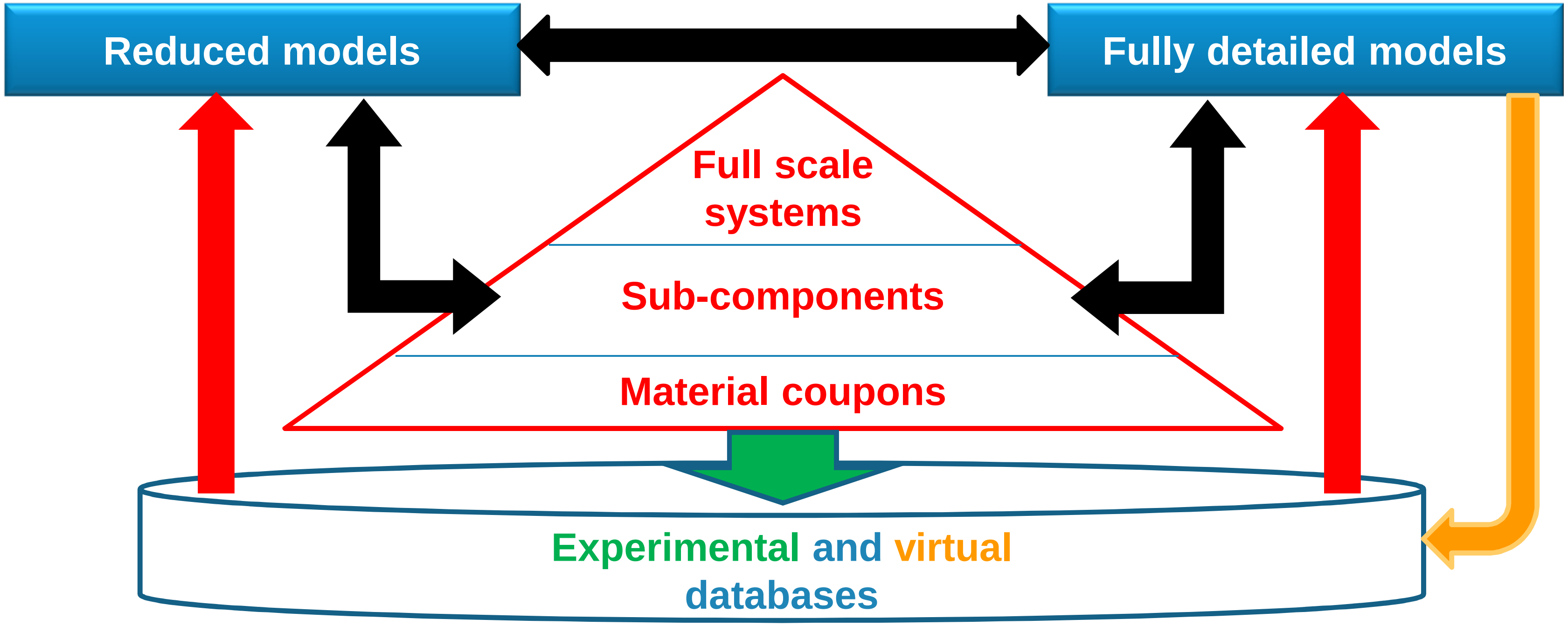
Material coupons

Experimental and virtual databases

The maturity of both sets of modelling tools is strongly dependent on **reliable databases** on **the entire field of application**

CONCLUSIONS

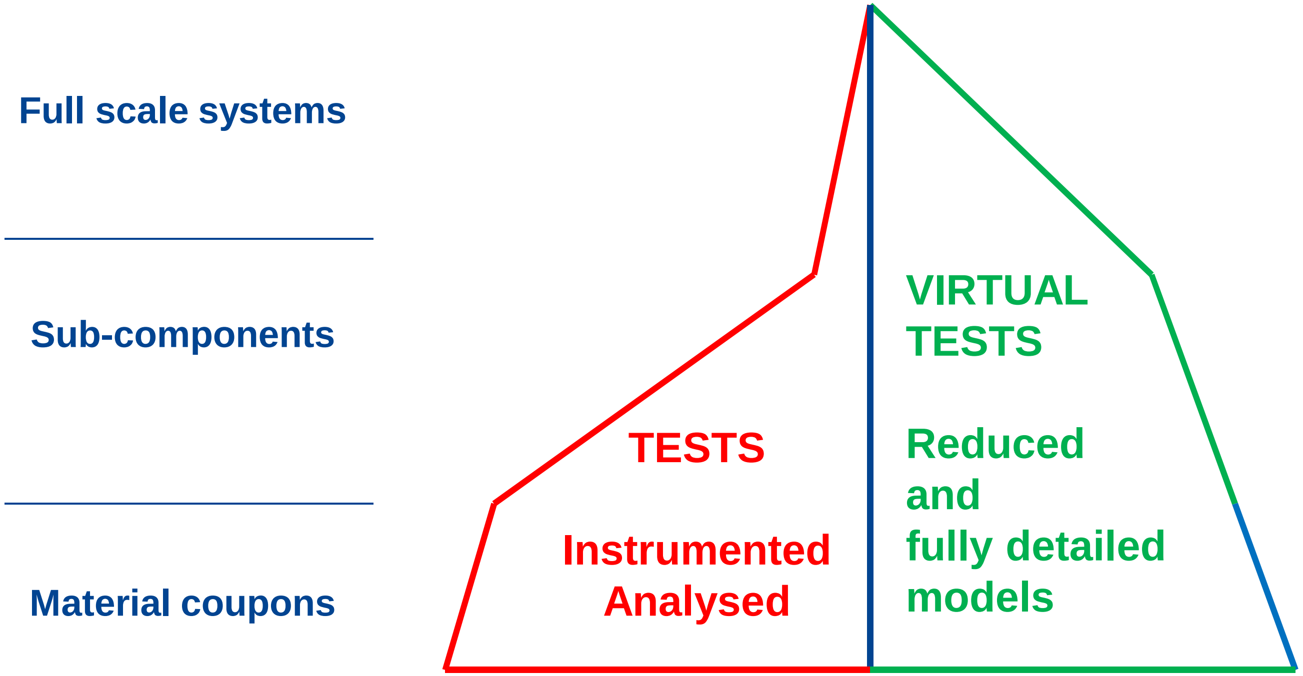
Testing pyramid



Validation of both sets of modelling tools via a refined exploitation of **highly instrumented tests mainly at sub-component scale**

CONCLUSIONS

Testing pyramid



Full scale systems

Sub-components

Material coupons

TESTS

Instrumented
Analysed

VIRTUAL
TESTS

Reduced
and
fully detailed
models

POWERED
BY TRUST