Nonlinear analysis in PE Design Codes

Recommendations for codified rules improvements

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Rev. 0

Content

- ✓ Short introduction
  - – Code Convergence Method
  - – Short Introduction of the Project
- ✓ Part 1: Existing Code Comparisons
  - – Monotonic loads
  - – Cyclic loads
- ✓ Part 2: Recommended Practices
  - – Table of content
  - – Proposed Rules by damage
  - – Appendix 2: Cyclic plasticity model
- ✓ Part 3: Benchmarks
- ✓ Other topics in the Project
- ✓ Open points
- ✓ Conclusion and planning

Code Convergence method…

On selected topics

1. Detailed Comparison of **existing Codes**: nuclear + non nuclear
2. Identify: Gaps and Needs
3. International review of corresponding report by each Code Org.
4. **Recommended practice document** associated with all proposals validation
5. International **Benchmarks** on "realistic" cases
6. Final **"Harmonized" Code Case**
7. **Large international participation & review** on 4-5-6
   by Code Organizations and International Expert Groups

- *Minimize Future Code Divergence*
- *Facilitate Areas of Convergence*

Procedure Successfully applied for:
- Class 1 design rules,
- NDE personal qualification,
- Welding qualification

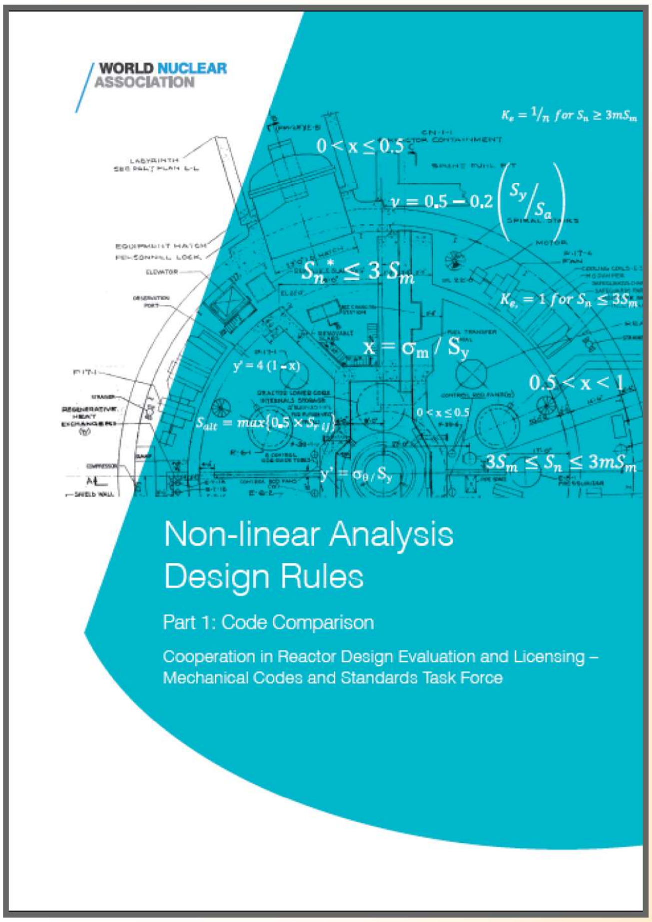
On-going for: Fatigue Rules

Short Introduction of the Project

✓ **Question**: **How to improve Pressure Equipment Code Design rules considering nonlinear behavior of material?**

- **Damages Concerned**
  - Plastic collapse
  - Plastic instability
  - Local Failure
  - Fracture of cracked PE
  - Fatigue: K_e and cyclic direct evaluation
  - Plastic shakedown and ratcheting
- **Other aspects**:
  - the stress classification rules : reinforced nozzles
  - Piping analysis : elastic follow-up (later); Dynamic cyclic loads (seismic)
  - Validation of more simple rules, analytical formulae…
- **Loads**:
  - Mechanical and thermal
  - Quasi-static, cyclic or dynamic
- **Analysis methods**:
  - Elastic
  - Elastic-plastic monotonic/cyclic
  - Limit load
- **No buckling; no creep** (later)

Existing Code comparisons



✓ Report available

- Main conclusions:
  - No available Code answers to all the "questions"; only partly
  - 2 Codes have more information to develop this type of analysis:
    - French AFCEN RCC-MRx
    - USA ASME BPVC Section VIII Div. 2
  - Large improvements of existing Codes is needed
- The corresponding report lists:
  - Major Open Points
  - Major Gaps and Needs

Monotonic loads

	Plastic collapse				Plastic instability				Stress triaxiality	
	Limit Analysis		Direct elastic-plastic analysis		Limit Analysis		Direct elastic-plastic analysis		Direct elastic-plastic analysis	
	Material properties	Criteria	Material properties	Criteria	Material properties	Criteria	Material properties	Criteria	Material properties	Criteria
RCCM	Y	Y	N	N	N	N	N	Y	N	N
ASME III	Y	Y	N	N	Y	Y	N	N	N	N
JSME	Y	Y	N	N	N	N	N	N	N	N
RCC-MRx	Y	Y	Y	Y	Y	Y	Y	Y	N	N
Russia	N	N	N	N	N	N	N	N	N	N
KTA	N	N	N	N	N	N	N	N	N	N
R5	N	N	N	N	N	N	N	N	N	N
ASME VIII	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
EN 13445	Y	Y	N	N	N	N	N	N	N	N

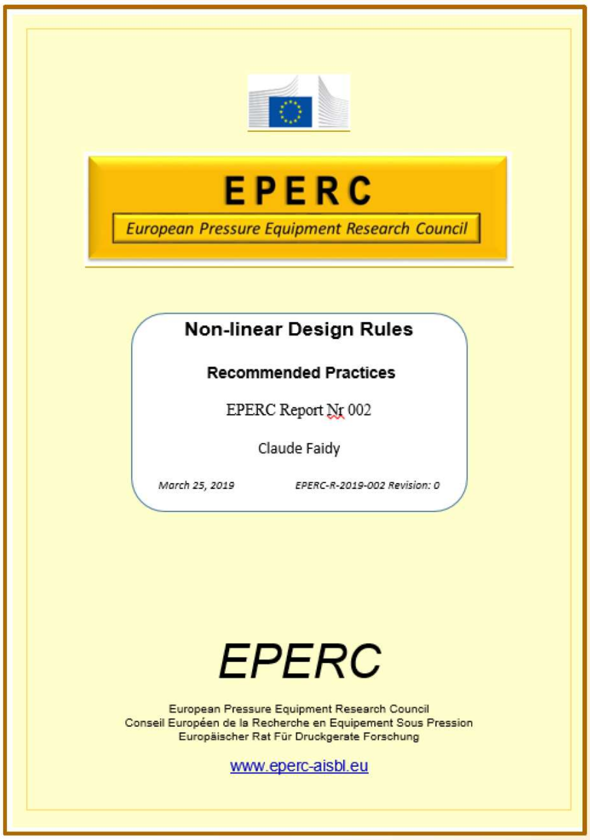
Y: Yes - **N**: No - **P**: Partially

Cyclic Loads

	Plastic shakedown				Fatigue and K_e		
	Direct elastic-plastic analysis				*Direct elastic-plastic analysis*		
	Material properties	Material constitutive equation	Criteria	Extrapolation rules	Material properties	Material constitutive equation	Criteria
RCCM	N	N	N	N	N	N	N
ASME III	N	N	N	N	N	N	N
JSME	Y	P	Y	N	Y	N	Y
RCC-MRx	P	P	N	Y	Y	P	N
Russia	N	N	N	N	Y	Y	Y
KTA	N	N	N	N	N	N	N
R5	N	N	Y	N	N	N	N
ASME VIII	Y	N	Y	N	Y	N	Y
EN 13445	N	N	N	N	N	N	N

Y: Yes - **N**: No - **P**: Partially

Part 2: Recommended practices



EPERC
European Pressure Equipment Research Council

Non-linear Design Rules

Recommended Practices

EPERC Report Nr 002

Claude Faidy

March 25, 2019 EPERC-R-2019-002 Revision: 0

EPERC

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EPERC New Draft Report (under preparation) :

- ✓ **1. References**
- ✓ **2. Introduction**
- ✓ **3. Background of Codified Elastic Rules**
- ✓ **4. Nonlinear design rules proposal**
  - ➢ 4.1 Scope
  - ➢ 4.2 Definition / Terms related to analysis
  - ➢ 4.3 Analysis Methods: limit load & elastic-platic analysis
  - ➢ 4.4 to 4.7 Plastic collapse, plastic instability, local failure, fatigue Ke, plastic shakedown, fatigue*
    - * *for each of them: Analysis methods, Material properties, Criteria, Practical recommendations*
  - ➢ 4.8 Quality management
  - ➢ 4.9 Stress classification & piping analysis
- ✓ **5. Learning from benchmarks** from Part 3 of the Project
- ✓ **6. Conclusions**
- ✓ **Appendix A1: Draft International Harmonized Code Case**
- ✓ **Appendix A2: Cyclic plasticity models**

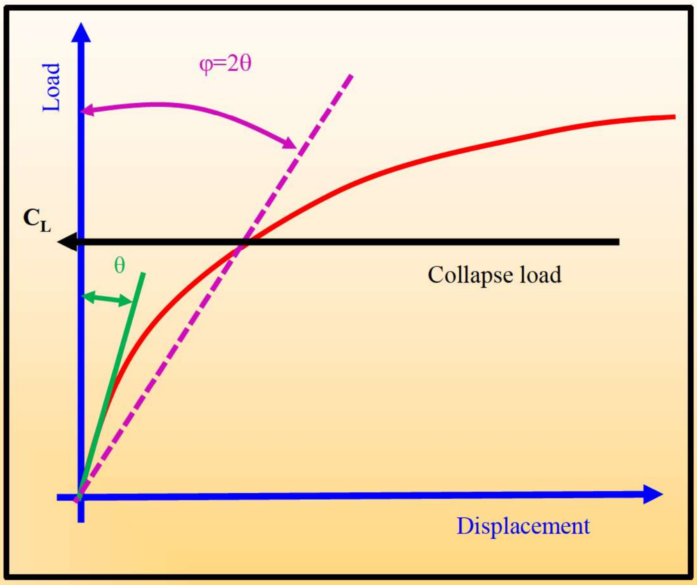
Guidelines for Plastic Collapse: C_L (1/2)

✓ Analysis Methods

- ✓ **Limit analysis**: C_L
- ✓ **Elastic plastic analysis**:
  - "double slope" method
    - C_L for $\varphi = 2\,\theta$
  - Alternative: $\varepsilon_{tot} \leq 1\%$

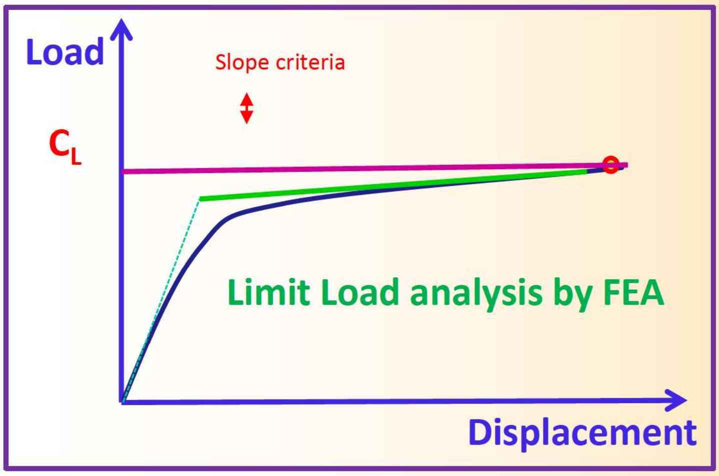
✓ Material properties

- ✓ **For limit analysis**
  - $R_{p0.2,T}$ at max temperature in the transient
- ✓ **For elastic-plastic analysis**
  - Engineering stress-strain curves versus temperature



Guidelines for Plastic Collapse: C_L (2/2)

- ✓ **Criteria**
- ✓ **For limit analysis or Elastic-plastic analyses: C_L**
  - *Level A(0) :* $C_{app} \leq 0.66\ C_L$
  - *Level B:* $C_{app} \leq 1.1 \times (0.66\ C_L)$
  - *Level C:* $C_{app} \leq 1.2 \times (0.66\ C_L)$



- ✓ **Practical recommendations**
- ✓ **For limit analysis by FEA**
  - Initial geometry / Small displacement
  - "flat" stress-strain curve : E / 100
  - Isotropic hardening rule
  - load line displacement "min slope criteria"
    mesh refinement : not too much
  - multi-material : lower stress-strain curve
  - no functional requirement: gaps…
  - Von Mises (generally without correction to connect with Tresca criteria)
- ✓ **Material properties: $R_{p0.2,T}$**
- ✓ **Sensitivity analysis**
- ✓ **Validation document and key references**

Proposed rules by damage

Guidelines for Plastic Instability: C_l (1/1)

✓ **Limit load analysis**

- No theoretical background for limit analysis ; nevertheless it can be used with "**precautions**" and $S_{flow} = (R_{p0.2\%} + R_m)/2$
- Same procedure than Collapse analysis, generally (**!!!**); C_L with $R_{p0.2}$ proportional to C_l with S_{flow}
- Some components can be subjected to large displacement: proposal in the report

✓ **Elastic-plastic analysis**

- using "true stress-strain curve"
- large displacement has to be the reference method
- Evaluation of C_l for A% /k (around **5%**)
- Criteria can be discussed material by material using (End Of Life ductility through maximum elongation A%)

Criteria

For limit Analysis and elastic-plastic Analysis

- *Level A:* $Capp \leq C_l / 2.5$
- *Level B:* $Capp \leq C_l / 2.25$
- *Level C:* $Capp \leq C_l / 2.0$
- *Level D:* $Capp \leq C_l / 1.25$

***Note**: Under certain conditions, (no large displacement), If limit load analyses were done, with limit load method:*

$S_{flow} / R_{p0.2} \geq 2.5/1.5 = 1.67$

no particular analyses required

Guidelines for Local Failure (1/1)

- $\sigma_I + \sigma_{II} + \sigma_{III}$ by direct elastic-plastic analysis will be proposed with a dedicated criteria if the stress are issued from :
  - Elastic analysis: $\sigma_I + \sigma_{II} + \sigma_{III} \leq 4\,S$ (1)
  - Non-linear analysis: $\varepsilon_{peq} + \varepsilon_{cf} \leq \varepsilon_L$ (2 to 7)
    (see appendix to this presentation)

- Not for level D criteria (accidental event) ,
- Only for class 1 in nuclear

- Refer to ASME VIII Div 2 background

New

Guidelines for Crack Analysis (1/2)

- Methods based on $J_{appl} \leq J_{\Delta a}$ and $dJ/da_{applied} < dJ/da_{material}$
  - Engineering approach based on Reference Stress and need plastic collapse load of "cracked components"
  - Direct J estimation by elastic-plastic stress analysis and J post-treatment modules,
- Reference stress → Similar analysis as plastic collapse on "un-cracked" components
- Direct J estimation → by FEA with dedicated recommendation

Guidelines for Crack Analysis (2/2)

FEM Analysis Recommendation

- Mesh recommendations
- Type of elements around the crack
- Size of elements at the crack tip
- Mesh of the remaining structure
- Analysis method
- Performing the analysis
  - Defining the material properties of the component part
  - Defining limit conditions
  - Defining load conditions
  - Performing the calculation
  - Verifying the calculation
  - Interpreting the results

Guidelines for Fatigue K_e - K_ν (1/1)

✓ Definitions

$$K_e = \frac{1+\nu}{1+\nu^*} \frac{\Delta\varepsilon^t_{eq,VM}}{\Delta\varepsilon^e_{eq,VM}}$$

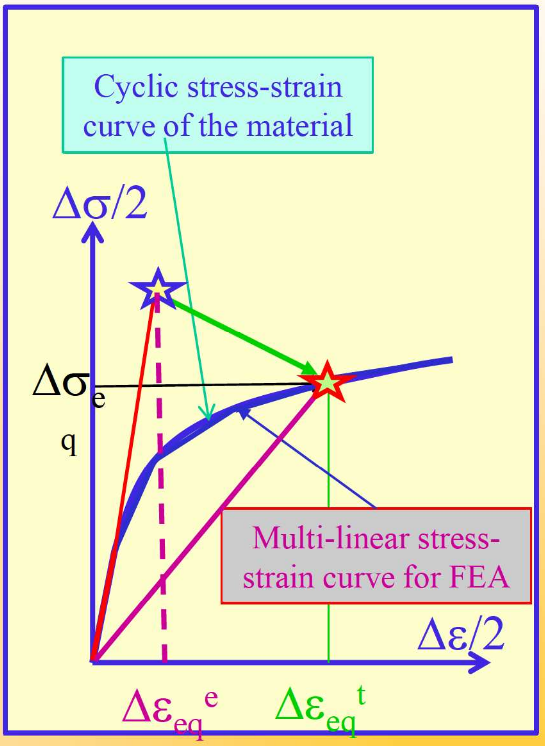
With

$$\nu^* = 0.5 - \frac{Es}{E}(0.5-\nu)$$

✓ Method:

$$Es = \frac{2(1+\nu^*)}{3} \frac{\Delta\sigma_{eq,VM}}{\Delta\varepsilon^t_{eq,VM}}$$

- Elastic-plastic analysis: $\Delta\varepsilon_{eq}^{e}$, $\Delta\sigma_{eq}$, $\Delta\varepsilon_{eq}^{t}$
- Multilinear kinematic hardening
- **Used of cyclic stress-strain curve as stress-strain curve for FEA**



Guidelines for Fatigue Direct cyclic strain amplitude evaluation (1/1)

- Direct cyclic elastic-plastic analysis
- Material constitutive equations
- Isotropic/ Kinematic/ Mixed
  - ➢ Multi-linear hardening
  - ➢ Chaboche models or similar
  - ➢ Others: Amstrong Frederick…

➢ NOT VALID EXISTING Model

- Chaboche "modified" in Appendix A2
  - Cyclic variation of Young modulus E
  - Cyclic variation of Yield strength
  - Cyclic variation of NLKH: Cl and γl

  - Variation of cyclic load amplitude

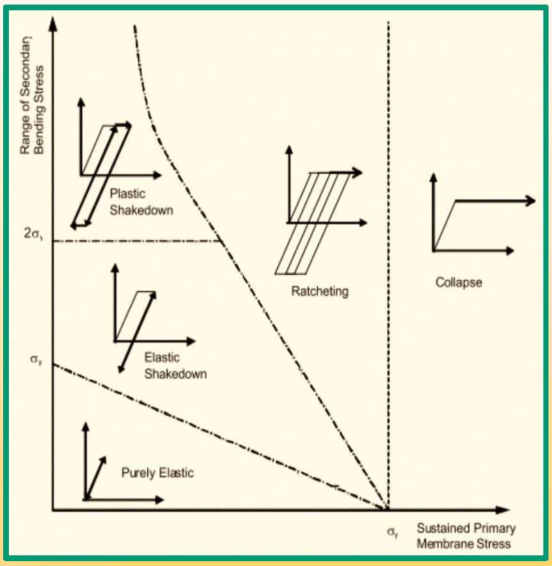
Guidelines for plastic shakedown (1/1)

✓ 2 methods proposed:

- Elastic-perfectly plastic stress-strain curve

- Same constitutive equations similar than Fatigue:

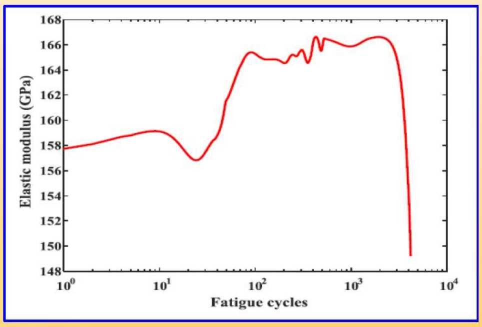
"Model Chaboche evolutive method"

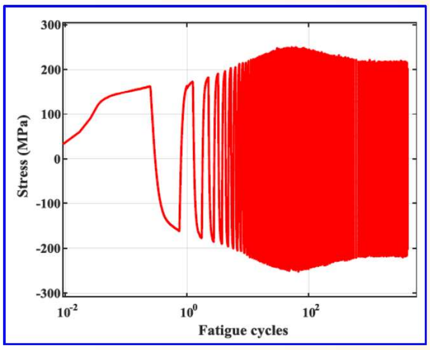


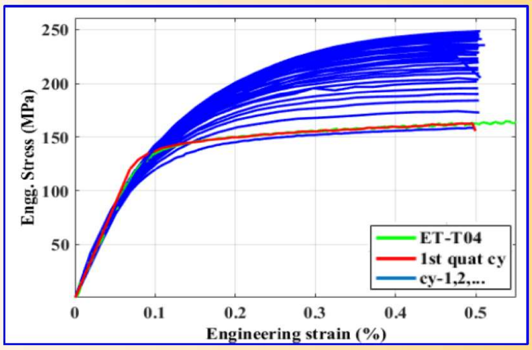
Detailed writing on-going

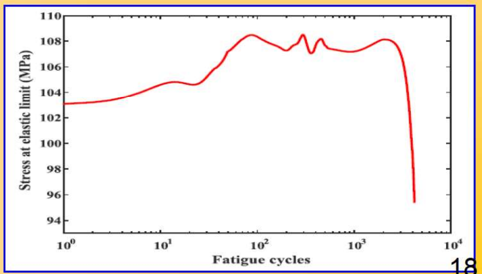
App. 2: NLK Cyclic Plasticity Constitutive equation 1/4

- ✓ Strongly material dependent
- ✓ For stainless steel, a step by step is in progress (mainly in ANL-USA)
  - Cold temperature creep negligible criteria
  - Simulation of specimen monodim. fatigue tests: hardening, followed by softening, significant change of Young Modulus and Yield stress versus cycles

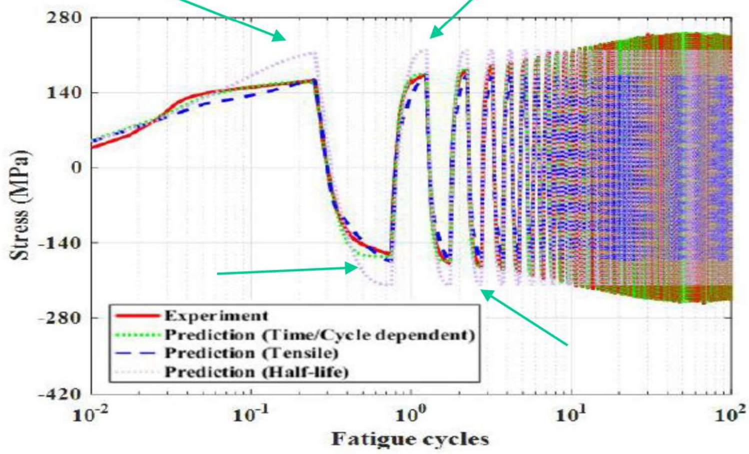








NLK Cyclic Plasticity Constitutive equation (2/4)

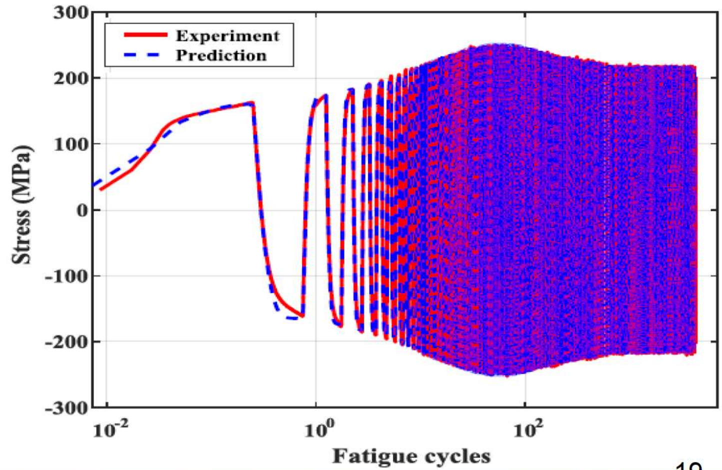


Chaboche classical models
(including Amstrong Frederic)
Does not fit experimental results

Based on ANL Chaboche
"evolutionary" model
Good fitting of experimental results

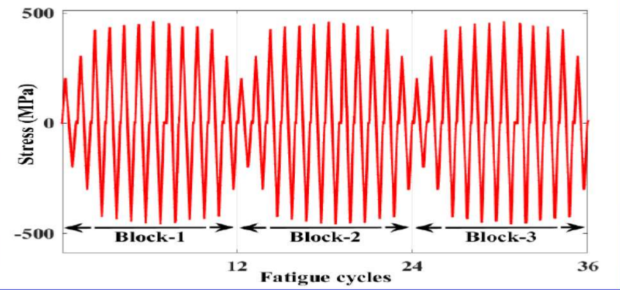
PVP2017-65890
Is it Possible to Get-rid of S-N Curve for Fatigue Evaluation? : A Fully Mechanistic Model of 316SS Reactor Steel for Fatigue Life Evaluation
and **PVP2017-65876**
Fatigue Modeling of 508 LAS under Variable Amplitude Loading: A Mechanistic Based Analytical Approach

Bipul Barua-Subhasish Mohanty-William K. Soppet-Saurindranath Majumdar-Krishnamurti Natesan (ANL)



Open points on NLK Cyclic Plasticity Models (3/4)

- ✓ Variable amplitude



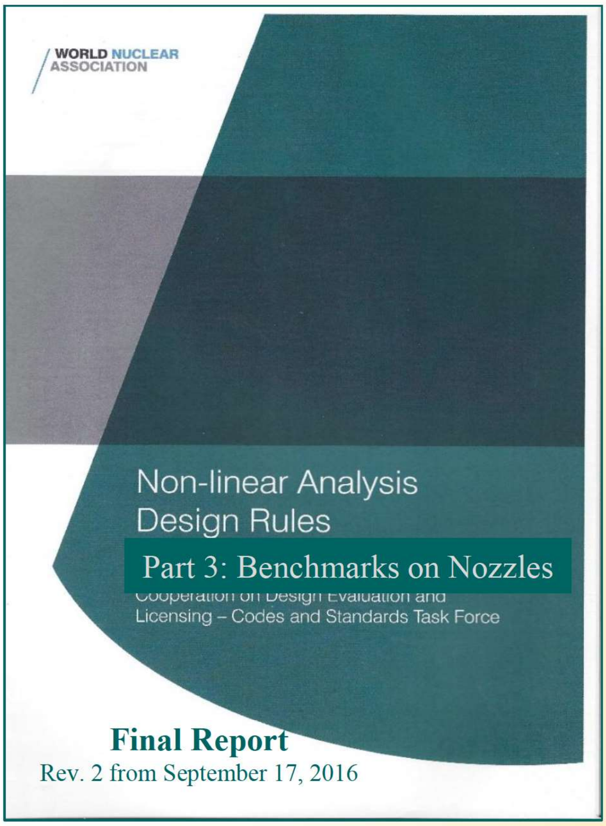
- ✓ Bi-axial loads
- ✓ Non-proportional loads
- ✓ Finally: real practical loads on industrial structures

➔ Needs of more reference tests…

Synthesis on cyclic plasticity model (4/4)

- ✓ Basic Chaboche or Amstrong Frederic models are not running on selected laboratory tests
- ✓ Before fatigue cyclic analysis, any model, as NLK model, has to be validated on very close material against:
  - a standard strain control fatigue test
  - a variable amplitude fatigue test
  - a bi-axial fatigue test
  - a non-proportional fatigue test
- ✓ Specific Dedicated QA will be required:
  - Validation tests program
  - Computer Code validation
  - User qualification through dedicated training

Benchmarks



✓ **2 benchmarks to apply and improve "guidelines report"**

- **Large LAS vessel nozzle** under pressure and piping loads
- **Small SS piping nozzle** under pressure and thermal loads

- All the data are in the report
- Result presentation are also in the report

Bench 1: Large vessel reinforced nozzle (160" x 28") under monotonic P and piping loads (Ferrit Steel)

- Elastic codified rules
- Elastic-plastic
- Limit loads

Bench 2: Piping tee (3" x 28") under cyclic thermal shocks (stainless steel)

- Elastic codified rules
- Simplified elastic-plastic and K_e in Fatigue
- Direct cyclic and plastic shakedown

Other topics in the Project

- **Project extension** will cover :

  - Stress classification rules, like nozzle areas:
    - **Ongoing with Benchmark 1**: nozzle reinforcement rules (by applying existing Codified rules for stress classification)
  - High seismic loads: fatigue-ratchetting and strain criteria
    - Ongoing outside of this project in international ASME Working Group on Design Methodology
  - Elastic follow-up rules for piping systems
    - refer to ASME III new App. F
    - Later review and strain criteria

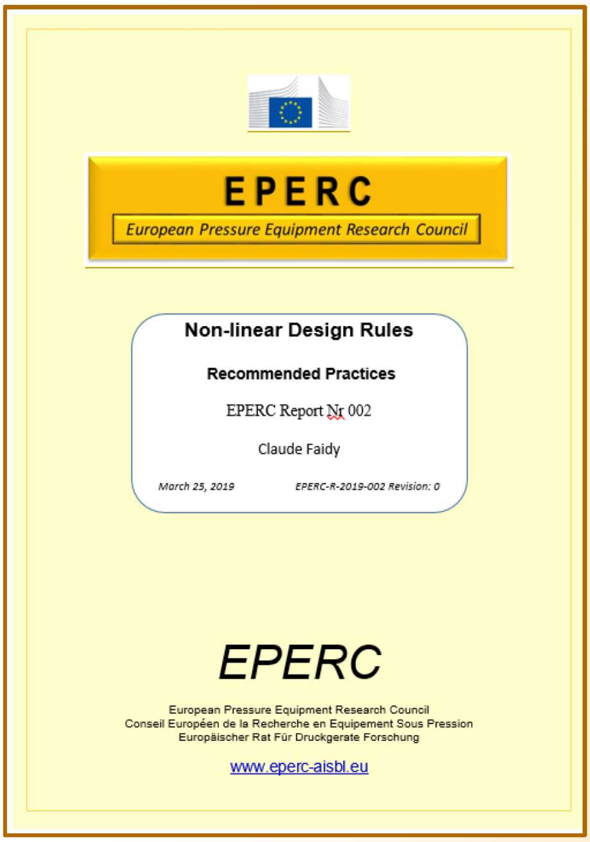
Open points

- ✓ Limit load:
  - using FEM ➔ upper bound
  - Criteria for "flat" stress-strain curve
  - Criteria for "flat" load-displacement curve
  - Large load for plastic instability ➔ large displacement
- ✓ Monotonic EP analysis
  - Monotonic stress-strain curves
- ✓ Cyclic stress-strain curves
  - Model selection: hardening/softening, Young Modulus, S_y variation, load variation
    ➔ **using monotonic stress-strain curve and fatigue test for material calibration**
  - Methods + Constitutive equation validation:
    - On simple specimen with different fatigue load histories
    - On simple "realistic structures"
- ✓ Environment: some cyclic tests results are different in air and in PWR ????
- ✓ Particular cases: piping systems and fittings
  - Elastic follow-up
  - Non-linear analysis of fittings and not on all the piping system
  - High plastic instability load
  - High seismic load
- ✓ Strain criteria: max or cumulative value
- ✓ More reference tests are needed…

Conclusion and updated planning

- ✓ **Code Comparison task is finished**
  - ➢ **No existing Code propose a detail procedure with all the material properties needed , in particular for cyclic loads**
- ✓ **Recommended practice Document**
  - ➢ **OK**: for plastic collapse, instability
  - ➢ **OK**: for local failure
  - ➢ **OK**: for crack rupture
  - ➢ **OK**: for K_e non linear evaluation
  - ➢ **On-going:** : for cyclic: fatigue and shakedown
  - ➢ **Supplementary experimental** and analysis program is needed
  - ➢ **First EPERC report**: **Summer 2019**
  - ➢ **Periodically revised associated to benchmark results**
- ✓ **Benchmarks**
  - – Elastic approaches :
  - – Final Benchmark results :
  - – Dedicated Workshop: **August 2019**
  - – Final report and Draft Code Case: **End 2019**

A dedicated EPERC TG on Non-Linear Analysis after this Conference…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Non-linear Design Rules

Recommended Practices

EPERC Report Nr 002

Claude Faidy

March 25, 2019 EPERC-R-2019-002 Revision: 0

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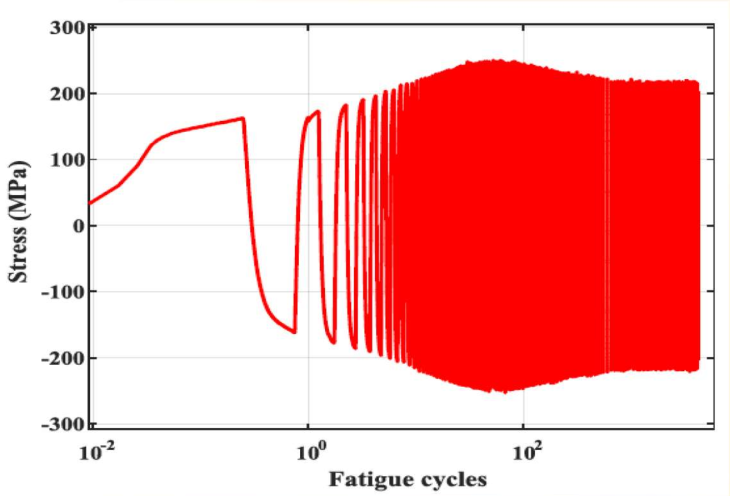
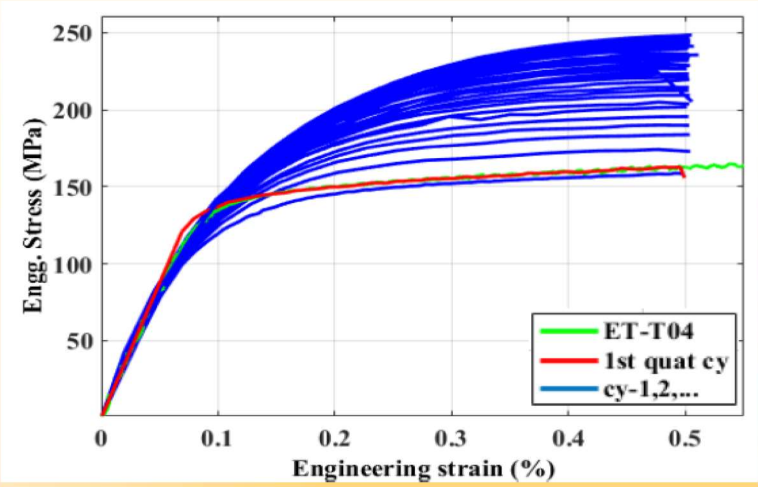
Thanks for your Attention !!!

Open for questions and/or comments…

Cyclic plasticity models for Fatigue and Ratcheting

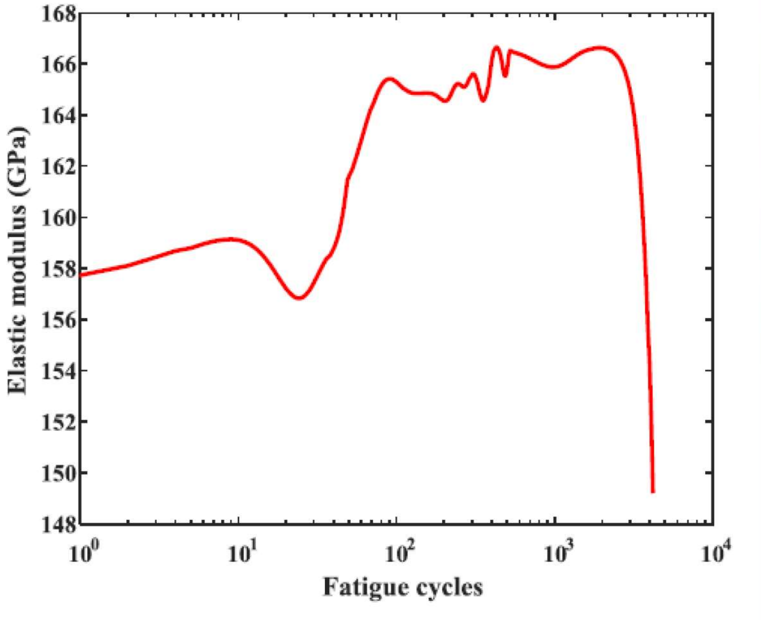
Based on Chaboche "evolutionary" model

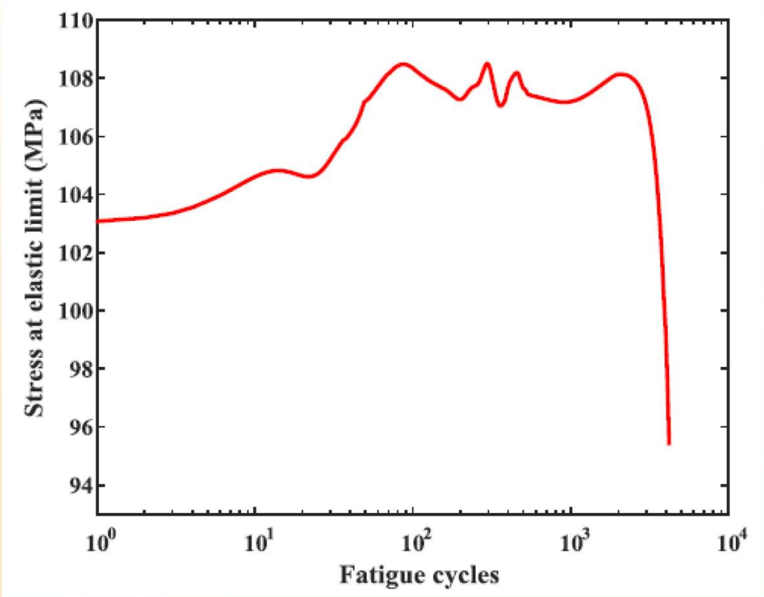




For 316 Stainless Steel

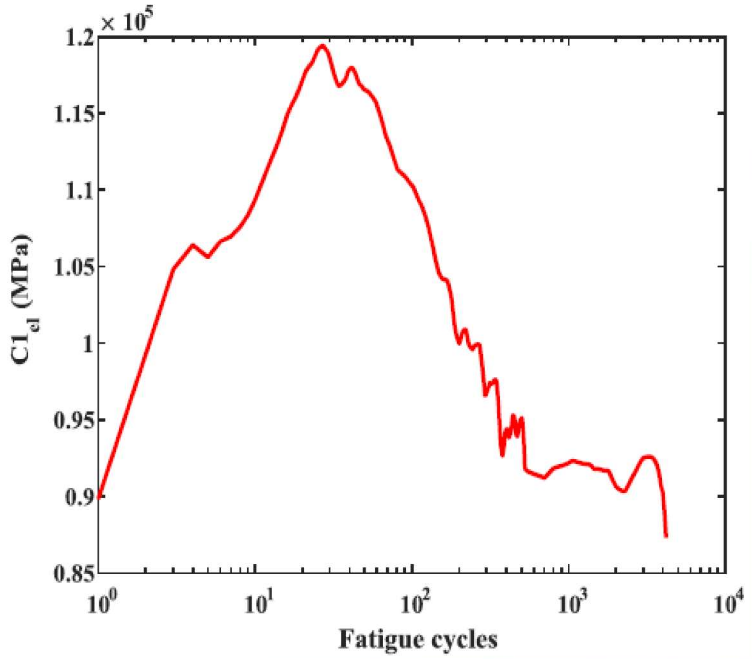
Cyclic plasticity models for Fatigue and Ratcheting

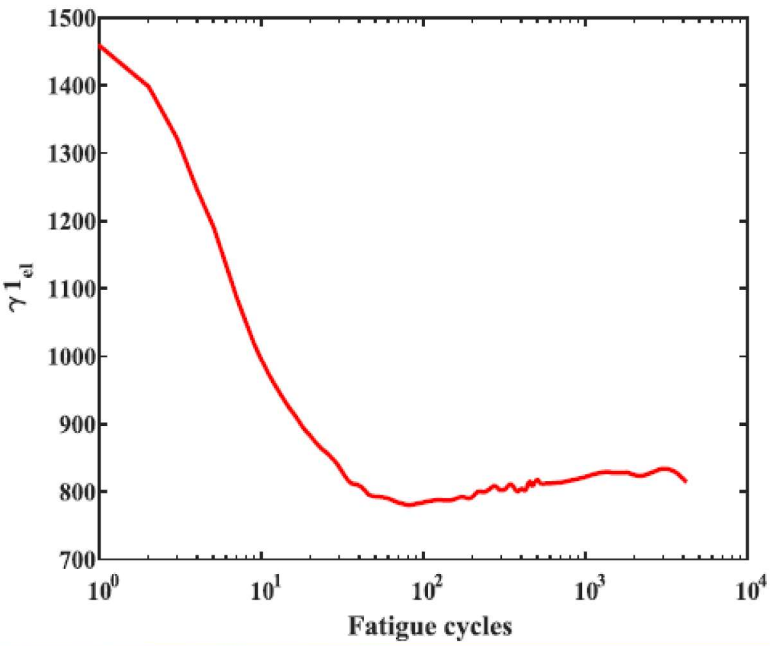




For 316 Stainless Steel

Cyclic plasticity models for Fatigue and Ratcheting

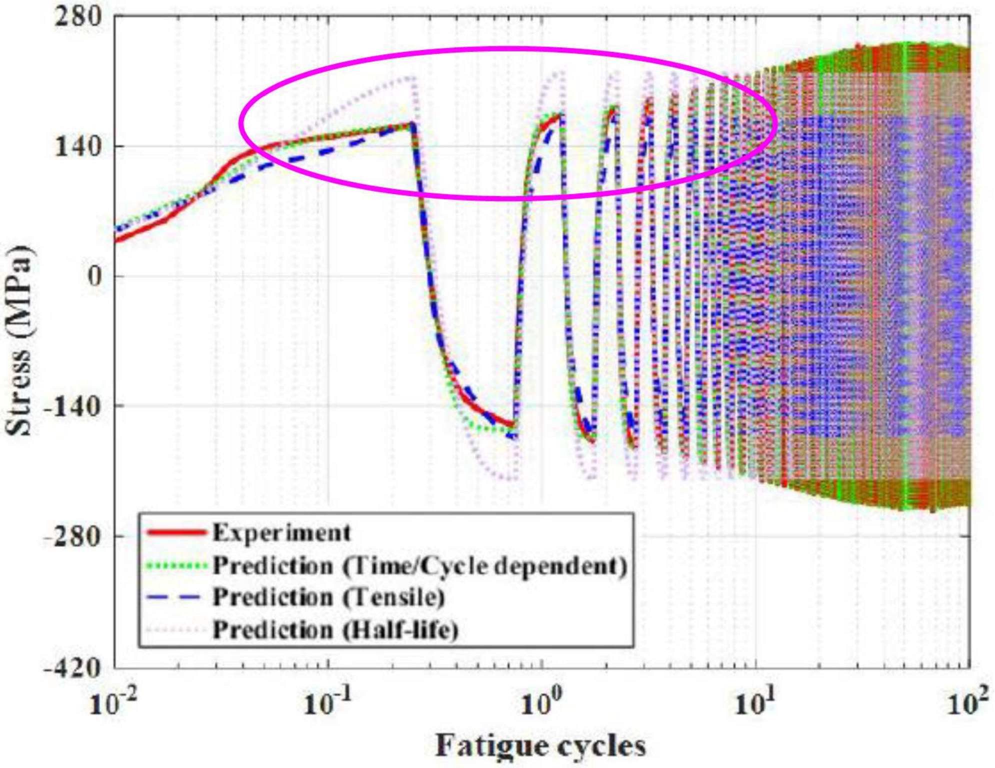




For 316 Stainless Steel

Cyclic plasticity models for Fatigue and Ratcheting

Based on Chaboche classical models (including Amstrong Frederic)

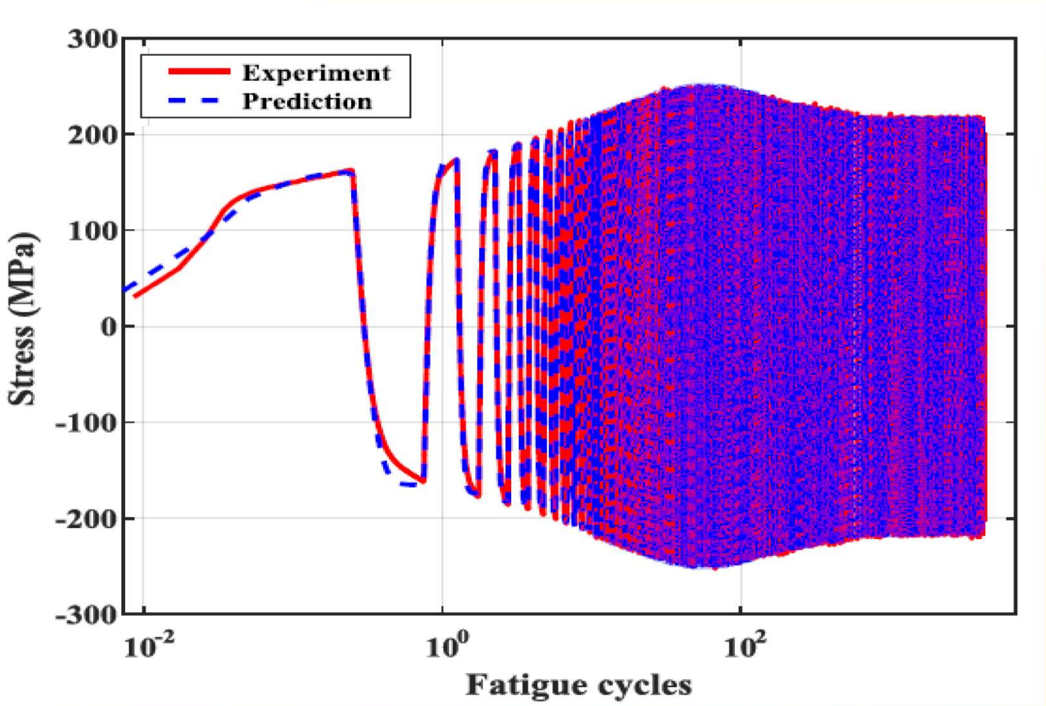


Simulated vs experimental axial stress history of specimen for first 100 cycles. Predictions are shown from simulation using time/cycle-dependent parameters and two sets of time-independent parameters (estimated from tensile test and half-life cycle of fatigue test, respectively)

For 316 Stainless Steel

Cyclic plasticity models for Fatigue and Ratcheting

Based on Chaboche "evolutionary" model

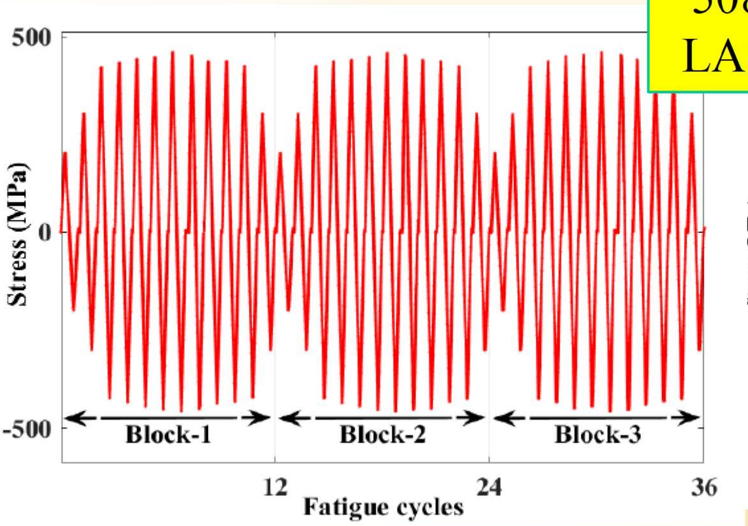


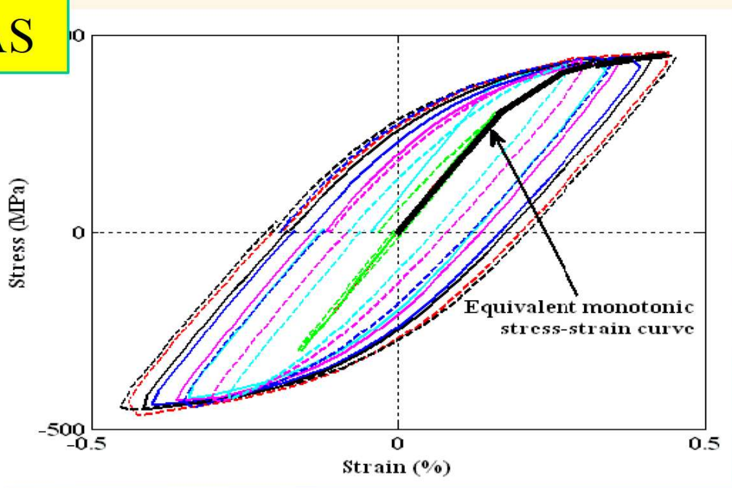
Simulated (using evolutionary cycle plasticity model) vs experimental axial stress history of specimen for whole fatigue life (4201 cycles)

For 316 Stainless Steel

Cyclic plasticity models for Fatigue and Ratcheting

508
LAS





Cyclic plasticity models for Fatigue and Ratcheting

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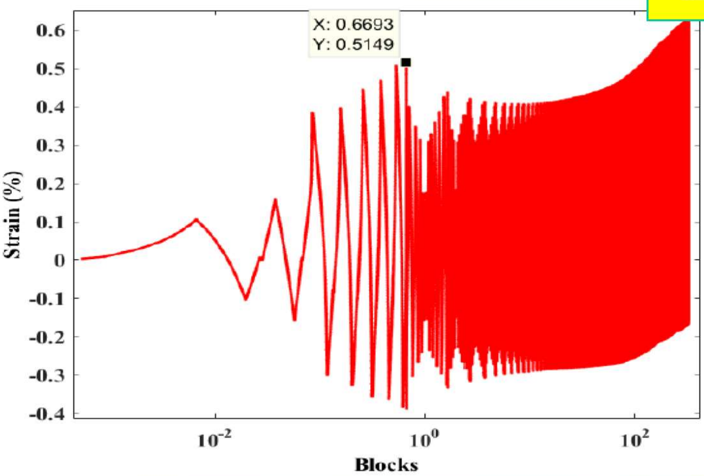
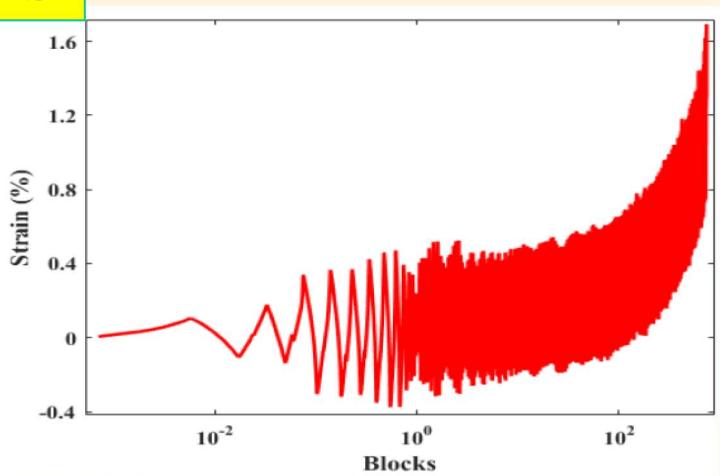


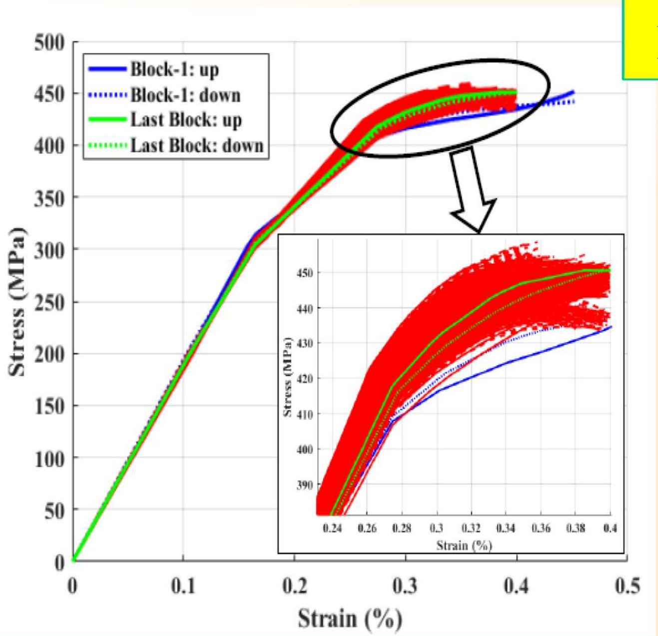
Time history of measured strain for Test 2 fatigue test (air, 300°C)



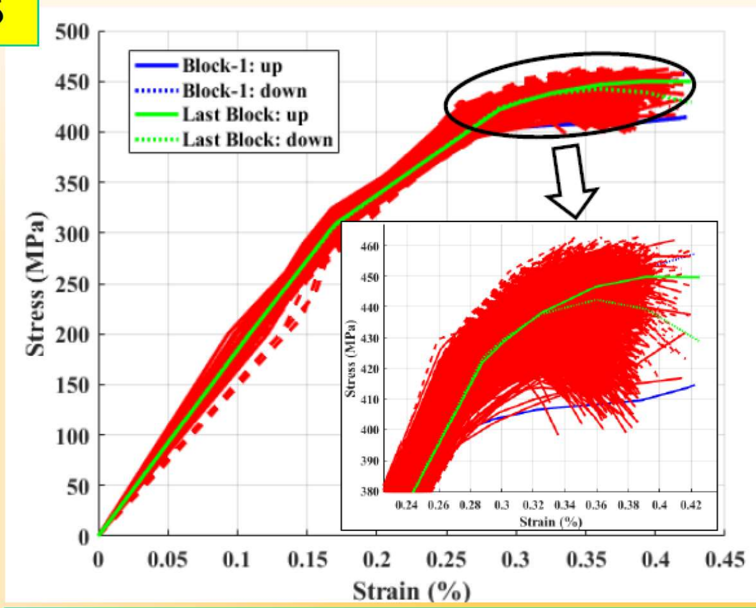
Time history of predicted strain for Test 3 fatigue test (PWR, 300°c)

Cyclic plasticity models for Fatigue and Ratcheting

508
LAS



Block average equivalent monotonic strain-stress graphs (estimated from Test 2 data) for base metal fatigue tested in air at 300°C

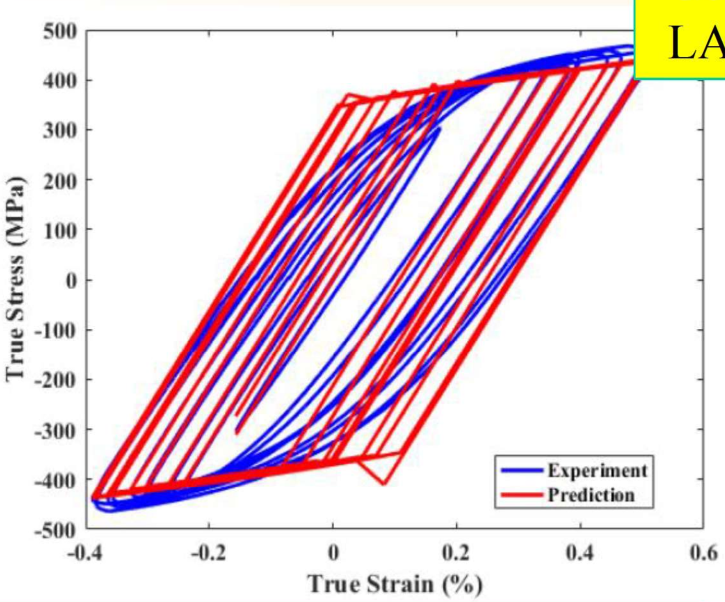


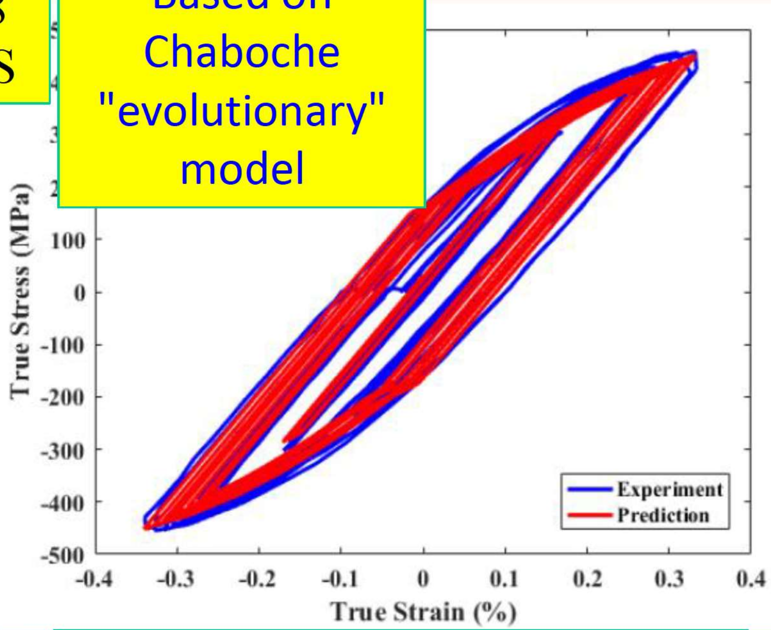
Block average equivalent monotonic strain-stress graphs (estimated from Test 3 data) base metal fatigue tested in PWR environment at 300°C

Cyclic plasticity models for Fatigue and Ratcheting

508 LAS

Based on Chaboche "evolutionary" model





Predicted (using time-independent parameters from Test 1) versus experimental hysteresis curves for first block (with 12 variable-amplitude cycles) of Test 2

Predicted (using time-dependent-amplitude-independent parameters) versus experimental hysteresis curves for 20th block (with 12 variable-amplitude cycles) of Test3

Cyclic plasticity models for Fatigue and Ratcheting

- Work continue on the subject at International level

- Experimental / Simulation of specimen and tests is needed before Code Developments