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Introduction to fatigue phenomena

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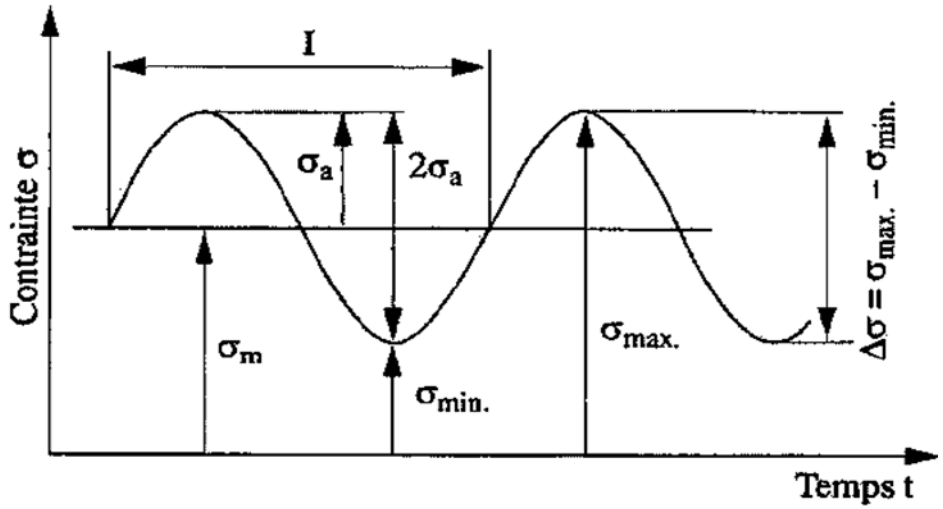
1. Introduction – Lessons learned from history

- Fatigue damage is caused by repeatedly applied loads
- This loading level is not sufficient to lead to the same damage with just one load application



1. Introduction – Lessons learned from history

- A very common industrial phenomenon, responsible for a very large number of the structural failures
- A phenomenon potentially affecting all materials
- For metals it corresponds to the development of local plasticity around a micro-crack or a pre-existing defect leading to the creation of a macroscopic crack
- Initiation stage followed by crack growth then sudden fracture

Fracture of an Al crank arm
Dark area: slow crack growth
Bright area: sudden fracture

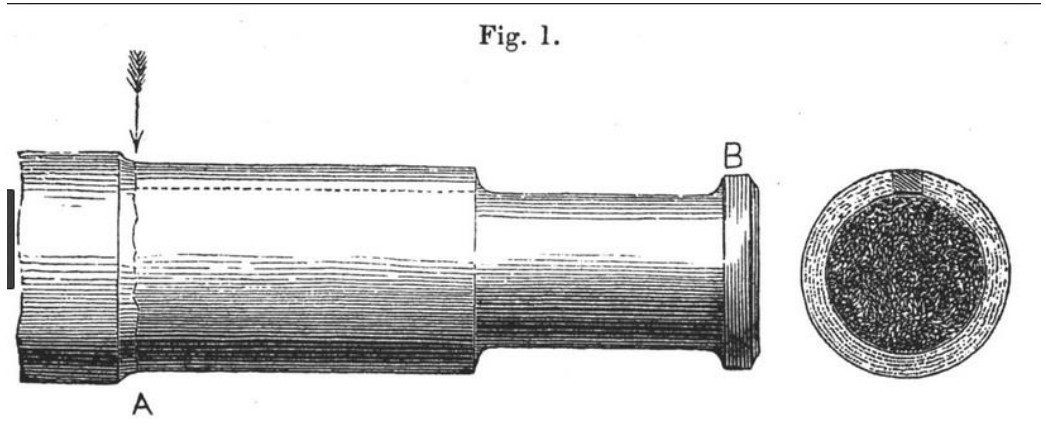
1. Introduction – Lessons learned from history

- Fatigue damage revealed to the public through a dramatic accident on the Paris-Versailles train in 1842
- A reporter wrote at that time:

The analysis of the accident shows that this is the fast fracture of one axle tree of the locomotive which is at the origin of the disaster. This appears to be strange since the equipment was in service since several months, without any problem or similar incident. The insidious fatigue phenomena is now reveal to public in a very dramatic manner.

1. Introduction – Lessons learned from history

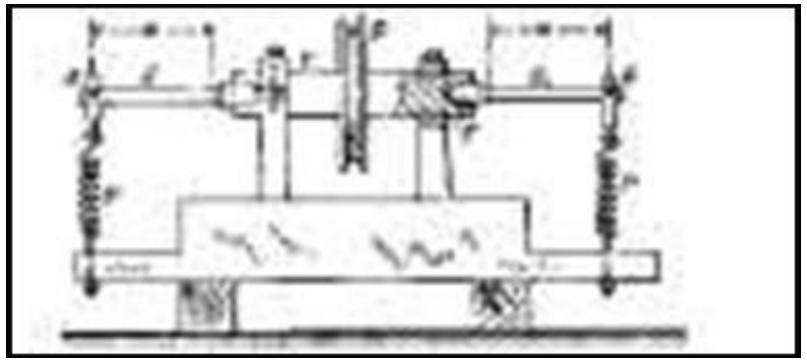
- This ‘insidious’ phenomenon was further explained by RANKINE (first publication on that topic in 1843)



Schematic view of a broken axle in an accident in the UK in 1844

1. Introduction – Lessons learned from history

- This was also the origin of the work performed by Wöhler and in particular the SN curves



Wöhler rotating bending device

1. Introduction – Lessons learned from history

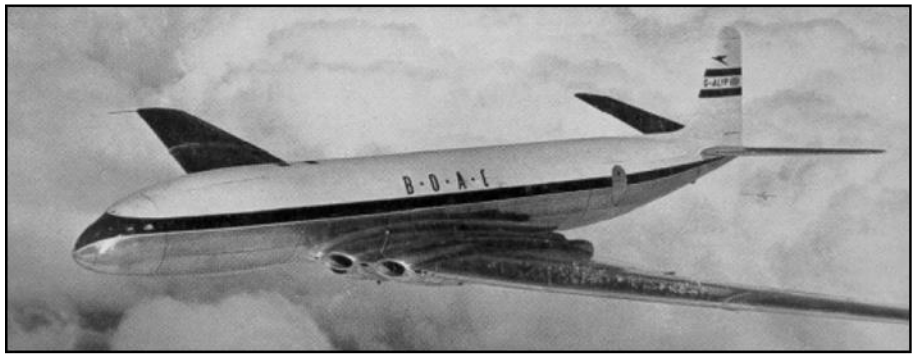
- Few important dates:

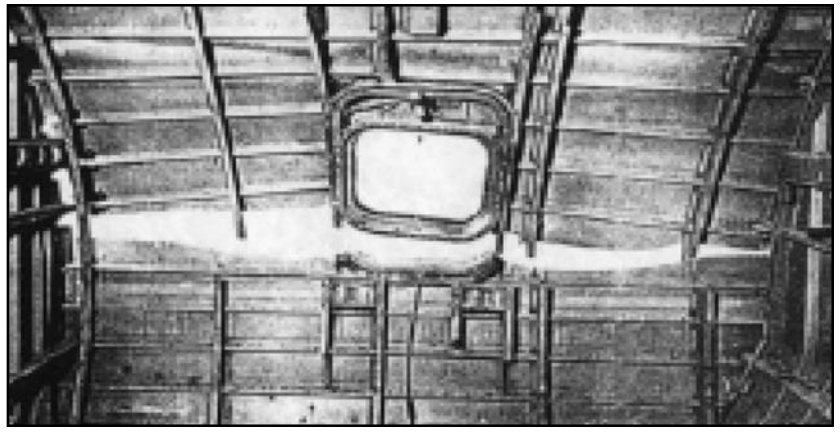
- 1867 : Wölher’s work presentation at Paris exposition
- 1903 : First observation of fatigue micro-cracks on surface (Ewing)
- 1945 : Accumulation Rule for fatigue damage evaluation (Miner)
- 1954 : Manson-Coffin fatigue curves
- 1960 : Paris’ law for fatigue crack propagation
- 1963 : Notch susceptibility of fatigue (Peterson)
- 1968 : Rainflow counting for random cyclic loadings
- 1970 : Crack closure quantification during propagation (Elber)

1. Introduction – Lessons learned from history

- Few spectacular and catastrophic accidents :

- 1953-1954 : the Comets air-crafts accidents



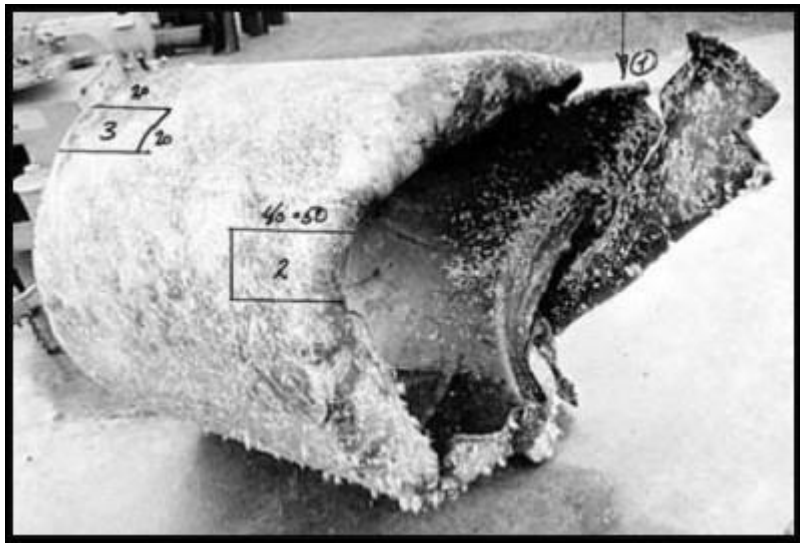


After 5 disasters, the planes were stopped : pressurization tests were performed and then it was shown that fatigue cracks initiate at the corner of square shape windows (important stress singularity)

1. Introduction – Lessons learned from history

- Few spectacular and catastrophic accidents :

- 1980 : the Alexandre Kielland plat-form sinking



After 40 months of exploitation, one of the 6 arms broke then the plate-form turned over in the northern see. The expertise showed that the fracture was due to a fatigue crack initiation at a stress singularity

1. Introduction – Lessons learned from history

- Few spectacular and catastrophic accidents :

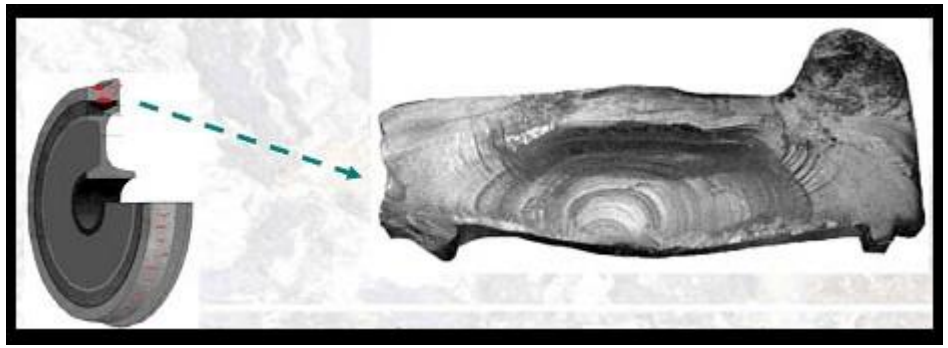
- 1988 : Aloha air lines incident

Another spectacular fuselage incident with air-crafts (only one victim !)

1. Introduction – Lessons learned from history

- Few spectacular and catastrophic accidents :

- 1998 : Wheel break of the ICE fast speed train broke at 200 km/h.



1. Introduction – Lessons learned from history

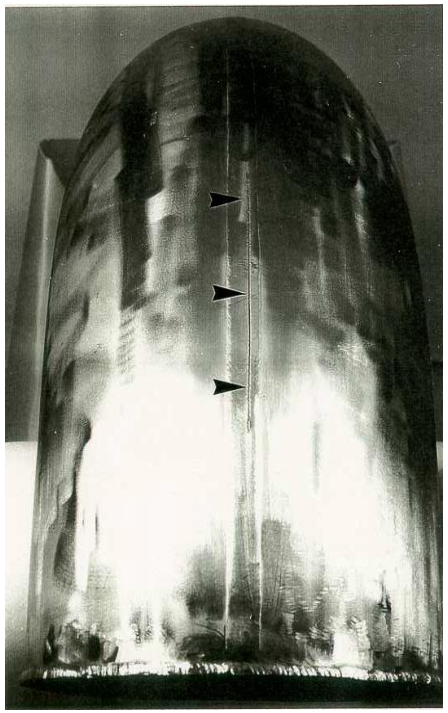
- Few spectacular and catastrophic accidents :

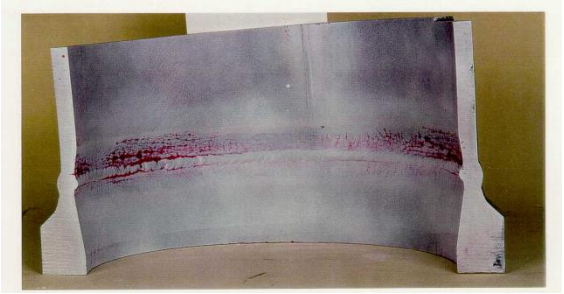
- 1999 : Erika's super-tanker sinking

The captain explained that he saw a large cracking on the ship deck that tried to stopped (without success) by smoothing the crack tip

1. Introduction – Lessons learned from history

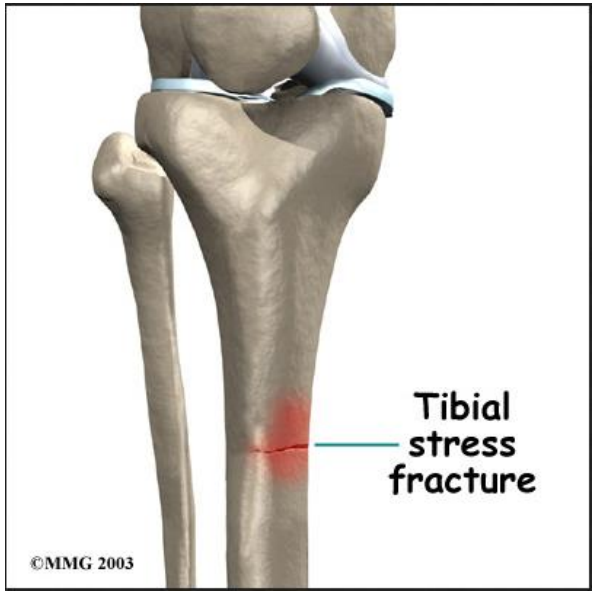
- Fatigue is affecting all kind of structure/industry and all type of variable loadings





1. Introduction – Lessons learned from history

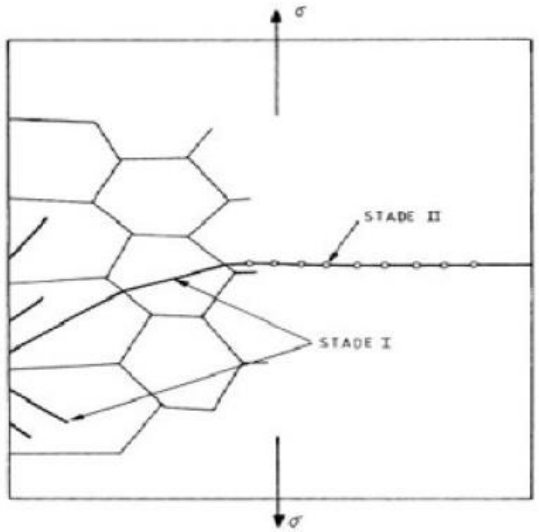
- And even your body is subjected to fatigue cracking

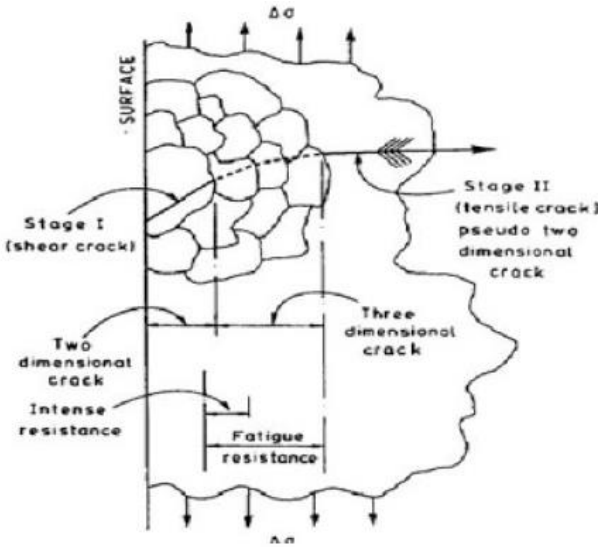


Cracking initiates by fatigue then complete fracture may appear since bone is a brittle material

2. Fatigue Crack Initiation

- Two phases generally considered regarding fatigue damage : initiation then propagation
- But in practice it corresponds to a continuous process from surface damage to macro-cracking with several barriers to overcome
- This behavior is strongly depending on material micro-structure and behavior, loading level…

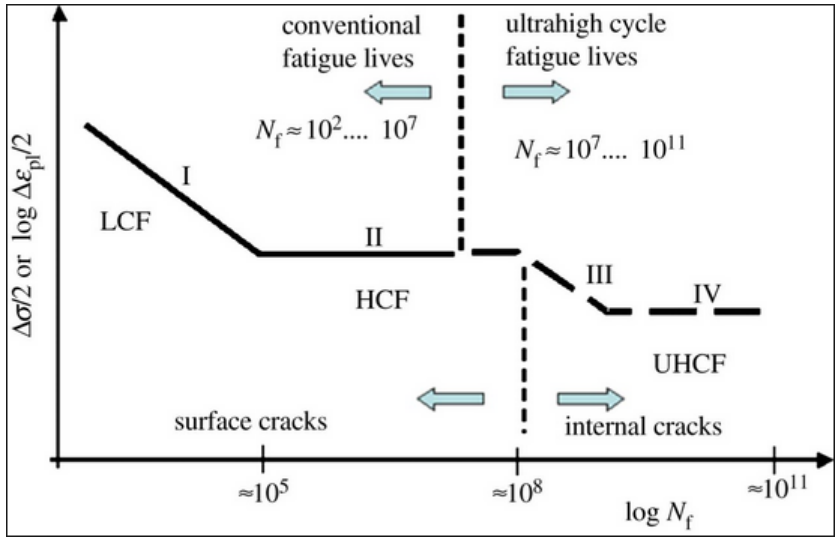


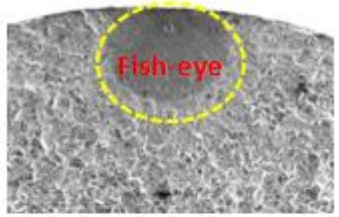


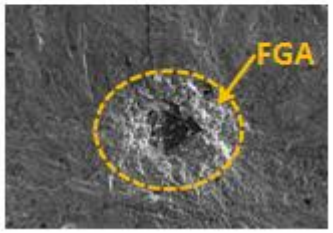
There is no unanimous definition of crack initiation and a conventional one has to be defined (base on the material, the structural applications (thicknesses), the loading, inspection capabilities…)

2. Fatigue Crack Initiation

- Regarding steels, three loading domains can be defined
- Low Cycle Fatigue (LCF) corresponding to significant plasticity during the loading cycles
- High Cycle Fatigue (HCF) corresponding to a low stress level of stress with no microscopic plastic strains → we are here close to the endurance limit
- In some applications and materials (eg. rotating structure) UltraHigh Cycle Fatigue (UHCF) may be encountered → we are speaking here about 10^{10} to 10^{12} cycles and thus very strong experimental difficulties







2. Fatigue Crack Initiation

- If we focus on Low Cycle Fatigue and High Cycle Fatigue, the damage is caused by strains which are:
  - Plastic
  - Cyclic
  - Local
  - Most often at the surface of the structure

- Those local plastic strain are due to the presence of microscopic defects

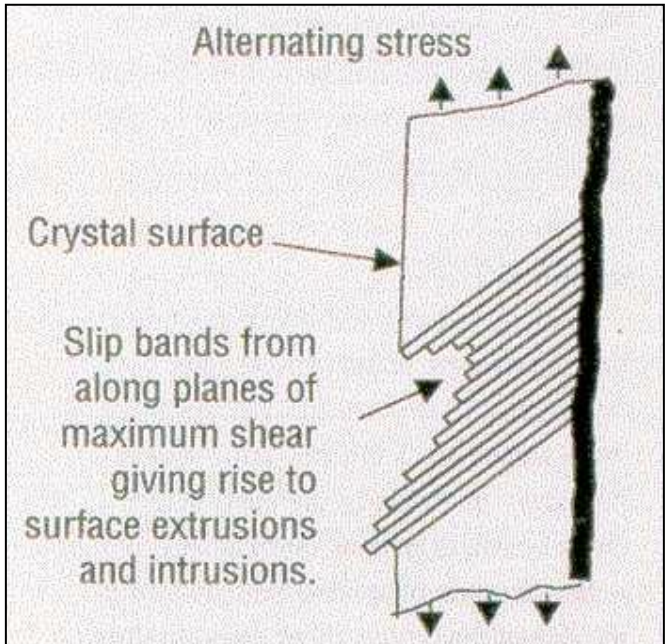


Figure 3: Illustration of persistant slip bands.

2. Fatigue Crack Initiation

- The main driving parameter is of course the cyclic strain amplitude
- But other parameters are also influencing fatigue crack initiation
  - Metallurgical microstructure
  - Geometry (stress concentrator)
  - Surface finish
  - Environment (corrosion)
  - Temperature (creep/fatigue)
  - Mean stress
  - Manufacturing residual stress (beneficial effect or not)
  - Loading history
  - …

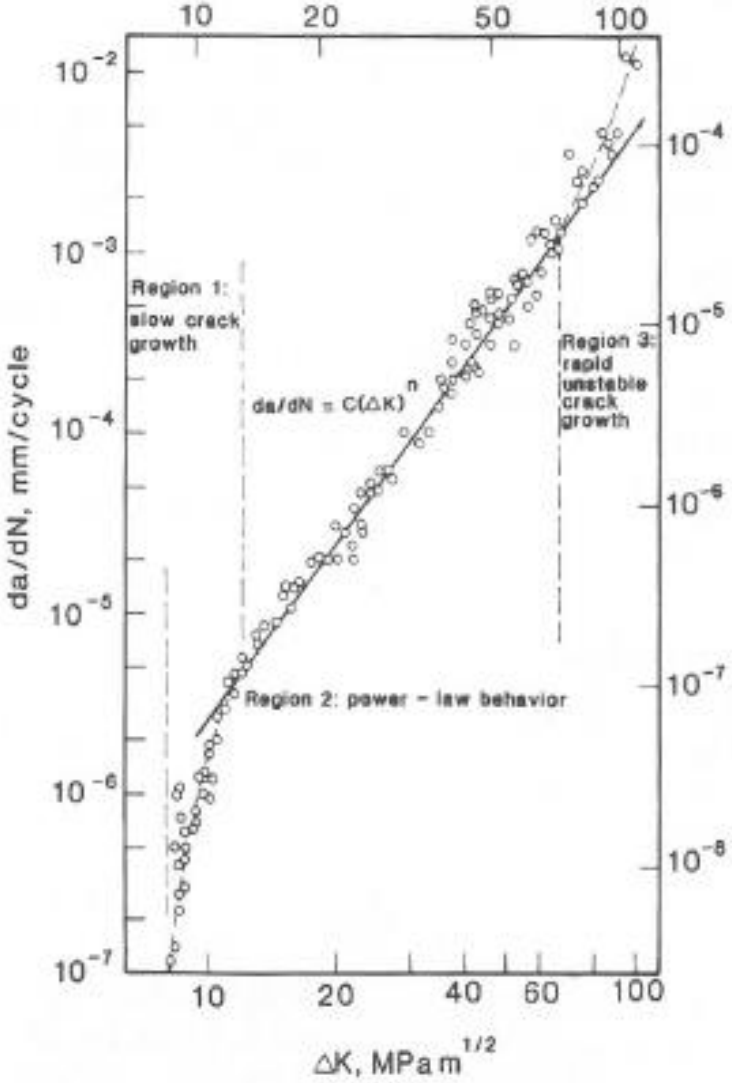
3. Fatigue Crack Propagation

- At propagation phase, it is assumed that a macro-crack is initiated
  → We are now dealing with fracture mechanics
- The main question is now the stability of this crack and the risk of component collapse

3. Fatigue Crack Propagation

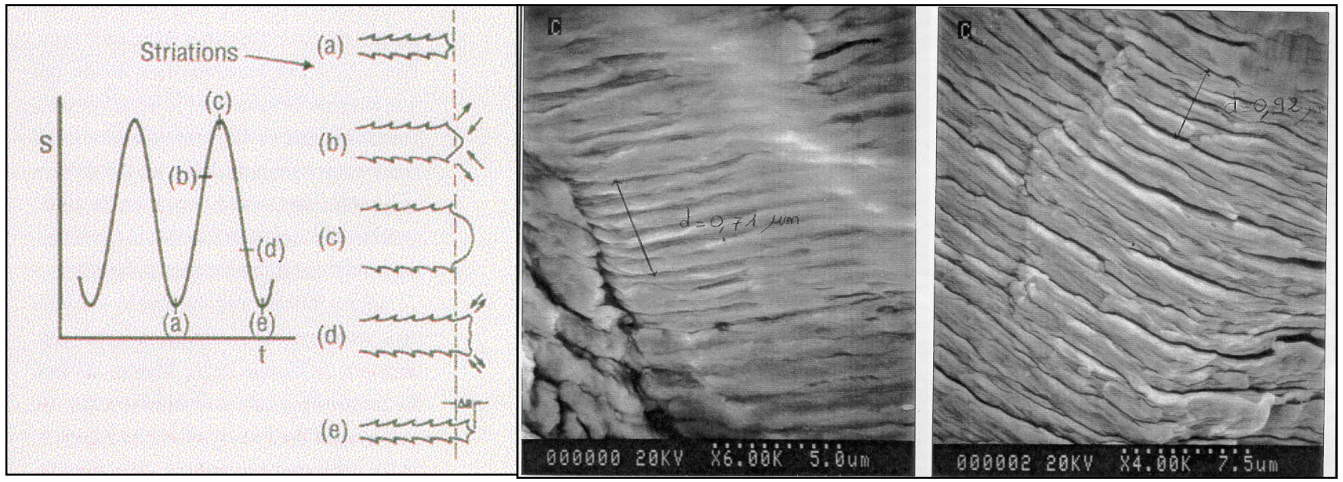
- Three main stages can be differentiated for this crack propagation phase
  - Stage I: Non propagation threshold or very slow crack growth
  - Stage II: Stable crack growth governed by Paris law
  - Stage III: Rapid and unstable crack growth

- Stage II is governed by the Paris' law: $da/dN = C.\Delta K^n$
  - a is the crack length and N the number of cycles
  - C and n material parameters
  - ΔK is Stress Intensity Factor amplitude



3. Fatigue Crack Propagation

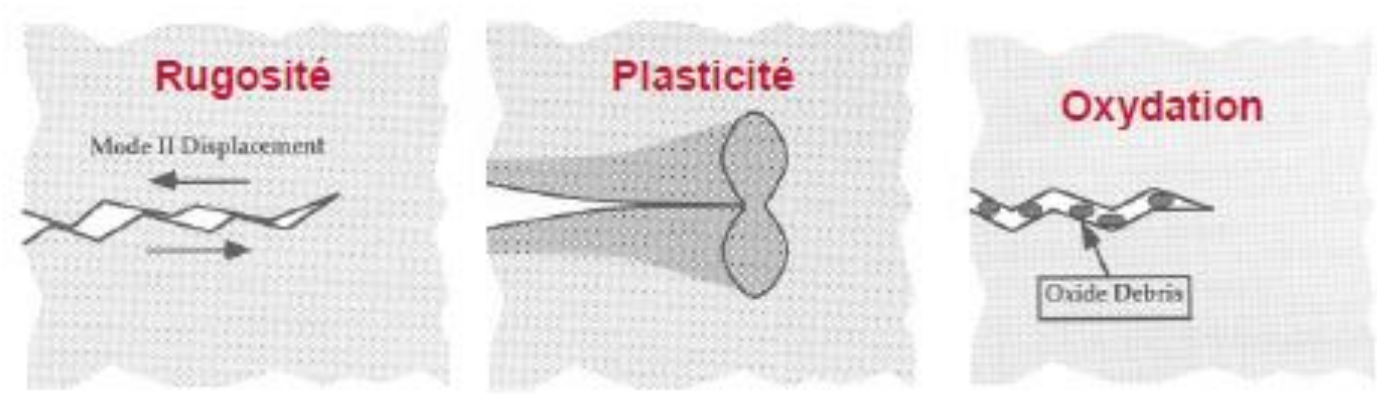
- Propagation in stage II by cyclic blunting of the crack tip
- Typical fatigue fracture surfaces with striations which allow :
  - Determining the root cause of the failure
  - Assessing the crack growth rate or the loading level (in Paris' regime)



- In stage III, accumulation of cyclic damage and tearing:
  - Ductile or quasi-brittle fracture depending on the material fracture behavior

3. Fatigue Crack Propagation

- Again many parameters may interact with Fatigue Crack Growth
  - Closure effect due to roughness, plasticity or oxidation



  - Environmental effect (crack tip embrittlement)
  - Frequency effect (competition between crack kinetics and chemical reaction one)
  - Loading effect (overload or mean stress)

4. Fatigue Consequences and Prevention

- Main consequences of fatigue damage (i.e. crack initiation and growth)

  → Leaks in many cases

  → Collapse or Fast Fracture in some of them

- Fatigue analysis has to be robust because of those potential damages (macroscopic crack) which are not easily detectable in industrial structures
- For that purpose, the main difficulty is associated to the knowledge of the loading history (each cycle contributes to fatigue damage) which can be :

  - An accumulation of small and large cycles variable occurrences with time
  - Random loading
  - Low or high frequency
  - Mechanical or thermal loading
  - Knowledge of the real structure (weld joint geometry, residual stresses)
  - …

- Number of margins are included in fatigue design rules to overcome those difficulties

4. Fatigue Consequences and Prevention

- Fatigue Monitoring and Periodic Non Destructive Examination are also important for preventing fatigue damage

  - Instrumentation of zones which are known to be potentially sensitive to fatigue damage

  → Counting of the loading situation and/or detection of any change in the structural behavior (eg. frequency mode)

  - NDE in planed and/or random localizations in order to detect cracking

- Fracture Mechanics may be in support of those two prevention modes

  - Simply evaluate the consistency between crack detection capabilities and critical defect size (in terms of fracture)

  - Decision making to repair or to replace components if critical fatigue crack growth is foreseen

  - Or do nothing if no evolution of the detected crack is expected

4. Fatigue Consequences and Prevention

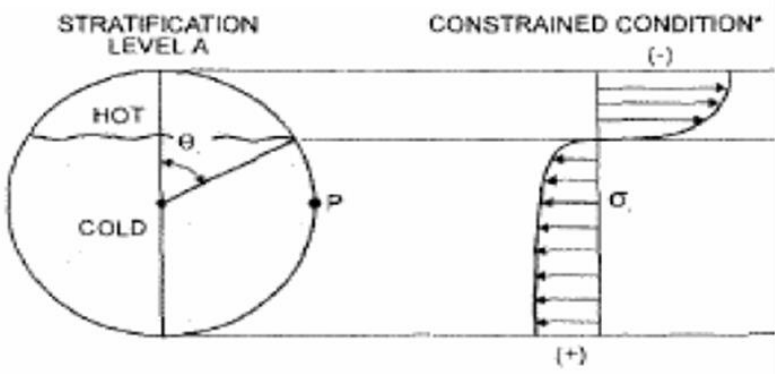
- From nuclear experience, number of unsuspected cracks quite limited. Those are associated to:

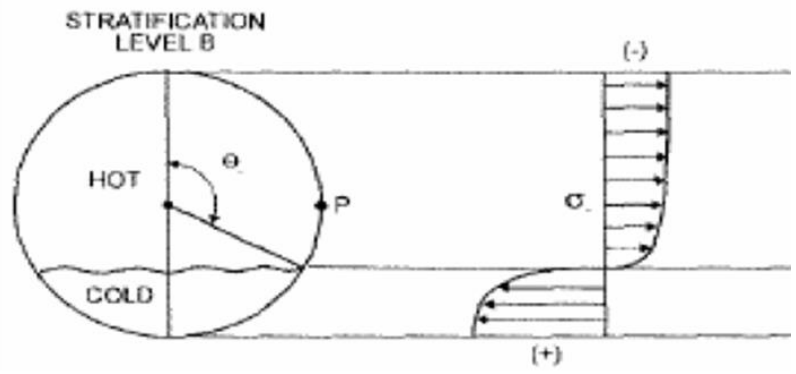
  - Components not justified in fatigue (safety classes and exemption rules issues)

  - Loading underestimated or completely omitted (most often linked to local thermal-hydraulic effects)

- In our field, the thermal loading is a major one with difficult problematics such as:

  - Thermal stratification





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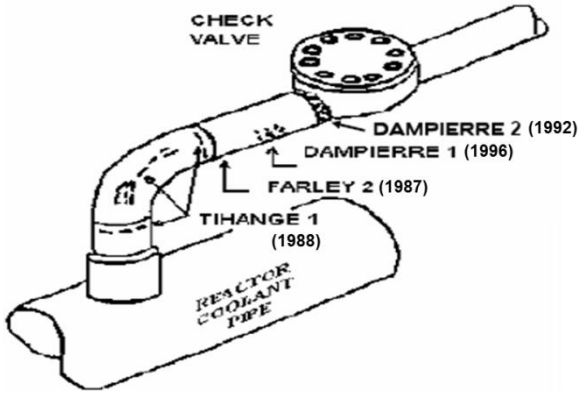
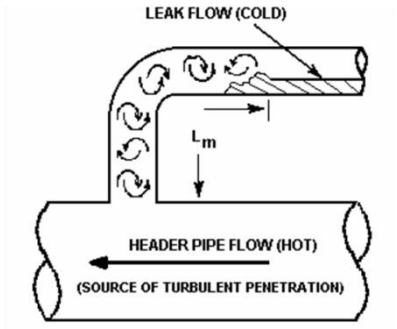
  - <u>Vortex and Farley-Tihange phenomenon in dead leg</u> configurations





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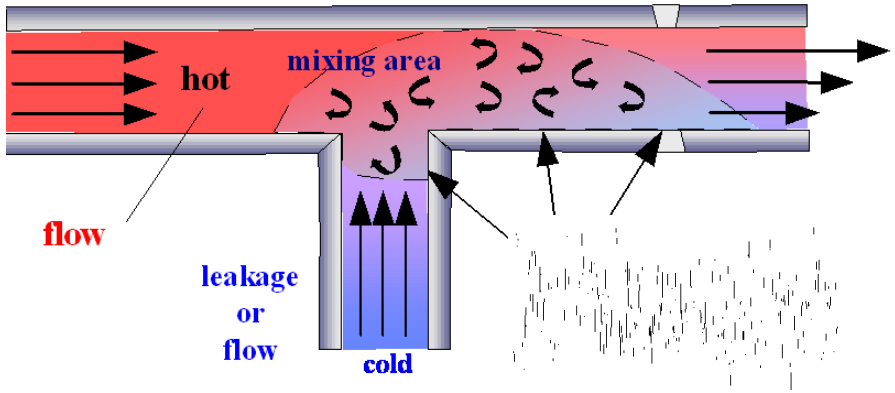
  - Mixing with high temperature difference ΔT



Synthesis and Conclusion

- Fatigue is a major damage for industrial structures

  → Possibly leaks in many cases

  → But also possibly catastrophic collapse if cracks are not detected in due time

- For that reason, Fatigue Analysis has to be robust because of those potential damages, with two different phases

  - Crack initiation from high stressed zones

  - Crack propagation

- But this could be a difficult exercise due to the number of parameters interacting with fatigue damage (loading history, corrosion, stress singularities…)

- NDE and monitoring are important complements to those fatigue damage evaluations

Thank you!

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