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APPLICATION OF CONTINUUM DAMAGE MECHANICS FOR IN-SERVICE REAL FATIGUE CRACKING SCENARIOS

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Agenda

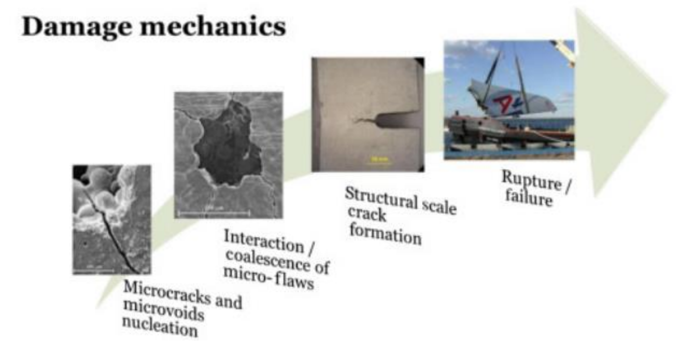
- **CONTINUUM DAMAGE MECHANICS**
  - *CDM Fundamentals & damage models for fatigue/residual strength evaluations*
- **NUMERICAL IMPLEMENTATION**
  - *Simulation framework & Numerical Implementations for fatigue/residual strength*
- **APPLICATION #1: CRACKING IN FUSELAGE FRAME FOOT ATTACHMENT**
  - *Preparing FEM and launching the CDM simulation for tested and in service configurations*
  - *Main Results*
- **APPLICATION #2: CRACKING IN HTP UPPER SKIN**
  - *Preparing FEM and launching the CDM simulation for tested and in service configurations*
  - *Main Results*
- **CONCLUSIONS AND WAY FORWARD**

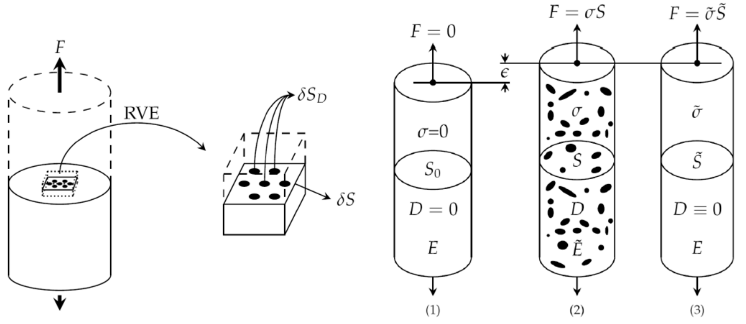
Continuum Damage Mechanics

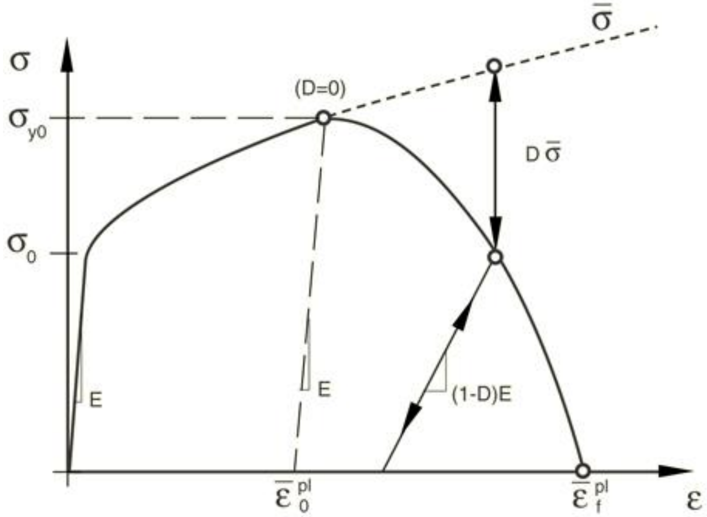
Continuum Damage Mechanics

- Concept introduced by L. Kachanov in 1958 for creep deformation evaluation
- Main strength and fatigue damage models introduced in the 90's and 2000's

- Discipline focused on the **material behaviour modelling in terms of properties degradation** from initiation of damage to final failure
- Study at macro-scale level ⟶ micro-scale phenomena (voids, dislocations…) are translated into material macro-scale properties ⟶ **Continuum Mechanics**
- **Different damage models defined** to characterize different failure modes
  - Ductile failure
  - Brittle failure
  - Dynamic failures (high strain rate)
  - Composite delamination
  - Fatigue
  - …







Damage initiation
Failure

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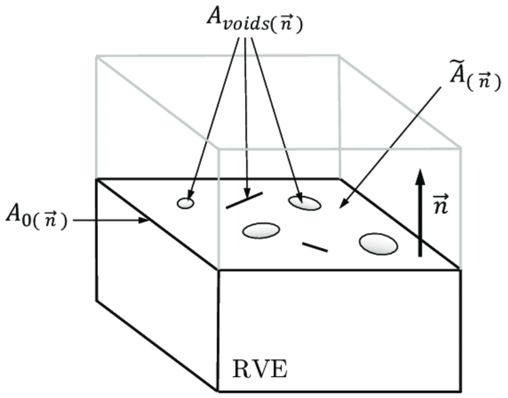
Continuum Damage Mechanics

What is needed for CDM formulation?

Definition of Damage Variable

$$D = \frac{\delta S_D}{\delta S}$$

- *Isotropic Damage → scalar*
- *Anisotropic Damage → tensor*



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Material Constitutive Model
(Stress-Strain Law)

$$D = 1 - \frac{\tilde{E}}{E}$$

$$\tilde{\sigma}_{ij} = \frac{\sigma_{ij}}{1 - D}$$

$$\varepsilon_{ij}^{e} = \frac{1+\upsilon}{E}\left(\frac{\sigma_{ij}}{1-D}\right) - \frac{\upsilon}{E}\left(\frac{\sigma_{kk}\delta_{ij}}{1-D}\right)$$

$$\dot{\varepsilon}_{ij}^{p} = \frac{3}{2}\left(\frac{\dot{\lambda}}{1-D}\right)\frac{S_{ij}/(1-D) - \alpha_{ij}}{\left(S_{ij}/(1-D) - \alpha_{ij}\right)_{eq}}$$

\+

Damage Evolution Law

$$\dot{D} = f(k)$$

where k is a material variable (i.e. equivalent stress)

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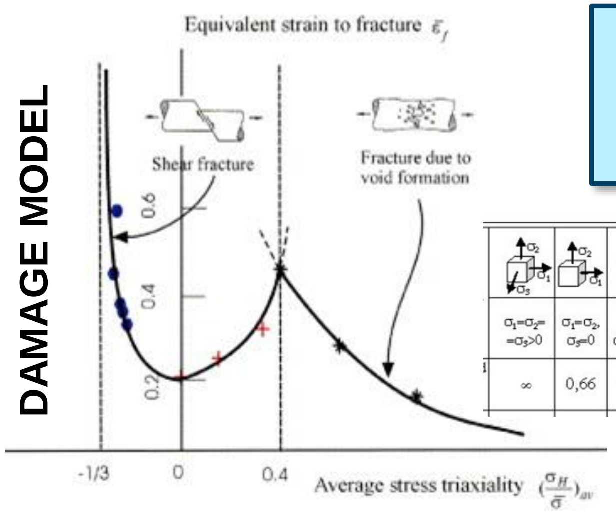
Continuum Damage Mechanics

Damage model for Static Failure

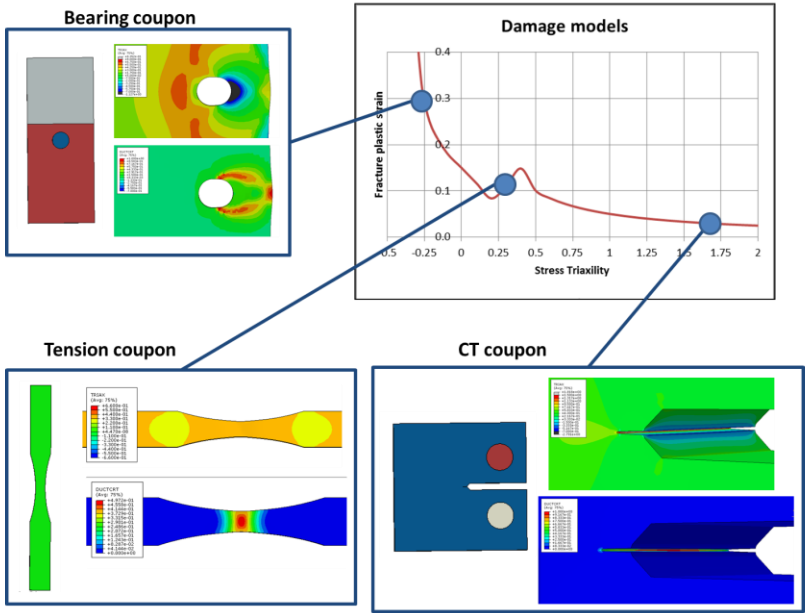
DUCTILE FAILURE DAMAGE MODEL



CDM with Ductile Damage model based on fracture strain evolution with stress triaxiality

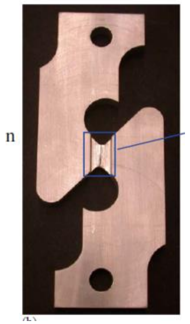
$\sigma_1=\sigma_2=\sigma_3>0$	$\sigma_1=\sigma_2$, $\sigma_3=0$	$\sigma_2>0$ $\sigma_1=\sigma_3=0$	$\sigma_1>0$, $\sigma_2=\sigma_3=-\frac{\sigma_1}{2}$	$\sigma_1=-\sigma_2$ $\sigma_3=0$	$\sigma_1<0$, $\sigma_2=\sigma_3=-\frac{\sigma_1}{2}$	$\sigma_2<0$ $\sigma_1=\sigma_3=0$	$-\sigma_1=-\sigma_2$, $\sigma_3=0$	$\sigma_1=\sigma_2=\sigma_3<0$
∞	0,66	0,33	0	0	0	-0,33	-0,66	-∞

SIMULIA ABAQUS + python™

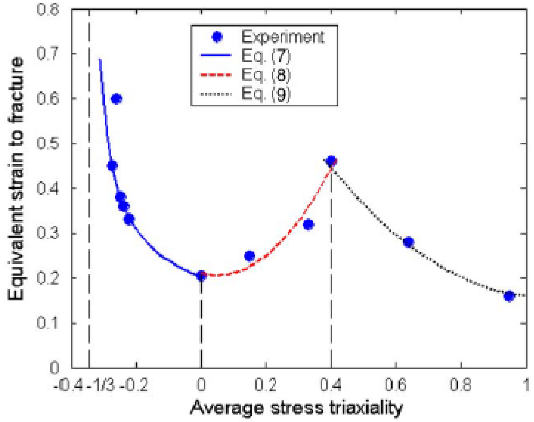


DAMAGE MODEL CALIBRATION PROCESS

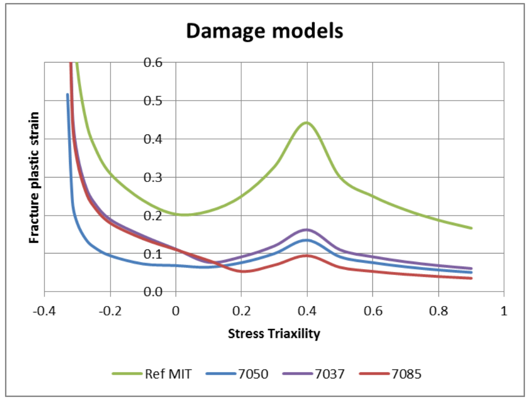
Physical Tests for 2xxx alloy



Damage model derived for 2xxx



Calibrated model for different materials using virtual coupons



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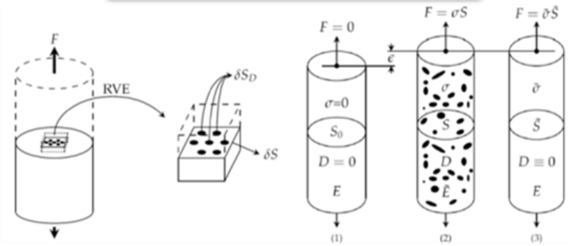
Continuum Damage Mechanics

Damage model for Fatigue Cracking

FORTRAN USER SUBROUTINES

Fatigue cracking damage model

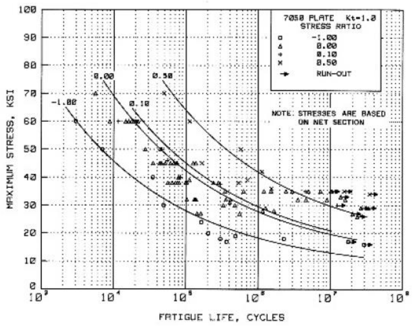
CDM with Peerlings' damage model based on uniaxial strains

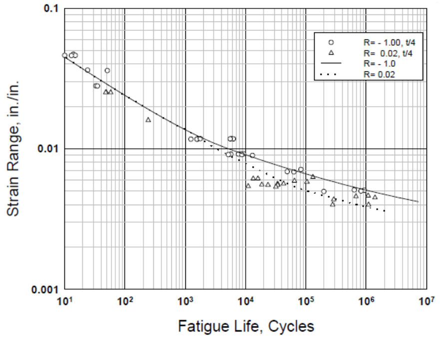


$$D = -\frac{1}{\alpha}\, ln\left(1 - \frac{2\,\alpha\,C}{\beta+1}\varepsilon_a{}^{\beta+1}\,N\right)$$

$$N_F = \frac{\beta+1}{2\,\alpha\,C}\,(1-e^{-\alpha})\;\varepsilon_a{}^{-(\beta+1)}$$

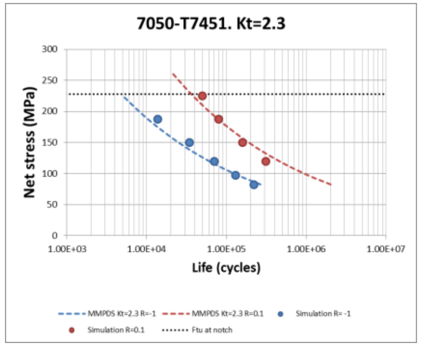
Unnotched fatigue material data for damage model calibration (material fatigue behavior)

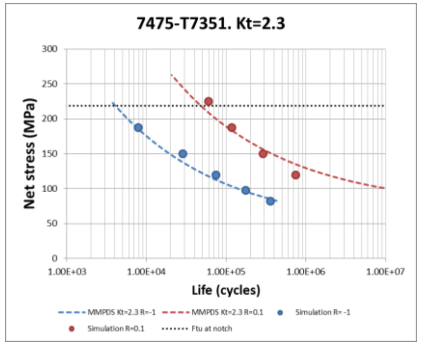


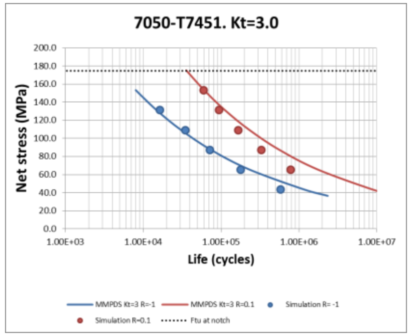


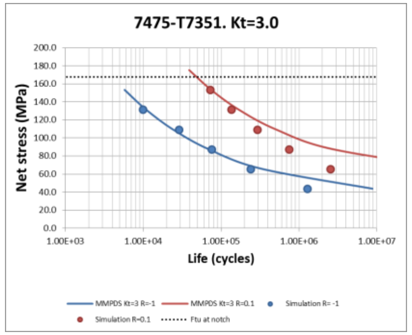
Validation of the calibration by reproducing fatigue design curves for different notched configurations

Fatigue Test Data source: AFI, Airbus DS database, MMPDS









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Numerical Implementation

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Numerical Implementation

RESIDUAL STRENGTH SIMULATION

- Abaqus Explicit
- Quasi-static simulation
- Progressive Damage Analysis
- Multi-node run compatible
- 3D MESH (C3D8 / C3D10). Size = 0.5 mm at CDM area

COMPUTATION TIMES (for reference)

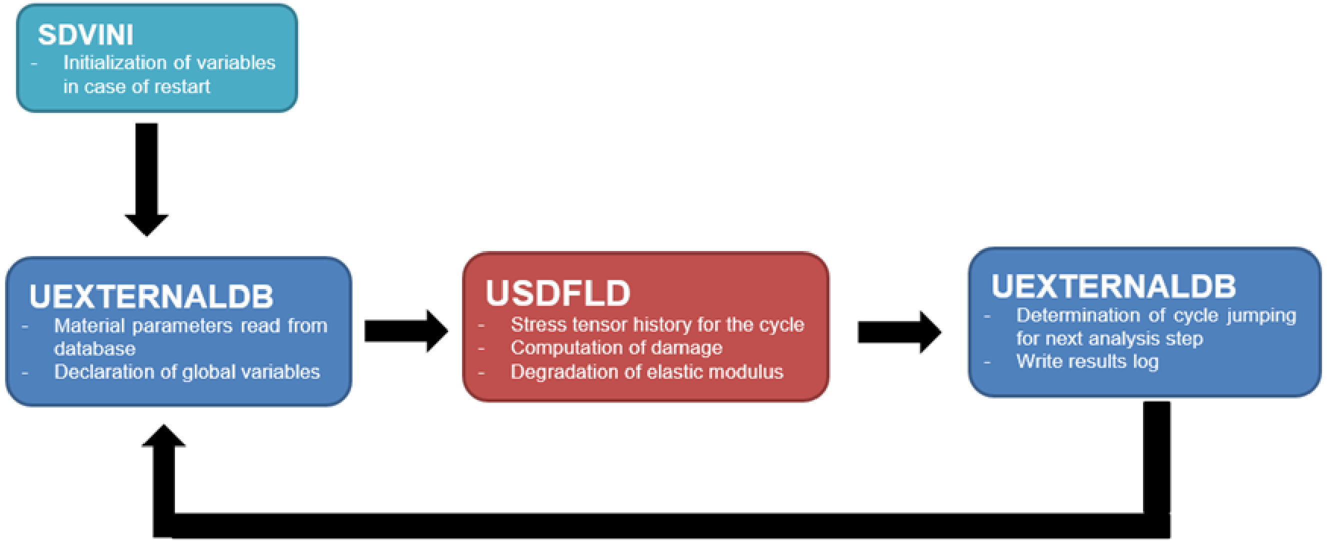
- Coupons < 3 hr
- Small components < 10 hr
- Large assemblies < 3 days

FATIGUE AND CRACK PROPAGATION SIMULATION

- Abaqus Standard
- General Static solution
- Abaqus User subroutine
- Single-node run
- 3D MESH (C3D8 / C3D10). Size = 0.5 mm at CDM area

COMPUTATION TIMES (for reference)

- Coupons < 1 day
- Small components < 1 week
- Large assemblies < 1 month



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Application #1: Cracking in Fuselage Frame Foot Attachment

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Application #1: Cracking in Fuselage Frame Foot Attachment

A

B

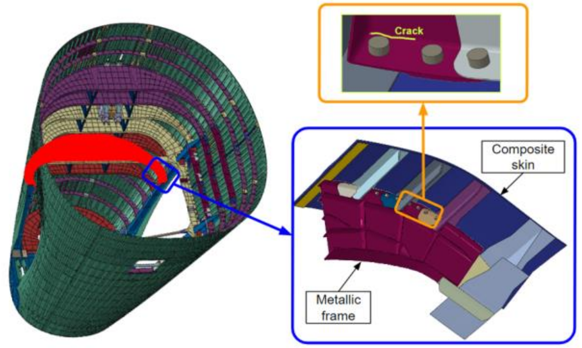
C

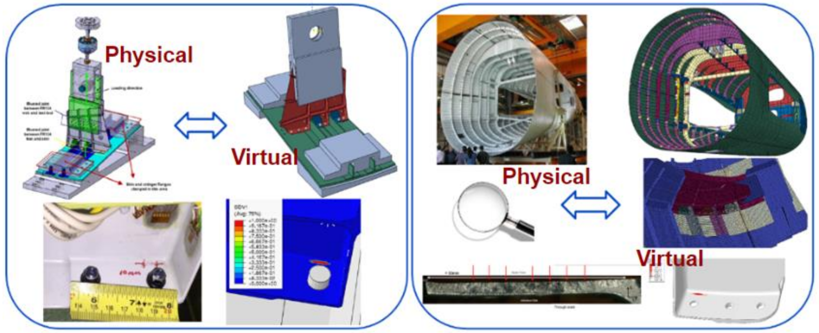
CDM

I. Preparing the CDM Simulation: Global and Detailed FEM Validation and Verification vs. Test

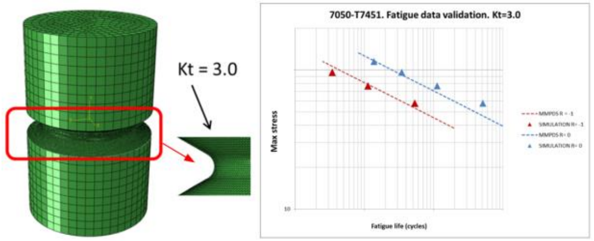
A. From the Fuselage Global FEM, the area of interest is detailed and remeshed for the CDM simulation.

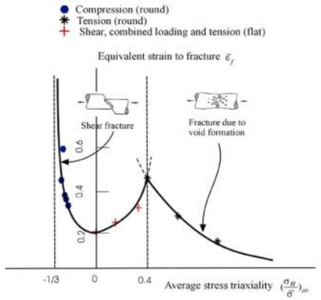
B. Considering the strain gauges of the subcomponent test, a correlation of the FEM is performed, showing an acceptable level of predictions.





C. The damage model selected for the CDM simulation is Peerlings[1)] for initiation and a ductile damage model [2) 3)] for residual strength : Material properties are calibrated against test data for the specific aluminium alloy of the structural component.





[1)] Peerlings, R. (1999). "Enhanced damage modelling for fracture and fatigue". *Proefschrift Technische Universiteit Eindhoven*
[2)] Hooputra, H.; Gese, H.; Dell, H.; Werner, H. (2004). A comprehensive failure model for crashworthiness simulation of aluminium extrusions. *International Journal of Crashworthiness, 9:5, 449-464.*
[3)] Bao, Y.; Wierzbicki, T. (2004). On fracture locus in the equivalent strain and stress triaxiality space. *International Journal of Mechanical Sciences 46 81-98.*

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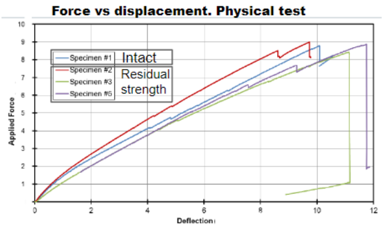
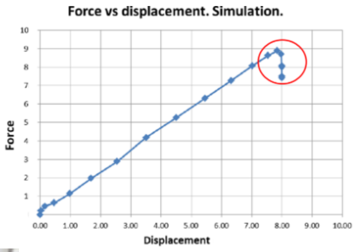
Application #1: Cracking in Fuselage Frame Foot Attachment

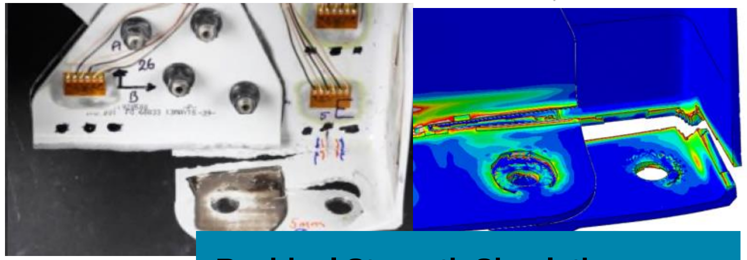
II. Launch of the CDM Simulation for the tested specimen

A. Using the material properties calibrated for the damage model and the detailed FEM properly validated with test results the CDM simulation is launched.

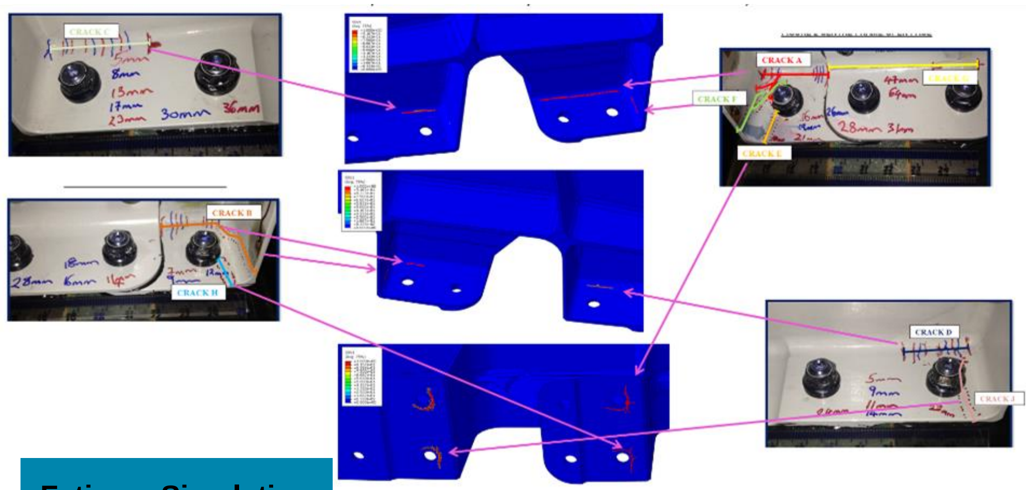
B. Main purpose is to let the simulation running, and see under which conditions, is capable of reproducing the test results in terms of static residual strength, crack initiation location, number of accumulated flights cycles predicted and subsequent propagation of the damage for this application case.



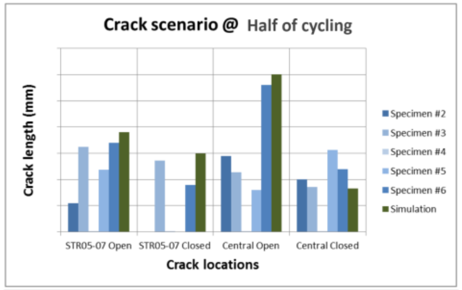


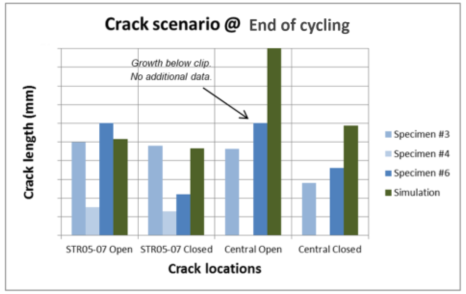


Residual Strength Simulation



Fatigue Simulation





C. **Conclusion vs Test**: Both residual strength and CDM fatigue simulations of the subcomponent test evidence were matching pretty well the static failure (mode and displacement at failure) and also the crack initiation location and subsequent propagation.

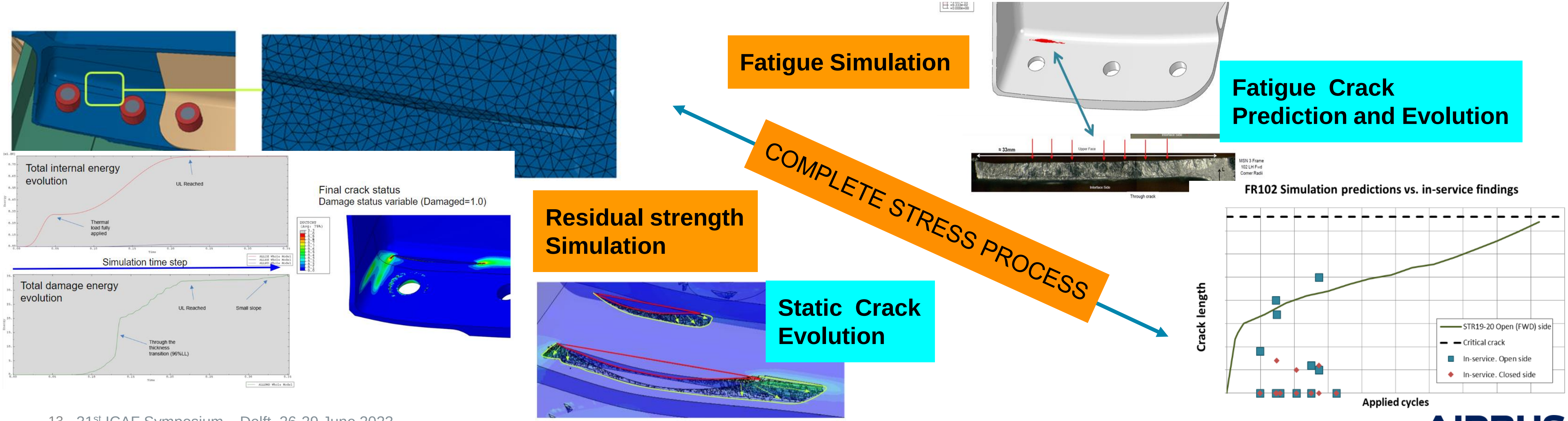
Application #1: Cracking in Fuselage Frame Foot Attachment

III. Launch of the CDM Simulation for the in service configuration

A. Once the CDM simulation has been proven to be validated in predicting the tested configuration, a new CDM simulation is launched based on the same parameters of the test simulation, but for the in service configuration.

B. To do so, all the experience from the test simulation is used in combination with the real static and fatigue load state applicable for the in service configuration.

C. Conclusion vs. Classical Analysis: Residual strength capability demonstrated by the simulation increased between **40% to 50%** and the crack initiation location prediction increased by a factor of **3 times**, covering the scenario detected in service and giving the proper time to react to repair the structure.



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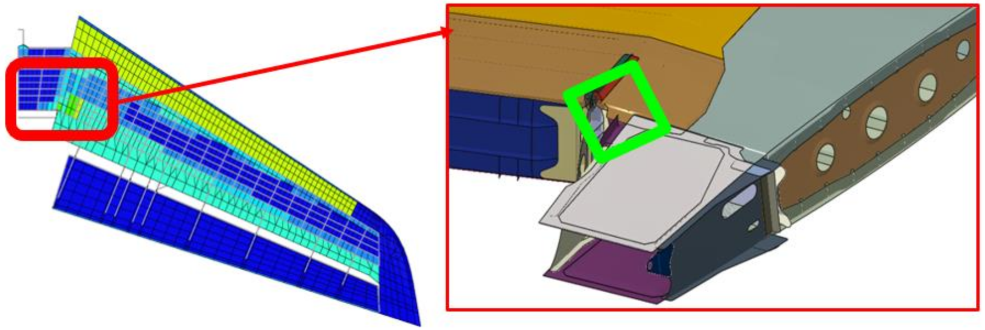
Application #2: Cracking in HTP Upper Skin

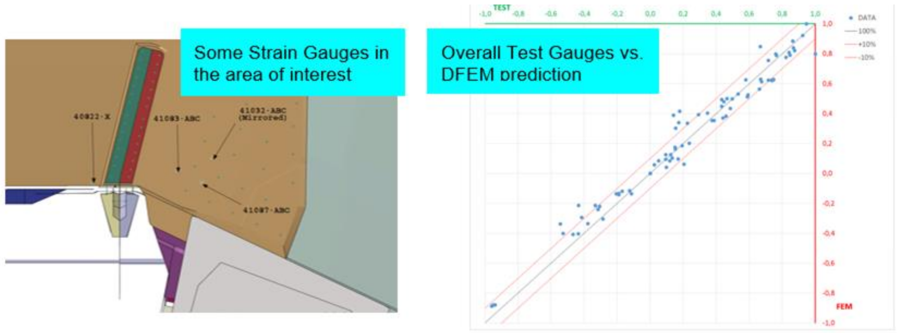
Application #2: Cracking in HTP Upper Skin

I. Preparing the CDM Simulation: Global and Detailed FEM Validation and Verification vs. Test

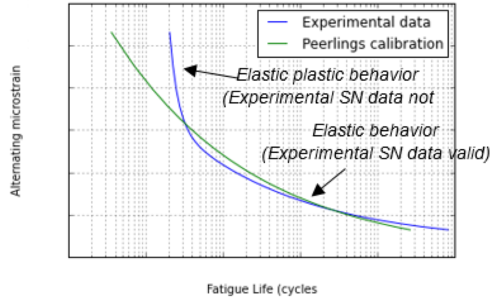
A. From the HTP Global FEM, the area of interest is detailed and remeshed for the CDM simulation.



B. Considering the strain gauges of the test, a correlation of the FEM is performed, showing an acceptable level of predictions.



C. The damage model selected for the CDM simulation is Peerlings[1)] : Material properties are calibrated against test data for the specific aluminium alloy of the structural component.



A

B

C

CDM

[1)] Peerlings, R. (1999). "Enhanced damage modelling for fracture and fatigue". *Proefschrift Technische Universiteit Eindhoven*

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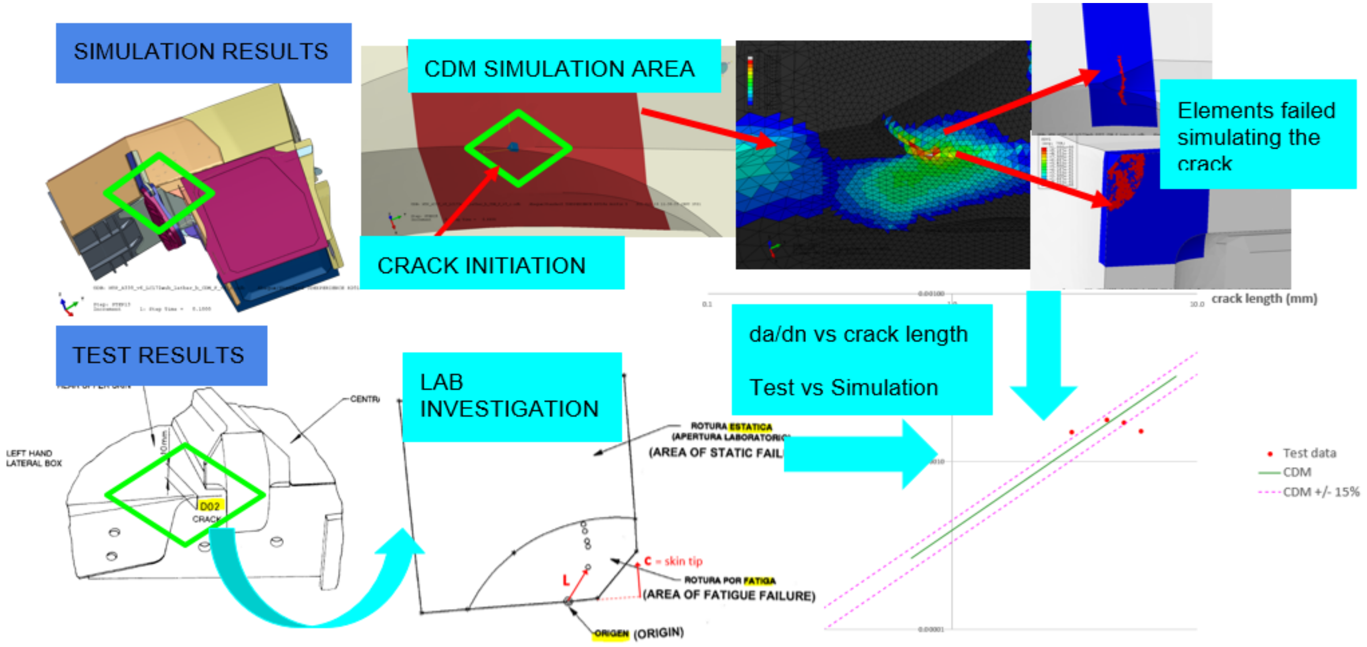
Application #2: Cracking in HTP Upper Skin

II. Launch of the CDM Simulation for the tested specimen

A. Using the material properties calibrated for the damage model and the detailed FEM properly validated with test results the CDM simulation is launched.

B. Main purpose is to let the simulation running, and see under which conditions, is capable of reproducing the test results in terms of crack initiation location, number of accumulated flights cycles predicted and subsequent propagation of the damage.



C. **Conclusion vs Test**: Despite of the limited test data (just for small crack size), very good match of the first damage initiation location and subsequent crack propagation.

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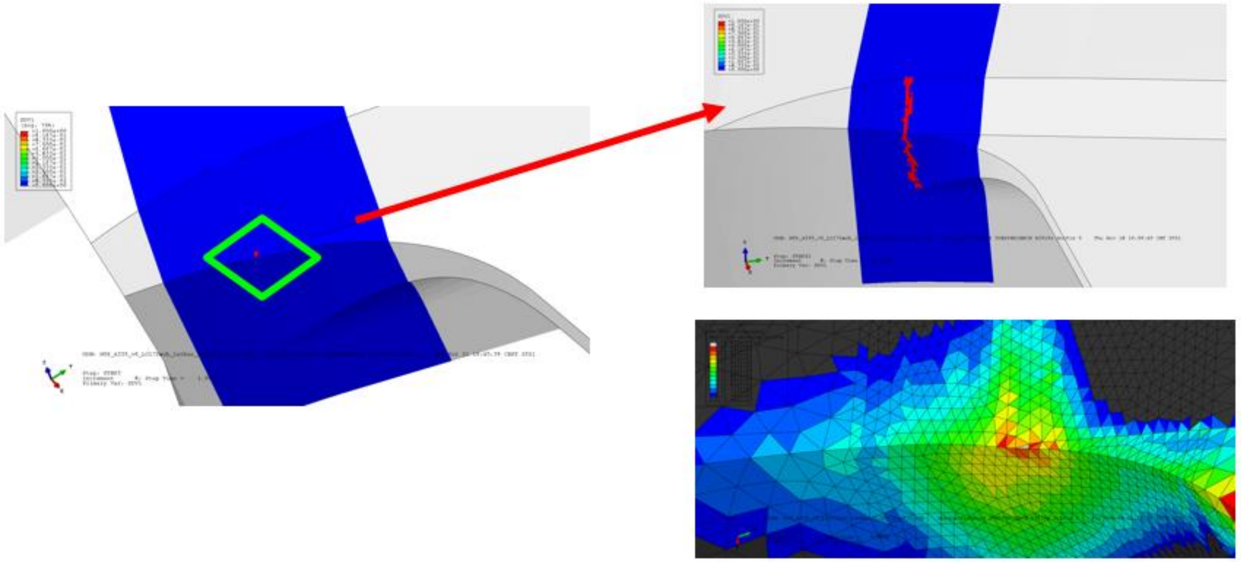
Application #2: Cracking in HTP Upper Skin

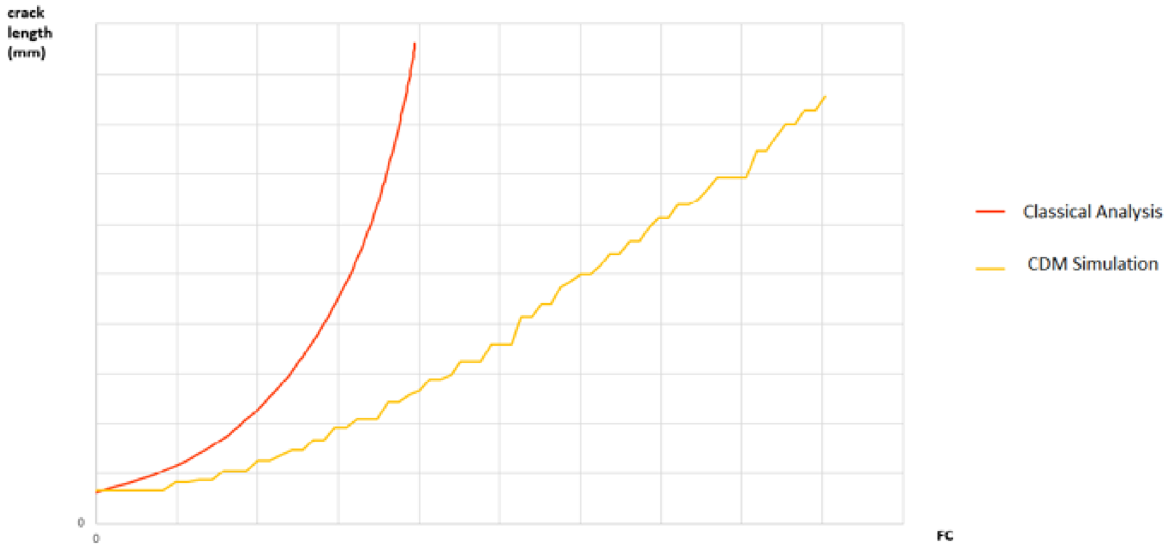
III. Launch of the CDM Simulation for the in service configuration

A. Once the CDM simulation has been proven to be validated in predicting the tested configuration, a new CDM simulation is launched based on the same parameters of the test simulation, but for the in service configuration.

B. To do so, all the experience from the test simulation is used in combination with the real fatigue load state applicable for the in service configuration.

C. **Conclusion vs. Classical Analysis**: Crack growth curve of the location of interest obtained based on CDM simulation predicts a slower crack propagation rate than the one obtained based on classical analysis, i.e. **2 times slower**.





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Conclusions and Way forward

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Conclusions and Way forward

I. The simulations presented, are based on **Continuum Damage Mechanics with ductile damage model** for strength prediction and a **fatigue damage model based on alternating strains** for fatigue cracking prediction.

II. The two applications presented are examples of different structure details, submitted to very different load states, where the **CDM simulation has proven its flexibility to predict the crack initiation**, propagation and failure of the real scenarios that occurred in the corresponding subcomponent or full-scale test.

III. An increase of **3 times on the prediction of loading cycles up to the crack initiation and +40% to +50% residual strength increase** shown in the case of the frame application. For the Horizontal tail plane, the prediction of **the crack propagation rate has been improved by a factor of 2**.

IV. The CDM predictions supported **the fleet safety assessment and the optimized inspection** plan further than the more conservative conventional methodology originally justified.

V. Airbus is committed to continue developing the CDM simulation capabilities, by means of exploring other damage models, with less limitation on triaxiality effects **always exploiting the in house extensive test**.

Thank you

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