ICAF

International Committee on Aeronautical Fatigue and Structural Integrity

Fatigue crack growth and life prediction methods

Rene Alderliesten, TU Delft The Netherlands | date

Topical Review covering European activities

- Methods based on FE-simulations for fatigue life and crack growth prediction
  - Lugs, CT-specimens, Beam specimens, Welded bars
- Methods for fatigue life and crack growth prediction
  - Thermoplastic composites, Engineering alloys, Additive Manufacturing
- Modelling through EIFS and Weibull distributions
  - PBF-LB Ti-6Al-4V notched geometries
- Multiaxial loading and load sequences
  - Continuous-time, multiaxial high-cycle fatigue model
- Fluid-Structure Interaction for aircraft life prediction

Methods based on FE-simulations for fatigue life and crack growth prediction

- **Introduction and self-heating method :**

High-cycle fatigue (HCF) is an insidious aspect of the mechanical behavior of metallic materials due to its progressive and hidden nature

Although significant progress has been made since the early 20th century, high-cycle fatigue sizing remains a major problem due to:

- numerous parameters such as the nature of the loading (e.g., load ratio, multiaxiality of the loading, loading history, ...), the environment (temperature, ...), the microstructure, and the method of obtaining the part.
- The probabilistic nature of the behavior (i.e., there is a large dispersion in the number of cycles to fatigue failure).
- The characterization times for fatigue properties in a given configuration using classical methods are prohibitive.

For several years, a number of research teams have been working on determining the fatigue properties at high cycle numbers of metallic materials from self-heating tests under cyclic loading.

These studies are based on the fact that the increase in temperature is related to the fatigue limit of the material.

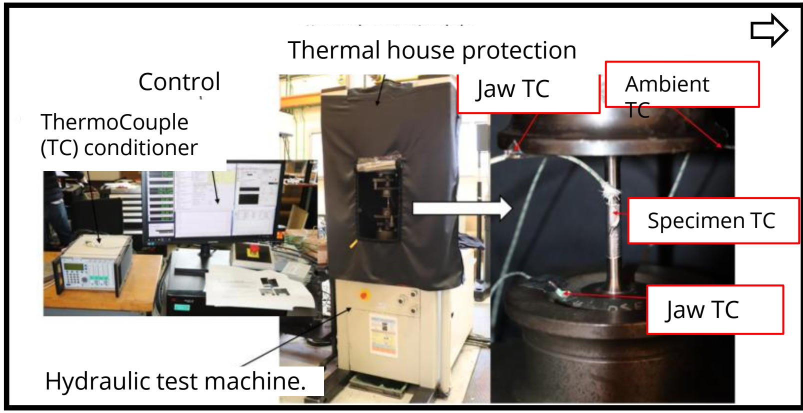
Advantages and DGA TA results:

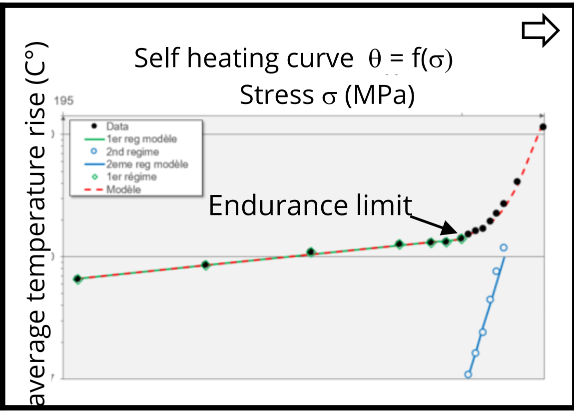
The method allows for the determination of the material's endurance limit :

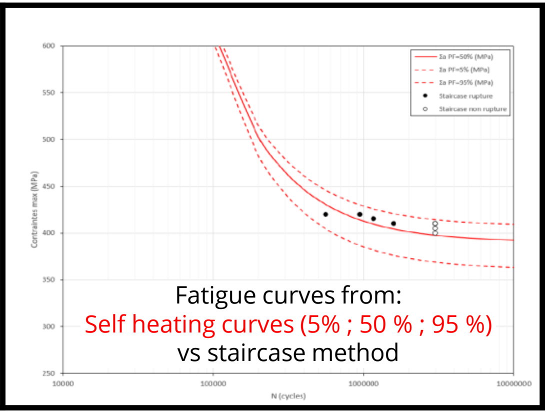
- with a reduced number of sample (around 2).
- quickly (reduced number of cycles), easily and with reduced costs (only thermocouples to install) .
- by eliminating of biases induced by sample fabrication methods (using “0D” technique).

Tests are done on steel samples by applying the '0D' technique i.e the measurement of the temperature is done only by thermocouples (2D and 3D methods, for complex structure, need IR camera).

Endurance limit corresponds to the slope modification of the curve $\theta = f(\sigma)$, indicating that damage at microstructural shift from dislocation movement to local plasticity.







Results obtained, compared to the staircase method are quite encouraging.

It is planned to apply the “0D” self heating method to other alloys, such as stainless steels and aluminum alloys.

Fatigue crack growth simulation with Abaqus at DGA

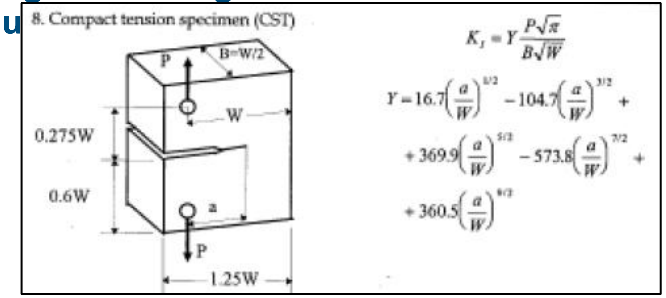
- **Introduction to the IFIP Study and ABAQUS Simulations**

This work is part of the IFIP (Fatigue Index/ Propagation Index) study, which aims to develop a tool in order to predict fatigue crack growth in metallic parts based on geometry, material, and cyclic loading.

The study uses Finite Element simulations with ABAQUS XFEM (eXtended Finite Element Method) to model fatigue crack growth, providing two key outputs: crack propagation visualization and stress intensity factor vs. crack length.

The stress intensity factor is crucial for estimating crack growth using laws like Elber's, Preffas, or Onera. ABAQUS uses the energy release rate, converted via Irwin's formu

$$K_{1c} = \sqrt{\frac{EG_{1c}}{1-\nu^2}}$$

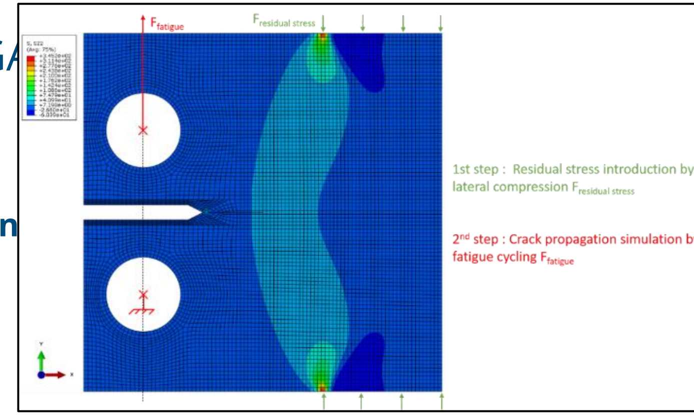


Irwin's formula and CT sample stress intensity factor formula

Simulations were conducted in 2D and 3D CT samples, with and without residual stress fields. Cracks are modeled using XFEM and crack growth with the Paris law.

For models with residual stress fields, an initial simulation introduces the stress field, defining material plastic.

Fatigue crack growth simulation with Abaqus at DGA



- **Simulation of Crack Growth in 2D and 3D CT specimen:**

  Crack growth in 2D CT specimens was simulated with two configuration

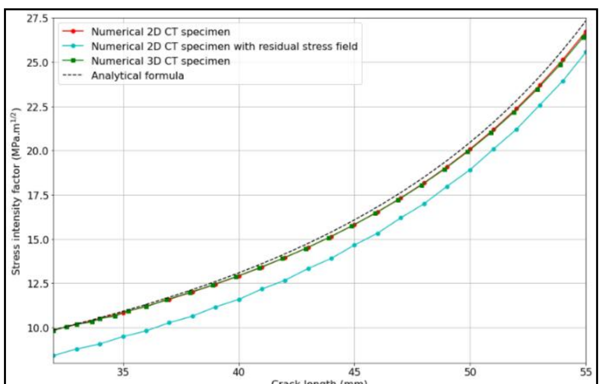
  - Conf. 1: Basic CT specimen without residual stress.
  - Conf. 2: CT specimen with residual stress from lateral compression.

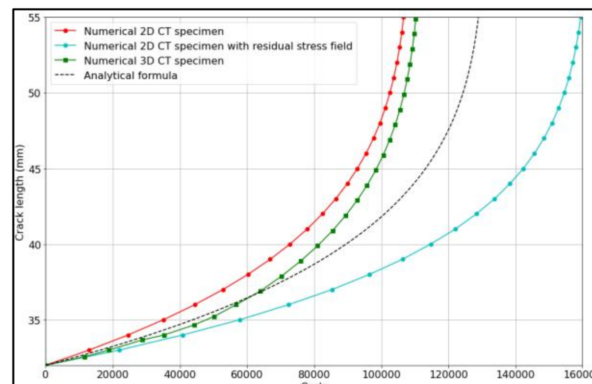
  => Residual stress is slightly positive (~few MPa).

  => It decreases the stress intensity factor, slowing crack growth.

  => Final crack length is reached after 160,000 cycles with residual stress vs. 110,000 cycles without.

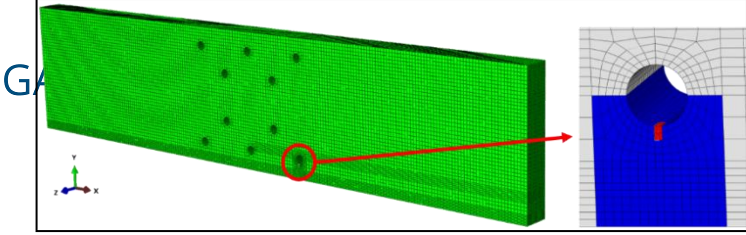
  Crack growth in 3D CT specimens was simulated without residual stress, crack length and stress intensity factor are computed by taking the average along the CT sample thickness.





The difference in stress intensity factor in 2D and 3D models is very small (< 0.01 MPa.m^1/2) but impacts significantly the number of cycles to reach the final crack length.

Fatigue crack growth simulation with Abaqus at DGA



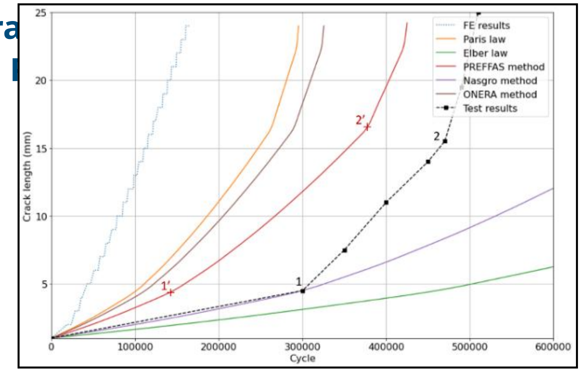
- **Simulation of crack growth in the wing beam specimen:**

  This specimen represents a simplified wing beam designed for the IFIP study. It features a predictable crack path and complex geometry with threads on the X-Y plane for attaching the wing skin.

  A pre-crack is introduced on a thread edge and the specimen is subjected to uniaxial tensile load in the X direction with a constant amplitude fatigue loading and a stress ratio R = 0.1, leading to predominant mode I rupture.

  Crack length 'a' is defined along the thread, studied between 1 mm (pre-crack) and 25 mm (full crack along the thread).

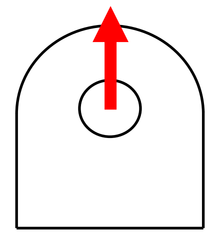
  The figure hereafter compares cra predictions using different methods: Elber law, ONERA method, Nasgros, and I

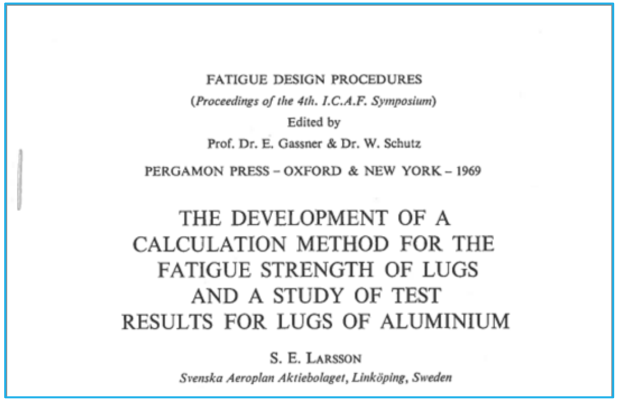


  Inflection points in test results (a ≈ 4.5 mm and a ≈ 15.5 mm) are visible in Paris, ONERA, and PREFFAS curves,

FE based method for calculation of fatigue life of lugs with arbitrary geometry and load direction

- Current method by Larsson (1969)
  - Only straight axially loaded lugs
- Proposed FE-based method
  - Arbitrary geometry and load (CA or spectrum)
  - 2D solution, on-the-fly
  - Fatigue life based on the reference lug concept
  - Ongoing master thesis work




FATIGUE DESIGN PROCEDURES
(Proceedings of the 4th. I.C.A.F. Symposium)
Edited by
Prof. Dr. E. Gassner & Dr. W. Schutz
PERGAMON PRESS – OXFORD & NEW YORK – 1969

THE DEVELOPMENT OF A CALCULATION METHOD FOR THE FATIGUE STRENGTH OF LUGS AND A STUDY OF TEST RESULTS FOR LUGS OF ALUMINIUM

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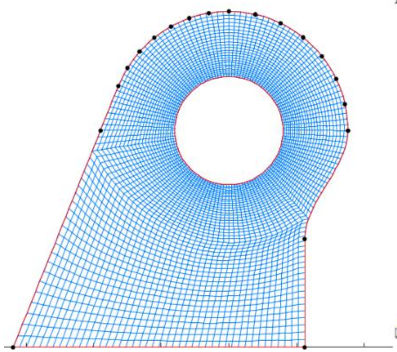
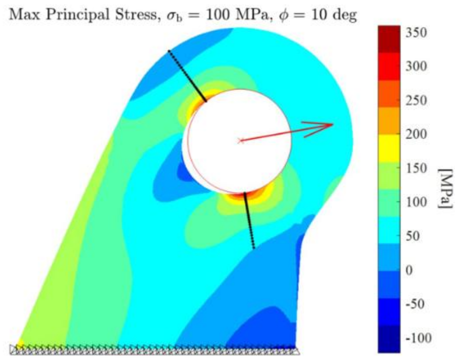
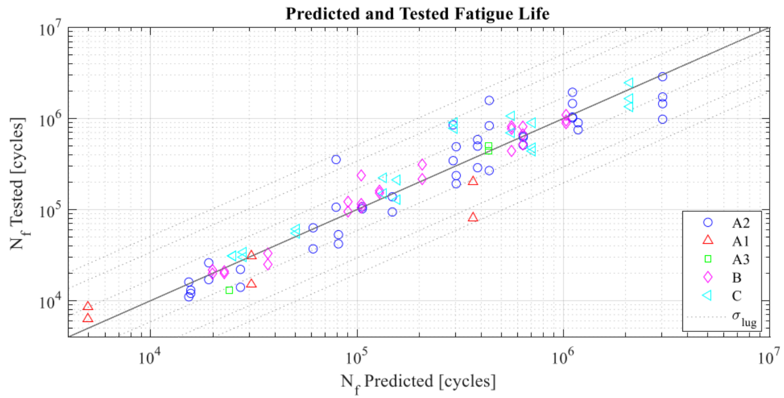
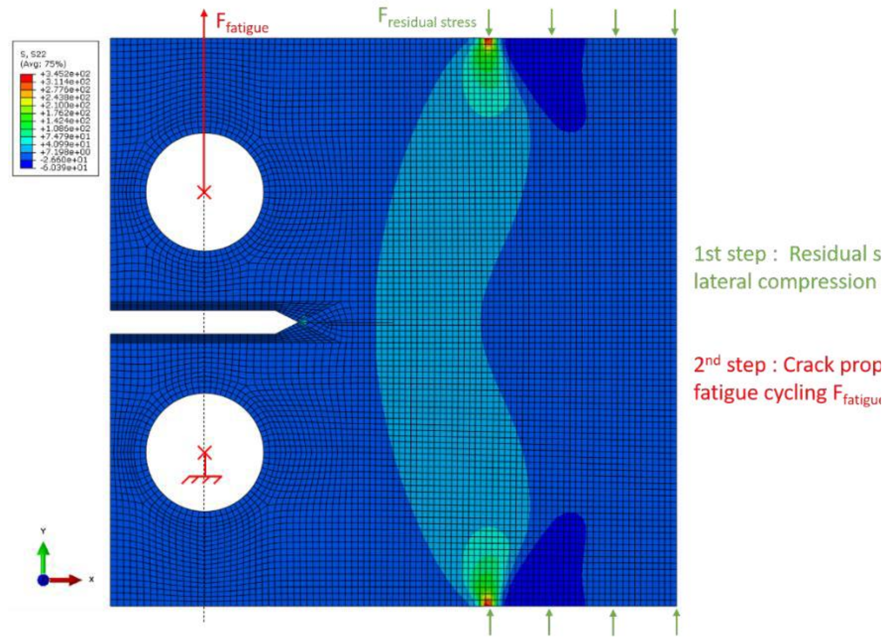


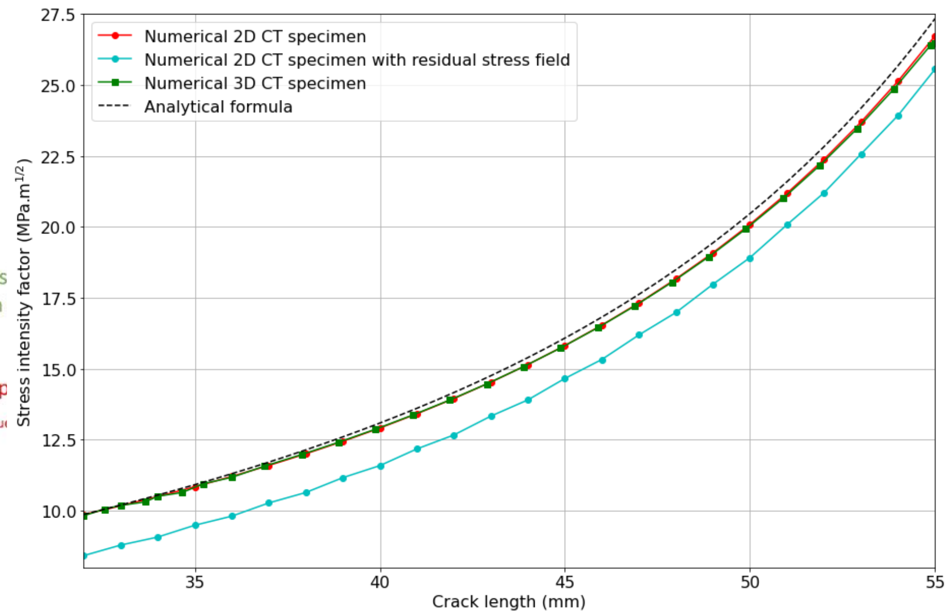




FE-simulations of fatigue crack growth

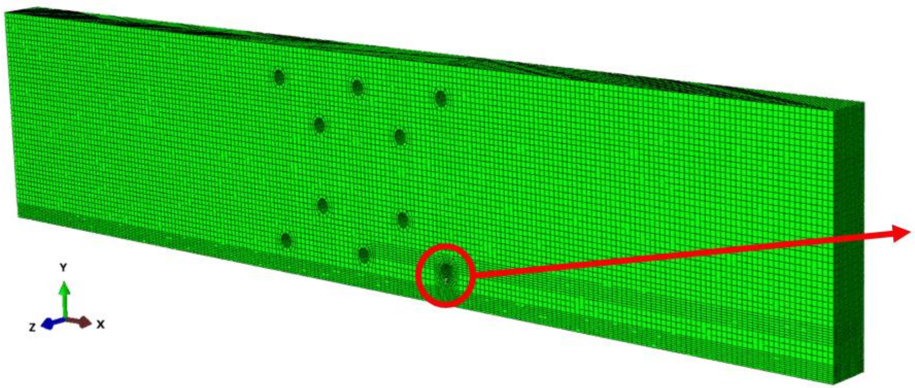
- 2D and 3D CT-specimens

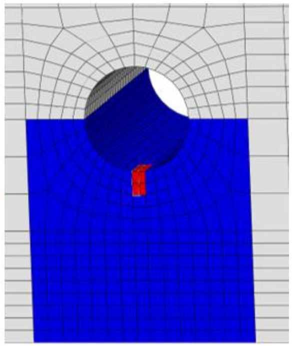


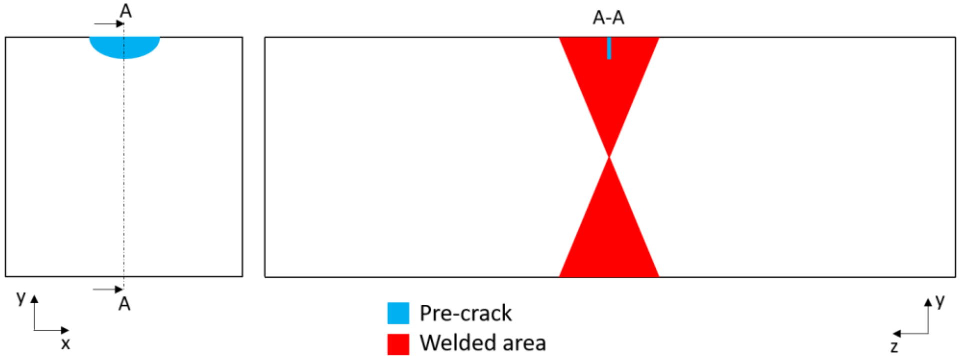


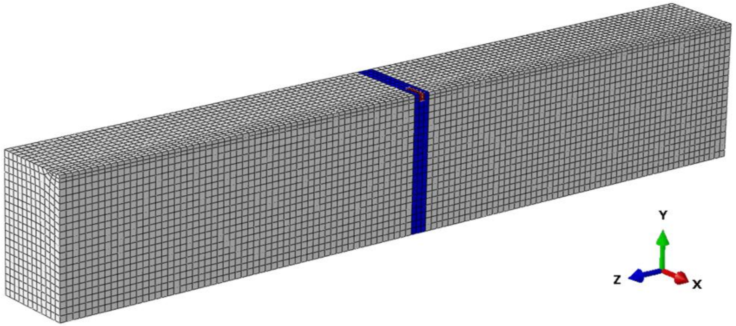
FE-simulations of fatigue crack growth

- Wing beam specimen & welded bar specimen









Methods for fatigue life and crack growth prediction

Prediction of fatigue in engineering alloys – part 2

- Develop unified probabilistic fatigue life assessment framework

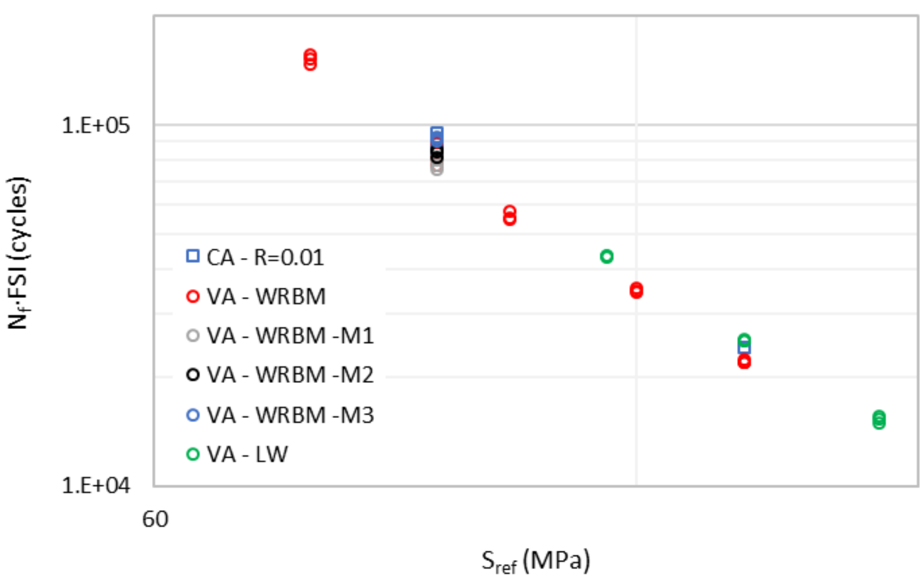
- For R>0 $$\frac{da}{dN} = C\left(\frac{\Delta G}{K_{max}}\right)^n = C\left(\frac{(1-R^2)K_{max}}{E}\right)^n$$

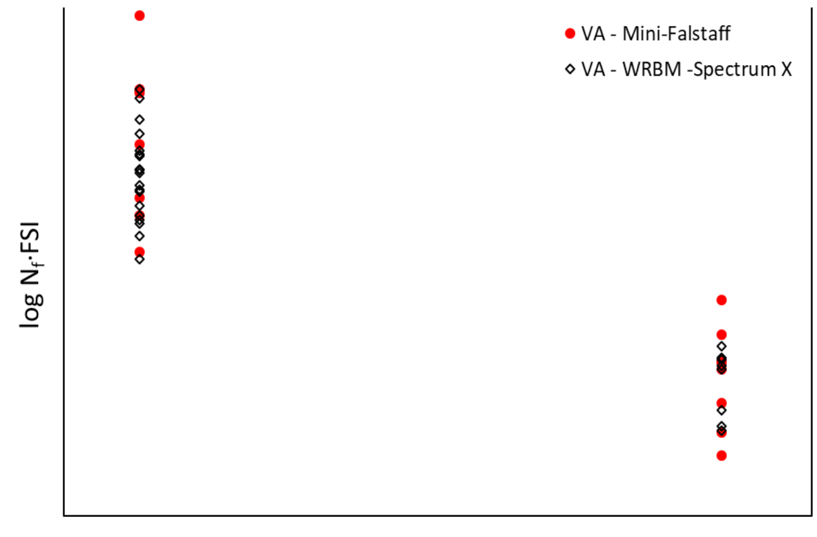
- Fatigue severity index $$FSI = \frac{1}{f}\sum_{t=1}^{f}\left|{R_t}^2 - {R_{t-1}}^2\right|^n$$
  - FSI=1 for CA loading @R=0

- Crack growth life from initial to final $$N_{CG} = \frac{C^*}{FSI} S_{MSS}^{-n}$$
    - Text
    - Text

Prediction of fatigue in engineering alloys – part 2

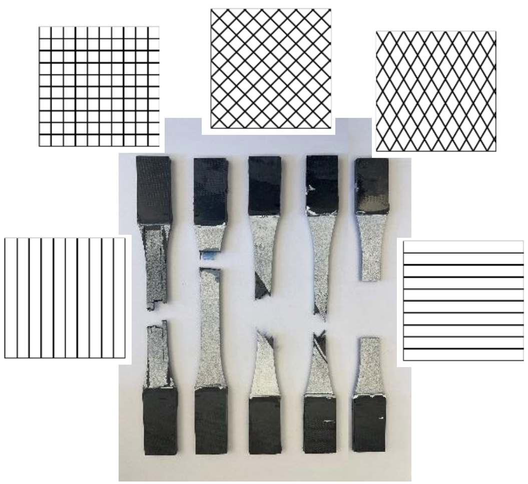
- Develop unified probabilistic fatigue life assessment framework

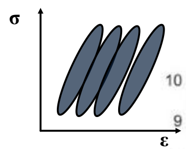


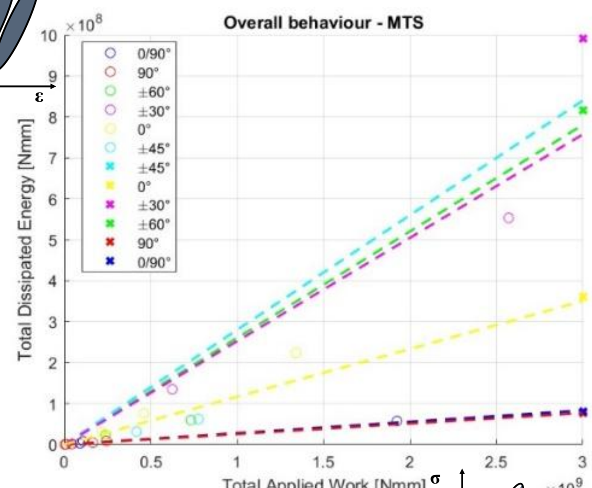


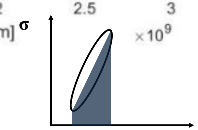
Fatigue of thermoplastic composites

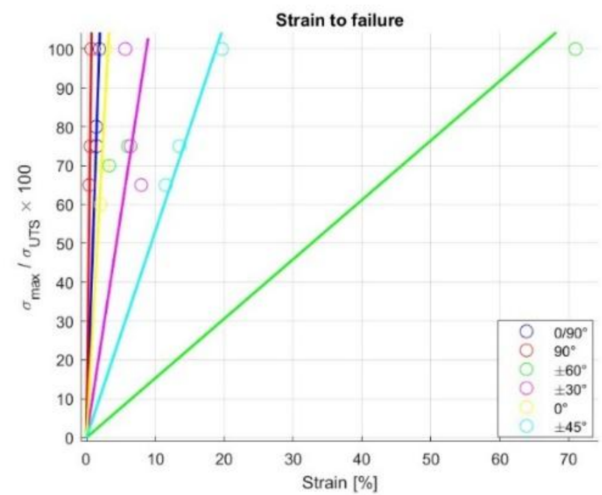
- Develop physics-based model to predict the fatigue behaviour of thermoplastic composites
- Strain energy dissipation characterized by ratio $= \frac{TDE}{W_{tot}}$









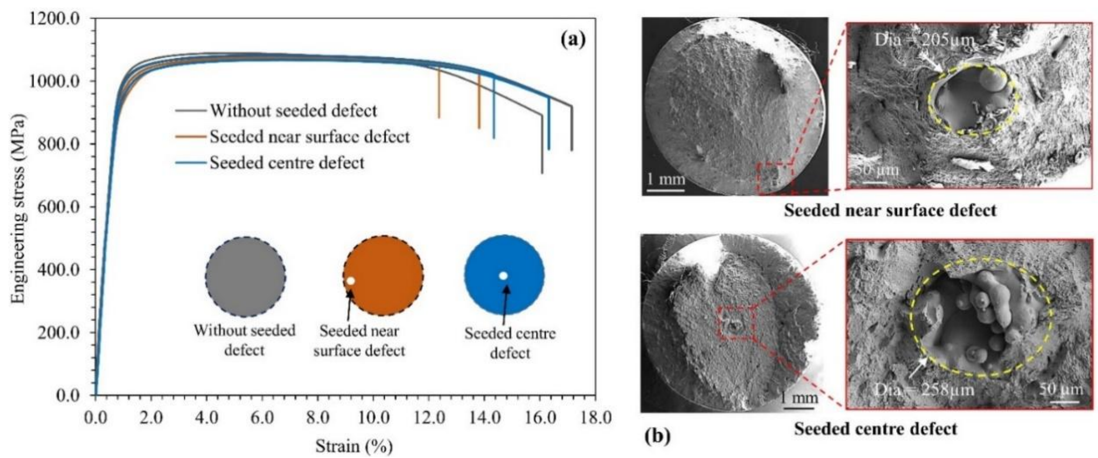


Defects tolerance & fatigue limit prediction for laser powder bed fusion Ti6Al4V- Coventry University

- Laser powder bed fusion (L-PBF) additive manufacturing (AM) of titanium alloy T6Al4V suffers from process-inherent gas porosity defects – Resulting in a large scatter in the fatigue test data due to different crack initiation sites or locations and associated mechanisms.
- Hot isostatic pressing (HIPing) can be effective in reducing the size and population of gas porosity defects, but it cannot eliminate.
- A better understanding of the criticality of defect location and size on fatigue performance is necessary for qualifying parts.
- A novel approach was taken where porosity defects were purposely seeded in the material using computer aided design (CAD) to control the L-PBF process.

Defects tolerance & fatigue limit prediction for laser powder bed fusion Ti6Al4V- Coventry University

- Effect of seeded pores on **tensile properties:**
  - The engineering stress-strain curves reveals that the presence of seeded defects had little or no influence on the yield and ultimate tensile strengths, but it caused considerable reduction in the elongation, by 26%, due to stress concentration at the seeded defects.



(a) Engineering stress vs. strain curves for samples with and without seeded porosity defects, (b) fracture surfaces showing the presence of seeded pores and the fracture path.

Defects tolerance & fatigue limit prediction for laser powder bed fusion Ti6Al4V- Coventry University

- Effect of seeded pores on **fatigue life**:
  - S-N data for the without seeded defect samples revealed that process inherent defects were the major source of crack initiation and the cause of considerable scatter in test data.

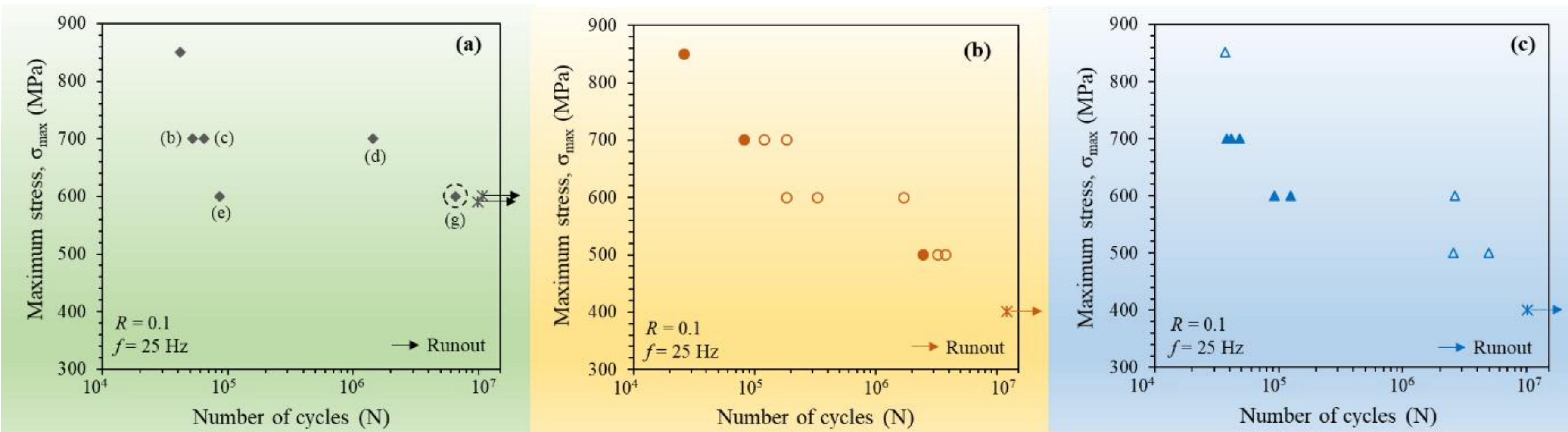


Fig. 3. S-N data for samples (a) without seeded pores (reference), (b) with seeded near-surface pores, (c) seeded internal pores. Open symbols represent crack initiation from seeded pores, solid symbols represent crack initiation from process inherent defects; encircled data points indicate crack initiation from a microscopic feature of either the α lath or α/β interface.

Coventry University 2025 UK ICAF National Review, pg 20-22

Defects tolerance & fatigue limit prediction for laser powder bed fusion Ti6Al4V - Coventry University

- Crack initiation from a lack-of-fusion defect caused 20x reduction in fatigue life compared to crack initiation from a seeded near surface pore.
- Overall, presence seeded defects caused 33% reduction in fatigue strength compared to the reference samples. Despite more than 72% of tested samples having seeded defects, only 27% of them had crack initiation from seeded defects.
- This highlights the criticality of process inherent defects and the need to eliminate them in the manufacturing process.

Coventry University 2025 UK ICAF National Review, pg 20-22

Defects tolerance & fatigue limit prediction for laser powder bed fusion Ti6Al4V - Coventry University

- **Fatigue strength limit**:
  - The modified K-T diagram obtained from the experimental results gives the infinite and finite life regions with three different limiting conditions:
    - The upper bound representing the material's intrinsic fatigue limit (defect free).
    - The lower bound representing the notch fatigue limit (Kt effect, due to gas pores in this study).
    - A transition between them by the threshold value for crack growth onset using the modified El Haddad's method.
  - This K-T diagram can be used to obtain allowable applied stress to achieve a damage tolerance design when defects are present in the material.

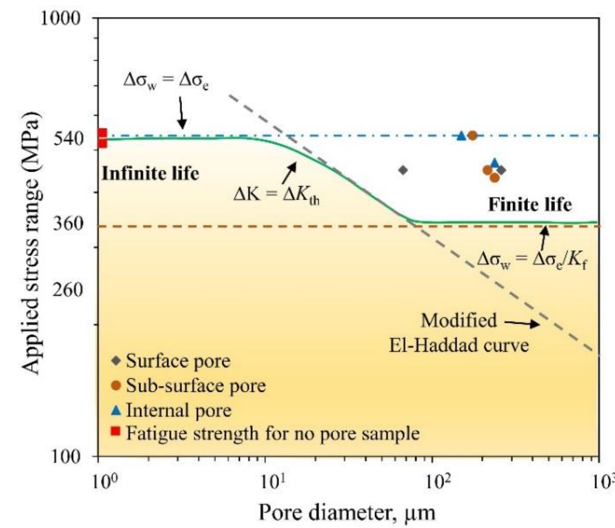


Fig. 5. K-T diagram showing the calculated fatigue strength limit curve (solid line) for L-PBF Ti64 as a function of porosity size. Symbols represent test data of this study with fatigue life greater than 106 cycles.

Fatigue failure mechanism in Al with structural repairs by the cold spray technology – Coventry University

- Study aimed to investigate the root causes for crack initiation in Al 7075 cold spray repairs and develop predictive models.
- Fatigue test was conducted on two types of specimens simulating repairs by either a groove notch or a dent notch to mimic the grinding and polishing of a corrosion pit before repairing it.

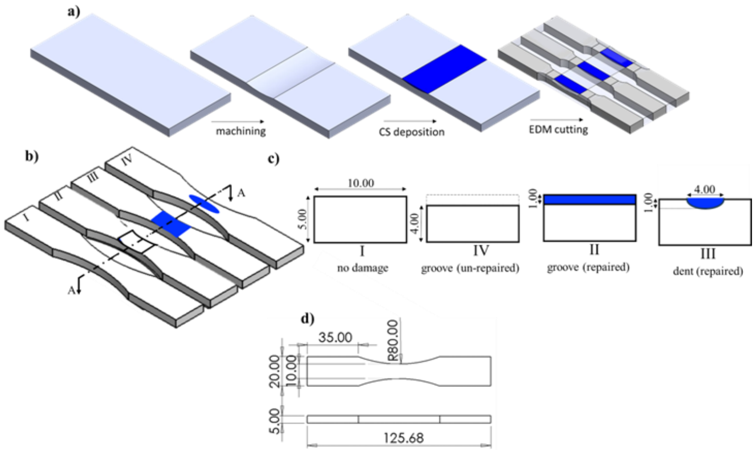


Figure 1: Sample preparation process, including the machining of a plate to introduce the artificial damage, the cold spray deposition process, and extraction of dog-bone specimens. (b) Different specimen types (from Left): wrought (undamaged), groove (damaged), groove (repaired), and dent (repaired). (c) Cross-sectional view of section A-A. (d) Fatigue test specimens.

Fatigue failure mechanism in Al with structural repairs by the cold spray technology – Coventry University

- The difference in fatigue life between the repaired & undamaged baseline specimens was more pronounced at higher stress levels due to the dominance of rapid growth of short cracks initiated from the "craters".

- In contrast, at lower stress levels, fatigue life was dominated by the crack initiation phase resulting in smaller difference with the undamaged baseline specimens.

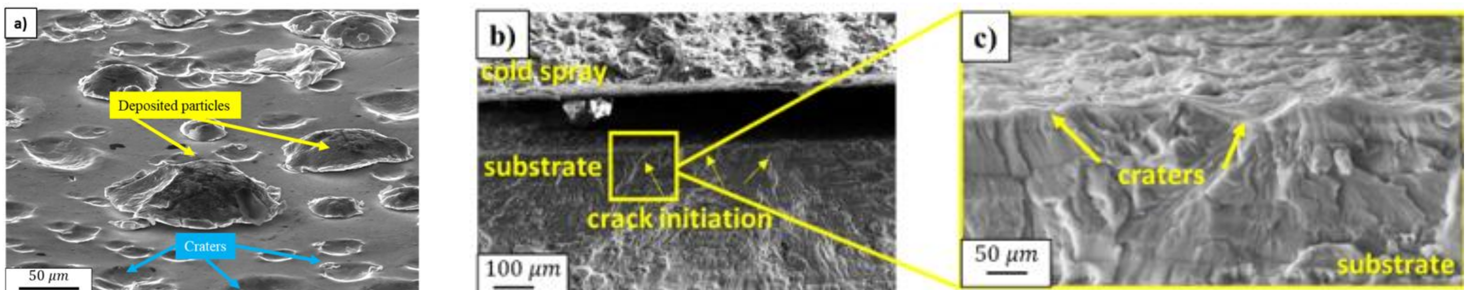


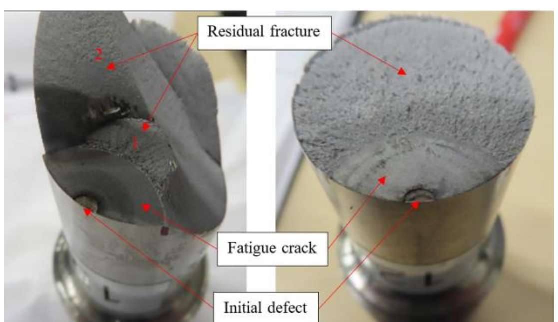
Figure 2: SEM images (a) the swipe test coupon showing the deposited particles and particle impact deformation called "craters" in this report; (b, c) fracture surfaces of repair interface showing crack initiation from the craters.

Modelling through EIFS and Weibull distributions

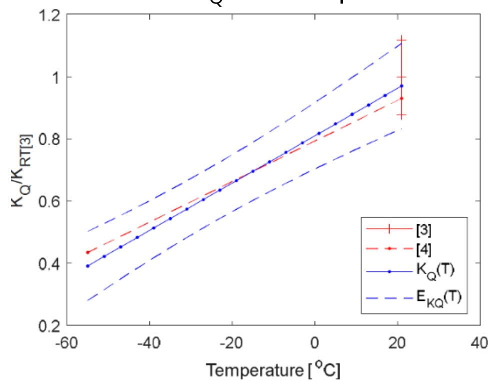
Fracture toughness testing of steel PH13-8Mo (Extra High Toughness) using round bar specimens

- Standard test (CT-specimen, ASTM E399-22)
  - Large, very expensive, difficult to machine and to test
- Non-standard test (Bar-specimen, semi-elliptical crack)
  - Small, relatively cheap, easy to machine and to test
  - Closer to applications (bolts and rods)
  - Requires SIF solution (FEM) and disp. measurements

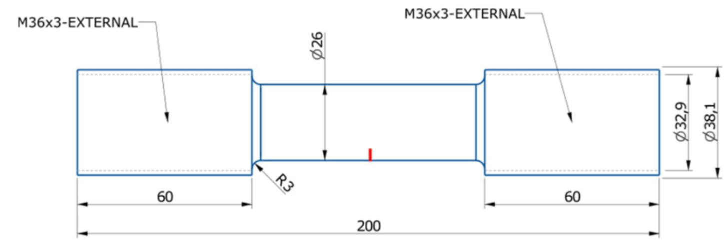
Two failure modes



K_Q afo temp



Bar-specimen

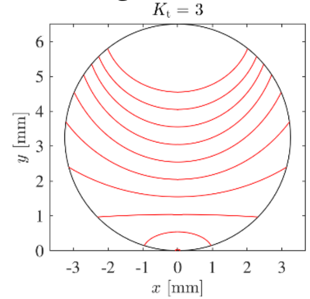


[3] MMPDS -10, Chapter 2 – Steel Alloys, FAA 2015.
[4] ATI Technical Data Sheet, 13-8 Supertough Alloy, Version 1, 2001.

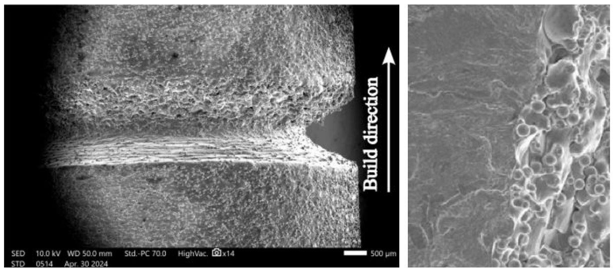
Equivalent initial damage sizes (EIDS) for PBF-LB Ti-6Al-4V notched geometries

- Crack growth model
  - Notched bar specimens
  - EIDS $a_i = g(N_f, \sigma_a, K_t, R, \ldots)$
- Weibull distr.
- Surface roughness
  - Mean R_v good estimate of median EIDS

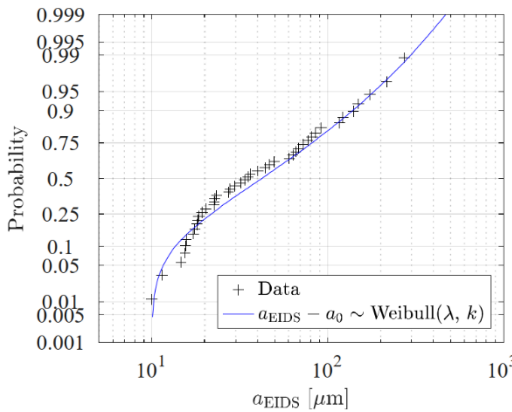
Crack growth model



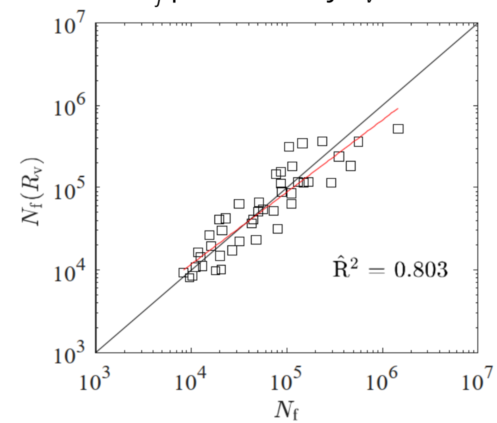
Test specimens



EIDS distribution



N_f predicted by R_v



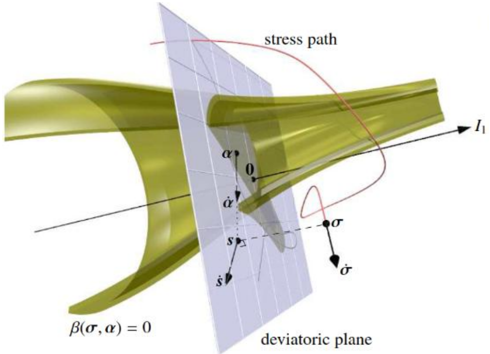
Z. Kapidžić, S. B. Lindström, J. Moverare, T. Lindström, C-J. Thore, D. Leidermark, M. Franke. Equivalent initial damage sizes for PBF-LB Ti-6Al-4V notched geometries, International Journal of Fatigue, 194, 108843, 2025.

Multiaxial loading and load sequences

Continuous-time, multiaxial high-cycle fatigue model (OSR)

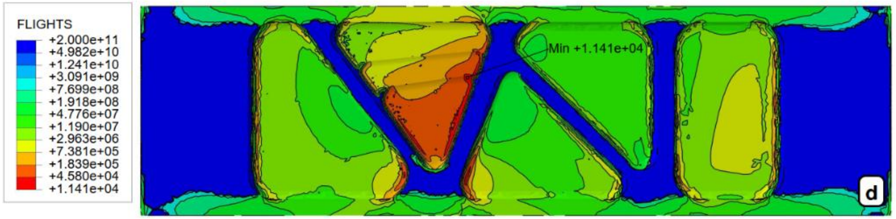
- OSR (Ottosen-Stenström-Ristinmaa) model [1]
  - General stress history + fatigue surface
  - No cycle counting, notch and surface effects, scatter
  - FE-implementation
  - AA 7050 [2] and AM PBF-LB Ti6Al4V [3]

OSR model



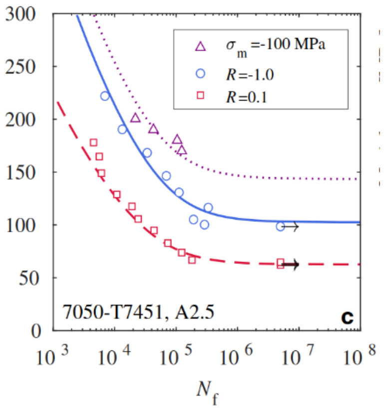
$$\dot{\alpha} = (s - \alpha)CH(\beta)\langle\dot{\beta}\rangle$$
$$\dot{D} = Ke^{L\beta}H(\beta)\langle\dot{\beta}\rangle$$

FE-implementation example



Fatigue crack

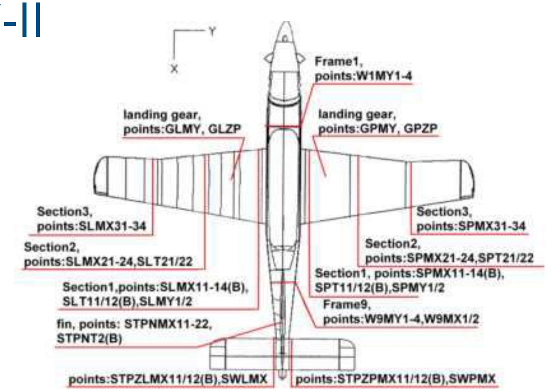
Fitting to CA test data



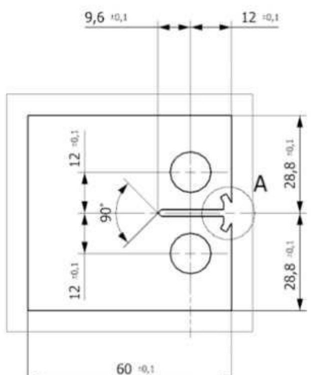
[1] N. S. Ottosen, R. Stenström, and M. Ristinmaa. Continuum approach to high-cycle fatigue modeling, Int. J. Fatigue, 30(6):996–1006, 2008.
[2] S. B. Lindström et.al. Service-life assessment of aircraft integral structures based on incremental fatigue damage modeling, Int. J. Fatigue, 172:107600, 2023.
[3] S. B. Lindström et. al. Fatigue life prediction for PBF-LB Ti6Al4V with as-built surface under nonproportional loads using an incremental fatigue damage model, Int. J. Fatigue, 193, 108777, 2025.

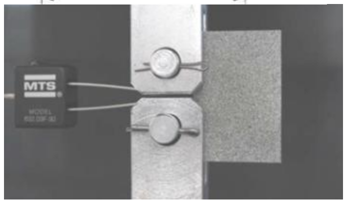
Crack Growth Tests for Load Sequences Developed using Different Flight Parameters

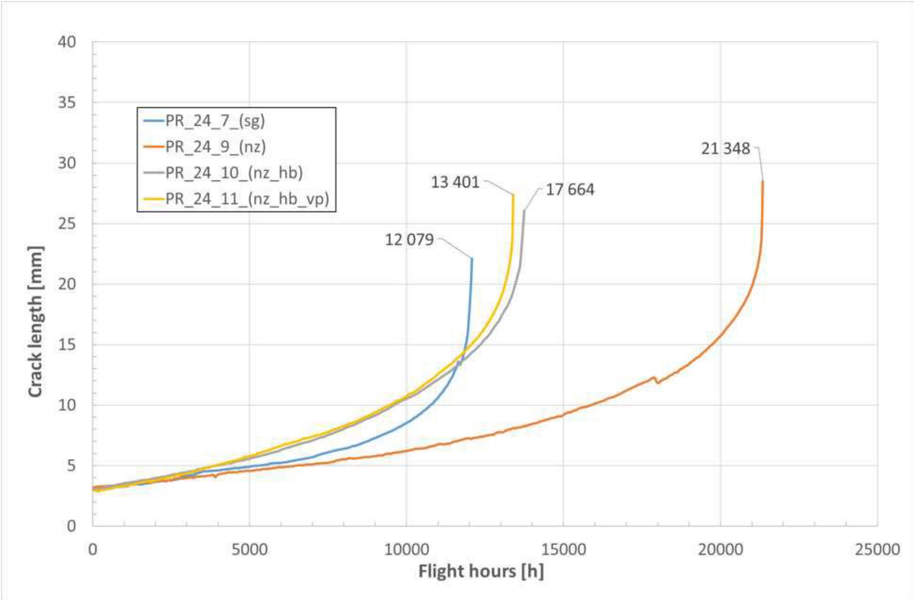
- OLM Service Life Extension Program of PZL-130 TC-II
  - Flight data acquisition and initial analysis
  - Load sequences definition



- Test preparation and execution



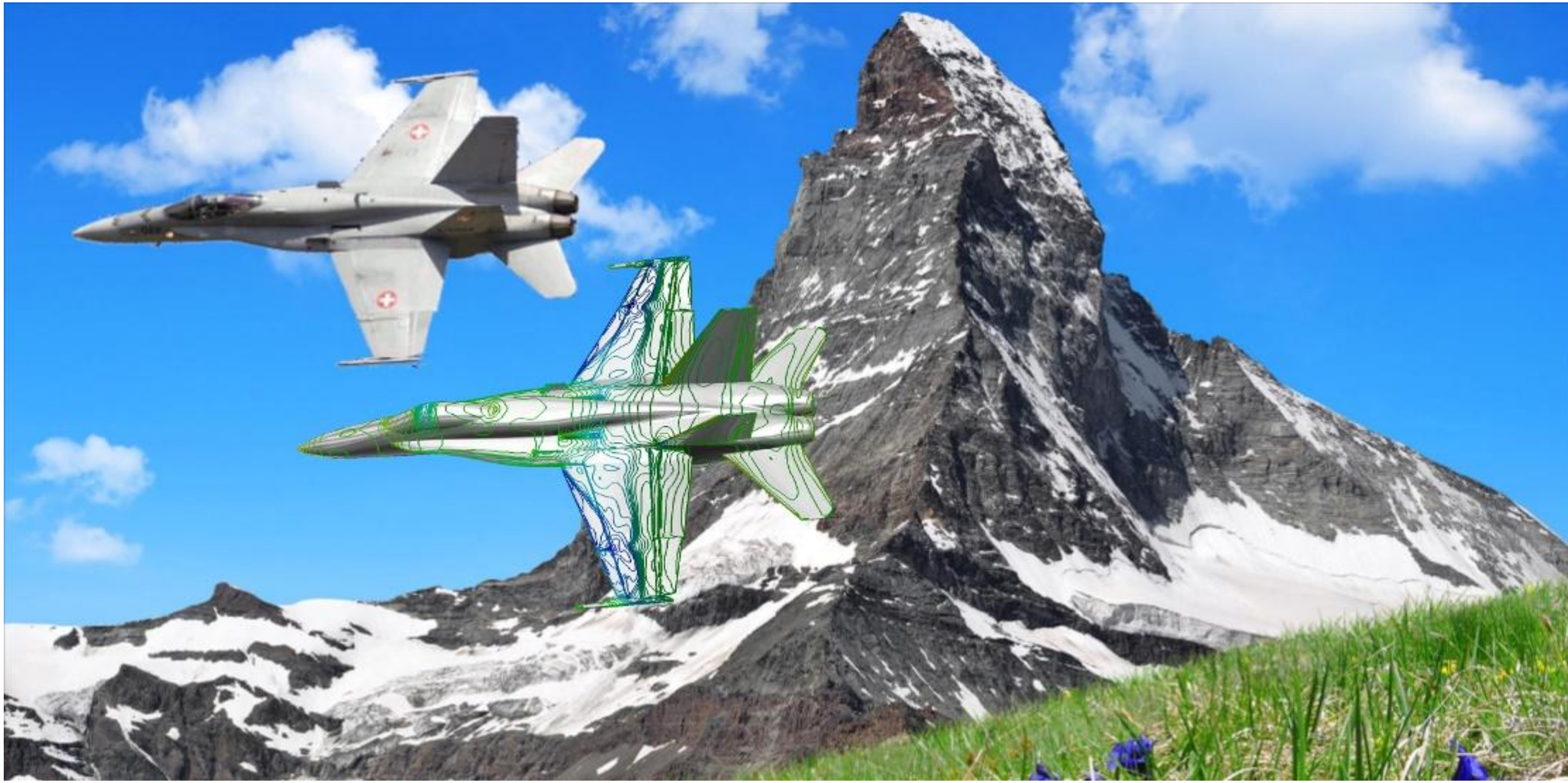




Fluid-Structure Interaction for aircraft life prediction

ICAF
International Committee on Aeronautical Fatigue and Structural Integrity

20 years of Finnish-Swiss collaboration



ICAF
International Committee on Aeronautical Fatigue and Structural Integrity

20 years of Finnish-Swiss collaboration

- Since more than 20 years Switzerland and Finland have been collaborating in loads development using Computational Fluid Dynamics (CFD)[1]
- The objective of the CFD simulations is to compute the aerodynamic loads on different components of the F/A-18 Hornet aircraft
- Switzerland is using the code from CFS Engineering[2] whereas Finland is using the FINFLO® code[1] at Elomatic Ltd and Patria Aviation Ltd
- Recently, Fluid-Structure Interaction (FSI) methods (FINFLO-MSC Nastran coupling via MpCCI software[3]) were developed in within the collaboration projects.

[1] FIN ICAF National Review 2025
[2] https://cfse.ch/about/collaborations/
[3] https://www.mpcci.de/en/mpcci-software.html

Fluid-Structure Interaction for aircraft life prediction

[1] https://www.elomatic.com/technology-solutions/fluid-dynamics/computational-fluid-dynamics-in-aerodynamic-and-light-structures/finflo/

Fluid-Structure Interaction for aircraft life prediction

- Fluid-Structure Interaction (FSI) refers to the multidisciplinary area of study that focuses on the mutual interaction of a fluid flow with a deformable solid structure.
- In FSI, the behavior of the fluid affects the structure (by pressure), and the structural response, in turn, influences the fluid flow (by changing the aircraft geometry). This coupling makes FSI problems nonlinear and complex.
- The deformed geometry creates a need to modify the computational grid.
- FSI problems are focused on transient (time-dependent) events but are equally important in determining loads at steady-state situations.

Fluid-Structure Interaction for aircraft life prediction

- In FSI CFD and FEA are coupled as a simulation environment for life predictions of the F/A-18 Hornet structures
- Separate solvers for fluid and structural domains, coupled by MpCCI
- Workflow 1(2)
  - CFD
    - Simulate flow environment
    - Extract surface force distribution
  - FEA
    - Apply surface forces as input
    - Evaluate a new deformed geometry. If not converged, return to CFD stage.
    - Extract stress/strain distribution for fatigue analysis.

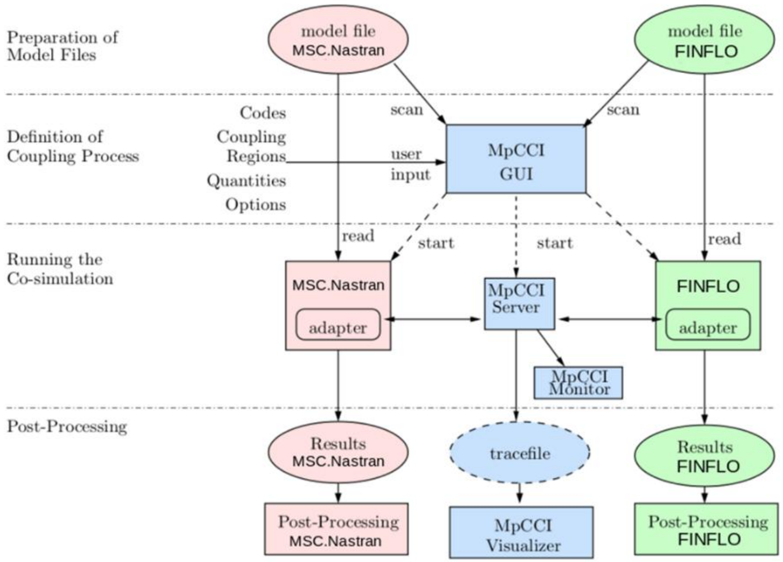


Figure 1. *Coupling between the MSC Nastran and FINFLO codes via the MpCCI software. Figure courtesy of Elomatic Ltd.* [1]

[1] FIN ICAF National Review 2023

Fluid-Structure Interaction for aircraft life prediction

- Workflow 2(2)
  - Fatigue Analysis
    - Crack initiation: strain-life
    - Crack propagation: fracture mechanics
  - Life estimation
    - Determine fatigue life at critical locations
    - Validate results against measurement or inspection data.

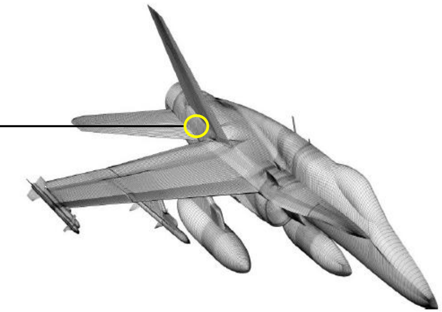


Figure 1. Surface mesh of the F/A-18 fighter.

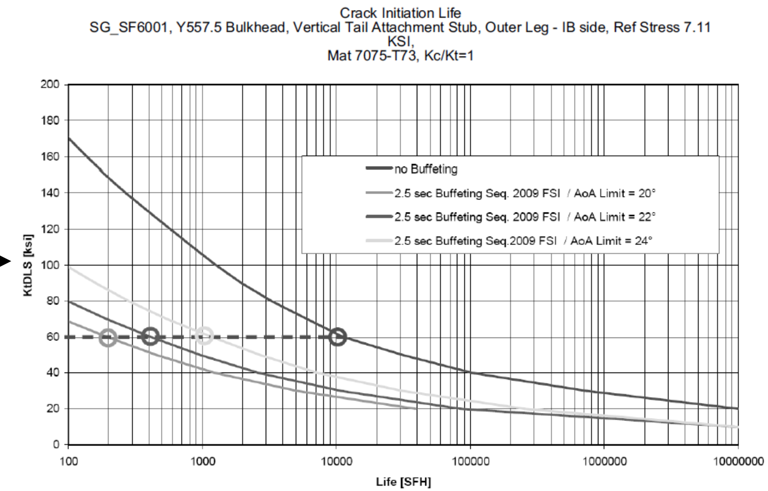


Figure 14. Kt DLS curves for different mixed spectra.

Figure 16: HARV flight test (left) and FINFLO simulation streaklines (right) at constant flight path with α = 30° and Ma = 0.2755. Figure courtesy of Elomatic Ltd.

[1] Guillaume, M., Gehri, A., Stephani, P., Vos, J. and Mandanis, G. (2011). "F/A-18 vertical tail buffeting calculation using unsteady fluid structure interaction", The Aeronautical Journal, 115(1167), pp. 285–294. doi:10.1017/S0001924000005777.

[2] Guillaume, M., Gehri, A., Stephani, P., Vos, J., Siikonen, T., Salminen, E. and Mandanis, G. (2012). Swiss/Finnish computational fluid dynamics simulation on the F/A-18. 28th Congress of the International Council of the Aeronautical Sciences, ICAS2012. 23 - 28 September, 2012, Brisbane, Australia.

[3] FIN ICAF National Review 2025

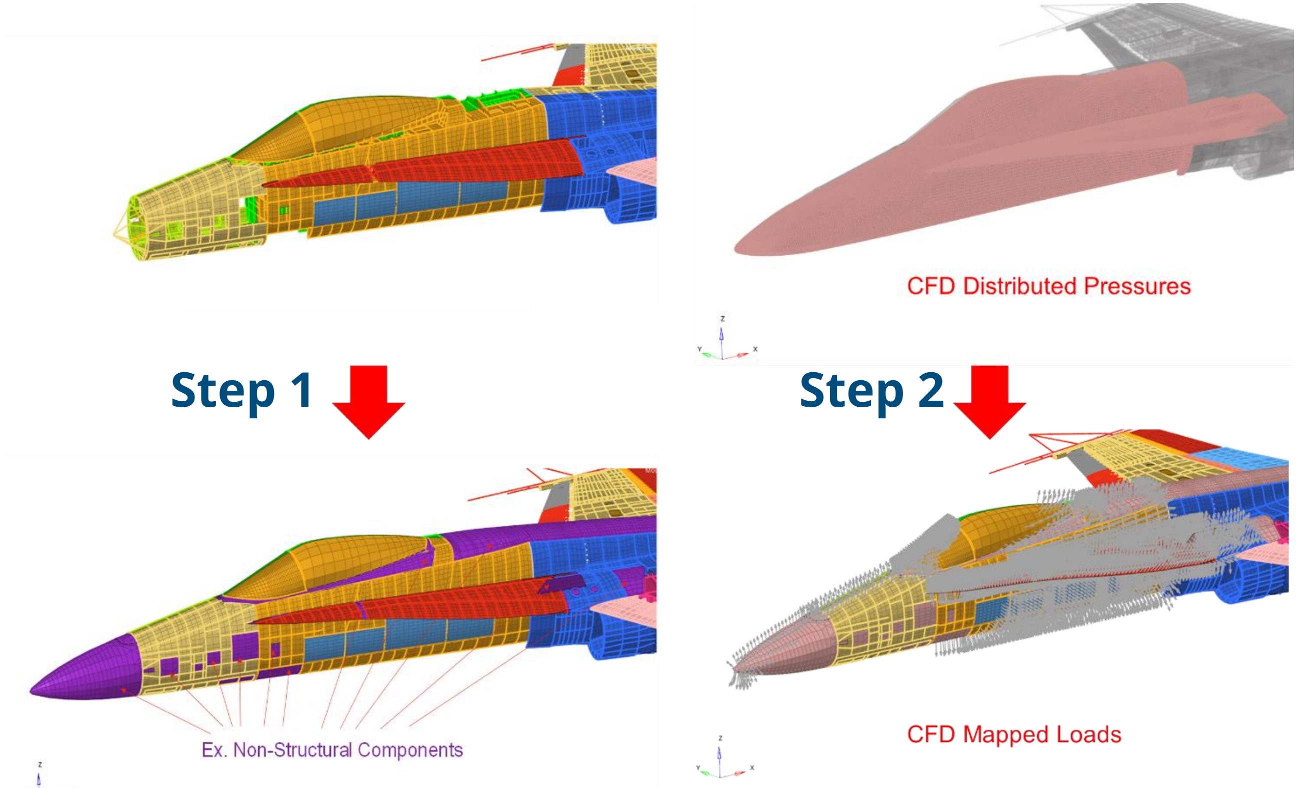
Example for the Swiss F/A-18

- To assess the structural life of Swiss Leading-Edge Extension (LEX), loads have to be simulated using CFD calculation to define the aerodynamic loads.
- Over one hundred CFD cases were simulated intended to cover the full flight envelope in terms of AoA and Dynamic incompressible Pressure (DYNI). Interpolation of these simulated cases was used to calculate all conditions found in the Swiss Baseline Operational Spectrum (BOS).
- The resulting CFD pressure distributions were mapped onto the Swiss structural Finite Element (FE) model to compute the LEX component interface loads and internal reaction loads at the LEX-fuselage connections.

[1] SWISS ICAF National Review 2025

Example for the Swiss F/A-18

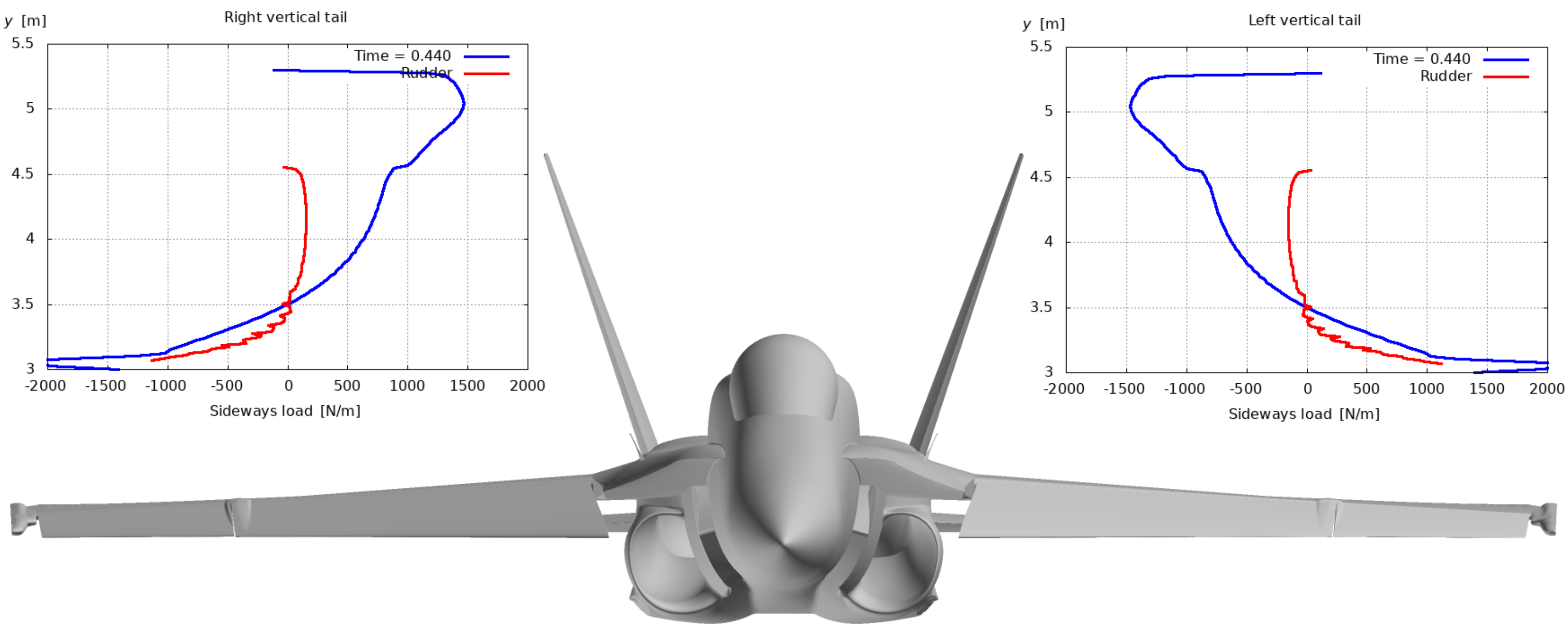
- This procedure required the creation of non-structural components within the FE model to facilitate accurate mapping of the CFD results.



[1] SWISS ICAF National Review 2025

Example for the Finnish F/A-18 Vertical Tail Buffeting

- FSI simulation, dt = 0.001 s, vertical-tail load distributions



Questions?

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