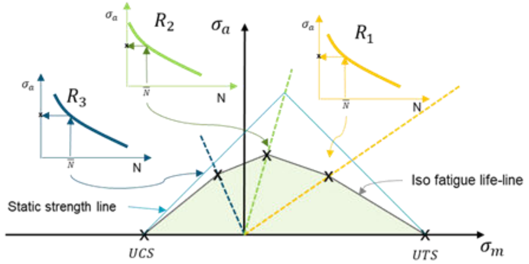
Composites material modelling with Digimat and Marc: fatigue life and failure

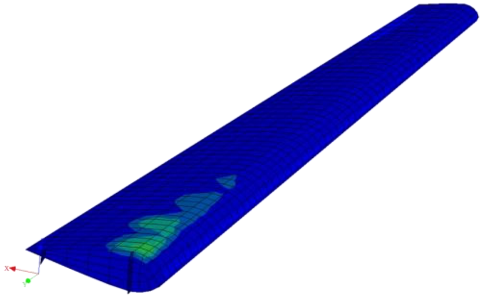
FINAL DISSEMINATION EVENT, NLR Amsterdam (NL), December 17th

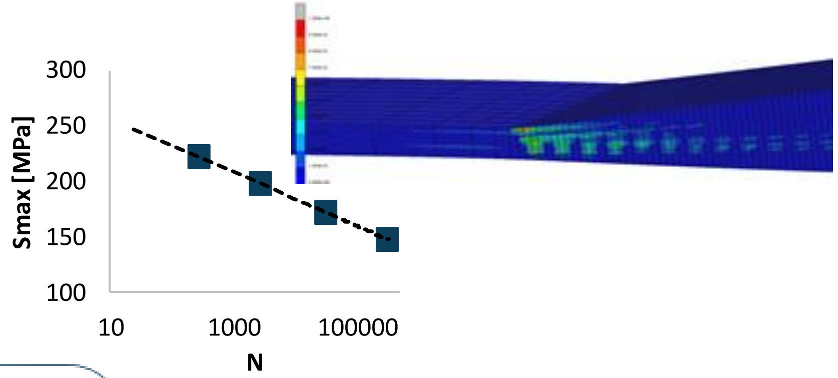
Fabio Malgioglio (HMI), Melle Gruppelaar (HMI)

Funded by
the European Union

Summary







- Chapter 1 — Hexagon Digital Materials at glance
- Chapter 2 — Fatigue modelling of CFRP with Digimat
- Chapter 3 — Example 1: Laminate selection exercise with Digimat
- Chapter 4 — Example 2: Fatigue life prediction in a composite wing
- Chapter 5 — D-Standart case study (Digimat)
- Chapter 6 — Introduction to nonlinear FEA with Marc
- Chapter 7 — Composites modelling with Marc: fatigue failure (fLaRC)
- Chapter 8 — D-Standart case study (Marc)
- Chapter 9 — Summary and outlook
- Chapter 10 — HMI AI approach

Chapter 1

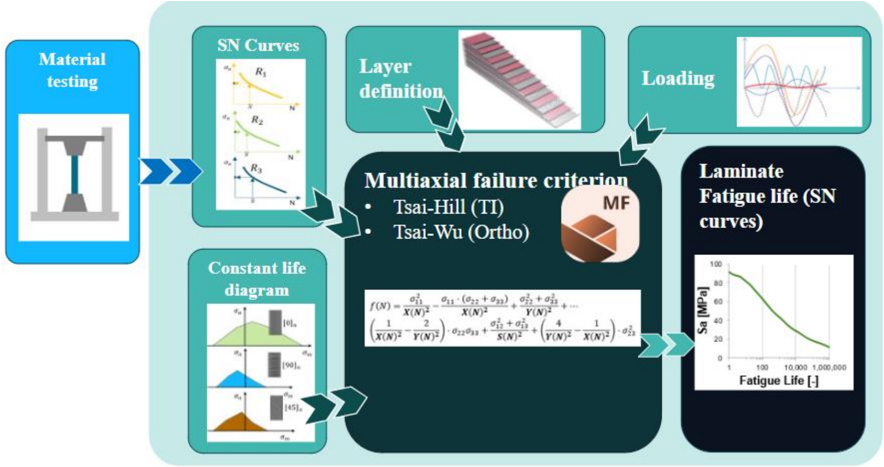
Hexagon MI approach

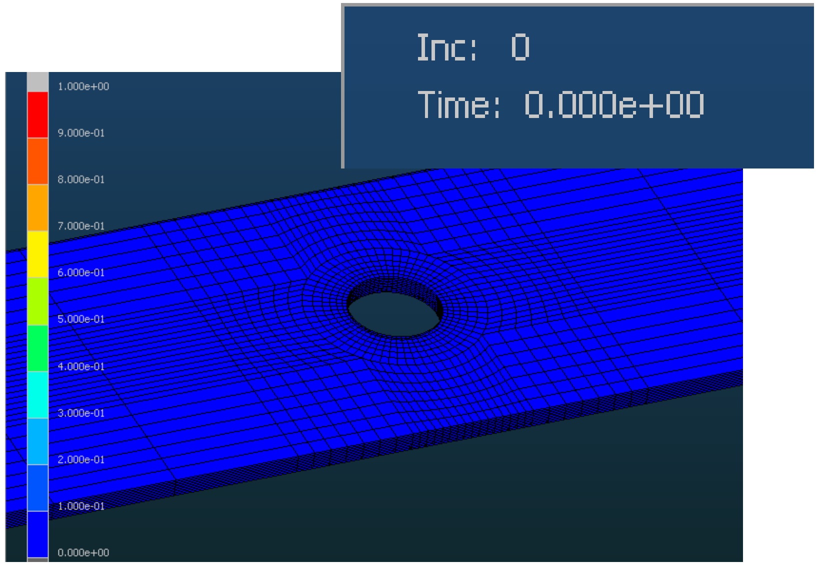
Fatigue using Digimat and Marc

Hexagon MI approaches to fatigue of composites

- **Digimat**:
  - Intra-laminar fatigue for UD composites, it predicts failure initiation in the plies.
  - Based on limited experimental data (S-N curves).
  - Suitable for fast assessment of fatigue performance of composite components and designs.

- **Marc**:
  - Detailed modelling of fatigue using progressive failure and damage models.
  - Delamination and intra-laminar fatigue.
  - Crack growth with Paris Law (short cycle / high cycle fatigue).
  - Suitable for detailed analyses of damage onset and propagation in components and designs.





01

Hexagon Digital Materials at glance

Brief introduction to Digimat

Hexagon Digital Materials at glance

Hexagon Digital Materials at glance

02

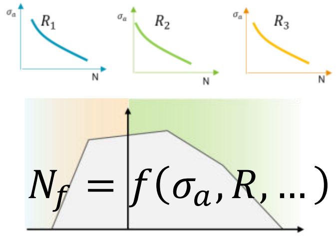
Fatigue modelling of CFRP with Digimat

Introduction to Digimat intralaminar fatigue model

Fatigue modelling of CFRP with Digimat

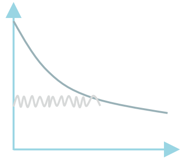
Classification of available modelling approaches

- **Fatigue life models**
  - Predict fatigue life (N_f)
  - Based on SN curves and/or CLD
  - Suitable for fast prediction of fatigue life in a structure
  - Present some limitations in accuracy (e.g., damage evolution not accounted for)

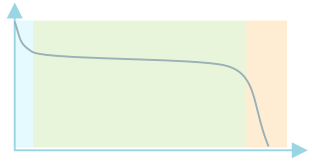


Digimat

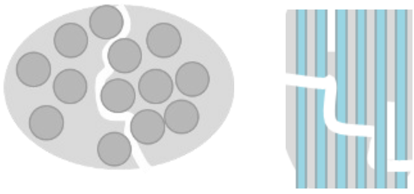
- **Residual strength**
  - Residual strength (σ_{Res}) after the material was loaded in fatigue
  - Phenomenological models, based on SN curves and CLDs



- **Residual stiffness**
  - Stiffness evolution is predicted by means of fatigue damage evolution laws (dD_i/dN)
  - Stiffness is predicted through whole fatigue life of the part, potentially allowing stress redistribution and accurate strains
  - Demanding in terms of simulation time and characterization from testing



- **Mechanistic models**
  - Typically, micro/meso models
  - Actual failure phenomena are modelled
  - Models can be either simplistic, or be computationally demanding

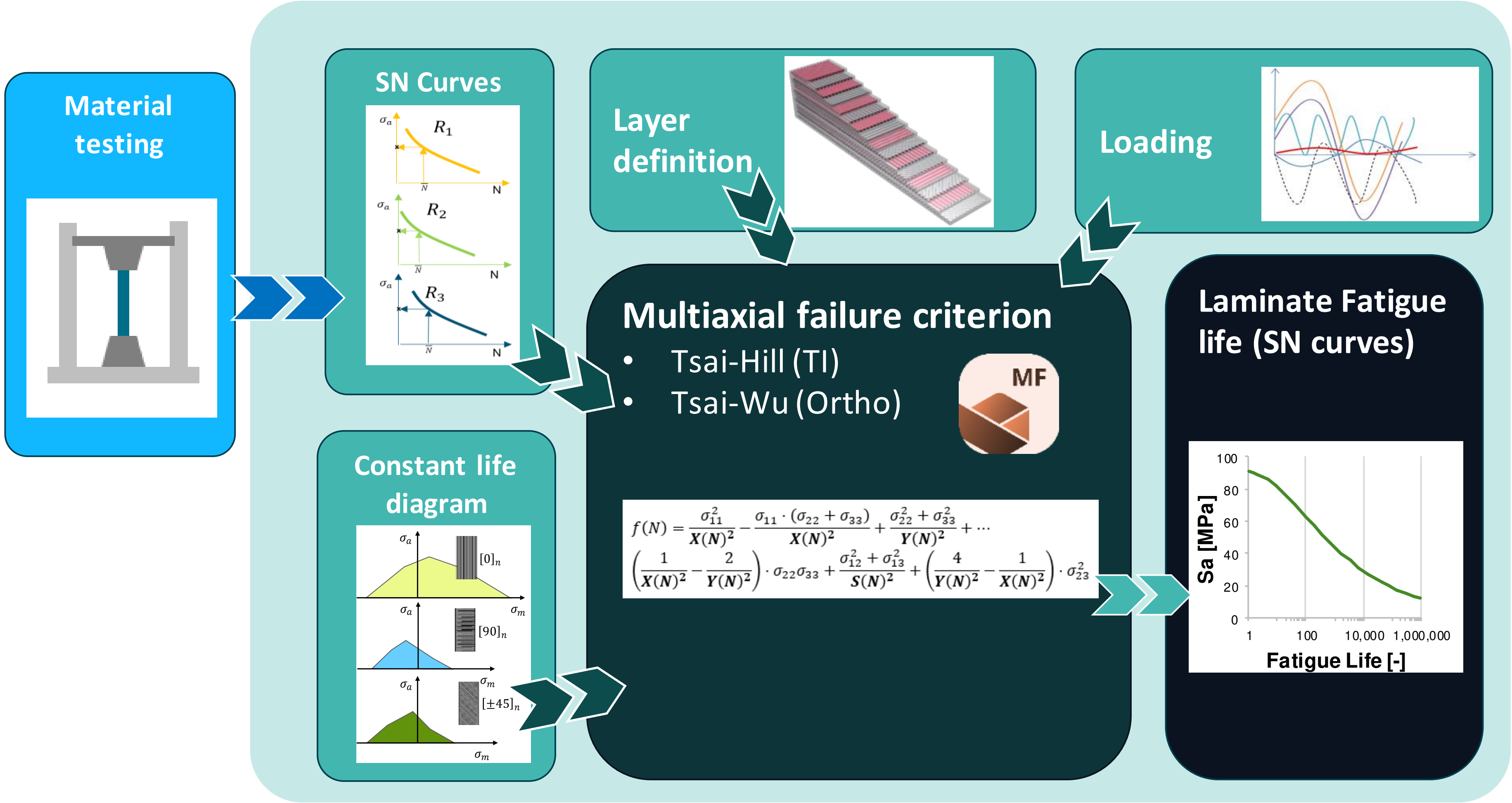


(Classification “borrowed” from Sevenois and Van Paepegem, 2015)

Fatigue modelling of CFRP with Digimat

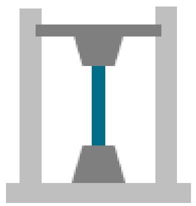
Digimat fatigue model

- **Advantages:**
  - Efficient
  - Lamina based
  - It works for multidirectional loads
- **Limitations:**
  - UD materials
  - No progressive damage
  - No delamination



Material testing and characterization

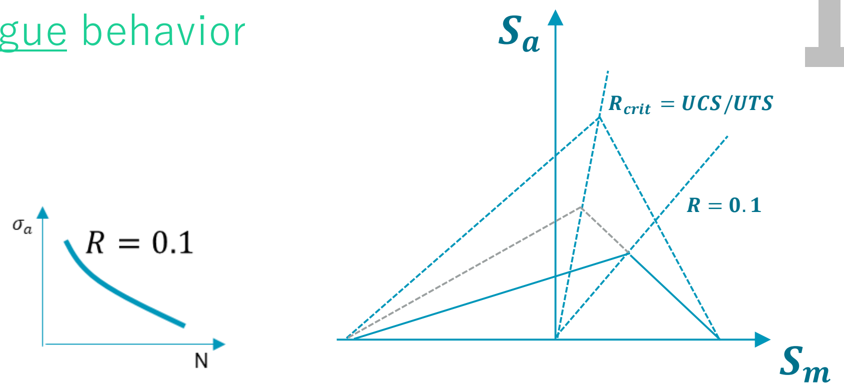
Recommended test campaign for identification of fatigue behavior



- **Minimal testing campaign:**
  - Limited available data / limited resources
  - Assumptions possible in modelling

Test type	Off-axis angles	Suggested R-ratio	# of rep.
T-T fatigue	• $[0]_n$ • $[90]_n$ • $[\pm 45]_n$	$R = 0.1$	8 – 10

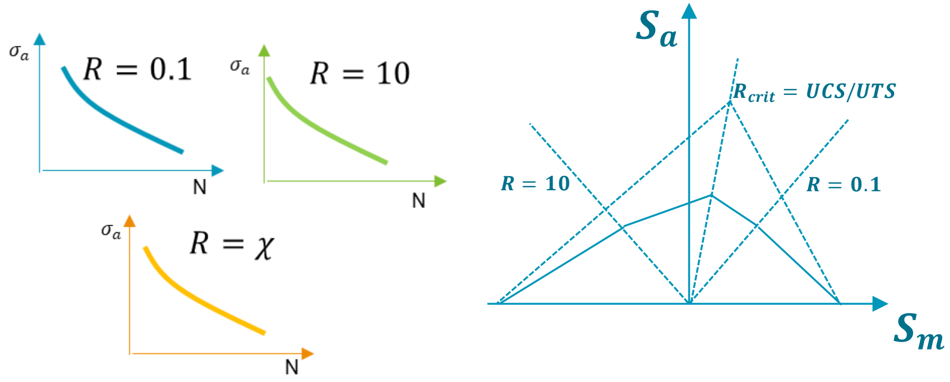
~24 – 30 individual fatigue tests



- **Optimal testing campaign:**
  - Access to complete experimental dataset
  - Lifetime predicted for wide range of R-ratios with high accuracy

Test type	Off-axis angles	Suggested R-ratio	# of rep.
T-T fatigue	• $[0]_n$ • $[90]_n$ • $[\pm 45]_n$	$R = 0.1$	8 – 15
C-C fatigue	• $[0]_n$ • $[90]_n$ • $[\pm 45]_n$	$R = 10$	8 – 15
T-C fatigue	• $[0]_n$ • $[90]_n$ • $[\pm 45]_n$	$R = \chi$	8 – 15

~72 – 135 individual fatigue tests



$$\chi = \frac{UCS}{UTS}$$

03

Example 1:

Laminate selection exercise with Digimat

Intralaminar Fatigue Modeling of Continuous Fiber-reinforced Plastics with Digimat: From Material Parameter Identification to Structural Applications

Fabio Malgioglio[1], Pierre-Yves Lavertu[1], Gourab Ghosh[1], and Marieme El Ghezal[1]

[1] Hexagon Manufacturing Intelligence, Design & Engineering business unit, Mont St. Guibert, Belgium
fabio.malgioglio@hexagon.com

Abstract. Continuous fiber-reinforced plastics (CFRPs) are extensively utilized in fatigue-critical engineering applications, such as wind turbine blades, automotive structures, and aerospace components. Accurate fatigue modeling is crucial for evaluating the durability of composite structures during the design phase. However, fatigue modeling presents significant challenges, including i) modeling complexity, ii) complex material parameter identification, and iii) high computational costs. To address these challenges, an efficient lamina-based fatigue failure

Presented at the American Society for composites 40th annual technical conference:

“**Intralaminar Fatigue Modeling of Continuous Fiber-reinforced Plastics with Digimat: From Material Parameter Identification to Structural Applications**”

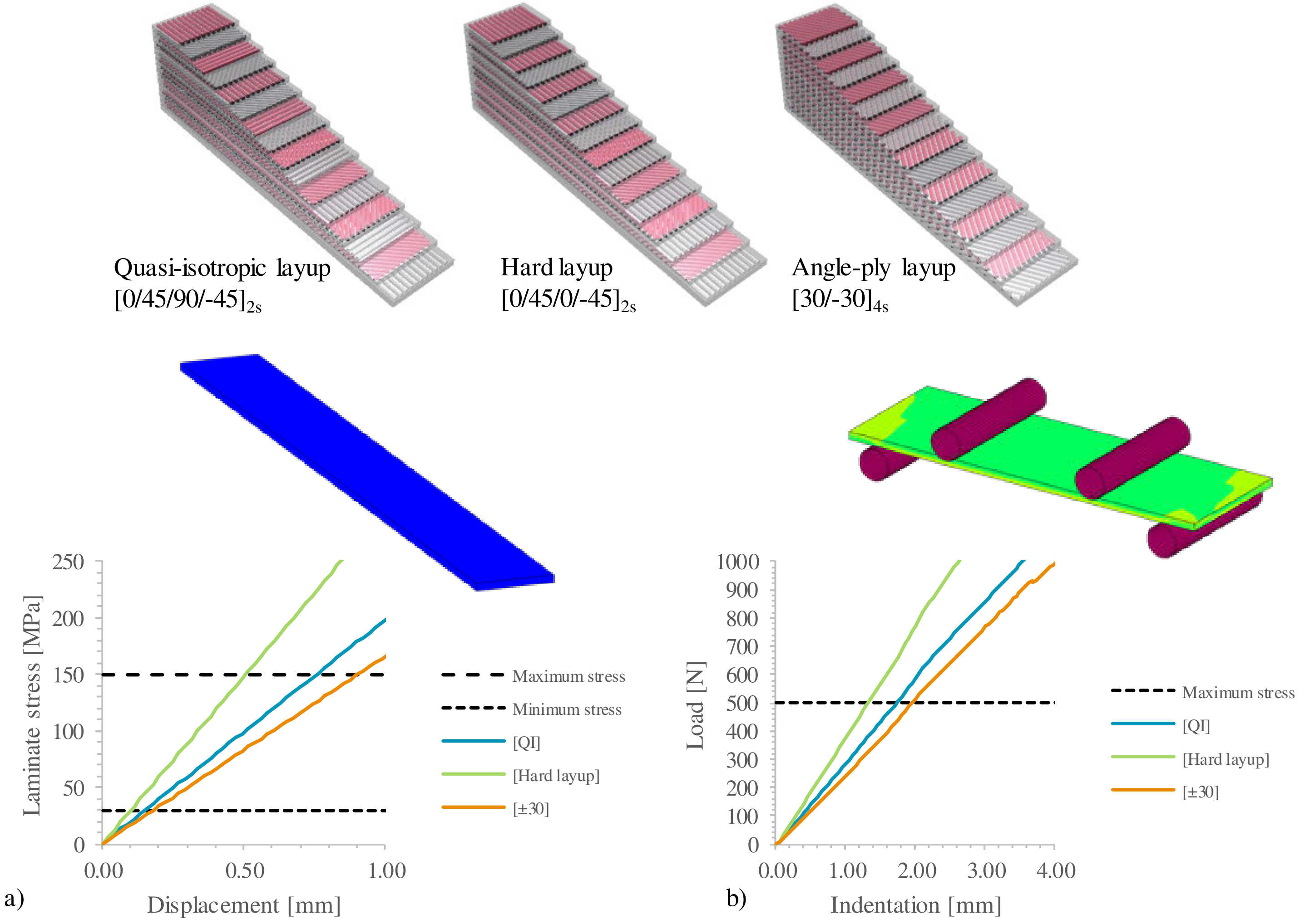
to be published in “Proceedings of the American Society for Composites 40th Technical Conference, 2025”

Laminate selection exercise with Digimat

Definition

- Goal of the exercise:
  - Rank different laminates under fatigue loading
- 3 laminates: [QI], [Hard layup], [± 30]
  - Same thickness (16 plies)
- 2 load cases:
  a) Tension-tension fatigue
  - Load between $30\ N/mm^2$ and $150\ N/mm^2$
  - Constant amplitude

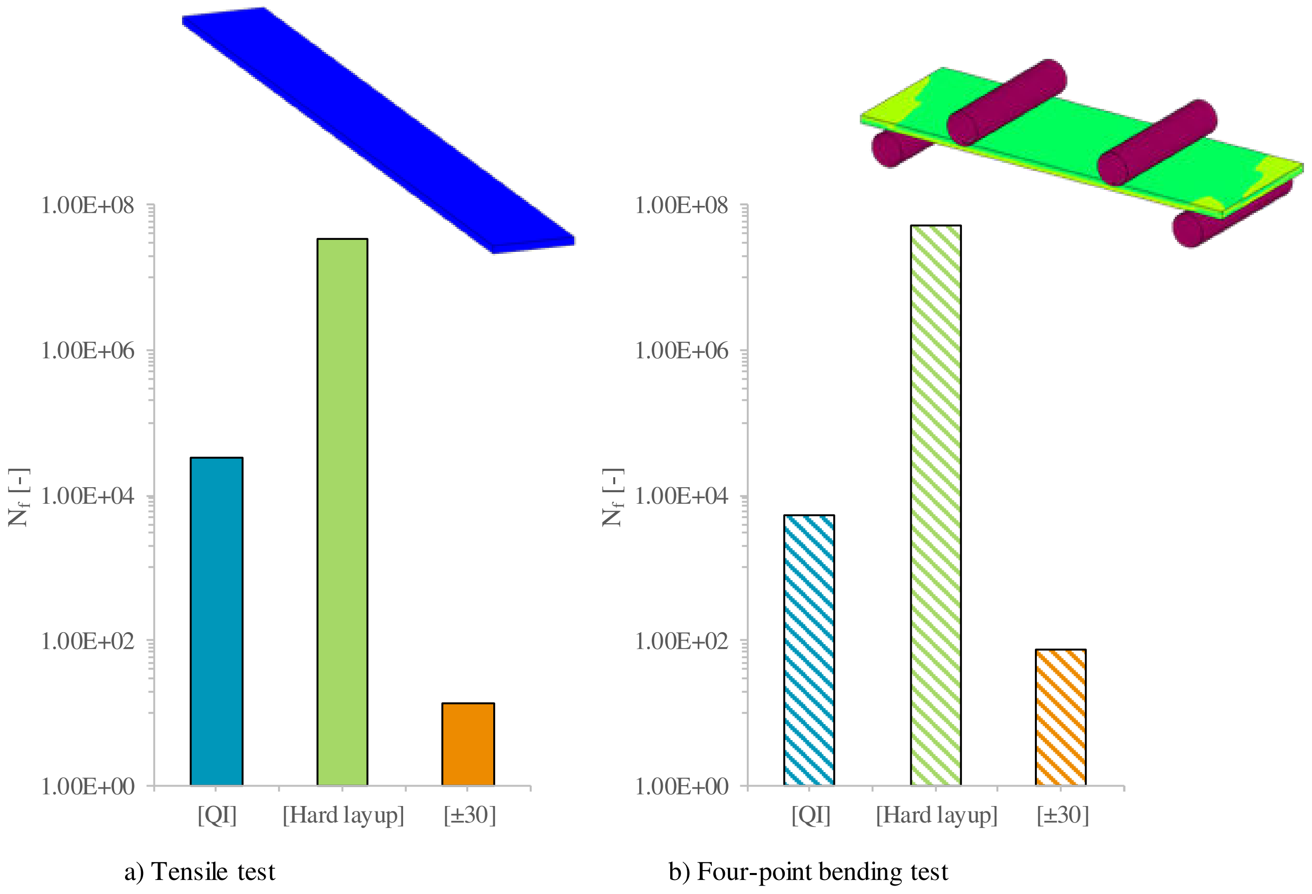
  b) 4-Point bending fatigue
  - Pulsating load between $0\ N$ and $500\ N$
  - Constant amplitude
- Material properties: T700S/2592 (Kawai 2013)



Laminate selection exercise with Digimat

Fatigue life prediction with Digimat-MS

- **Fatigue Performance**: Hard layup > Quasi-isotropic > Angle-ply.
- **Tension-Tension Fatigue**:
  - Hard layup: 3.40·10^7 cycles (failure in 0° plies).
  - Quasi-isotropic: 3.34·10^4 cycles (failure in 90° plies).
  - Angle-ply: 14 cycles (poor performance).
- **Bending Fatigue**:
  - Hard layup: ~5.3·10^7 cycles (failure in tensile 0° ply).
  - Quasi-isotropic: ~5400 cycles (failure in compressed 90° ply).
  - Angle-ply: 70 cycles (poor performance).
- **Key Insight**: Stiffer laminates perform better due to lower strain and stronger 0° plies.
- **Note**: Results are case-specific, not generalizable



04

Example 2:

Fatigue life prediction in a composite wing

Intralaminar Fatigue Modeling of Continuous Fiber-reinforced Plastics with Digimat: From Material Parameter Identification to Structural Applications

Fabio Malgioglio[1], Pierre-Yves Lavertu[1], Gourab Ghosh[1], and Marieme El Ghezal[1]

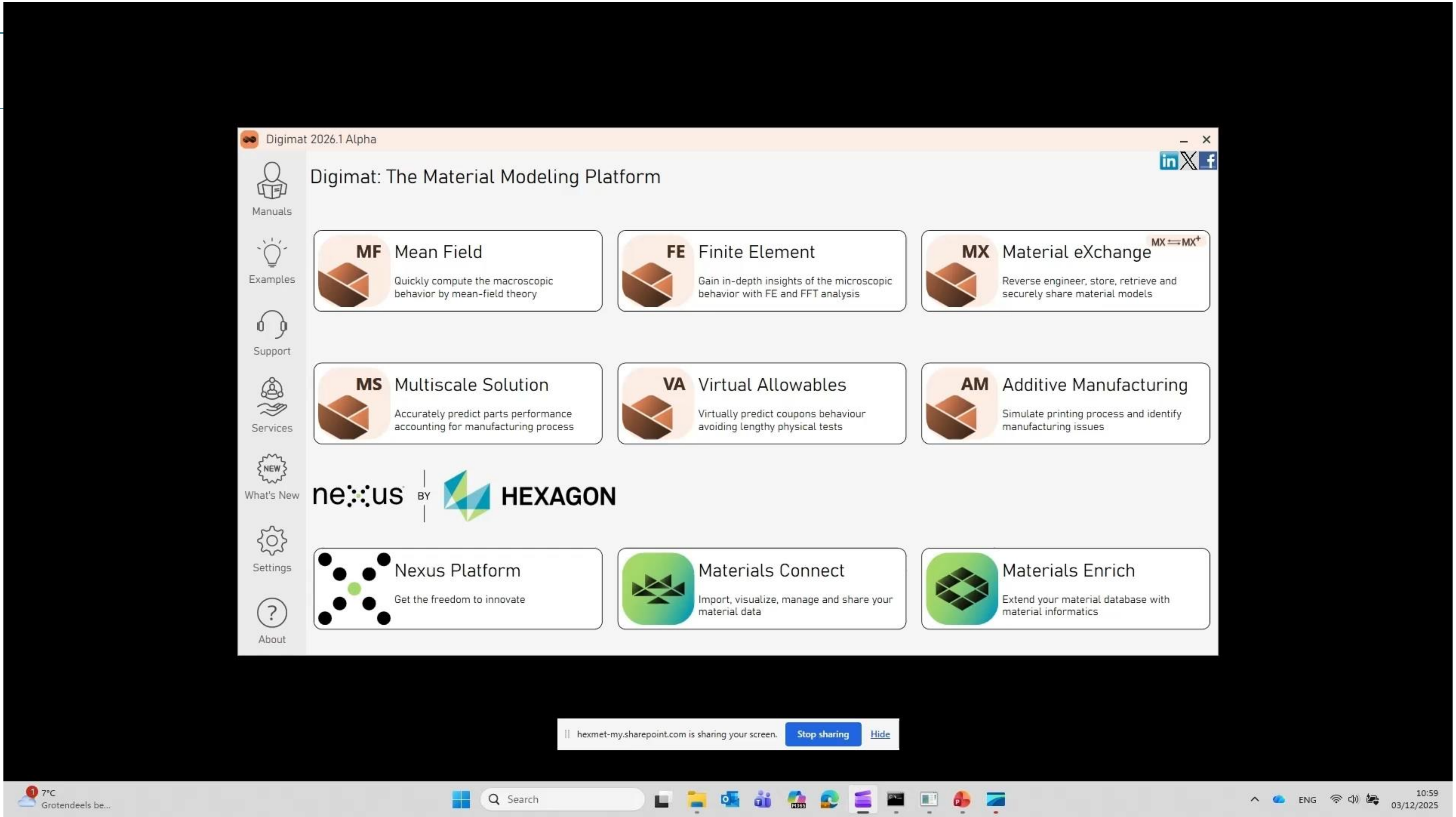
[1] Hexagon Manufacturing Intelligence, Design & Engineering business unit, Mont St. Guibert, Belgium
fabio.malgioglio@hexagon.com

Abstract. Continuous fiber-reinforced plastics (CFRPs) are extensively utilized in fatigue-critical engineering applications, such as wind turbine blades, automotive structures, and aerospace components. Accurate fatigue modeling is crucial for evaluating the durability of composite structures during the design phase. However, fatigue modeling presents significant challenges, including i) modeling complexity, ii) complex material parameter identification, and iii) high computational costs. To address these challenges, an efficient lamina-based fatigue failure

Methodology presented at the American Society for composites 40th annual technical conference:

“**Intralaminar Fatigue Modeling of Continuous Fiber-reinforced Plastics with Digimat: From Material Parameter Identification to Structural Applications**”

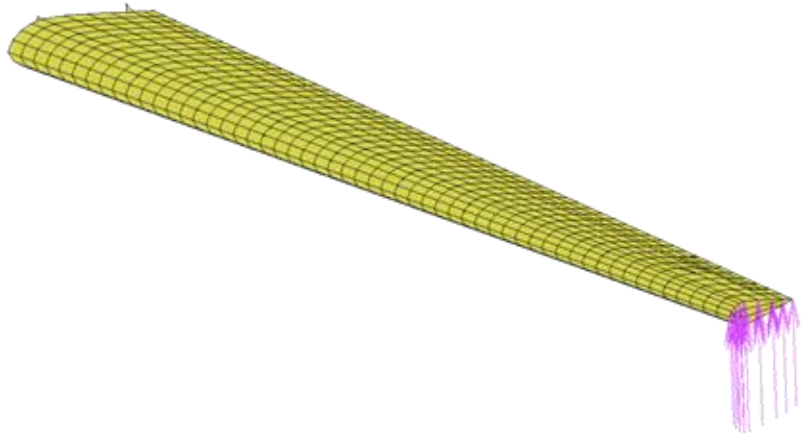
to be published in “Proceedings of the American Society for Composites 40th Technical Conference, 2025”

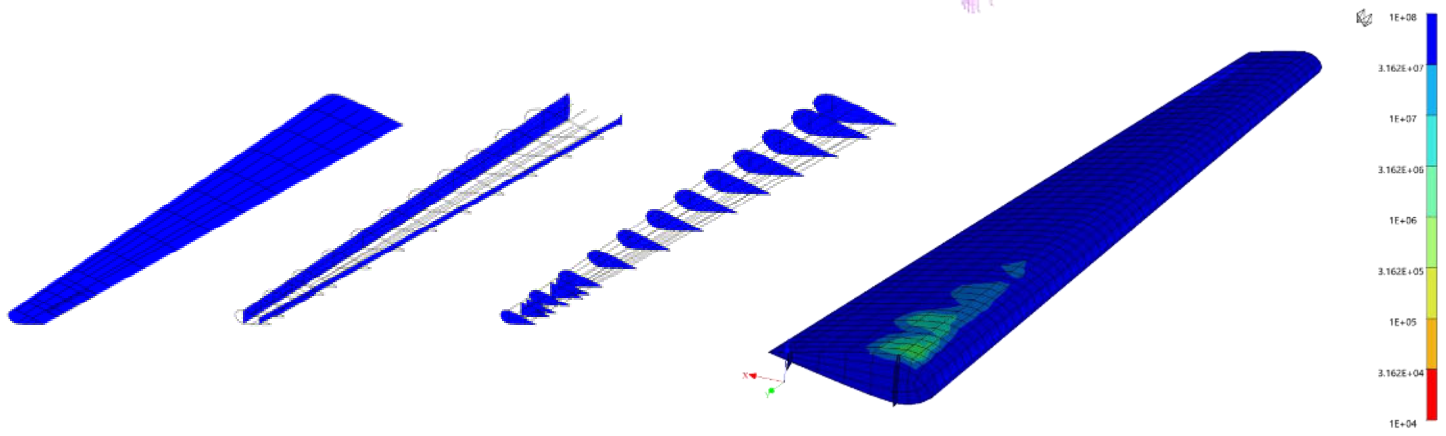

Digimat 2026.1 Alpha
Digimat: The Material Modeling Platform
Manuals
Examples
Support
Services
What's New
Settings
About
MF Mean Field
Quickly compute the macroscopic behavior by mean-field theory
FE Finite Element
Gain in-depth insights of the microscopic behavior with FE and FFT analysis
MX Material eXchange
Reverse engineer, store, retrieve and securely share material models
MS Multiscale Solution
Accurately predict parts performance accounting for manufacturing process
VA Virtual Allowables
Virtually predict coupons behaviour avoiding lengthy physical tests
AM Additive Manufacturing
Simulate printing process and identify manufacturing issues
nexus BY HEXAGON
Nexus Platform
Get the freedom to innovate
Materials Connect
Import, visualize, manage and share your material data
Materials Enrich
Extend your material database with material informatics
hexmet-my.sharepoint.com is sharing your screen.
Stop sharing
Hide
7°C
Grotendeels be...
Search
ENG
10:59
03/12/2025

Fatigue life prediction in a composite wing

Fatigue life prediction with Digimat-MS

- Finite Element Modeling
  - Wing modeled using MSC MARC/Mentat™
  - Shells with composite layup definition (~3000 elements)
  - Model size: ~3000 elements
  - Assembly includes composite spar, ribs, panels, and aluminum connecting joints
- Prediction of fatigue life
  - ~10,000 cycles
- Prediction of failure location
  - [0] degree plies, compression side
- Model performance
  - Static simulation: <2min
  - Fatigue simulation: <1 min
  - Total time for the user: ~7min
- Material: IM7/8552 from D-Standart project





05

D-Standart case study:

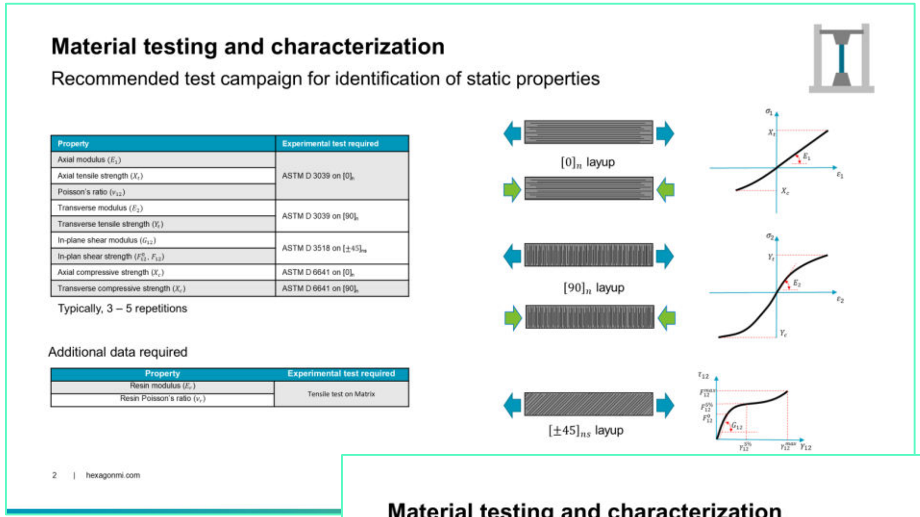
- Material parameter identification of IM7/8552
- Application to D-Standart demonstrator

Parameter identification for IM7/8552 carbon/epoxy system

Intralaminar fatigue model parameters

- Required test data:
  - ✓ Static properties
  - × S-N curves for $[0]$, $[90]$, $[\pm 45]$ laminates (T-T, T-C, C-C)

- Material data available in D-Standart project:
  - S-N curves for [QI] laminates
  - T-T fatigue ($R = 0.1$, $R = 0.5$)
  - T-C fatigue (R =-1)



Material testing and characterization

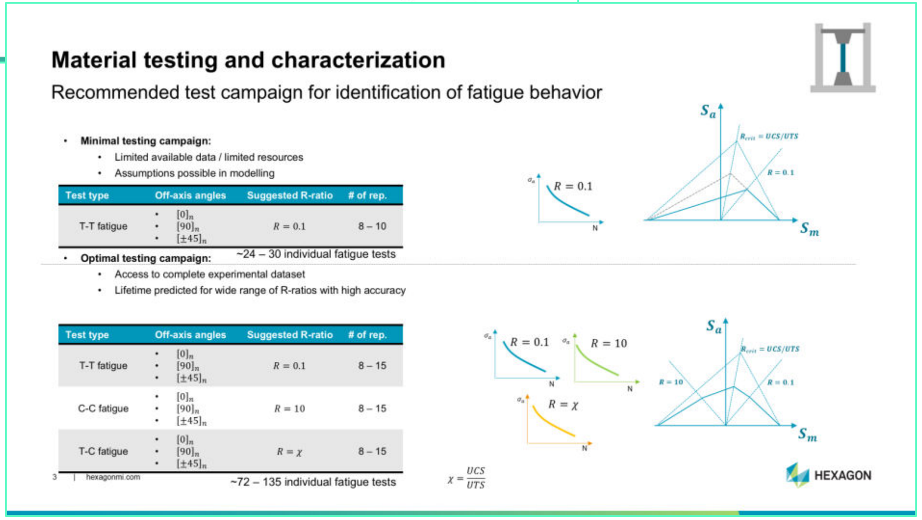
Recommended test campaign for identification of static properties

Property	Experimental test required
Axial modulus (E_1)	ASTM D 3039 on $[0]_n$
Axial tensile strength (X_t)	
Poisson's ratio (ν_{12})	
Transverse modulus (E_2)	ASTM D 3039 on $[90]_n$
Transverse tensile strength (Y_t)	
In-plane shear modulus (G_{12})	ASTM D 3518 on $[\pm 45]_{ns}$
In-plan shear strength (F_{12}^0, F_{12})	
Axial compressive strength (X_c)	ASTM D 6641 on $[0]_n$
Transverse compressive strength (X_c)	ASTM D 6641 on $[90]_n$

Typically, 3 – 5 repetitions

Additional data required

Property	Experimental test required
Resin modulus (E_r)	Tensile test on Matrix
Resin Poisson's ratio (ν_r)	



Material testing and characterization

Recommended test campaign for identification of fatigue behavior

- **Minimal testing campaign:**
  - Limited available data / limited resources
  - Assumptions possible in modelling

Test type	Off-axis angles	Suggested R-ratio	# of rep.
T-T fatigue	$[0]_n$, $[90]_n$, $[\pm 45]_n$	$R = 0.1$	8 – 10

~24 – 30 individual fatigue tests

- **Optimal testing campaign:**
  - Access to complete experimental dataset
  - Lifetime predicted for wide range of R-ratios with high accuracy

Test type	Off-axis angles	Suggested R-ratio	# of rep.
T-T fatigue	$[0]_n$, $[90]_n$, $[\pm 45]_n$	$R = 0.1$	8 – 15
C-C fatigue	$[0]_n$, $[90]_n$, $[\pm 45]_n$	$R = 10$	8 – 15
T-C fatigue	$[0]_n$, $[90]_n$, $[\pm 45]_n$	$R = \chi$	8 – 15

~72 – 135 individual fatigue tests

$\chi = \frac{UCS}{UTS}$

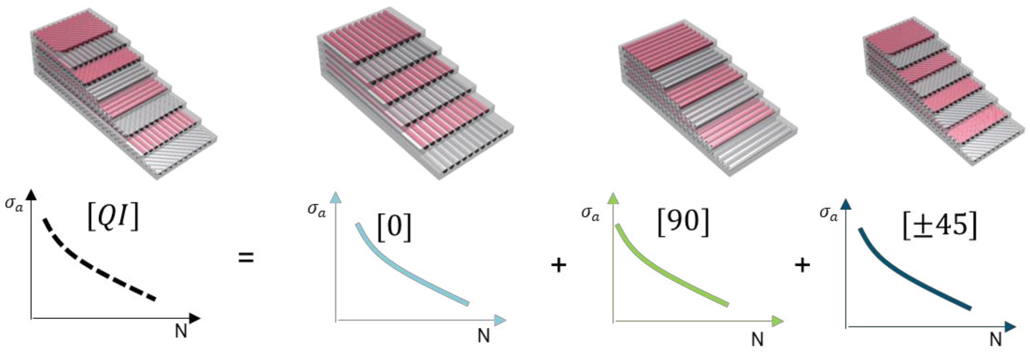
Parameter identification for IM7/8552 carbon/epoxy system

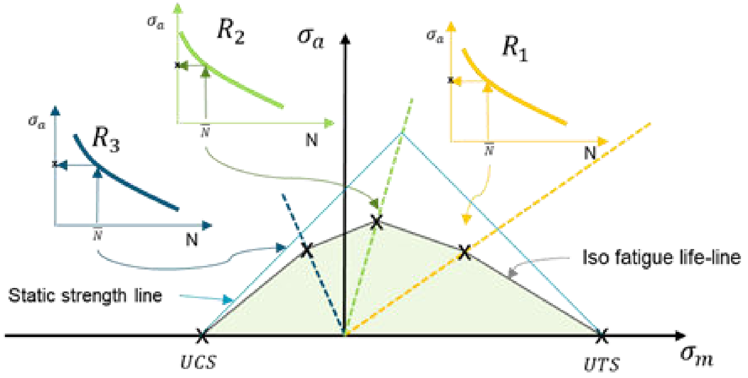
Intralaminar fatigue model parameters: identification procedure

1. Static properties

2. Reverse-engineering of S-N curves

3. Mean stress sensitivity (MSS)



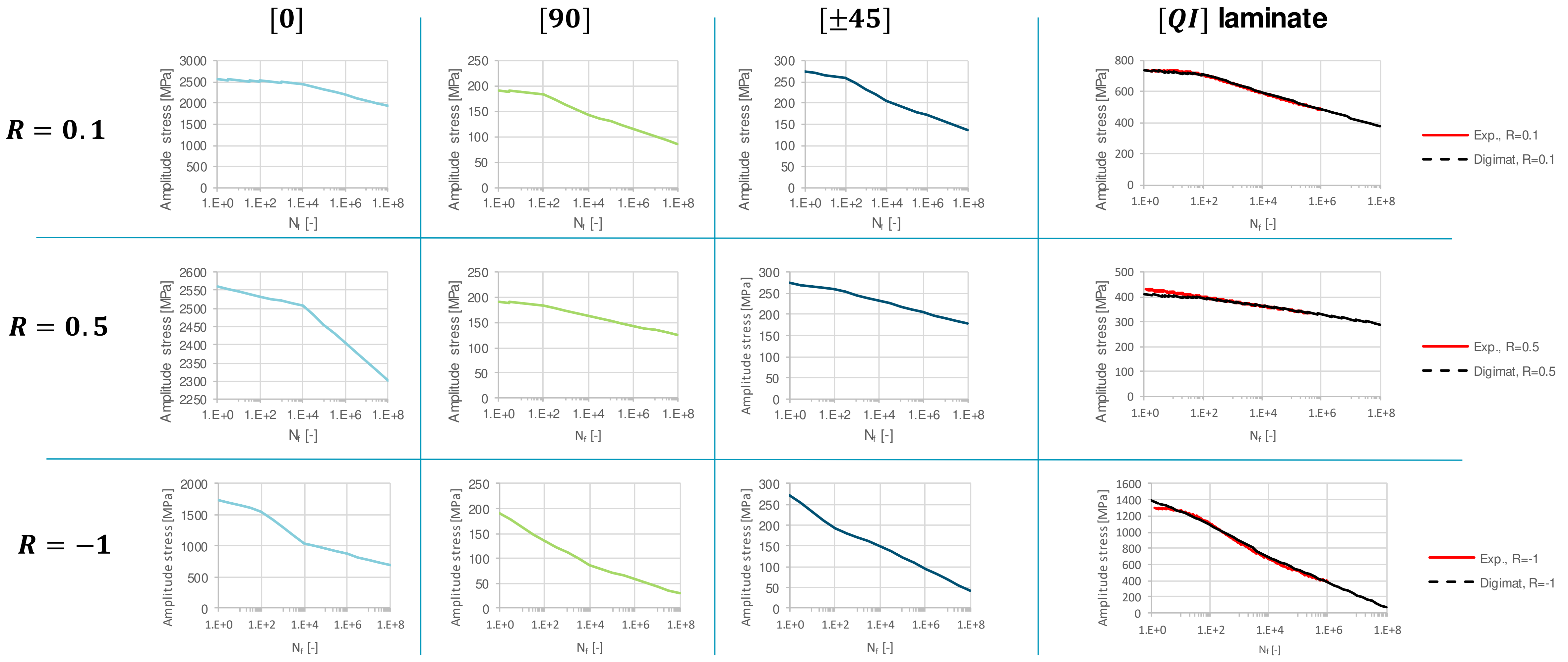


Note:

- The optimization problem is under constrained. Reasonable assumptions were made for S-N curves to match target curve
- Optimization based on Tsai-Hill TI fatigue failure criterion: S-N curves may not match other failure theories

Parameter identification for IM7/8552 carbon/epoxy system

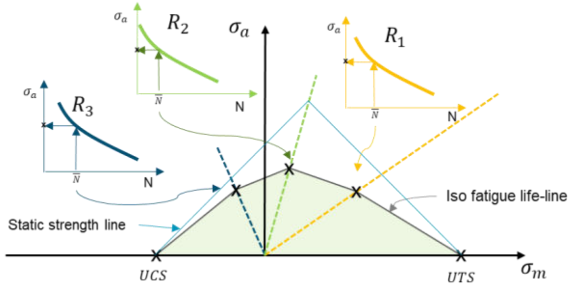
Intralaminar fatigue model parameters: reverse engineering of SN curves



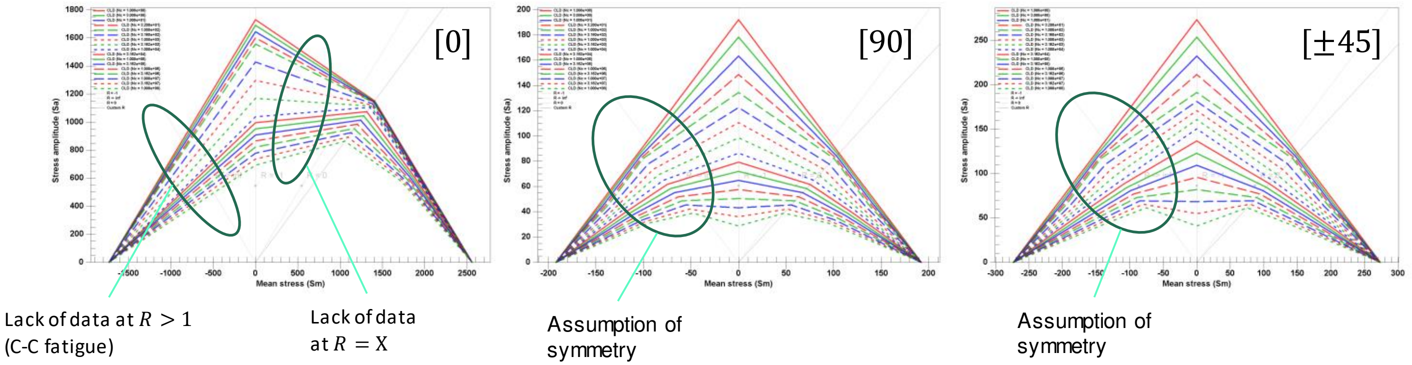
Parameter identification for IM7/8552 carbon/epoxy system

Intralaminar fatigue model parameters: mean stress sensitivity (MSS)

- CLD diagram reconstructed in Digimat, based on the reconstructed S-N curves



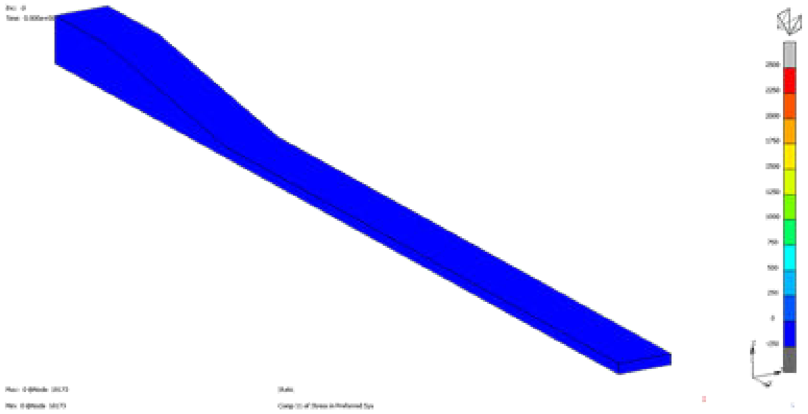
- Remarks:
  - Some areas of CLD diagram are uncertain (e.g., missing C-C data):
    - Interpolation between available data
    - Assumption of symmetry in [90] and [±45] behavior
- Recommendations to improve data:
  - Test pure laminates ([0], [90], [±45])
  - Add critical $R = UCS/UTS$
  - Add C-C fatigue (e.g., $R = 10$) if possible

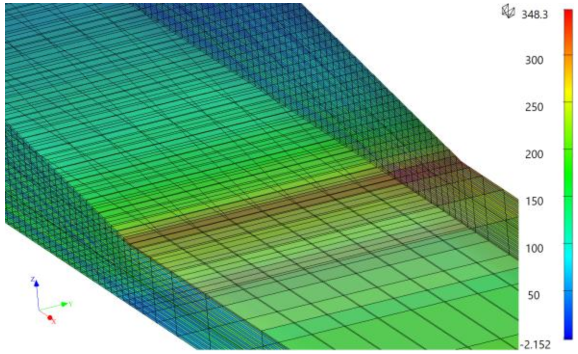


D-Standart demonstrator

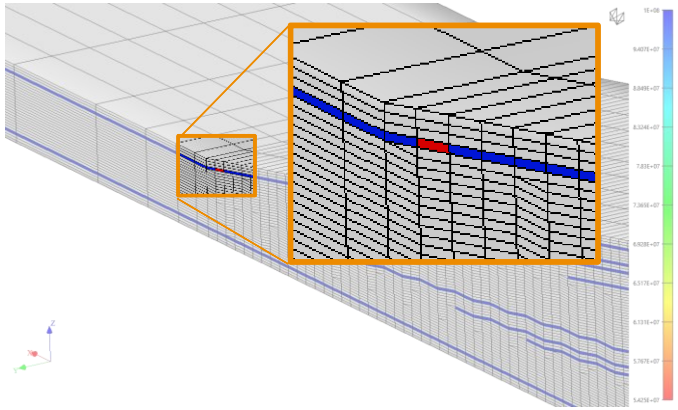
Qualitative results

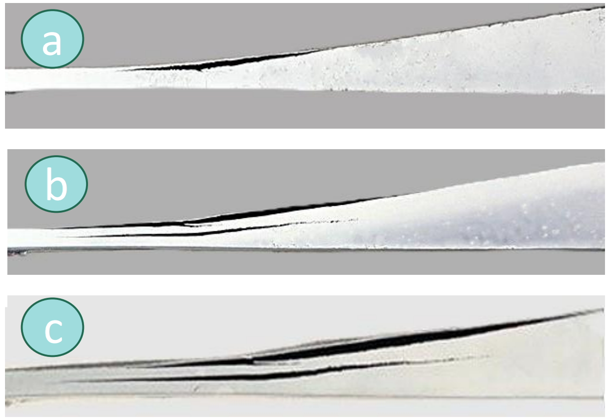
- Model description:
  - 1 solid element per ply
  - No interface/cohesive elements
  - Full model size: ~400,000 elements
  - Simplified model size: ~100,000 elements
- Observations:
  - Higher stress concentrations near the change of section
  - First failure in the 90° ply
  - Failure location compatible with experimental results
- Model performance
  - Static simulation: <50min
  - Fatigue simulation: ~5 min
  - Total time for the user: ~1h





Stress amplitude





Experimental results (UB)

a: ~ 5% stiffness drop
b: ~15% stiffness drop
c: ~25% stiffness drop

Chapter 5

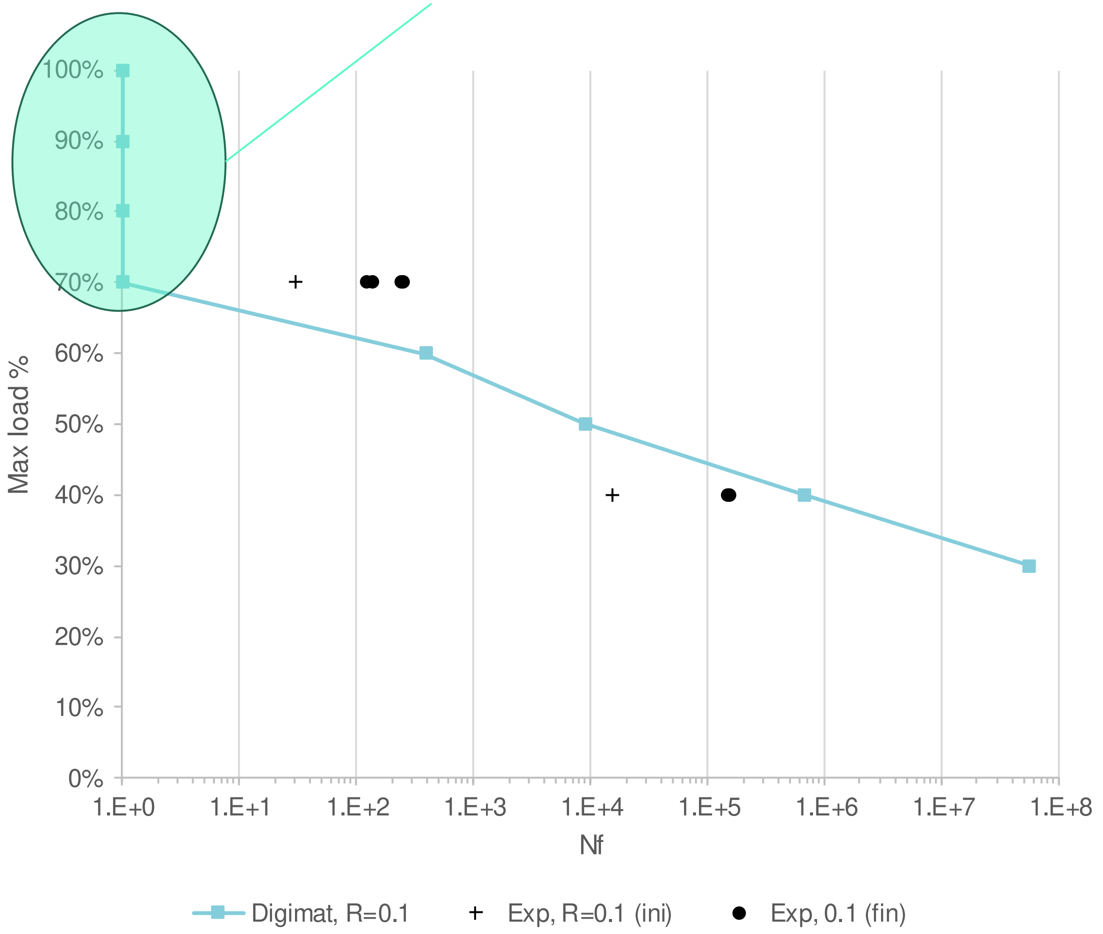
D-Standart demonstrator

S-N curves

- Fatigue life evaluated with Digimat for different load levels
- $\sim 5\ min$ per evaluation

- Observations:
    - Between 70% and 100% of the maximum load, failure is detected for 1 cycle. This is in agreement with experiments, where delamination is detected prior catastrophic failure
    - At 70% of the maximum load, the model seems conservative vs. experiments
    - At 40% of the maximum load, the model over predicted fatigue life by a factor of ~4.

Failure initiation detected in experiments

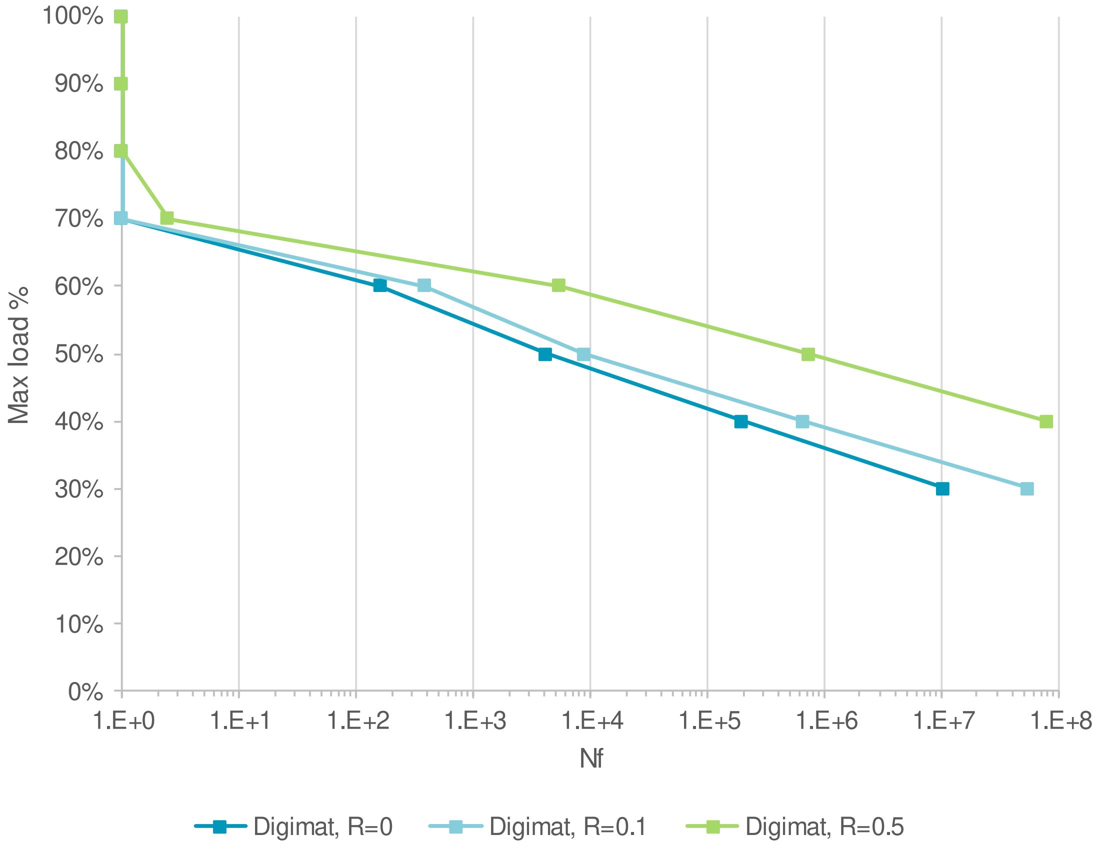


D-Standart demonstrator

S-N curves

- Effect of R ratio
  - Higher R ratios here translate to lower amplitudes: increasing R ratio should result in extended fatigue life
  - Total time: ~1h30 for 3 S-N curves

- Remarks:
  - The test is designed to induce interlaminar fatigue damage: not modeled here.
  - Nevertheless, the model predicts failure in 90° plies, which could trigger delamination
  - The model is still able to predict satisfactory trends, given the limited data availability



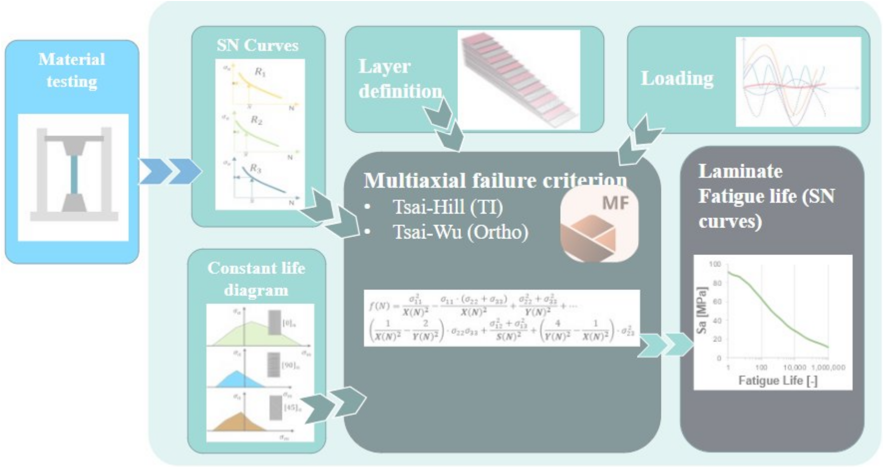
06

Nonlinear FEA modelling with Marc

Failure and damage in monotonic and fatigue loading

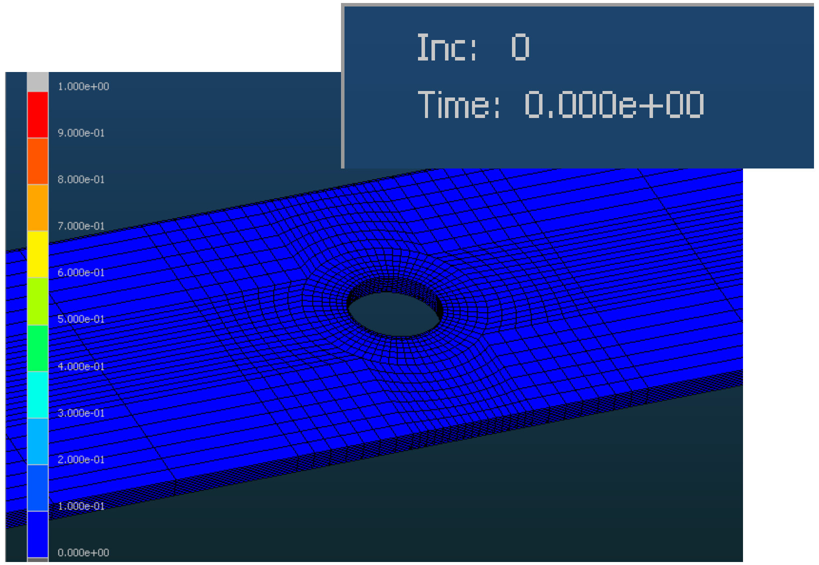
Hexagon MI approach

Fatigue using Digimat and Marc



Hexagon MI approaches to fatigue of composites

- **Digimat**:
  - Intra-laminar fatigue for UD composites, it predicts failure initiation in the plies.
  - Based on limited experimental data (S-N curves).
  - Suitable for fast assessment of fatigue performance of composite components and designs.



- **Marc**:
  - Detailed modelling of fatigue using progressive failure and damage models.
  - Delamination and intra-laminar fatigue.
  - Crack growth with Paris Law (short cycle / high cycle fatigue).
  - Suitable for detailed analyses of damage onset and propagation in components and designs.

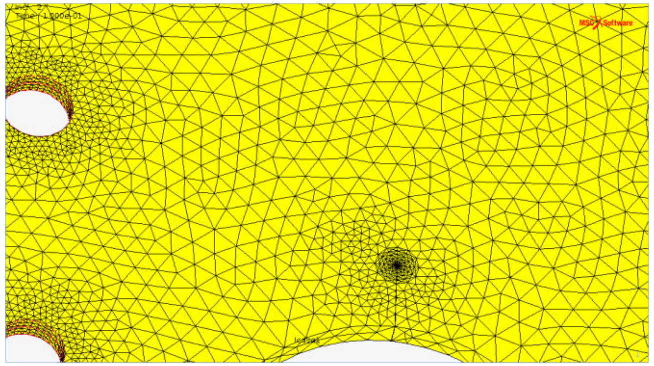
What is Marc?

Advanced nonlinear simulation solution

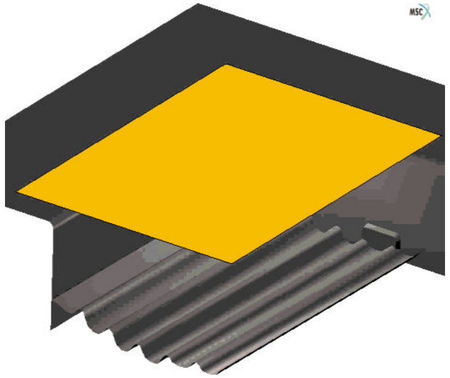
50+ years of development

- Marc is the 1st commercial nonlinear FEA Program (1971).
- Provides solutions for nonlinear structural, thermal, multiphysics and co-simulation problems.
- Marc has a wide and broad industry presence among automotive, aerospace, biomedical, etc.
- Marc solver and technology used in FEA tools (Digimat, Simufact, Nastran Sol400).

Remeshing

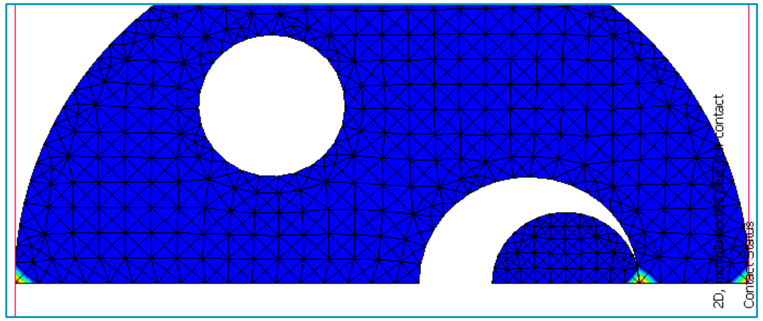


Large deformations

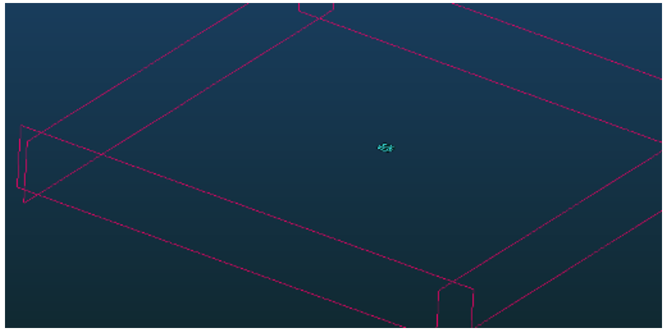


Marc excels at:

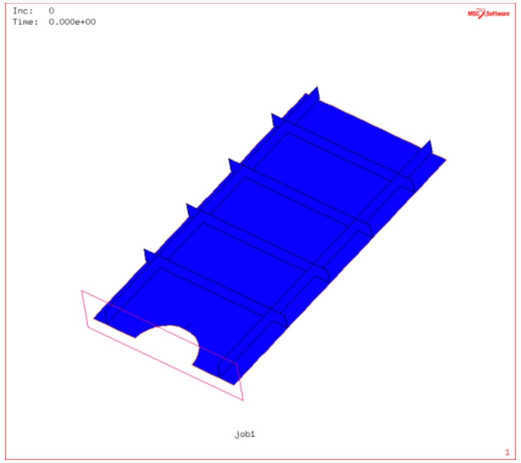
Robust contact methods



Element insertion / removal



Failure and damage analysis



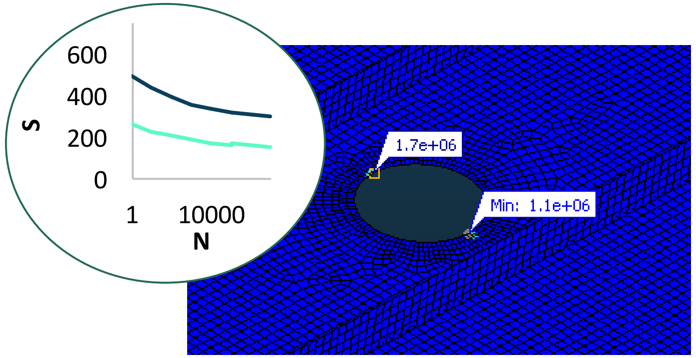
Fatigue modelling

FEA approaches to fatigue

Empirical fatigue life estimates

Method: obtain static FEA results file and post-process stress or strain based on fatigue life curves.

Possible also through Digimat-MS.

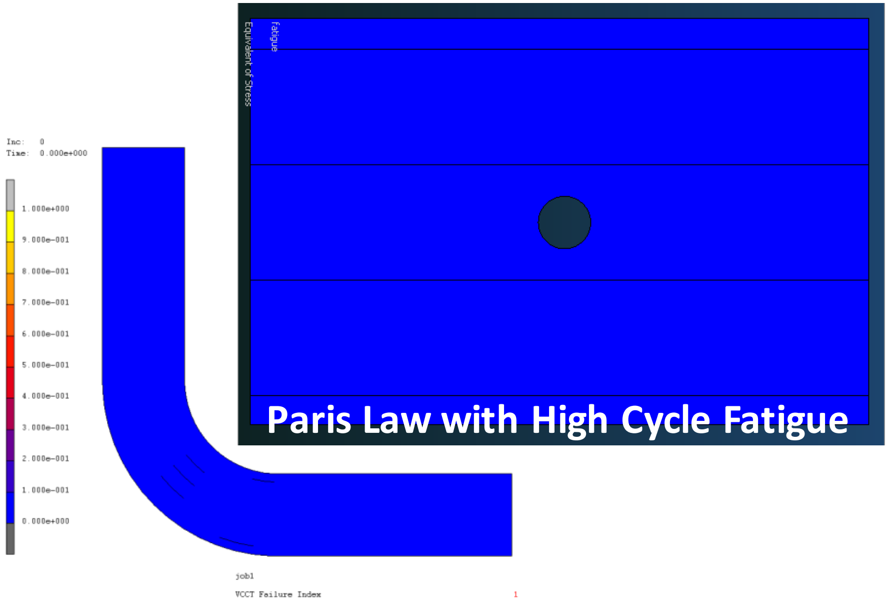


M. Kaminski, F. Laurin, J.F. Maire, C. Rakotoarisoa, E. Hemon. AerospaceLab, 2015, p. 1-12.
Davila, C.G.. NASA Tech. Report, 2018, p. 1-34.

Fatigue crack growth models

No damage ahead of crack.

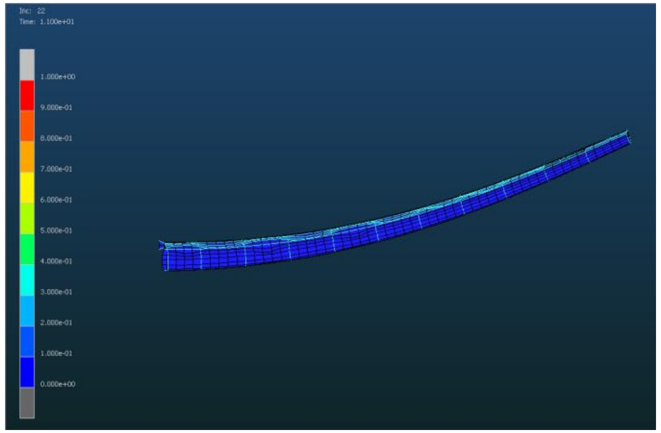
Paris Law, relating SIF and da/dN, using re-meshing and fracture mechanics techniques to advance the crack.



Delamination (VCCT & CZM)

Fatigue failure and damage

Element failure when fatigue criterion is met, or progressive stiffness degradation with increasing fatigue cycles.



07

Composites fatigue modelling with Marc

Implementation of a failure model (fLaRC)

Chapter 7

Fatigue failure

Demonstration of fatigue modelling using MARC

1. LaRC failure criterion implemented into MARC

What is LaRC?

Failure criterion based on micromechanics.

Accounts for interactions between fibres and matrix and multiaxial loading.

Distinction between fibre and matrix failure modes.

Well known and adopted.

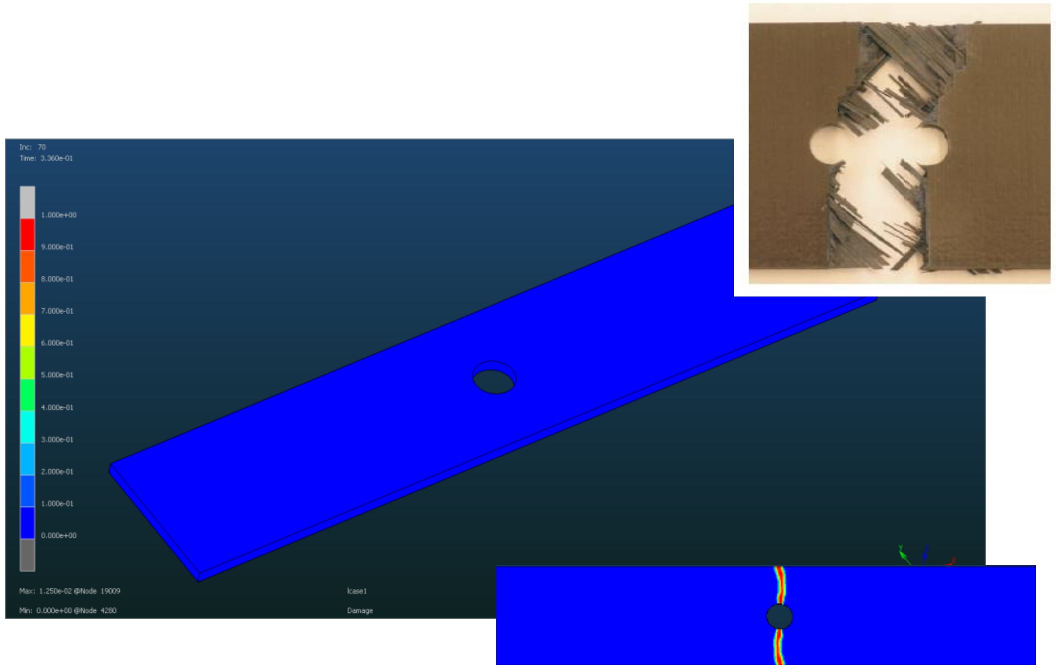
Fatigue based on LaRC

It is implicitly assumed that interactions between fibre and matrix failure are maintained.

Multiaxial loading and distinction between fibre and matrix failure modes.

Minimal testing requirements.

No damage evolution.



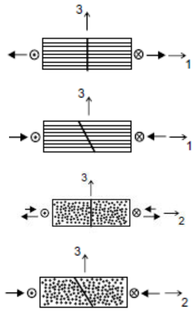
Failure indexes

Fibre breakage (tension failure)

Fibre compression failure due to buckling or kinking

Matrix cracking (tensile failure)

Matrix crushing under transverse compression



Davila *et al.*, J Compos Mater (2005)

Fatigue failure

Demonstration of fatigue modelling using MARC

2. LaRC criterion extended to fatigue

- **Strength parameters connected to SN curves**

1. SN curves from UD plies converted to Constant Life Diagrams
2. Account for mean stress effects and R-ratio using CLD

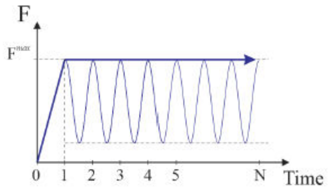
- **Cycle counting (Palmgren-Miner rule, PM)**

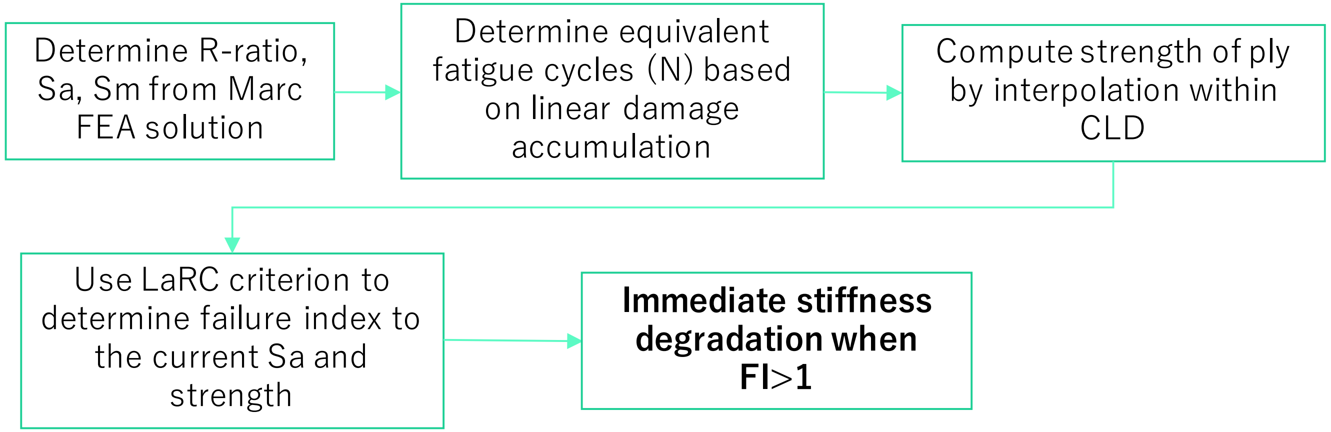
Determine equivalent number of cycles, based on counting the cycles experienced at different stress levels.

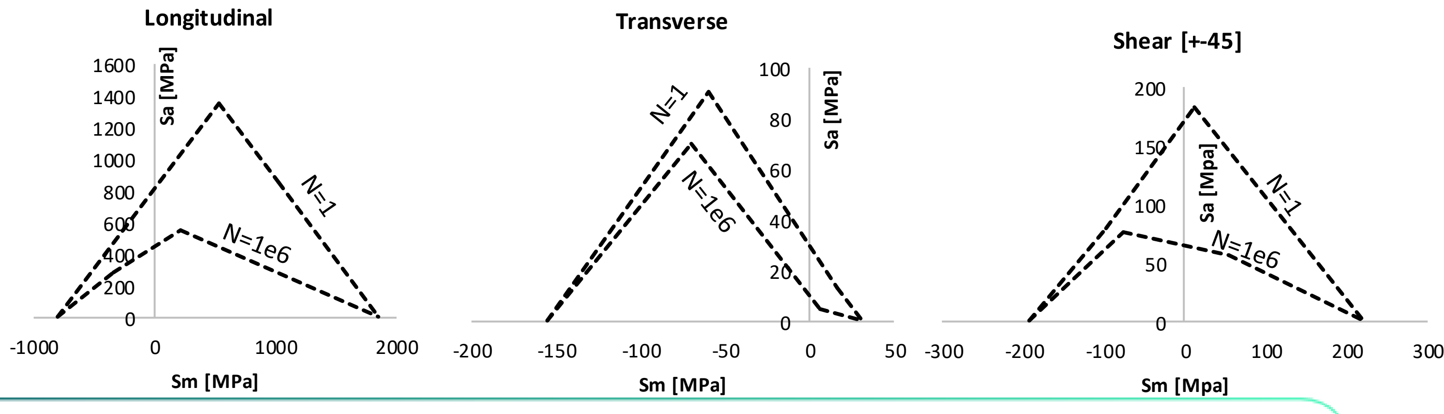
- **Simplified Cyclic Loading**

Fatigue loading kept constant at maximum load and pseudo-time represents number of cycles.

R-ratio is used to represent the effect of fatigue cycles.







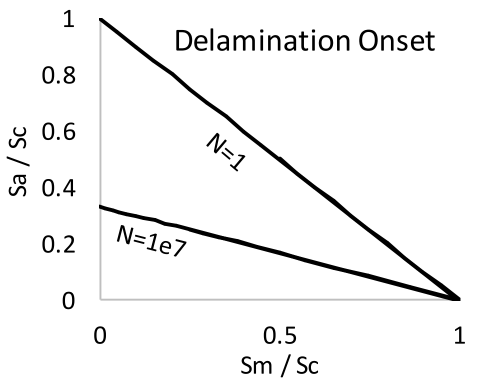
Fatigue failure

Demonstration of fatigue modelling using MARC

3. Extension for delamination fatigue

Quadratic Intralaminar Stress Criterion (interface failure)

- Delamination onset criterion adapted for fatigue based on CLD diagrams.
- Mesh-splitting technique without cohesive elements (no progressive damage evolutions).



Dávila, Carlos & Rose, Cheryl & Murri, Gretchen & Jackson, Wade. (2020). Evaluation of Fatigue Damage Accumulation Functions for Delamination Initiation and Propagation.

4. Fatigue data-needs

- **Mean stress effects captured using an estimated Constant Life Diagram**

inc=0 of simulation

SN curve data for UD and +-[45] plies (tension & compression)

Static delamination strength and endurance limits (Goodman criterion)

→ Compute anchor points on CLD diagrams based on R-ratio and SN curves

- **Minimal testing campaign**

Test type	Off-axis angles	Suggested R-ratio	# of rep.
T-T fatigue	• $[0]_n$ • $[90]_n$ • $[\pm 45]_n$	$R = 0.1$	8 – 15
C-C fatigue	• $[0]_n$ • $[90]_n$ • $[\pm 45]_n$	$R = 10$	8 – 15

Fatigue modelling

Demonstration of fatigue modelling using MARC

5. Verification against literature

- **Literature data from UD plies**

UD ply data for [0], [90] and [±45] with R=0.1 (TT) and R=10 (CC) used to drive failure mode (data from Kawai and Itoh, 2014).

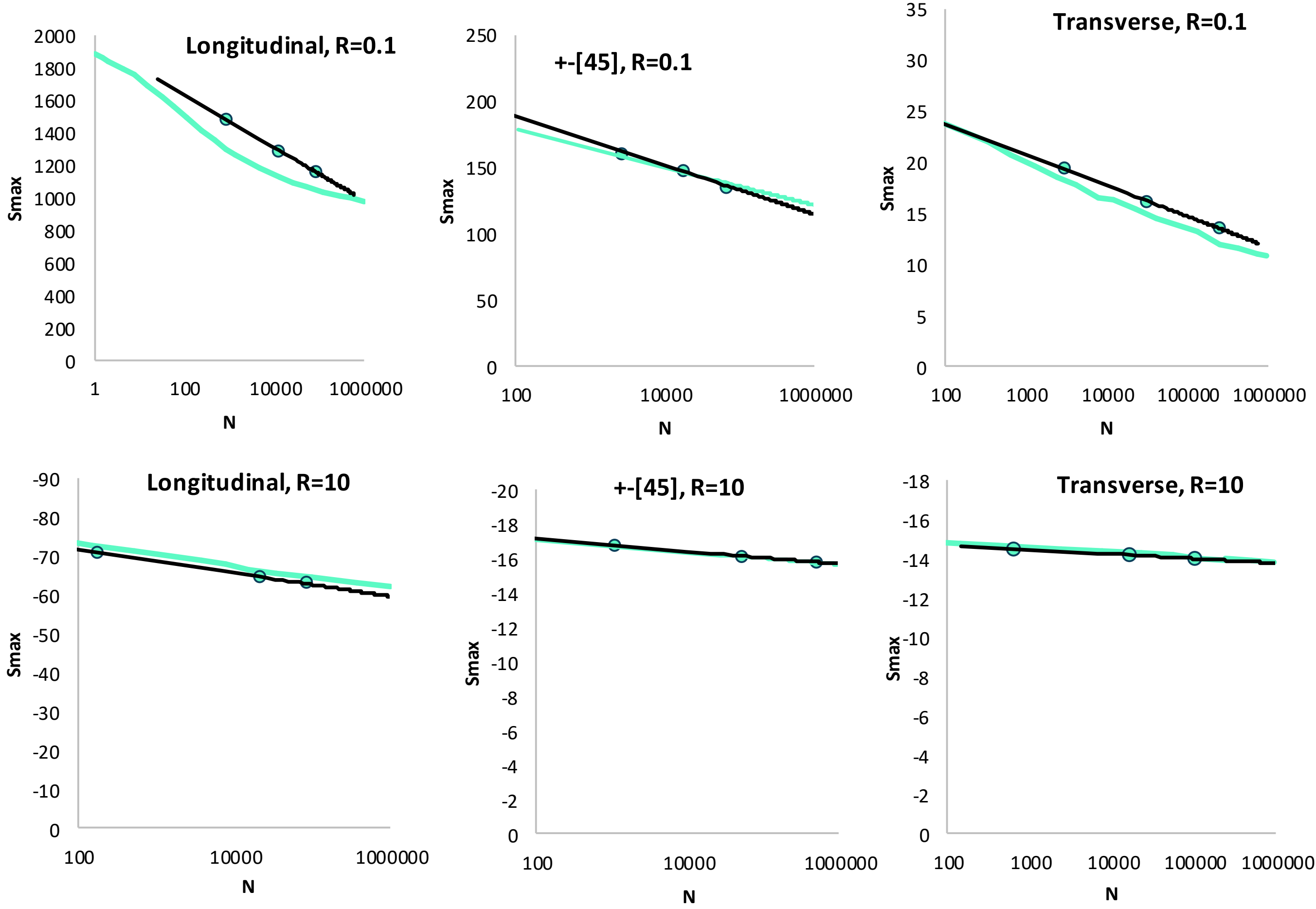
- **Approach yields consistent results with input.**

Some differences related to the interpolations in CLD diagrams from static strength and endurance limits.

- **Testing methods**

Plans to develop optimal testing to combine practicality and accuracy (test setup and key R-ratio).

Further developments needed to validate delamination model and confirm data-needs.



Kawai M, Itoh N. *Journal of Composite Materials*. 2013;48(5):571-592.

Fatigue modelling

Demonstration of fatigue modelling using MARC

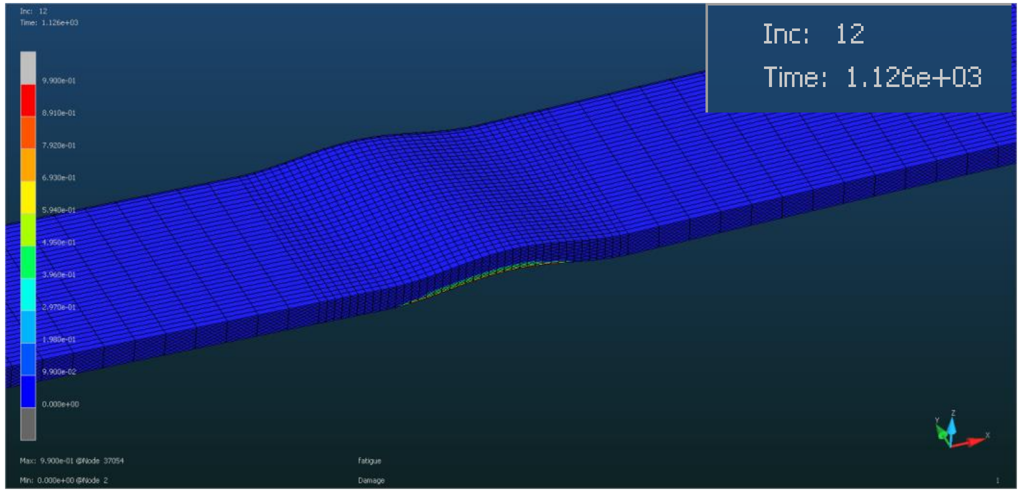
6. Implementation and effect of defects

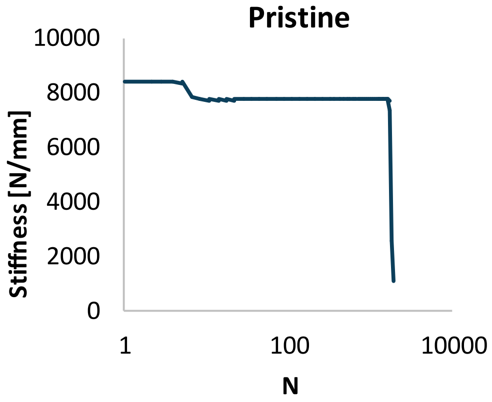
- **Implementation tested for QI layups in pristine and waviness coupons.**
- **Progressive stiffness degradation**

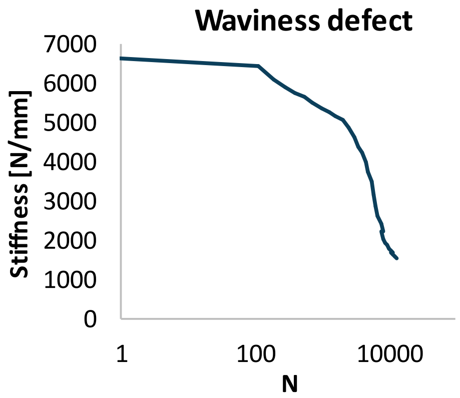
Pristine: initial stiffness degradation due to matrix damage followed by catastrophic fibre failure

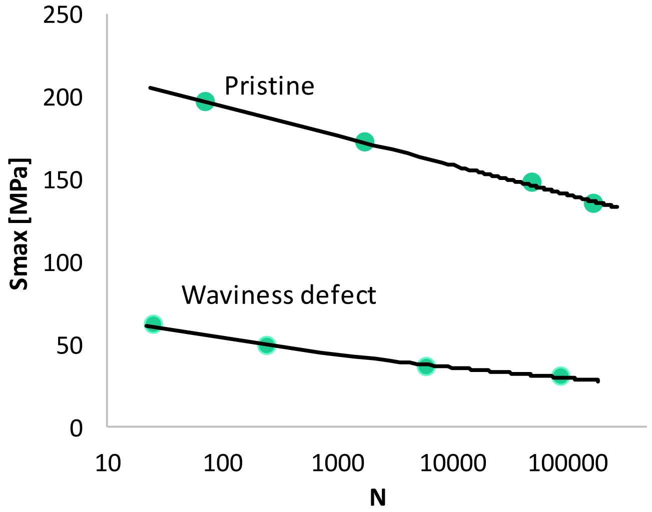
Waviness: progressive matrix and fibre failure lead to continuous stiffness degradation

- **Significant knockdown in fatigue strength due to waviness defect**







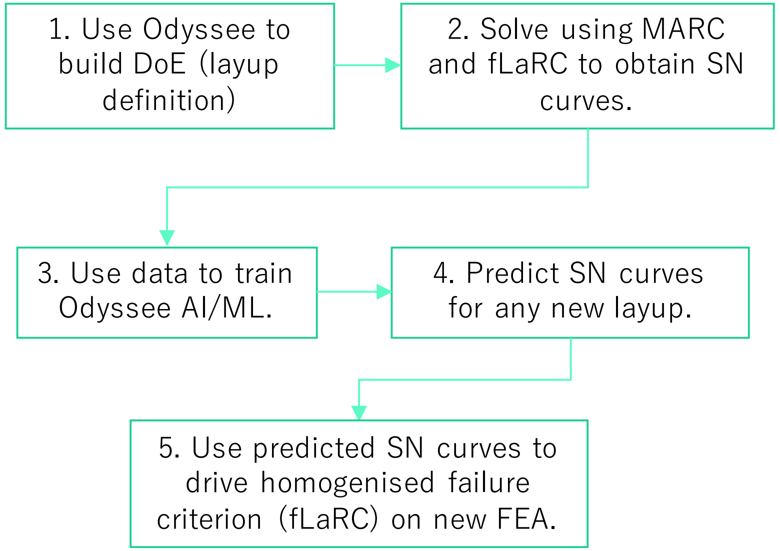


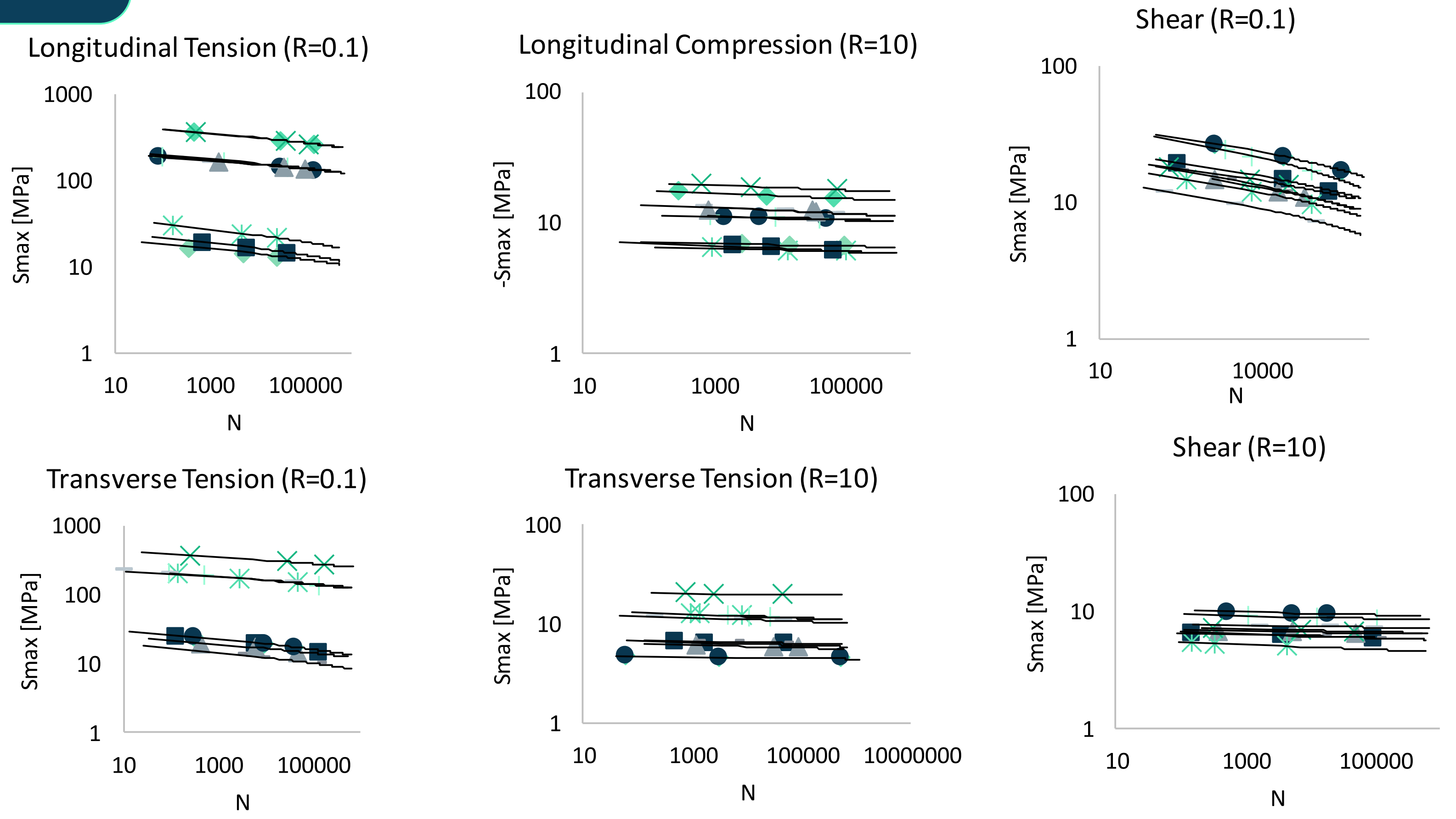
Fatigue modelling

Demonstration of fatigue modelling using MARC

7. Using AI/ML to predict SN curves

- **AI approach (Odyssee):**





Fatigue modelling

Demonstration of fatigue modelling using MARC

7. Using AI/ML to predict SN curves

- **AI model (Odyssee) / validation:**

9 different layups used as training data.

1 verification case (pristine coupon, homogenised material)

~14% difference in fatigue strength

- **Benefits**

Quick lookup of SN curves for alternative layups in pre-design

Can enable FEA with shells and delamination

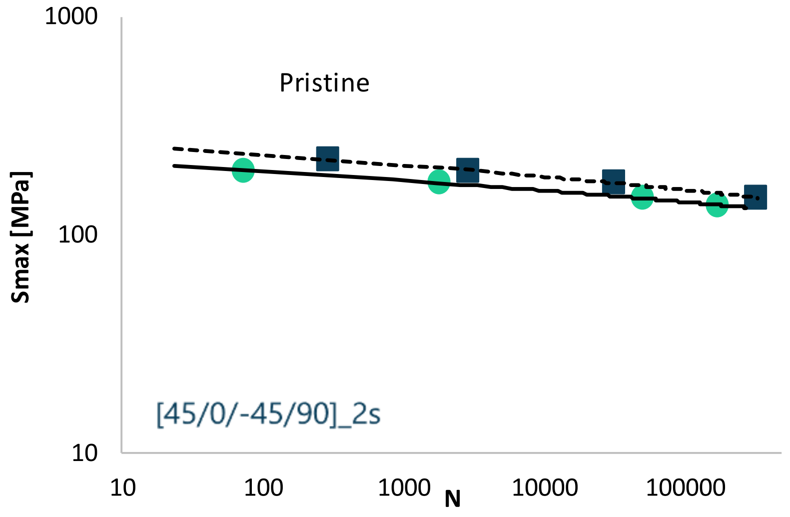
- **Limitations and improvements**

Database generation can require significant resources.

Improvements can be made through automation.

Does not to account for delamination.

Implementation of homogenised model lacks detail.



- **Waviness tests:**

Test on waviness coupon revealed significant difference.

Failure modes and progressive damage not captured.

- **Alternative approach to Effect of Defects (EoD):**

Meso-scale modelling of defects computing fatigue strength knockdown.

Capability already existing for static loading (Digimat VA).

Integration of static EoD with AI in development.

08

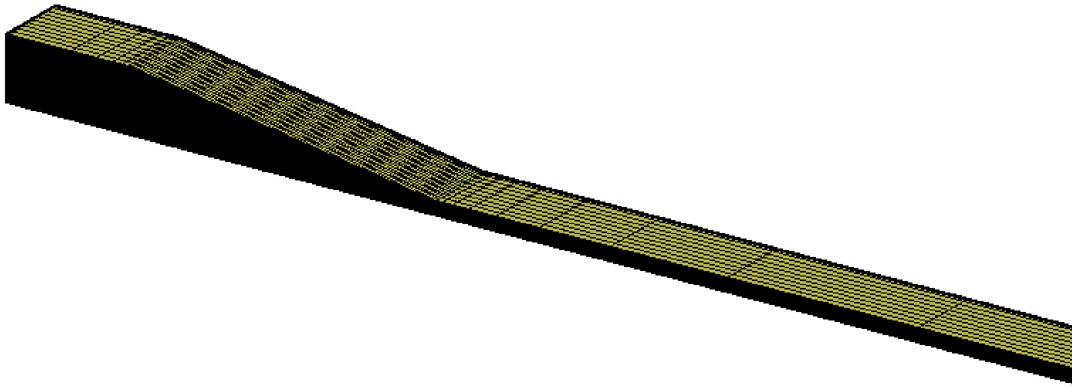
D-Standart case study

Application of fatigue failure to aero demonstrator

D-Standart Demonstrator

Fatigue failure

1. FEA model



- **Tapered specimen (NLR model, UoB experiments)**

1 element per ply.

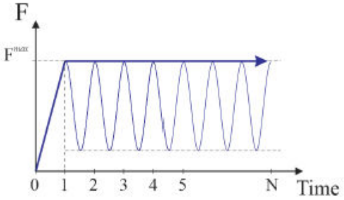
Model size reduced to 50k 8-noded hex. els with full integration.

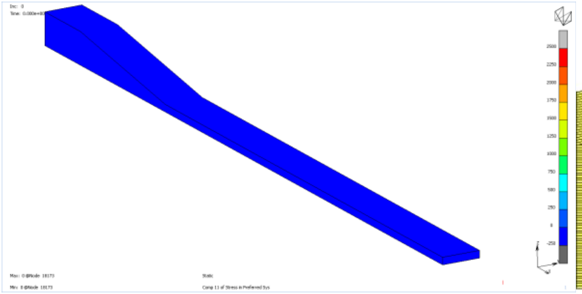
No cohesive elements.

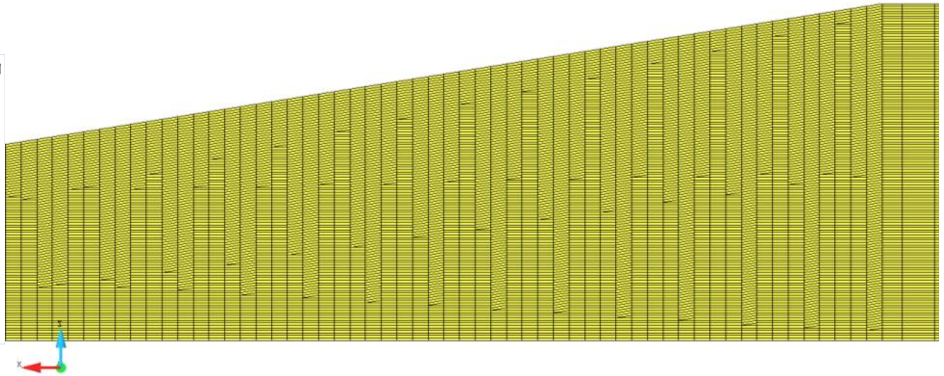
- **Fatigue loading**

Tension-tension (R=0.1), with $0.4Sc < Smax < 0.7Sc$.

Simplified cyclic loading



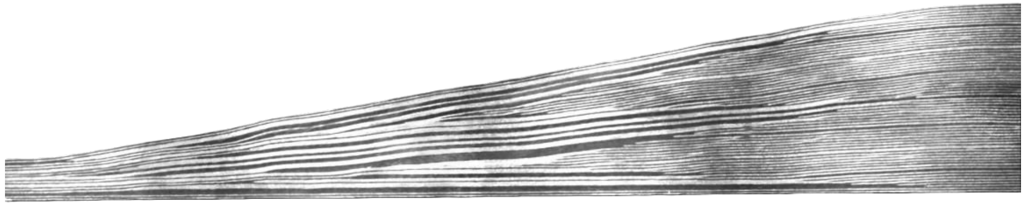




- **Material model**

Based on reverse engineering from experiments

Intra and inter-laminar failure (fLaRC, with delamination)



Source: University of Bristol

- **Solution**

The analysis takes approx. 2h (on 8 CPU cores) to compute.

Delamination recycles where the major contributor to the run-time.

Fatigue modelling

Demonstration of fatigue modelling using MARC

2. Reverse engineering from QI specimens

- **D-Standart experiments (NCC)**

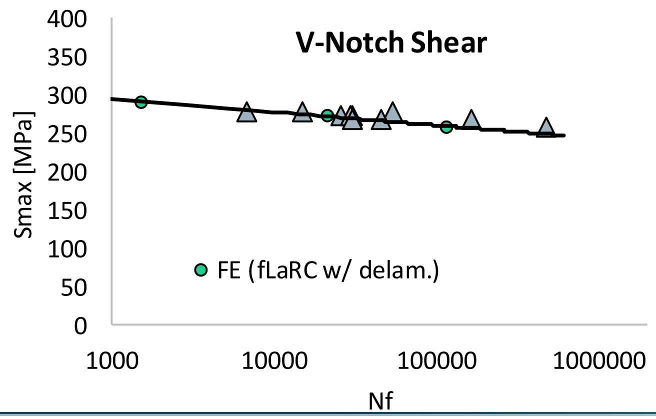
SN curves for quasi-Isotropic TT and TC coupons.

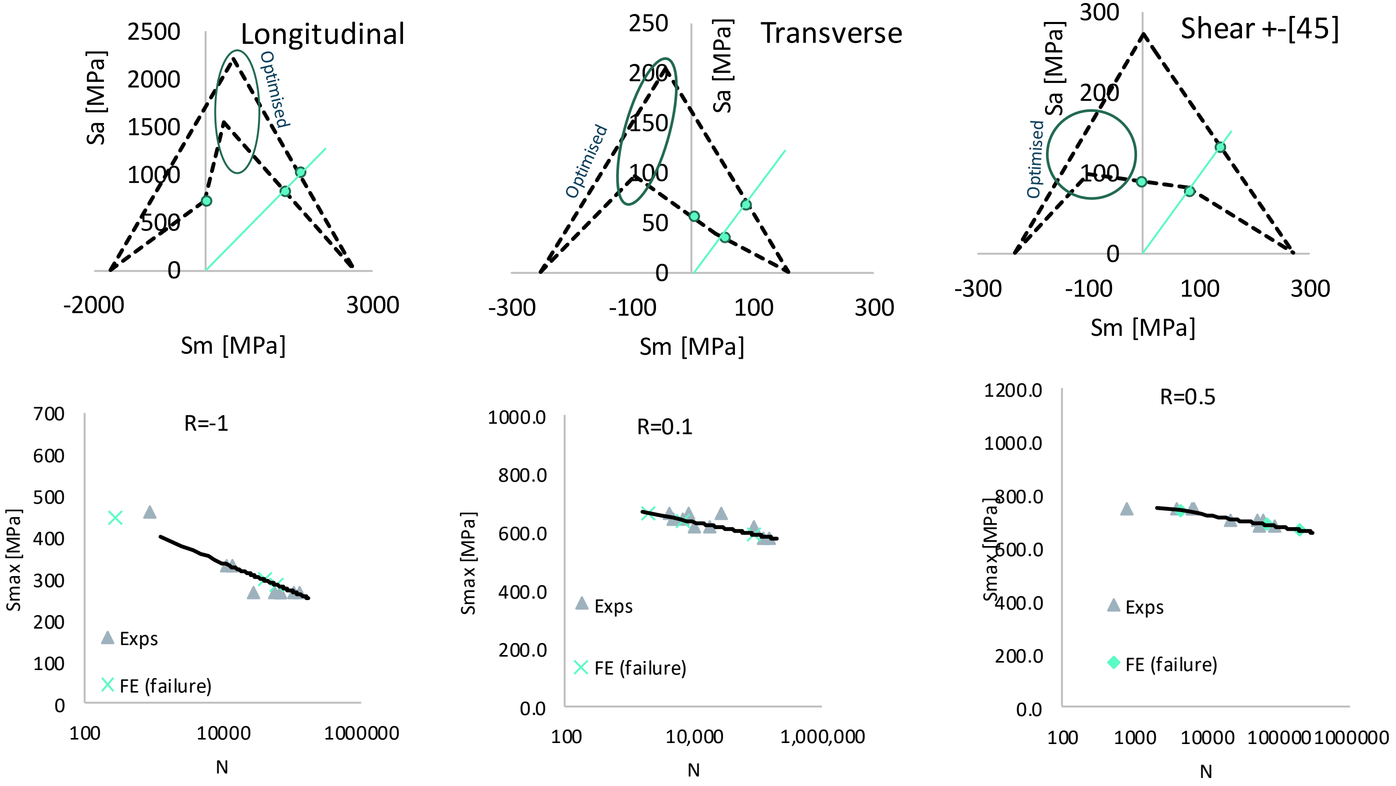
- **Reverse engineering CLD diagrams for fLaRC**

Initial failure CLD diagrams for UD plies from Digimat.

CLD diagrams adapted for more precise matrix failure definition (compression).

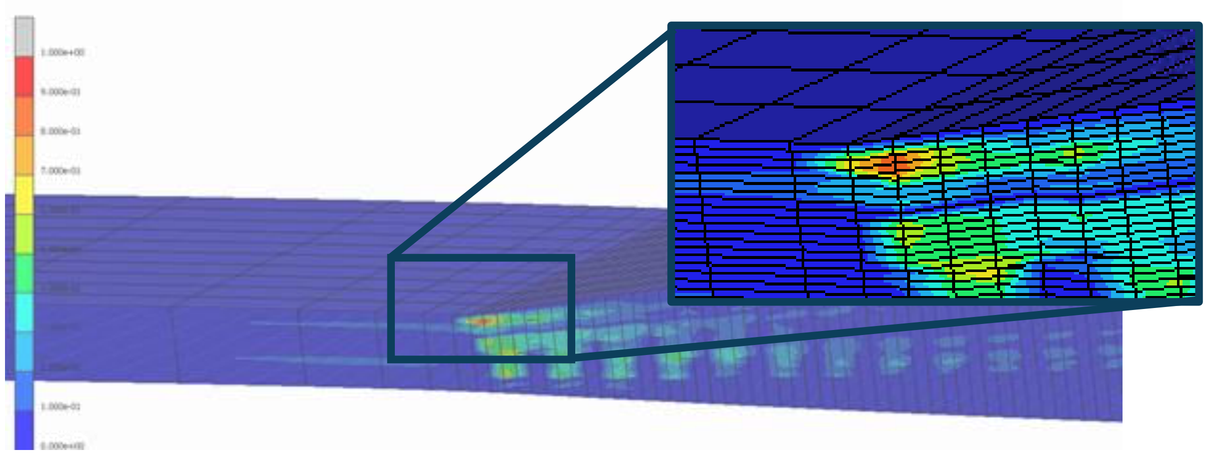
- **VNS tests used to verify results**





D-Standart Demonstrator

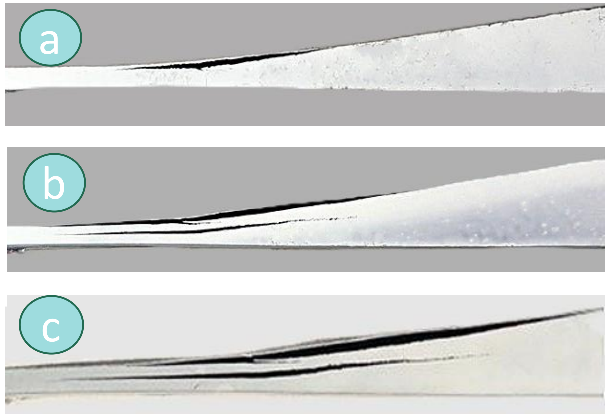
Fatigue failure



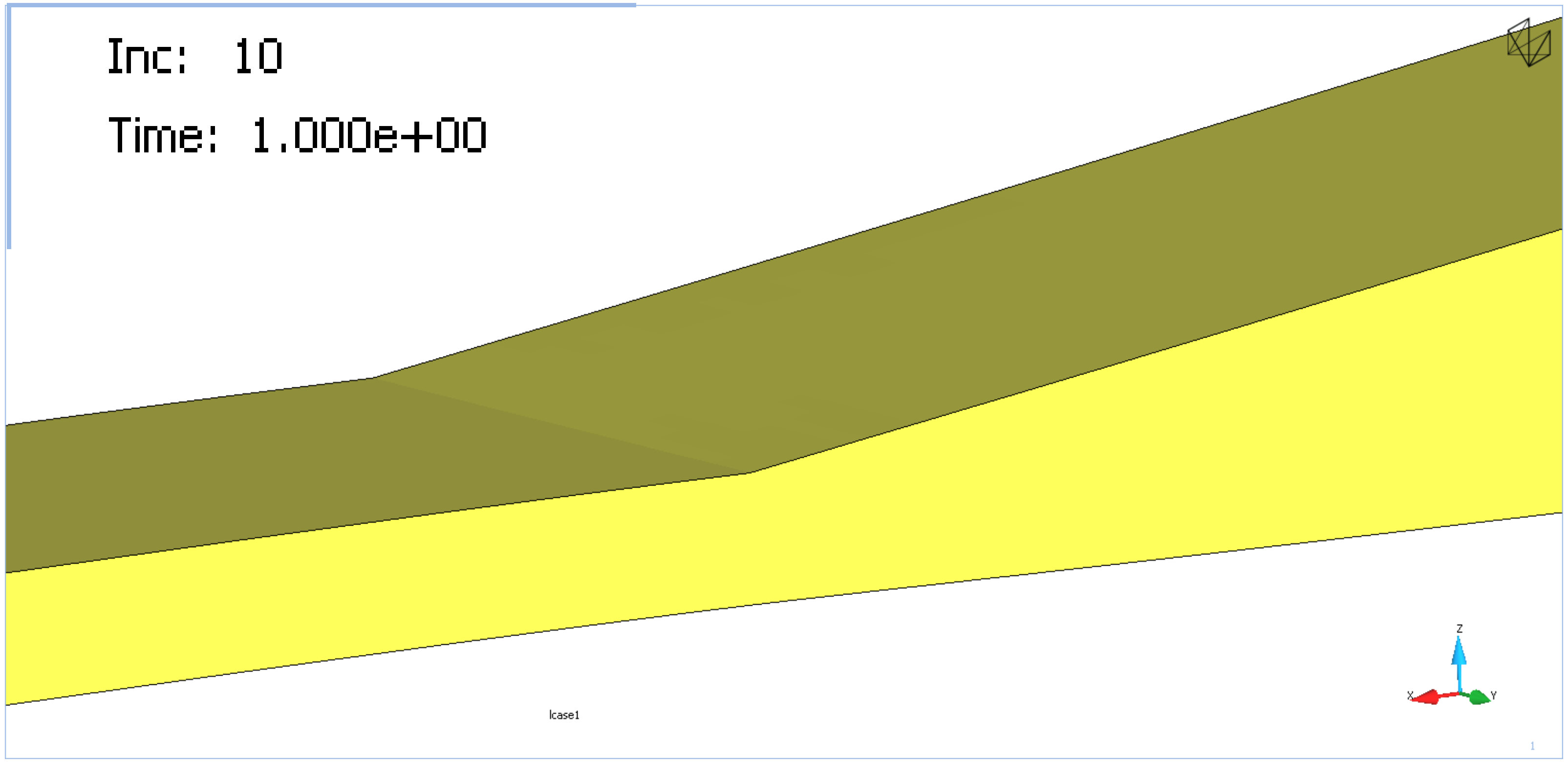
3. Failure (50% load)

Progressive delamination due to tangential stress

- First interface split in agreement with Digimat.
- Slow progression of damage, from N=45 to N=437 (1% stiffness loss).
- Two dominant delamination interfaces develop.



Source: University of Bristol



D-Standart Demonstrator

Fatigue failure

4. Damage evolution

- **Gradual stiffness degradation**

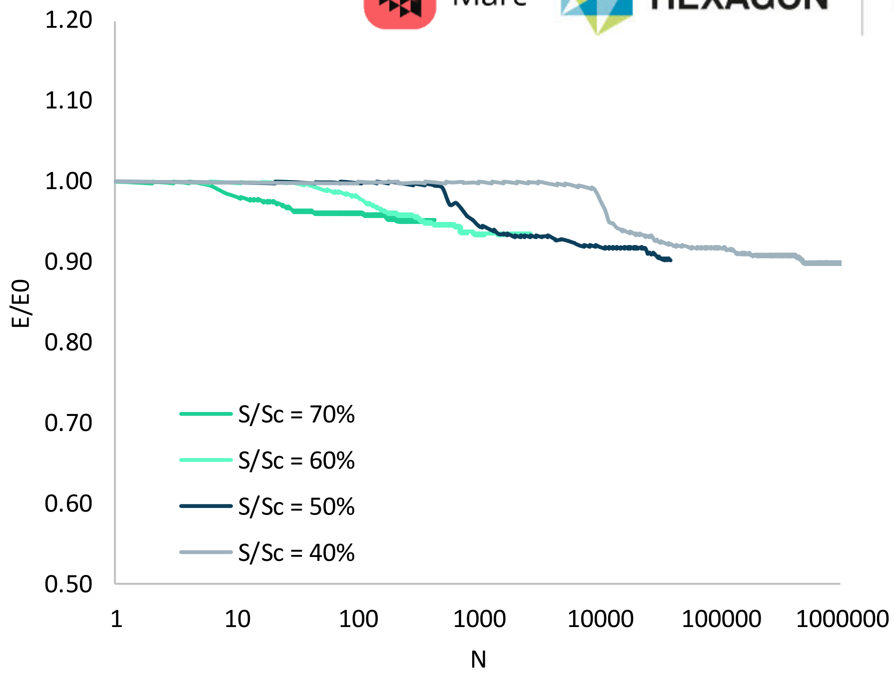
Stiffness plateau between 90% and 95% percent of the static stiffness (5% larger residual stiffness compared to experiment)

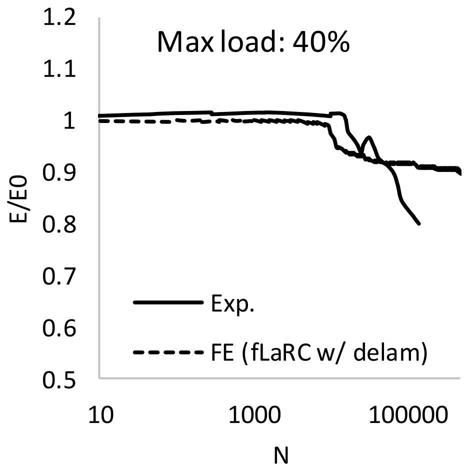
More gradual stiffness loss compared to experiment.

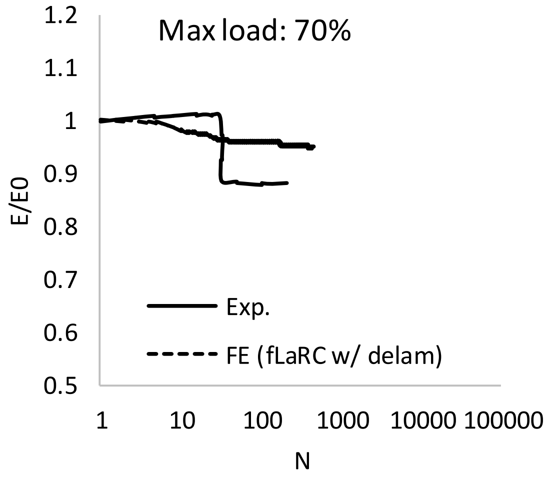
- **Good agreement with onset of delamination at 40% load**
- **Sudden catastrophic failure at 70% not captured**
- **Paris law driven delamination may improve results**

Technique already available in Marc.

Needs additional experiments for calibration.







D-Standart Demonstrator

Fatigue failure

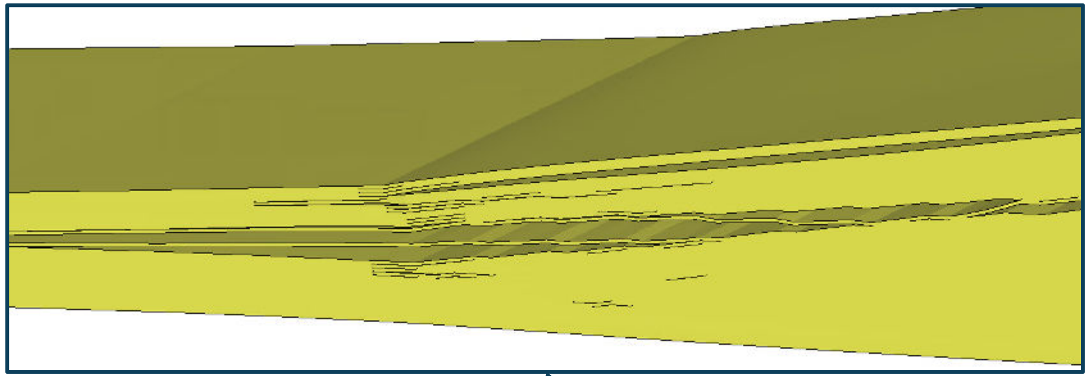
5. Stress life plots

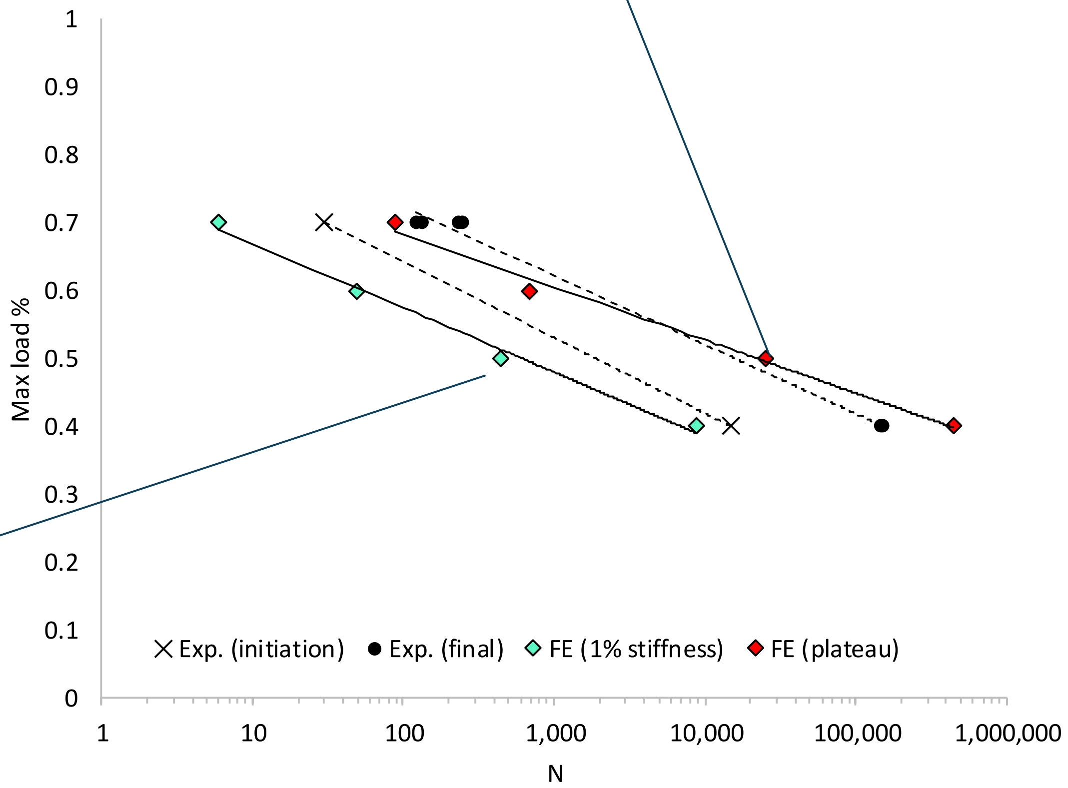
- **Numerical vs experiment:**

Number of cycles for 1% stiffness degradation correspond to visually observed fatigue cracks.

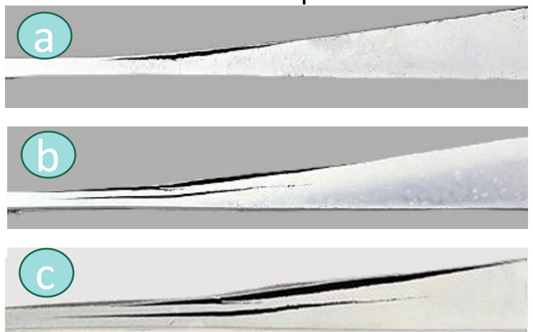
Number of cycles to achieve the plateau stiffness (90-95% stiffness) correspond to the number of cycles where the experiments were interrupted (80%-88% stiffness).

More tests needed: delamination failure criterion and calibration.

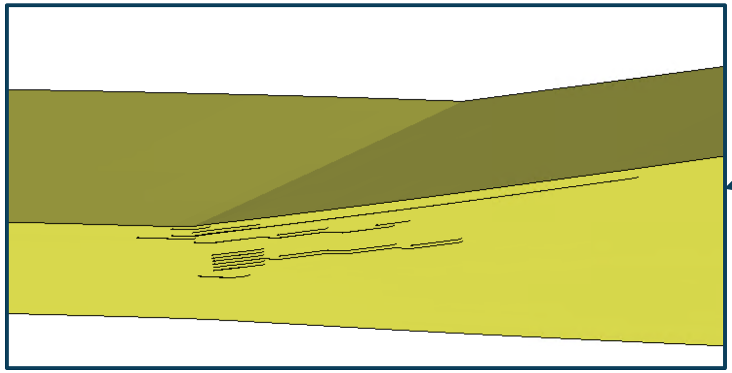




a: ~ 5% stiffness drop
b: ~15% stiffness drop
c: ~25% stiffness drop



Source: University of Bristol



09

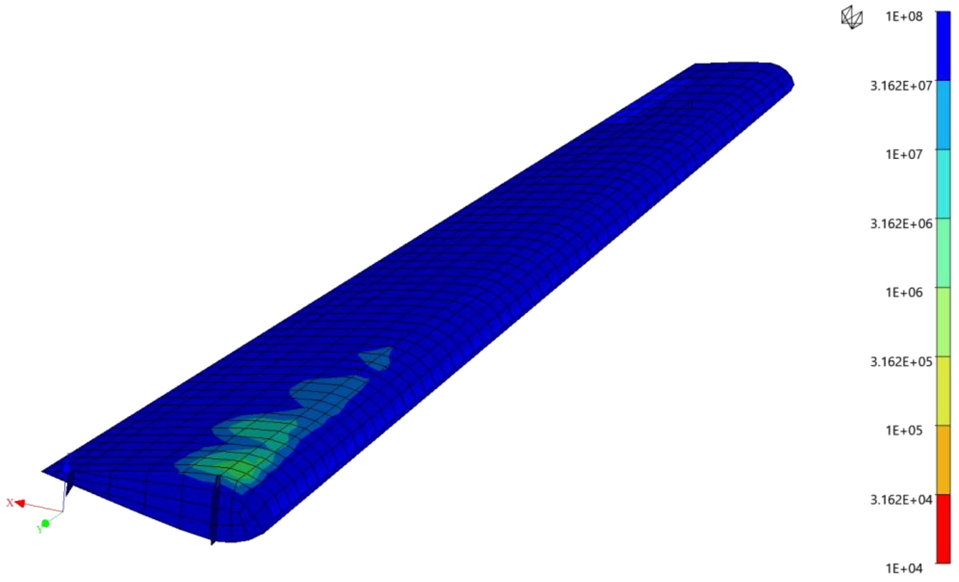
Summary and outlook

Fatigue modelling with Digimat and Marc

Other D-Standart developments

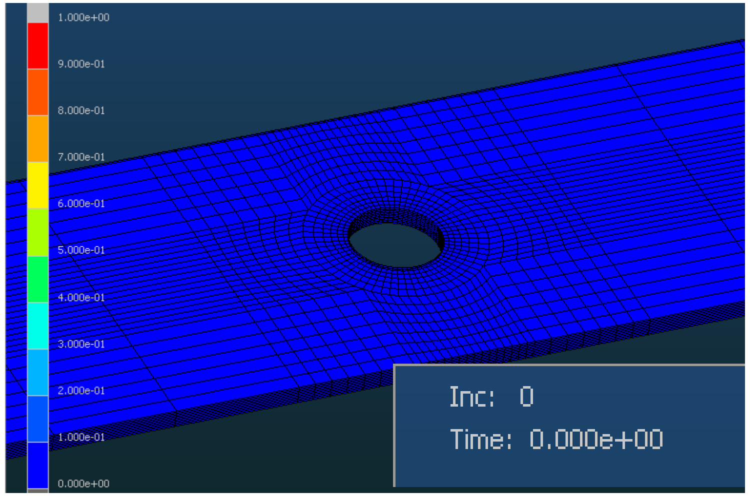
Summary and outlook

Fatigue modelling with Digimat and Marc



Digimat fatigue model

- Intralaminar fatigue model, it works on UD multidirectional composites.
- Model parameters from S-N curves at lamina level.
- Fast evaluation of fatigue life in composite components.
- Available from Digimat 2024.2.



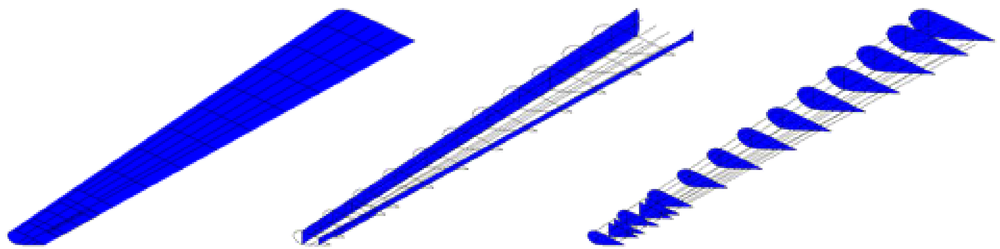
Marc fatigue failure

- Detailed intra and inter-laminar progressive fatigue failure model for composite materials.
- Minimal testing requirements (SN curves at lamina level, delamination characterisation).
- Implemented through Implicit FEA user subroutine (ufail).
- Final verification of approach in progress (requires SN curves for lamina and layup.

Chapter 9

Summary and outlook

Fatigue modelling with Digimat and Marc



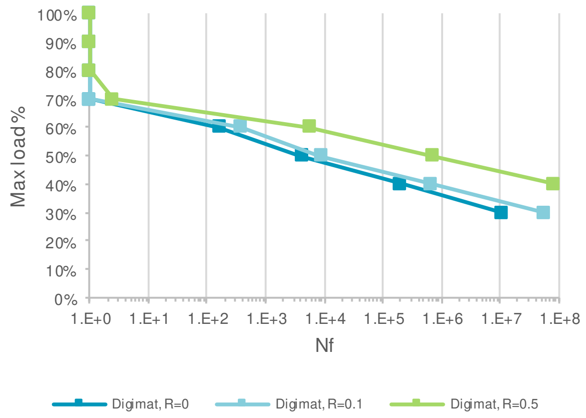
Model application in the context of D-Standart

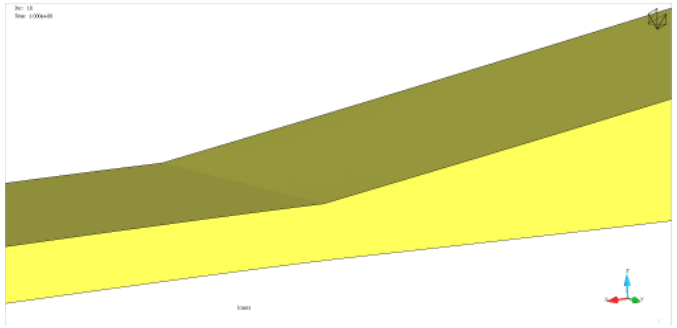
Fatigue modelling with Digimat:

- Parameter identification achieved on limited test data from the project. Required S-N curves at lamina level efficiently reverse-engineered with Digimat.
- D-standart fatigue test demonstrator was reproduced with Digimat, with fairly good agreement between test and simulation.
- Full S-N curves obtained for various R ratios in less than 2 hours in total.

Fatigue modelling with Marc:

- Failure inputs calibrated from test data, and model validated against literature.
- AI implementation of fatigue failure model to determine SN curves of full layups.
- D-Standart demonstrator showed similar damage mechanisms and good agreement to experiment, with slightly overestimated residual stiffness.
- Further tests are needed to better determine model accuracy.





Umaterial subroutine

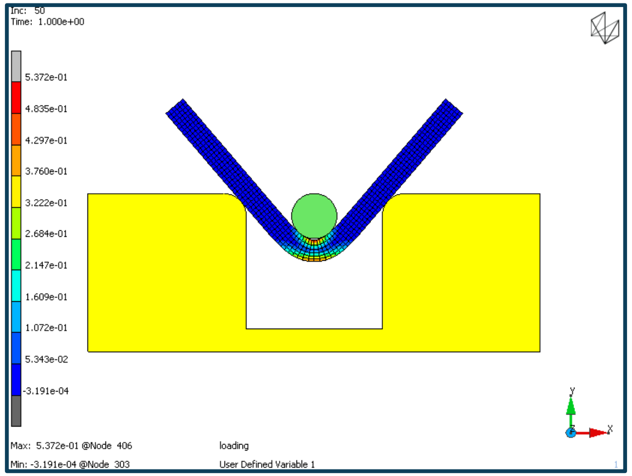
New addition to MARC

New subroutine framework developed for material behaviour in Marc 2025.1.

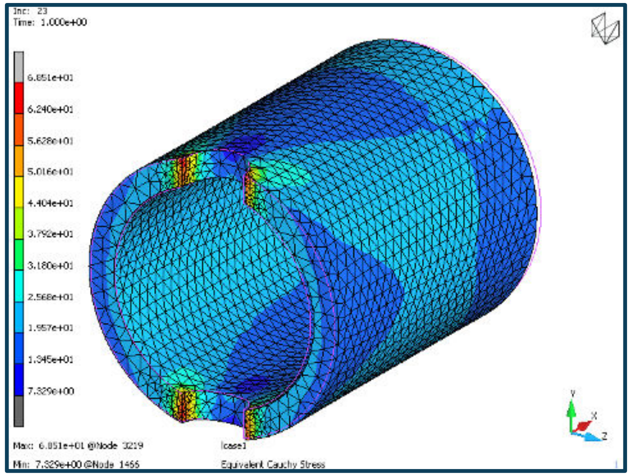
- Simplified user interface within pre-processor (Mentat)
- Reading of ‘umat’ (abaqus) directly in Marc 2025.2.

Within D-Standart it enabled:

- Connect with partners by simplifying implementation of the developed codes for Marc.
- Lamination parameters set within pre-processor (Mentat) environment, for user friendly implementation.
- Implementation of ONERA fatigue damage model.



*Forming of a Metal Bracket using the **UMATERIAL** Subroutine example available in the User’s Guide*



*Tube compression simulation using the **UMATERIAL** Subroutine example available in the User’s Guide*

ONERA fatigue model

New addition to MARC

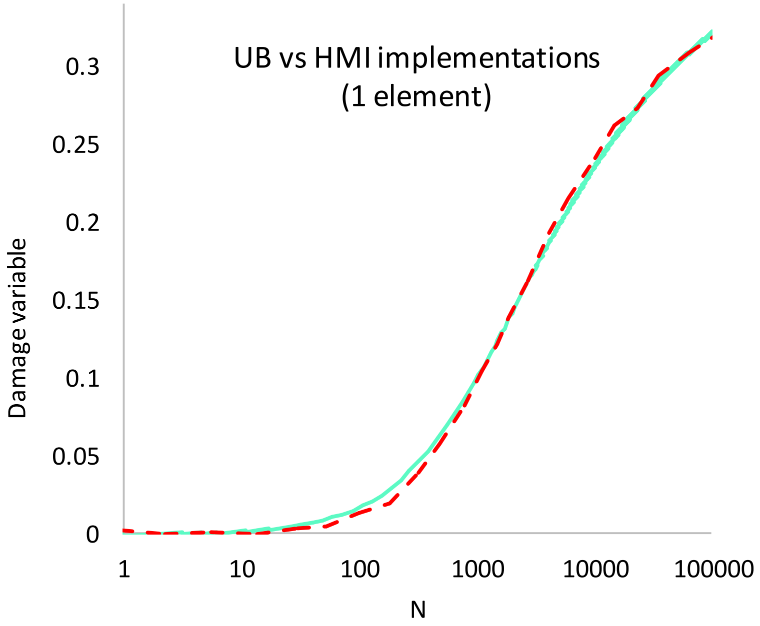
ONERA fatigue damage model (Rakotoarisoa, 2013)

- Originally developed for woven fabric composites, gives increment of damage, dD, with fatigue cycles, dN.

$$\frac{\partial d_{i\,total}^{(m)}}{\partial N} = \left(d_{c(i)}^{Fatigue} - d_{i\,total}^{(m)}\right)^{\gamma_i}\left(1+\left(\frac{\Delta y_i}{\Delta y_{0(i)}^{Fatigue}}\right)^{\beta_i}\right)\left(\frac{\left\langle y_{(i)max}^{(m)} - y_{0(i)}^{Fatigue}\right\rangle_+}{y_{c(i)}^{Fatigue}}\right)^{\delta_i}$$

- Implemented in Marc 2025.1 via UMATERIAL subroutine.
- Developed in agnostic form, based on 5 material parameters in 3 directions.
- Verified against University of Bristol data & model.
- Further validation against experiments planned for 2026.

Relevant model parameters
Static
$E_{11} = 53815 MPa$
$h_{11}^{1} = 1.0$
$y_1^c = 0.849\ MPa;\ y_1^0 = 0.4728\ MPa$
$p_1 = 1.913;\ d_1^c = 0.4$
Fatigue
$d_1^{c,f} = 0.4;\ \gamma_1 = 4.0;\ \beta_1 = 10.0;$
$y_1^{c,f} = 50.0 MPa;\ y_1^{0,f} = 0.155\ MPa$



C. RAKOTOARISOA - *Prévision de la durée de vie en fatigue des composites à matrice organique tissés interlock*. 2013. Doctorate thesis, Université de Technologie de Compiègne, France.

06

HMI AI approach

AI Agent and Model Context Protocol

Chapter 6

Hexagon and AI

AI Agent and Model Context Protocol

Level I-II: Assisted
- CAE + Sensors
- ML & ROM Support

→

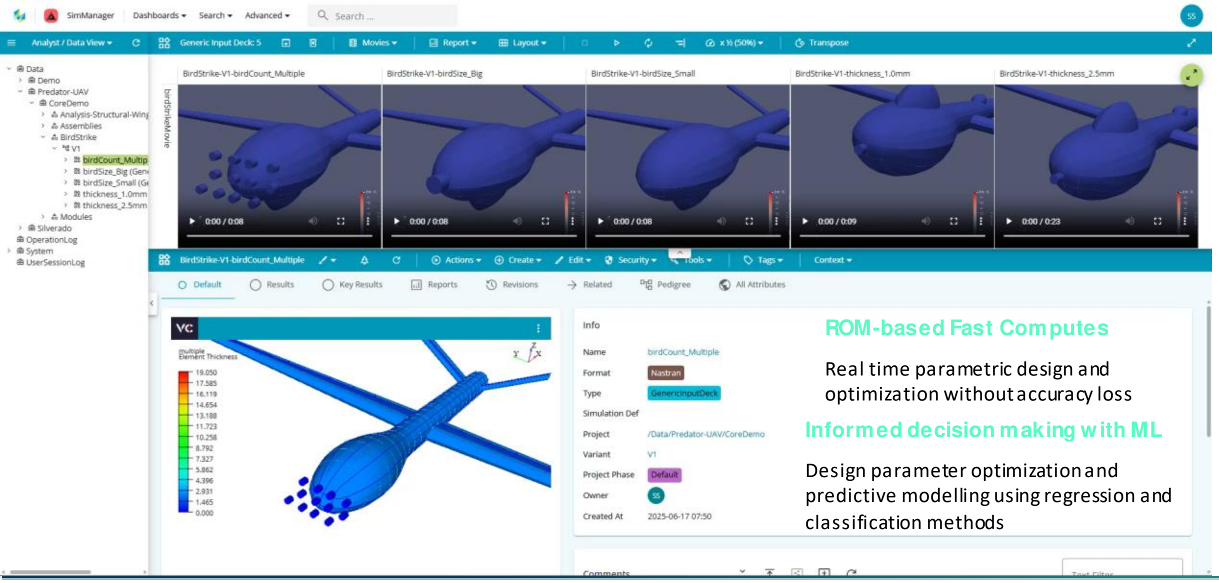
Level III-IV: Intelligent
- Physics AI
- AI Agents

→

Level V: Orchestrated
- Scaled Systems
- Multi-Agent

Example: Odyssee fatigue

Example: D-Standart Static AI



Physics AI
- Data is essential
- Data is limited
- Data is not shared

HMI data related to
Model Setup
NASTRAN, MARC, APEX, etc.

→

New approaches for AI and FEA
- AI agents
- Model Context Protocol

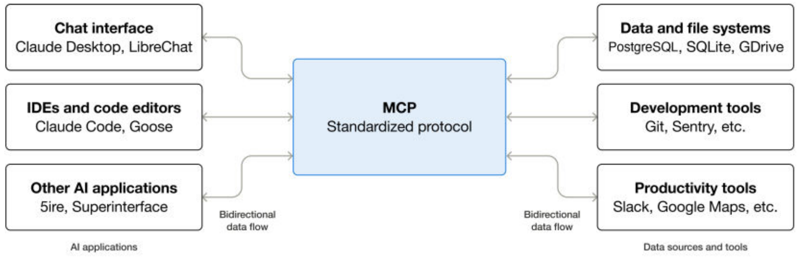
Chapter 6

Hexagon and AI

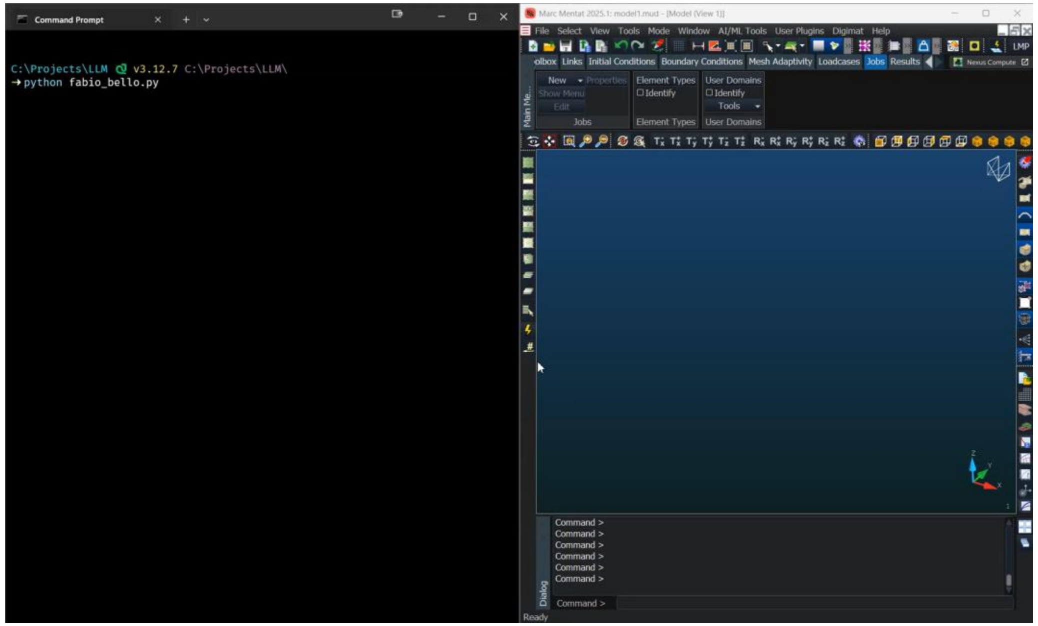
AI Agent and Model Context Protocol

Hexagon's new approach to AI:
AI Agent and MCP

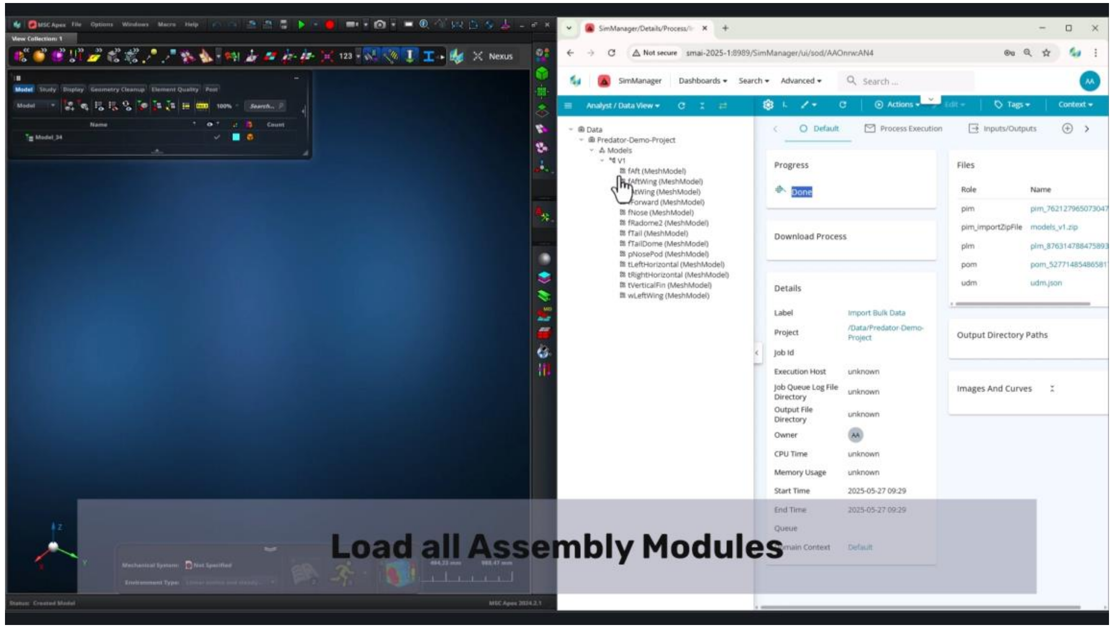
- Each company owns their own AI and/or data.
- HMI tools link with external AI tools (MCP)



AI agent implementation with Marc/Mentat:



AI integrated into SimManager and Apex:



Thank you!

Contact points for any question:

Presenters

- Fabio Malgioglio
- Email: fabio.malgioglio@hexagon.com
- Melle Gruppelaar
- Email: melle.gruppelaar@hexagon.com

HEXAGON

MSC Software

FOLLOW US ON:

zenodo

d-standart.eu

Coordinator

- Marco NAWIJN (NLR)
- Email: Marco.Nawijn@nlr.nl
- Phone: +31 88 511 44 86

Project Management Officer

- Mathieu LIONS (LUP)
- Email: mathieu.lions@l-up.com
- Phone: +33 7 83 28 19 82

Communication Officer

- Peggy FAVIER (LUP)
- Email: peggy.favier@l-up.com
- Phone: +33 6 75 64 10 78

standart

for Durability Modelling of Composites

Funded by
the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

UK Research
and Innovation