



# Session 2: AI surrogate model

**FINAL DISSEMINATION EVENT**, NLR Amsterdam (NL), December 17<sup>th</sup>

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van Hoorn (NLR), Gruppelaar (HMI), Soimoiris (TUD), Main (HMI), Talagani (NLR)**



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# Introduction



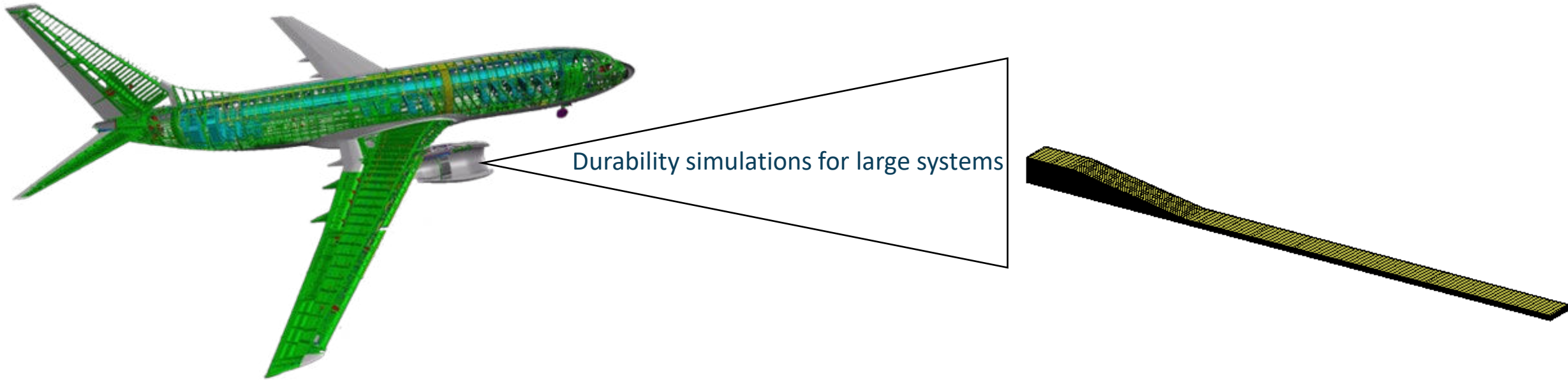


- › **Objective 1:** Develop modelling capabilities of the fatigue behaviour at the Micro-scale level.
- › **Objective 2:** Develop a probabilistic modelling capability at the Meso-scale level.
- › **Objective 3:** Develop capabilities for AI surrogate model at the Meso-scale level.
- › **Objective 4:** Exploit AI trained surrogate models for fatigue prediction of Macro-scale structure.
- › **Objective 5:** Experimental validation of the predictive modelling capabilities.

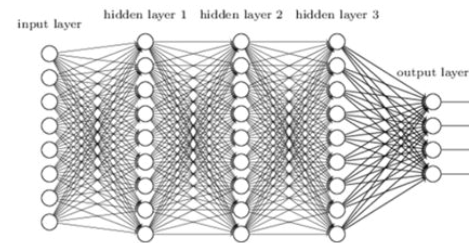
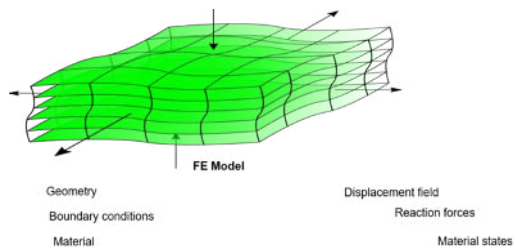
# Workflow highlights

Fatigue: large scale aerostructure

The major challenge is to develop simulation capabilities at macro scale maintaining the accuracy of mesoscale



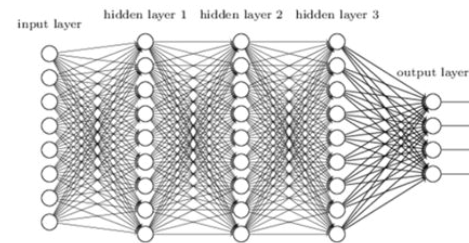
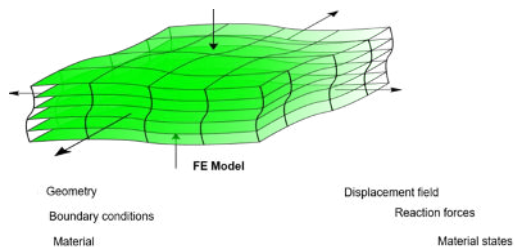
- Generate and exploit a cloud of probabilistic fatigue database to train AI.
- Integrate a surrogate fatigue model into subroutines.
- Use macroscale modelling exploiting subroutines for fatigue simulations.



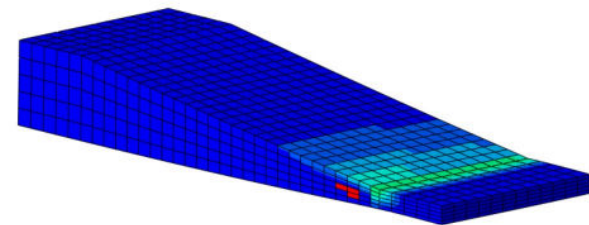
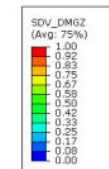
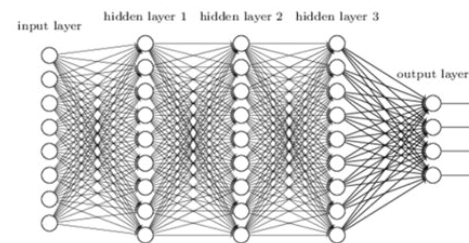
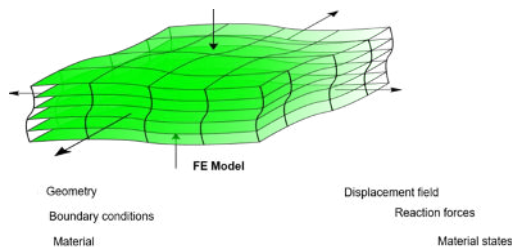
# Workflow highlights

## Exploitation of AI

- Generate and exploit a cloud of probabilistic fatigue database to train AI.
- Integrate a surrogate fatigue model into subroutines.
- Use macroscale modelling exploiting subroutines for fatigue simulations.



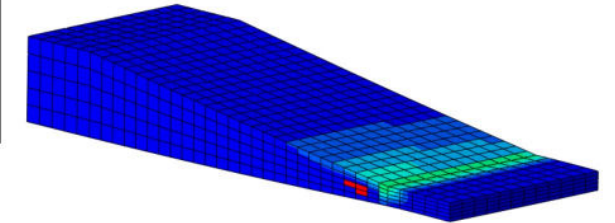
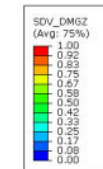
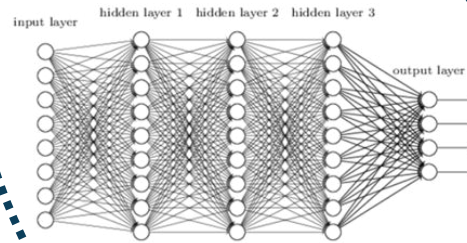
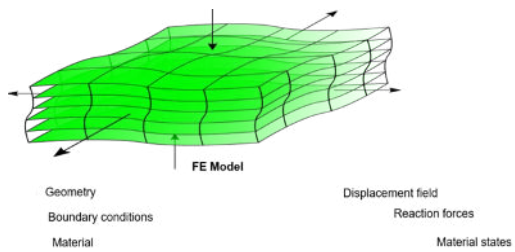
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# Workflow strategy

Static and Dynamic loading

**Strategy-1:** verify the surrogate model for a defect-free case under static loading



**Strategy-2:** develop and exploit the surrogate model fatigue analysis

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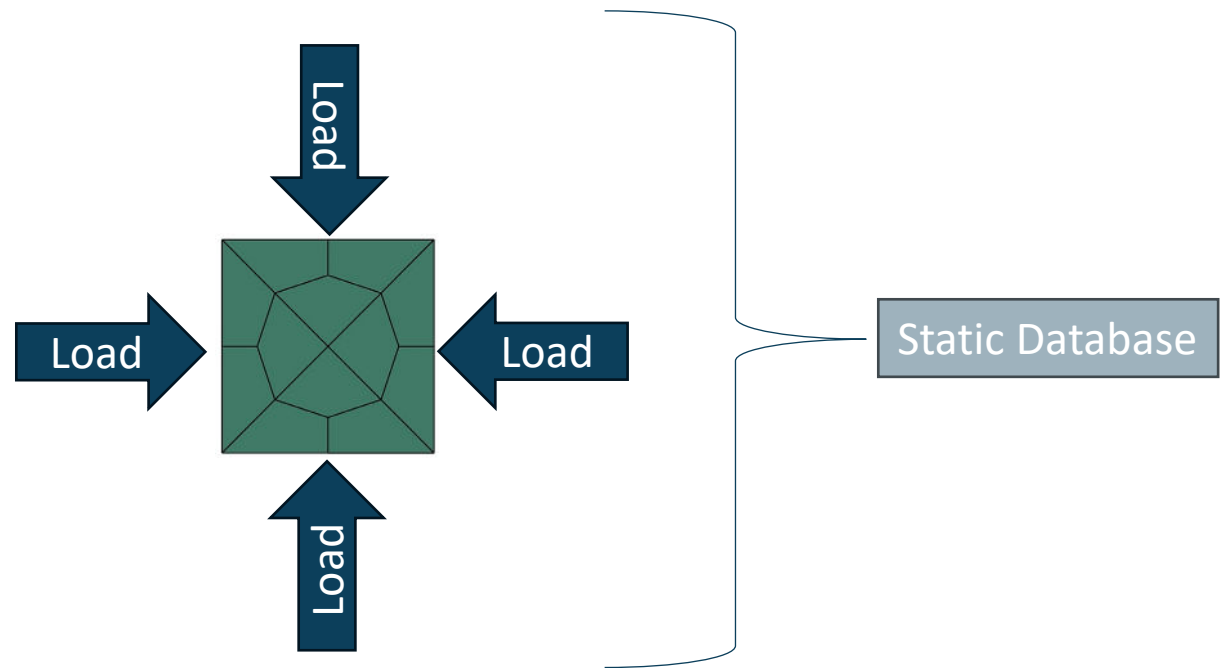
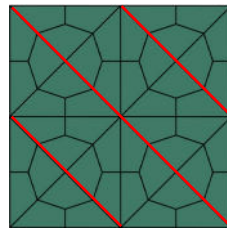
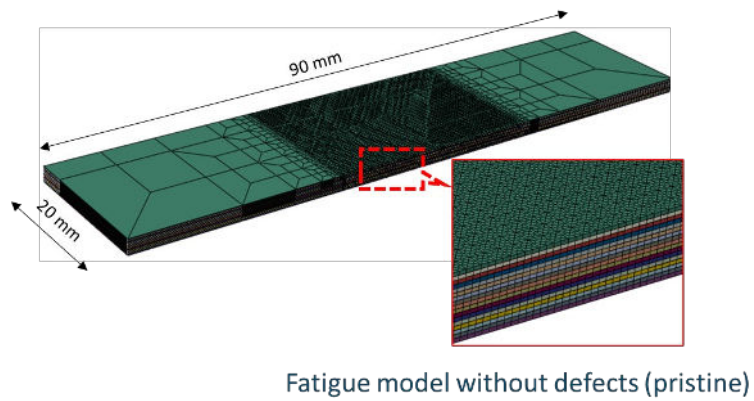
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for a defect-free case  
under static loading



# Representative Volume Element

Static database

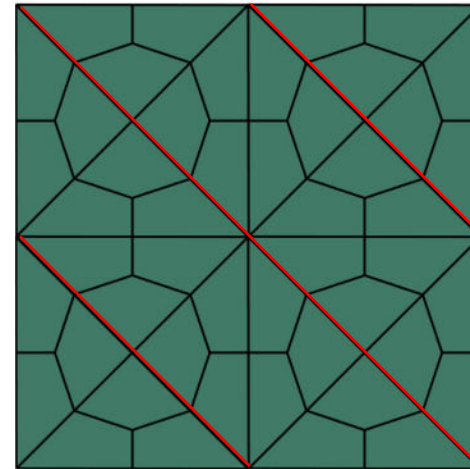
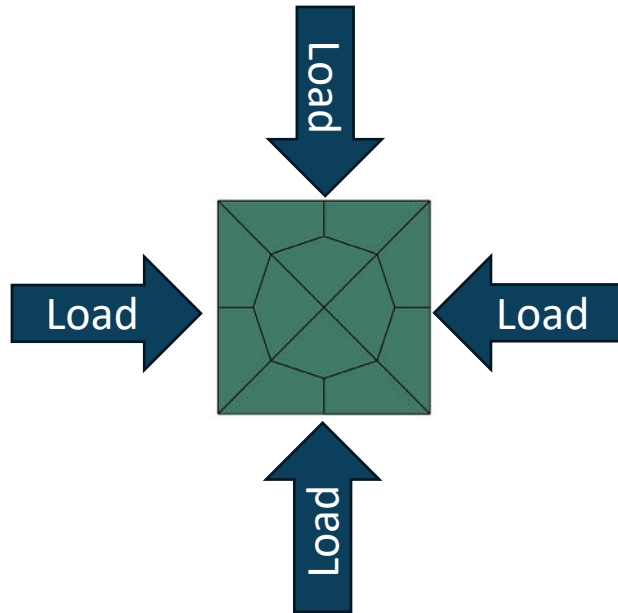
The mesoscale model with unit cell RVE used for generating the static database



# Boundary conditions

## Lesson learnt

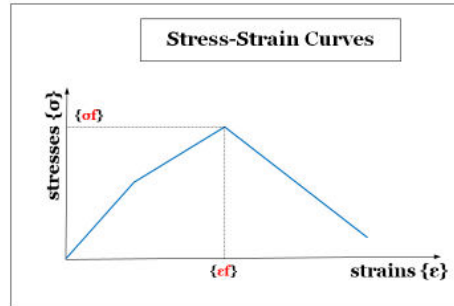
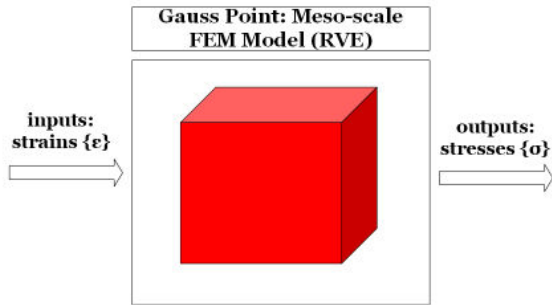
The RVE boundaries are not periodic in the mesoscale model. Hence, the static database presented inconsistencies which had to be corrected before the database could be used for the Ai training.



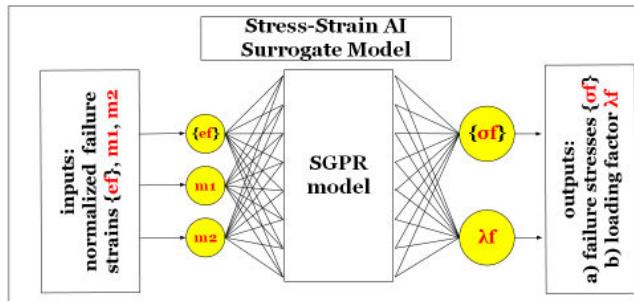
# Ai training

## The static database for AI training

Static Database

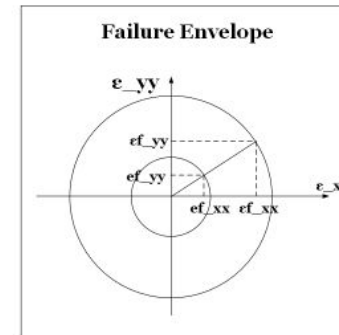


1. Get the failure strains of the samples:  
 $\{\epsilon_f\} = \{\epsilon_{f\_xx}, \epsilon_{f\_yy}, \epsilon_{f\_zz}, \epsilon_{f\_xz}, \epsilon_{f\_yz}, \epsilon_{f\_xy}\}$
2. Calculate the normalized failure strains:  
 $\{\epsilon_f\} = \{\epsilon_f\} / \lambda_f$   
 where:  $\lambda_f = ||\{\epsilon_f\}|| \rightarrow$  load factor (failure strains norms)
3. Get the failure stresses of the samples:  
 $\{\sigma_f\} = \{\sigma_{f\_xx}, \sigma_{f\_yy}, \sigma_{f\_zz}, \sigma_{f\_xz}, \sigma_{f\_yz}, \sigma_{f\_xy}\}$
4. Build the AI-surrogate using as:  
 inputs:  $\{\epsilon_f\}, m_1, m_2$   
 outputs:  $\{\sigma_f\}, \lambda_f$   
 $\{\epsilon_f\}, m_1, m_2 \leftarrow (GP) \rightarrow \{\sigma_f\}, \lambda_f$



### Multi-scale Procedure:

1. From macro-scale model: get strains at each Gauss point at time t:  $\{\epsilon_t\}$
2. Stresses from Hooke's Law:  $\{\sigma_t\} = [D] \{\epsilon_t\}$
3. Normalized strains at time t:  $\{\epsilon_t\} \Rightarrow \{\epsilon_t\}$
4. Calculate failure stresses along that direction from AI-surrogate:  
 input:  $\{\epsilon_t\} \Rightarrow$  output:  $\{\sigma_f\}, \lambda_f$
5. Compare actual stresses from step 2) with failure stresses from step 4):
  - i. if  $\{\sigma_t\} < \{\sigma_f\} \Rightarrow$  return  $\{\sigma_t\}$  to the macro-scale
  - ii. else if  $\{\sigma_t\} \geq \{\sigma_f\} \Rightarrow$  failure occurs

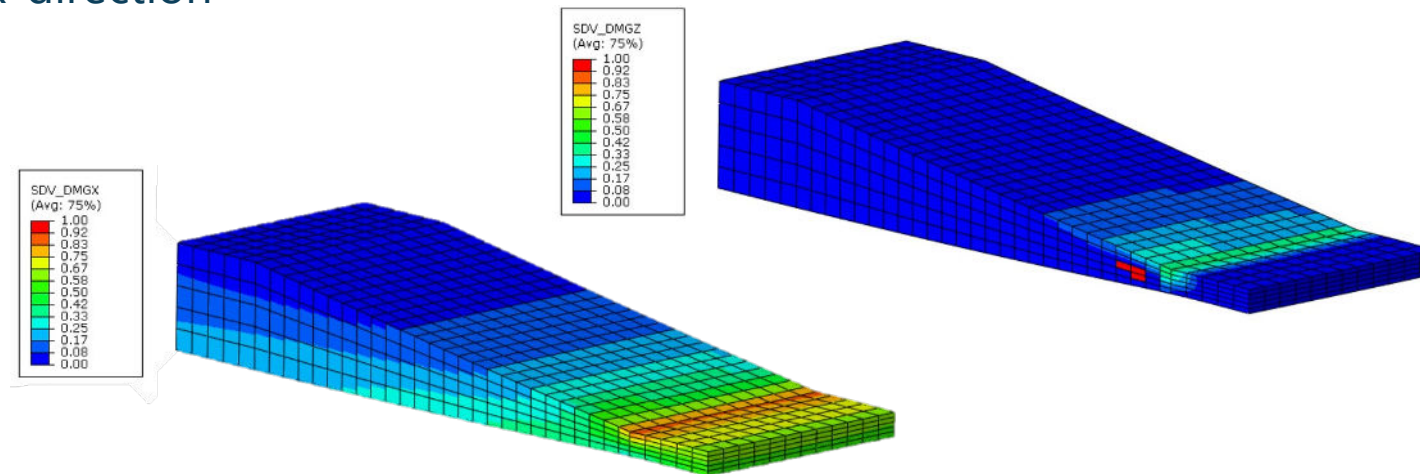


# Macro model validation

## Integration of AI static surrogate model

The macro-scale methodology, utilising the AI surrogate model VUMAT, has been applied to the aero demonstrator.

Despite limitations, the model provides a good qualitative prediction of the delaminations observed during testing, with damage initiation in the z-direction combined with a relatively high damage parameter in the x-direction



Predicted damage initiation parameters in the ply drop region of the aero demonstrator at a static load of 140 kN.



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- › **Objective 5:** Experimental validation of the predictive modelling capabilities. → 😊

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**Strategy-2:**  
develop and exploit  
the surrogate model fatigue analysis



## Some insights

From RVE to Material clustering

- The probabilistic mesoscale fatigue modelling based on RVE was replaced by a novel and more efficient strategy.
- Material clustering is a process which divides an FE model into clusters, called material cluster.
- Each cluster embeds part of the stacking sequence including features like ply-drops.
- A partition of a structure into cluster is like performing a macroscale meshing.
- The material clustering can generate redundant clusters which can be dismissed, if desired.
- Each material cluster can be loaded to generate stress-strain relationships to build a fatigue database.

## Some insights

### From RVE to Material clustering

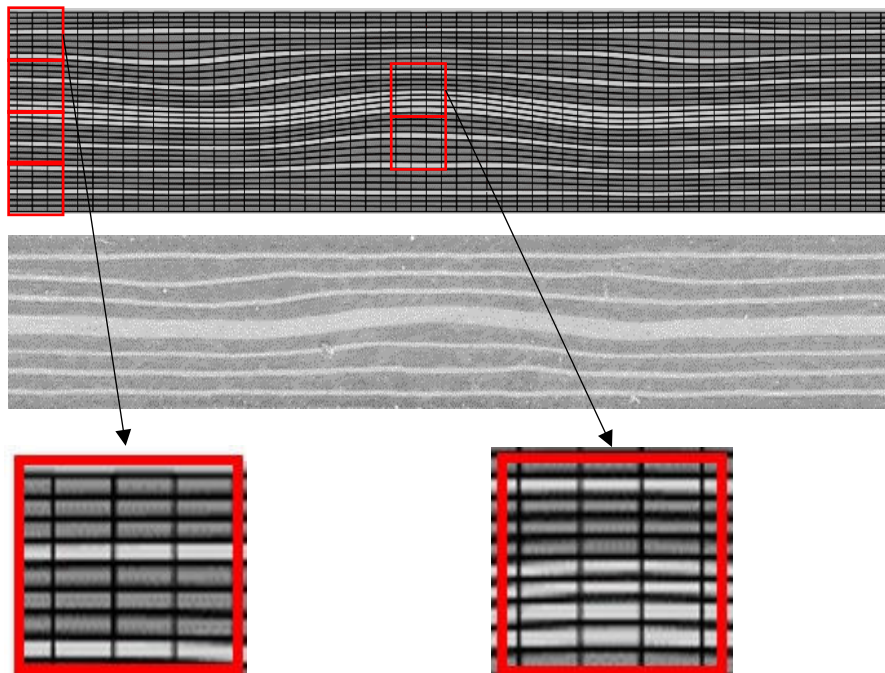
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# Example of material clustering

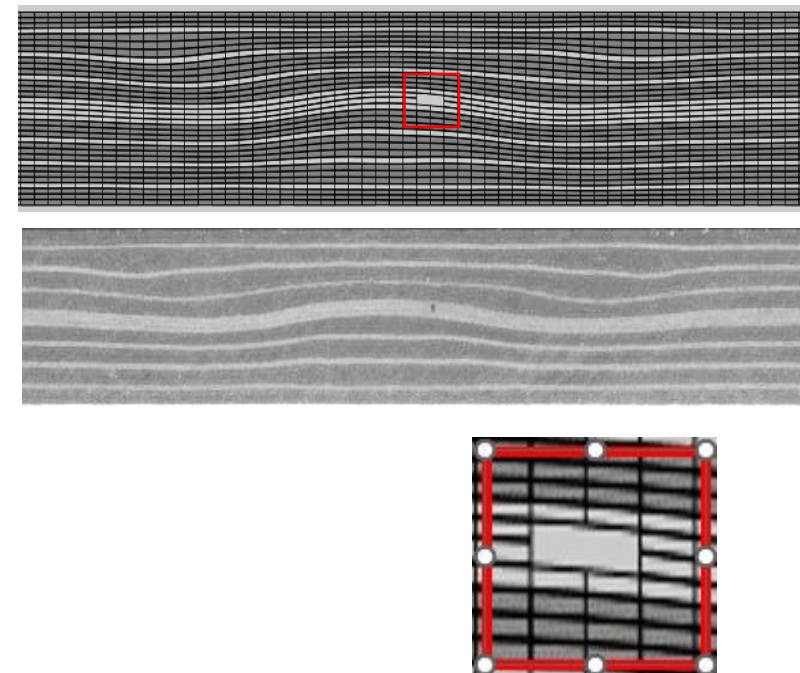
## Coupon with waviness

The coupon is partitioned in many clusters (red boxes); some examples of clusters are presented indicating features like waviness or cut-ply

Mesoscale model of coupon with waviness

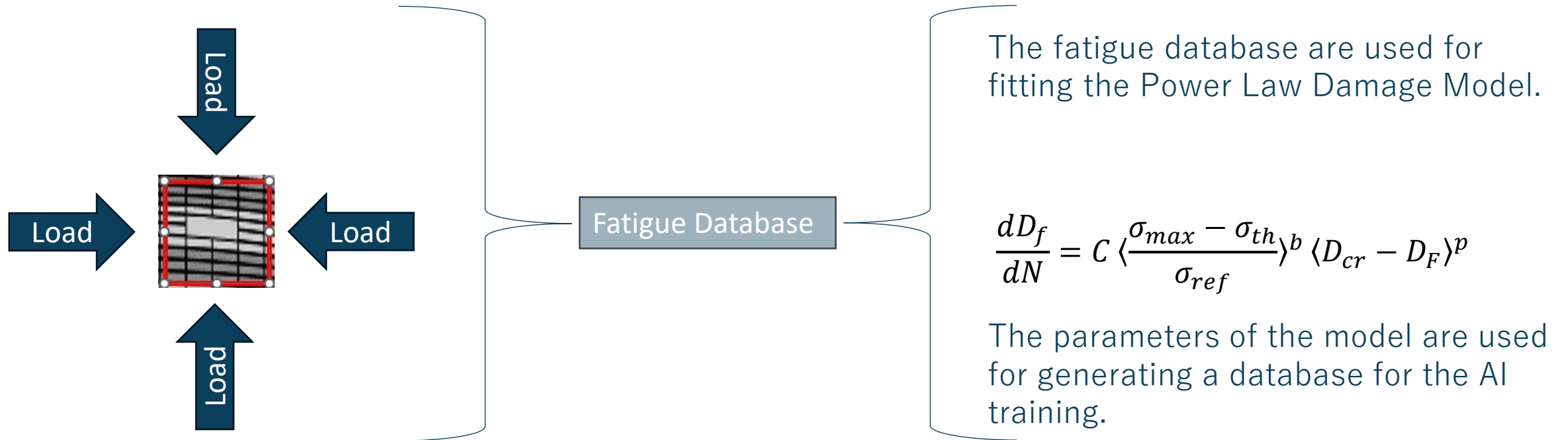


Mesoscale model of coupon with waviness and cut-ply



# Fatigue database generation

Using material clusters



# Power Law Damage Model

## Calibration and use

The cyclic loading applied to the clusters was tension-tension.

The use of the stress-strain data from the simulation resulted in a one direction damage model.

The number of parameters generated were insufficient for any AI training.

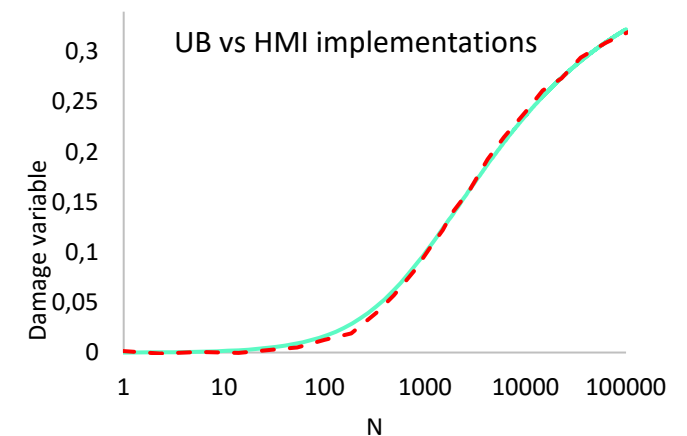
The model was implemented into HMI subroutine to attempt a comparison.

Both the material clustering and the single axis cyclic loading reduced the complexity of the fatigue problem.

Although the AI could not be trained, it does not indicate the strategy being invalid.

## Other developments:

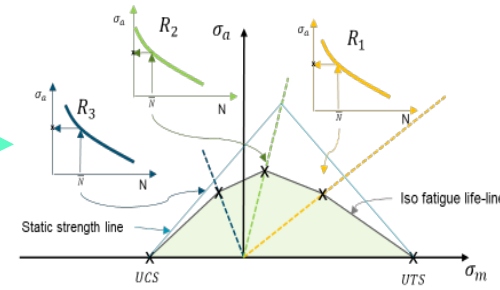
- › Umaterial subroutine
- › Power Law Damage Model



# Fatigue using Digimat and Marc

New fatigue of composites techniques:

Experiments:  
SN curves



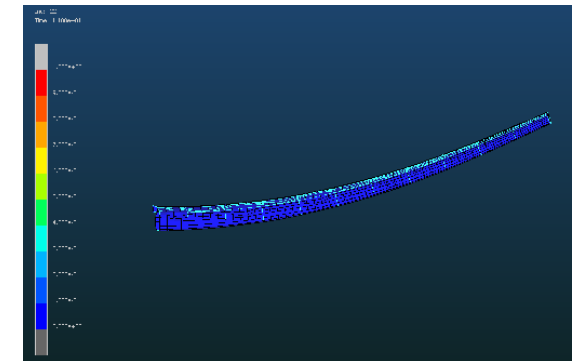
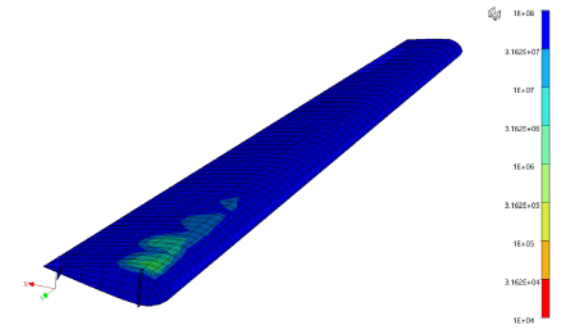
Digmat fatigue life  
Marc failure FEA

› **Digmat:**

- › 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:**

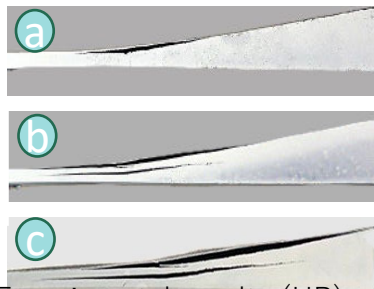
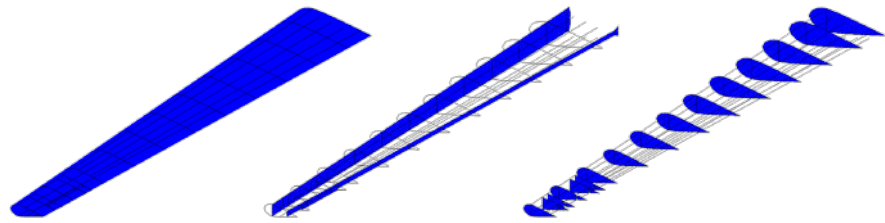
- › Detailed modelling of fatigue using progressive failure and damage models.
- › Delamination and intra-laminar fatigue.
- › Crack growth with Paris Law (short cycle or high cycle fatigue).
- › Suitable for detailed analyses of damage onset and propagation in components and designs.



Chapter 3

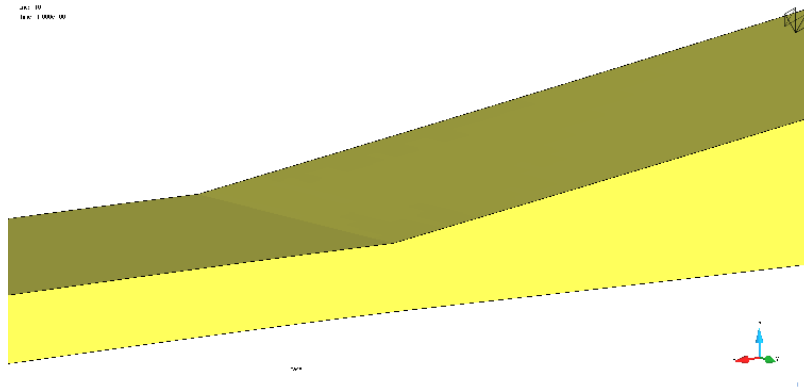
# Aero demonstrator and AI/ML

## Aero demonstrator

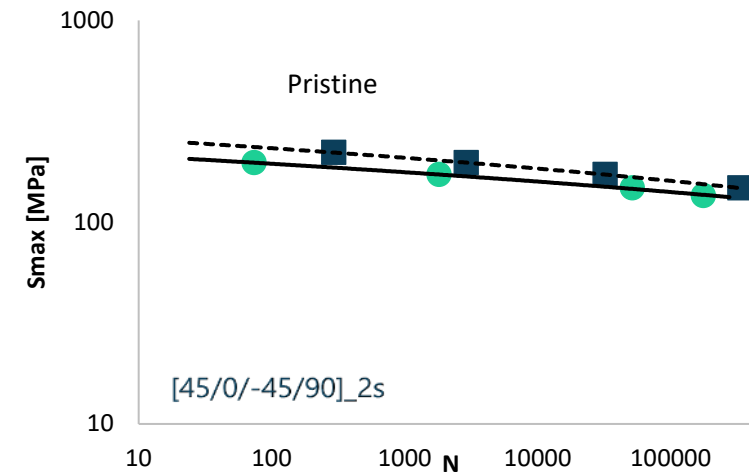
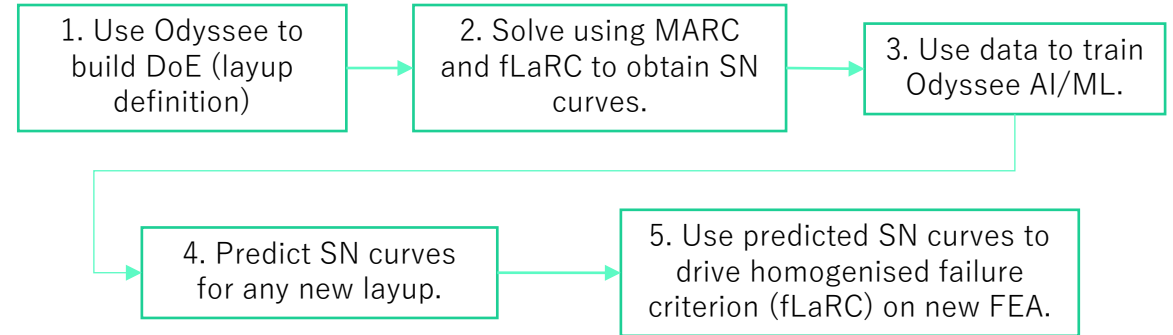


Experimental results (UB)

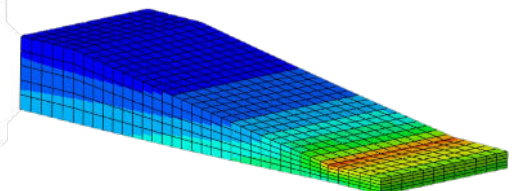
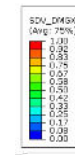
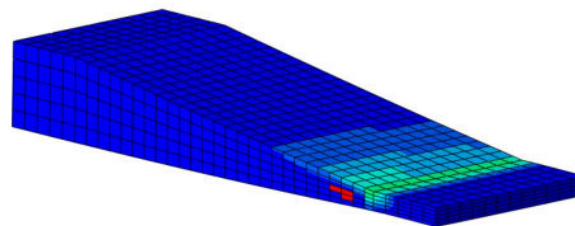
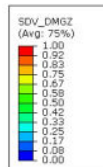
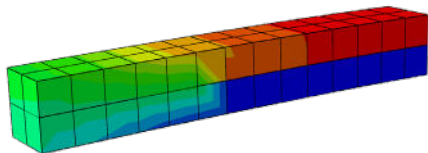
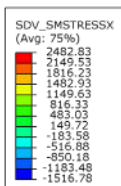
- a: ~ 5% stiffness drop
- b: ~ 15% stiffness drop
- c: ~ 25% stiffness drop



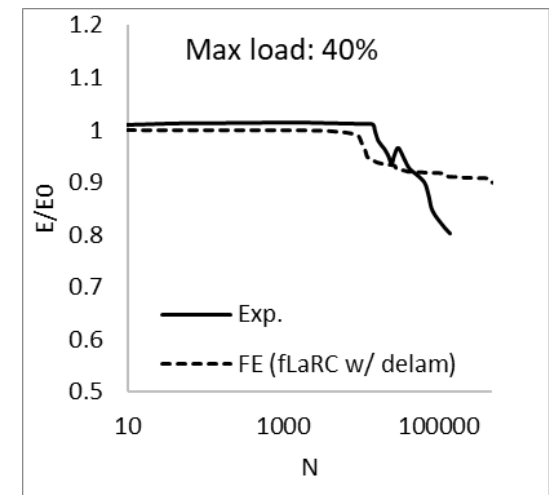
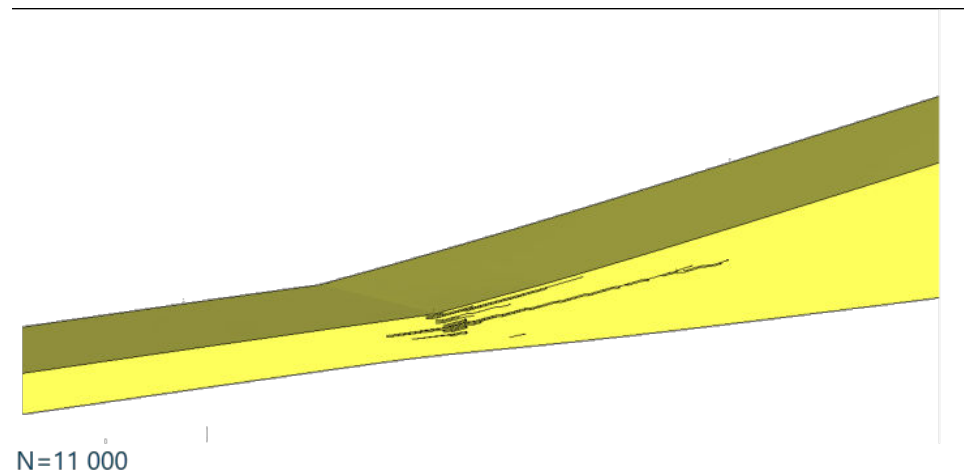
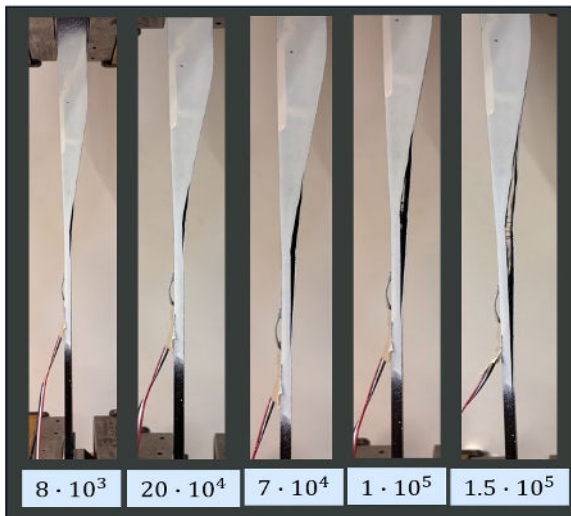
## AI/ML proof of concept (fatigue)



- **Integration of a Sparse Gaussian Process Regression (SGRP) surrogate model into Finite Element Analysis: bridging the gap between meso- and macro-scale**
  - With high-fidelity meso-scale modelling the UB generated a database that linked the strain components and material properties (i.e., inputs) to the failure stresses (i.e., outputs) for a defect free IM7/8552 composite specimen.
  - This database was used by TUD for training a Sparse Gaussian Process Regression (SGPR) surrogate model. The parameters of this surrogate model were extracted and integrated in a VUMAT subroutine for Abaqus/Explicit.
  - A SGPR surrogate model was implemented by NLR in the commercial FEM software Abaqus and verified using single element, cantilever beam, and coupon models. The methodology replaces expensive, high-fidelity meso-scale models with more efficient and easier-to-set-up macro-scale models.



- › **The fatigue failure model (fLaRC) was added to the advanced nonlinear implicit FEA solver Marc through a user subroutine.** The fLaRC technique with delamination was employed in the study of the aero demonstrator at load levels between 40% and 70% of the static strength. The numerical analyses revealed a progressive stiffness degradation with a plateau between 90% and 95% of the static stiffness.
- › In all cases, fatigue damage initiated through delamination of the interface near the top edge of the specimen, followed by progressive increase of the size and number of delaminated interfaces. Intra-ply damage was observed, but without major contribution to the failure process.



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## Conclusions





› **Objective 2:** Develop a probabilistic modelling capability at the Meso-scale level. → 😊 😞

› The development of a probabilistic modelling capability based on RVE failed to deliver a fatigue database.

› The use of material clustering simplified the selected fatigue test case (coupon with waviness). The Power Law Damage Model did not generate enough parameters for a fatigue database.

› **Objective 3:** Develop capabilities for AI surrogate model at the Meso-scale level. → 😞

› The task suffered the lack of data for training AI. It is highly recommended adding a deliverable on fatigue database, ie O2 and O3, to ensure that a **very large** dataset is generated for an AI training exercise.



› **Objective 4:** Exploit AI trained surrogate models for fatigue prediction of Macro-scale structure. → 😊 😞

› This objective was managed by HMI which could exploit their internal resources to deliver a macroscale modelling approach.

› The use of DIGIMAT, Marc and the failure model (fLaRC) allowed simulating the fatigue behaviour of the wind and aero demonstrator.

› **Objective 5:** Experimental validation of the predictive modelling capabilities. → 😞

› The coupon with waviness, the aero and wind demonstrator did not present a complex fatigue behaviour, meaning that delamination was the dominant damage mechanism.

› The modelling of the aero and wind demonstrator was resolved using state-of-the-art cohesive analysis.

› It is advisable developing for a future project a test structure exhibiting richer damage mechanisms which will make the material clustering data generation and AI training more valuable.

## Chapter 4

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**D-STANDART - Experimental mechanical test data set**

Monticeli, Francisco (Researcher)<sup>1</sup>; Biagini, Davide (Researcher)<sup>1</sup>; Pascoe, John-Alan (Work package leader)<sup>1</sup>; Mosleh, Yasmine (Project member)<sup>1</sup>; Di Maio, Dario (Work package leader)<sup>2</sup>; Ren, Yunxia (Researcher)<sup>3</sup>; Beketova, Hanna (Researcher)<sup>4</sup>; Allegri, Giuliano (Work package leader)<sup>5,6</sup>; Amsterdam, Emiel (Researcher)<sup>7</sup>; van den Brink, Robbert-Jan (Researcher)<sup>7</sup>

| Name  | Size     | Actions           |
|---|----------|-------------------|
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| DCB (Fibre Orientation effect) - Fatigue Mode I.rar       | 4.8 GB   | Download          |
| DCB (Fibre Orientation effect) - Quasi-static Mode I.rar  | 4.1 MB   | Download          |
| DCB (Fibre orientation effect)_NLR_final.7z               | 481.3 MB | Download          |
| ELS (Fiber Orientation effect)- Fatigue Mode II.rar       | 569.3 MB | Download          |
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