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Coupling of Deep Learning on Graphs and Model Order Reduction for Efficient Preliminary Sizing of Mechanical Structures in Aircraft Crash Simulations

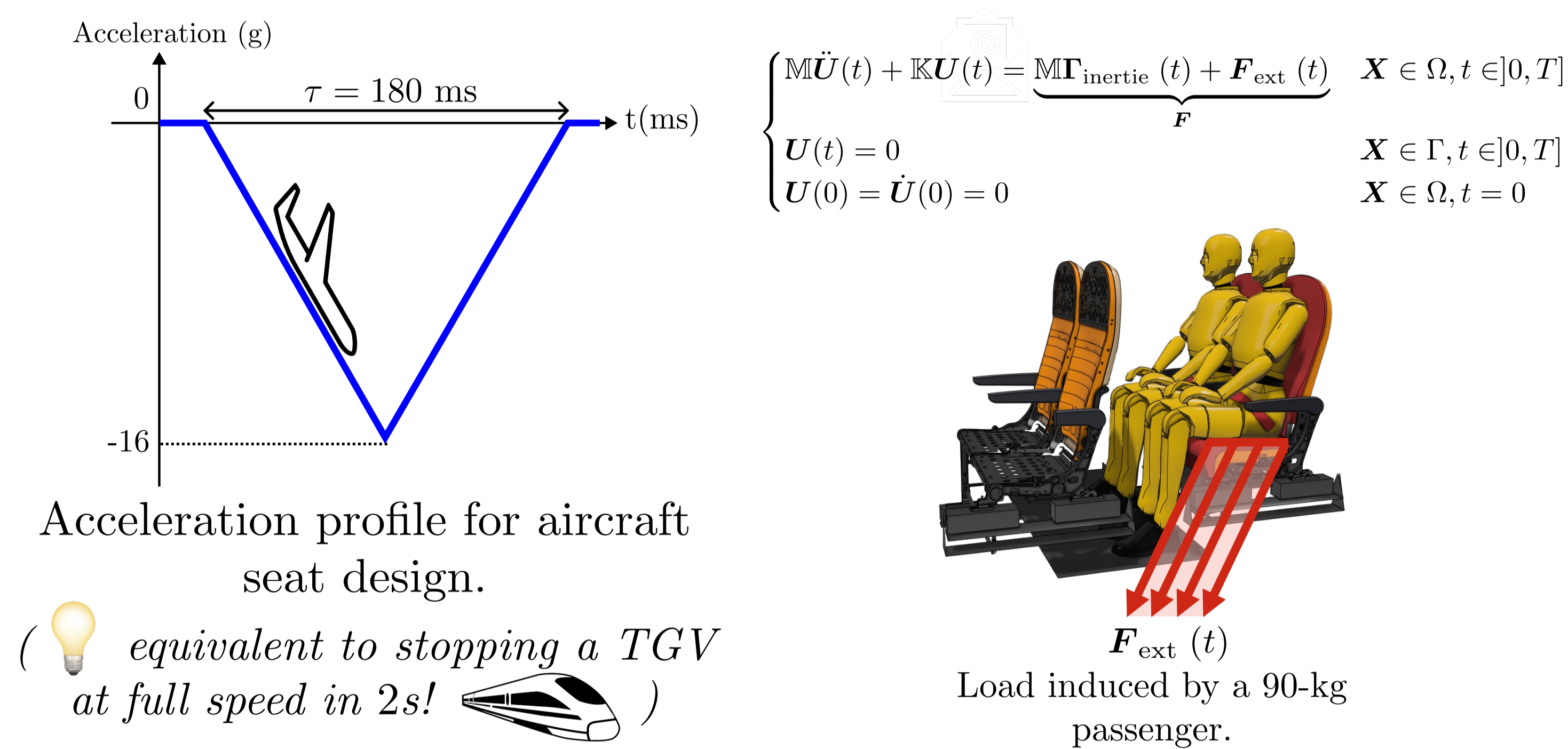
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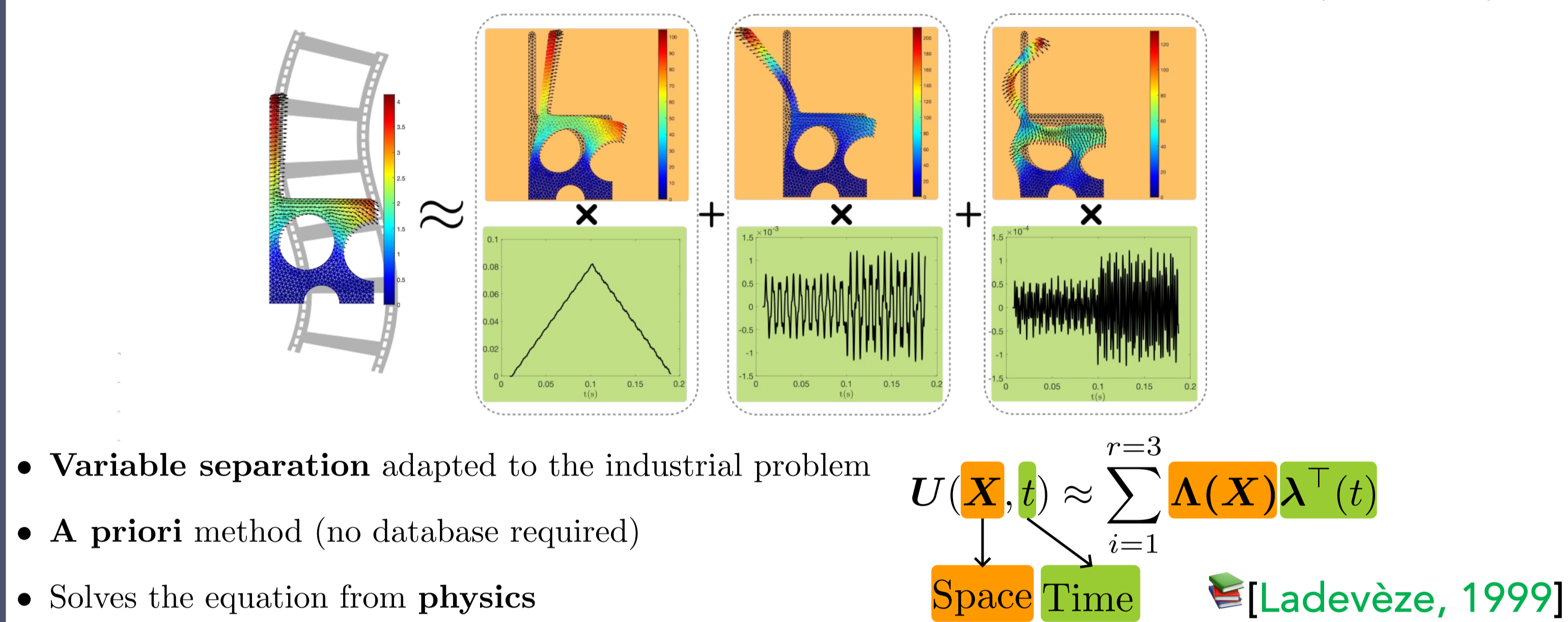
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Keywords: Reduced Model (POD-PGD), Non-Parametric Problem, Deep Learning, Graph Neural Networks

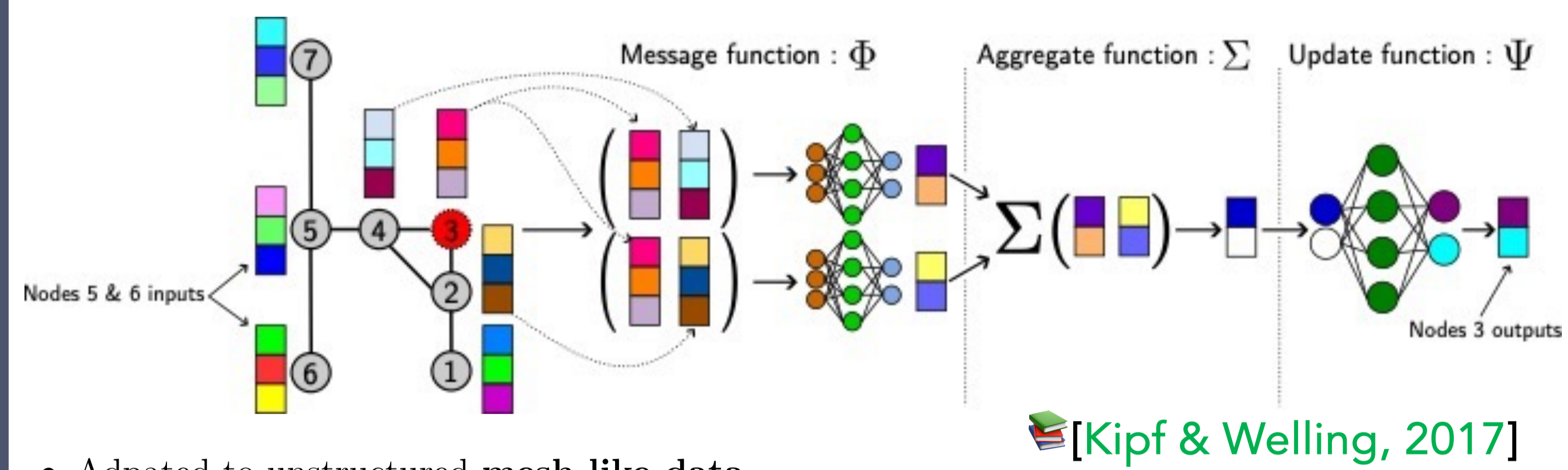
1-Loading case:



2-The Proper Generalized Decomposition (PGD):



3-Graph Neural Networks (GNN):



- Adapted to unstructured mesh-like data
- Does not depend on the number of nodes and edges in the input graph, only in the number of input features (through permutation-invariant aggregate function)
- High flexibility and generalisability

Developed spatial convolution layer:

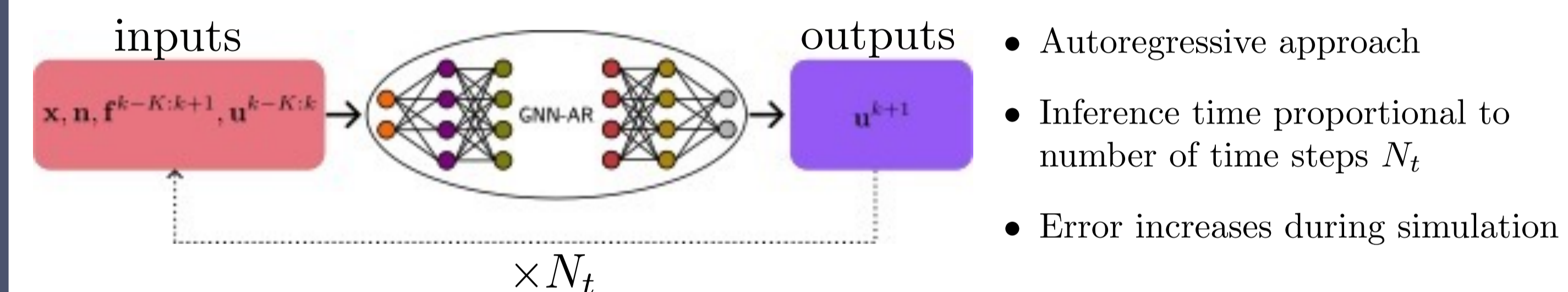
node i embedding: $v_i^0 = \text{MLP}_{\text{encoder}}(F_i, n_i)$,

edge $j \rightarrow i$ message: $m_{ij}^l = \phi(v_i^l, v_j^l, F_i, F_j, n_i, n_j)$, [Huang et al., 2018]

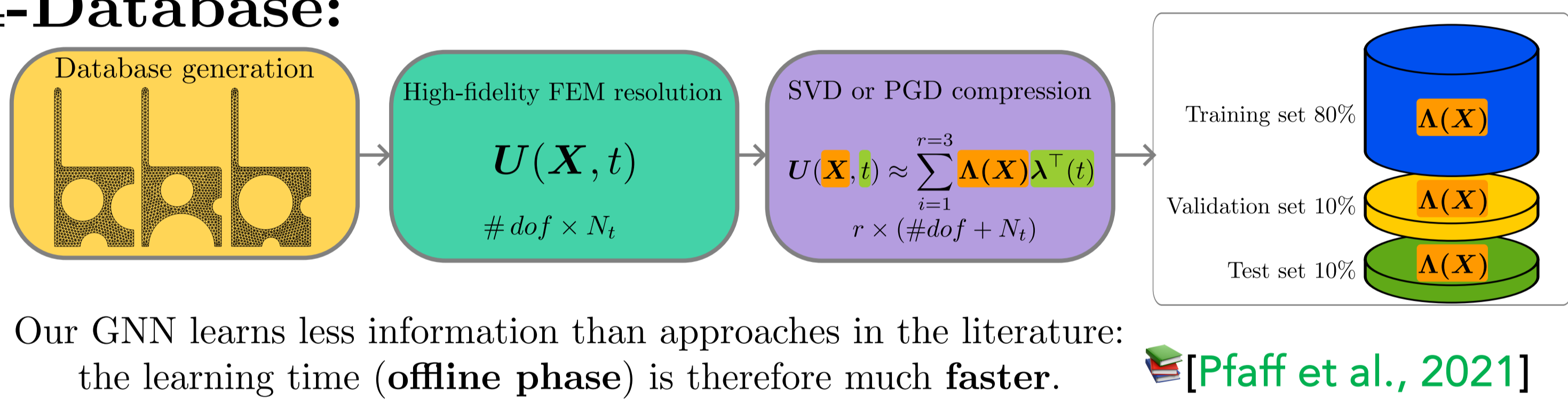
node i update: $v_i^{l+1} = \psi(v_i^l, \sum_{j \in \mathcal{N}(i)} m_{ij}^l, F_i, n_i)$,

node i final state: $\Lambda_i^{\text{GNN}} = \text{MLP}_{\text{decoder}}(v_i^L)$ [Brandstetter, 2022]

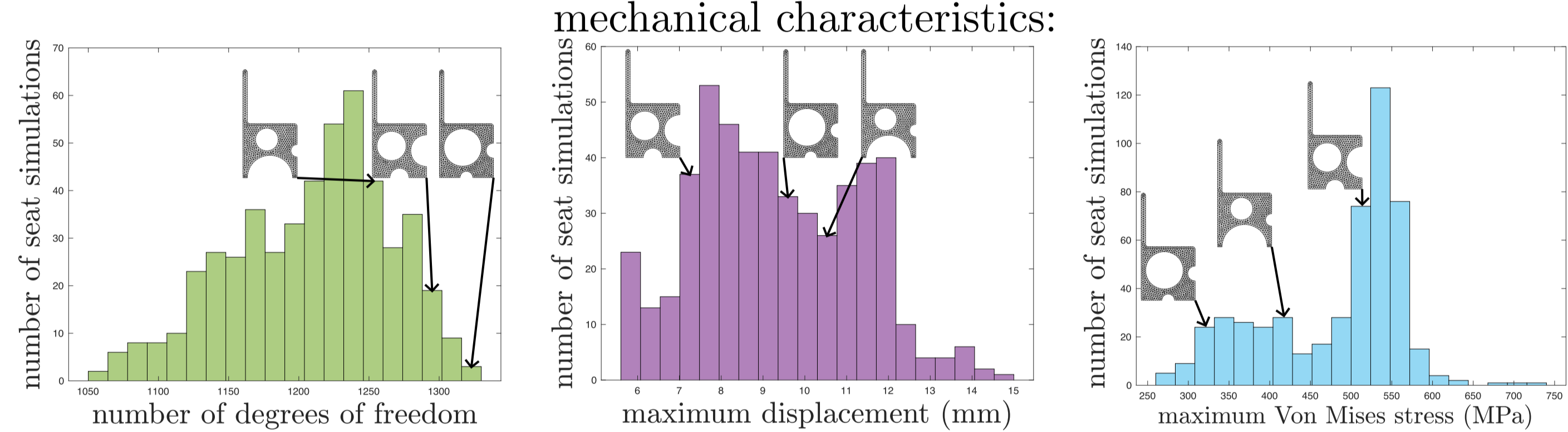
Popular approach in the literature: [Pfaff et al., 2021]



4-Database:



The small database (500 seats) contains a wide variety of seats with very different mechanical characteristics:



5-Proposed algorithm and results:

We only consider seats **never seen by the network** during training (test base).

We want to calculate the time modes: λ

Finite element operator calculation: M et K

Galerkin projection on P :

$$P^T \cdot M \cdot P \ddot{\lambda}^T + P^T \cdot K \cdot P \lambda^T = P^T \cdot F$$

-POD trick- use a suitable scalar product to precondition the problem,

$$\langle \circ, \square \rangle_{\mathbb{K}-1} = \circ^T \mathbb{K}^{-1} \square$$

Finally, we only solve the small ODE system ($r \times r$):

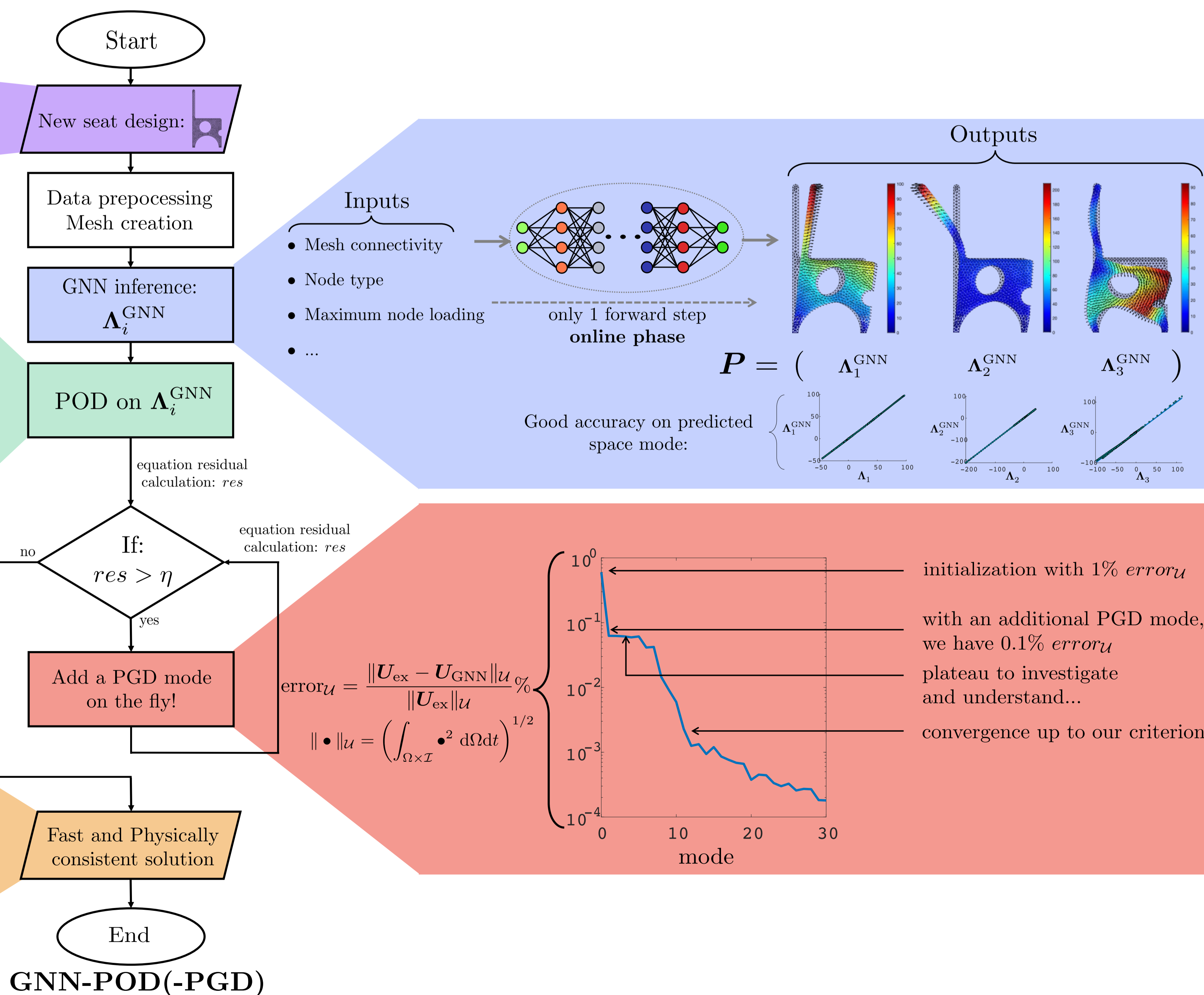
$$P^T \mathbb{K}^{-1} M P \ddot{\lambda}^T + P^T \mathbb{I} P \lambda^T = P^T \mathbb{K}^{-1} F$$

For the 50 seats tested, we obtained an $error_u$ of less than 1% immediately after the GNN-POD phase.

Furthermore, as soon as an on-the-fly PGD mode is added, we obtain an $error_u$ of at least less than 0.1% for all the seats tested.

In all cases, we solve the physical equation: **physics has the final say!**

For all the seats tested, we speed up the calculation thanks to the prediction of GNN spatial modes, but if this were not the case, we wouldn't take longer than a reduced-order PGD model.



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