



# DEVELOPMENT OF COMPUTATIONALLY EFFICIENT MULTI-FIDELITY MODELS for SPACE SYSTEMS

C. Franceschini, M. Petrolo, M. Filippi, A. Pagani, E. Zappino, E. Carrera

MUL2 Lab, Department of Mechanical and Aerospace Engineering, Politecnico di Torino

Spoke 2

Spoke 8

## Advanced structural simulations for SPACE STRUCTURES

The main challenges in structural simulation of space structures are the accurate modelling of advanced materials (e.g., composites and anisotropic behaviour) and the inherently multiphysics nature of the problem. In addition, thermal effects and harsh space environments (thermal cycling, vacuum, radiation) must be accounted for, together with nonlinear responses such as large deformations, contact, and buckling.

**1D**

$$u_x = u_{x1} + Xu_{x2} + Zu_{x3} + x^2u_{x4} + xZu_{x5} + \dots$$

$$u_y = u_{y1} + Xu_{y2} + Zu_{y3} + x^2u_{y4} + xZu_{y5} + \dots$$

$$u_z = u_{z1} + Xu_{z2} + Zu_{z3} + x^2u_{z4} + xZu_{z5} + \dots$$

\*E. Carrera, Applied Mechanics Reviews (2003), 56, pp. 287-308  
E. Zappino et al., CMAME, Volume 415, 1 October 2023, 116212

**2D**

$$u_x = u_{x1} + Zu_{x2} + z^2u_{x3} + z^3u_{x4} + \dots$$

$$u_y = u_{y1} + Zu_{y2} + z^2u_{y3} + z^3u_{y4} + \dots$$

$$u_z = u_{z1} + Zu_{z2} + z^2u_{z3} + z^3u_{z4} + \dots$$

**3D**

**MUL2**

**BENEFITS**  
Accurate prediction  
Computational efficiency  
Engineering robustness

**WHAT IS THE CORE CHALLENGE?**  
Finding a balance between:

**ACCURACY OF THE RESULTS** vs **COMPUTATIONAL COST**

DOF vs Error graph showing a decreasing curve.

**APPLICATIONS**  
Composite primary structures  
Nonlinear response  
Progressive damage

**Composite module\***

**Mesh refinement**

\*Collier et al., AIAA 2008-2251, 2008, doi:10.2514/6.2008-2251.

## What MULTI-FIDELITY is

Multi-fidelity methods combine low-fidelity (LF) and high-fidelity (HF) data to achieve accurate model predictions while reducing computational and experimental cost. Node-Dependent Kinematics (NDK) within the CUF framework enables variable kinematic approximations to be assigned locally, so that different regions of the same structural model can be represented at different fidelity levels.

### MULTI-FIDELITY GLOBAL-LOCAL STRATEGY USING NDK:

high-fidelity kinematics are introduced only in critical local zones (e.g., near damage initiation)

a lower-fidelity description is retained for the remaining global structure

The result is a single, integrated global-local model solved in one step, delivering improved computational efficiency without sacrificing accuracy where it matters most.

Legend:

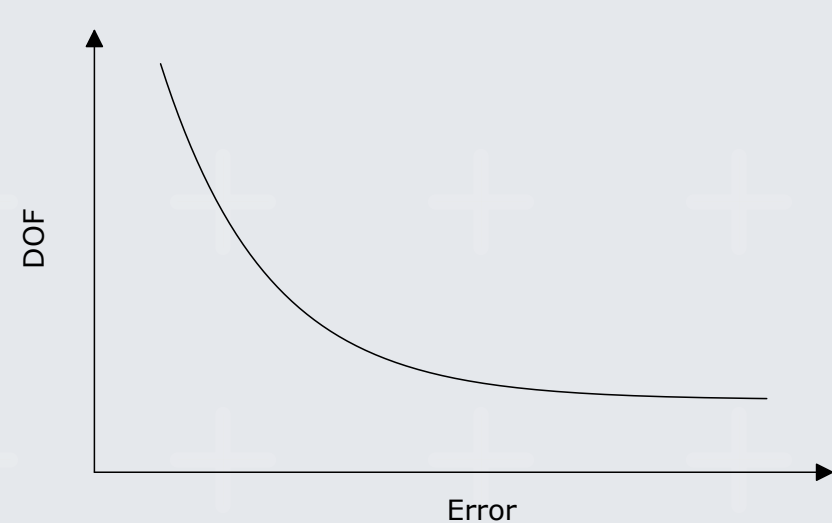
- Refined through-thickness expansion
- Transition elements with variable kinematics
- Coarse through-thickness expansion

**Q4 CUF-2D element (4 nodes) with variable kinematics.**

## Synergies with AI

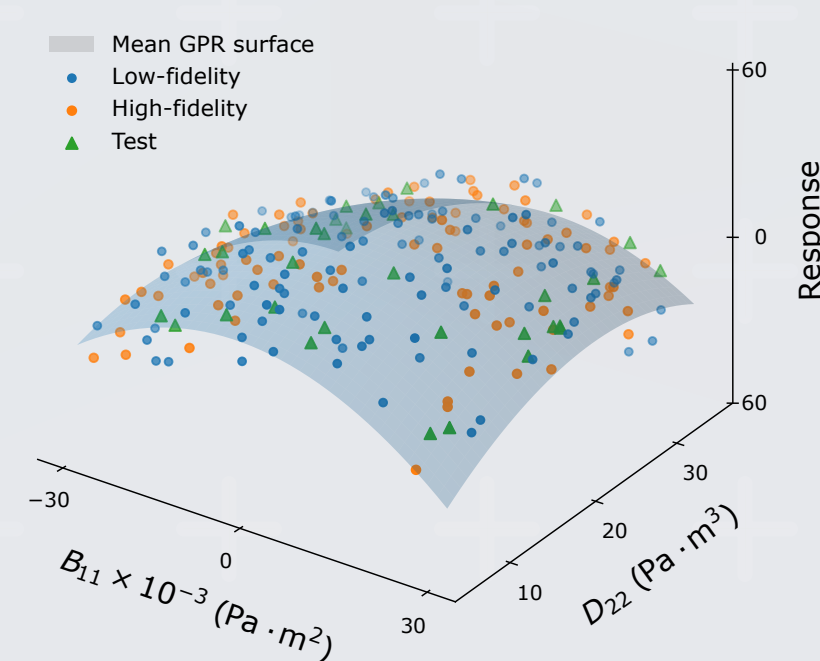
### AI-based Multifidelity Strategies

AIM: building numerical models with the best accuracy/cost trade-off  
TOOL: Neural Networks



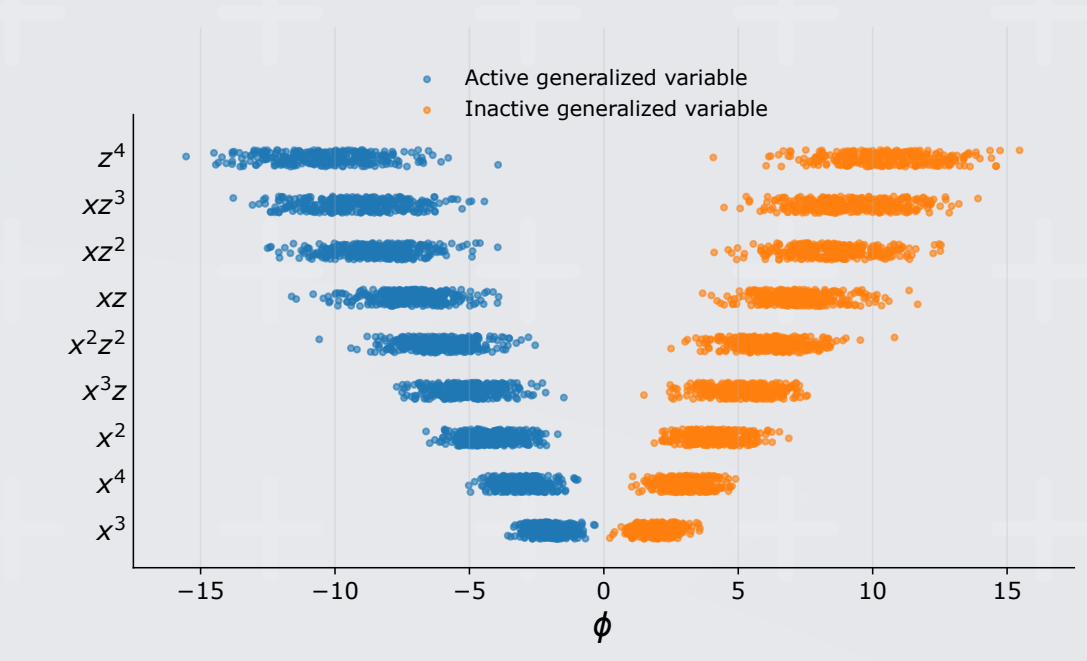
### Optimize Training Datasets

AIM: Blend of LF/HF models as training datasets, with minimum HF for a reliable surrogate model  
TOOLS: Bayesian Optimization and GPR



### Fidelity Sensivity: Features & Variables

AIM: find the problem features and problem unknowns that most affect fidelity  
TOOL: eXplainable Machine Learning (XML)



## Application Case: Impact Analysis on Composite Panels

Nonlinear structural impact analysis by implementing explicit solution techniques (Central Difference Scheme)

- Contact modelling (Node-surface contact discretisation)
- Interlaminar damage (Cohesive elements)
- Intralaminar damage (3D Hashin criterion)

**Contact modelling**

**3D Hashin criterion**

$$F_{ft} = \left( \frac{\sigma_{11}}{X_T} \right)^2 + \alpha_f \left[ \left( \frac{\sigma_{12}}{S_{12}} \right)^2 + \left( \frac{\sigma_{13}}{S_{13}} \right)^2 \right]$$

$$F_{mt} = \left( \frac{\sigma_{22} + \sigma_{33}}{Y_T} \right)^2 + \frac{1}{S_{23}^2} (\sigma_{23}^2 - \sigma_{22}\sigma_{33}) + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 + \left( \frac{\sigma_{13}}{S_{13}} \right)^2$$

$$F_{fc} = \left( \frac{\sigma_{11}}{X_C} \right)^2$$

$$F_{mc} = \left( \frac{\sigma_{nt}}{S_{A_{23}} - \eta_{nt}\sigma_{mn}} \right)^2 + \left( \frac{\sigma_{nl}}{S_{13} - \eta_{nl}\sigma_{mn}} \right)^2$$

**Computational efficiency: MUL2 requires only a fraction of the DOFs of a full 3D FEM model.**

Model	Discretisation of the laminate	DOFs
CUF-LE1	400 Q9 (1 LE1/ply)	85,731
CUF-LE2	400 Q9 (1 LE2/ply)	166,419
CUF-LE3	400 Q9 (1 LE3/ply)	247,107
CUF-3LE1	400 Q9 (3 LE1/ply)	247,107
ABQ	512000 C3D8R (5 el./ply)	1,594,323

$\frac{247'107}{1'594'323} = 0,15 = 15\%$

