Davide Fleres
Ph.D. Candidate
davide.fleres@siemens.com

A Non-Intrusive Physics-Informed Neural Network Hyper Reduction approach for Nonlinear Structural Finite Elements

Davide Fleres[1,2], Daniel De Gregoriis[1], Onur Atak[3] and Frank Naets[2,4]

In Collaboration with [1,3] Siemens Digital Industries Software ([1] Belgium, [3] United Kingdom), [2] Department of Mechanical Engineering at KU Leuven (Belgium), and [4] E2E core lab Flanders Make @ KU Leuven (Belgium)

Background

Digitalization

- **Simulation and Modeling**
  Pillars of digitalization, since they enable the creation of Digital Twins over the entire product life cycle.
- **Digital Twin**
  Digital representations of a product which mirror the physical system in the digital word.
- **Numerical Models**
  Require a fine spatial-temporal resolution, leading inevitably to larger-scale complex models.

Model Order Reduction (MOR)
Aims to reduce the computational burden by creating a low-dimensional, faster approximation of high-fidelity model, i.e. the so-called **Reduced Order Model** (**ROM**).

Speed Up
Alleviation of the computational burden of high-dimensional numerical simulations.

Exchangeability
Compress, transfer and execute simulation models in other embedded or cloud environments.

Challenges

Physics-Based Model Order Reduction

Nonlinear · Intrusive

- MOR approaches struggle to handle complex coupled **Nonlinear** parametric systems.
- Hyper-Reduction approaches have been found to be **Intrusive** in nature.

Data Driven Model Order Reduction

Overfitting · Extrapolation · Physics Properties

- Suffer from **Underfitting/Overfitting.**
- Reduced capacity to **Extrapolate.**
- **Violation of key physics properties.**

Objectives

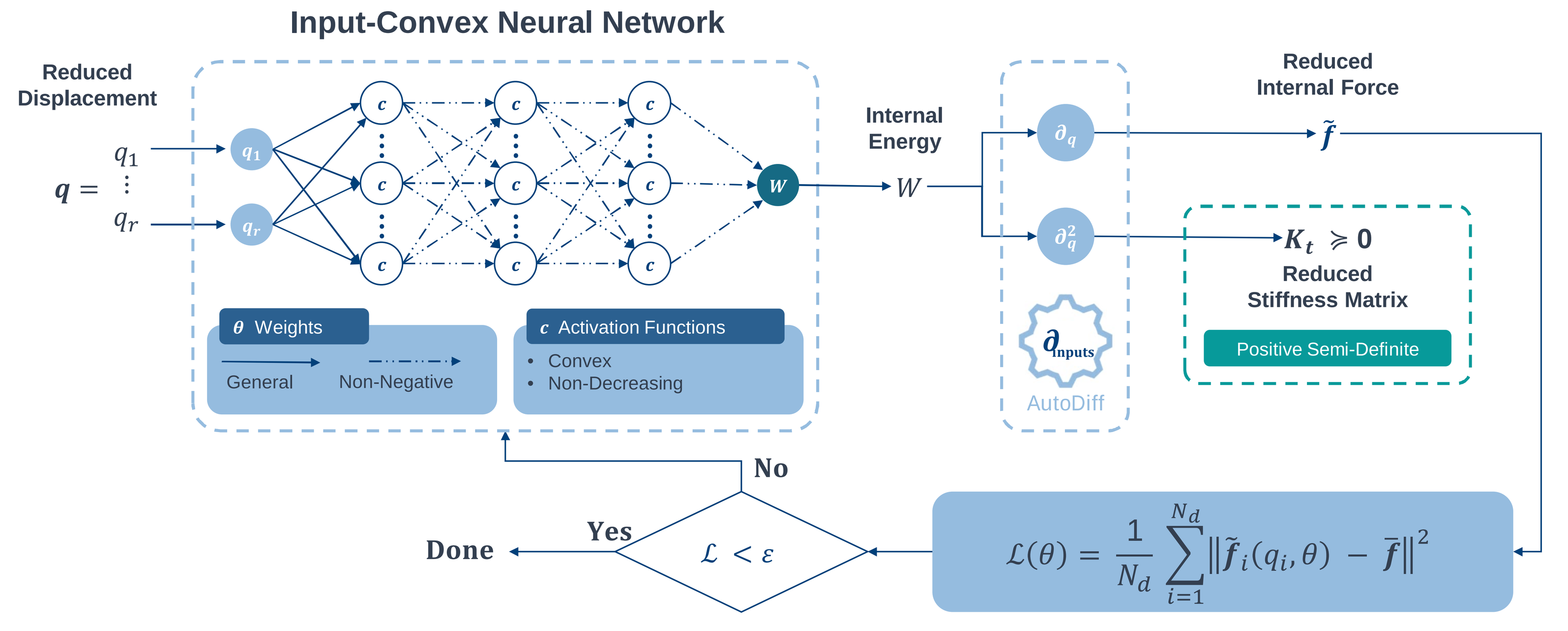
Stability Properties of Hyper-Reduction Approaches

Non-Intrusive Properties of Data-Driven Approaches

Robustness and Stability in Numerical Simulation

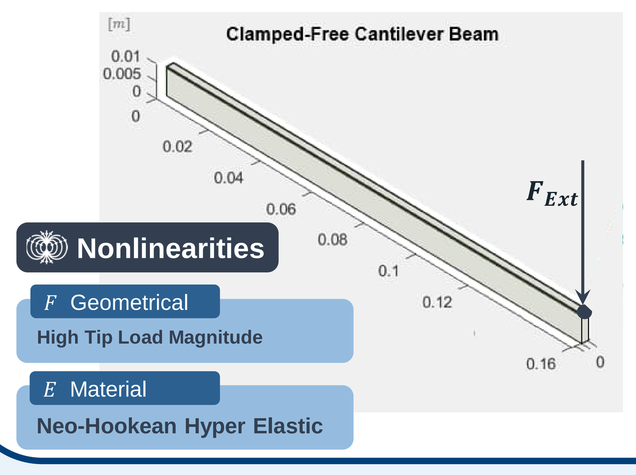
Methodology

1. Projection-Based MOR via Proper Orthogonal Decomposition (POD)
2. Non-Intrusive Hyper-Reduction via artificial Neural Network
3. Physics-Augmentation via Input-Convex architecture
4. Online ROM Execution

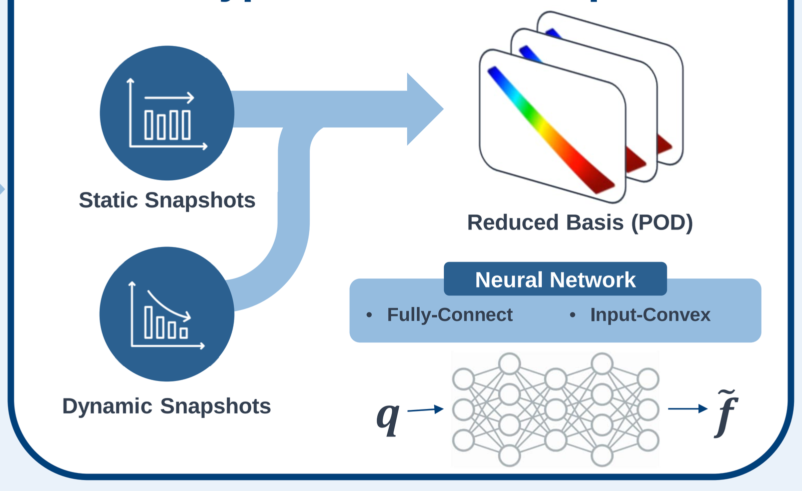


Benchmark Case

Structural Finite Elements



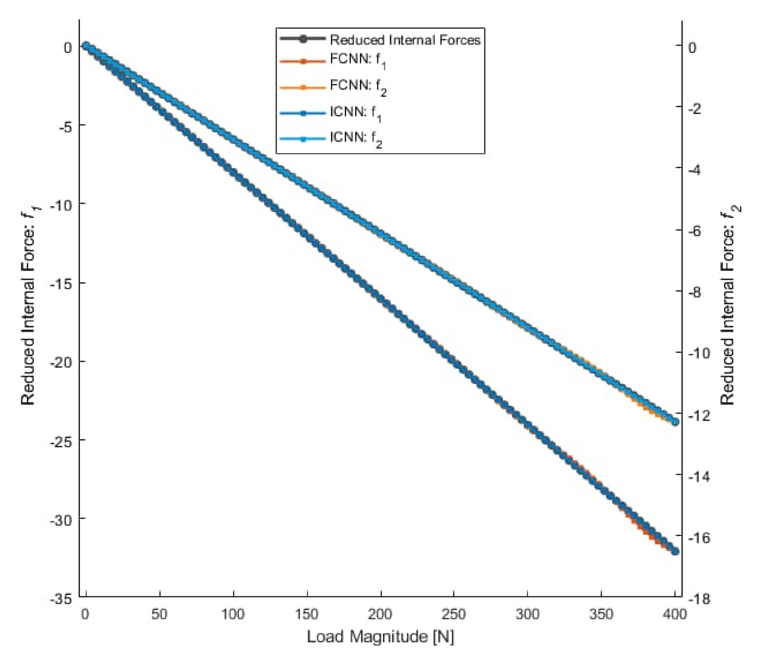
Hyper-Reduced Map



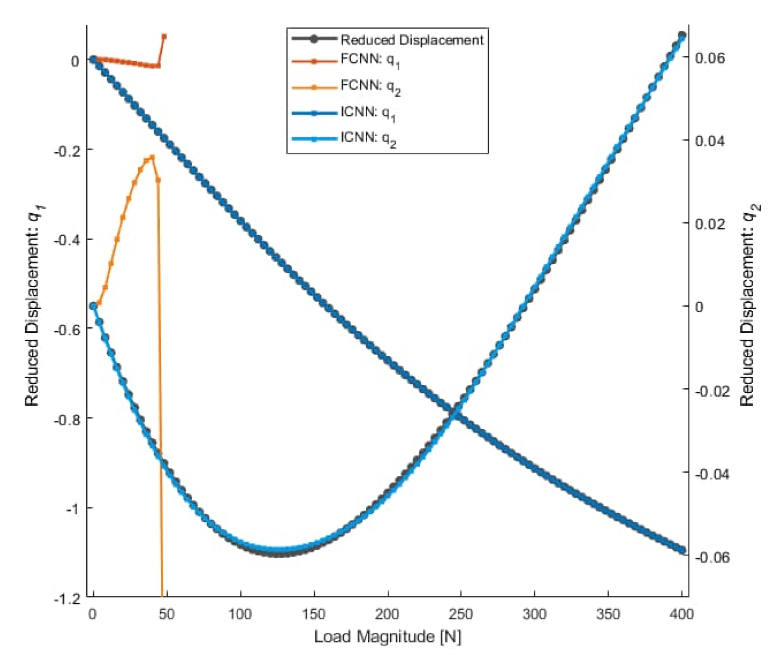
Results

Static

Hyper-Reduced Nonlinear Internal Map



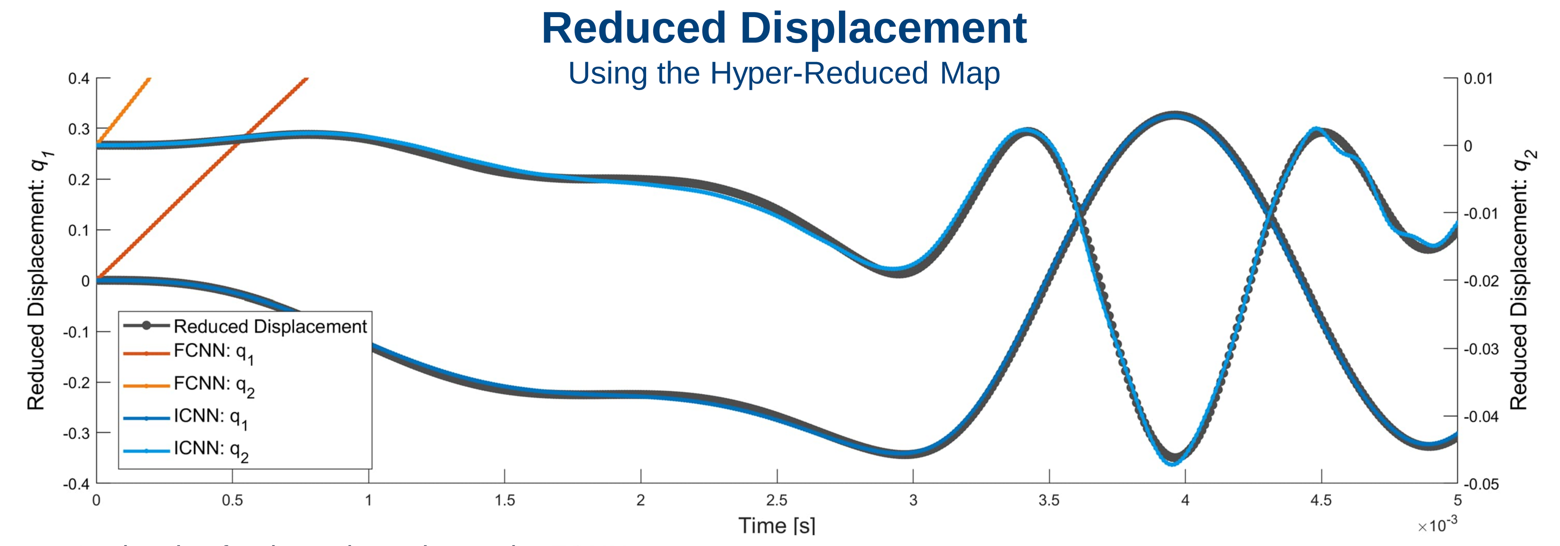
Reduced Displacement
Using the Hyper-Reduced Map



- Comparison of **Fully Connected Neural Network (FCNN)** and **Input-Convex Neural Network (ICNN)**.
- Both approaches provide a **good approximation** of the reduced internal forces.
- The **FCNN** architecture does **not** ensure **stability-preserving properties** which leads to the unstable behavior and related convergence issues.
- The **ICNN** architecture does **guarantee** the a priori enforcement of the **physical constraints** and therefore provides stable and consistent results.

Dynamic

Reduced Displacement
Using the Hyper-Reduced Map



- Again, also for dynamic analyses, the **FCNN** architecture does **not** ensure **stability-preserving properties.**
- The **ICNN** architecture, once again, **guarantee** the a priori enforcement of the **physical constraints.**

Future Works

- Extend the methodology to retrieve the **Parametric** dependencies within the model, allowing its use in different operational conditions and settings.
- Extend the methodology to multi-physics settings such as in complex coupled nonlinear **Thermomechanical** systems.
- Explore methods to ensure ROM **Portability** such that they can be effectively distributed, deployed and executed on edge devices.

Conclusion

1. **Model Order Reduction** approach able to reduce the computational cost of Nonlinear Structural Finite Element analyses.
2. **Non-Intrusive** Hyper-Reduction approach easy to integrate into simulation frameworks and existing commercial software.
3. **Robust** approach thanks to embedded Physics Properties via Scientific Machine Learning Physics-Augmentation.

Acknowledgments

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