Master Thesis

Architecture Development to Replace Finite Element Methods with Deep Neural Networks

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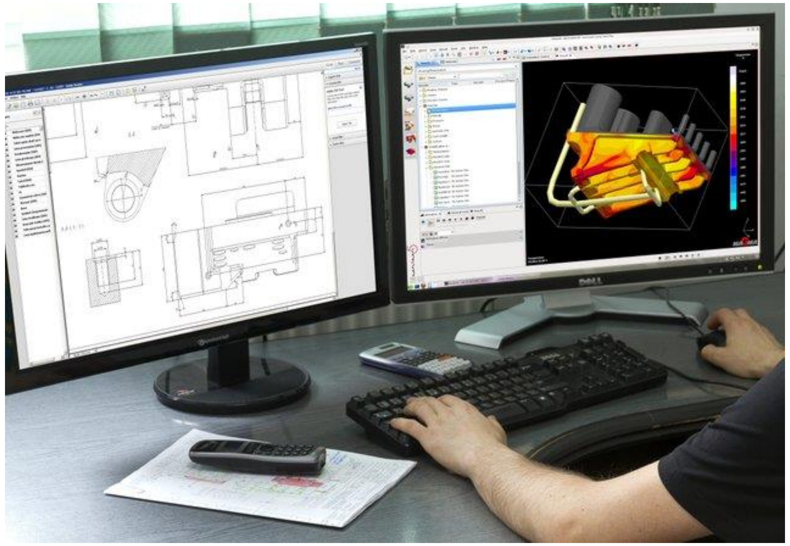
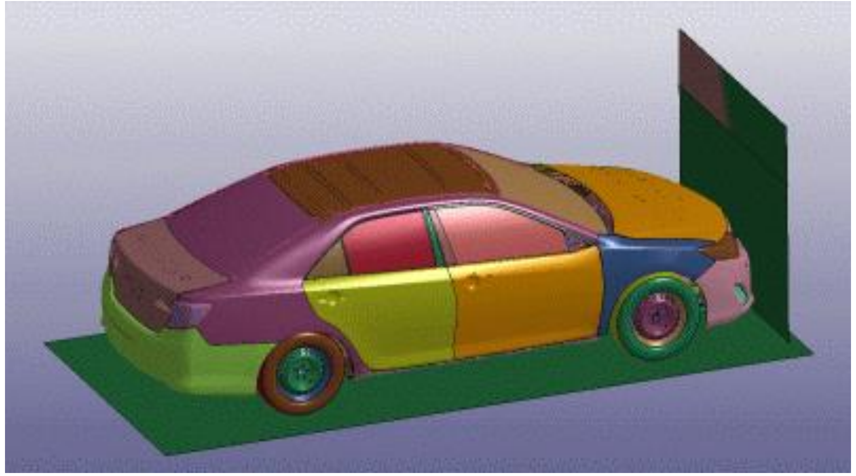
1 Introduction



Computer Aided Engineering (CAE)

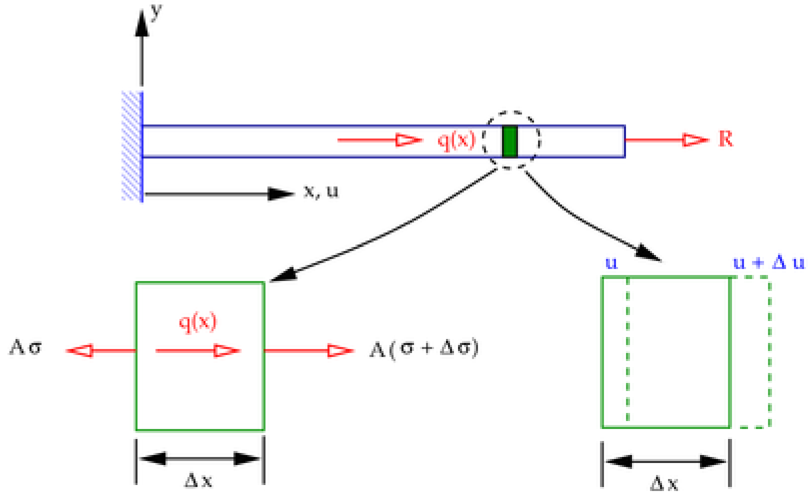
The use of computer software to simulate performance in order to -

- Improve product design
- Assist in resolution of engineering problems



Finite Element Method (FEM)

- FEM is a numerical method used to obtain the approximate solution in CAE
- Most systems can be mathematically represented by differential equations
- Analytical solution is easy to calculate for simple geometries and difficult for complex geometry



System

$$[\kappa]\{u\} = \{F\}$$

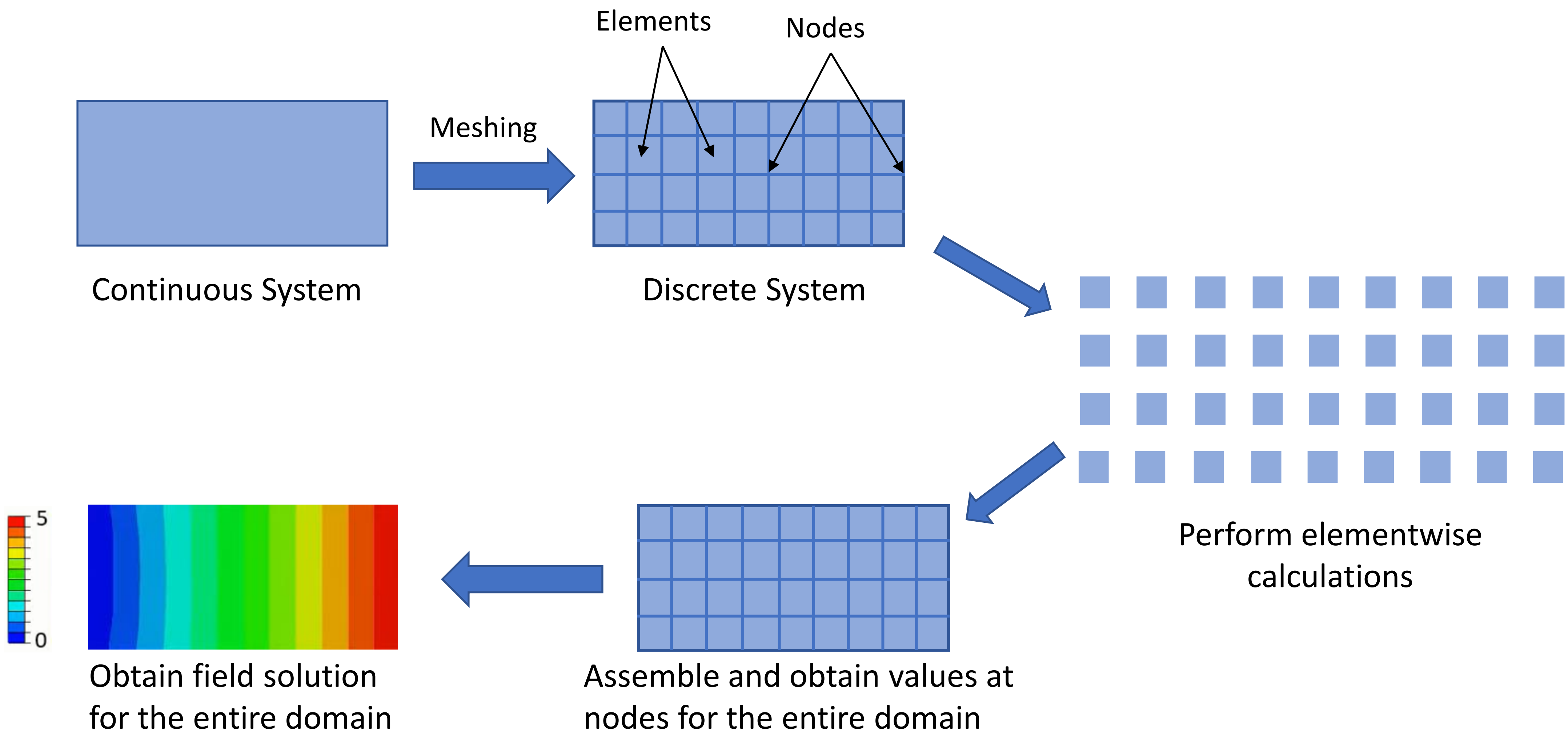
$$AE\frac{d^2\mathbf{u}}{dx^2} = -a\mathbf{x}$$

$$\mathbf{u}(0) = 0$$

$$\left.\frac{d\mathbf{u}}{dx}\right|_{\mathbf{x}=L} = \frac{\mathbf{R}}{AE}$$

$$\frac{AE}{h}\begin{bmatrix} 2 & -1 & 0 \\ -1 & 2 & -1 \\ 0 & -1 & 1 \end{bmatrix}\begin{bmatrix} u_2 \\ u_3 \\ u_4 \end{bmatrix} = \frac{a}{h}\begin{bmatrix} \left(\frac{x_2^3-x_1^3}{3}-\frac{x_1(x_2^2-x_1^2)}{2}\right)+\left(\frac{x_3(x_3^2-x_2^2)}{2}-\frac{x_3^3-x_2^3}{3}\right) \\ \left(\frac{x_3^3-x_2^3}{3}-\frac{x_2(x_3^2-x_2^2)}{2}\right)+\left(\frac{x_4(x_4^2-x_3^2)}{2}-\frac{x_4^3-x_3^3}{3}\right) \\ \left(\frac{x_4^3-x_3^3}{3}-\frac{x_3(x_4^2-x_3^2)}{2}\right)+\mathbf{R}\frac{h}{a} \end{bmatrix}$$

The FEA Procedure (Practical visualization)

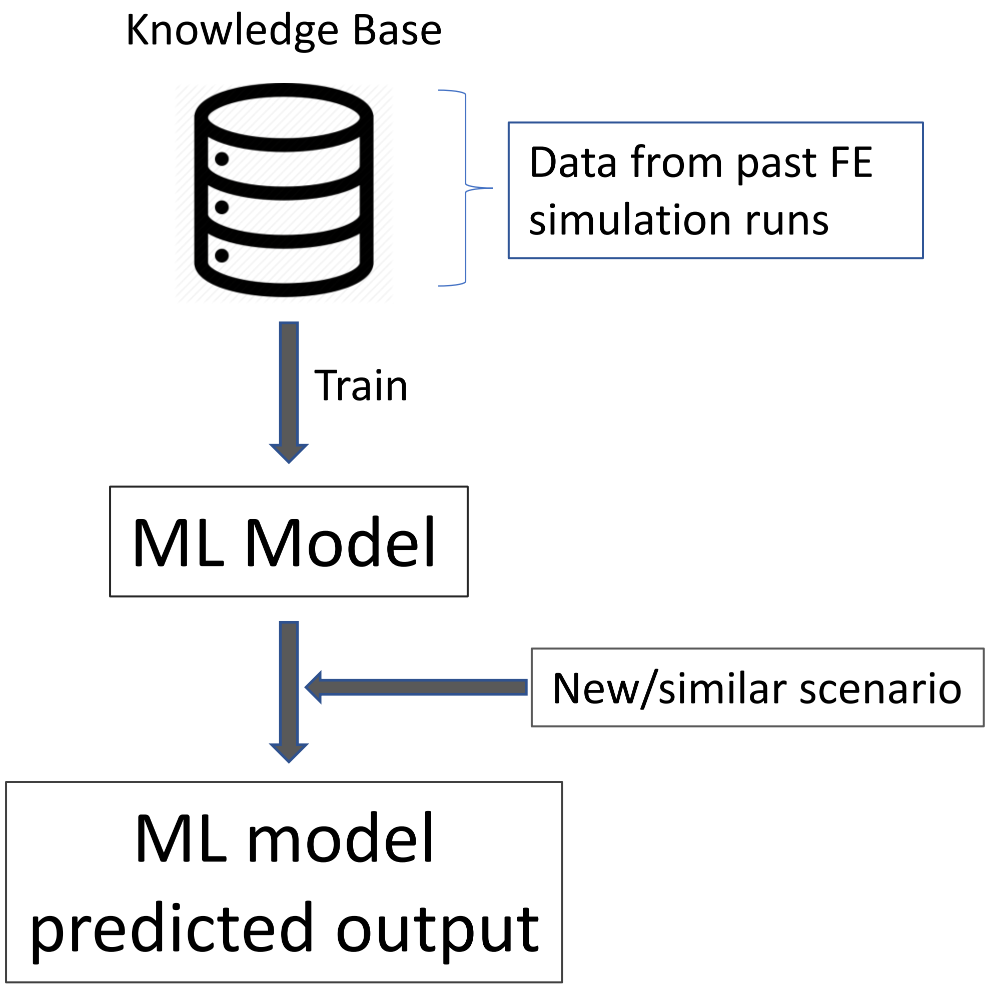


Limitations of FEA

- Re-running the complete scenario for slightest change in the inputs (time consuming)
- Highly complex scenarios are computationally expensive

Machine Learning as a Solution

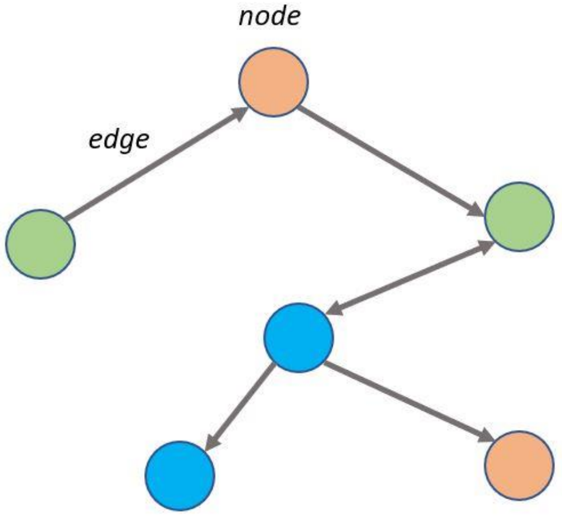
- ML model learns relation between inputs and outputs from historical simulation data
- Predicts the new simulation scenario based on learned relations



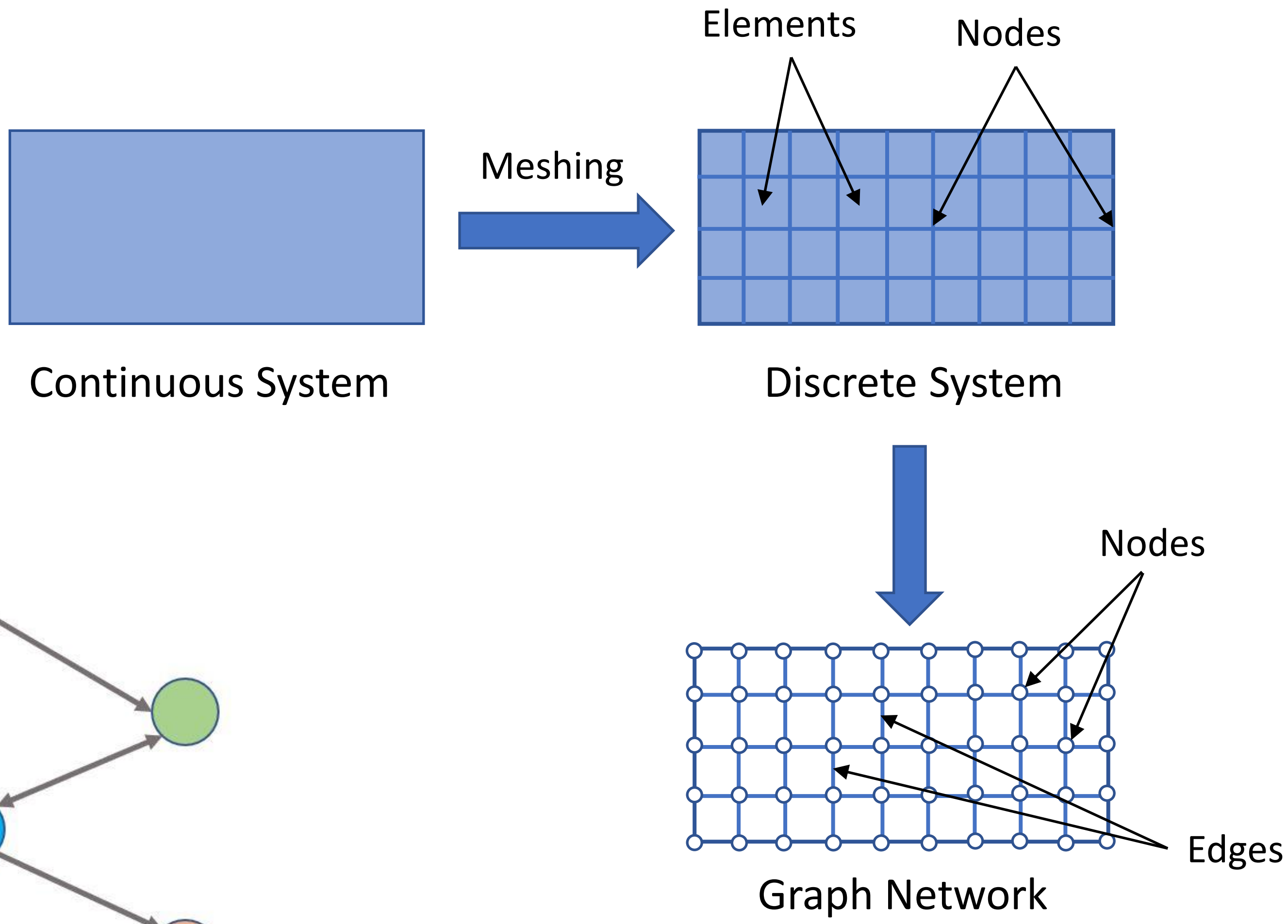
3 Deep Learning

Graph Neural Networks

- Data structure consisting of nodes and edges
- Structural analogy with discrete system in FEM
- A discrete system ca graph network

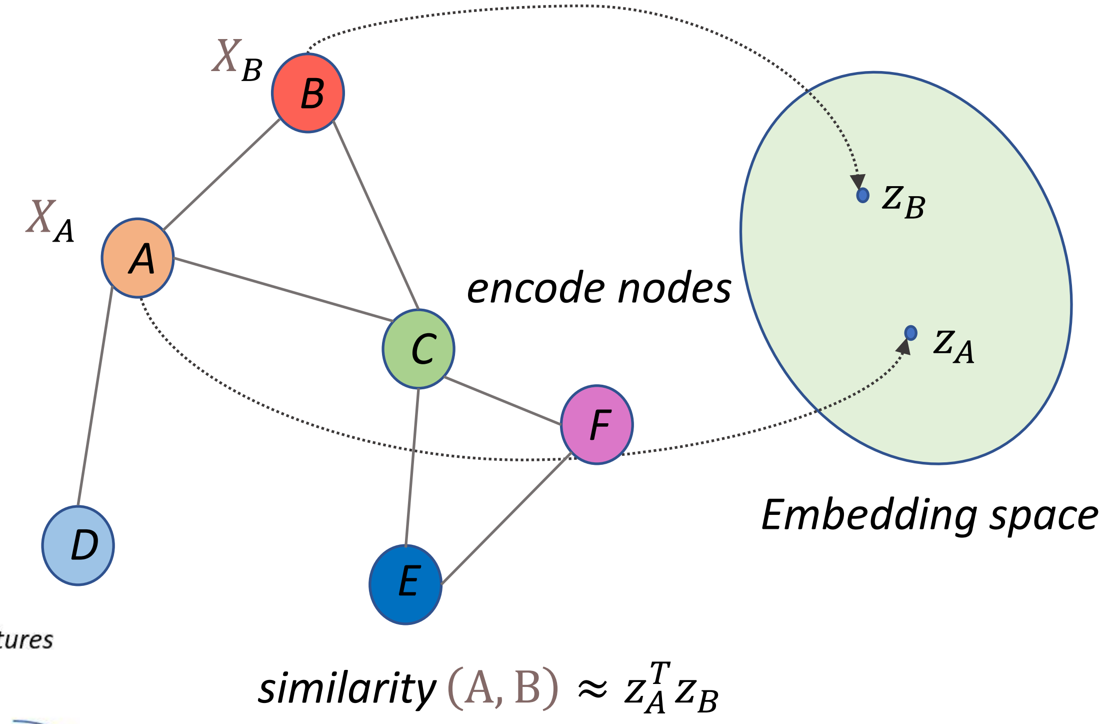


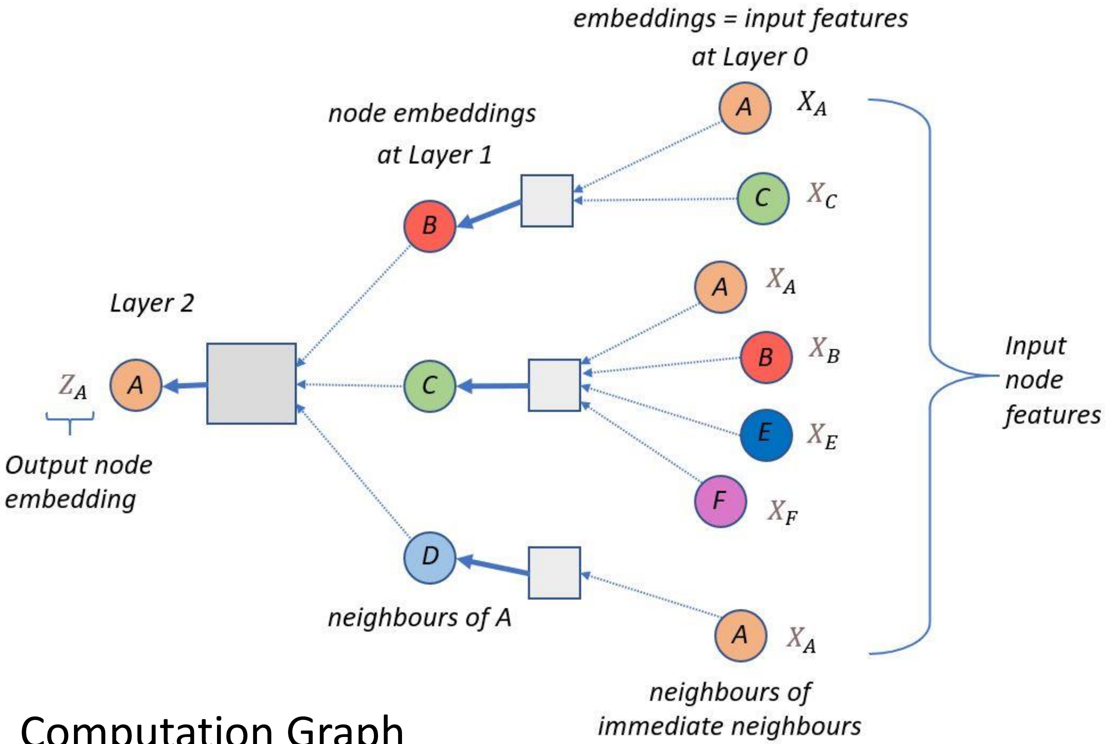
$$G = (V, E)$$



Working of GNNs

- Gather locality information
- Aggregate and compute the information through multiple layers
- Obtain the final node embeddings

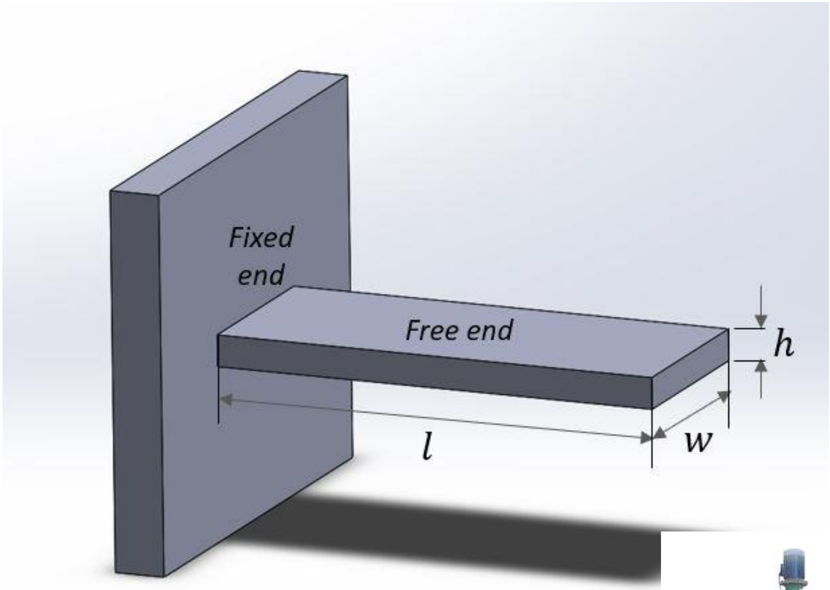




Computation Graph

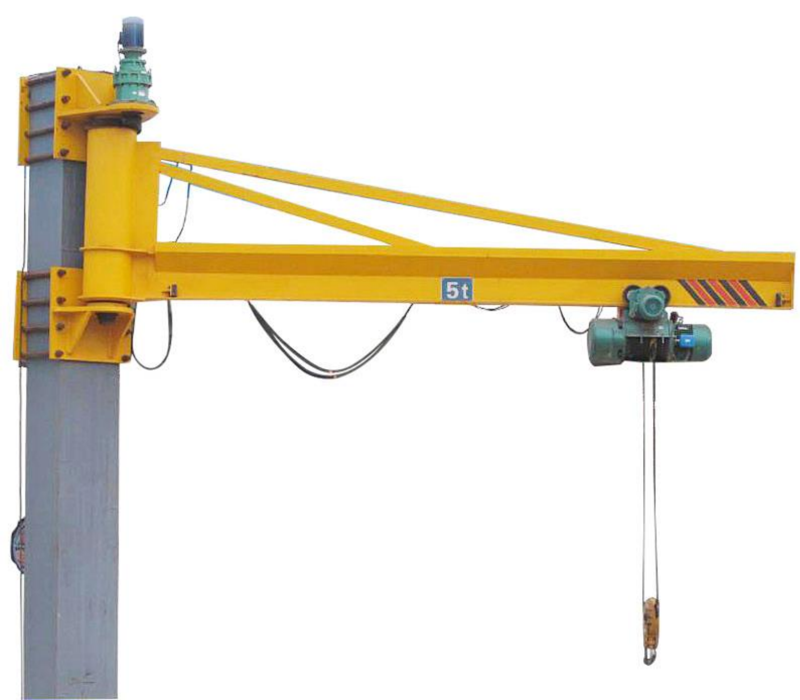
4 Case Study Scenario: Cantilever Beam

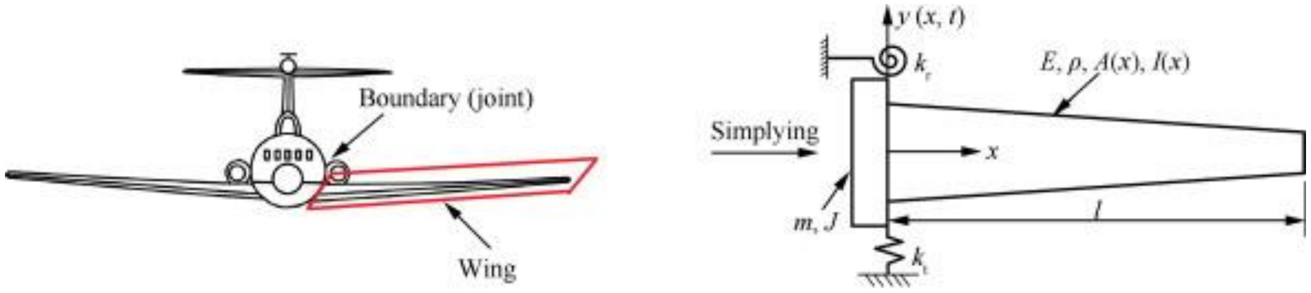
- A rigid structural element supported at one end and free at other



Applications:

- Aesthetic roofs
- Cranes
- Span of bridges
- Aircraft wing



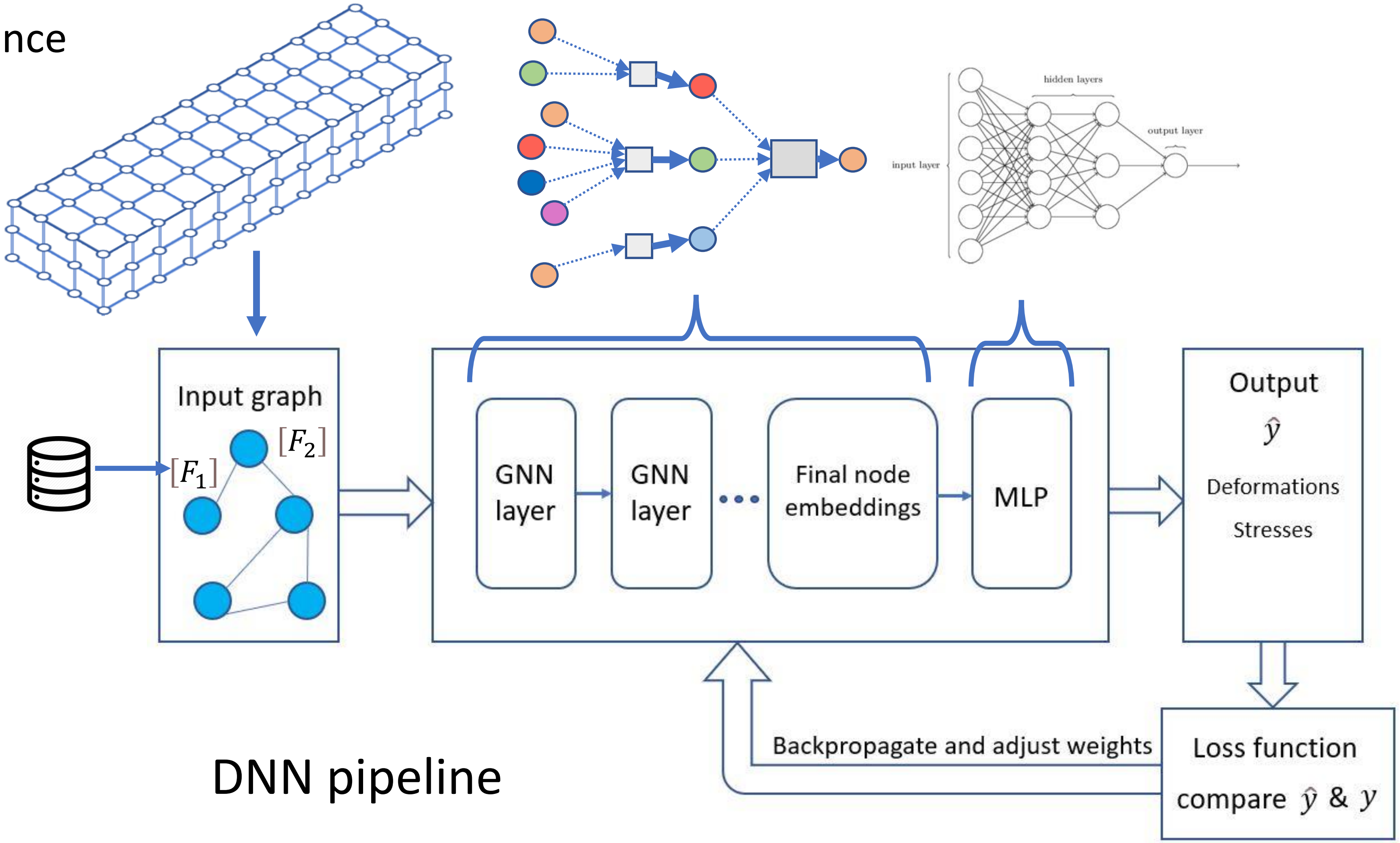


(a) Schematic diagram of aircraft

(b) Cantilever beam with end constraint

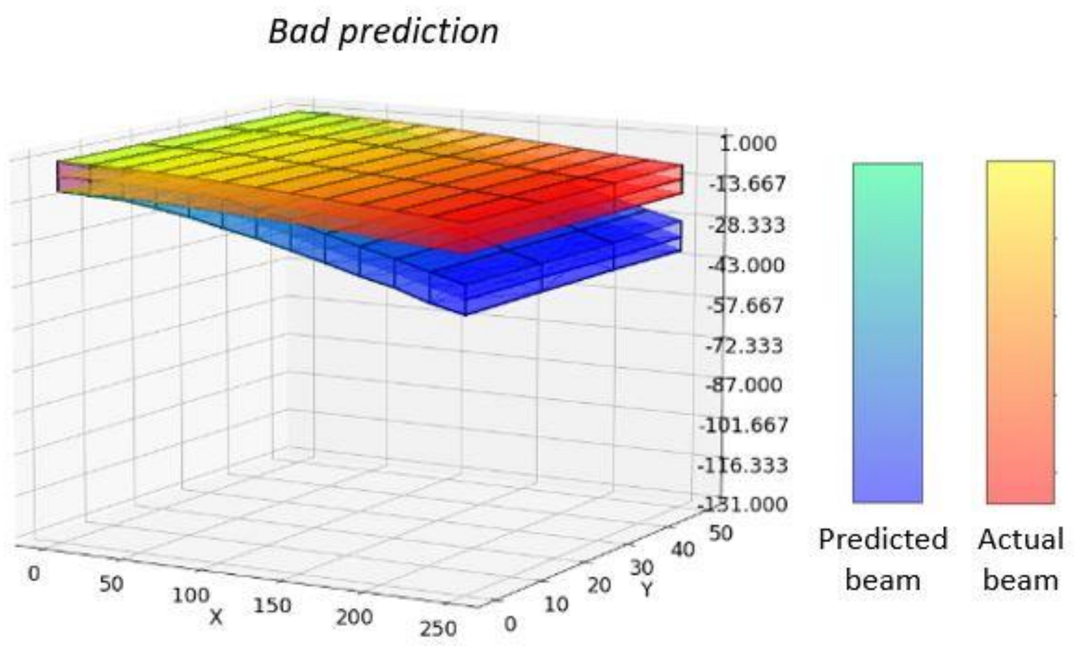
5 Building the DNN Model

- Model the discrete system to GNN
- Input node features as sequence of forces
- Graph computations through multiple GNN layers
- Pass the final node embeddings to MLP
- Obtain output deformation and stress



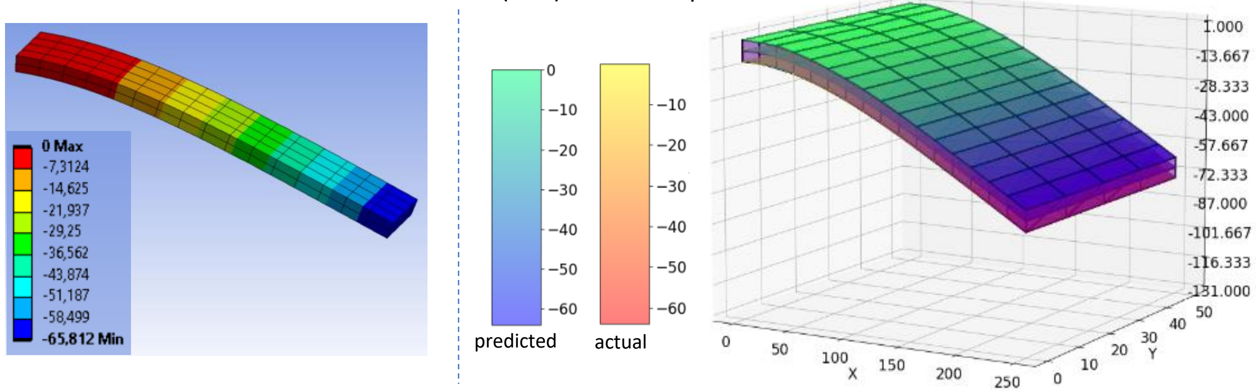
DNN pipeline

3D Deformation Plots

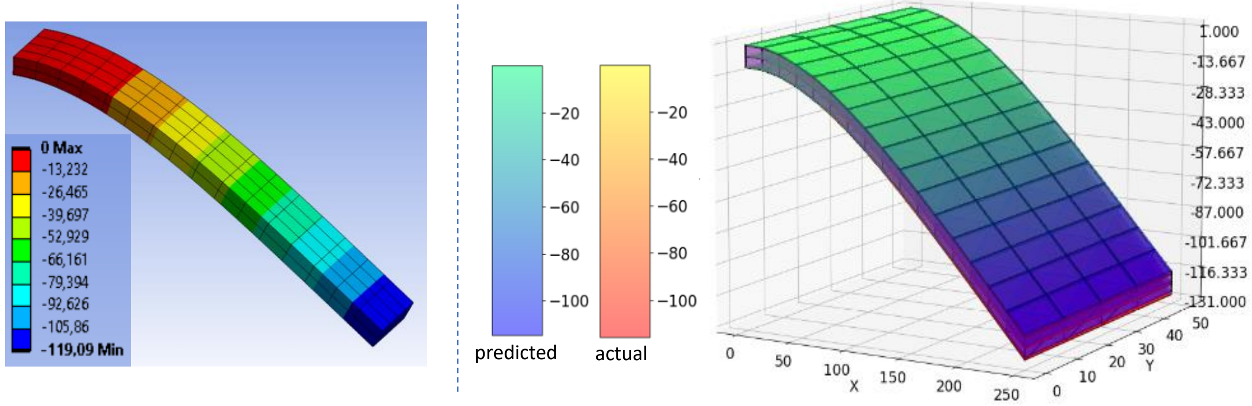


Experiment Results
3D Deformation Plots

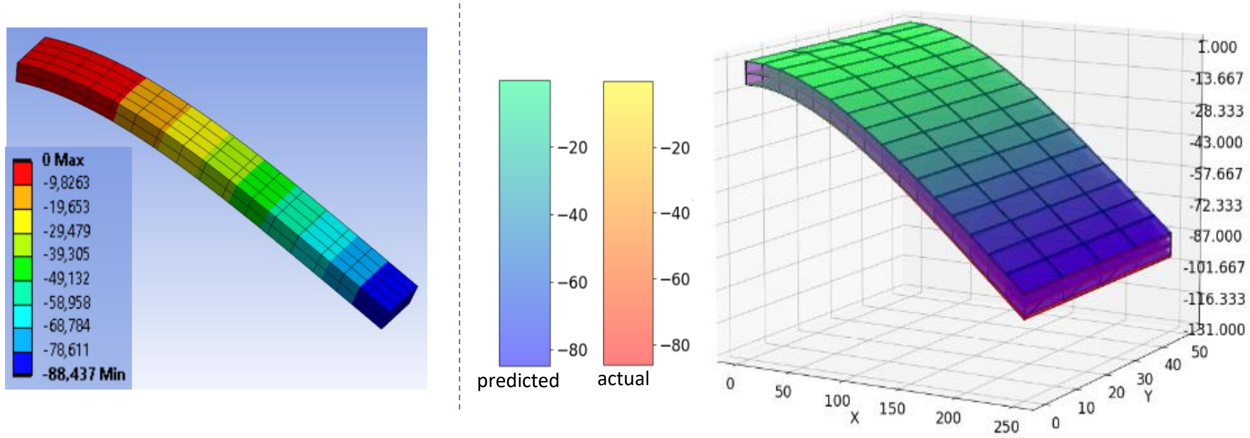
Deformation (mm) at time step 1



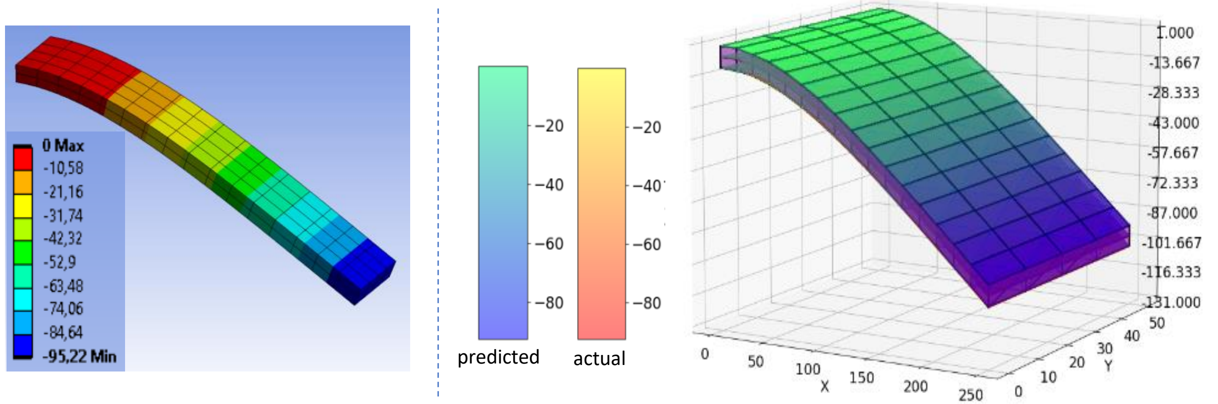
Deformation (mm) at time step 2



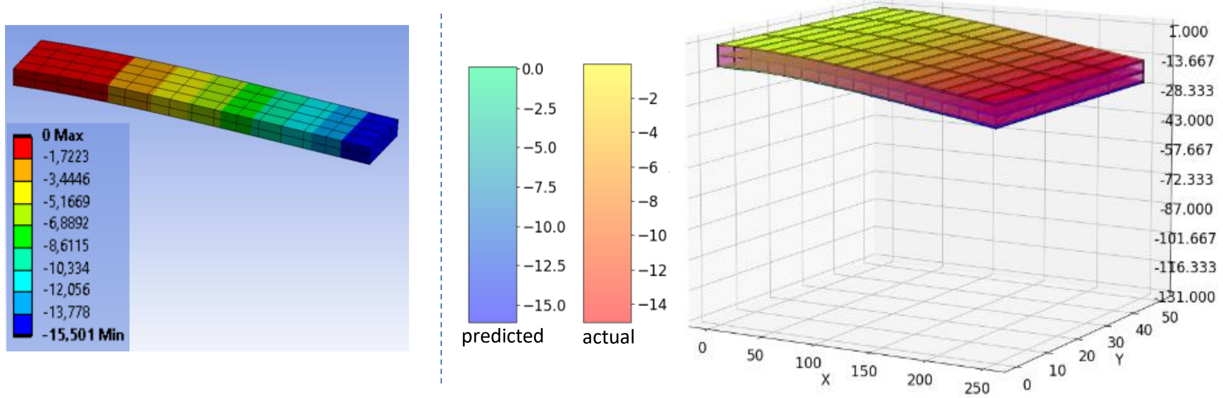
Deformation (mm) at time step 3



Deformation (mm) at time step 4

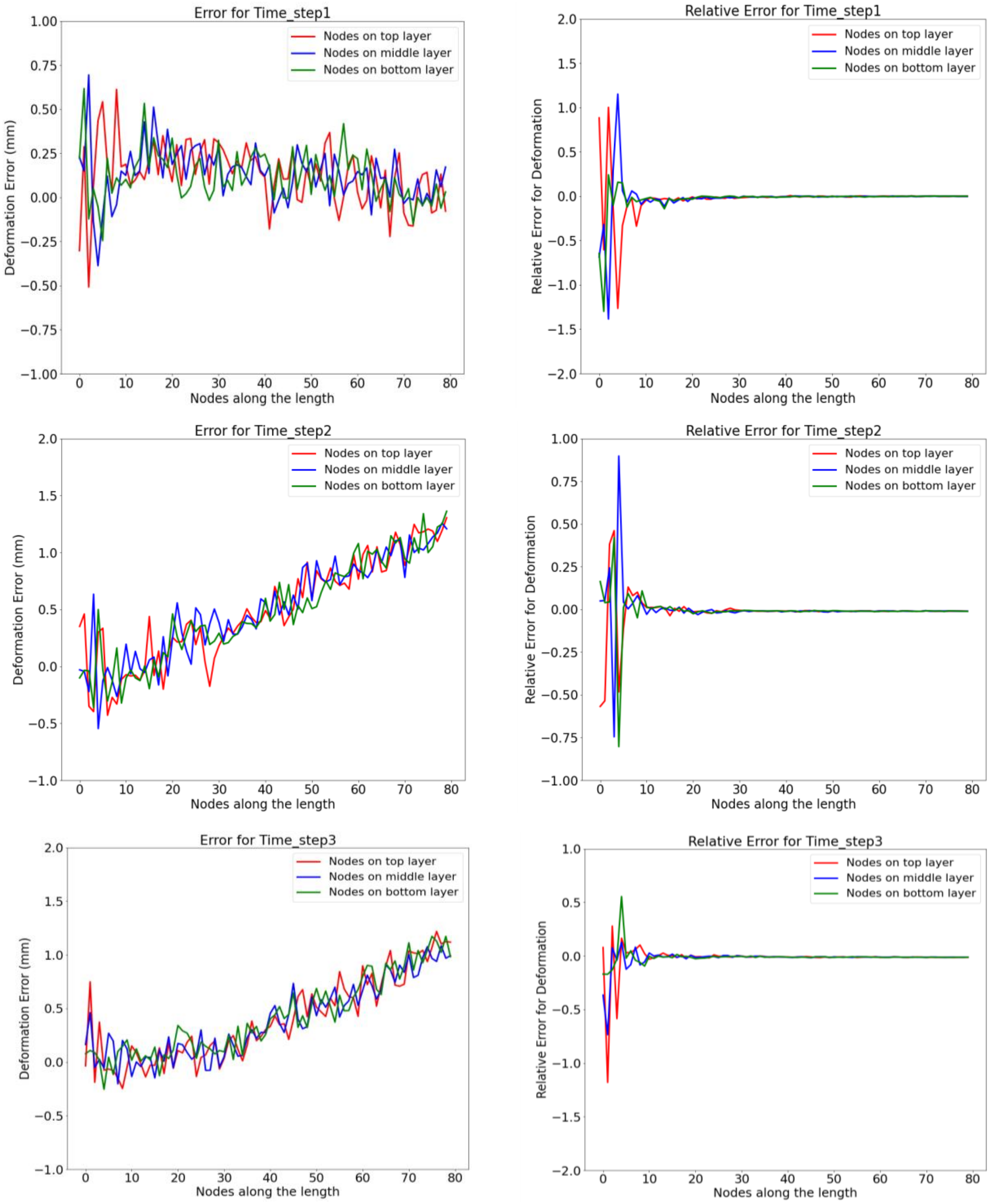


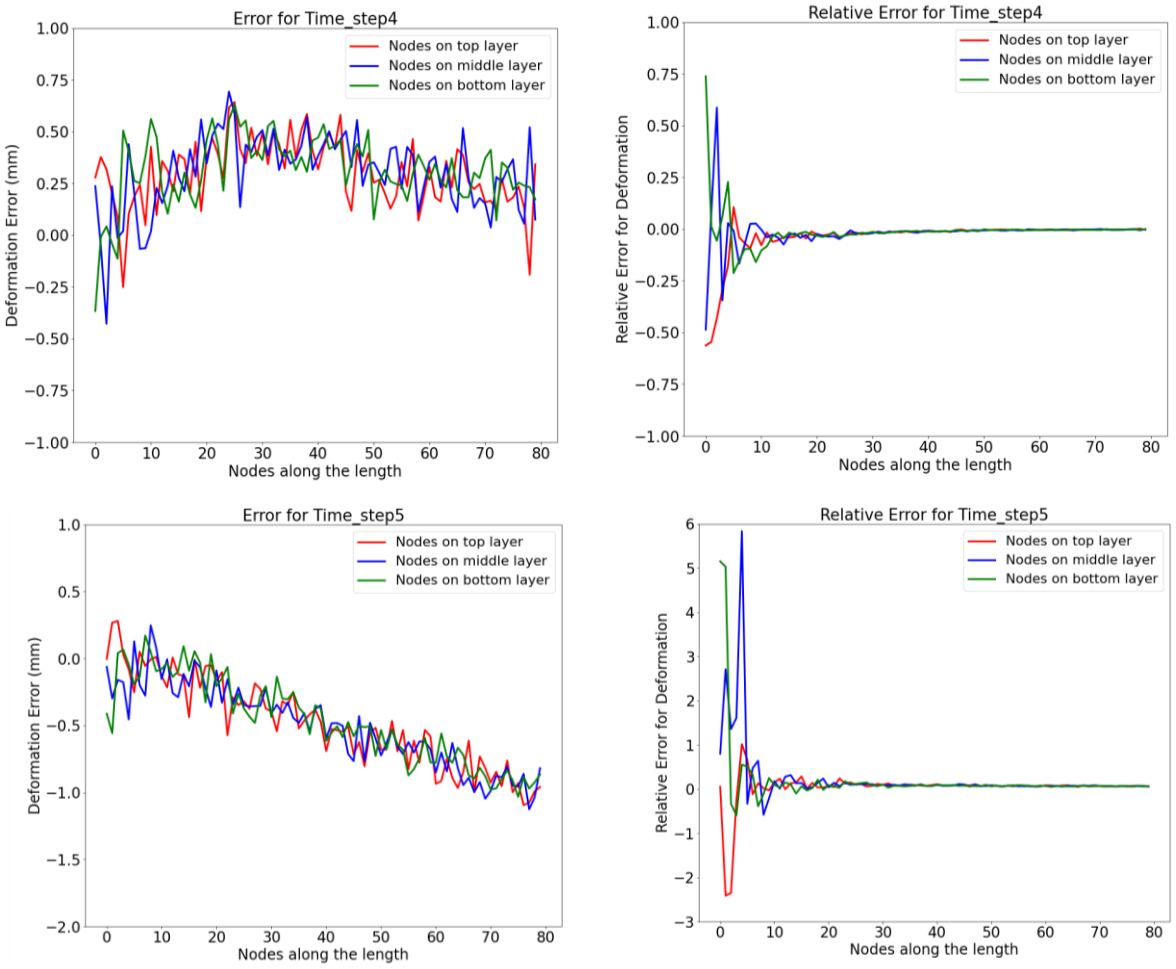
Deformation (mm) at time step 5



- Excellent deformation prediction

Deformation Error Visualization

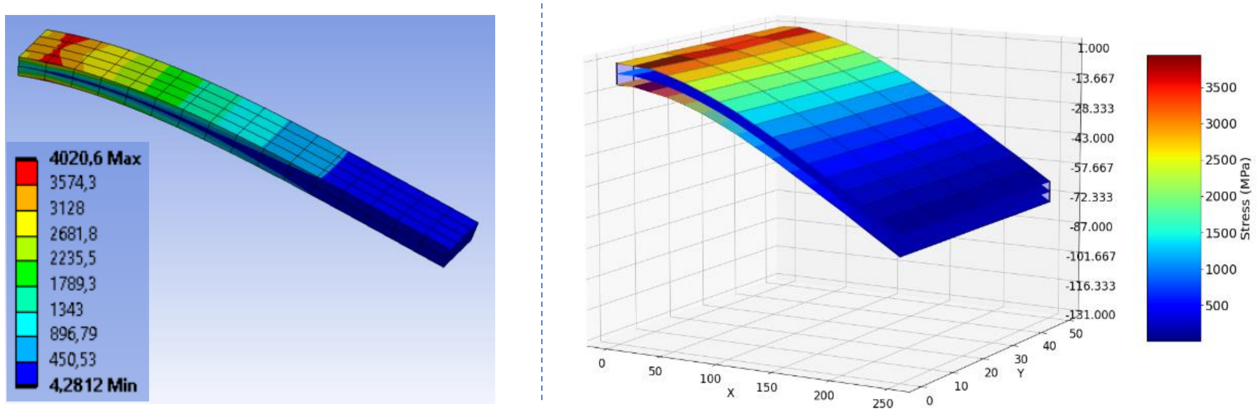




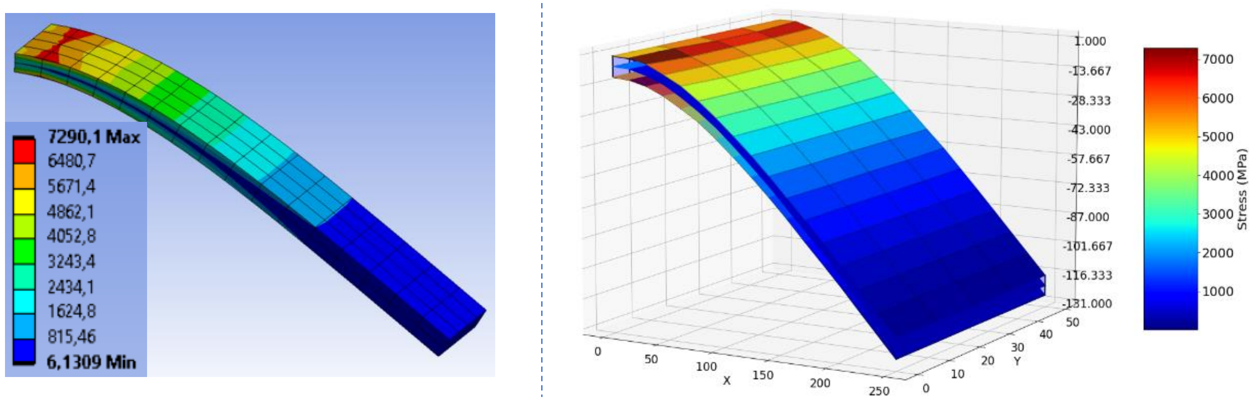
- Deformation error varies between -1 to +1.5 mm
- Relative error is close to zero for higher deformation values at the free end

Stress Distribution Plots

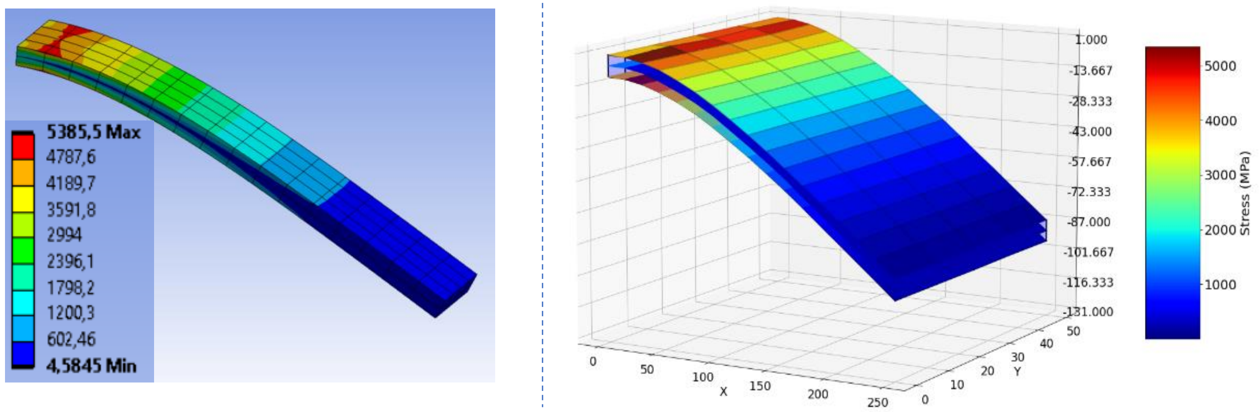
Stress (MPa) at time step 1



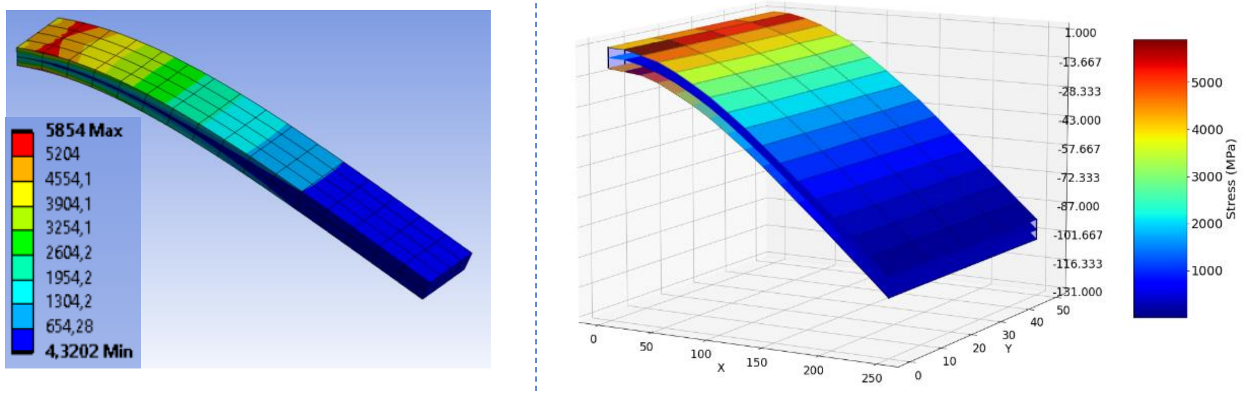
Stress (MPa) at time step 2



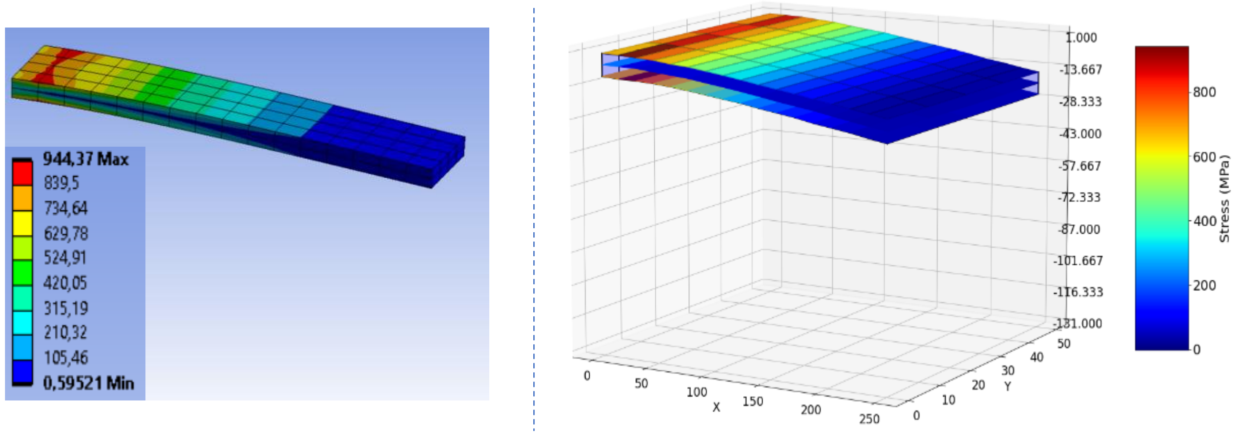
Stress (MPa) at time step 3



Stress (MPa) at time step 4

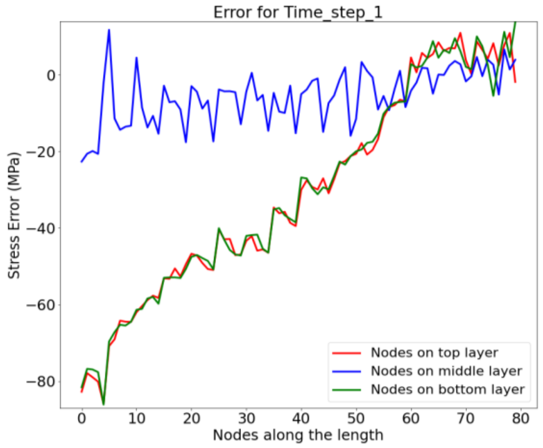


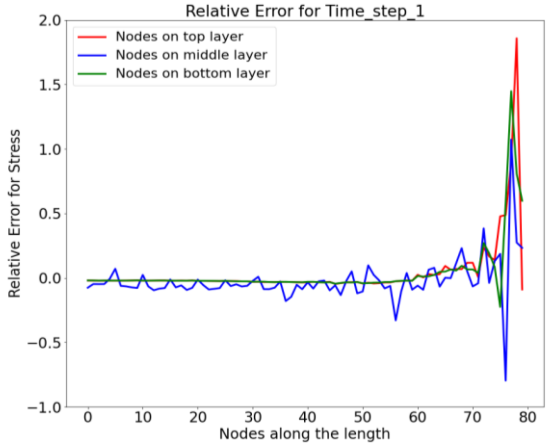
Stress (MPa) at time step 5

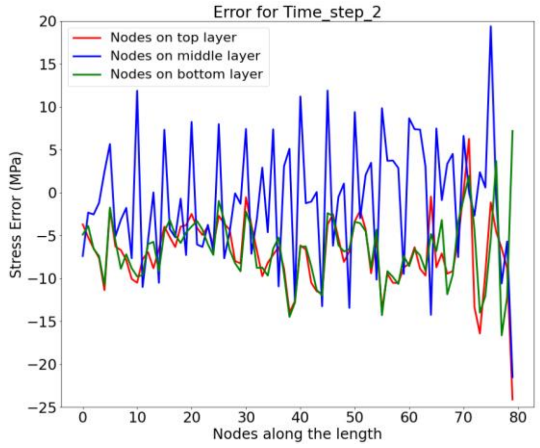


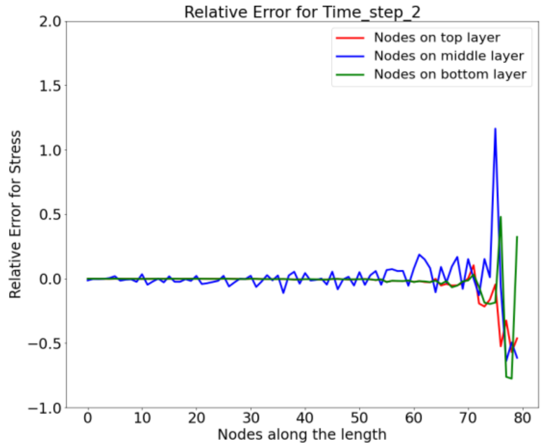
- The stress concentration regions are rightly predicted by the model

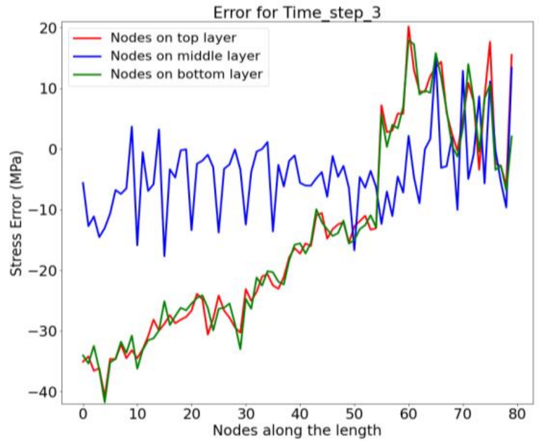
Stress Error Visualization

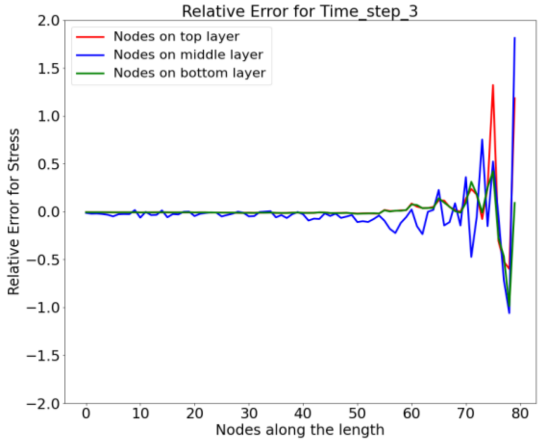


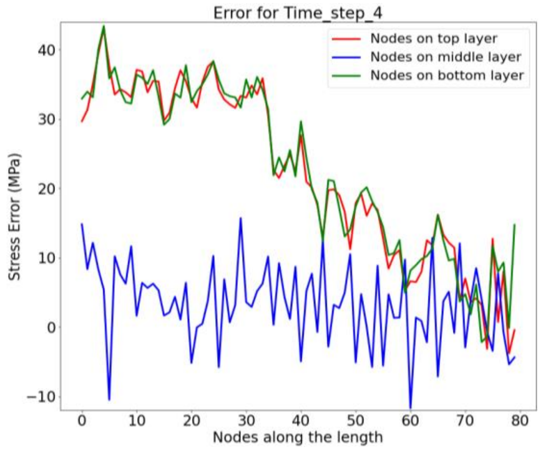


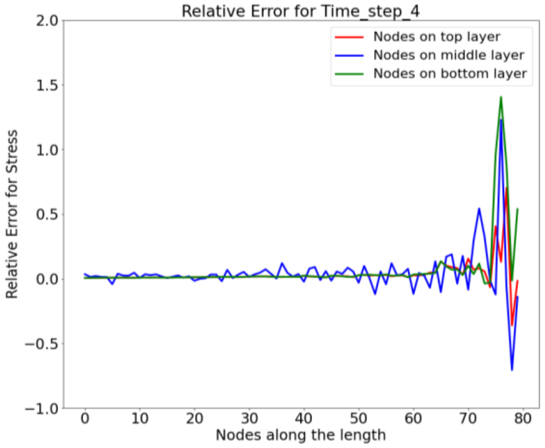


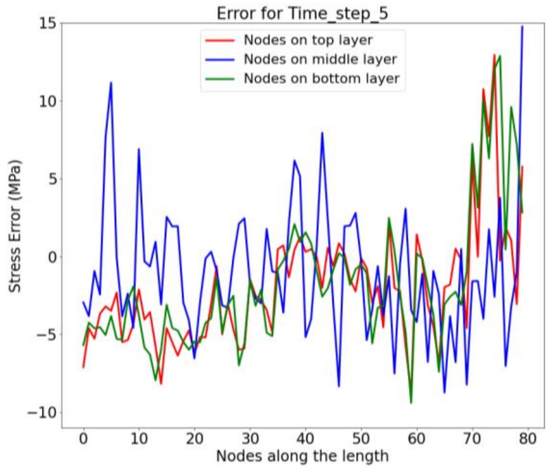


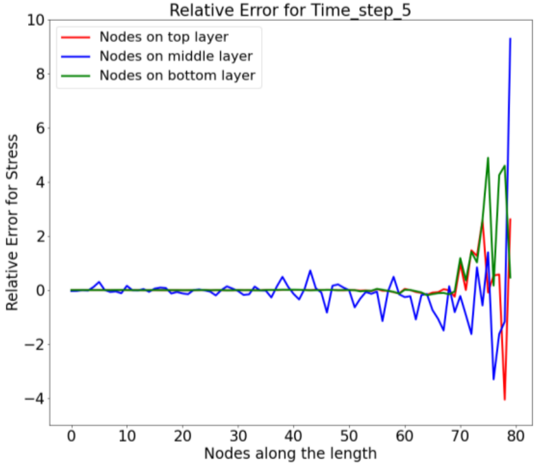












- Stress error varies between -40 to +40 MPa
- Relative stress error is close to zero for higher stress values

Time Analysis

FE Simulation time for 300 rows

112.5 hrs

DNN computation time for 300 rows

9 min

7 Conclusion

Conclusion

- Model with GCN architecture replicates the FEM results obtained from the simulation software, thus capable of replacing FEM based simulation
- Required computation time for DNN model is very less as compared to FE simulation software

Thank You!

Any questions?