Advancing Blast Fragmentation Simulation of RC Slabs: A Graph Neural Network Approach

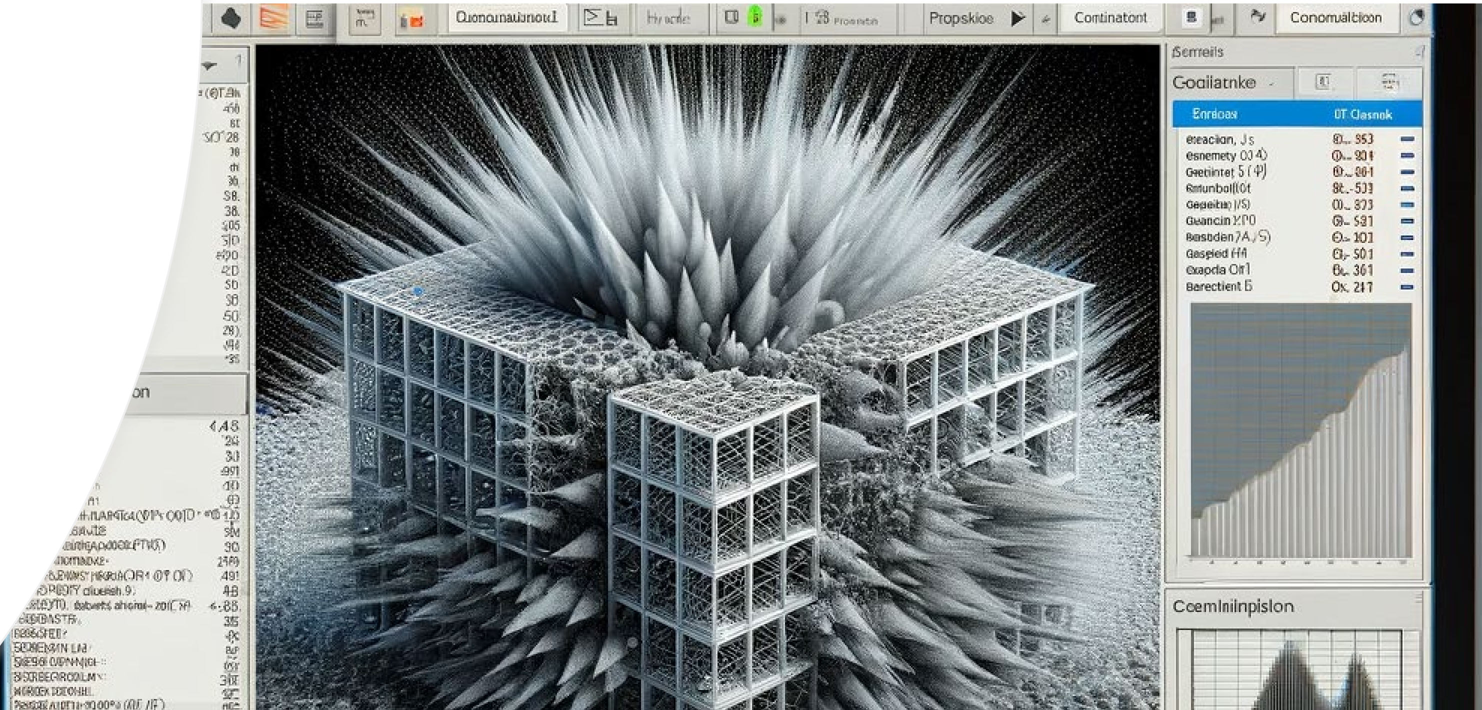
Qilin Li, Zitong Wang, Wensu Chen, Ling Li, Hong Hao

Introduction

- Blast fragmentation simulation is crucial
  - Predict and mitigate blast effects
  - Terrorist attacks or industrial accidents
- Accurate simulation aid protective design
  - Withstand blast impacts
  - Structural integrity and public safety

Existing Approaches

- Experimental testing
  - Expensive
  - Difficult to collect comprehensive data
- Numerical Modelling
  - Computationally intensive
  - Scalability



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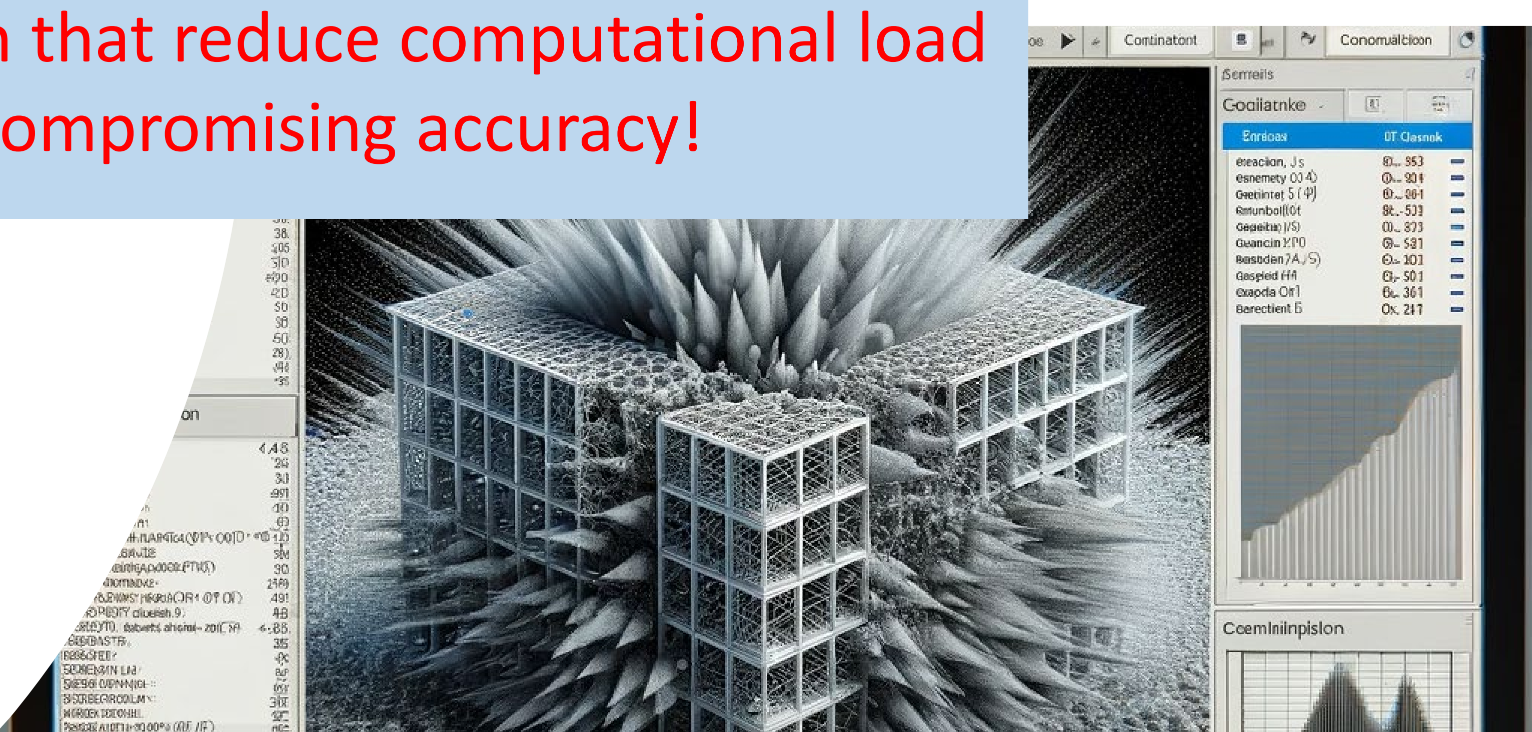
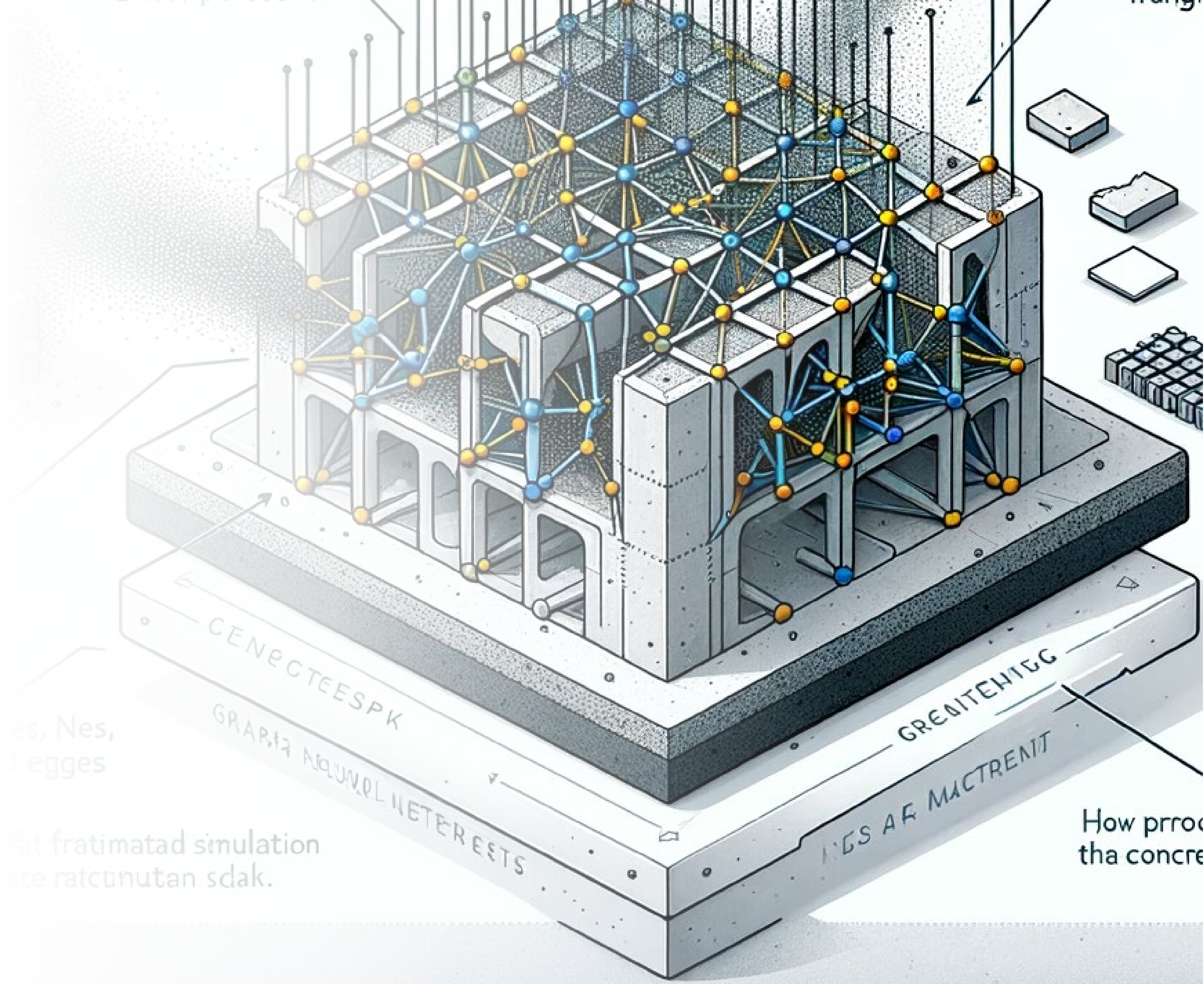


We need a solution that reduce computational load without compromising accuracy!

Overview of Graph Neural Networks (GNN)

- Brief explanation of GNN
  - Graph structured data + deep learning
  - Capturing interactions between elements
- Why GNN for this problem?
  - GNN is like FEM
  - Divide and conquer



Numerical modelling

- FEM-SPH-ALE coupling

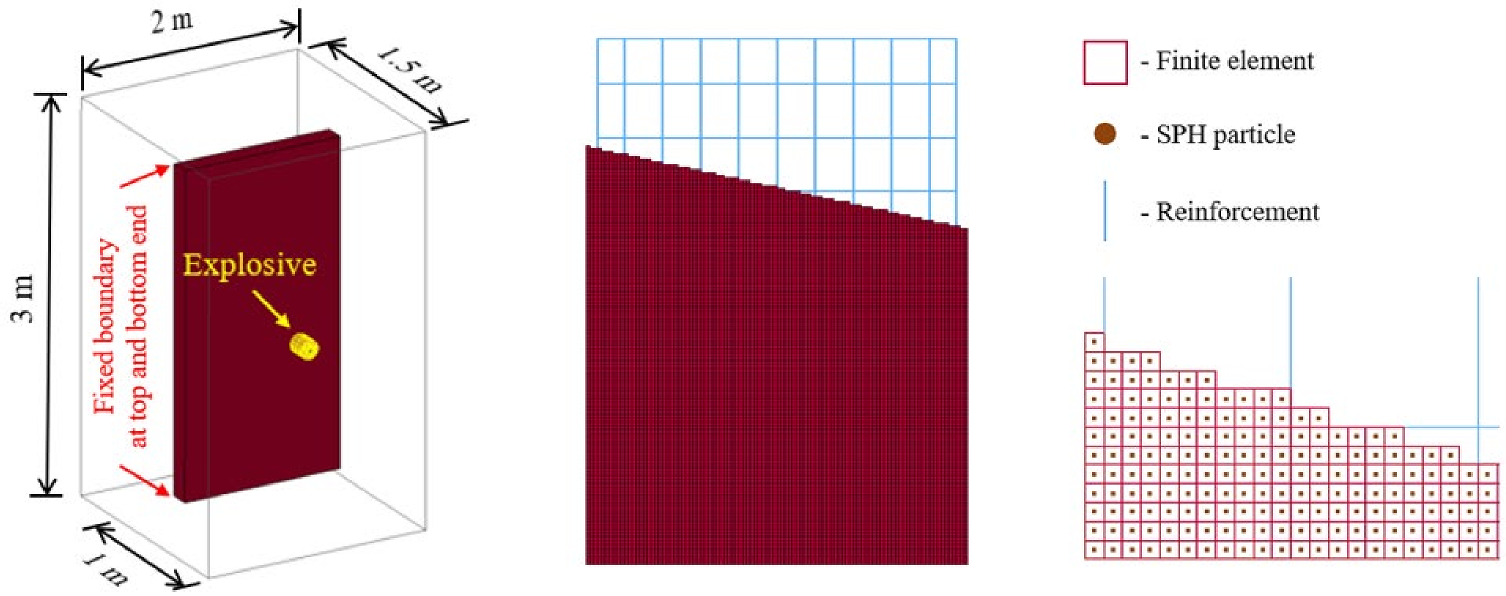


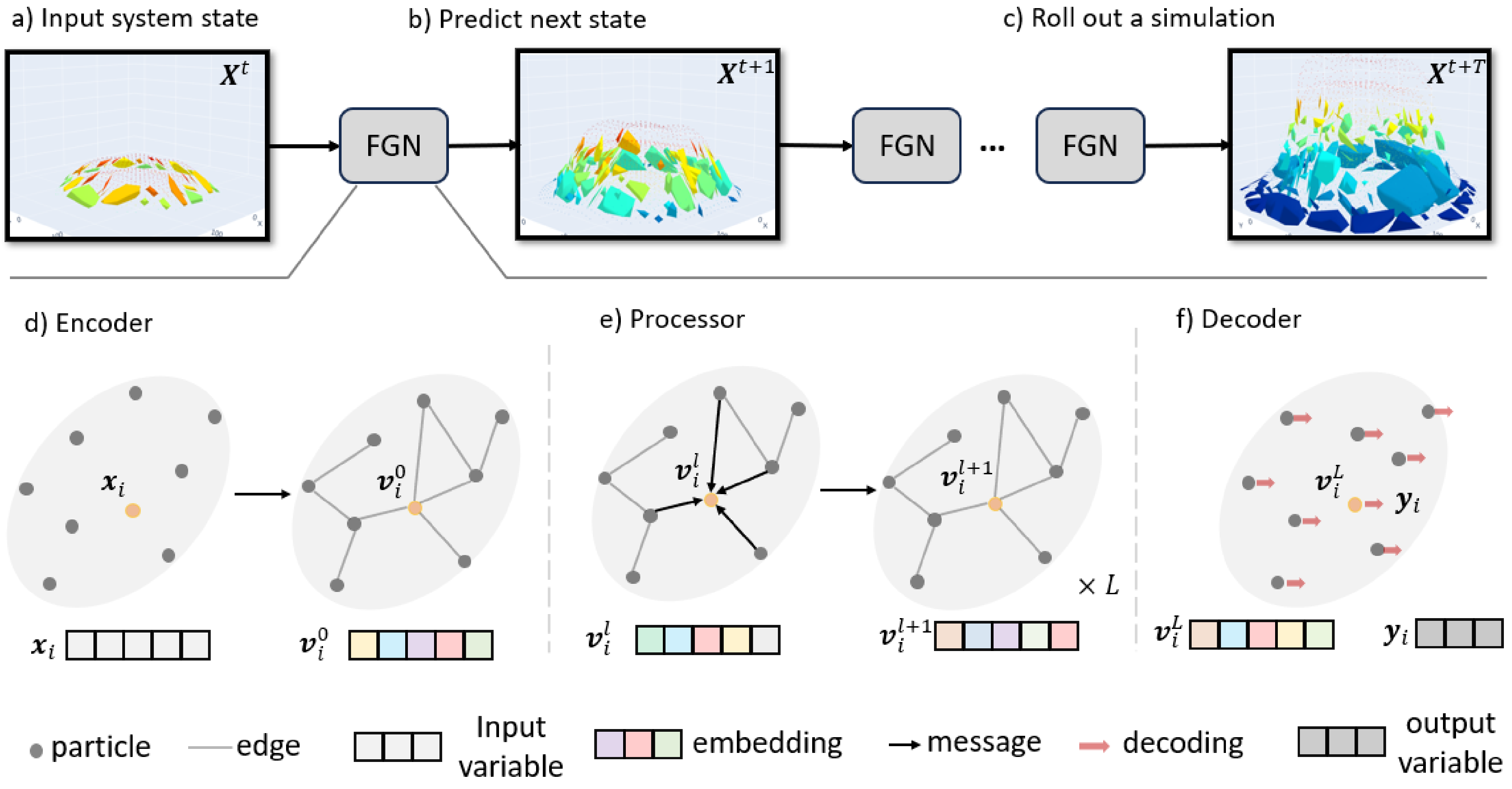
Table 3 Material properties of concrete [24, 53]

Density (kg/m^3)	Poisson's ratio	Compressive strength (MPa)	Tensile strength (MPa)	A0	A1
2400	0.2	30.7	2.95	10.90125	0.466388
A2	A0Y	A1Y	A2Y	A1F	A2F
0.003641	6.923877	0.730823	0.005082	0.4773	0.003583

Table 4 Material properties of HRB 400 steel reinforcement [24]

Density (kg/m^3)	Yield stress (MPa)	Ultimate stress (MPa)	Poisson's ratio	Young's modulus (MPa)
7,800	400	540	0.3	2×10^5

Fragment Graph Network (FGN)



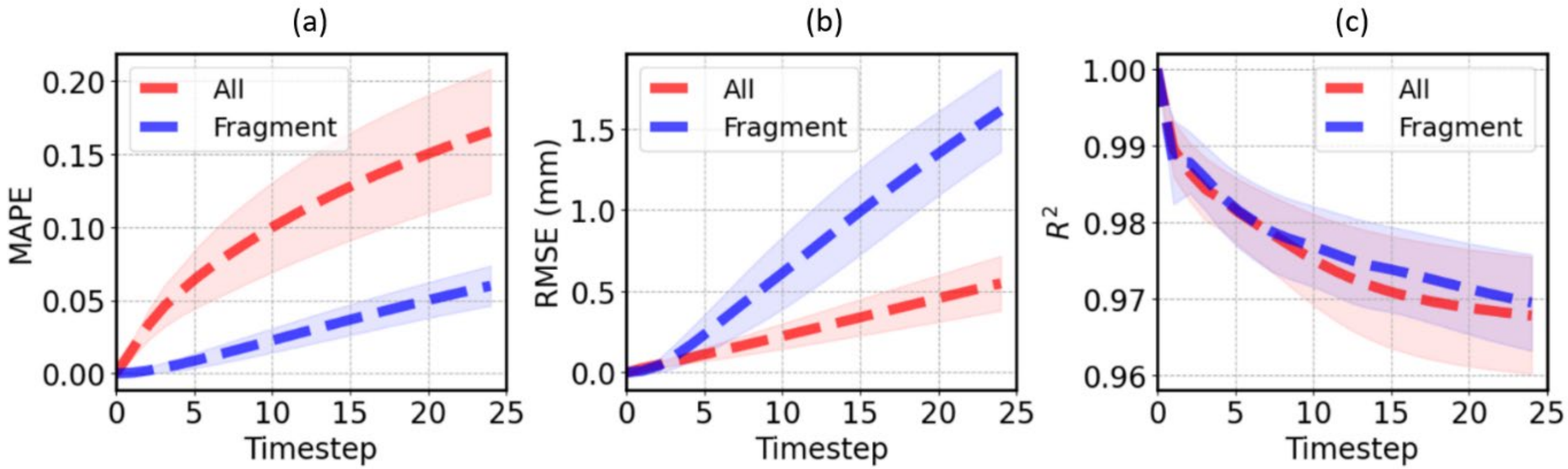
Training details

- 149 cases, each with ~180K particles for 35 steps over 2ms, 9M+ data points in total
- Trained on a NVIDIA TITAN RTX GPU for ~24h

Variable	Data range
Charge weight (kg)	2, 3, 4, 5, 6
Standoff distance (mm)	300, 400, 500
Concrete strength	C30, C50, C80
Slab size (mm) and reinforcement layout	1000×2000×60, H φ12@100, V φ12@200 (one layer) 1000×2000×90, H φ12@100, V φ12@200 (two layers) 1000×2000×120, H φ12@100, V φ12@200 (two layers with stirrup)

Overall Quantitative Evaluation

- Averaged over all particles or fragment particles
- Fragments: ~6% relative error, 1.7 mm absolute error, 96%+ R^2



Time and Memory Efficiency

- FGN is several magnitudes faster than LS-DYNA
- And consumes less memory, which makes it more scalable

Table 6 Runtime comparison between LS-DYNA and FGN

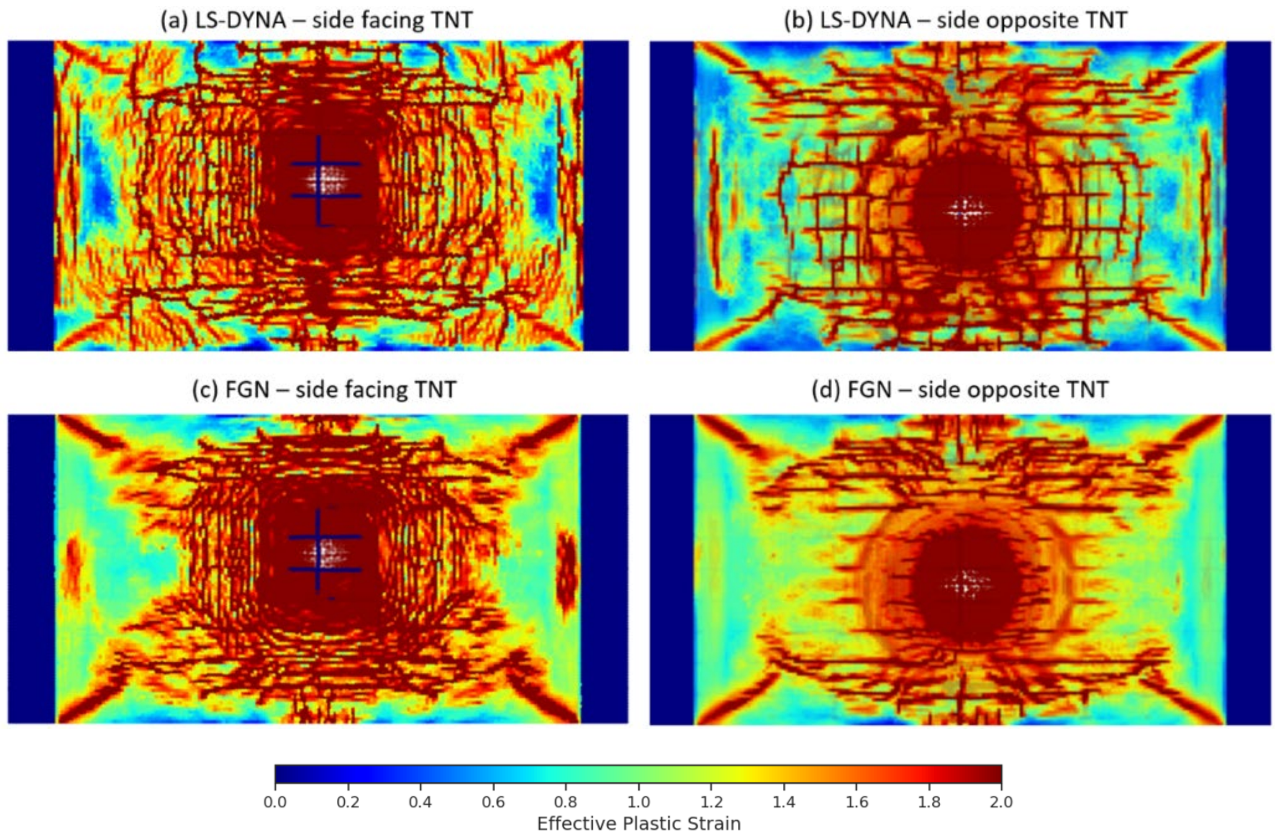
Number of particles	**Runtime (second)**		
	LS-DYNA-CPU	FGN-CPU	FGN-GPU
123K	10,560	74	5
186K	10,800	116	8
246K	11,400	146	12

Table 7 Maximum memory usage comparison between LS-DYNA and FGN

Phase	**Memory Usage (GB)**		
	LS-DYNA-CPU	FGN-CPU	FGN-GPU
Training	-	23	24
Inference	62	16	21

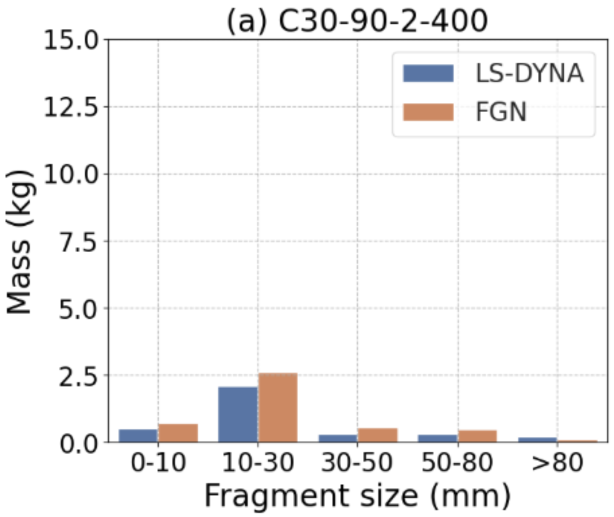
Effective Plastic Strain Prediction

- FGN can predict other parameters, e.g., effective plastic strain

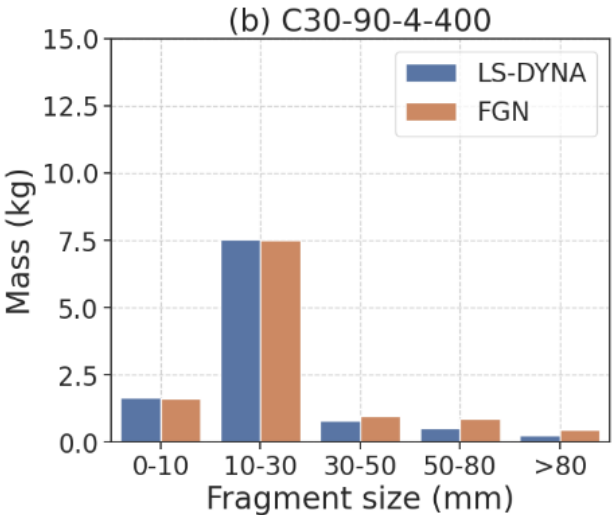


Fragments Mass Distribution

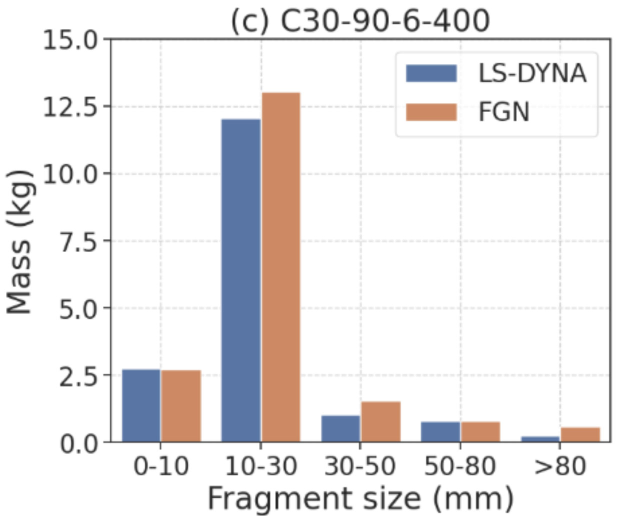
- FGN matches well with LS-DYNA, in terms of fragments distribution



2 kg



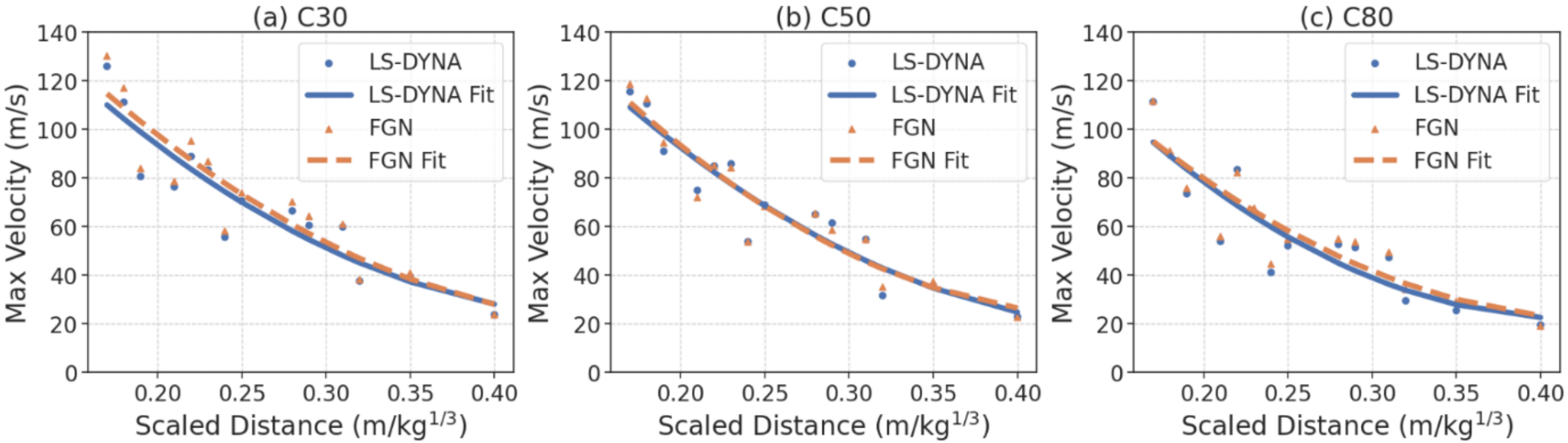
4 kg



6 kg

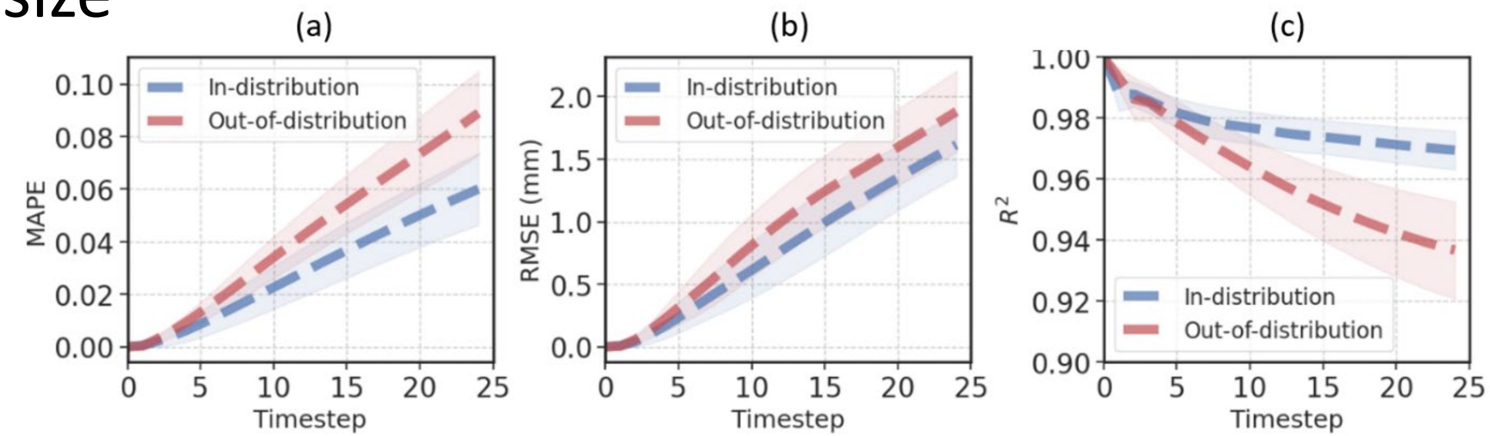
Fragments Max Ejection Speed

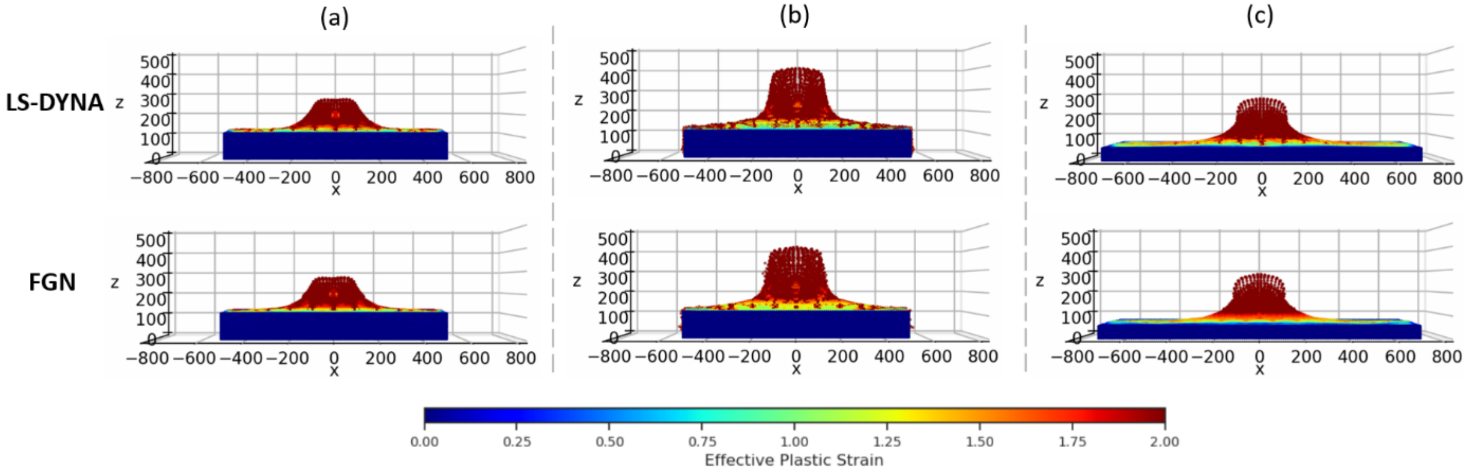
- FGN well capture the max ejection speed of fragments
- FGN is well suited for data-hungry parametric analysis



Generalization and Robustness

- FGN exhibits good generalizability, e.g., extrapolating scaled distance or slab size

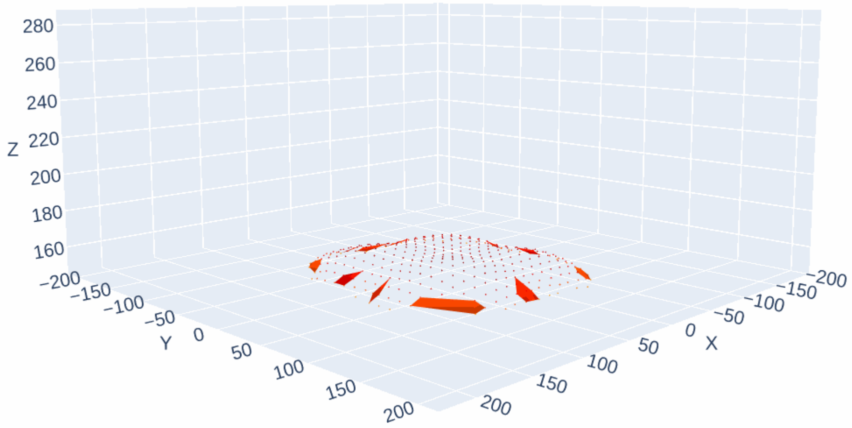




Simulation Animation

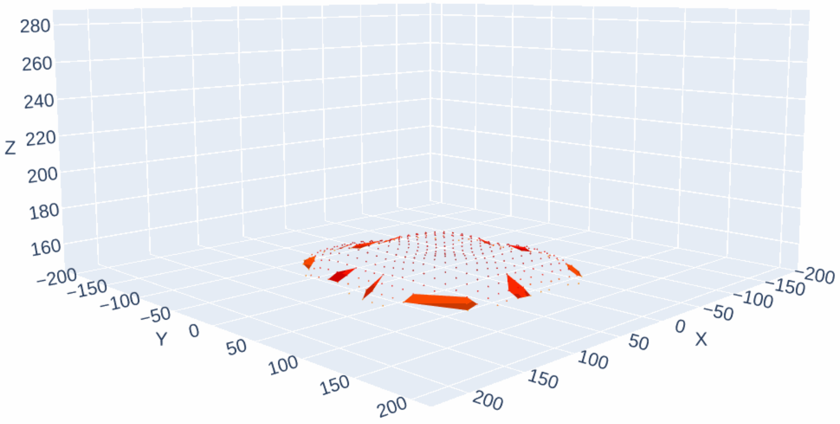
LS-DYNA

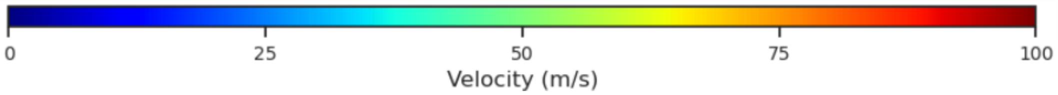
Step: 00, time: 0.600 ms, fragment mass: 0.840 kg



FGN

Step: 00, time: 0.600 ms, fragment mass: 0.840 kg





Takeaway

- GNN is well suited for surrogating discretization-based numerical modelling, such as FEM, SPH, or even Eulerian grid
- Paper and code

❑ Li, Qilin, Yang Wang, Wensu Chen, Ling Li, and Hong Hao.
"Machine learning prediction of BLEVE loading with graph neural networks."
Reliability Engineering & System Safety 241 (2024): 109639.

https://github.com/qilinli/bleve-graph-net

❑ Li, Qilin, Zitong Wang, Ling Li, Hong Hao, Wensu Chen, and Yanda Shao.
"Machine learning prediction of structural dynamic responses using graph neural networks."
Computers & Structures 289 (2023): 107188.

https://github.com/qilinli/gns-fragment

Thank you for your attention! Questions?