ICML 2020

Learning to Simulate and Design for Structural Engineering

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Problem: Structural Design for Buildings

Why is this important?

Problem: Structural Design for Buildings

According to the International Energy Agency (IEA 2017),

Buildings and construction caused ~ 40% of global energy-related CO_2 emissions.

*Buildings: 28%; Construction 11%

Source: derived with IEA (2017), World Energy Statistics and Balances, IEA/OECD, Paris, www.iea.org/statistics

Problem: Structural Design for Buildings

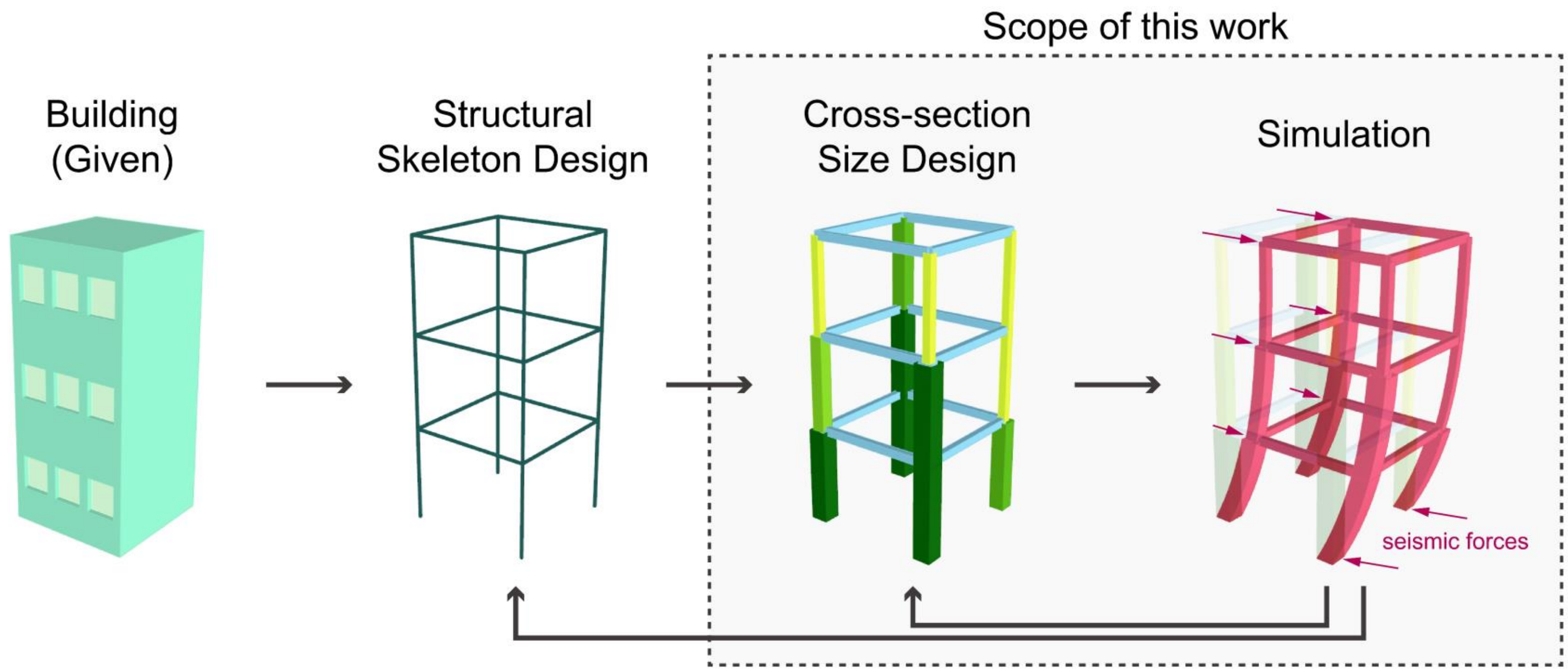
Optimized structural design for buildings → Less construction materials used

→ Reduced cost

→ Decreased corresponding CO_2 emissions

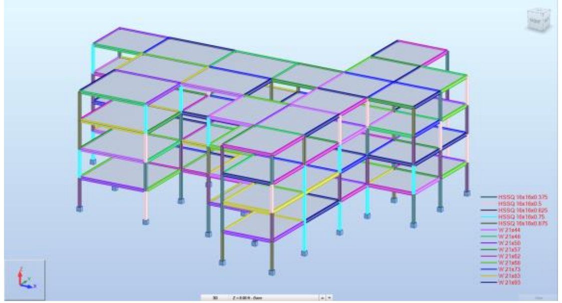
What Is Structural Design?

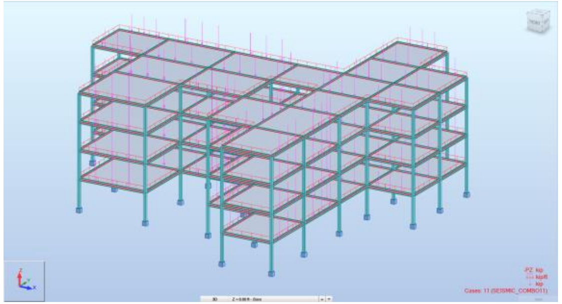
A common structural design workflow:

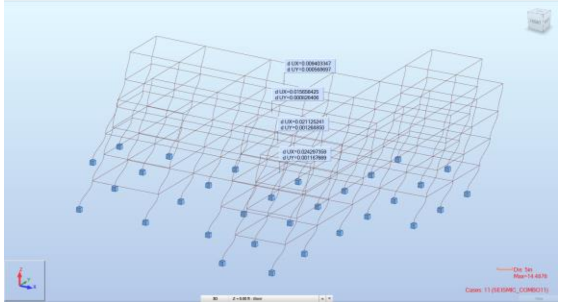


The design iterations in practice are laborious and mostly manual!

Components and Constraints







Cross Section Library

Column	Beam
HSSQ 16x16x0.375	W21x44
HSSQ 16x16x0.5	W21x48
HSSQ 16x16x0.625	W21x50
HSSQ 16x16x0.75	W21x57
HSSQ 16x16x0.875	W21x62
	W21x68
	W21x73
	W21x83
	W21x93

Load Cases

<u>Dead Load (L)</u>
- Self Weight
- Super-imposed
- Roof
- Cladding Load

<u>Live Load (Lr)</u>
- Floor
- Roof

<u>Seismic (E)</u>

<u>Combination</u>

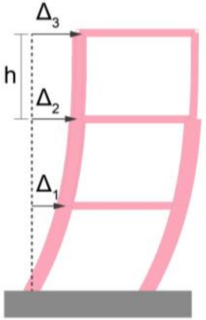
- 1.2D + 1.6L + 0.5Lr
- 0.9D + 1.0E (X and Y)

Simulation Results

Drift Ratio in Ex and Ey

For each story

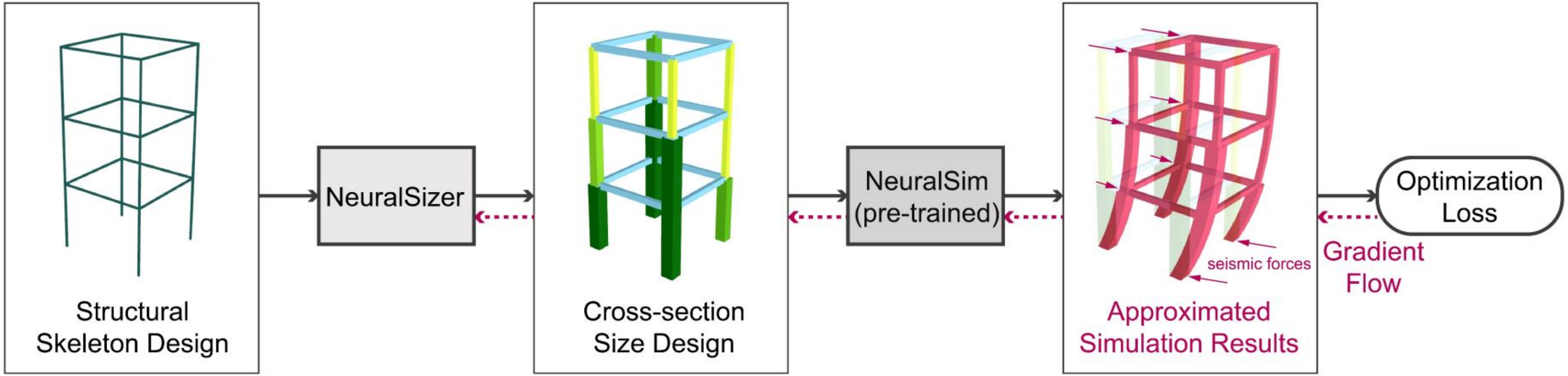
$$dr_x, dr_y$$



<def> $dr_i = \dfrac{\Delta_i - \Delta_{i-1}}{h}$

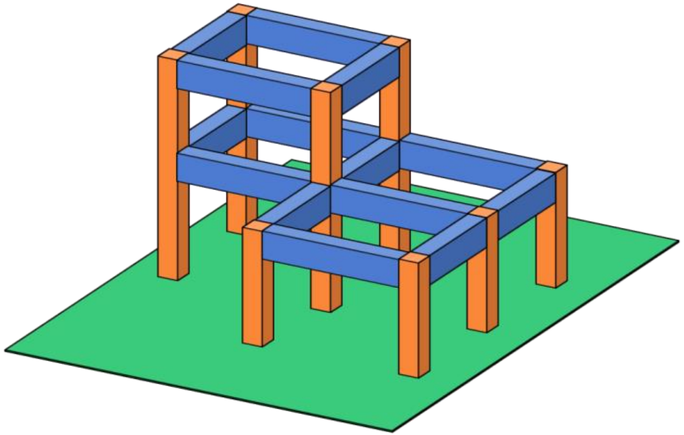
Pipeline

Structural design in practice:
Using Genetic Algorithm (GA) for optimization
Our approach (NeuralSizer + NeuralSim):



Slow, and completely relying on the engineer’s knowledge, experience, and intuition

What is the proper representation?



Building Structure

Voxel?

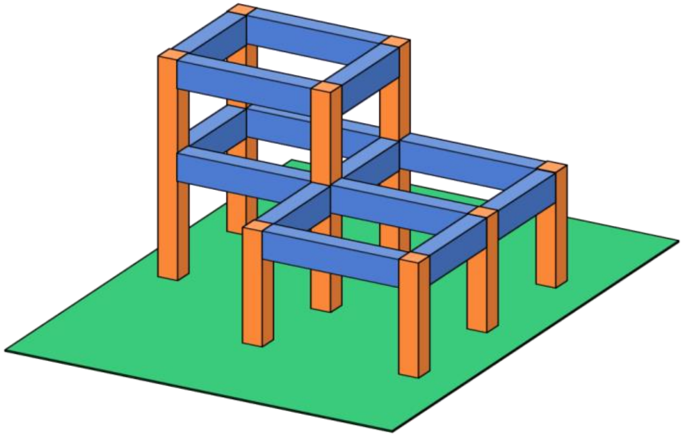
Point clouds?

Meshes?

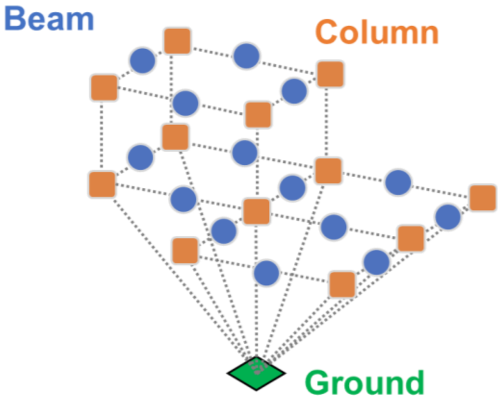
Images with multi-views?

It contains discrete components, is usually large at scale, and has strong connectivity relations.

Intuition: Representing Structures as Graphs



Building Structure

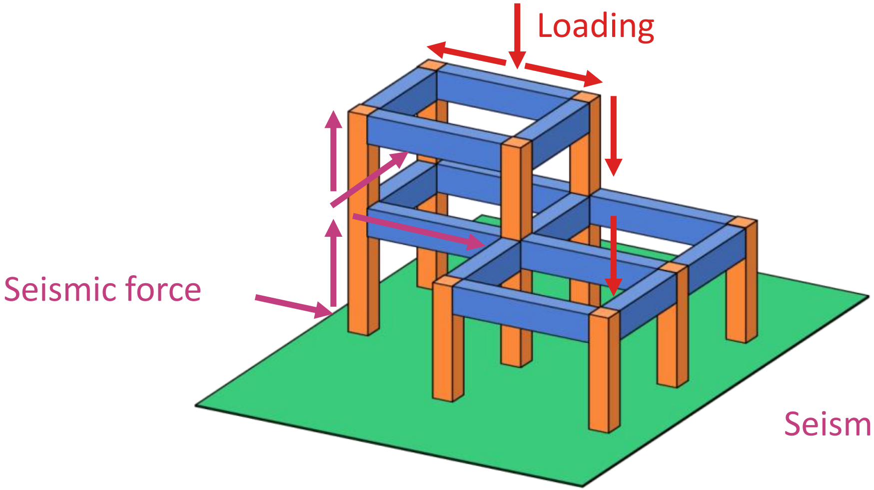


Structural Graph

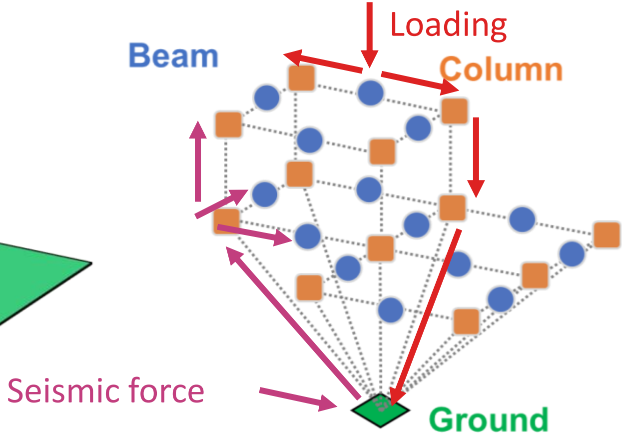
Node feature

Positions		0: column 1: beam	One hot vector of cross section type	if roof	Metal deck area	if boundary
x_1, y_1, z_1	x_2, y_2, z_2					

Force Transmissions vs. Message Passing

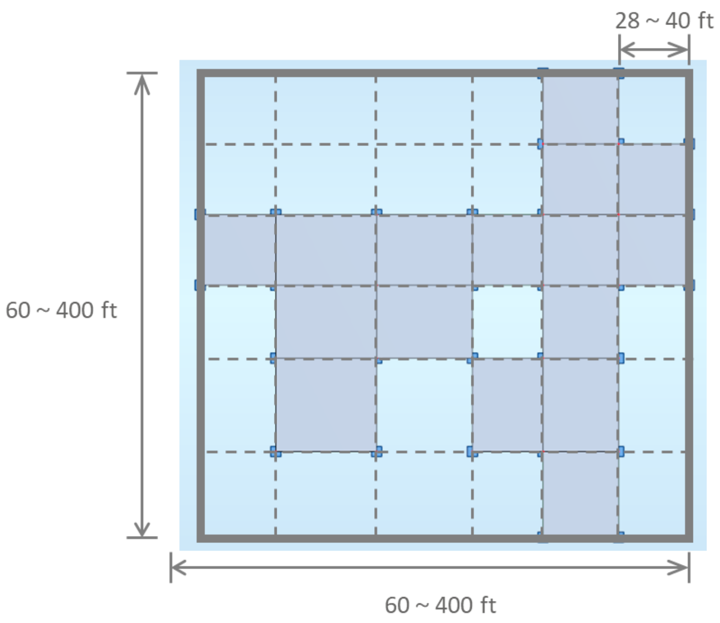


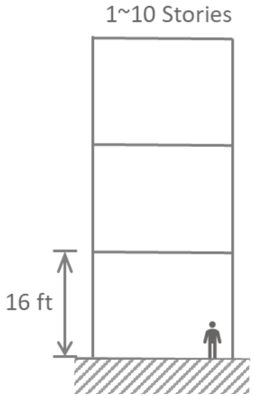
Building Structure



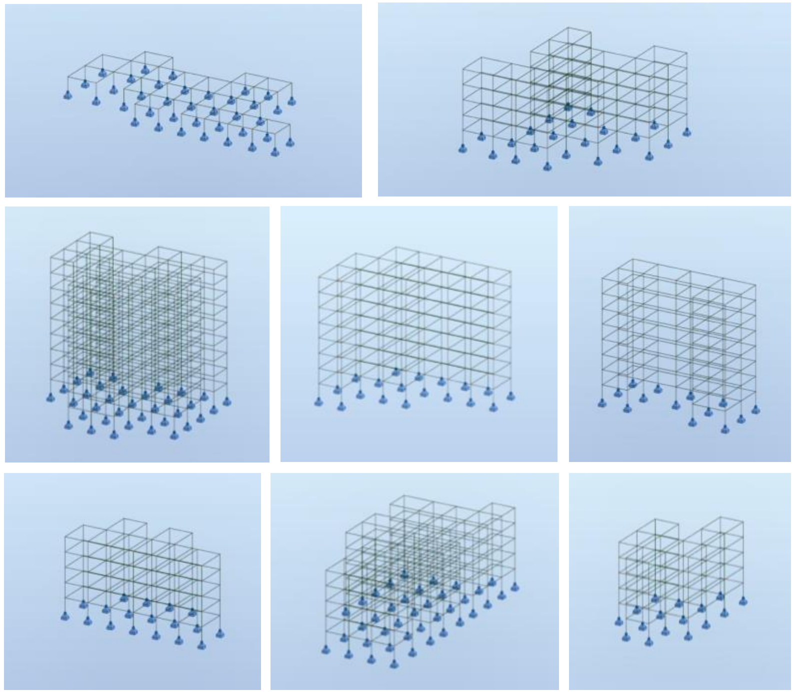
Structural Graph

Data Generation



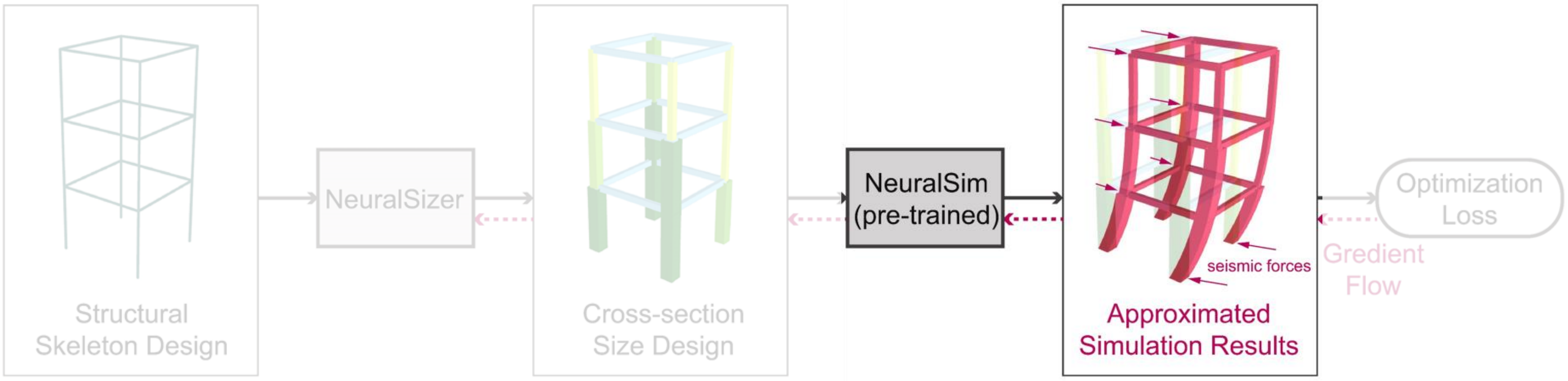


Using Autodesk® Robot™ Structural Analysis
(free for educational use)



NeuralSim

A Graph-Based Neural Approximator for Structural Simulation

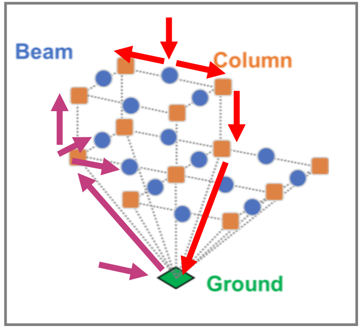


NeuralSim

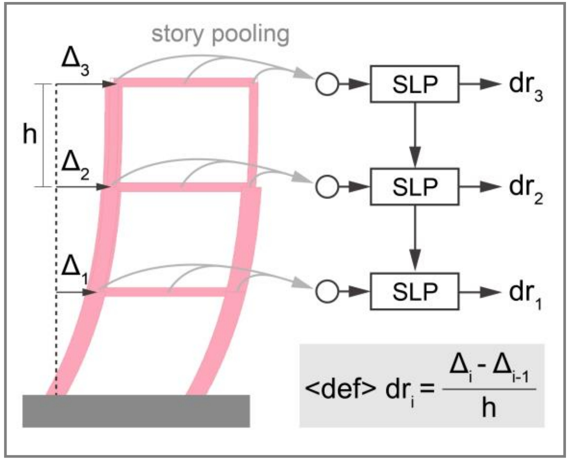
A Graph-Based Neural Approximator for Structural Simulation

Node Encoder

Message Passing



Structured Decoder



Drift Ratio Output

Classifier Output

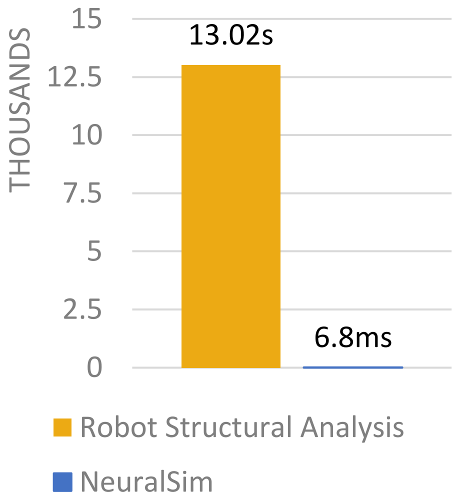
$$Loss = L1Loss(groundtruth, \underline{output}) + BCE(\underline{if\ output > lim}, if\ groundtruth > lim)$$

NeuralSim: Performance

Table 1. NeuralSim Performance Compared To Other Models

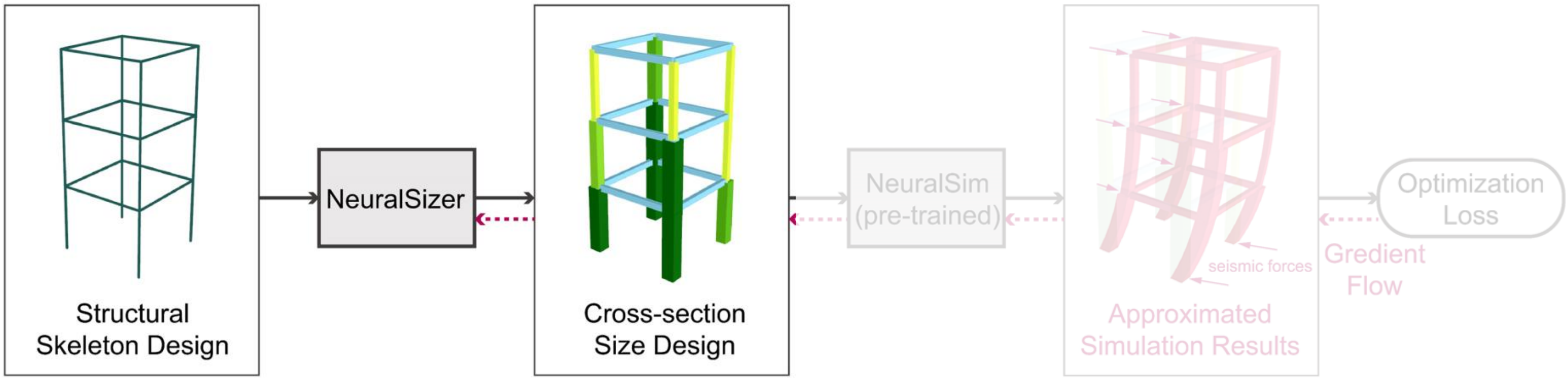
Model	L1 Loss $\times$1e$-$4	Relative Accuracy	Classification Accuracy
GCN	16.01	94.86	89.22
GIN	33.85	89.62	84.27
GAT	10.87	96.41	93.35
PGNN	9.39	96.72	94.83
NeuralSim	**7.57**	**97.36**	**95.64**
NeuralSim + PGNN	**5.01**	**98.22**	**96.43**
NeuralSim(no SD)	10.24	96.65	92.71
NeuralSim(only L1 loss)	16.47	95.24	n/a

Speed: ~ 1900x faster



NeuralSizer

A Graph Neural Network for Proposing Optimal Size Design

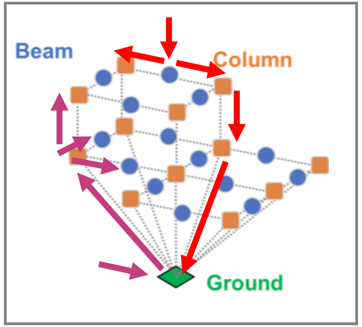


NeuralSizer

A Graph Neural Network for Proposing Optimal Size Design

Node Encoder

Message Passing



Node Decoder

Gumbel Softmax

Cross-section Output

NeuralSizer + NeuralSim:

Optimization Setup

min objective s.t. constraints

- Mass Objective

$$obj = \sum_{bar} length \times area \times density$$

- Drift Ratio Constraints

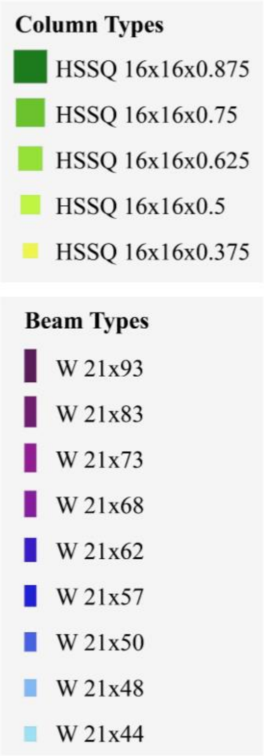
$$l_{dr} = Mean\{LeakyReLU(|dr_k| - lim)\} \leq 0$$

- Variety Constraints

$$l_{var} = 1 - SumTop6\left(usage_{percentage}\right) = 0$$

- Entropy Constraints

$$l_H = Mean\{H_i\}/H_{max} - \alpha = 0$$



NeuralSizer + NeuralSim:

Table 3. NeuralSizer Results Under Different Scenarios

Scenario	Objective Weight	Objective	Constraints	
		Mass Objective	Drift Ratio Constraint	Variety Constraint
High Safety Factor	1	0.870	$6.00\times 1e{-7}$	$0.01\times 1e{-8}$
	10	0.735	$1.34\times 1e{-7}$	$1.04\times 1e{-8}$
Low Safety Factor	1	0.592	$6.42\times 1e{-5}$	$1.67\times 1e{-8}$
	10	0.596	$3.32\times 1e{-5}$	$1.78\times 1e{-8}$

High / Low Safety Factor : Drift Ratio Limit 0.015 / 0.025

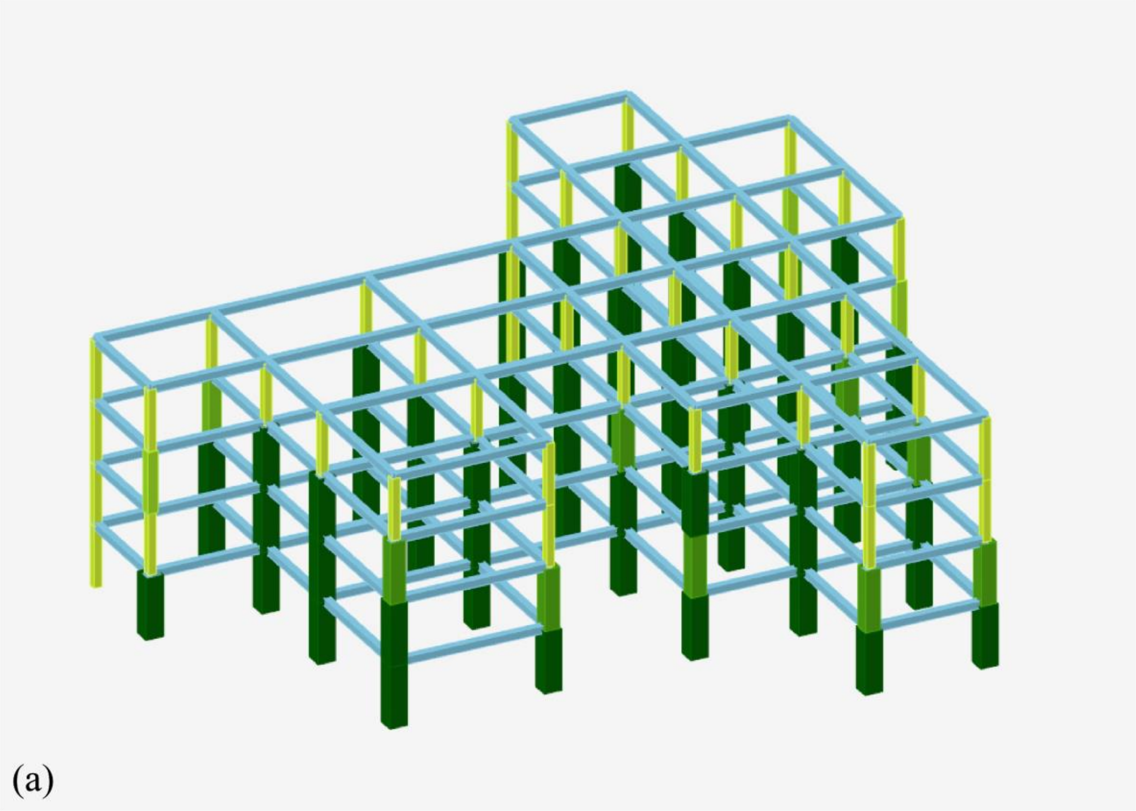
Table 4. NeuralSizer Generalizability (High Safety Factor, Objective Weight = 10)

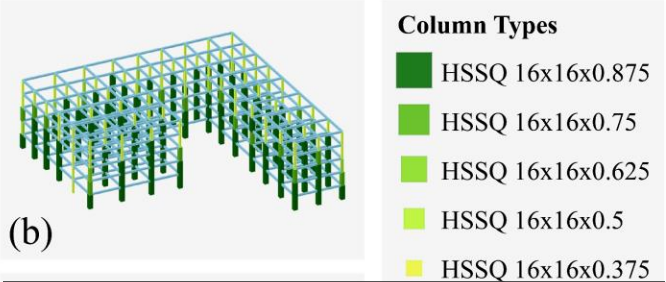
Train Data	Test Data	Objective	Constraints	
		Mass Objective	Drift Ratio Constraint	Variety Constraint
1~10 story (Baseline)	1~3 story	0.738	$1.62\times 1e{-7}$	$0.80\times 1e{-8}$
	4~7 story	0.725	$1.28\times 1e{-7}$	$0.97\times 1e{-8}$
	8~10 story	0.711	$1.69\times 1e{-7}$	$1.06\times 1e{-8}$
4~7 story	1~3 story	0.773	$2.96\times 1e{-7}$	$1.30\times 1e{-8}$
	4~7 story	0.746	$3.50\times 1e{-7}$	$1.25\times 1e{-8}$
	8~10 story	0.728	$3.68\times 1e{-7}$	$1.01\times 1e{-8}$

- Inference Time: 5.41ms

NeuralSizer + NeuralSim:

Result Visualization





Structural Engineers' Insights

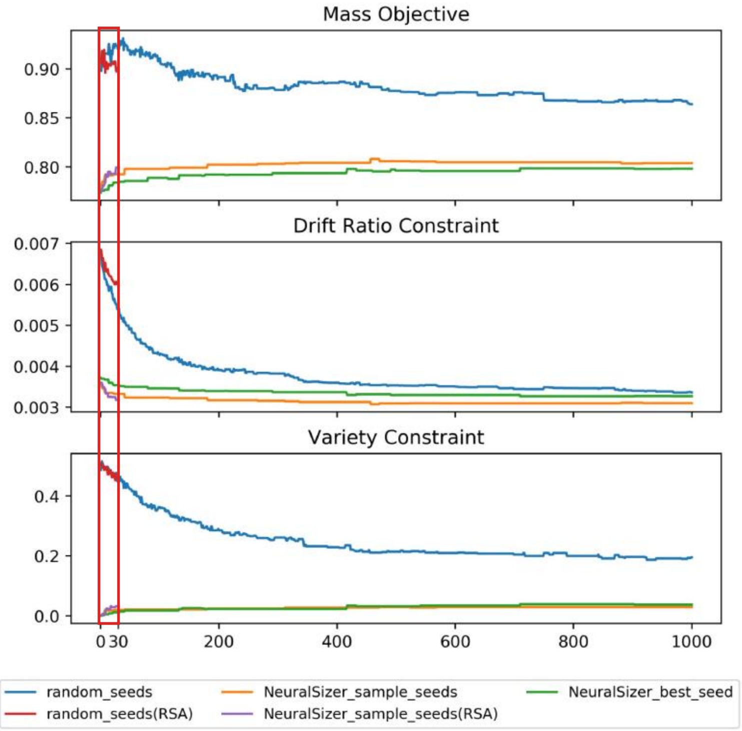
1. Columns are generally thicker on lower floors
2. Prioritize using stronger columns over beams
3. Similar patterns/strategies across different buildings

Speed Comparison with Genetic Algorithm (G.A.)

Table 5. Time Comparison of GA under Different Setups

Setup	Time	Total Iterations	Time / Iteration
NeuroSizer	10.07 ms	-	-
GA + RSA	24 hr	30	-
$\rightarrow$ *(estimated)*	2 weeks	1000	20.16 mins
GA + NeuralSim	30 mins	1000	0.03 mins

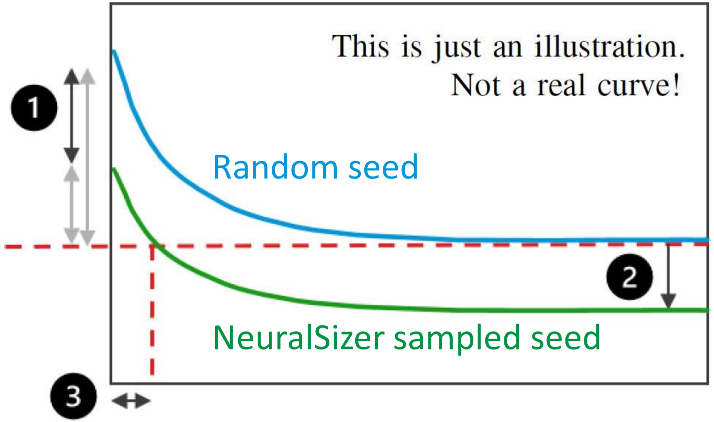
Figure 3. Performance Curves of GA Using Different Seeding Approaches.



G.A. with Random vs. NeuralSizer Seed

Table 6. NeuralSizer Seeding Performance

Metric	Mass Objective	Drift Ratio Constraint	Variety Constraint
High Safety Factor			
1	232.60%	115.30%	186.20%
2	7.43%	25.70%	95.82%
3	0	25.6	0
Low Safety Factor			
1	83.15%	95.35%	156.22%
2	4.16%	49.22%	32.53%
3	128	0	0



Conclusion

- We propose an end-to-end pipeline for cross-section size design optimization problem in structural engineering
  - NeuralSim – Fast, accurate
  - NeuralSizer – Qualified design comparable GA results
- Research on improving building and construction performance can bring positive impact, especially on energy consumptions and CO_2 emissions
- Open-source data is public at https://github.com/AutodeskAILab/LSDSE-Dataset