Design of Lego-inspired Reconfigurable Modular Blocks for Automated Construction of Engineering Structures

Rojyar Barhemat [1], Victor C. Li [2], Yi Bao [1,*]

[1] Department of Civil, Environmental & Ocean Engineering, Stevens Institute of Technology, Hoboken, NJ 07030

[2] Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48105

* Email: yi.bao@stevens.edu

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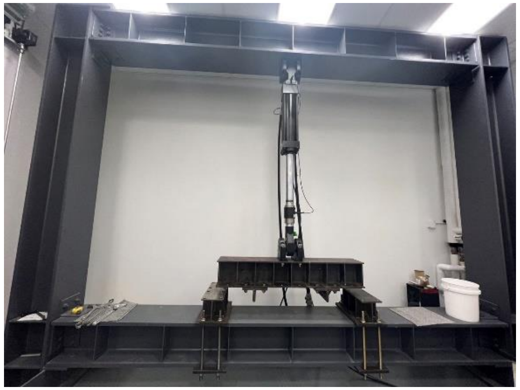
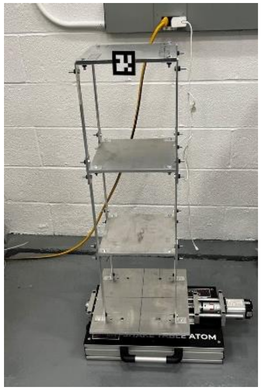
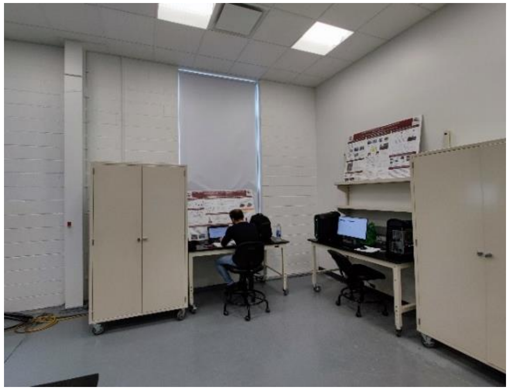
➢Smart Infrastructure Lab has versatile facility for performing large-scale structural testing, computing, and monitoring.







Background

- Modular structures has many benefits
  - Accelerate construction process
  - Reduce Labor expenses
  - Increase quality and safety

References: https://cnim-groupe.com/en/businesses/defense-security-and-digital-intelligence/modular-assault-bridge.
https://www.bimcommunity.com/files/images/userlib/ChapmanTaylor.jpg
N. Bertram, S. Fuchs, J. Mischke, R. Palter, G. Strube, J. Woetzel, Modular construction: from projects to products McKinsey & Company: Capital Projects & Infrastructure (2019), pp. 1-34

- **Lego-inspired structures** are the reconfigurable modular structures that can be assembled, disassembled, and reassembled for different structures.

Reference: Y. Bao, V.C. Li, Feasibility study of Lego-inspired construction with bendable concrete, Automation in Construction, 113 (2020), 103161, doi: 10.1016/j.autcon.2020.103161

Advantages of using Lego-inspired structures

- Improve sustainability and resilience
- Improve construction efficiency and productivity
- Reduce the adverse impact of construction on the environment

Current challenges on design of Lego structures

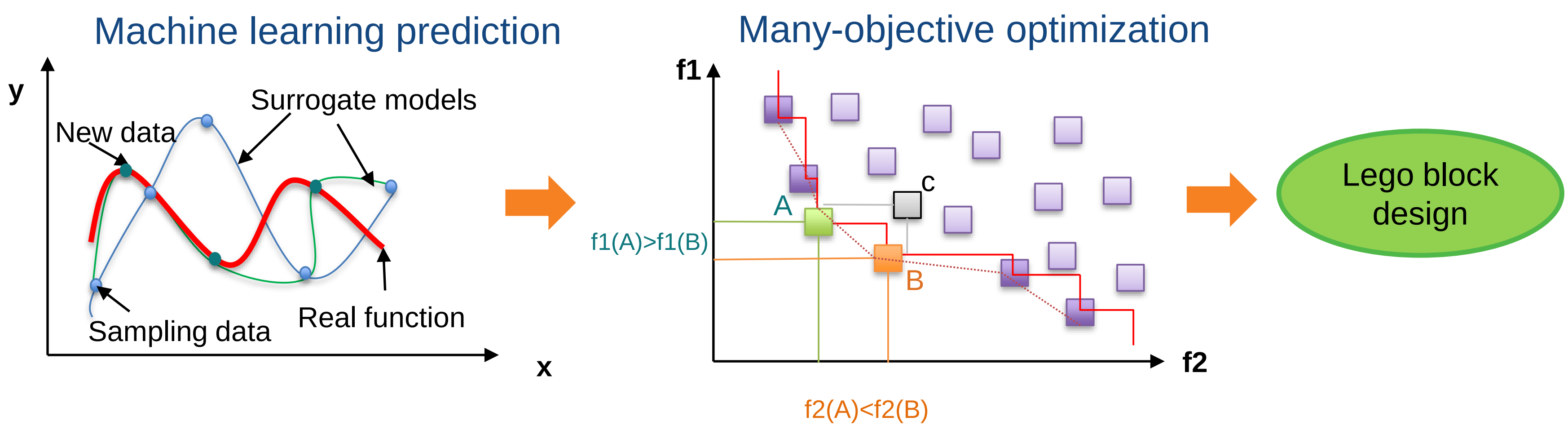
- There is lack of a knowledge about the computer-aided design and modeling of modular blocks.
- It is unclear how the modular blocks should be designed to improve the mechanical performance of modular structures while minimizing the mass.

Research goal and objectives

- This study aims to develop a many-objective optimization method to optimize the design of Lego-inspired modular blocks for achieving high mechanical performance of reconfigurable structures.

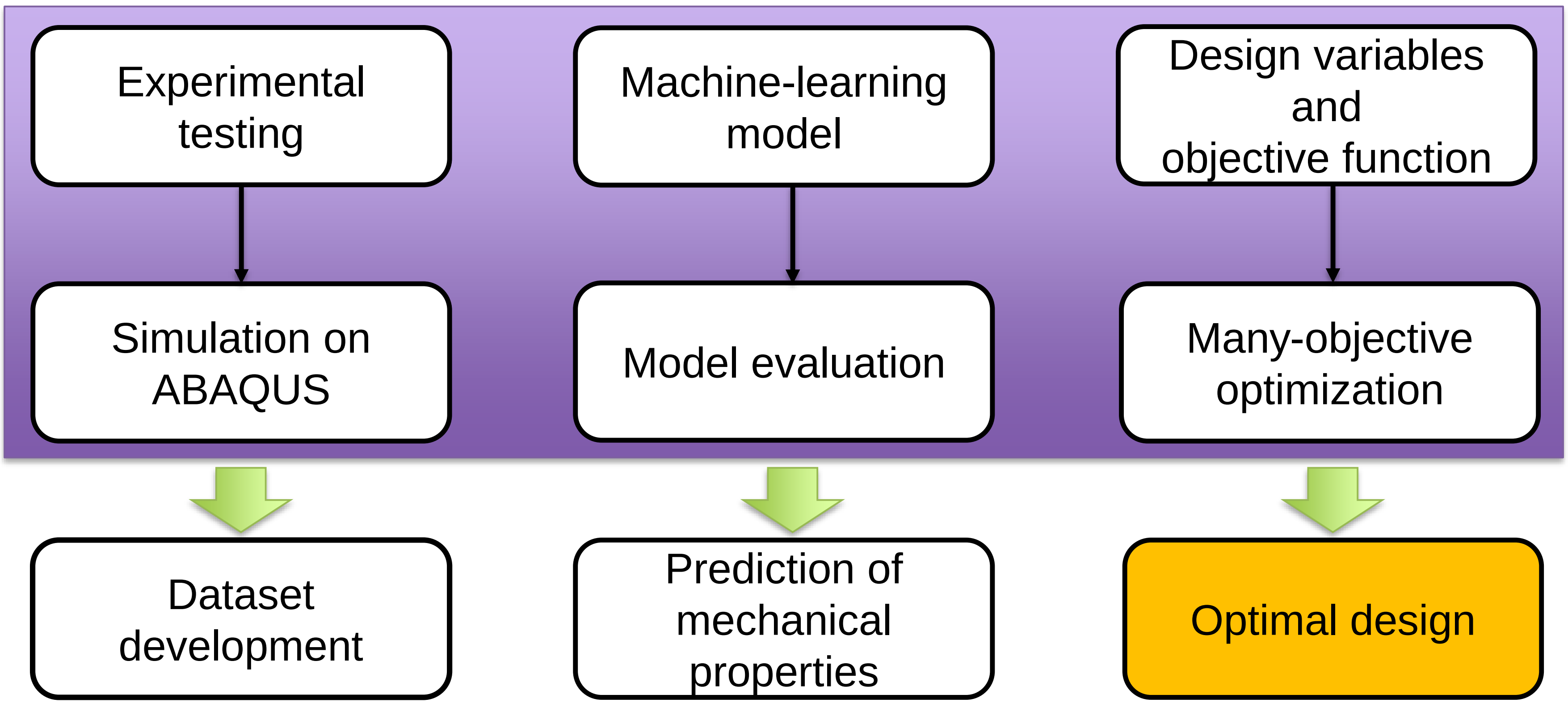
- Objectives:

  - To develop high-fidelity surrogate models to predict the load-carrying capacity, stiffness, and ultimate deflection
  - To develop a new many-objective optimization method to obtain optimal design



Methodology

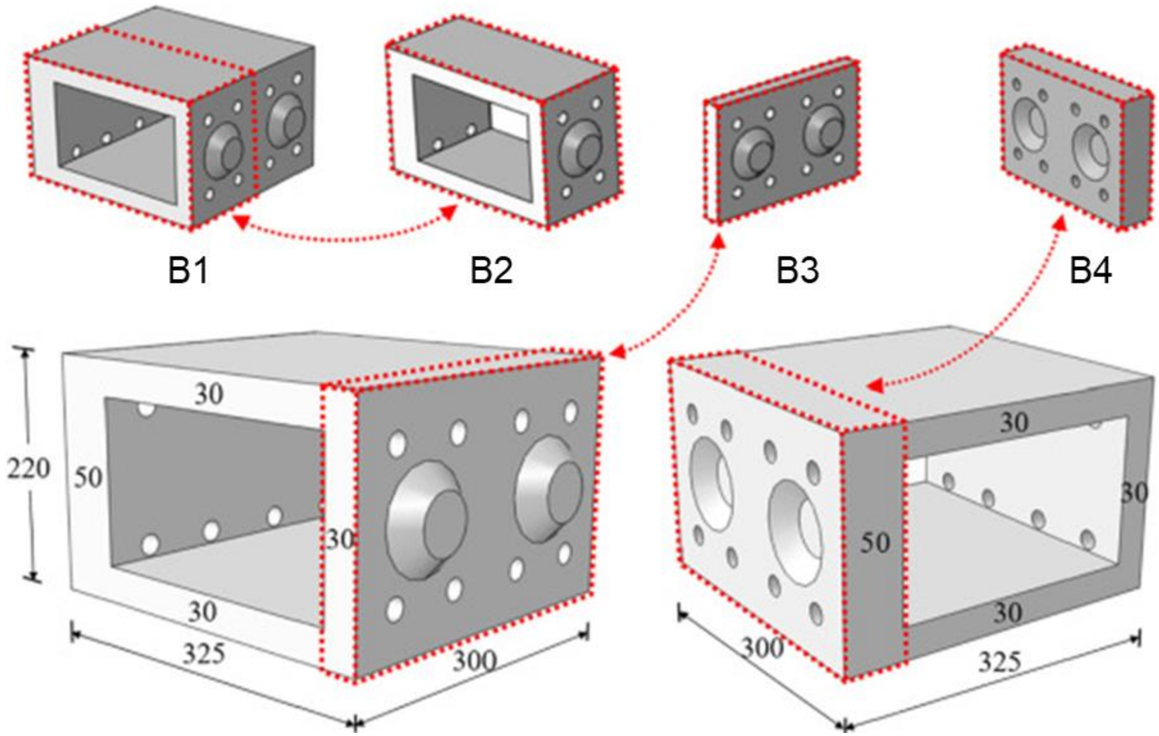
Experiment and simulation | **Machine learning** | **Optimization**



Experimental test

❑ Initial design

A set of four types of Lego-blocks was selected as the initial design for the experiment and optimization process.

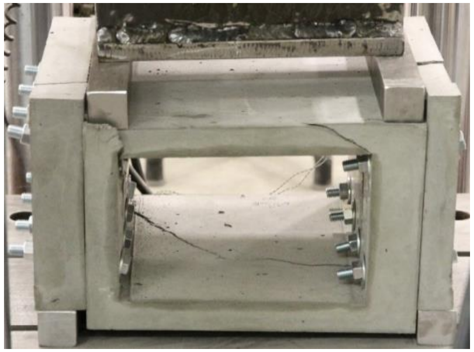


Specimens, test set-up

- Engineered cementitious composite (ECC) is used.
- Three-point bending test was conducted.

Specimen 1

Specimen 2



Finite element model

Simulation details

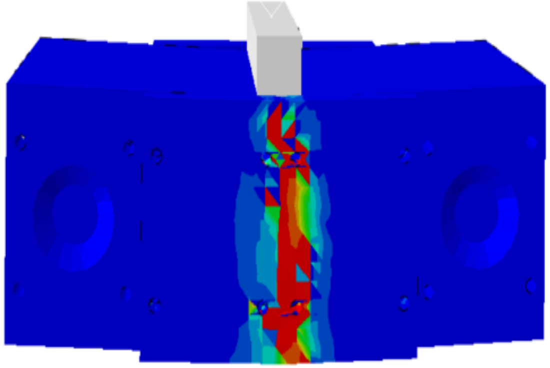
- Assemblages were modeled using eight-node solid elements (C3D8R).
- Contact between blocks were modeled by surface-to-surface hard contact.
- The behavior of concrete was modeled using concrete damage plasticity (CDP), as shown in Table 1 below.

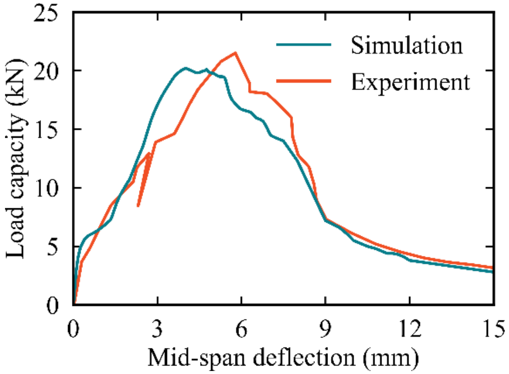
Parameters of the CDP model

Density (kg/mm^3)	Poisson's ratio	Young's modulus (GPa)	Dilation angle	Eccentricity	fb_0/fc_0	K	Viscosity parameter
2200	0.2	30	36	0.1	1.16	0.67	0

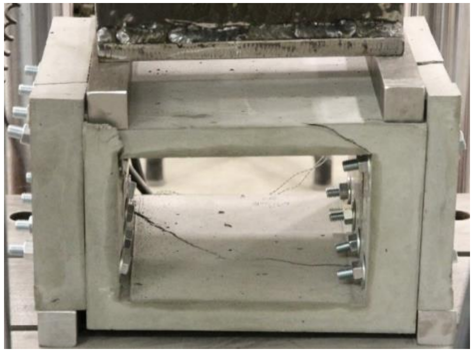
Finite element analysis

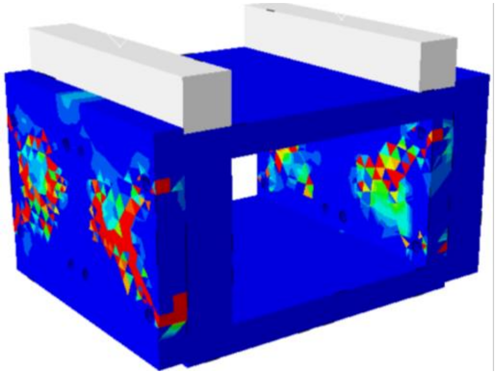
Specimen 1

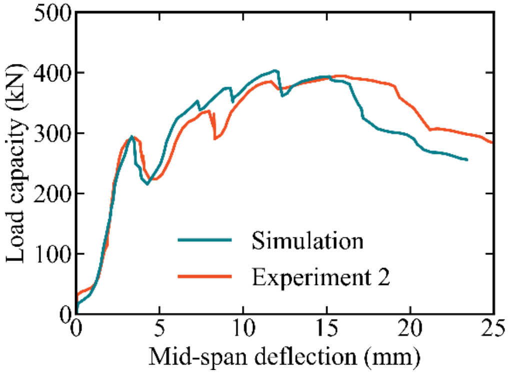




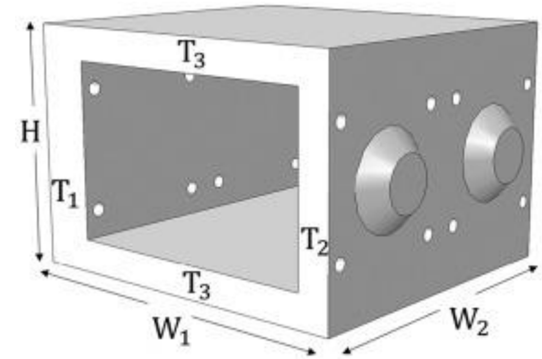
Specimen 2







Dataset development



Dataset generation

Input

- H
- W1
- W2
- T1
- T2
- T3

Design variables

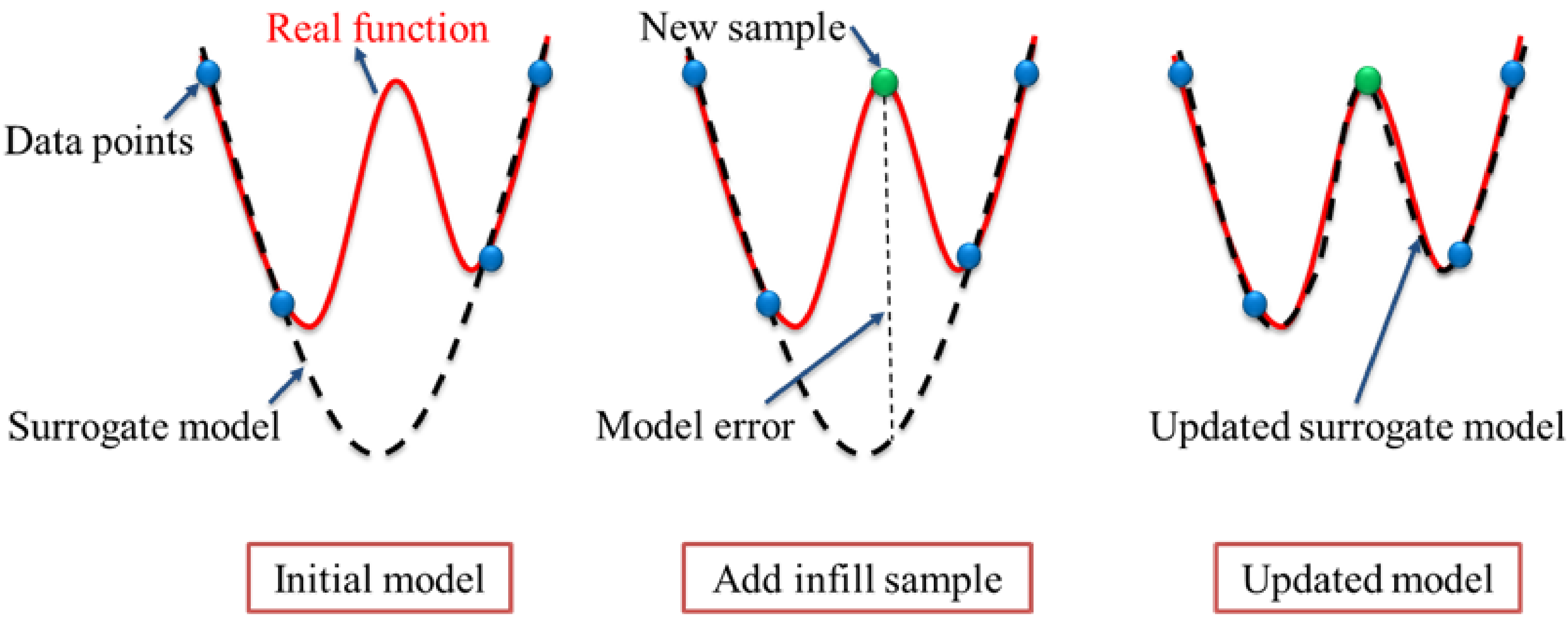
Finite element analysis

Output

- Load capacity
- Ultimate Deflection
- Stiffness

Mechanical properties

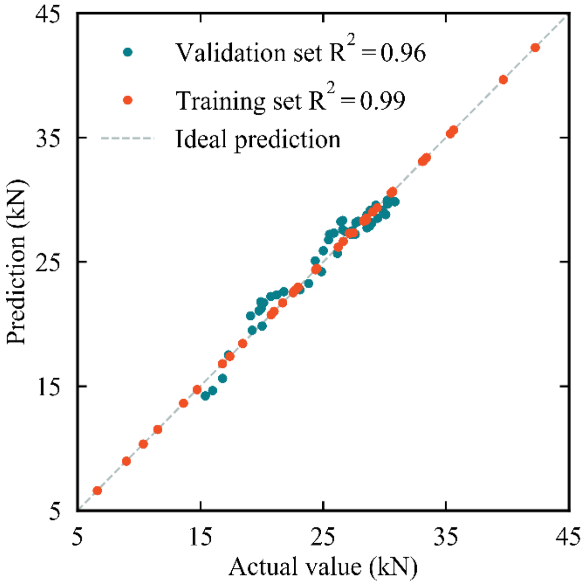
Machine learning (sequential surrogate modeling)



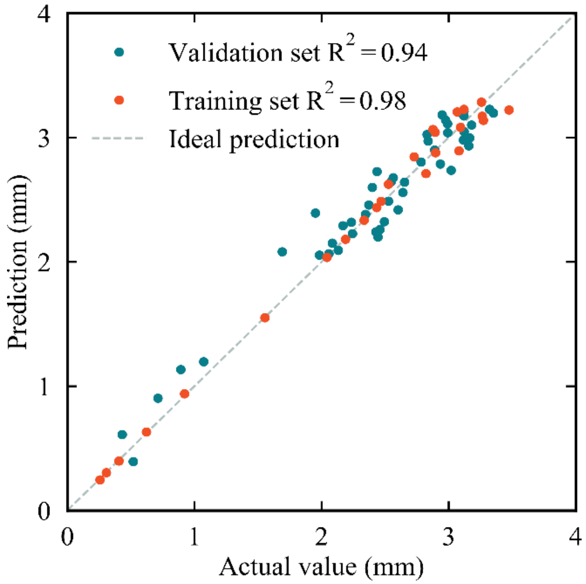
Reference: S.-S. Jin, H.-J. Jung, Sequential surrogate modeling for efficient finite element model updating, Comput. Struct., 168 (2016), pp. 30-45, 10.1016/j.compstruc.2016.02.005

Machine learning models

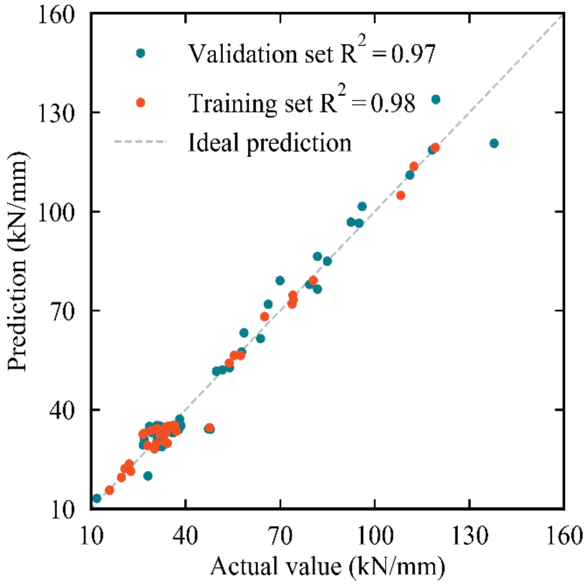
- Three machine learning models were developed for the load-carrying capacity, ultimate deflection, and stiffness



Load-capacity



Deflection



Stiffness

Prediction accuracy

- The typical performance metrices indicate that the models have high accuracy and generalization performance

Set	Metric	Mechanical properties		
		Load capacity	Deflection	Stiffness
Training	R^2	0.99	0.98	0.98
	RMSE	0.04	0.10	0.18
Validation	R^2	0.96	0.94	0.97
	RMSE	0.91	0.16	0.93

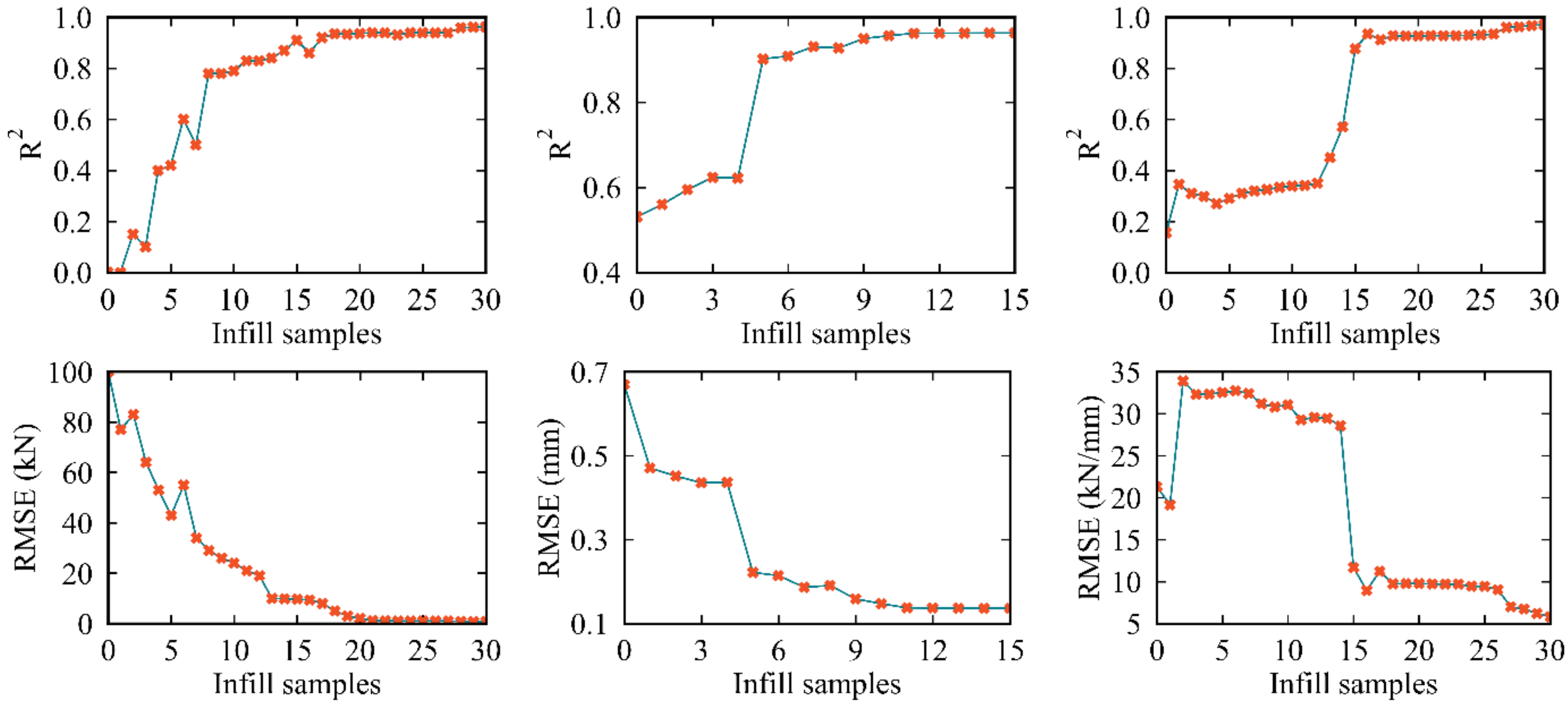
Coefficient of determination $$\mathrm{R}^2(P) = 1 - \frac{\sum_{i=1}^{n}(p_i - a_i)^2}{\sum_{i=1}^{n}[a_i - mean(a_i)]^2}$$

Root mean square error $$RMSE(P) = \sqrt{\frac{\sum_{i=1}^{n}(p_i - a_i)^2}{\mathrm{n}}}$$

Predictions $$P = \{p_1, p_1, \ldots, p_n\}$$

Actual values $$A = \{a_1, a_1, \ldots, a_n\}$$

Model evaluation



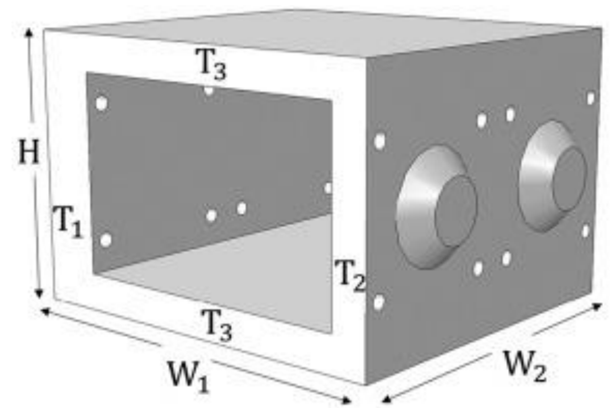
Load-capacity Deflection Stiffness

Many-objective optimization

- A many-objective optimization problem is formulated to optimize the design of Lego-inspired block

- Six design variables were considered: H, W1, W2, W3, T1, T2, T3

- Four objective functions were considered
  - Load-capacity (maximize)
  - Deflection (maximize)
  - Stiffness (maximize)
  - Volume (minimize)

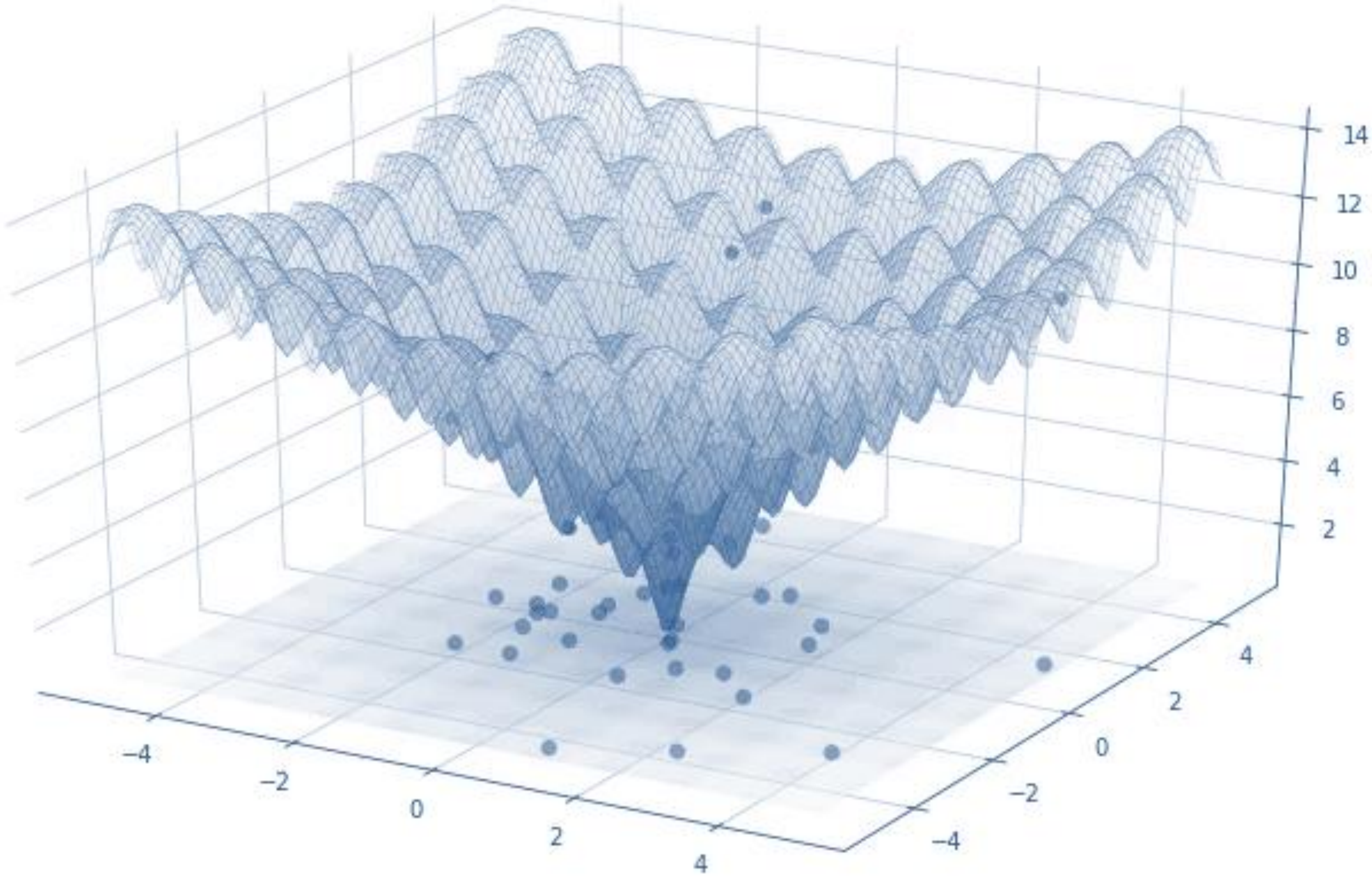


- one design constrains are applied:
  - The maximum mass of blocks is limited to 61 kg

Reference: Josyula, S. P., Krasemann, J. T., & Lundberg, L. (2020). Parallel computing for multi-objective train rescheduling. IEEE Transactions on Emerging Topics in Computing.

Optimization process

- A genetic algorithm is used to solve the optimization problem.



The iterative process for optimization

Optimization results

- A set of solutions are obtained from the optimization
- A decision-making algorithm TOPSIS is used to select the optimal design
- The optimal design of the Lego blocks has highest mechanical properties and minimum volume.

	Optimal design	Initial design	Discrepancy
H (mm)	231	220	5%
W_1 (mm)	216	325	-33.5%
W_2 (mm)	275	300	-8.3%
T_1 (mm)	30	50	-40.0%
T_2 (mm)	18	30	-40.0%
T_3 (mm)	18	30	-40.0%
Load capacity (kN)	24.8	20.2	22.8%
Stiffness (kN/mm)	25.9	11.3	129.2%
Deflection (mm)	2.9	2.6	11.5%
Volume (L)	4.7	9.7	-51.6%

Conclusions

- The developed machine learning models can predict the mechanical performance of modular blocks with high accuracy and generalization performance.
- The framework provides an effective solution for design optimization of Lego-inspired modular blocks.
- The optimal design increased the load-carrying capacity, deformability, and stiffness by 22.8%, 11.5%, and 129.2%, respectively, and reduced the volume by 51.6%.

Thank you!

Questions & Answers

Email: yi.bao@stevens.edu