

Tailoring Automated Design Approaches to Enable Built Infrastructure Design with Reduced Embodied Carbon

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Civil and Environmental Engineering, MIT

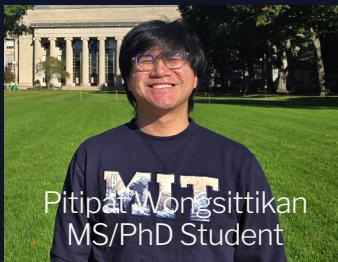
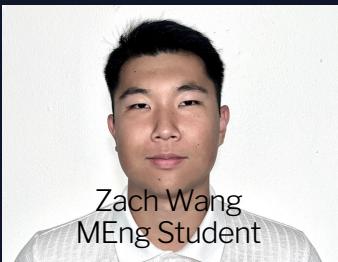
March 17, 2025



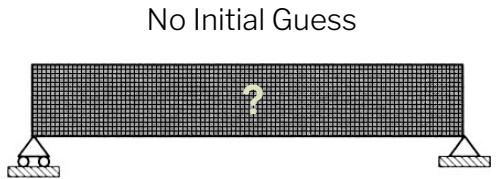
cg carstensen
group



Civil and
Environmental
Engineering



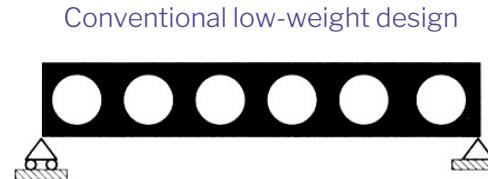
High-Performance Design with Topology Optimization (TO)



Where to
Place Material?



Topology optimized design:
~42% stiffer for same weight



Where to
Place Material?



Topology optimized design:
~48% lighter for same (elastic)
stiffness

Can be difficult to **solve** and to **construct**

High-Performance Design with Topology Optimization (TO)

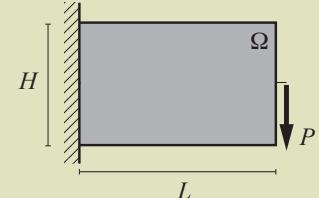
Problem formulation:

$$\min_{\mathbf{x}} : \quad c = \mathbf{U}^T \mathbf{K}(\mathbf{x}) \mathbf{U} \quad \text{Min compliance}$$

$$\text{s.t.:} \quad \mathbf{K}(\mathbf{x}) \mathbf{U} = \mathbf{F} \quad \text{equilibrium}$$

$$V(\mathbf{x})/V_0 \leq f \quad \text{volume (mass) constraint}$$

$$0 \leq \mathbf{x} \leq 1 \quad \text{Design variable bounds}$$



Design Domain

SIMP (Bendsoe, 1989; Rozvany et al., 1992):

$$E_e(\bar{x}_e) = E_{min} + \bar{x}_e^p (E_0 - E_{min})$$

Optimizer: Method of Moving Asymptotes (MMA) (Svanberg, 1987)

Sensitivities: Adjoint method

Filter: Heaviside Projection Method (HPM)

High-Performance Design with Topology Optimization (TO)

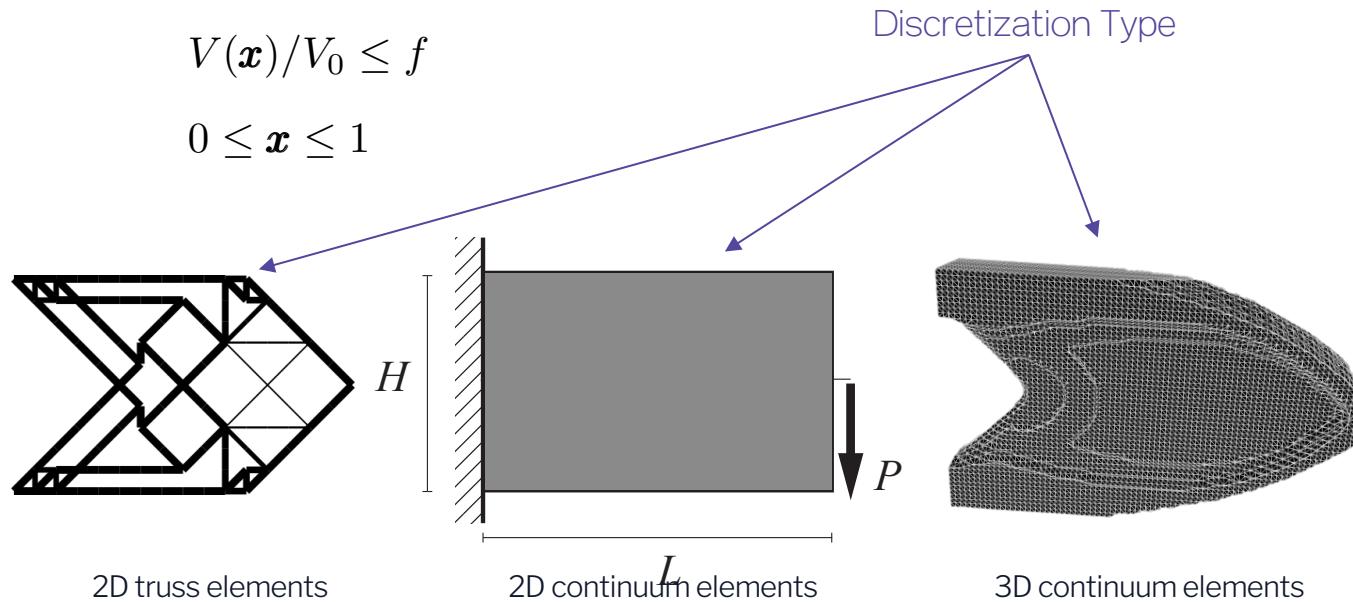
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$$\min_{\mathbf{x}} : \quad c = \mathbf{U}^T \mathbf{K}(\mathbf{x}) \mathbf{U}$$

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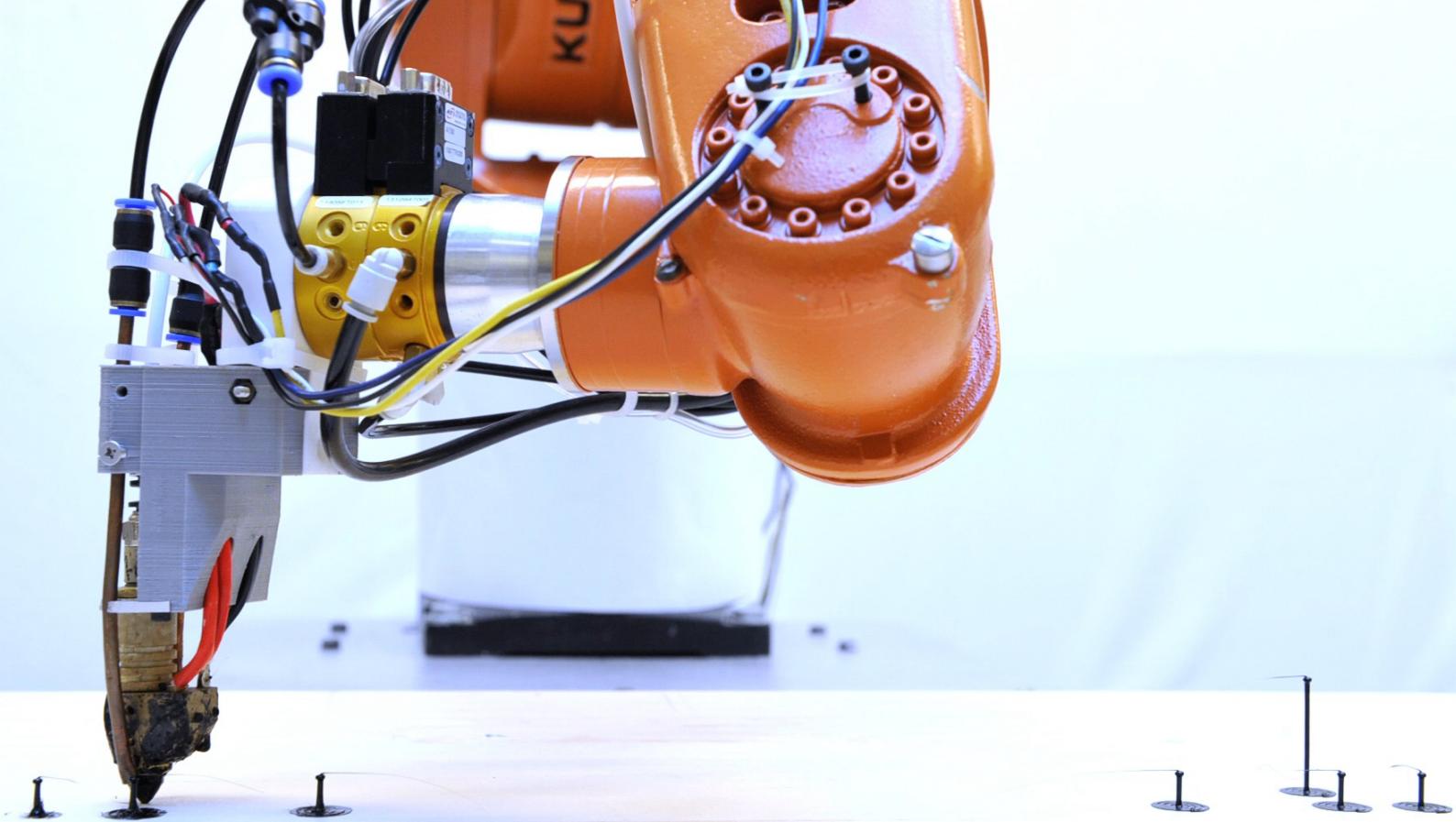
$$V(\mathbf{x})/V_0 \leq f$$

$$0 \leq \mathbf{x} \leq 1$$

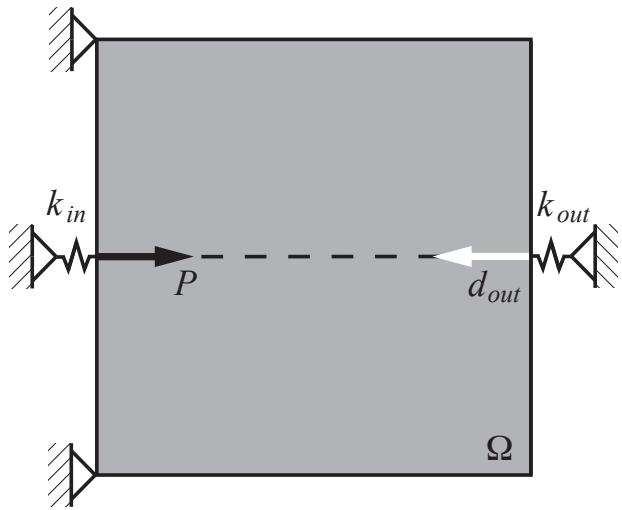


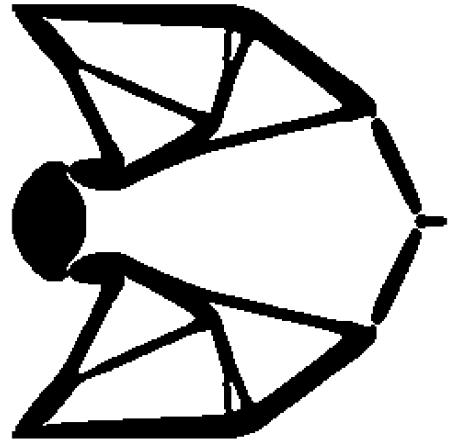


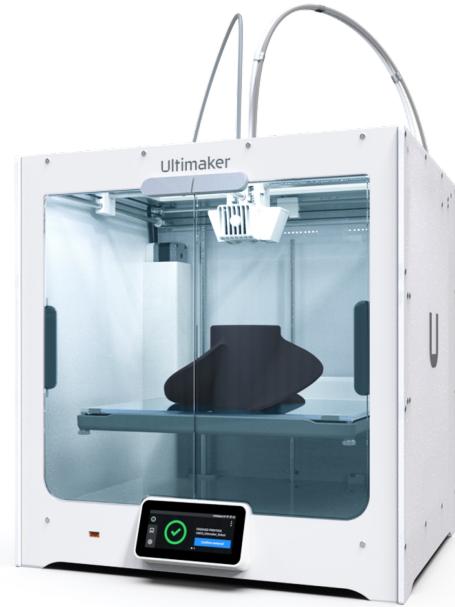
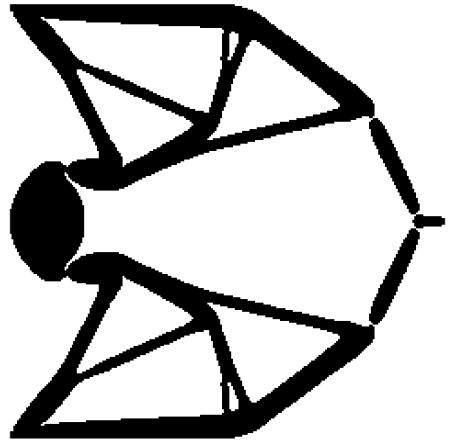
Westworld - Season one, opening credit,
HBO 2017

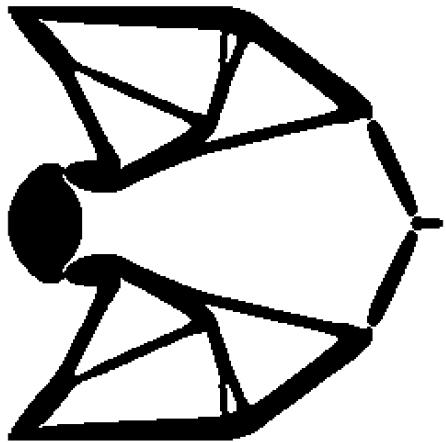


TO and the designer

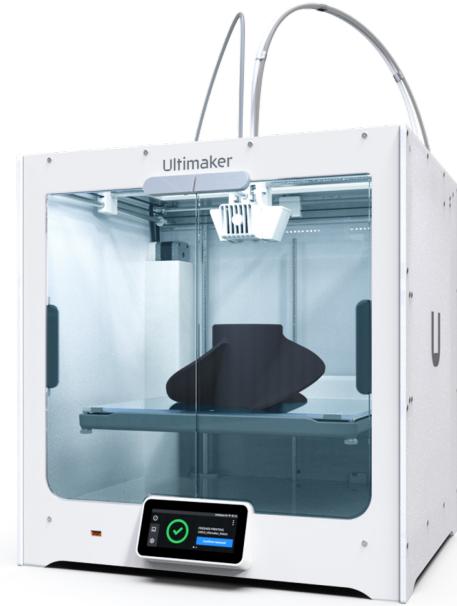


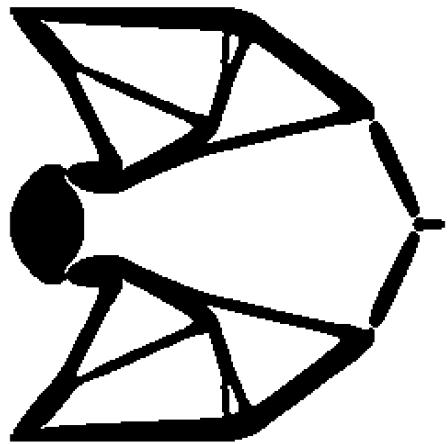




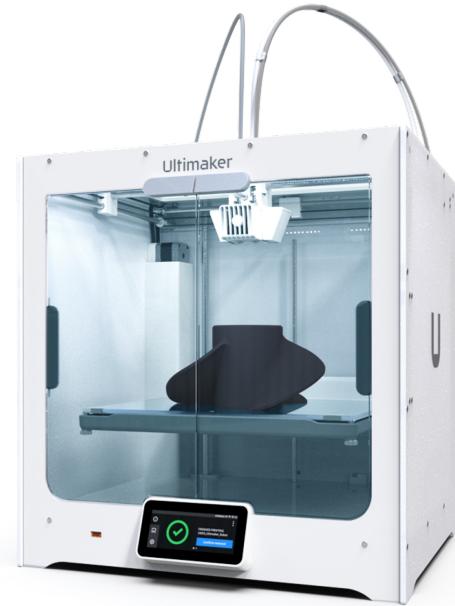


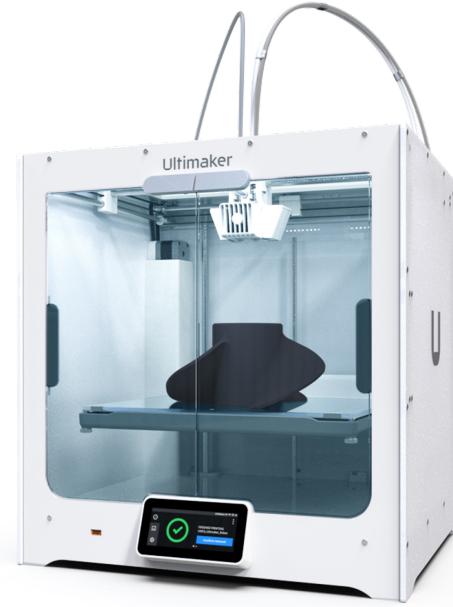
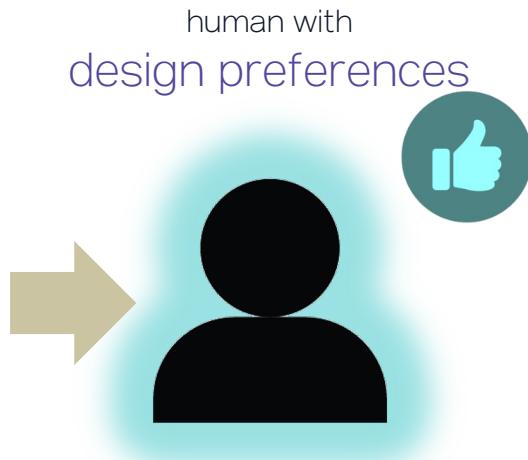
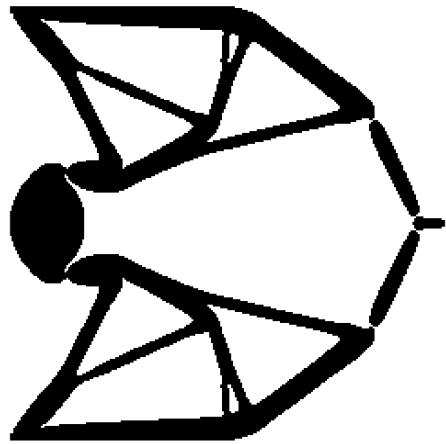
human with
design preferences

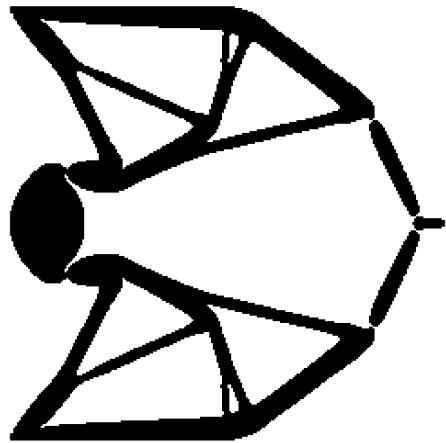




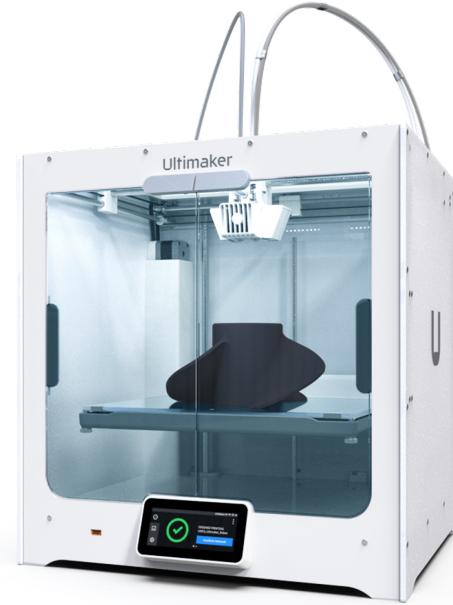
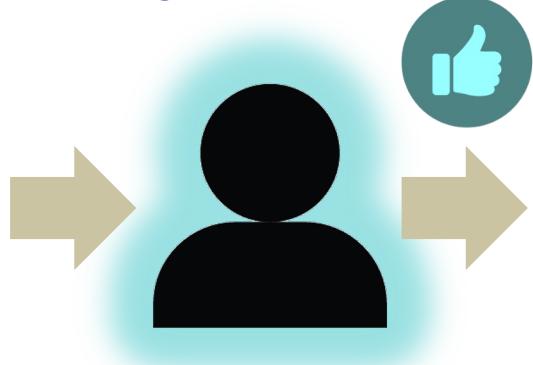
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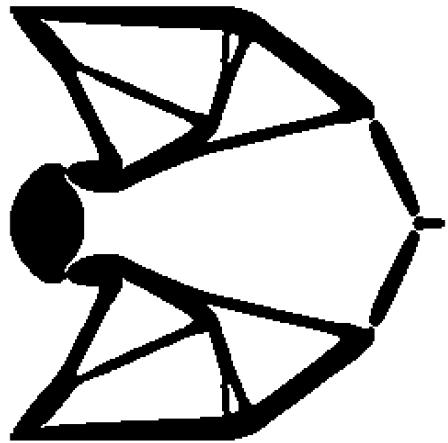




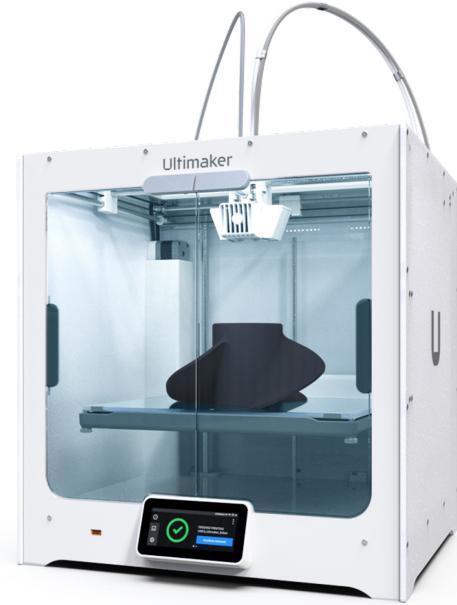


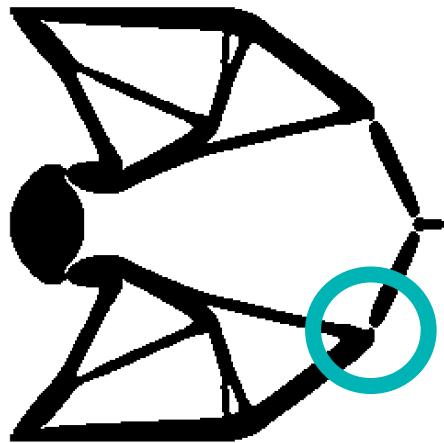
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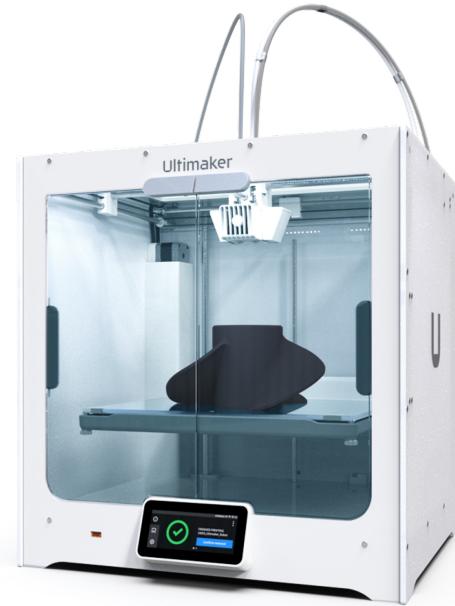


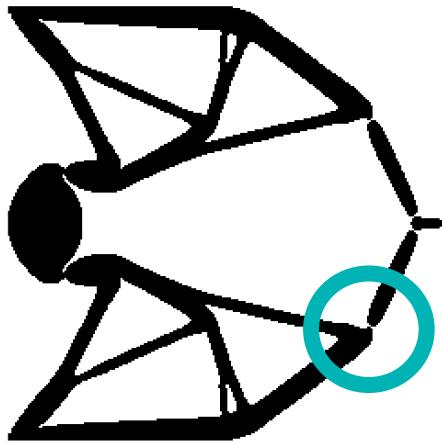
human with
design preferences



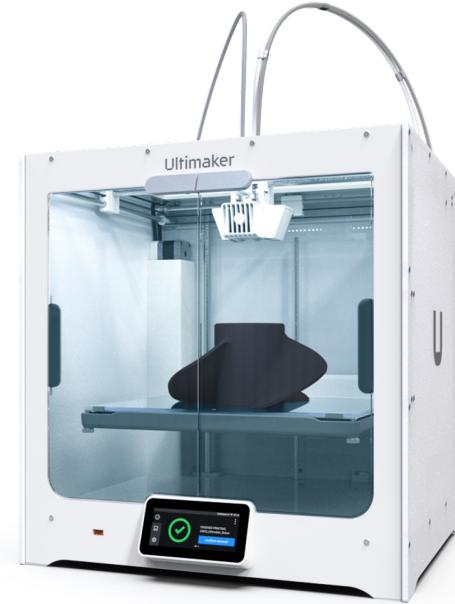


human with
design preferences





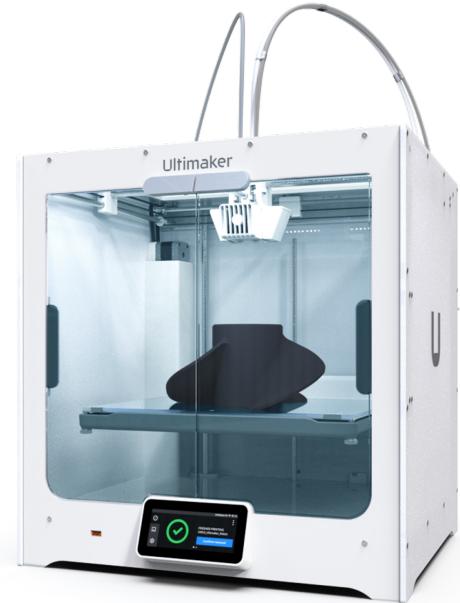
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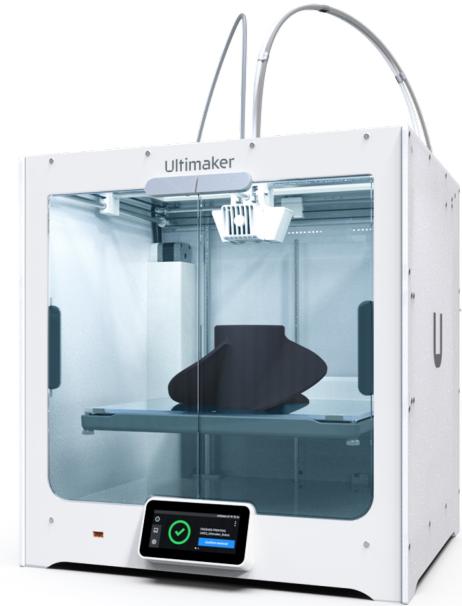
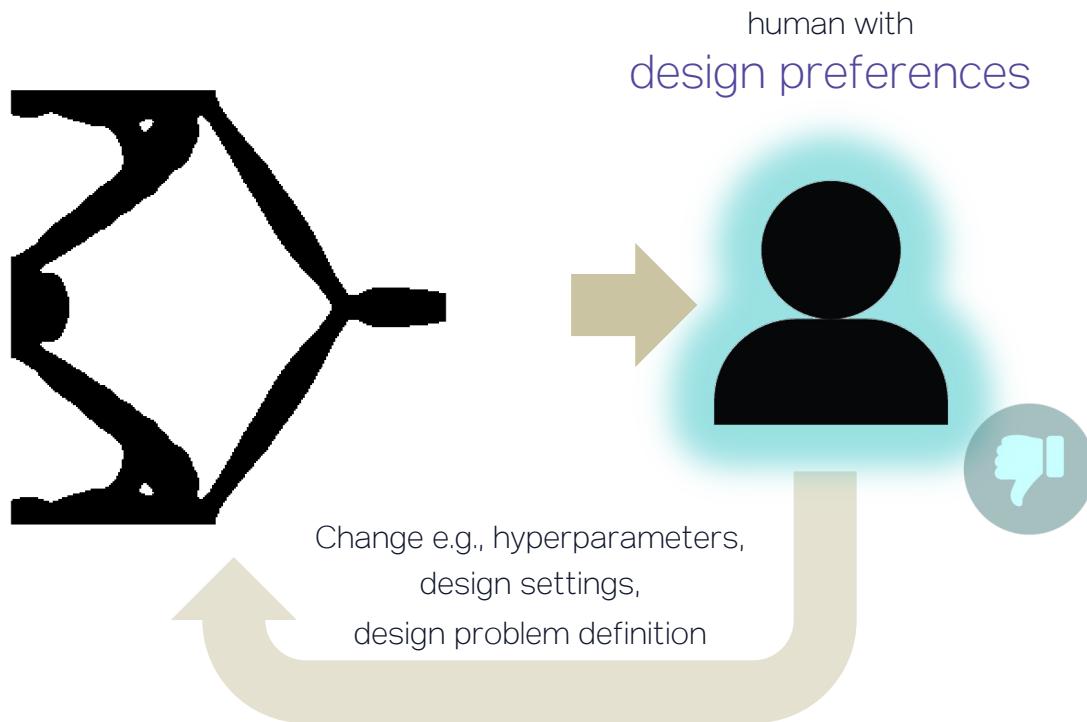


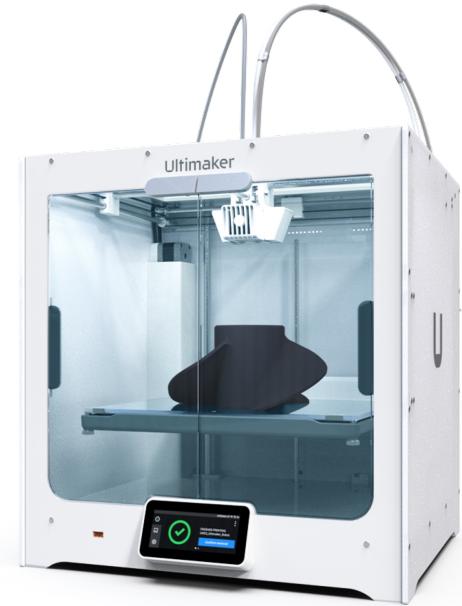
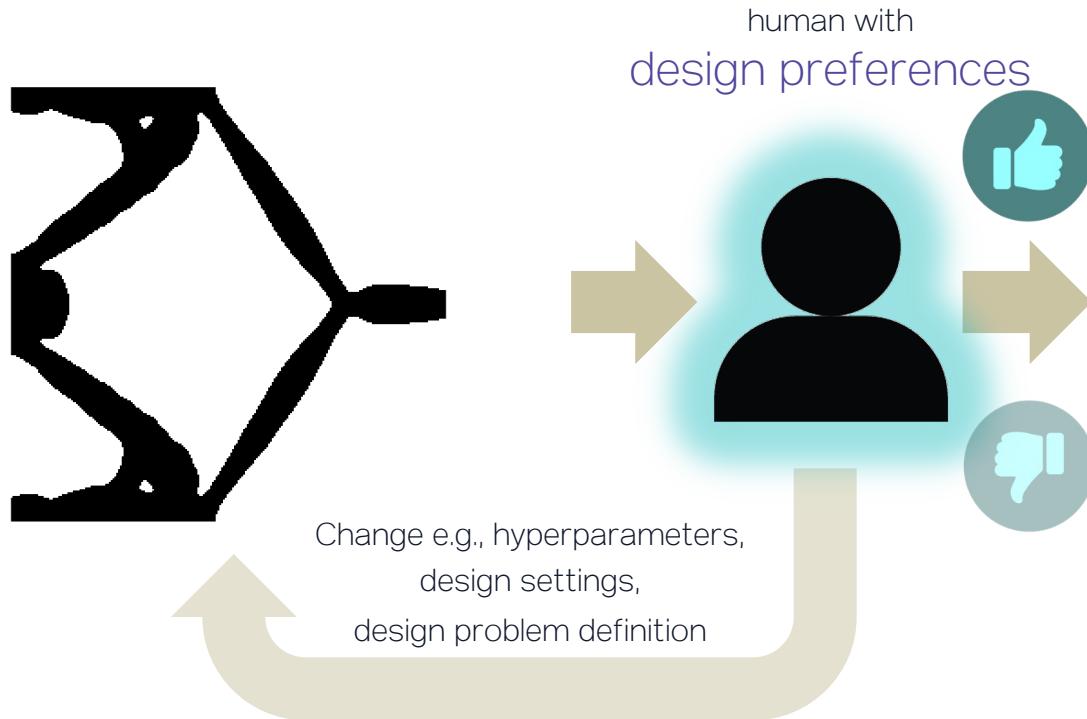
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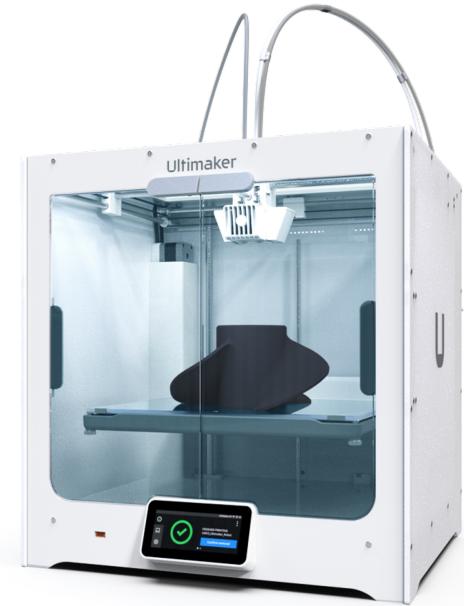
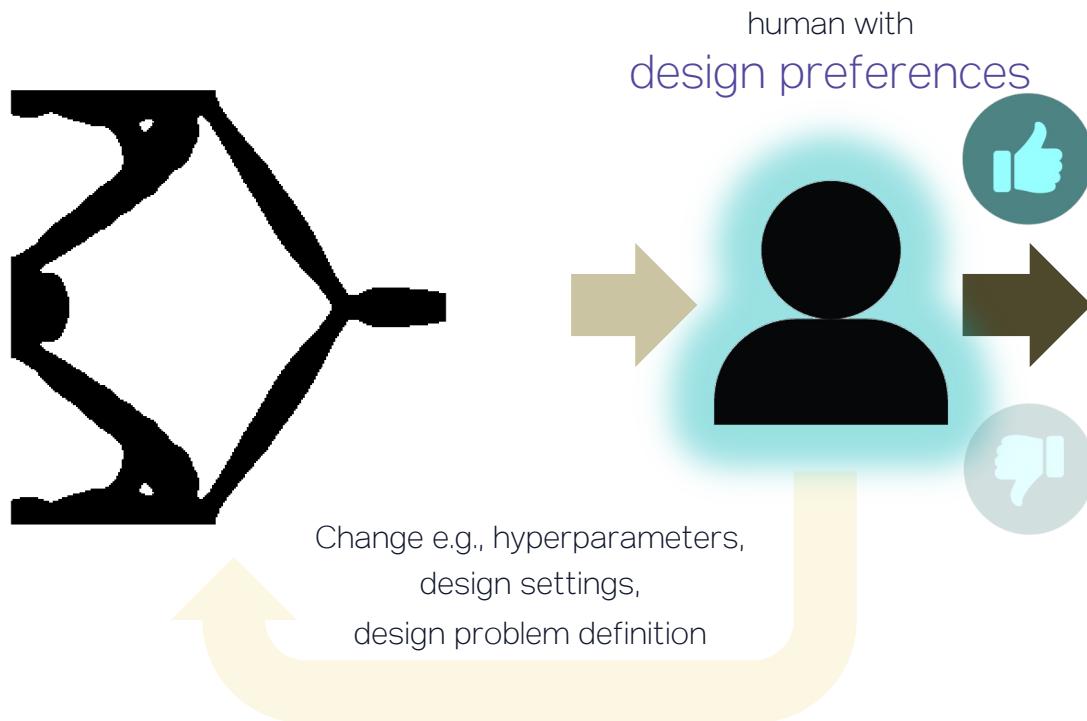


Change e.g., hyperparameters,
design settings,
design problem definition



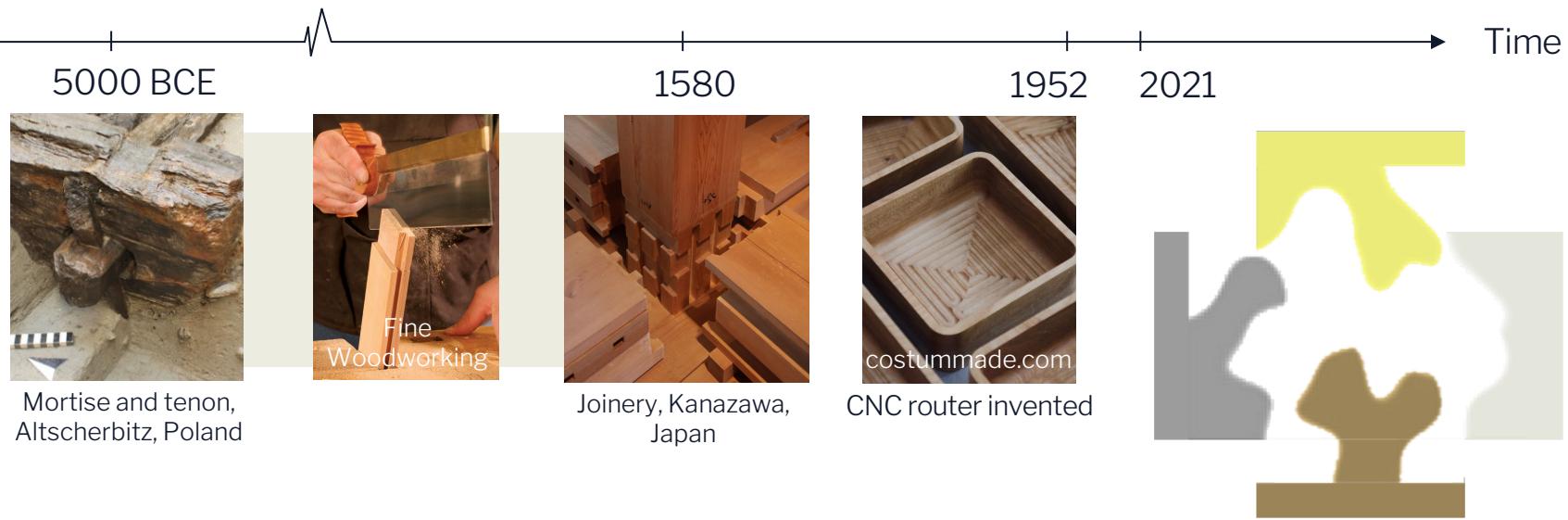






Advanced manufacture allows for
realization of improved designs

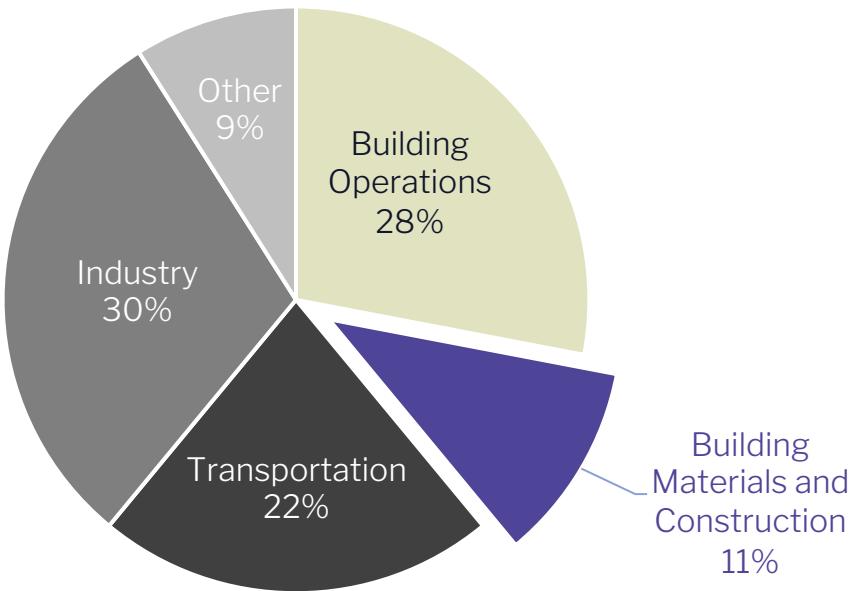
Design of Interlocking Joints



Topology-Optimized
Interlocking Joint

Need for Reducing the CO₂ Emissions of Construction

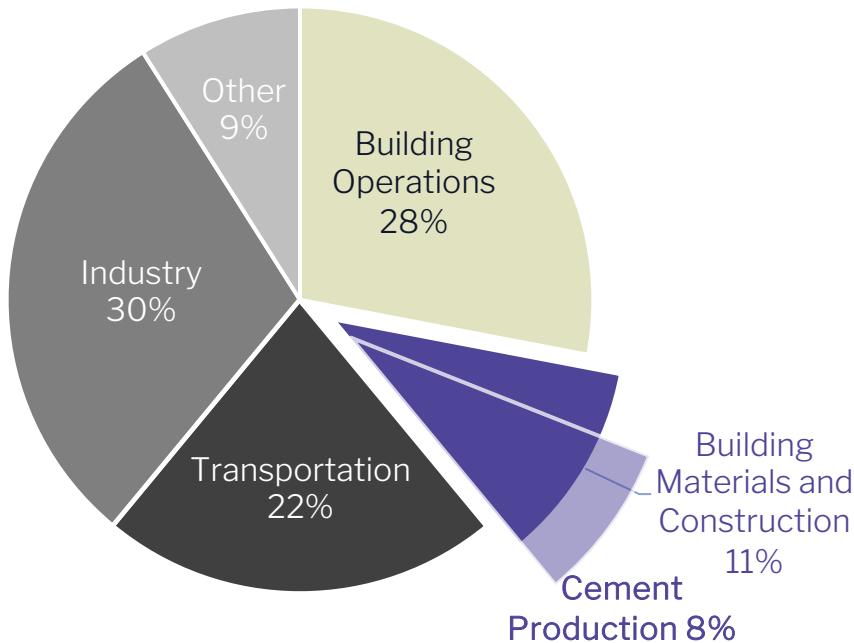
Global Annual CO₂ Emissions by Sector



*Data from UN Environmental Status Report 2017

Reducing the Carbon Impact of Reinforced Concrete Structures

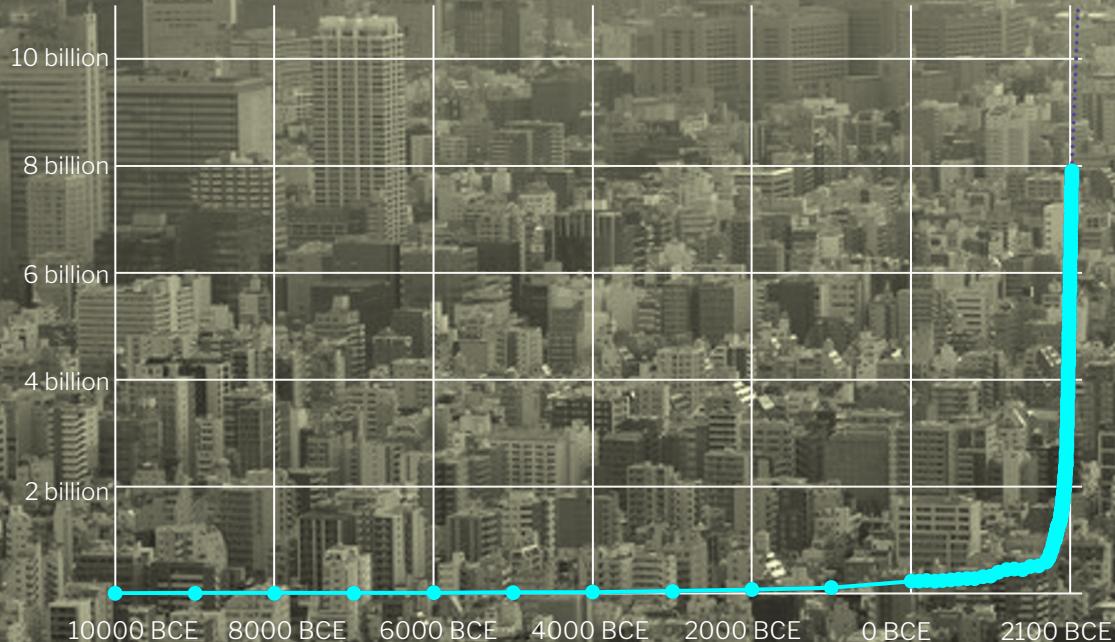
Global Annual CO₂ Emissions by Sector



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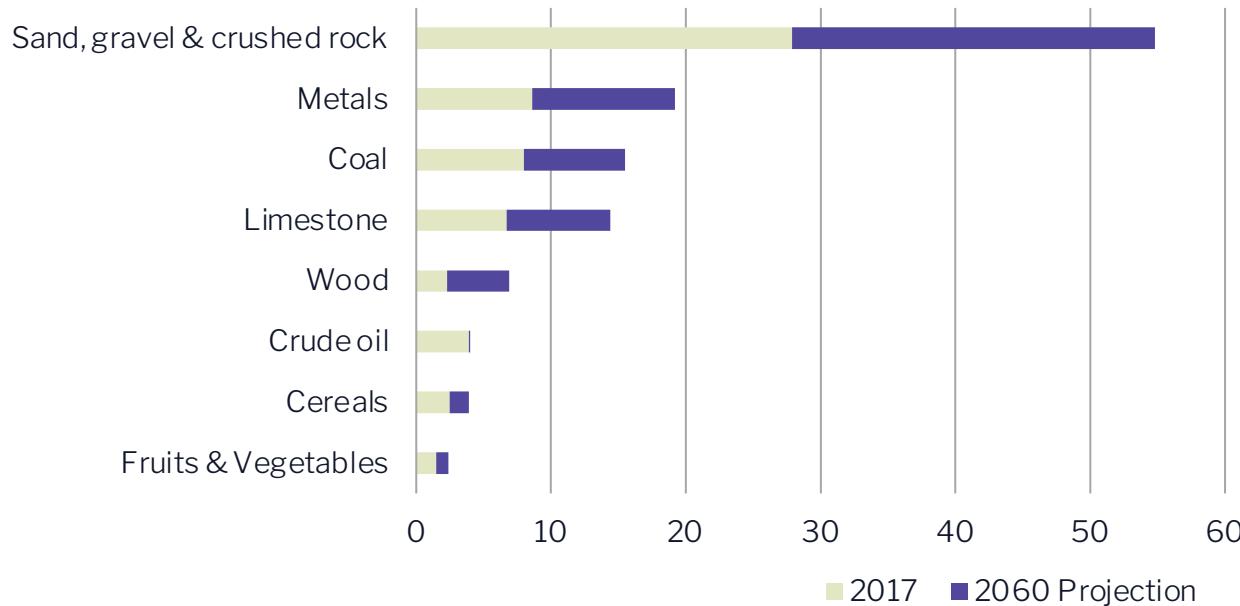
World Projection over the Last 12,000 Years and UN Projection until 2100

World economic forum



*Data from OurWorldInData.org/world-population-growth; Medium Projection – UN Population Division (2019)

Global Construction Material Consumption in Gigatonnes



*Data from OECD Global Material Resource Outlook to 2060

Global Warming Potential or Embodied Carbon

The embodied carbon of a structure can be estimated through the global warming potential:

$$GWP = \sum_{e \in \Omega} A^e L^e (\rho^e ECC^e)$$

Sum over all elements weight of element Embodied carbon coefficient of material

De Wolfe et al. 2015

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Sum over all elements

weight of element

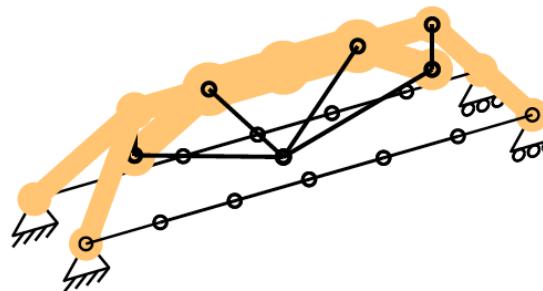
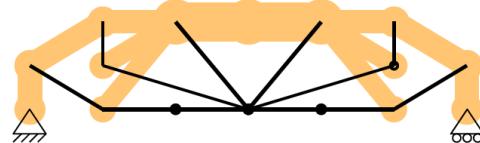
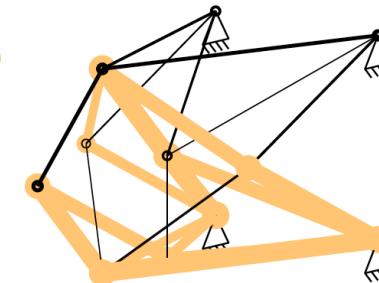
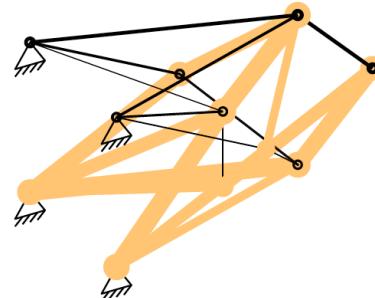
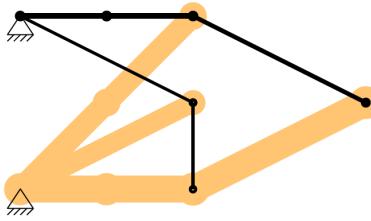
design structures with alternative materials

Tailoring the Design of Timber-Steel Trusses to Minimize the Embodied Carbon

UMass Amherst Design Building, MA

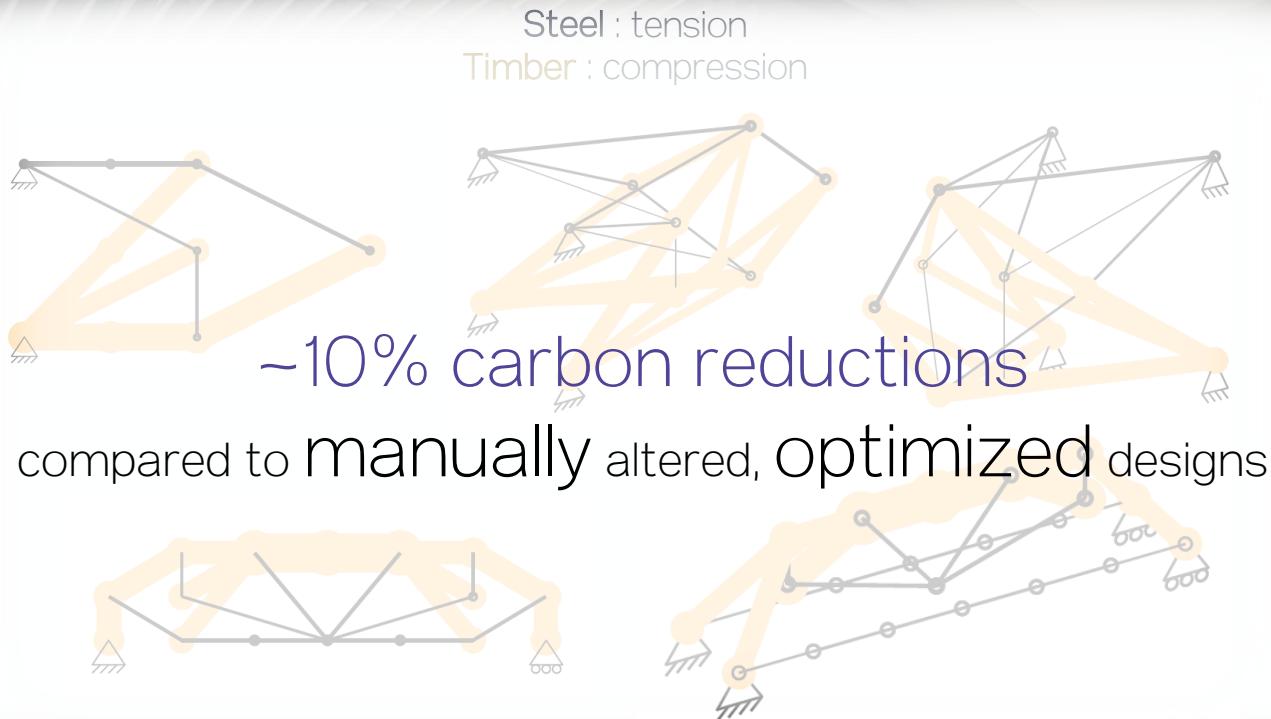
Steel : tension

Timber : compression



Tailoring the Design of Timber-Steel Trusses to Minimize the Embodied Carbon

UMass Amherst Design Building, MA

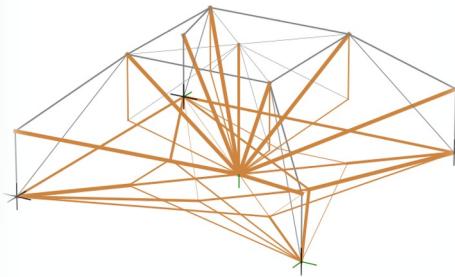


Tailoring the Design of Timber-Steel Trusses to Minimize the Embodied Carbon

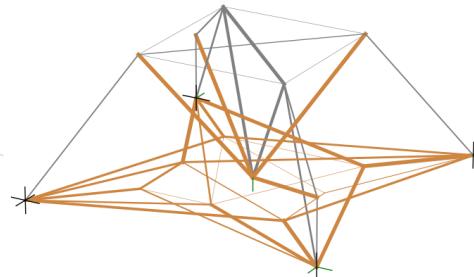
UMass Amherst Design Building, MA

Steel : tension

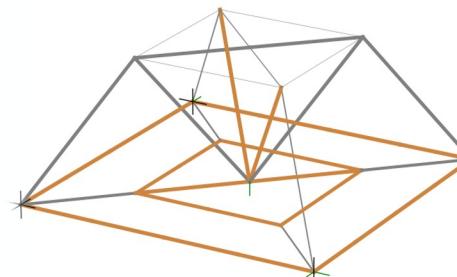
Timber : compression



Multi-Material



Reduced Member Connections



Minimum Angle Between Members

Global Warming Potential or Embodied Carbon

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Sum over all elements

weight of element

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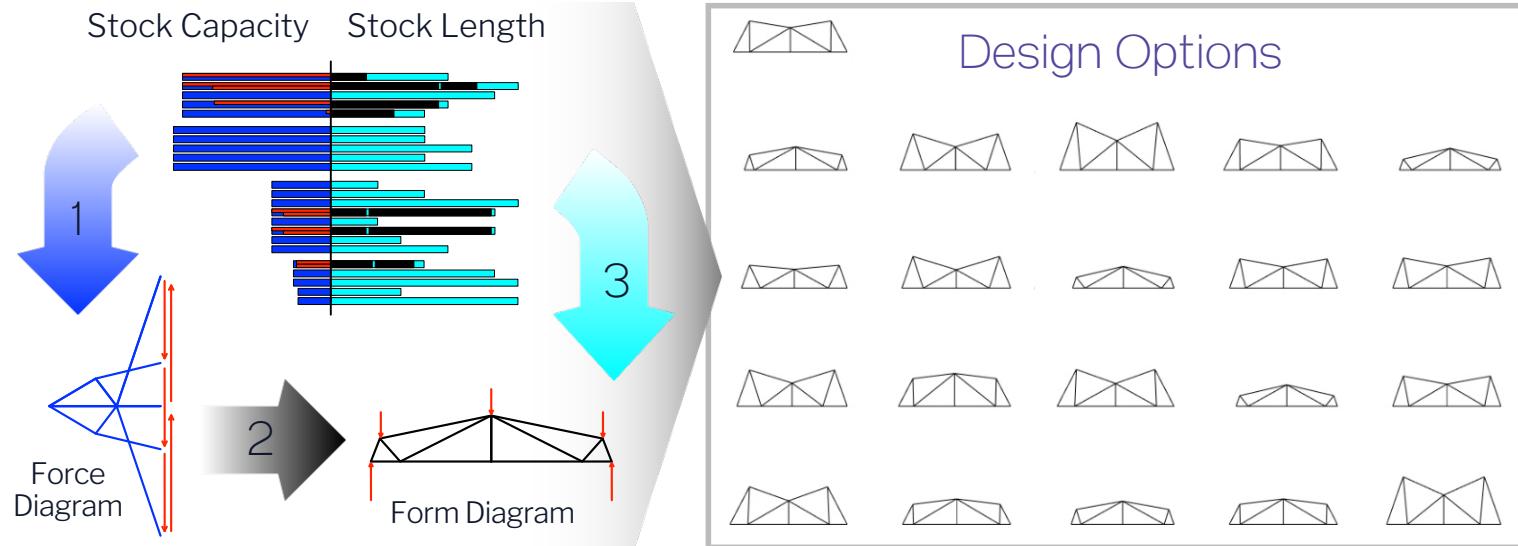
A black and white photograph showing a large, sprawling pile of metal scrap and debris in the foreground. The scrap consists of various twisted metal rods, pipes, and structural components. Behind the pile is a dark brick wall, and above it is a building with a corrugated metal roof and a triangular skylight. The scene suggests a demolition or recycling site.

reuse structural components in new design

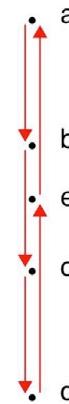
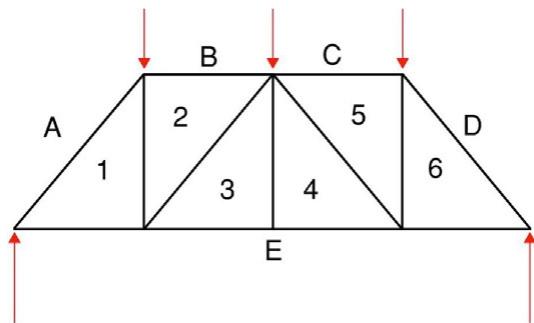
Automatic Generation of Stock Constrained Trusses using Graphic Statics



Automatic Generation of Stock Constrained Trusses using Graphic Statics



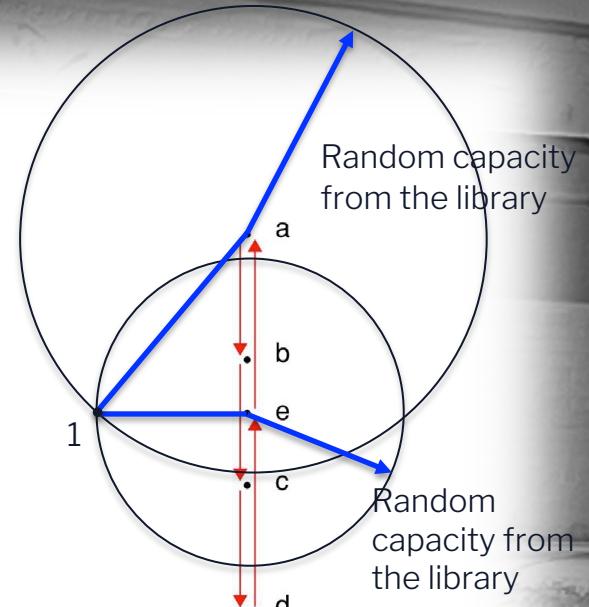
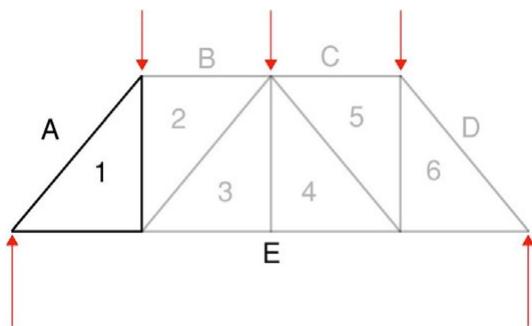
The user pre-determines a **connectivity pattern** that is used to construct the force diagram:



Force diagram

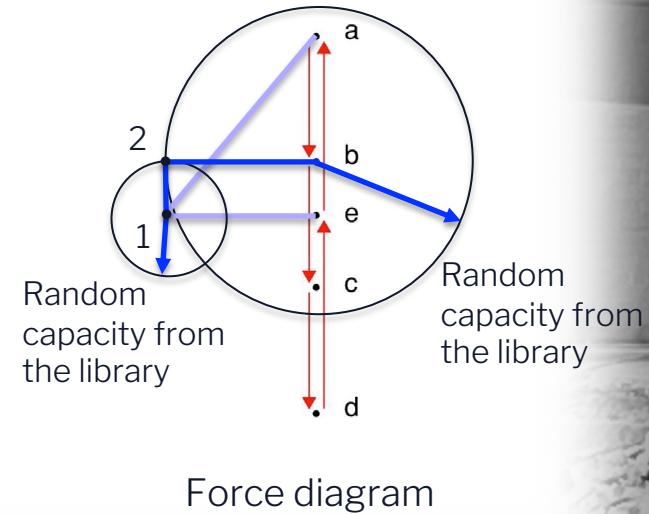
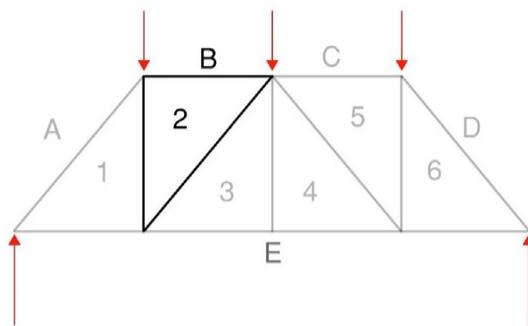
Automatic Generation of Stock Constrained Trusses using Graphic Statics

The user pre-determines a **connectivity pattern** that is used to construct the force diagram:

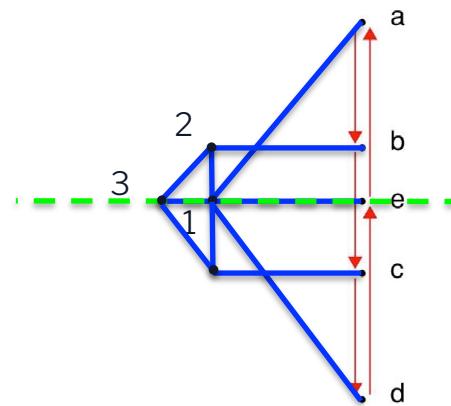
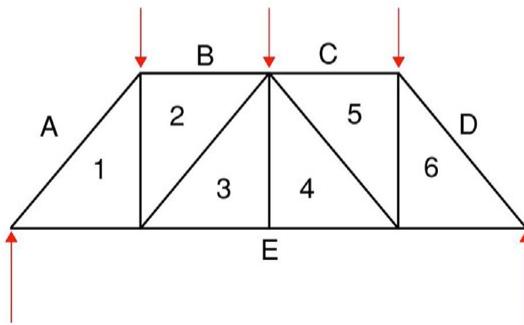


Force diagram

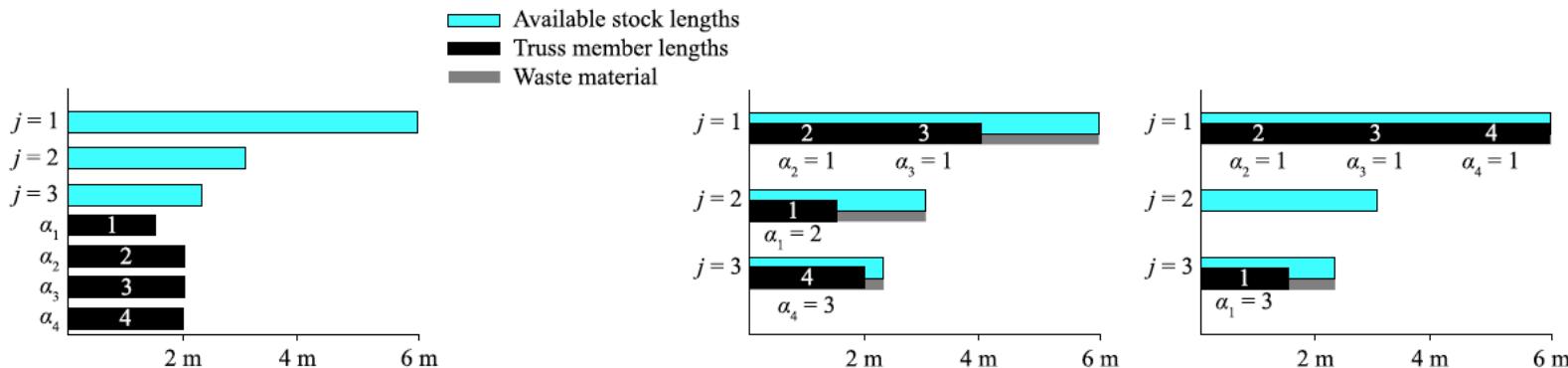
The user pre-determines a **connectivity pattern** that is used to construct the force diagram:



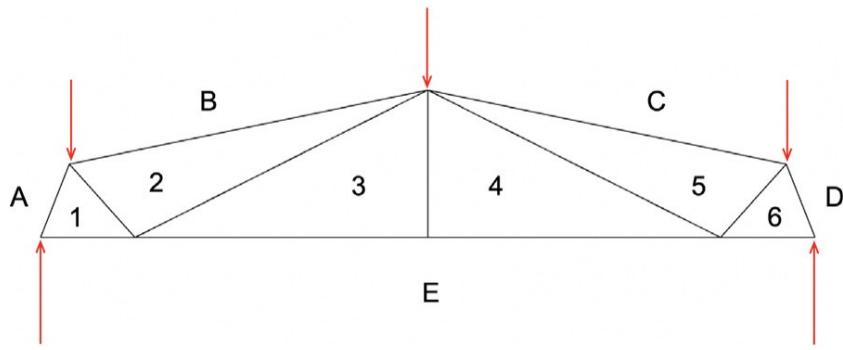
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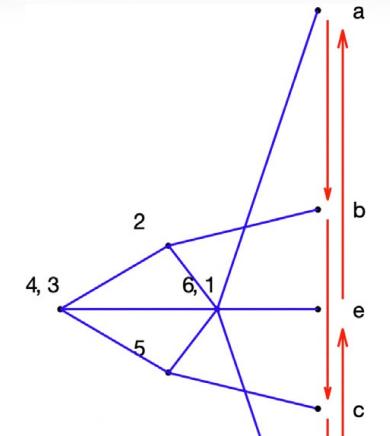
GA is used to minimize wasted length if multiple library members have the same capacity



Automatic Generation of Stock Constrained Trusses using Graphic Statics



Form diagram



Force diagram

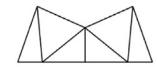
Inherent stochasticity
means different solutions
are obtained when
executing 100 times



27



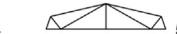
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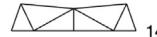
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54



59



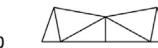
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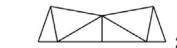
19



20



21



23



8



9



11



12



13



1



2



3

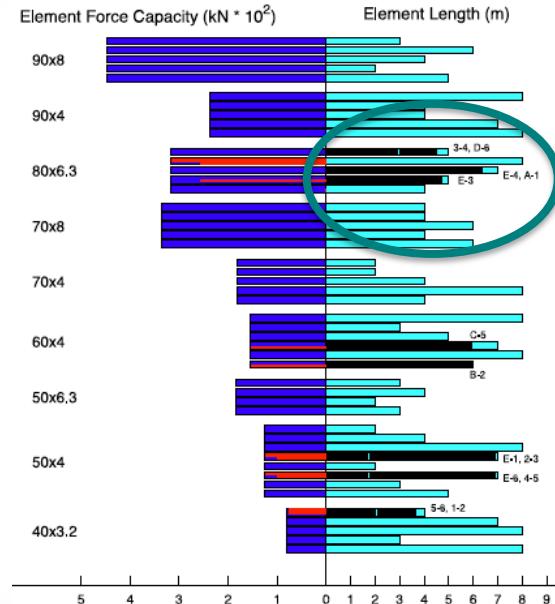
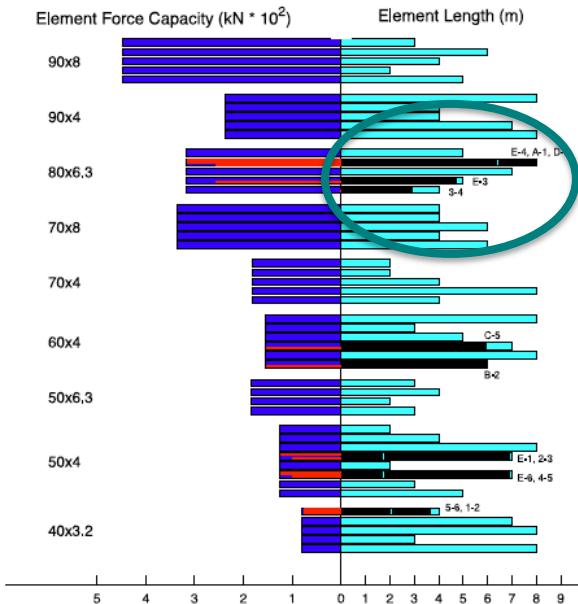


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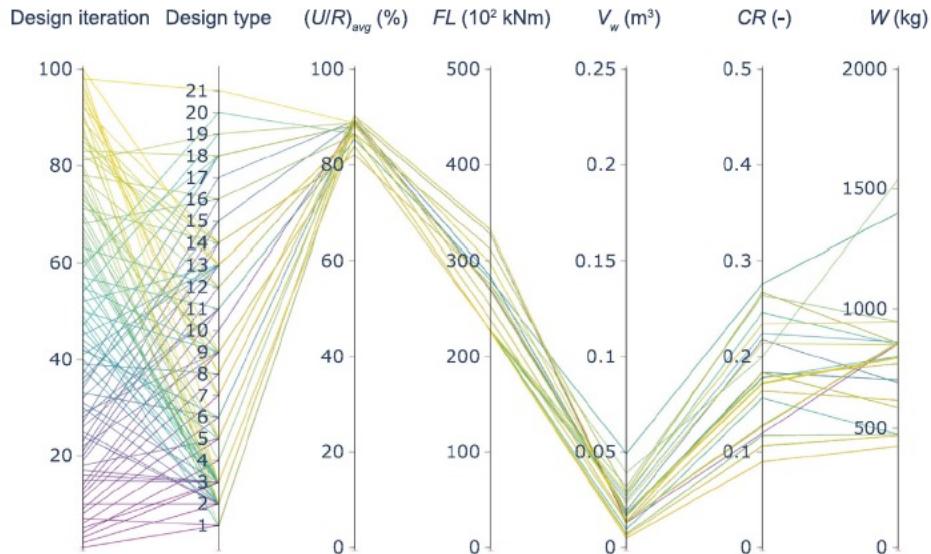


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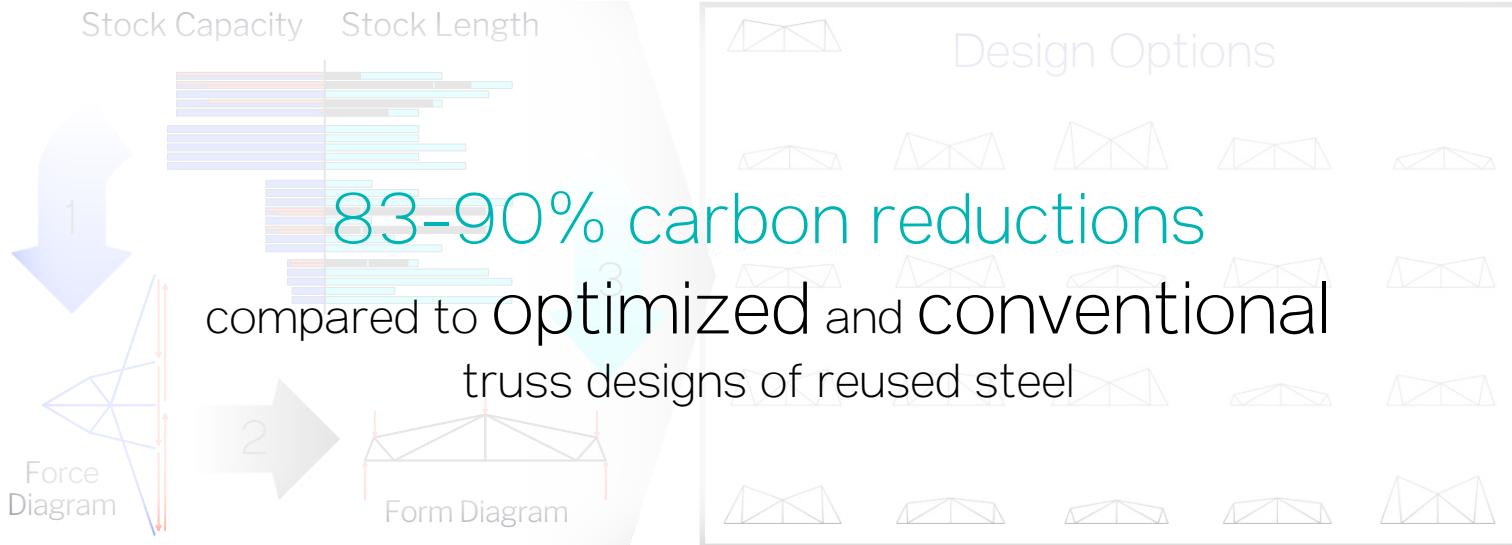
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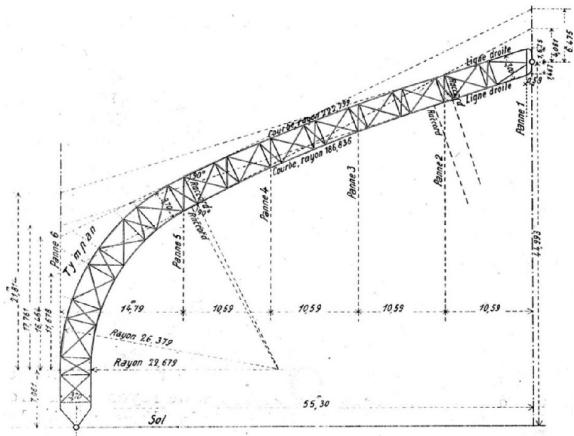
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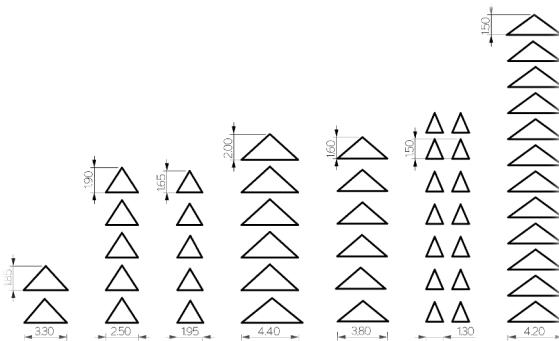


Automatic Generation of Truss Designs with Partially Disassembled Trusses



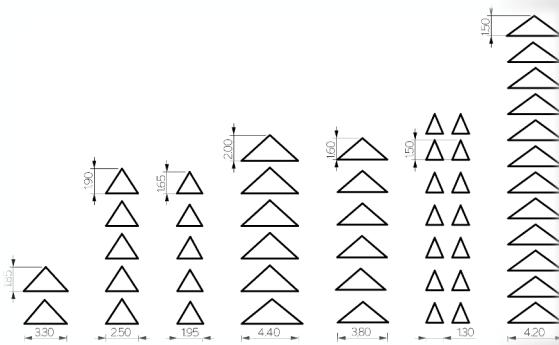
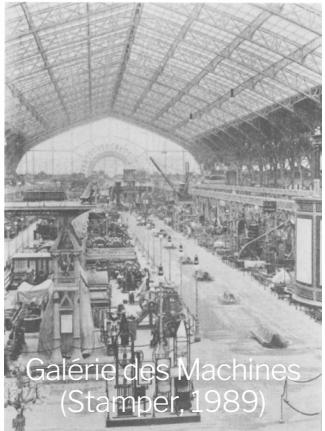
Automatic Generation of Truss Designs with Partially Disassembled Trusses

Library of Partially Disassembled Components

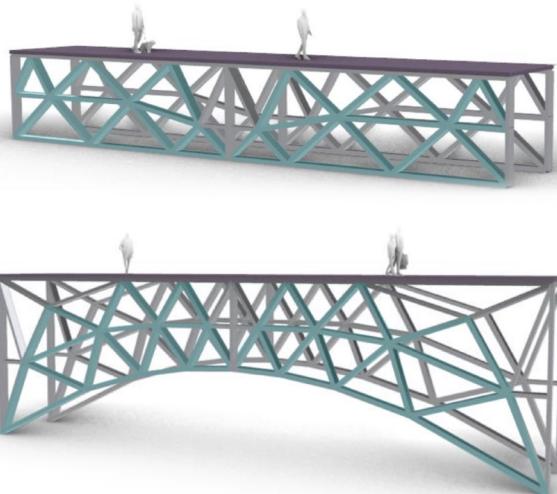


Automatic Generation of Truss Designs with Partially Disassembled Trusses

Library of Partially Disassembled Components



Optimized Designs



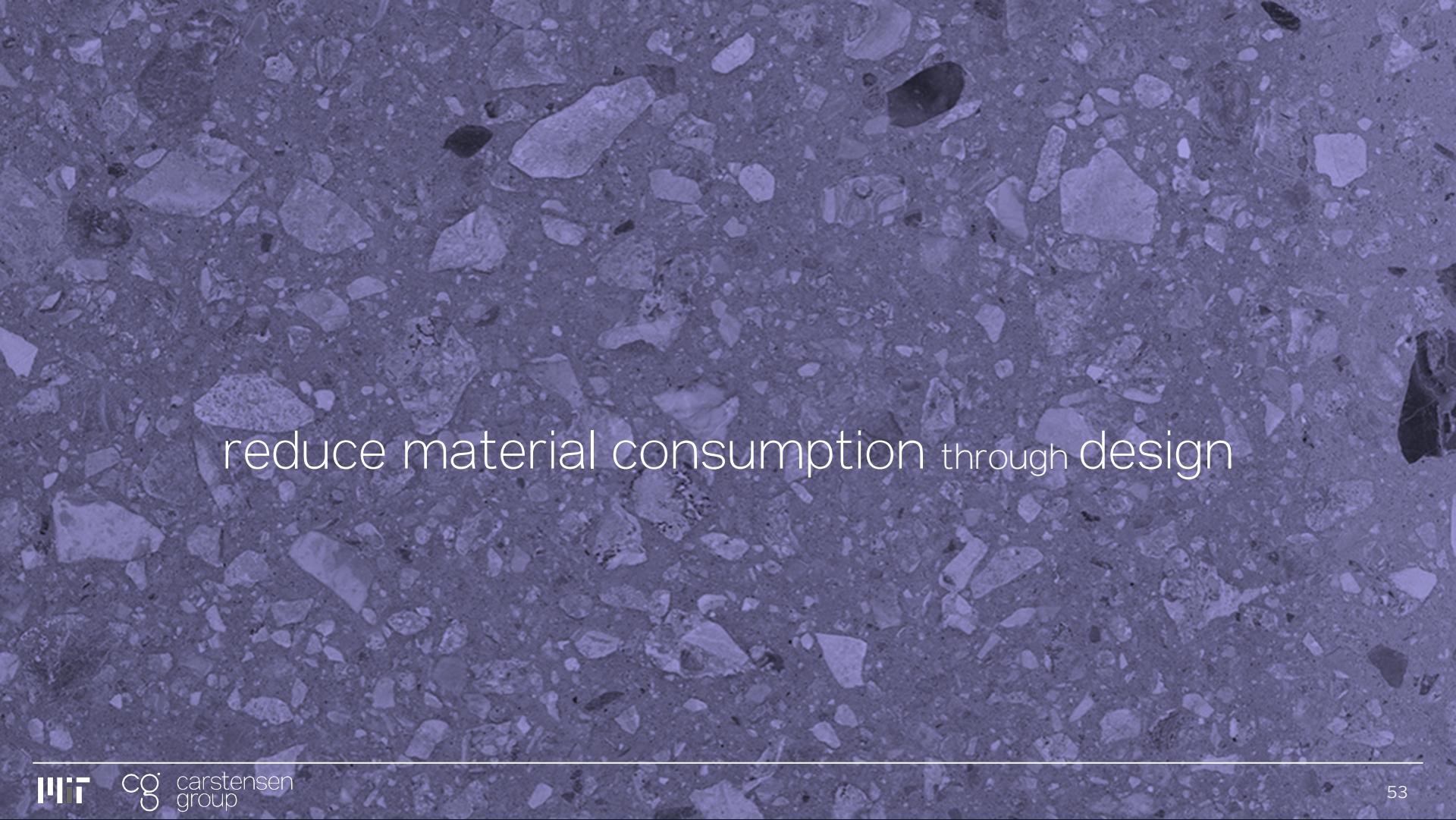
Global Warming Potential or Embodied Carbon

The embodied carbon of a structure can be estimated through the global warming potential:

$$GWP = \sum_{e \in \Omega} A^e L^e (\rho^e \underbrace{ECC^e}_{\substack{\text{small} \\ \text{Embodied carbon} \\ \text{coefficient of} \\ \text{material}}})$$

Sum over all elements

weight of element



reduce material consumption through design

Reducing Concrete Weight

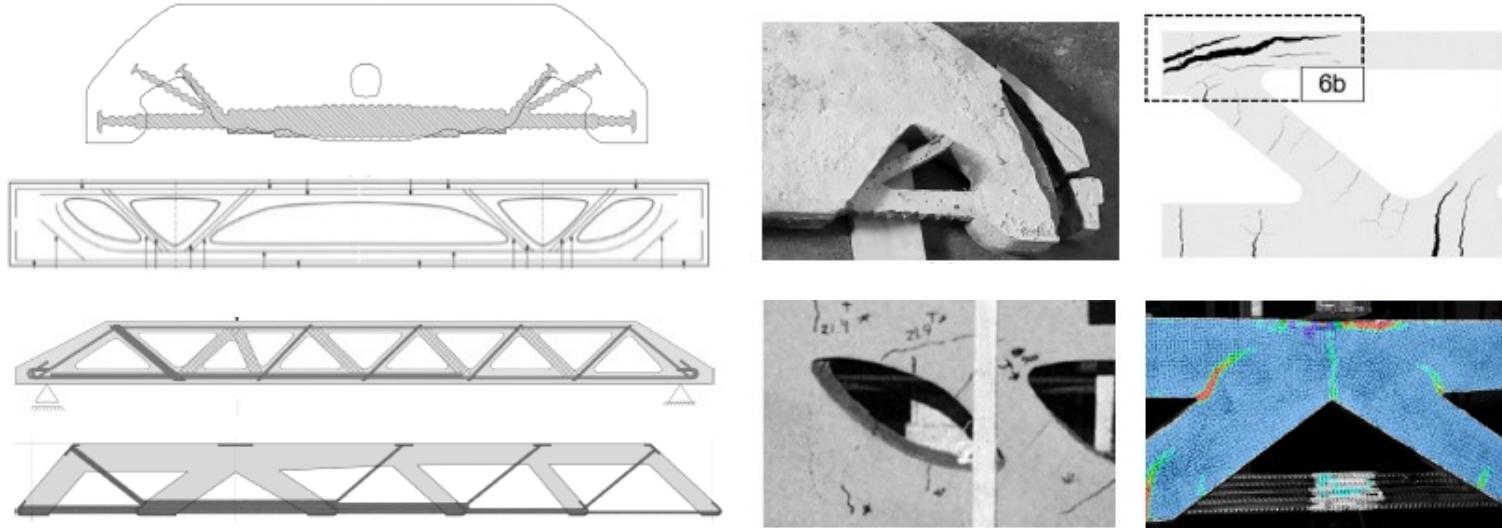


design with 25% less concrete
that maintains the elastic performance

Improving the performance of fabricated designs requires:
inclusion of all relevant behavioral and fabrication
characteristics

Behavioral
characteristics
of a design reflect its ability
to meet the
industry-specific needs

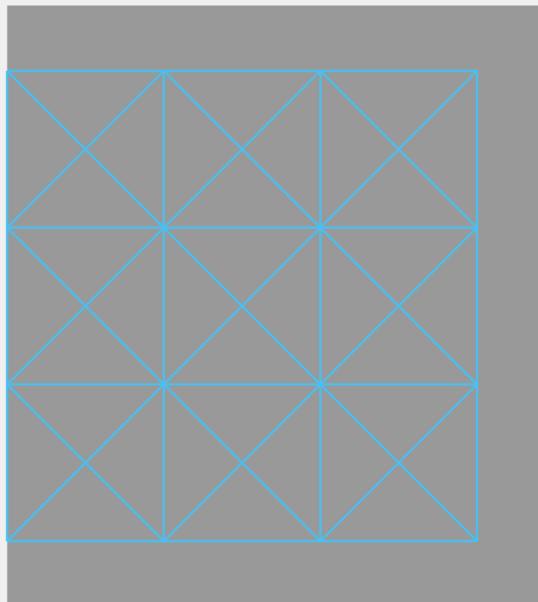
All Experimental Tests Have Observed Shear Failure at Joints



Li et al. 2020
Wethyavivorn et al. 2022
Pressmair and Kromoser 2023
Pressmair et al. 2023.

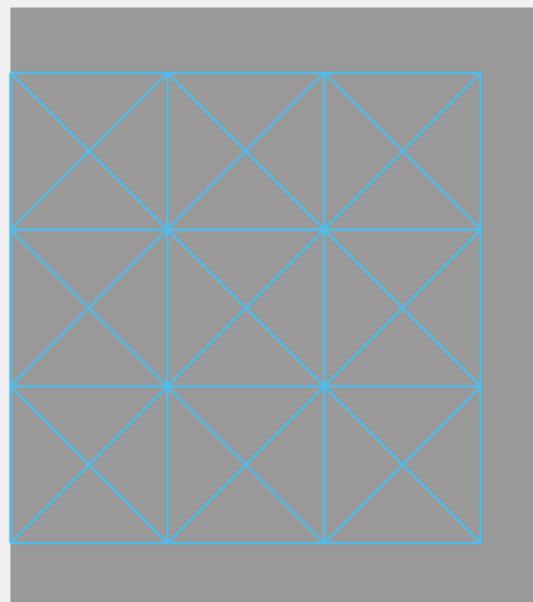
Possible Solution: Use a Different TO Approach

Static Trusses 0-1



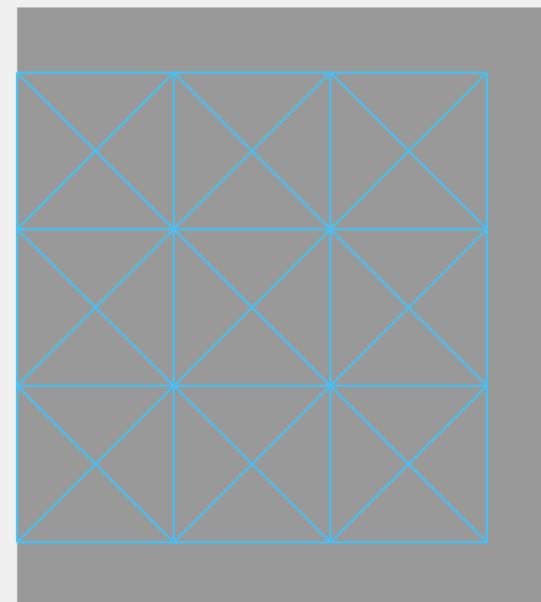
$C = 3.8$

Moving Truss Nodes 0-1



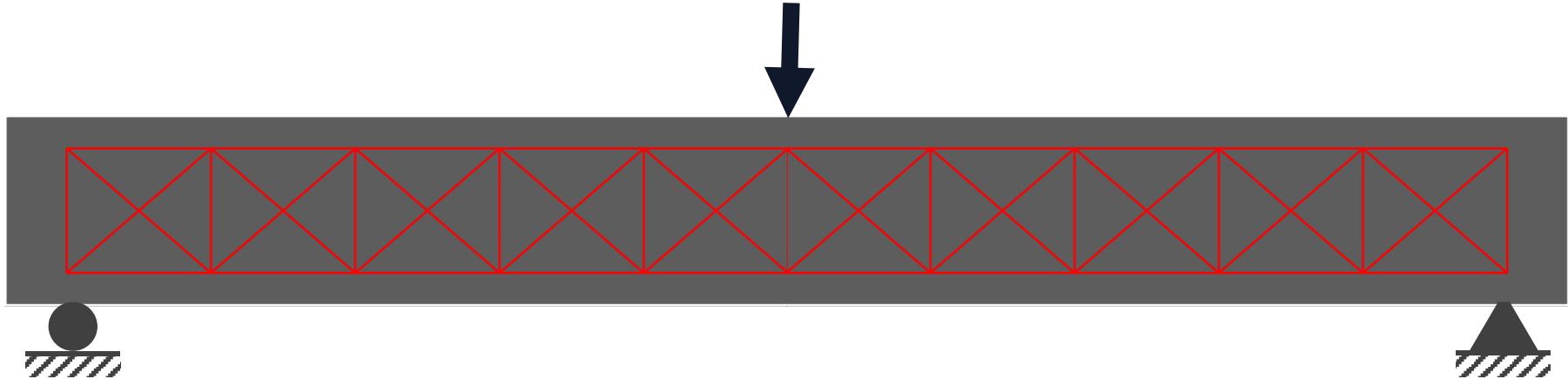
$C = 3.7$

Variable Thickness Sheet



$C = 3.3$

Experimental Comparison



Compare

{ 0-1 result
VTS result

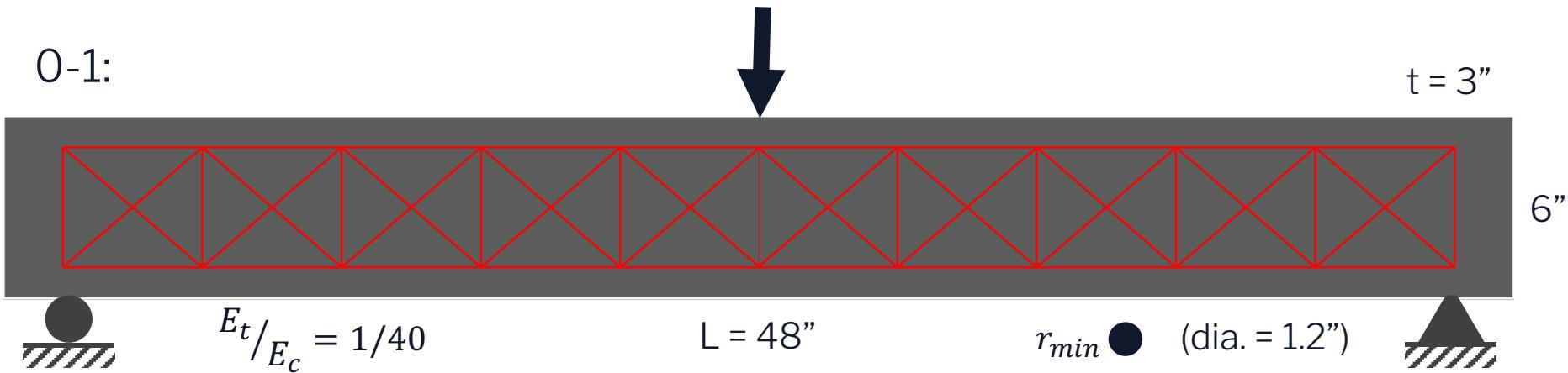
Constants:

Concrete volume

Steel volume

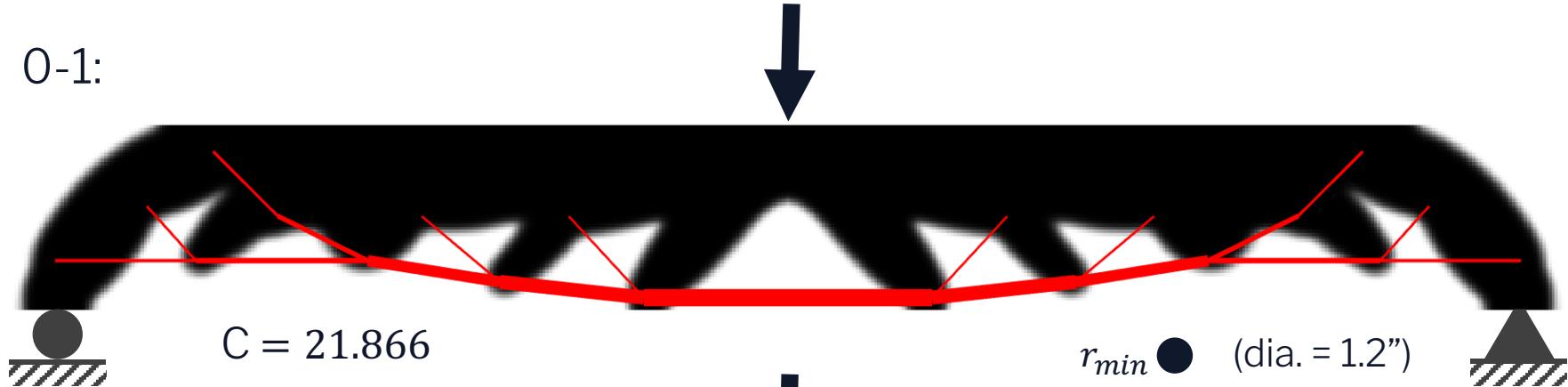
Optimization parameters

Experimental Comparison

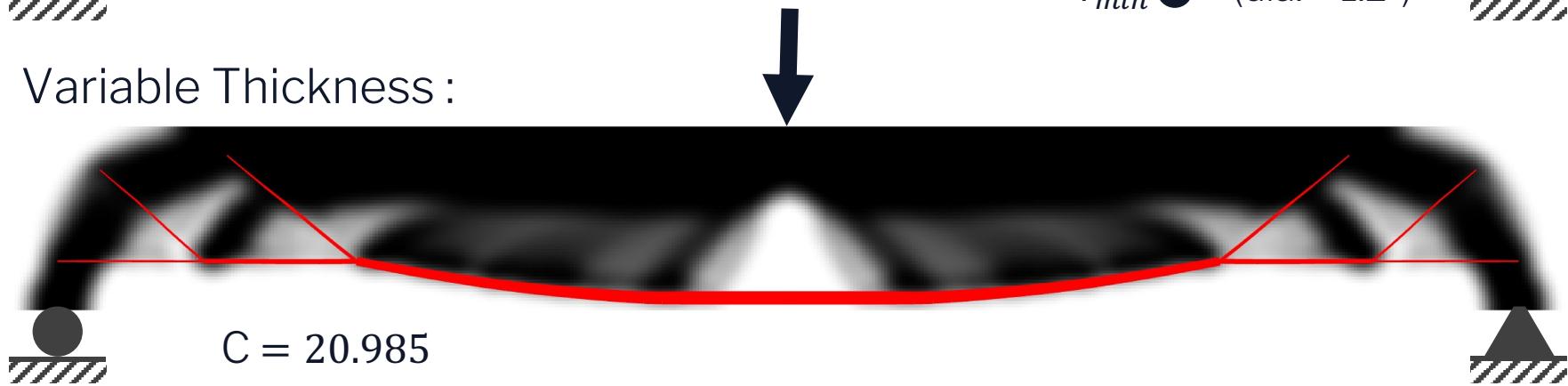


Experimental Comparison

0-1:

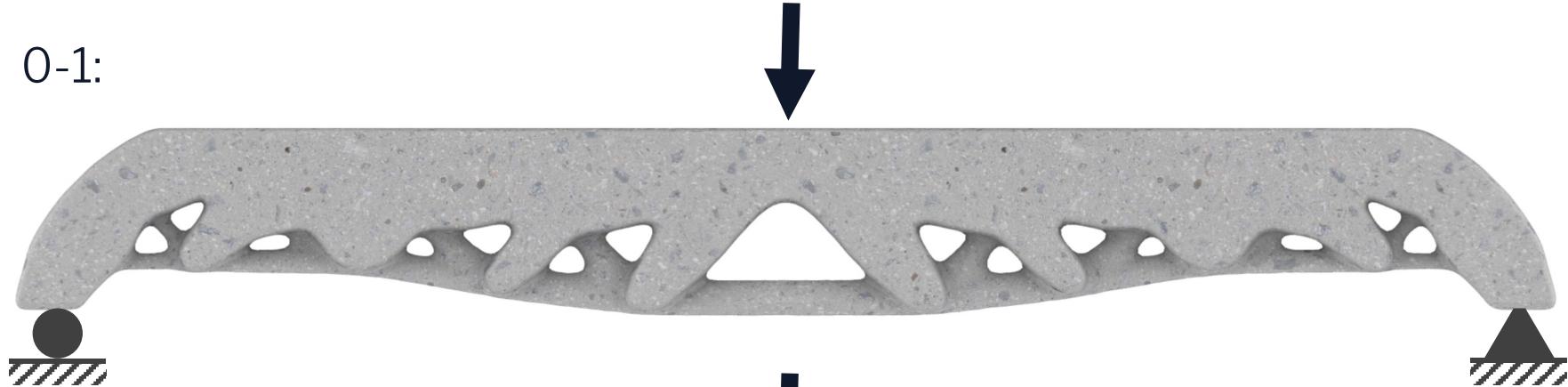


Variable Thickness :

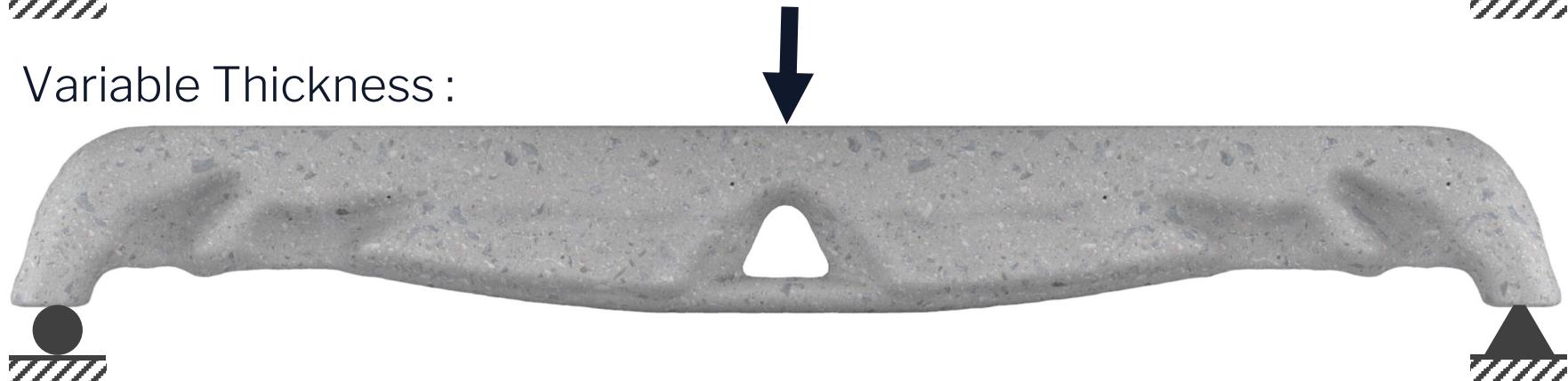


Beam Designs

0-1:

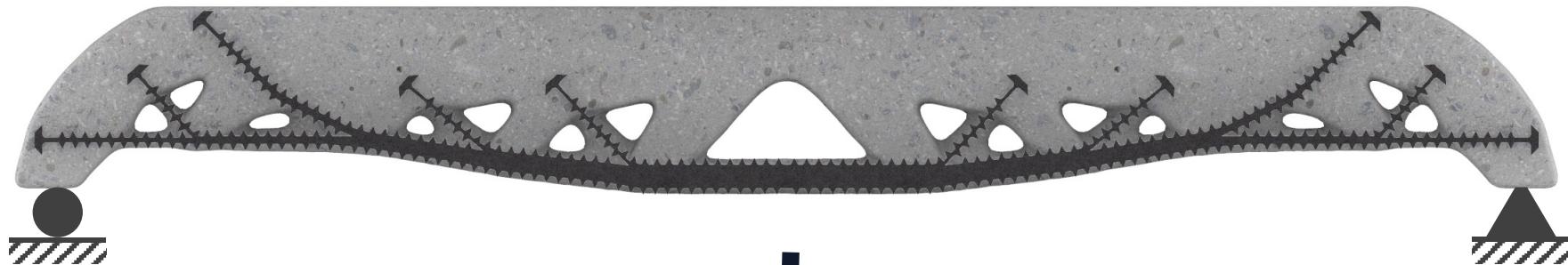


Variable Thickness :

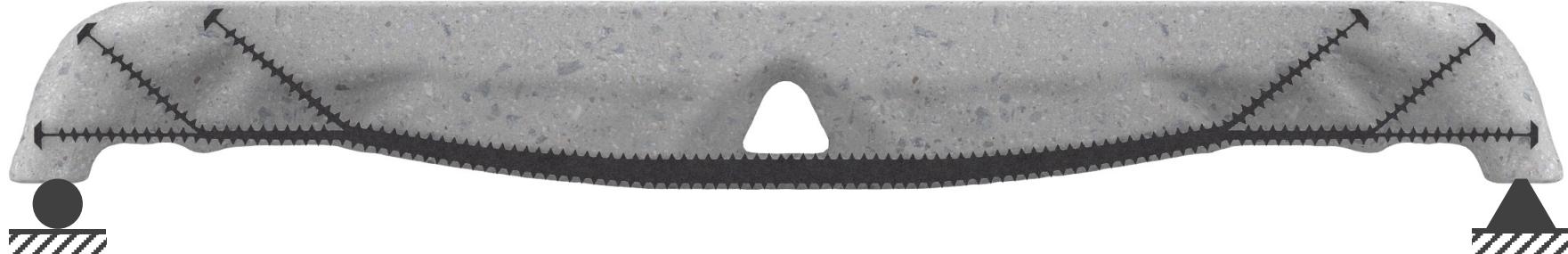


Beam Designs

0-1:

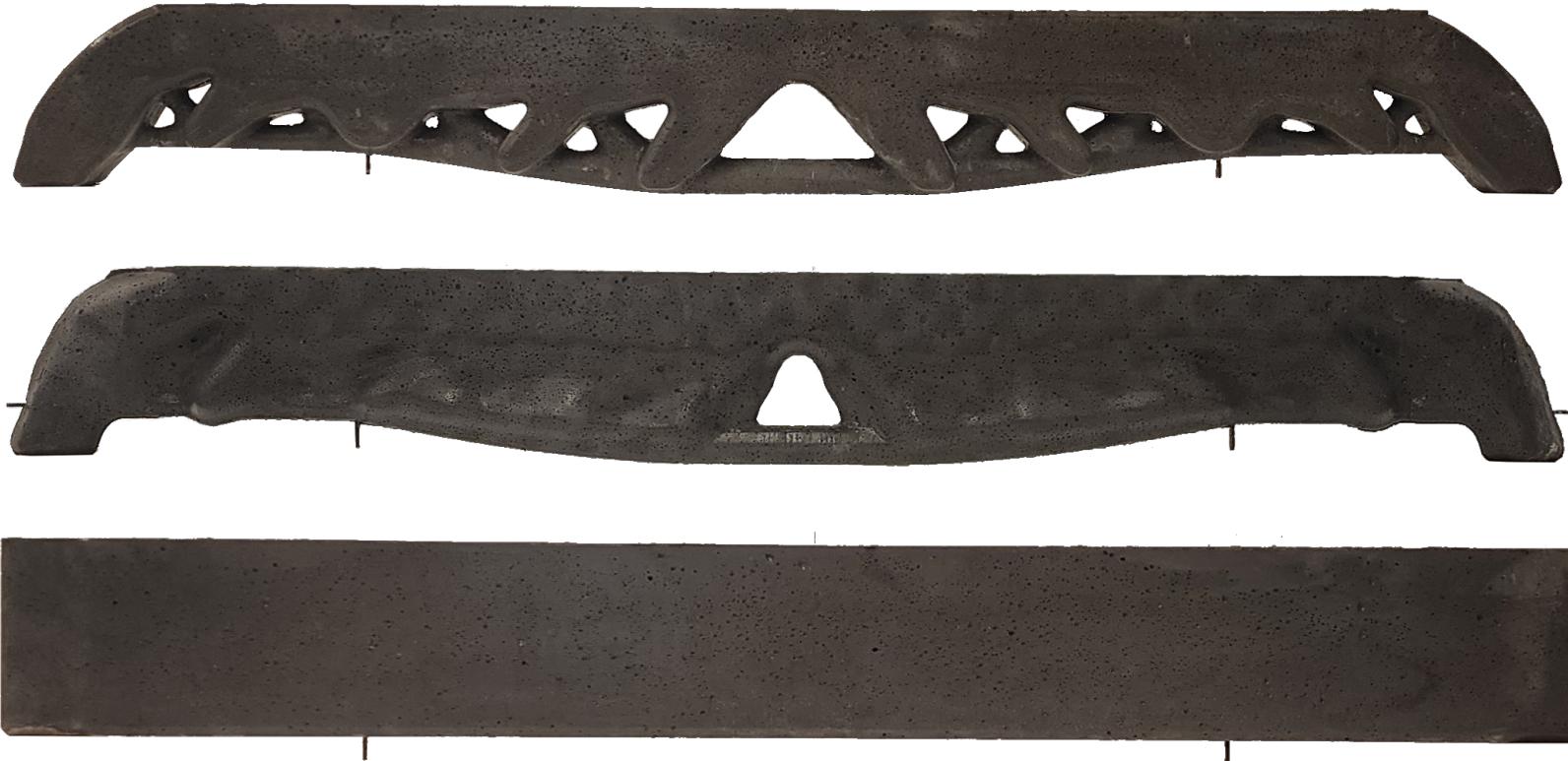


Variable Thickness :



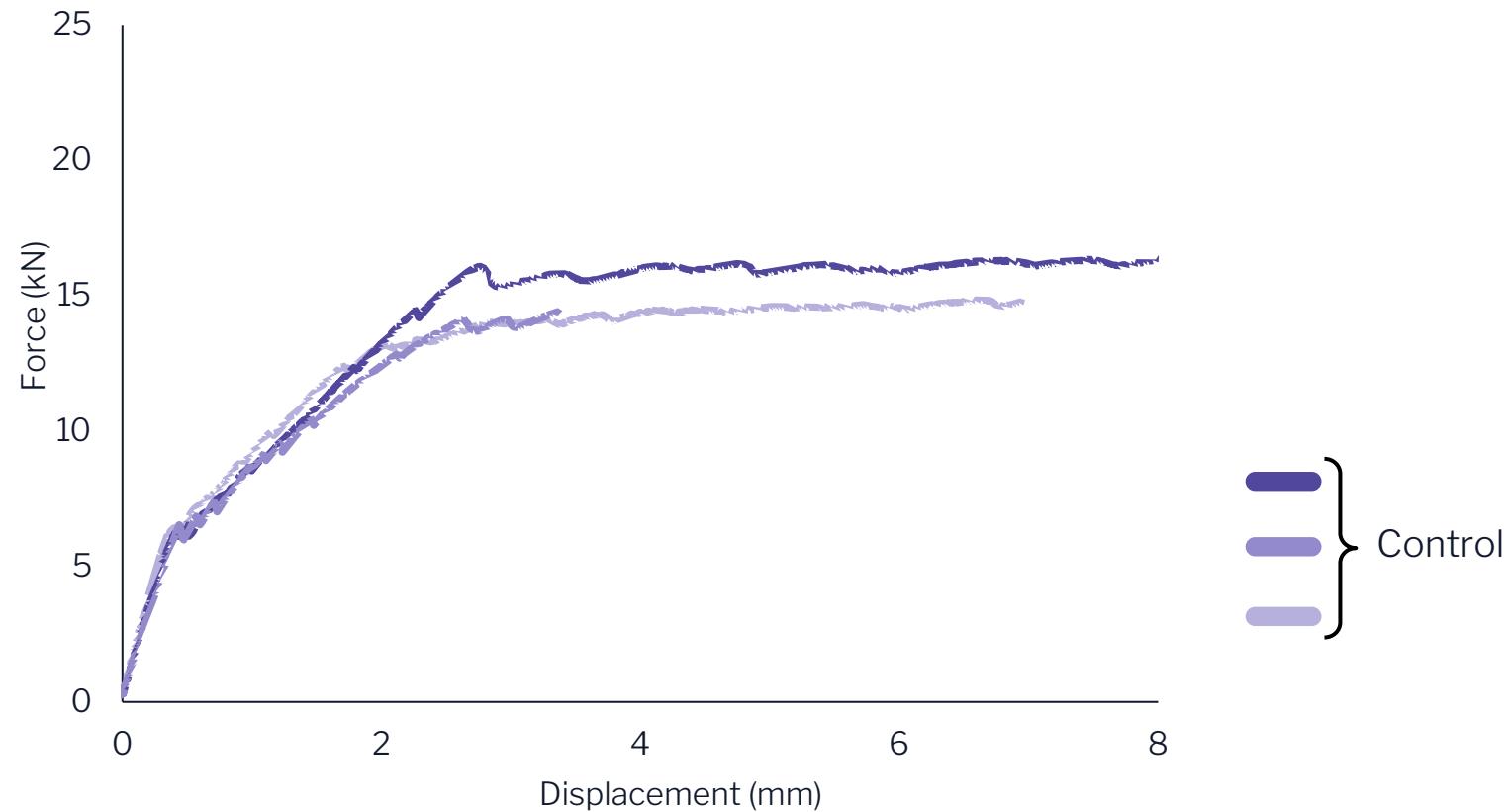


Three Beam Designs with the Same Structural Material

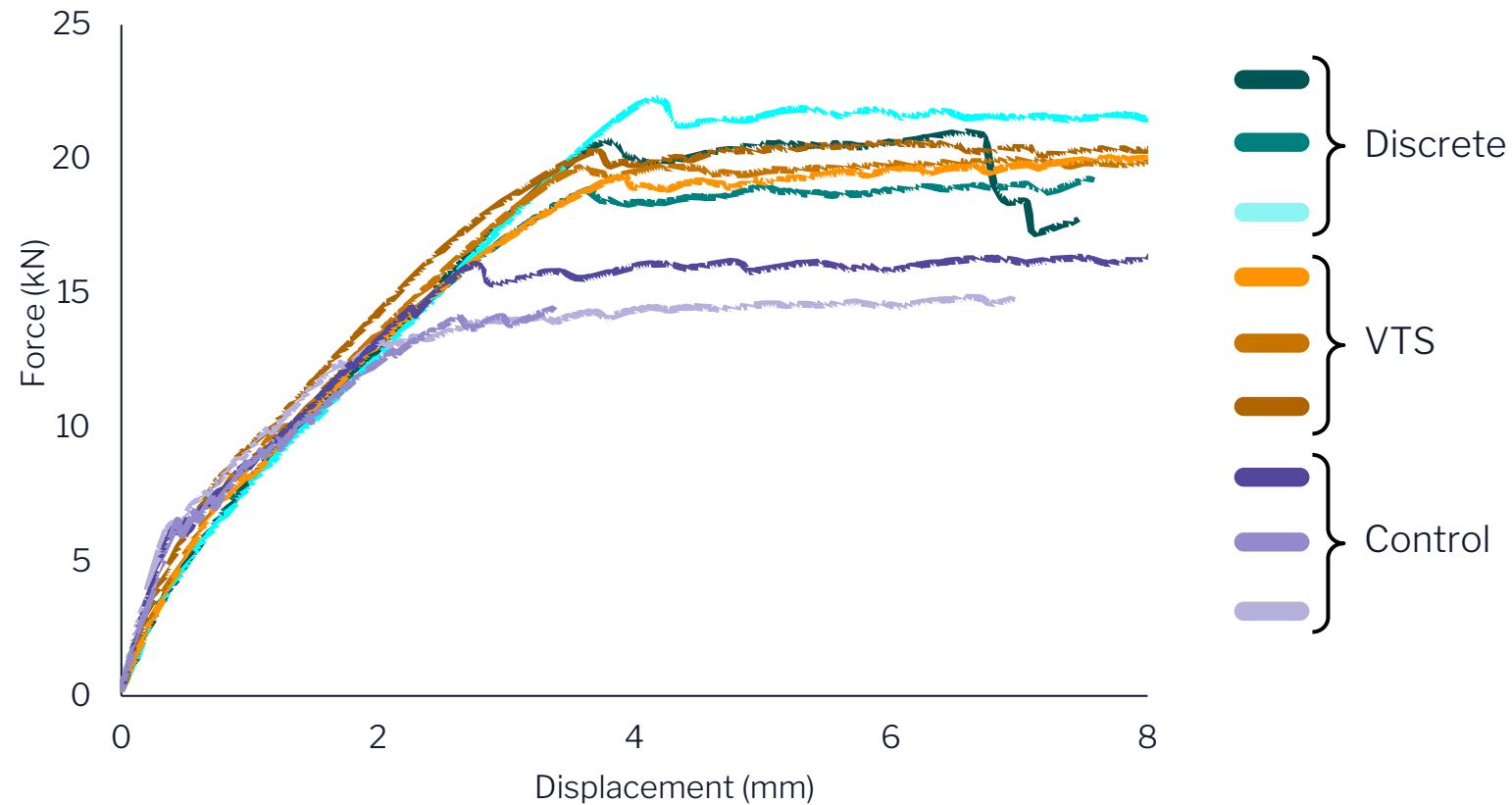




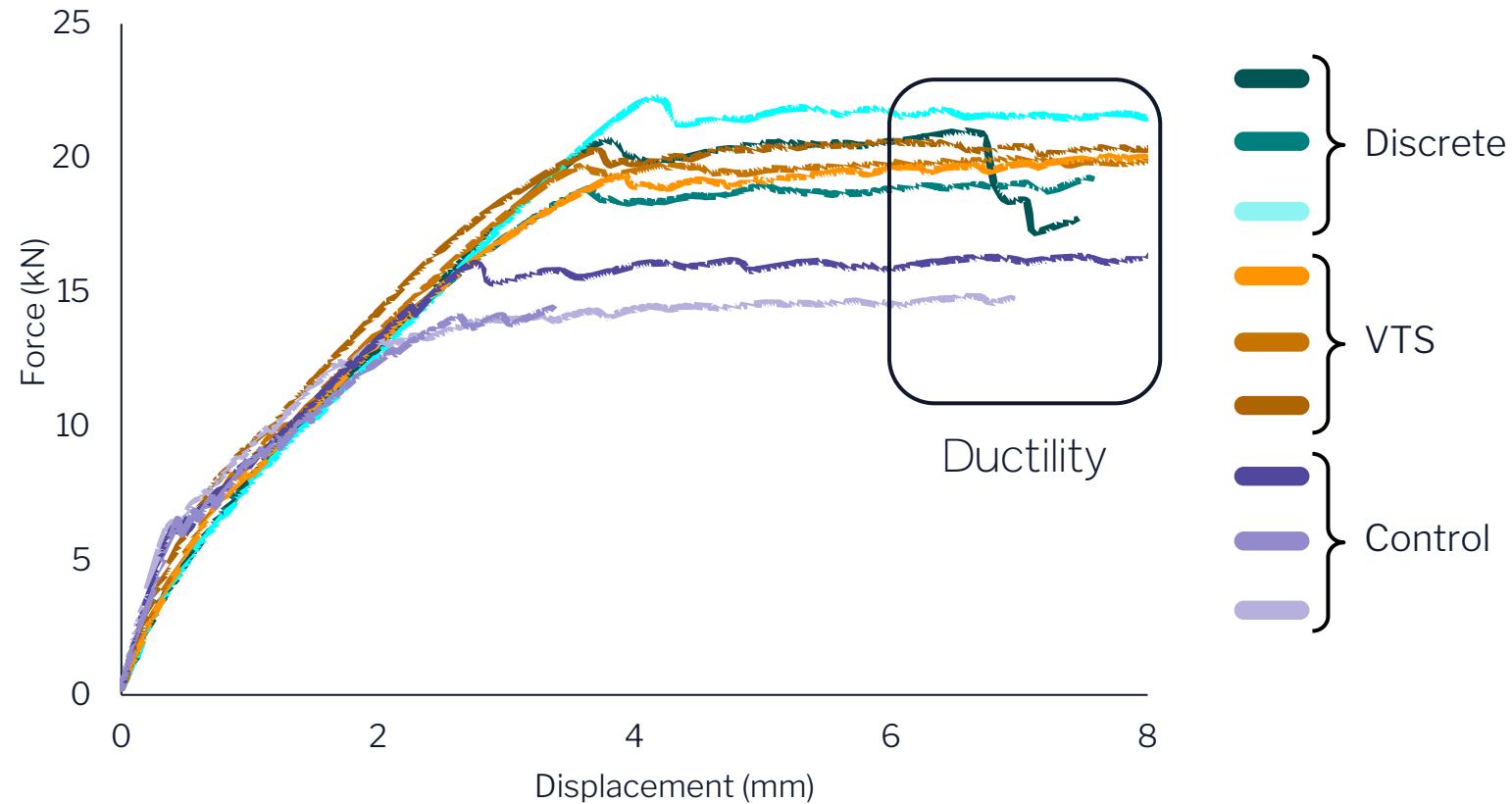
Experimental Results



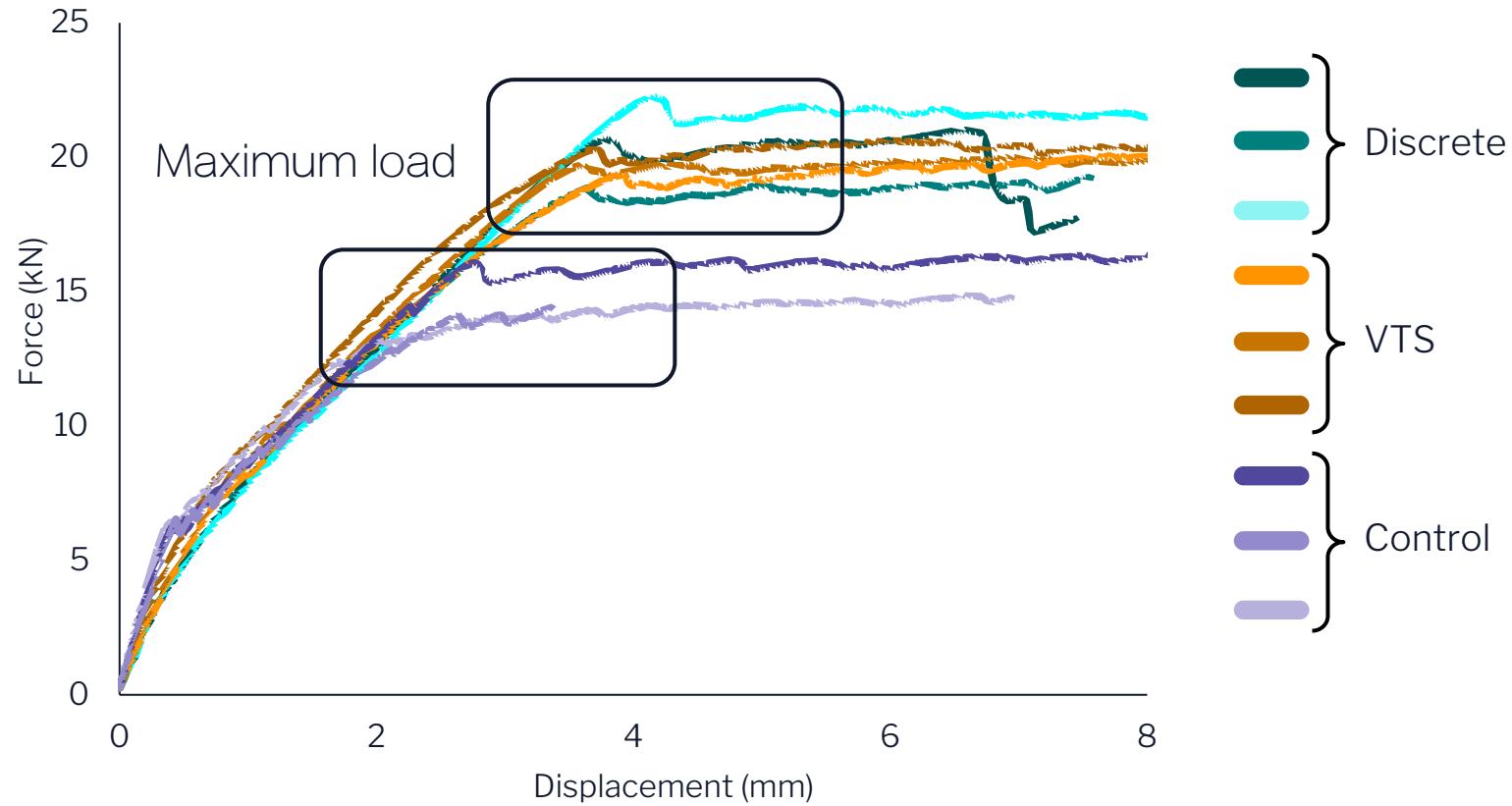
Experimental Results



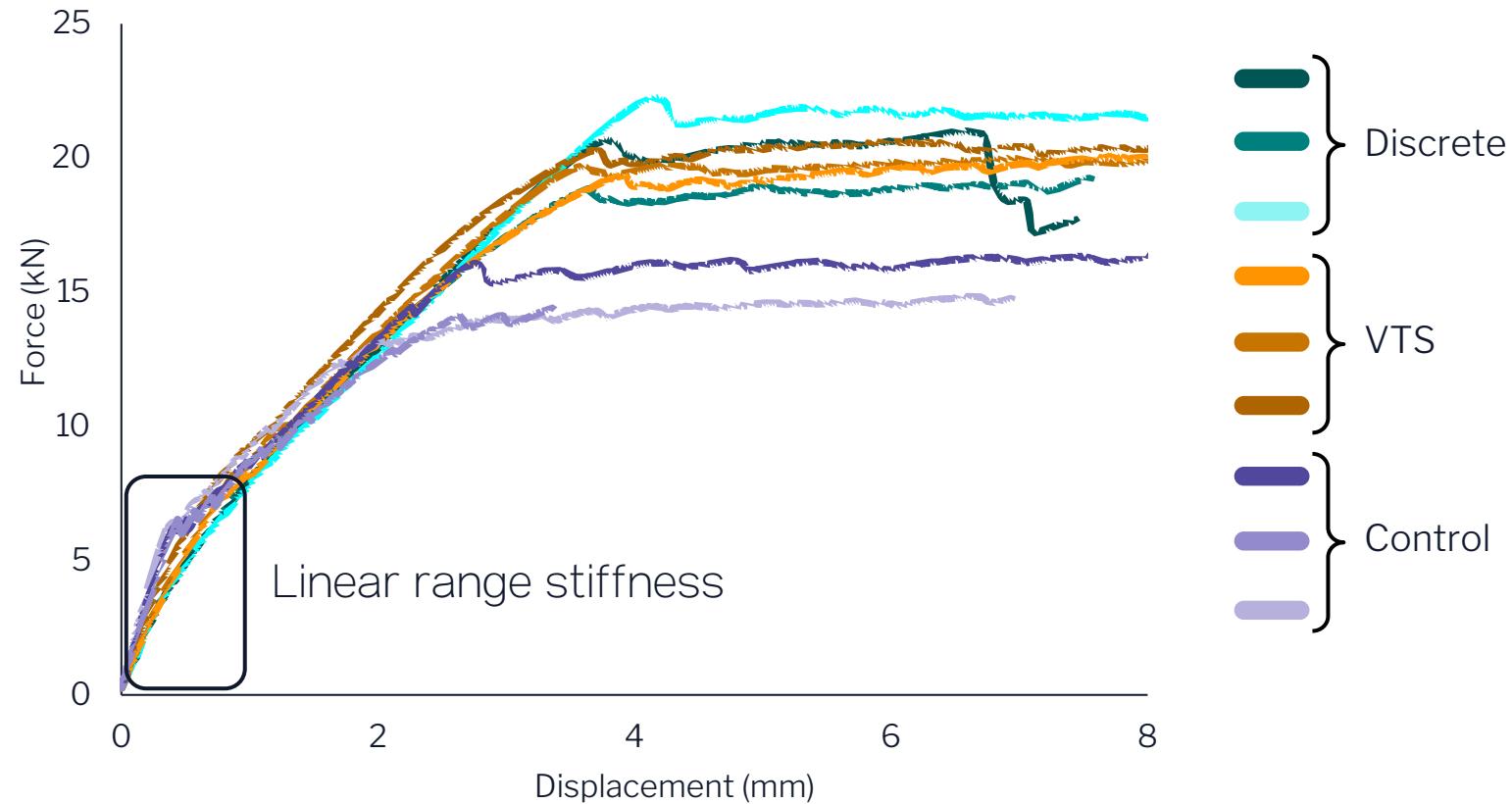
Experimental Results



Experimental Results

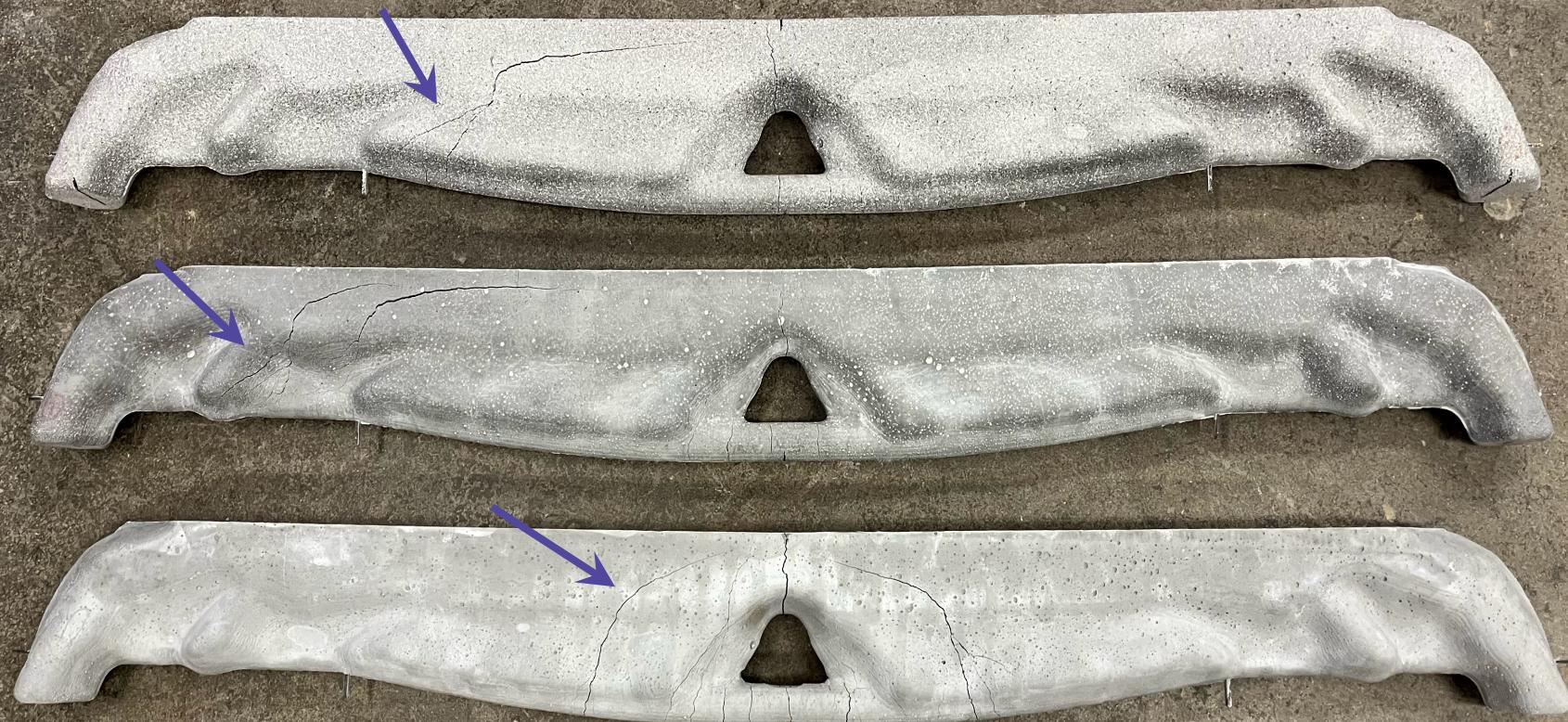


Experimental Results

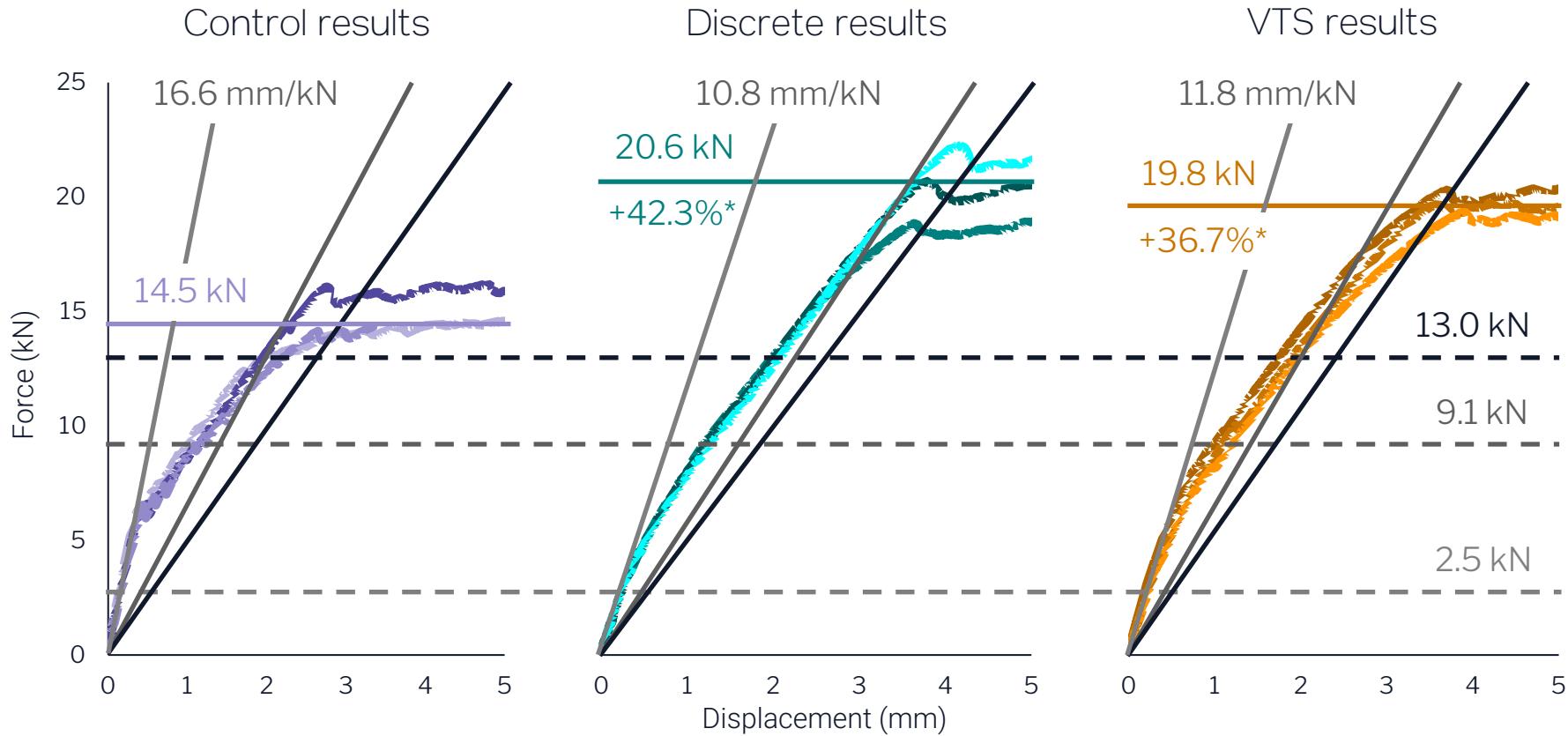


Failure Modes

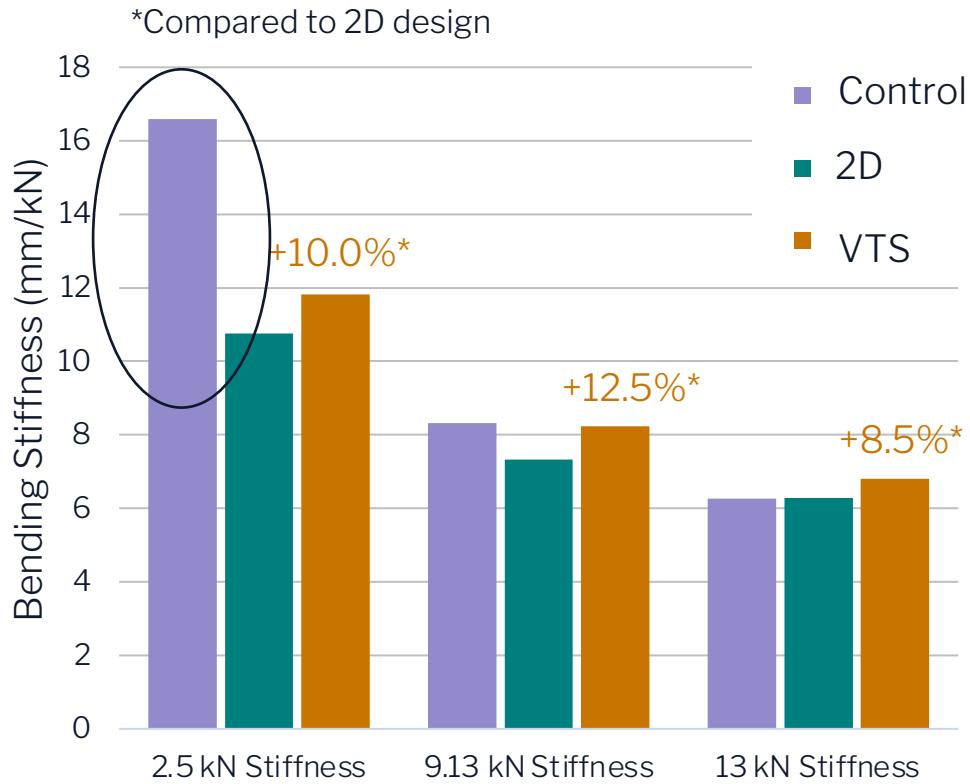
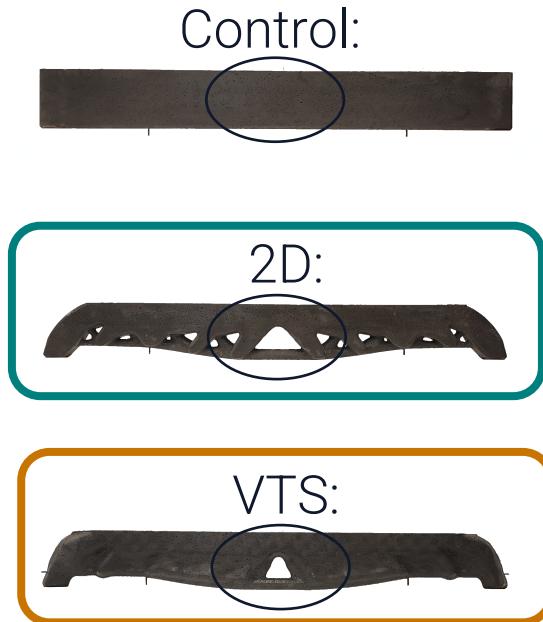
Photo: Kittipong Thiamchaiboothawee



Results Comparison



Results Comparison



Improving the performance of fabricated designs requires:
inclusion of all relevant behavioral and fabrication
characteristics

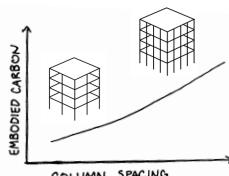
Behavioral
characteristics
of a design reflect its ability
to meet the
industry-specific needs

Improving the performance of fabricated designs requires:
inclusion of all relevant behavioral and fabrication
characteristics

But also that:
the TO design framework fits the given
industry-specific needs

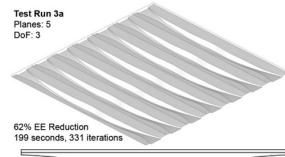
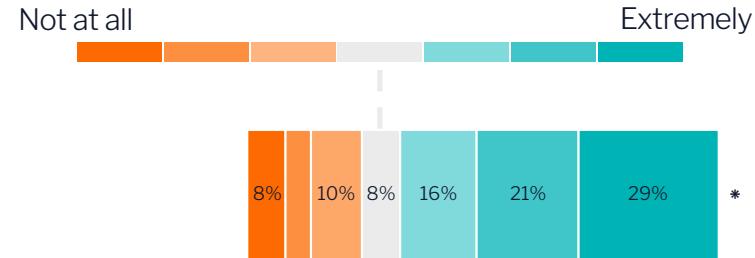
Survey of Civil Engineering Practice

In a future project, would you **use**:



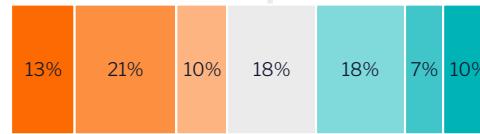
Trinh et al. (2021)

Parametric Design ?



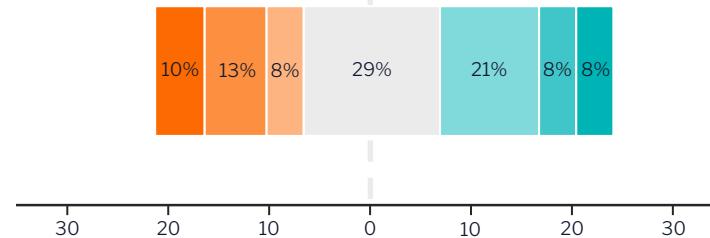
Ismail, M. A., & Mueller, C. T. (2021)

Shape Optimization ?



Galjaard et al. (2015)

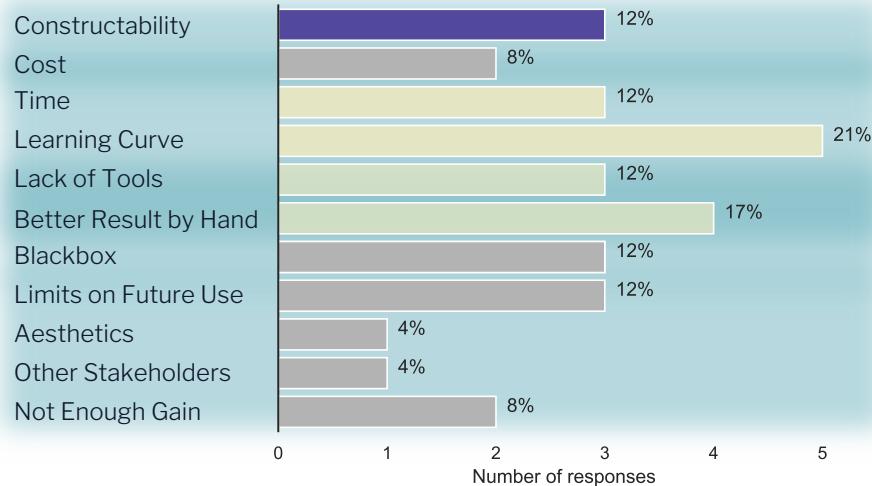
Topology Optimization?



Barriers Faced by Civil Engineering Practice

Construction Related
Time Related

To using automated design tools:



Construction

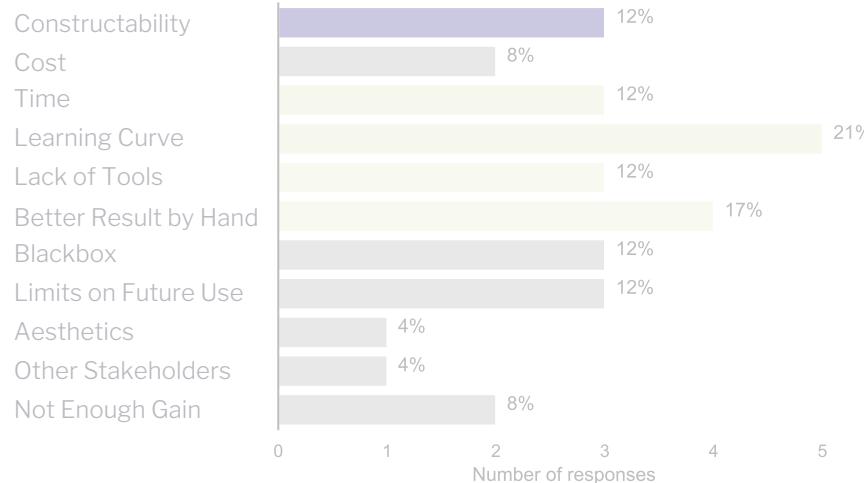
Design Time
Tools

Other

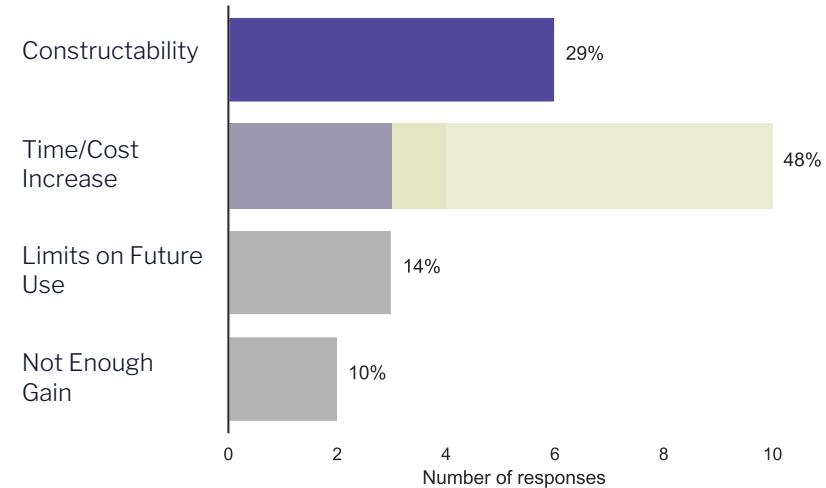
Barriers Faced by Civil Engineering Practice

Construction Related
Time Related

To using automated design tools:



To using TO:



Time Requirements Associated with TO

Set-Up

Problem Formulation

$$\min_{\mathbf{x}} : \quad c = \mathbf{U}^T \mathbf{K}(\mathbf{x}) \mathbf{U}$$

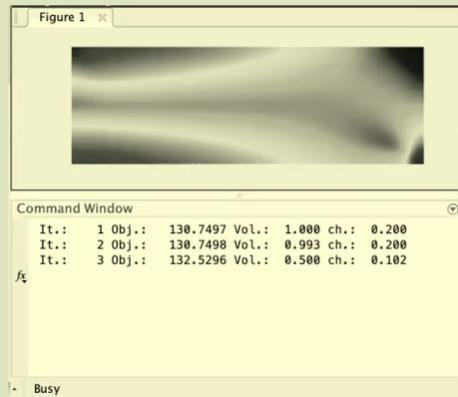
$$\text{s.t.:} \quad \mathbf{K}(\mathbf{x}) \mathbf{U} = \mathbf{F}$$

$$V(\mathbf{x})/V_0 \leq f$$

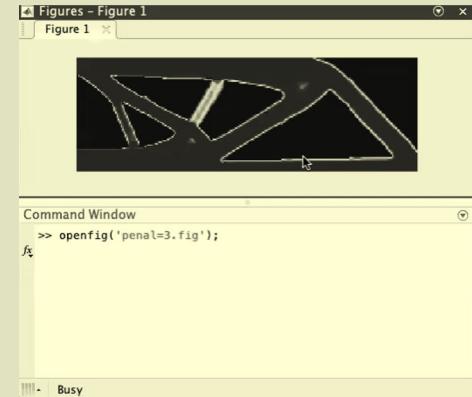
$$0 \leq \mathbf{x} \leq 1$$

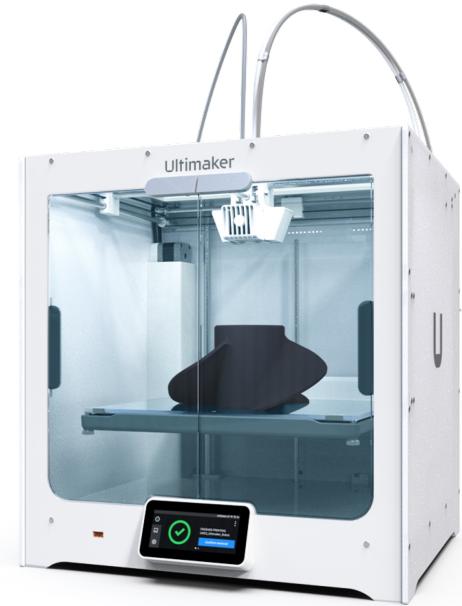
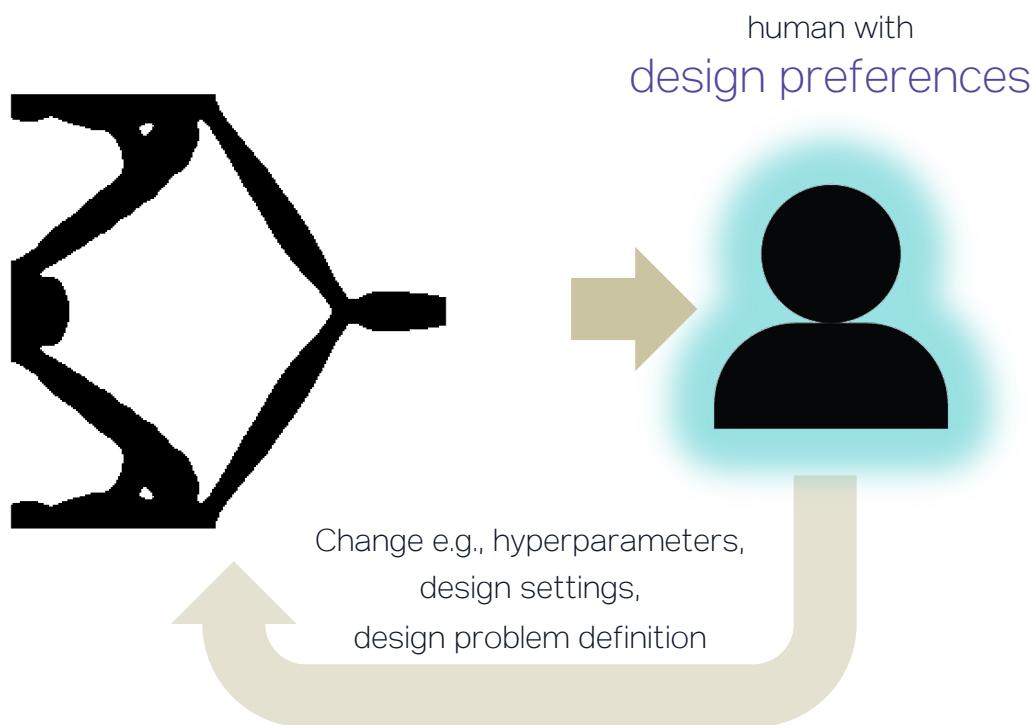
Derive Sensitivities

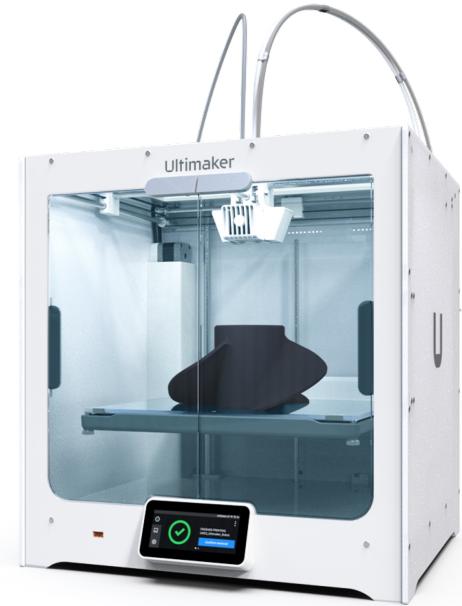
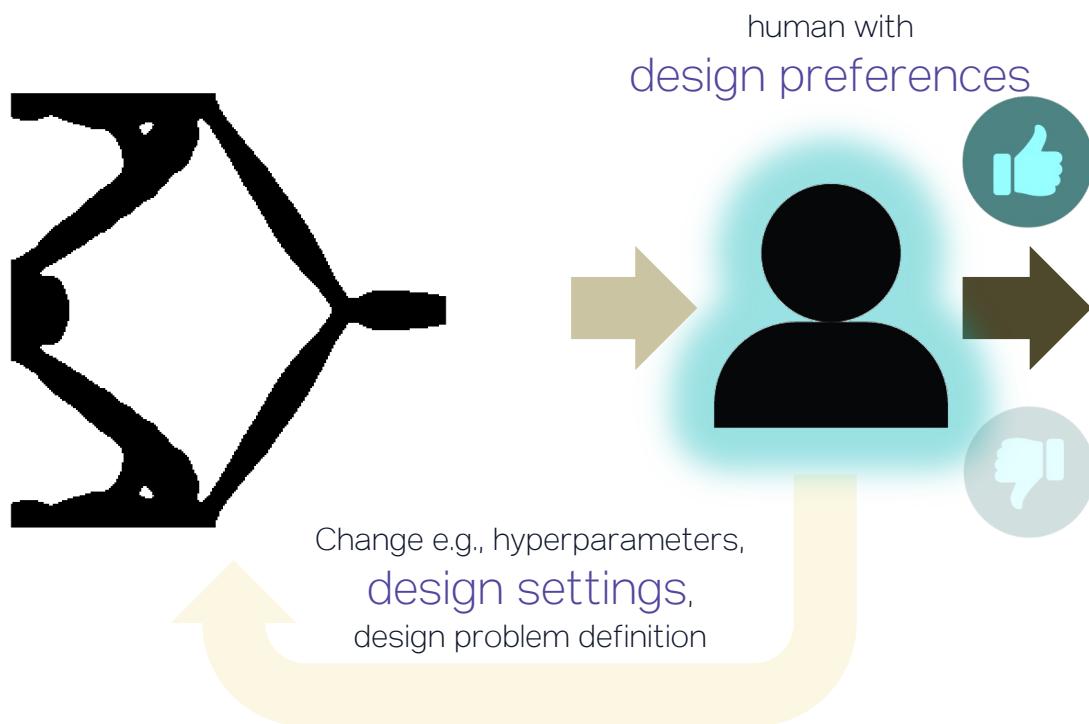
Runtime



Hyperparameter Tuning







reducing set-up and runtime by
solving more complex TO with



Computer



Human Input

Ha, D.Q. and Carstensen, J.V., *Struct Mult Opt*, 2023;
Schiffer, G.L, Ha, D.Q. and Carstensen, J.V., *Virtual Phys Prototyp*, 2023
Schiffer, G.L, Schmidt, M.-P., Pedersen, C.W., and Carstensen, J.V., *Virtual Phys Prototyp*, 2024

Playing with the Minimum Feature Sizes – The Case of Buckling



Improved buckling performance

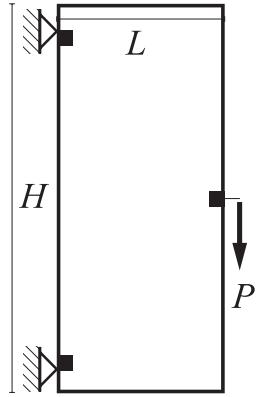
HiTop with Control of Minimum Solid and Void, and Maximum Solid Features



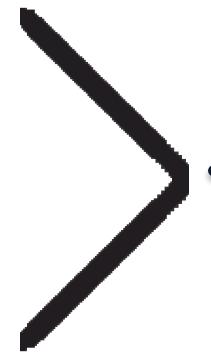
310 seconds \approx 5 minutes 25 seconds

Short Cantilever Example – Improving Buckling

Design Domain



Typical TO Design



Region of Interest

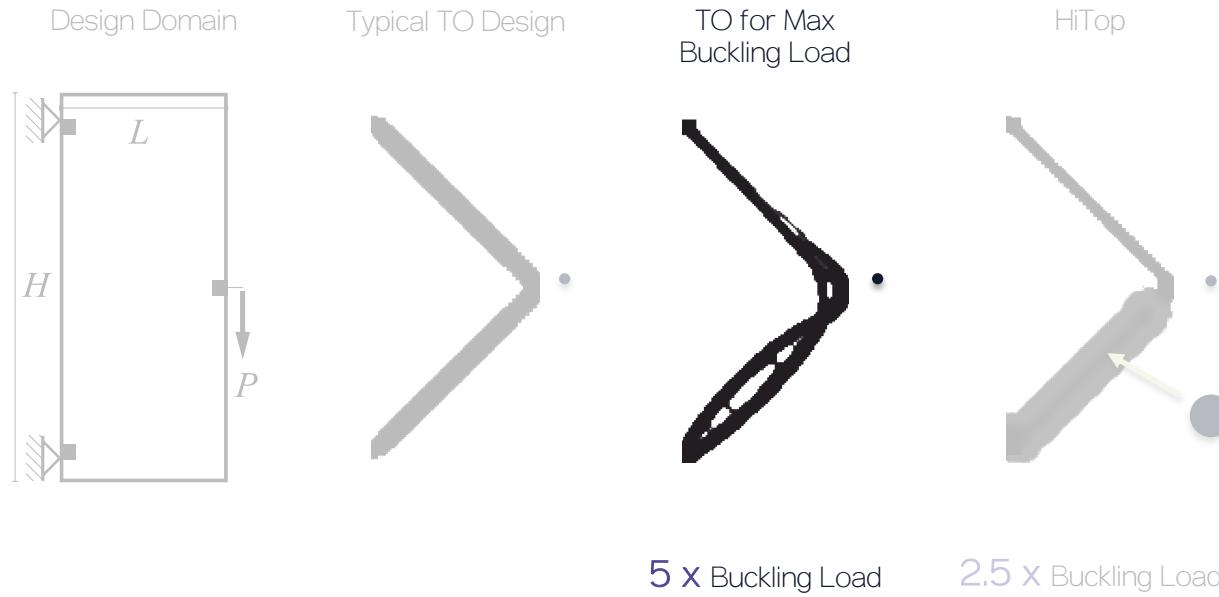


HiTop

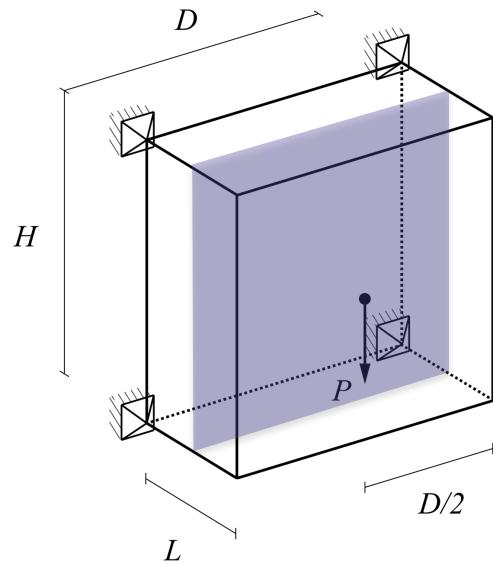


2.5 x Buckling Load

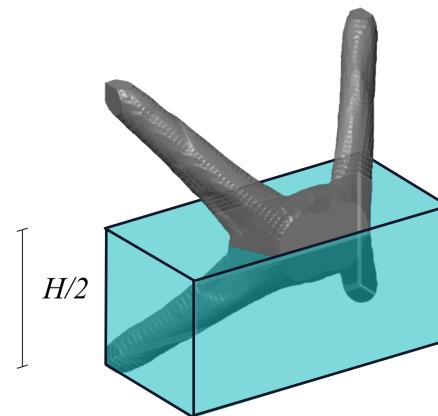
Short Cantilever Example – Improving Buckling



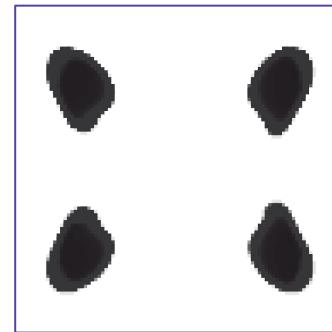
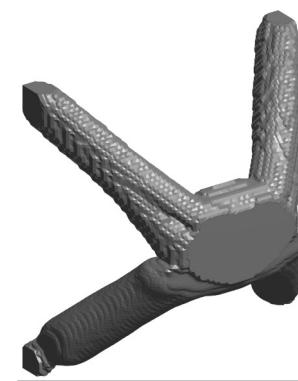
HiTop in 3D – Short Cantilever Example

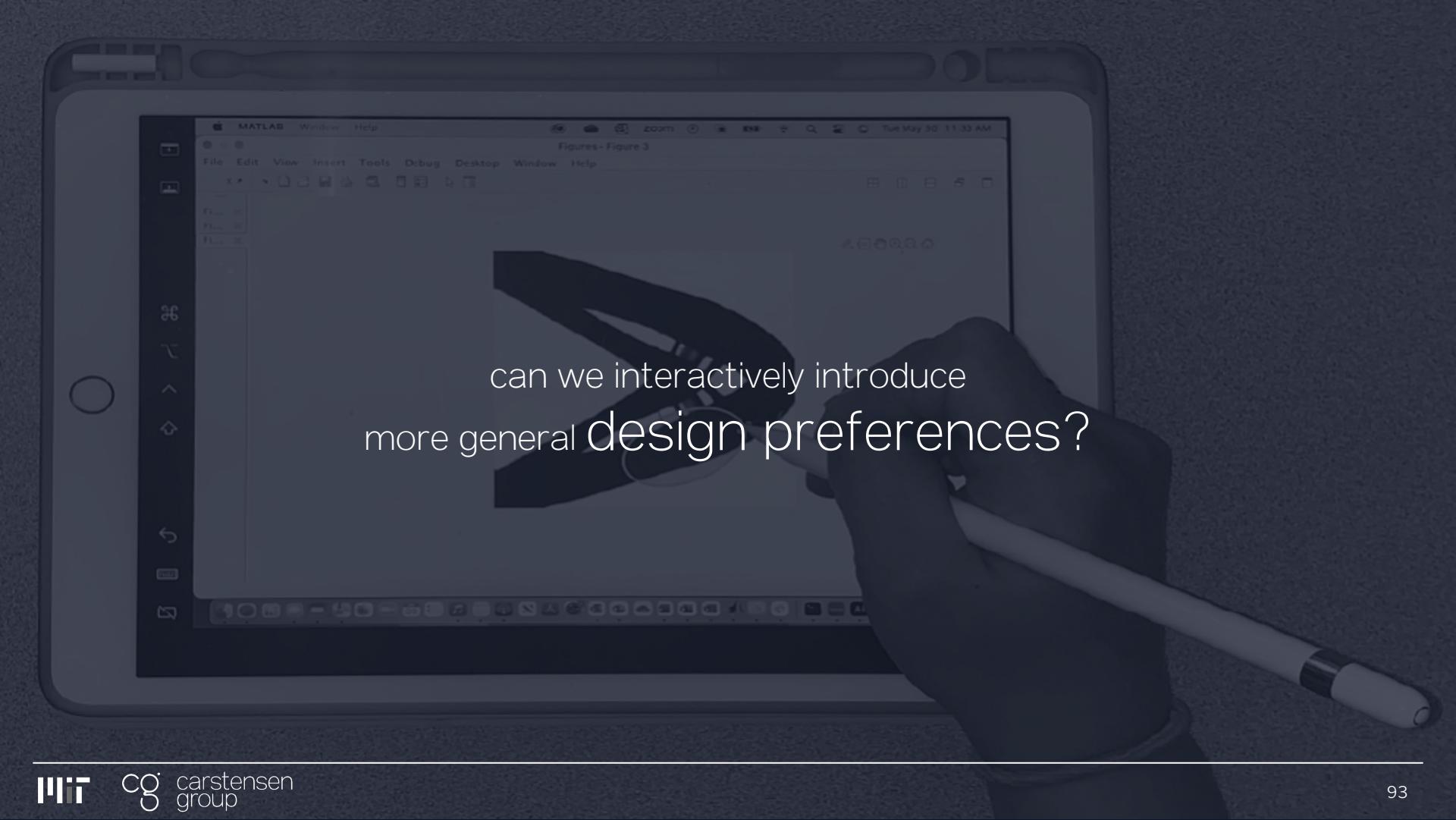


Typical TO Design



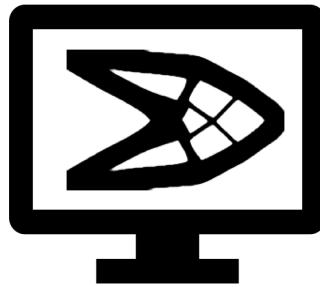
HiTop Design





can we interactively introduce
more general design preferences?

HiTop with user-drawn preferences

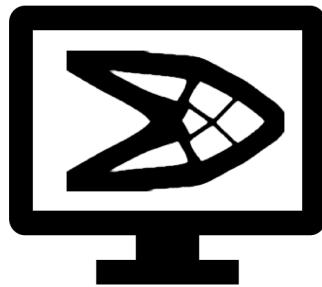


Computer



Human Input

HiTop with user-drawn preferences



Computer



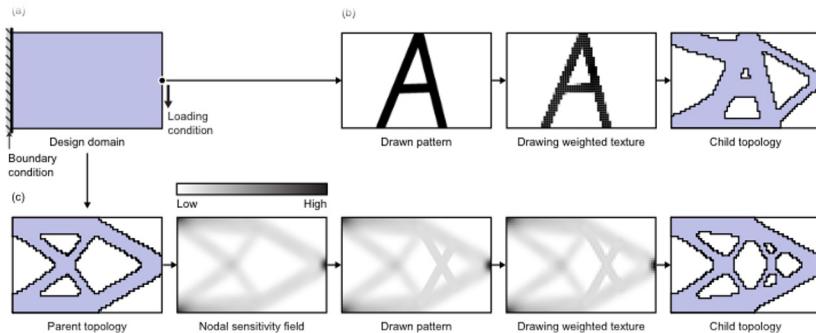
Human Input



Computer

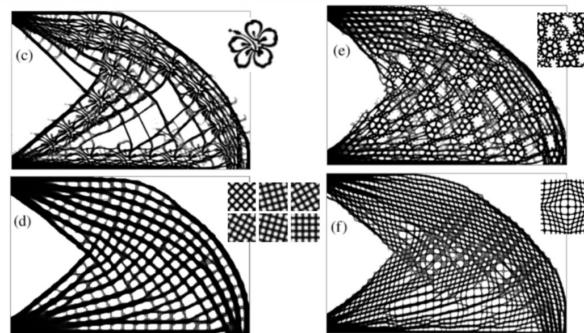
Options for Image Matching in TO

1. Impose passive regions



Li et al. (2023)

2. Encourage similarity through constraint



Navez et al. (2022)

- TO Approach: Evolutionary structural optimization
- **Input:** User-drawn pattern
- Maps image as passive region onto topology

- TO Approach: Density-based topology optimization
- **Input:** Images patches with patterns
- Uses additional constraint and patch-match to map image patches to topology

Options for Image Matching in TO

1. Initial TO design for minimum compliance



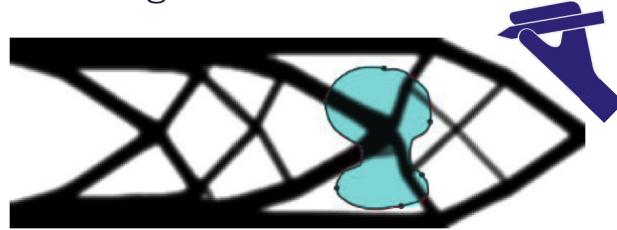
Options for Image Matching in TO

1. Initial TO design for minimum compliance

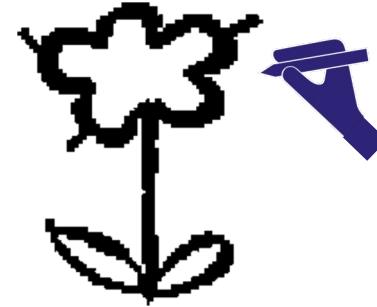


2. User selects:

- a. Region where they want to change the design



- b. Drawn input that they want reflected



Options for Image Matching in TO

1. Impose passive regions



Flower replicated **exactly** as drawn

Options for Image Matching in TO

1. Impose passive regions



Flower replicated **exactly** as drawn

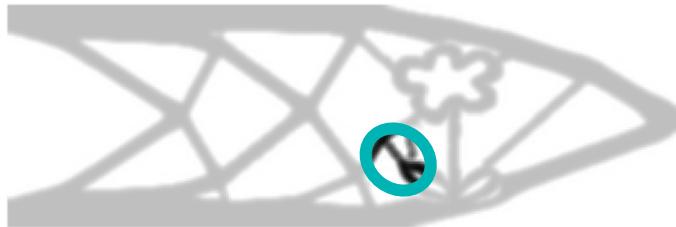
2. Encourage similarity through constraint



Flower replicated **somewhat** as drawn

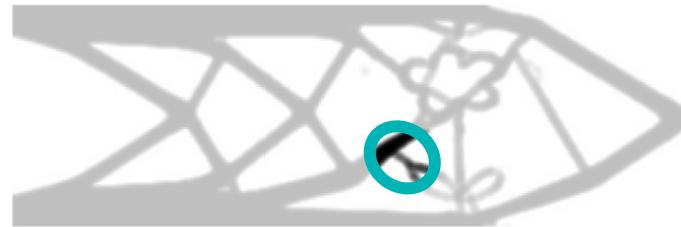
Options for Image Matching in TO

1. Impose passive regions



Flower replicated **exactly** as drawn

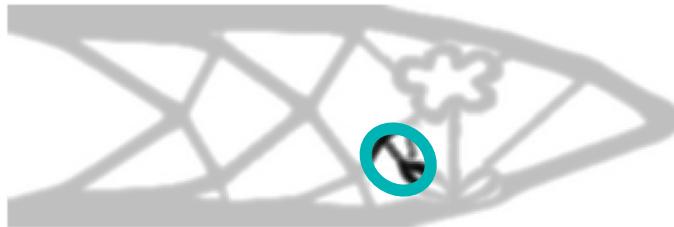
2. Encourage similarity through constraint



Flower replicated **somewhat** as drawn

Options for Image Matching in TO

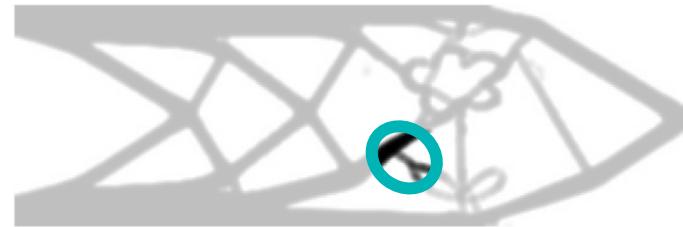
1. Impose passive regions



Flower replicated **exactly** as drawn

$$c = 242.1$$

2. Encourage similarity through constraint

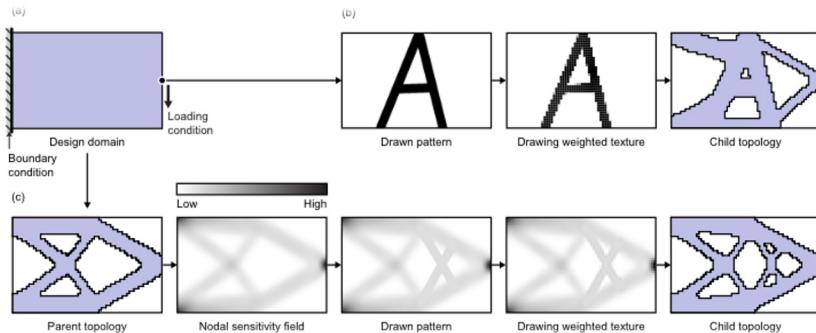


Flower replicated **somewhat** as drawn

$$c = 233.0$$

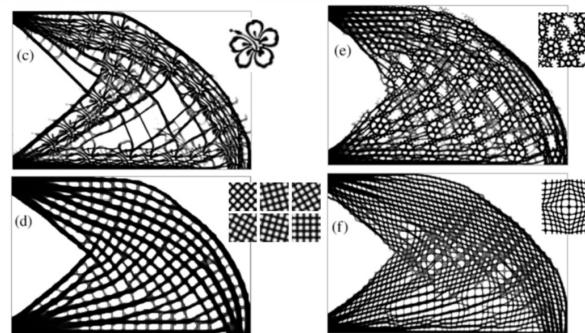
Options for Image Matching in TO

1. Impose passive regions



Li et al. (2023)

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- **Input:** Images patches with patterns
- Uses **additional constraint** and **patch match** to map image patches to topology

← human

HiTop with User-Drawn Preferences

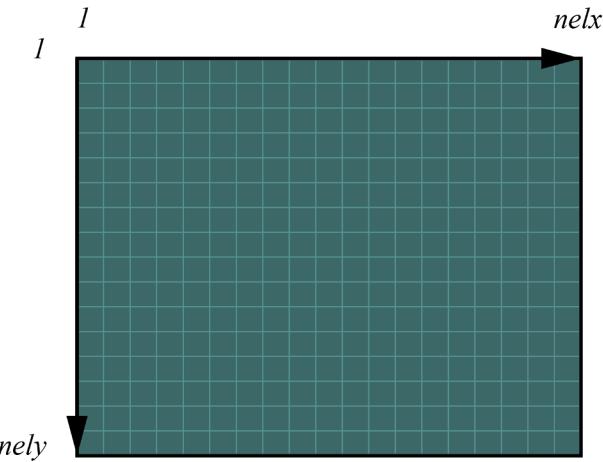
Problem formulation:

$$\min_{\mathbf{x}} : \quad c = \mathbf{U}^T \mathbf{K}(\mathbf{x}) \mathbf{U}$$

$$\text{s.t.:} \quad \mathbf{K}(\mathbf{x}) \mathbf{U} = \mathbf{F}$$

$$V(\mathbf{x})/V_0 \leq f$$

$$0 \leq \mathbf{x} \leq 1$$



HiTop with User-Drawn Preferences

Problem formulation:

$$\min_{\mathbf{x}} : \quad c = \mathbf{U}^T \mathbf{K}(\mathbf{x}) \mathbf{U}$$

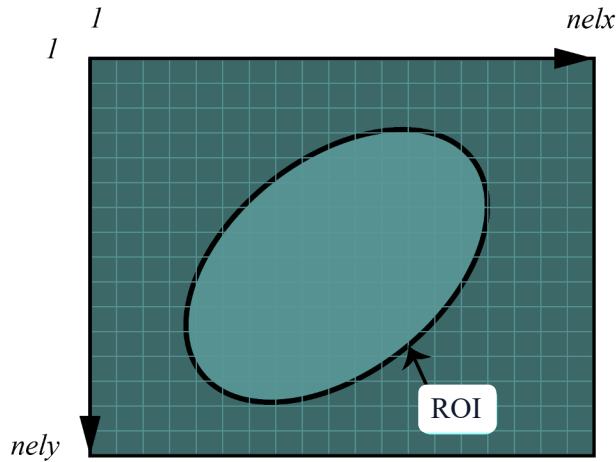
$$\text{s.t.:} \quad \mathbf{K}(\mathbf{x}) \mathbf{U} = \mathbf{F}$$

$$V(\mathbf{x})/V_0 \leq f$$

$$A(\mathbf{x}) \leq 1$$

$$0 \leq \mathbf{x} \leq 1$$

Interactively Apply
Appearance Constraint



HiTop with User-Drawn Preferences

Problem formulation:

$$\min_{\mathbf{x}} : \quad c = \mathbf{U}^T \mathbf{K}(\mathbf{x}) \mathbf{U}$$

$$\text{s.t.:} \quad \mathbf{K}(\mathbf{x}) \mathbf{U} = \mathbf{F}$$

$$V(\mathbf{x})/V_0 \leq f$$

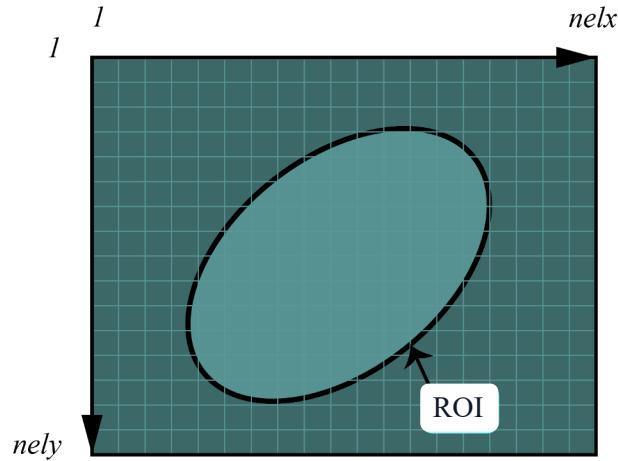
$$A(\mathbf{x}) \leq 1$$

$$0 \leq \mathbf{x} \leq 1$$

Appearance constraint (Navez et al. 2022):

$$A(\mathbf{x}) = \frac{1}{\gamma A_{50} |\text{ROI}|} \sum_{e \in \text{ROI}} \mathbf{D}_e(\mathbf{x}, \boldsymbol{\alpha})$$

Interactively Apply
Appearance Constraint



HiTop with User-Drawn Preferences

Problem formulation:

$$\min_{\mathbf{x}} : \quad c = \mathbf{U}^T \mathbf{K}(\mathbf{x}) \mathbf{U}$$

$$\text{s.t.:} \quad \mathbf{K}(\mathbf{x}) \mathbf{U} = \mathbf{F}$$

$$V(\mathbf{x})/V_0 \leq f$$

$$A(\mathbf{x}) \leq 1$$

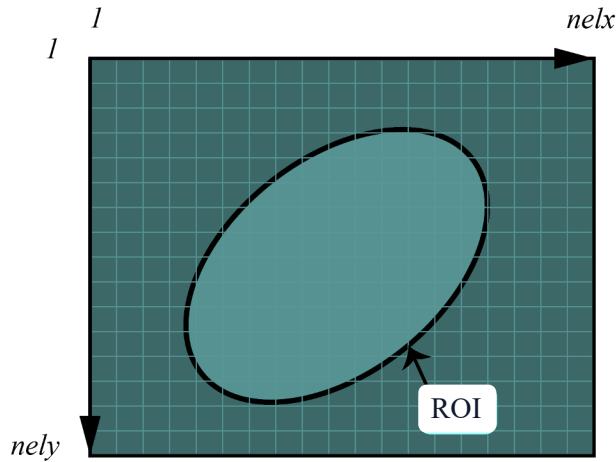
$$0 \leq \mathbf{x} \leq 1$$

Appearance constraint (Navez et al. 2022):

$$A(\mathbf{x}) = \frac{1}{\gamma A_{50} |\text{ROI}|} \sum_{e \in \text{ROI}} \mathbf{D}_e(\mathbf{x}, \boldsymbol{\alpha})$$

where $\mathbf{D}_e(\mathbf{x}, \boldsymbol{\alpha})$ is the squared difference between the element densities $\bar{\mathbf{x}}$ and the user-drawn image $\boldsymbol{\alpha}$.

Interactively Apply
Appearance Constraint



HiTop with User-Drawn Preferences

Problem formulation:

$$\min_{\mathbf{x}} : \quad c = \mathbf{U}^T \mathbf{K}(\mathbf{x}) \mathbf{U}$$

$$\text{s.t.:} \quad \mathbf{K}(\mathbf{x}) \mathbf{U} = \mathbf{F}$$

$$V(\mathbf{x})/V_0 \leq f$$

$$A(\mathbf{x}) \leq 1$$

$$0 \leq \mathbf{x} \leq 1$$

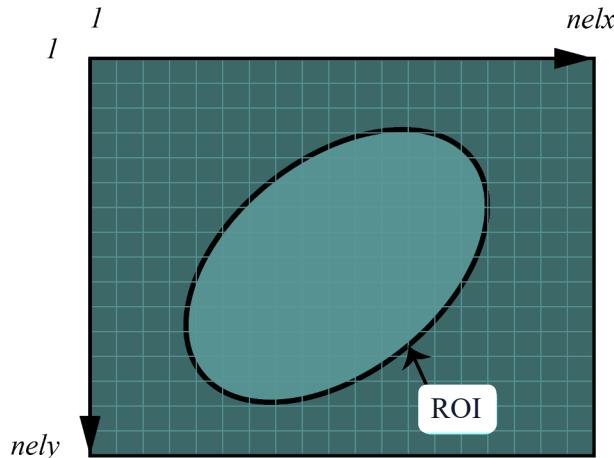
Appearance constraint (Navez et al. 2022):

$$A(\mathbf{x}) = \frac{1}{\gamma A_{50} |\text{ROI}|} \sum_{e \in \text{ROI}} \mathbf{D}_e(\mathbf{x}, \boldsymbol{\alpha})$$

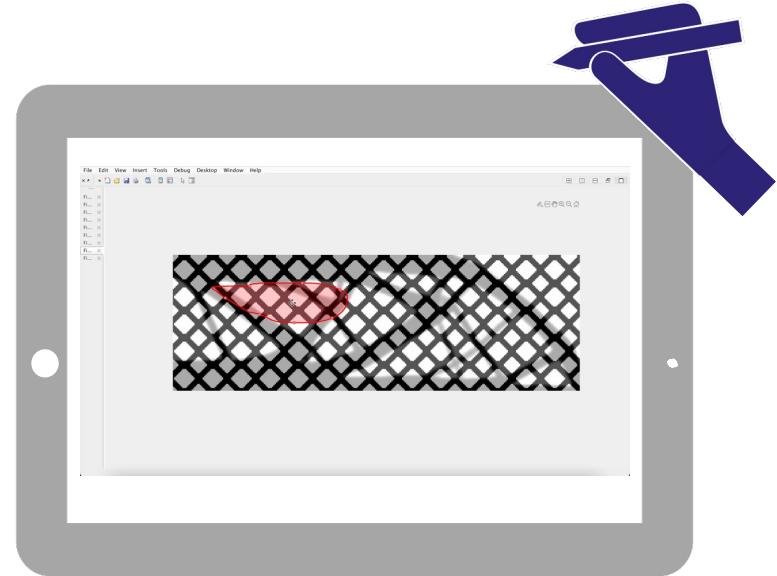
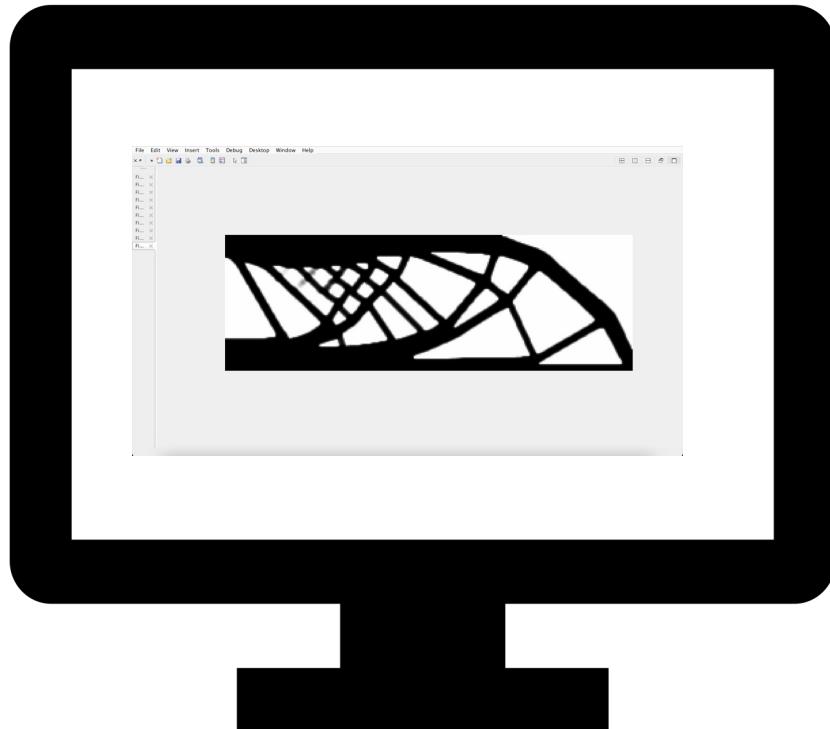
where $\mathbf{D}_e(\mathbf{x}, \boldsymbol{\alpha})$ is the squared difference between the element densities $\bar{\mathbf{x}}$ and the user-drawn image $\boldsymbol{\alpha}$.

γ is a user-set parameter that defines how closely the material distribution must match the provided image.

Interactively Apply
Appearance Constraint



HiTop with User-Drawn Preferences



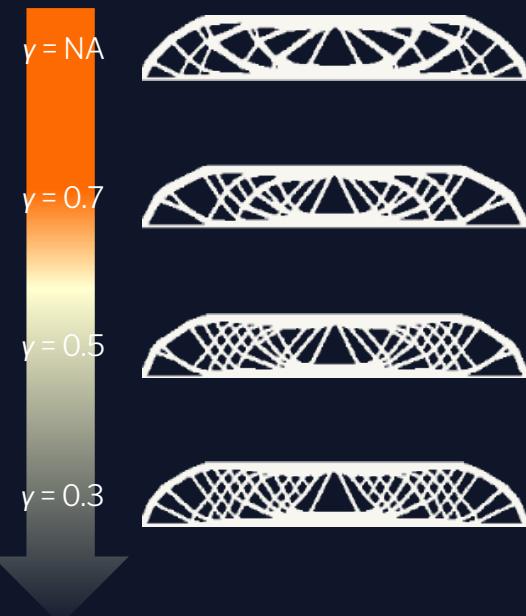
User input:

- Drawn pattern to be repeated.
- ROI where the pattern is desired.

Run time \approx 18 minutes to complete entire process.

Reducing AM Support Material with Interactive Infill

Digital Designs



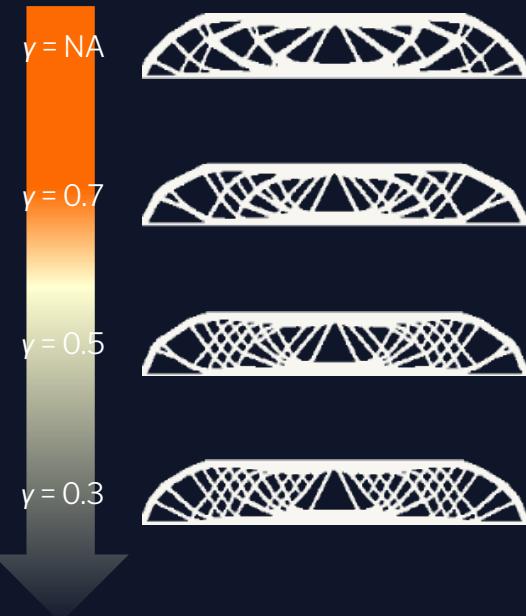
Appearance constraint more strictly applied

Reducing AM Support Material with Interactive Infill

Digital Designs

Fabricated Designs

with
support material



support
material [g]



Appearance constraint more strictly applied

Reducing AM Support Material with Interactive Infill

Digital Designs

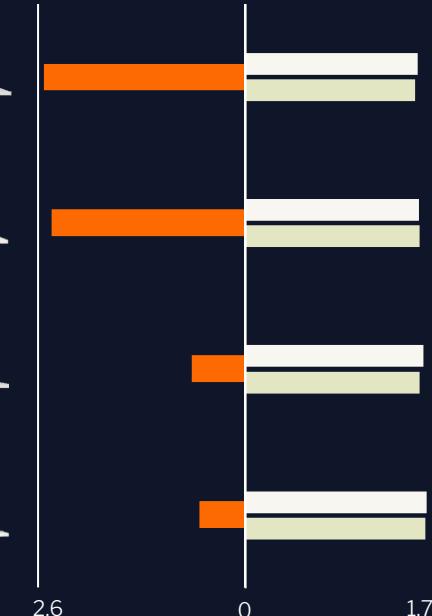
Fabricated Designs

with
support material

after
support material removal



support
material [g] compliance
[kNmM]



Appearance constraint more strictly applied

exp. num. exp.

Reducing AM Support Material with Interactive Infill

Digital Designs

Fabricated Designs

with
support material

after
support material removal

support
material [g]

compliance
[kNm]



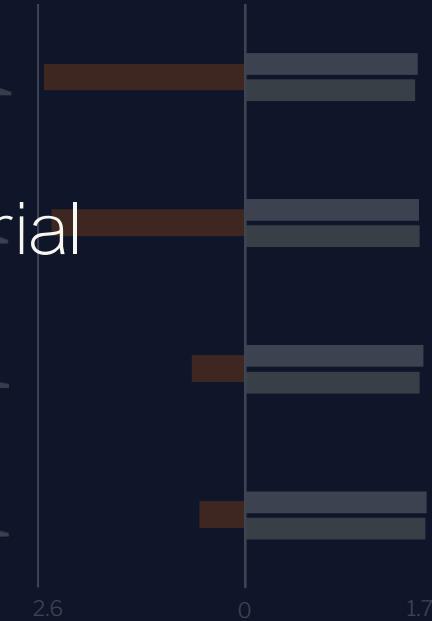
upto 73% reduction of support material



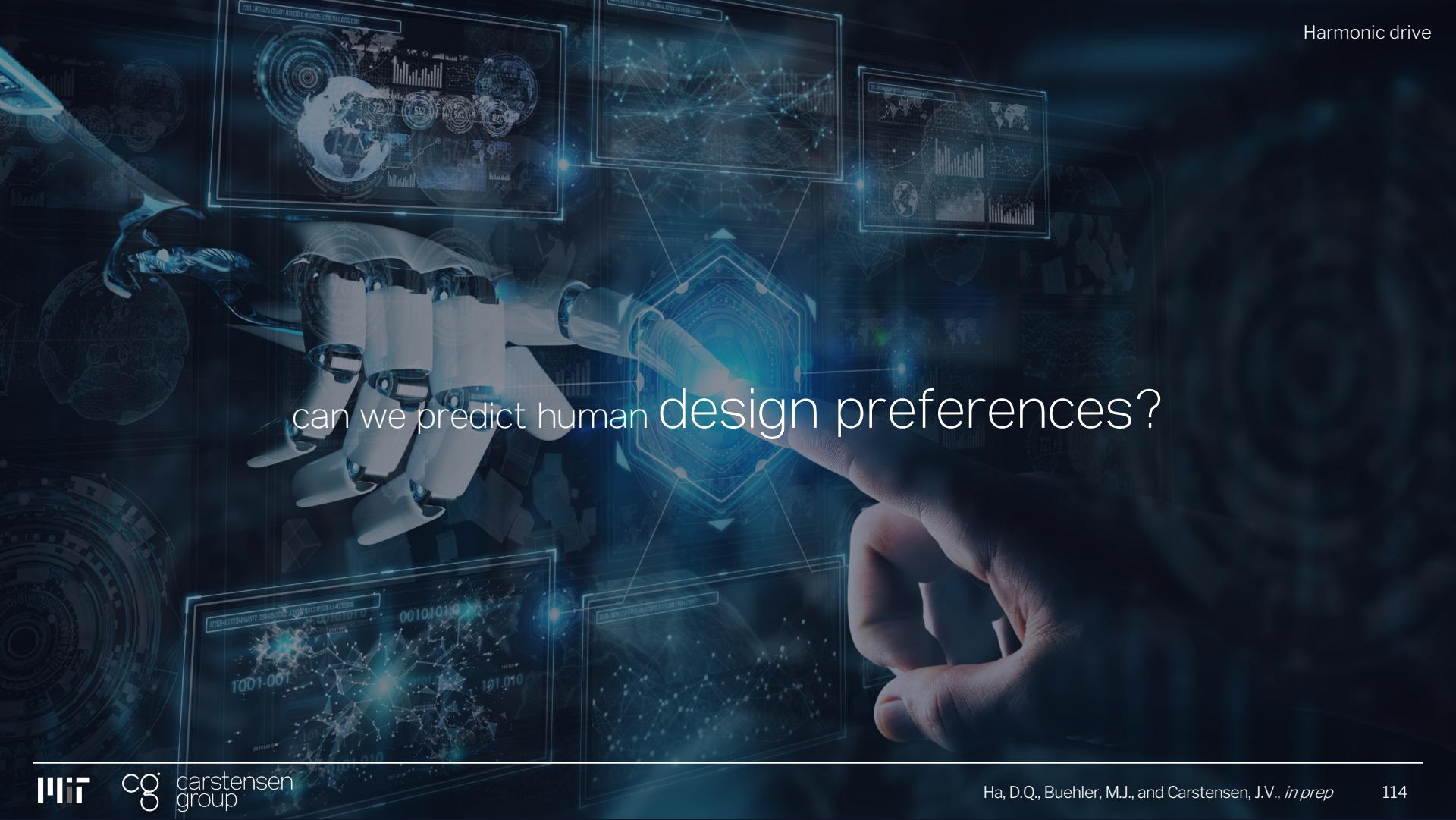
with 3% decrease in stiffness



Appearance constraint more strictly applied



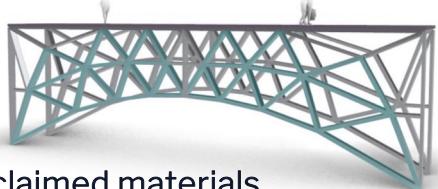
■ exp. ■ num. ■ exp.



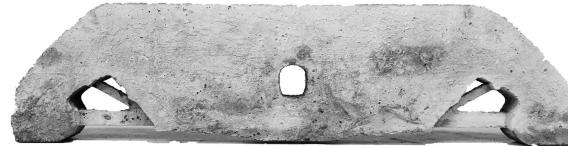
can we predict human design preferences?

Contributions

- Shown that automated design frameworks are necessary to identify high-performing, low-carbon solutions for civil structures that:



reuse reclaimed materials



reduce material consumption

- Developed an interactive structural optimization design technology where human experience is leveraged to improve known problematic, complicated performance metrics.
 - Examples include buckling, energy absorption, eigenvalues, and manufacturability.



Impact

Carbon reductions of civil structures

- Contributions will reduce the quantities of new construction materials that we need.

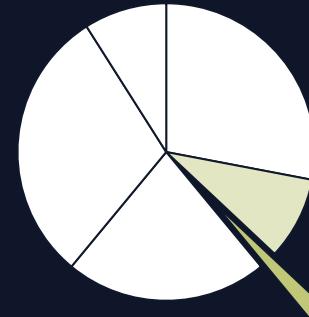
Industry

- Contributions will change how design engineers work.

Data

- Contributions will create the currently unavailable data for future generative AI design methods.

Global Emissions



**Potential savings by 25%
concrete reduction:
2% of Annual CO₂

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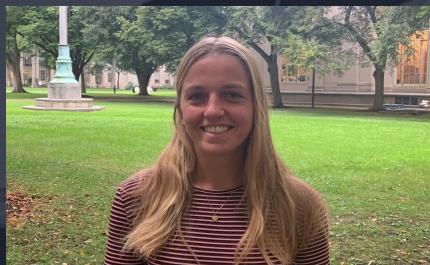
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