Optimizing Steel-Reinforcement in Concrete: Using Topology Optimization and Digital Fabrication to Develop Ductile Concrete for Specific Loading Conditions

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Outline

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    - Steel Reinforcement Manufacturing
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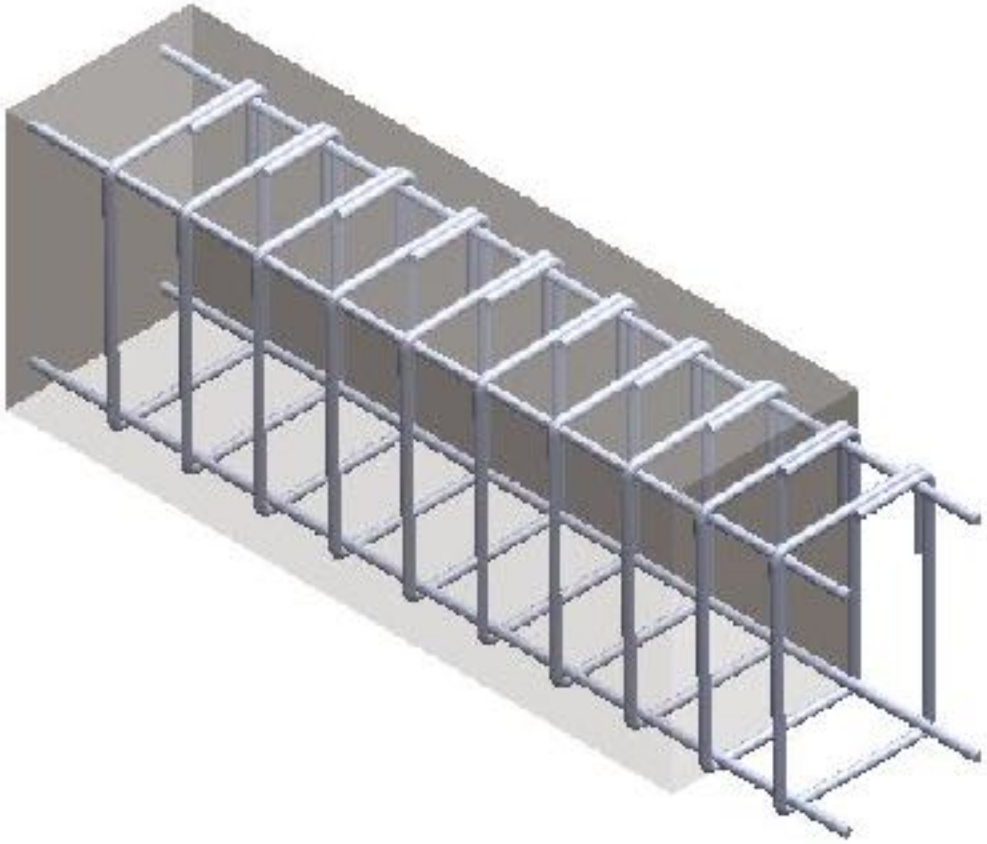
There is a need to reduce the environmental impacts when building concrete structures

- Concrete is the second most commonly used material in the world
- Cement emits 8% of global CO_2 emissions
- Small improvements in the way concrete structures are designed can have drastic effects on global emissions

(1) C. R. Gagg, “Cement and concrete as an engineering material: An historic appraisal and case study analysis,” Eng. Fail. Anal., vol. 40, pp. 114–140, 2014, doi: 10.1016/j.engfailanal.2014.02.004.
(2) J. Lehne and F. Preston, “Making Concrete Change; Innovation in Low-carbon Cement and Concrete,” Chatham House Rep., pp. 1–122, 2018, [Online]. Available: www.chathamhouse.org.

Concrete is a very brittle material

- It must always be reinforced, typically with steel rebar
- The steel rebar cage geometry is not specific to the loading scenario

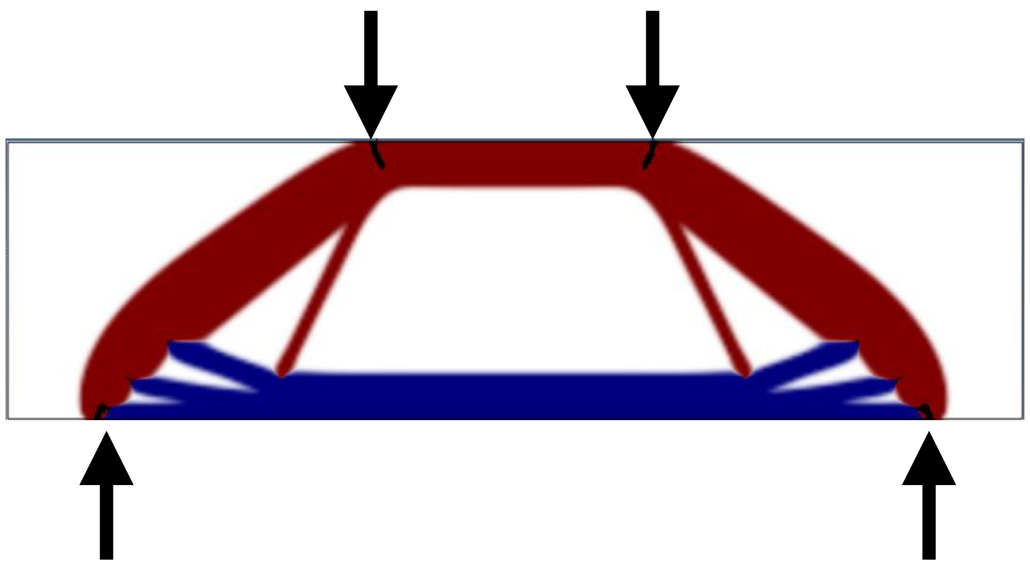


We seek to minimize amount of steel and concrete used in concrete structures

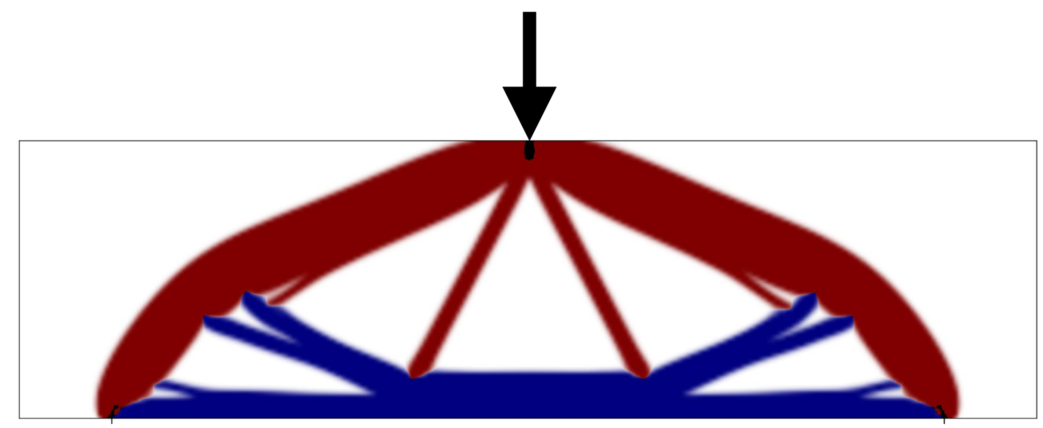
- Steel is expensive, heavy, and thermally conductive
- In seismic applications, a reduction in mass leads to better performance

Idea: use topology optimization to strategically place steel and concrete where needed for the specific loading scenario

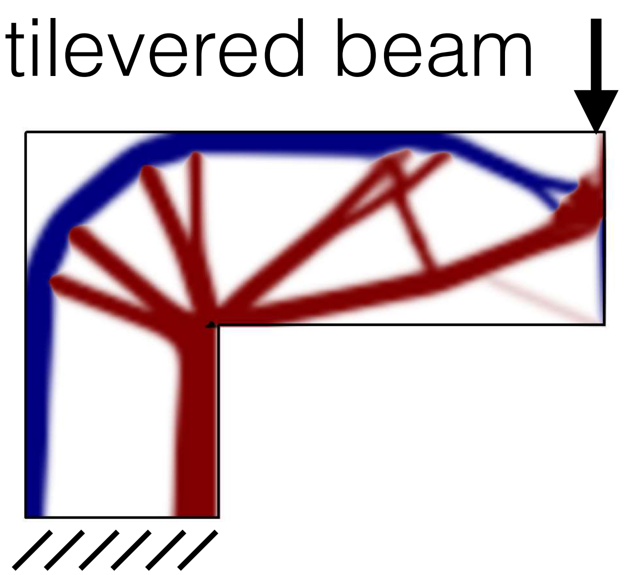
Loading scenario 1: four point bending



Loading scenario 2: three point bending



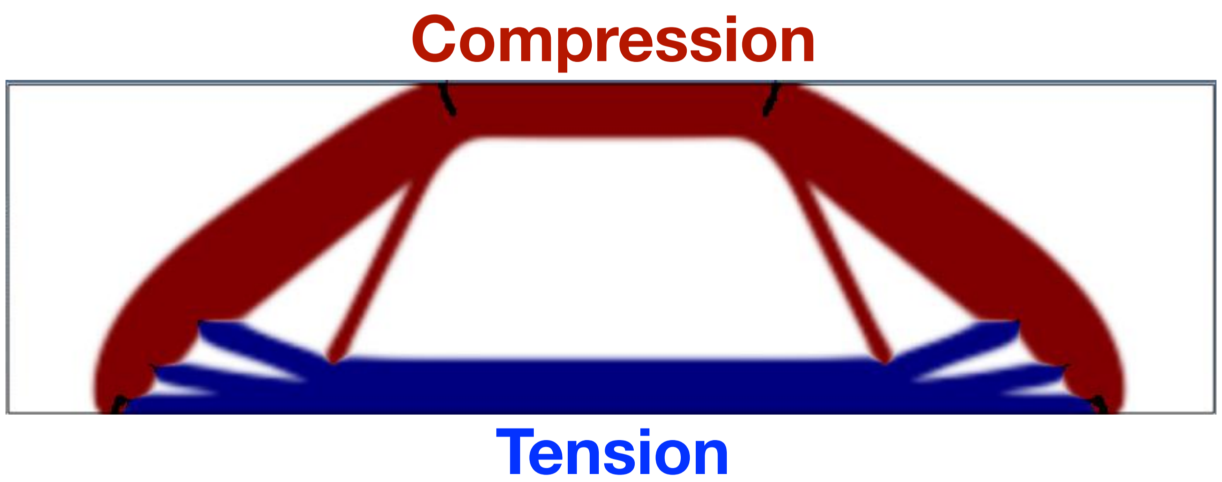
Loading scenario 3: cantilevered beam



Compression

Tension

We use the TopOpt package to perform topology optimizations on a given loading scenario. Simulations assume linear material properties

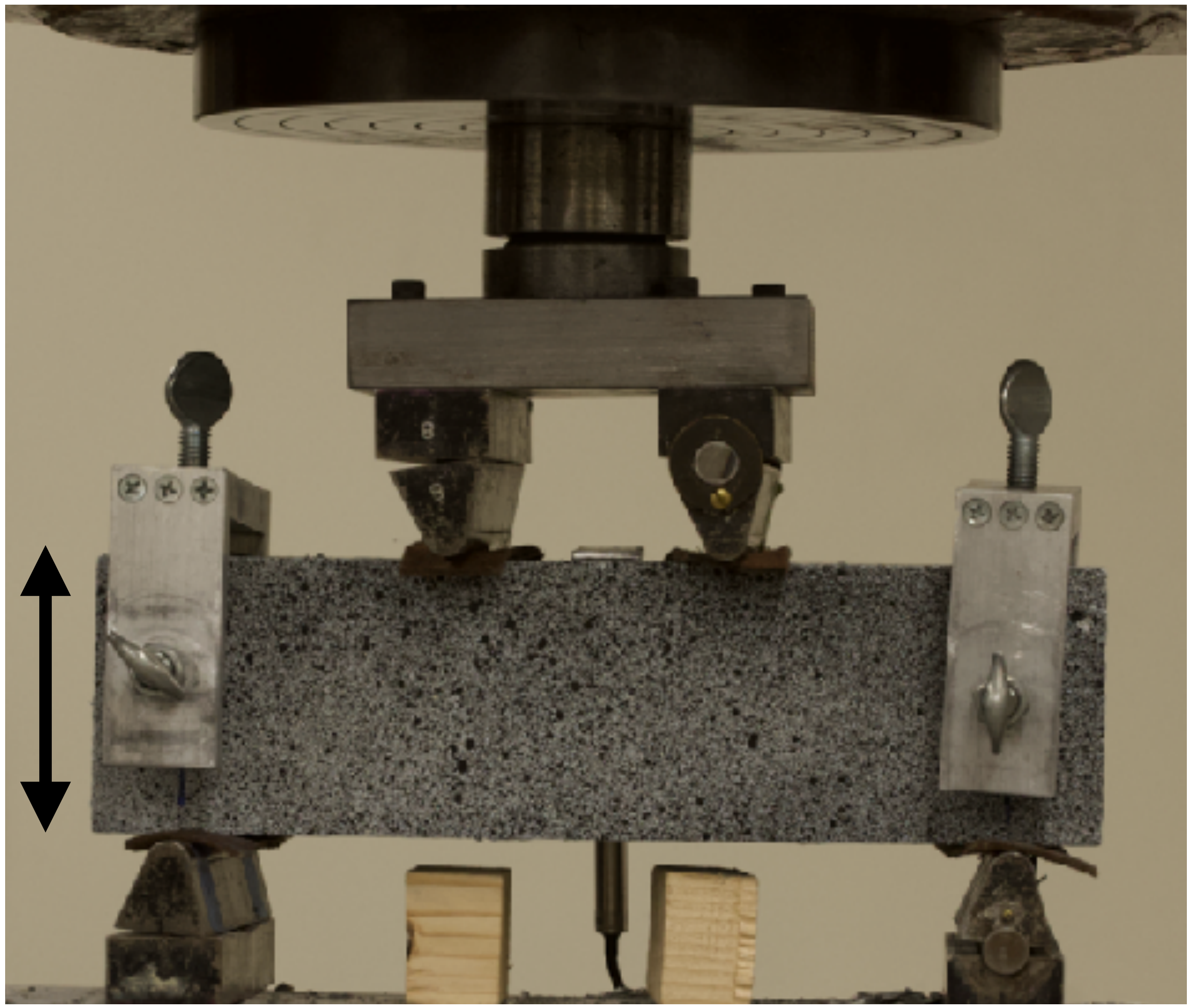


Topology optimization results

Geometry to fabricate

[3] https://www.topopt.mek.dtu.dk

The specific loading scenario discussed here is four-point bending



76.2 mm

279.4 mm

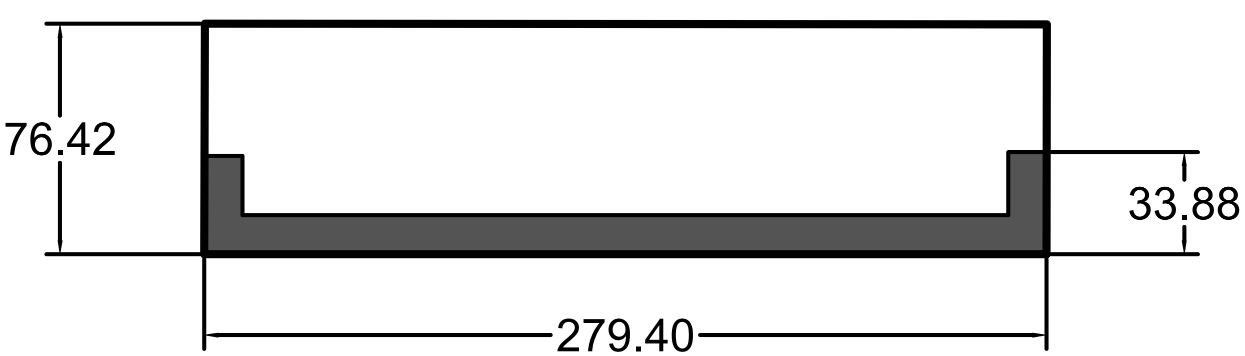
Loading span: 76.2 mm
Support span: 228.6 mm

Beams are tested up to a deflection of the support span length divided by 150 (i.e. 1.5 mm) and do not fracture

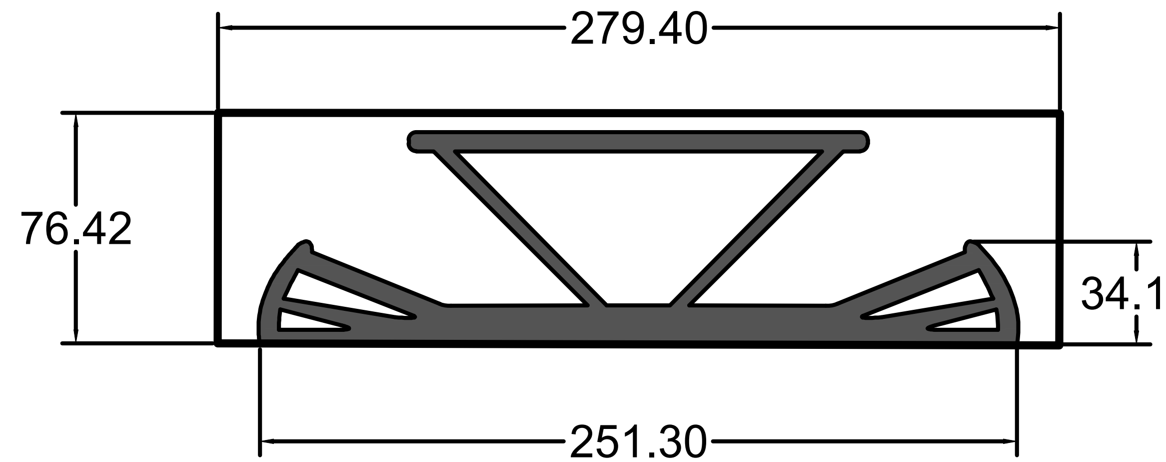
[4] ASTM International. (2012). ASTM C1609/C1609M-12 standard test method for flexural performance of fiber-reinforced concrete (using beam with third-point loading).

We experimentally test four designs

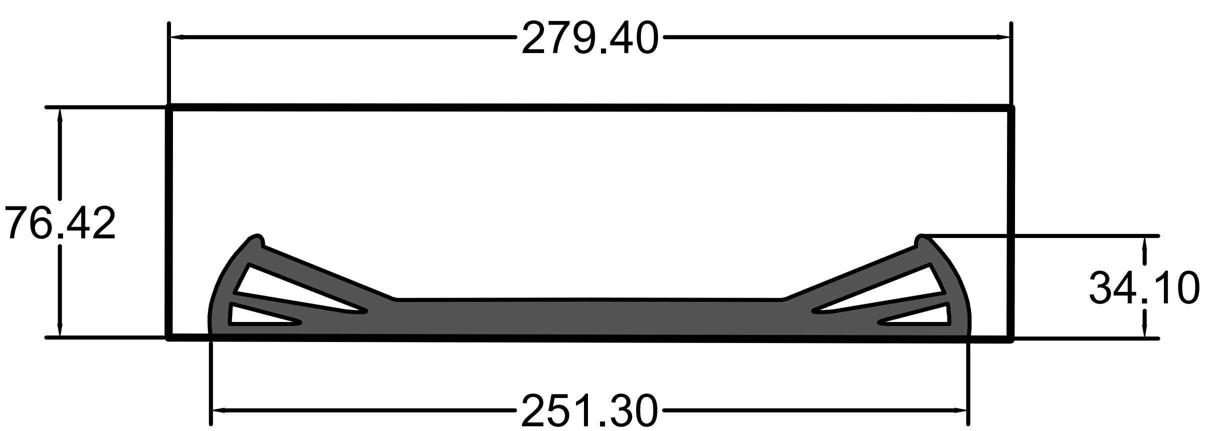
Control geometry



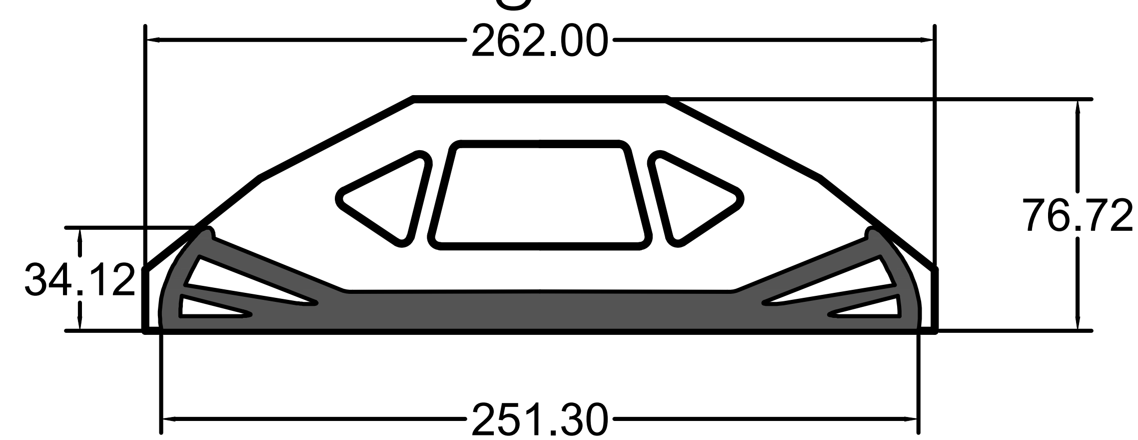
Optimized steel geometry with additional steel



Optimized steel geometry



Optimized steel and optimized concrete geometries



All units are given in mm

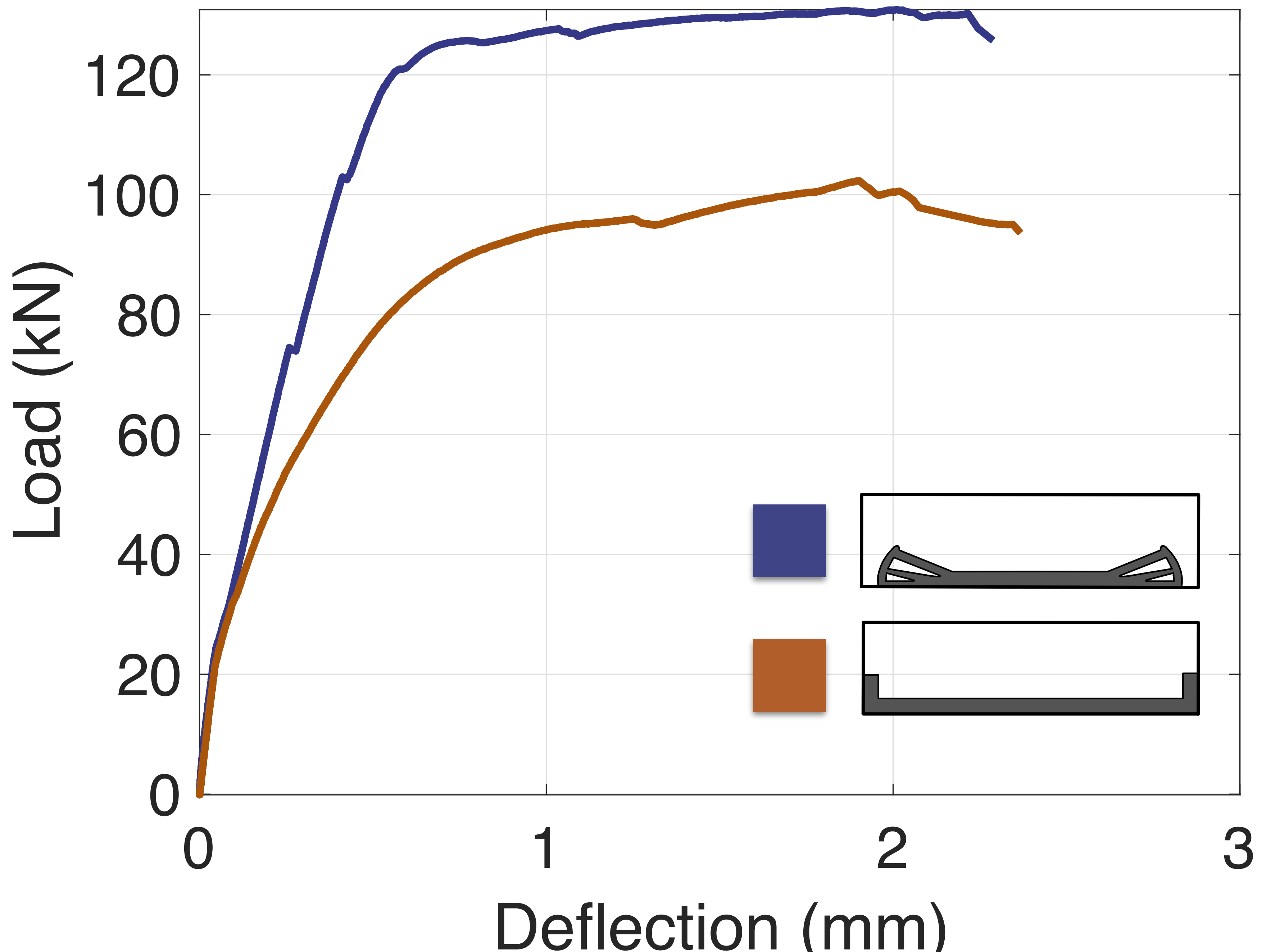
Steel reinforcement geometries were prototyped using abrasive waterjet cutting

Procedure: lattices are placed into molds, and concrete is poured as vibration is applied

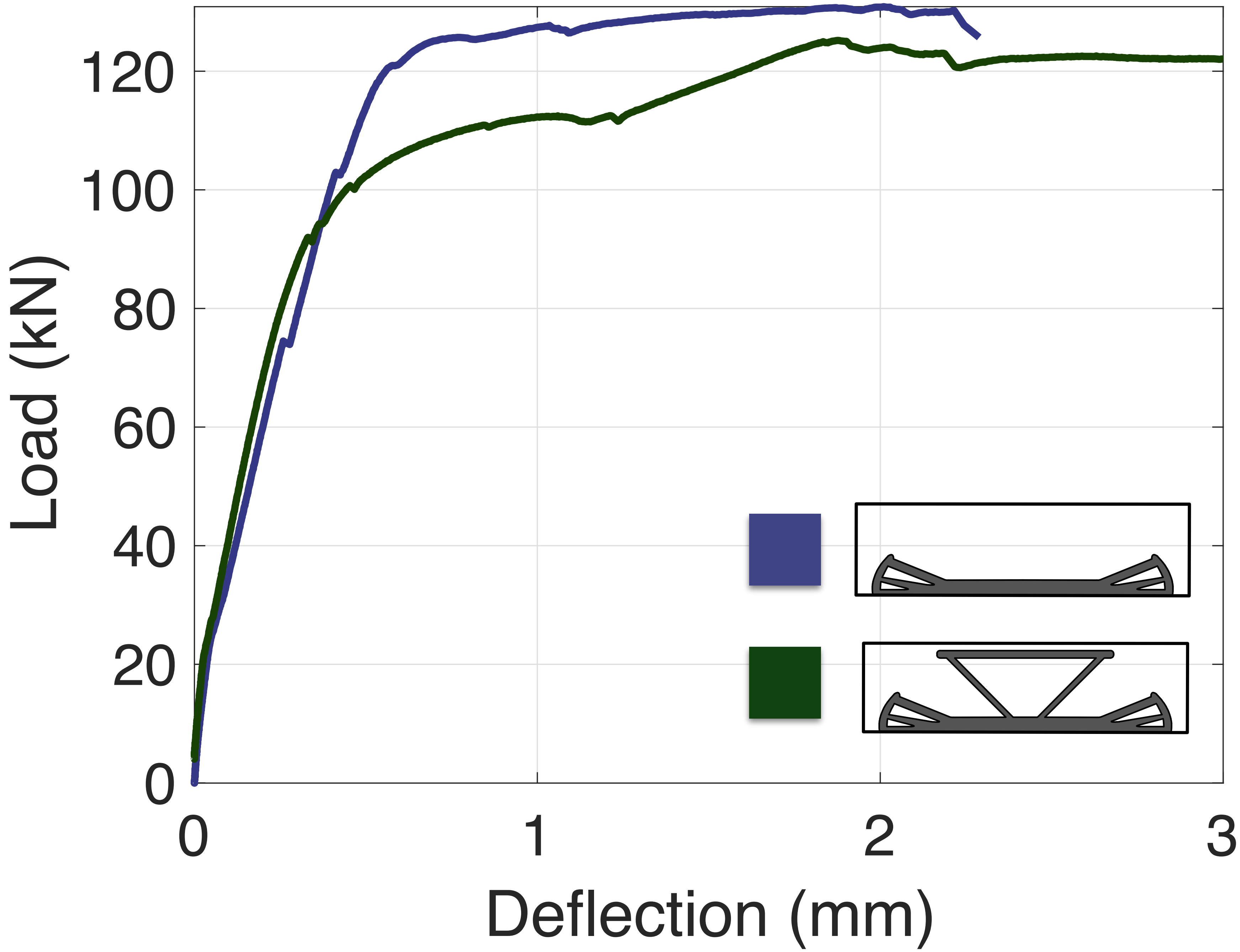
Concrete mixture is a green, ultra-high-performance, steel fiber-reinforced concrete, which replaces 50% of cement with slag and fly ash

[5] P. Aghdasi, C.P. Ostertag, Green ultra-high performance fiber-reinforced concrete (G-UHP-FRC), Constr. Build. Mater., 190 (2018), pp. 246-254.

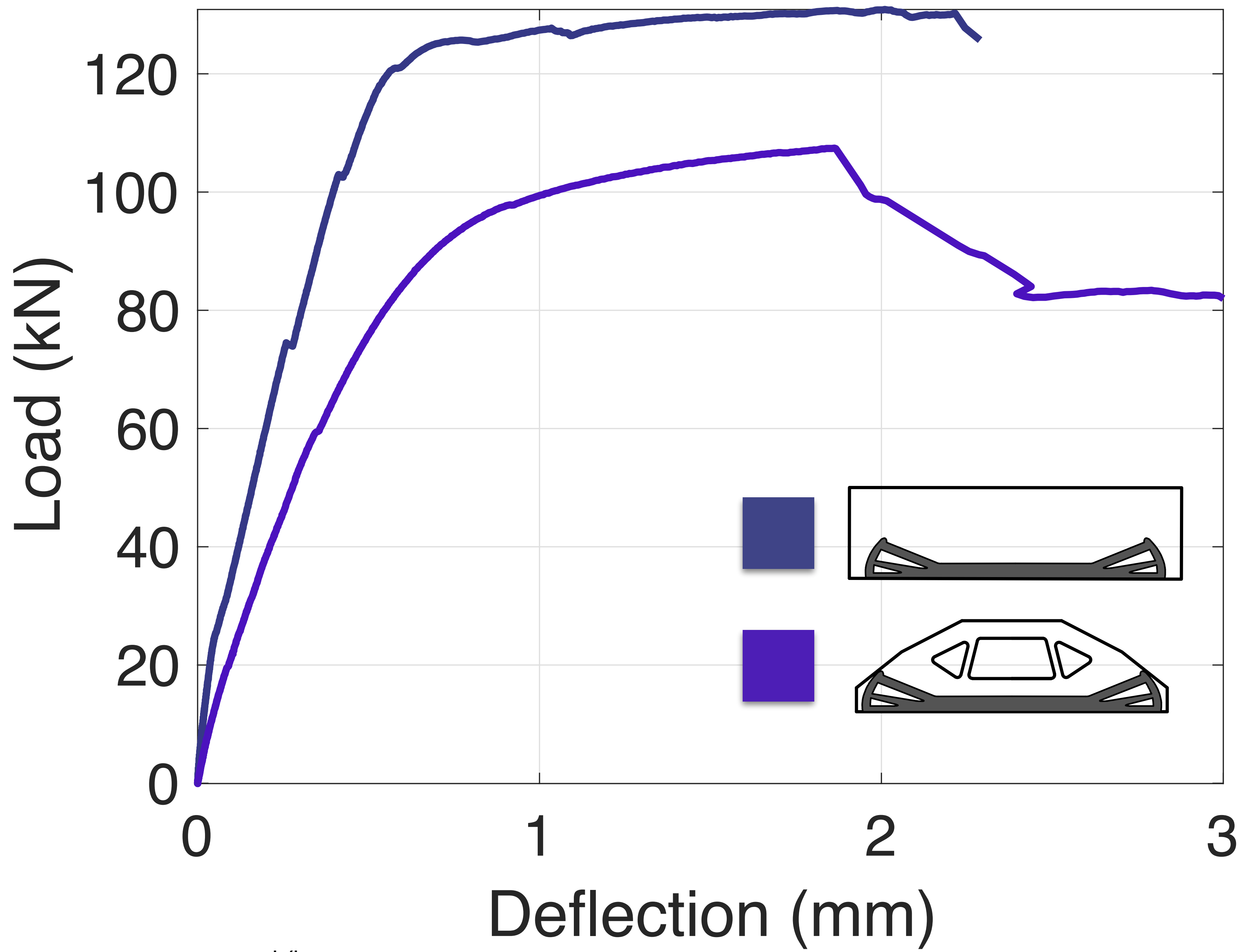
The beam where the steel geometry is optimized achieved a higher peak load (28% greater) and a higher toughness (38% greater) than the peak load achieved by the control beam



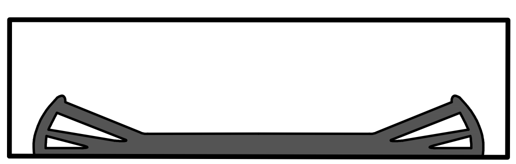
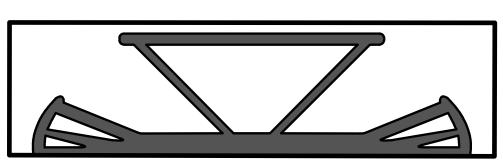
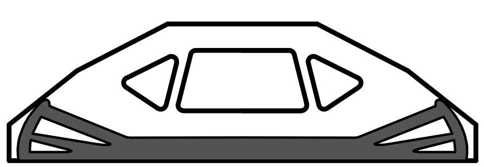
Slightly modifying the steel design, by incorporating more steel than the topology optimization's output, surprisingly resulted in an 8% reduction in toughness



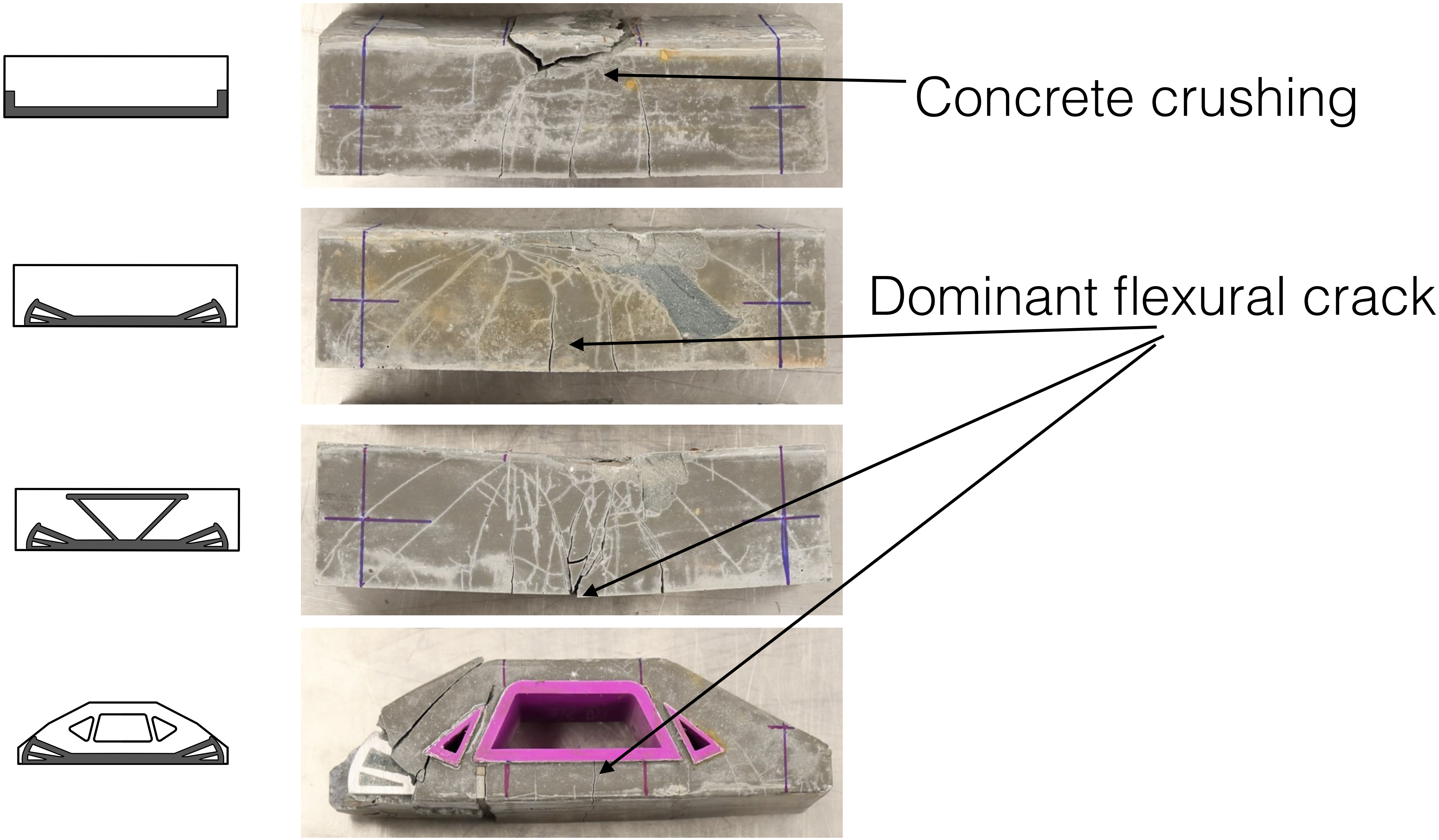
The beam where the concrete geometry is optimized experienced a peak load reduction of 18% and a toughness reduction of 26%, which may be sufficient for many applications



Results show that the beam where the steel geometry was optimized (using TopOpt) resulted in the highest performing beam. Additionally, using TopOpt to optimize the concrete placement resulted in significant weight savings (35% reduction in weight)

Beam design	Toughness (kN*mm)	Peak load (kN)	Mass (kg)
	119	102	4.4
	164	131	4.4
	150	125	4.5
	122	107	2.8

Beam fracture surfaces show multiple crack formations



Conclusions and contributions

- The steel reinforcement geometry has a large effect on overall structure performance
- Topology optimization can be used to inform the design of concrete structures, and can result in significant weight and material savings
- This work presented a new method for creating reinforcement geometries that are customized to the specific loading scenario

Acknowledgement

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Questions?