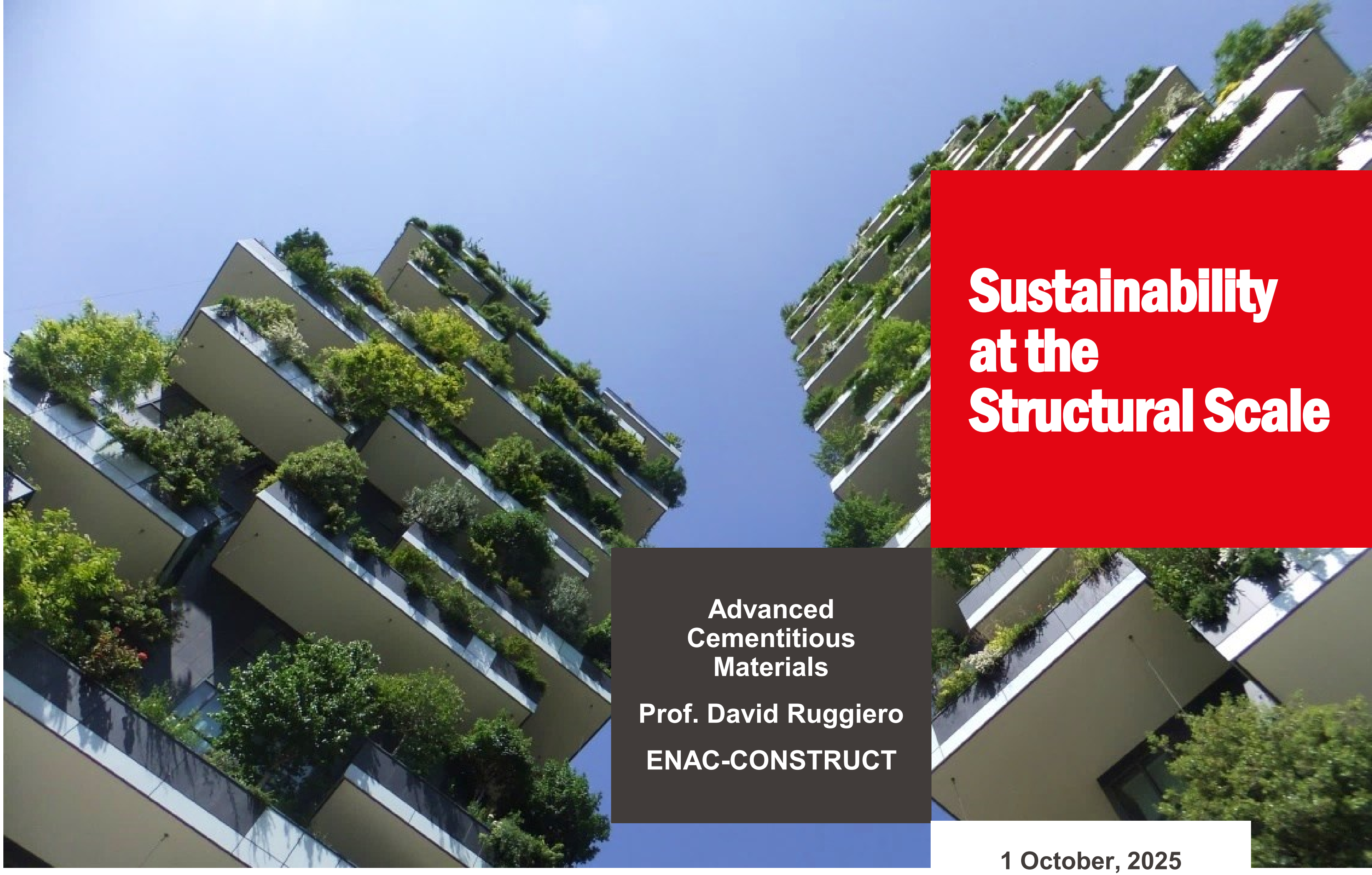


Sustainability at the Structural Scale

Advanced Cementitious Materials

Prof. David Ruggiero

ENAC-CONSTRUCT

1 October, 2025

École
polytechnique
fédérale
de Lausanne

Introduction

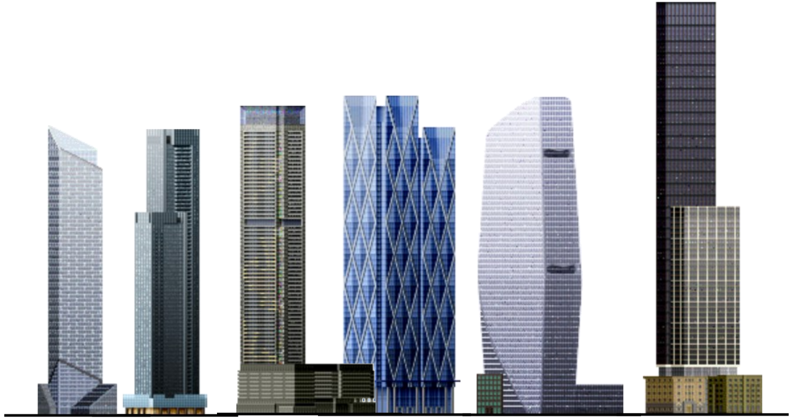
Case studies

Problems

Solutions

About me

- Ph.D. from University of Toronto: “The Behaviour of Reinforced Concrete Subjected to Reversed Cyclic Shear”
- Postdoctoral studies in seismic engineering at the Institute for Advanced Studies of Pavia, Italy
- 5 years as structural engineer at Read Jones Christoffersen (RJC) Toronto
- Associate Member of Canadian Standards Association CSA A23.3 Technical Committee on Design of Concrete Structures
- Chair of Joint Committee on the GLOBE Consensus



SkyscraperPage contributor Koops65

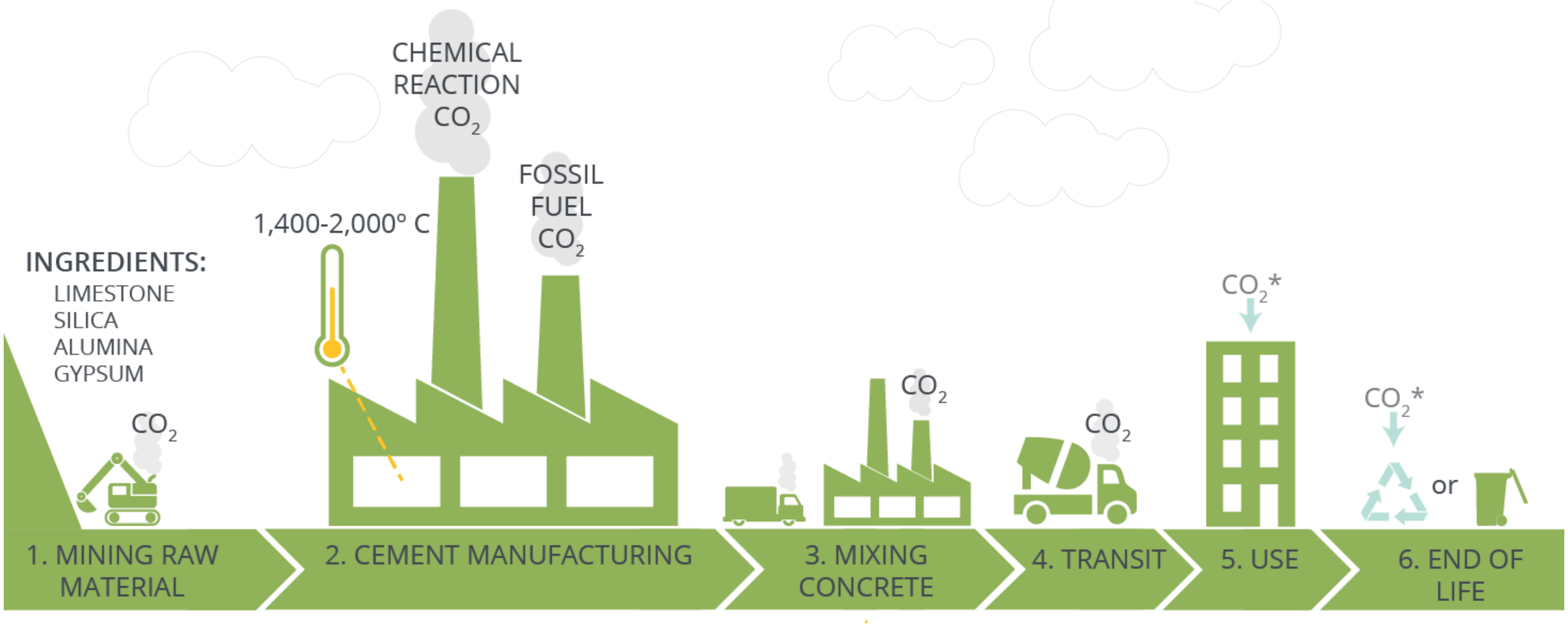
Concrete Behaviour and Structural Design Laboratory – ENAC-CONSTRUCT

Lower-carbon alternatives

Design for reuse and longevity

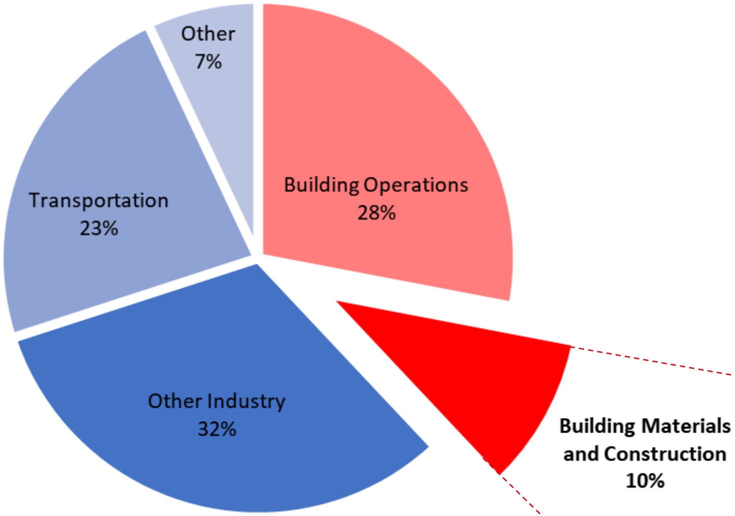
Better mechanical modelling and optimization

Carbon impacts of concrete



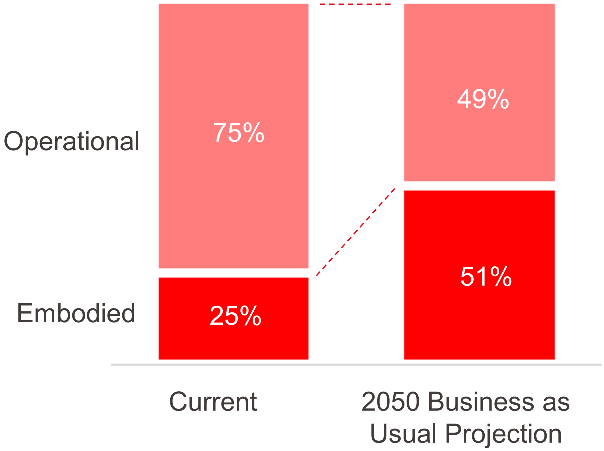
Architecture 2030

Embodied carbon

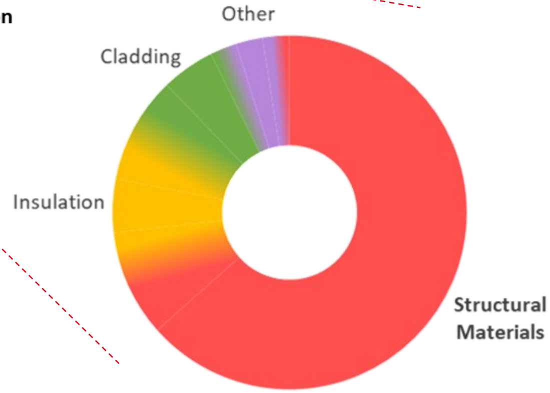


Estimated Global CO_2 Emissions by Sector

UN 2020 Global Status Report for Buildings and Construction



Architecture 2030

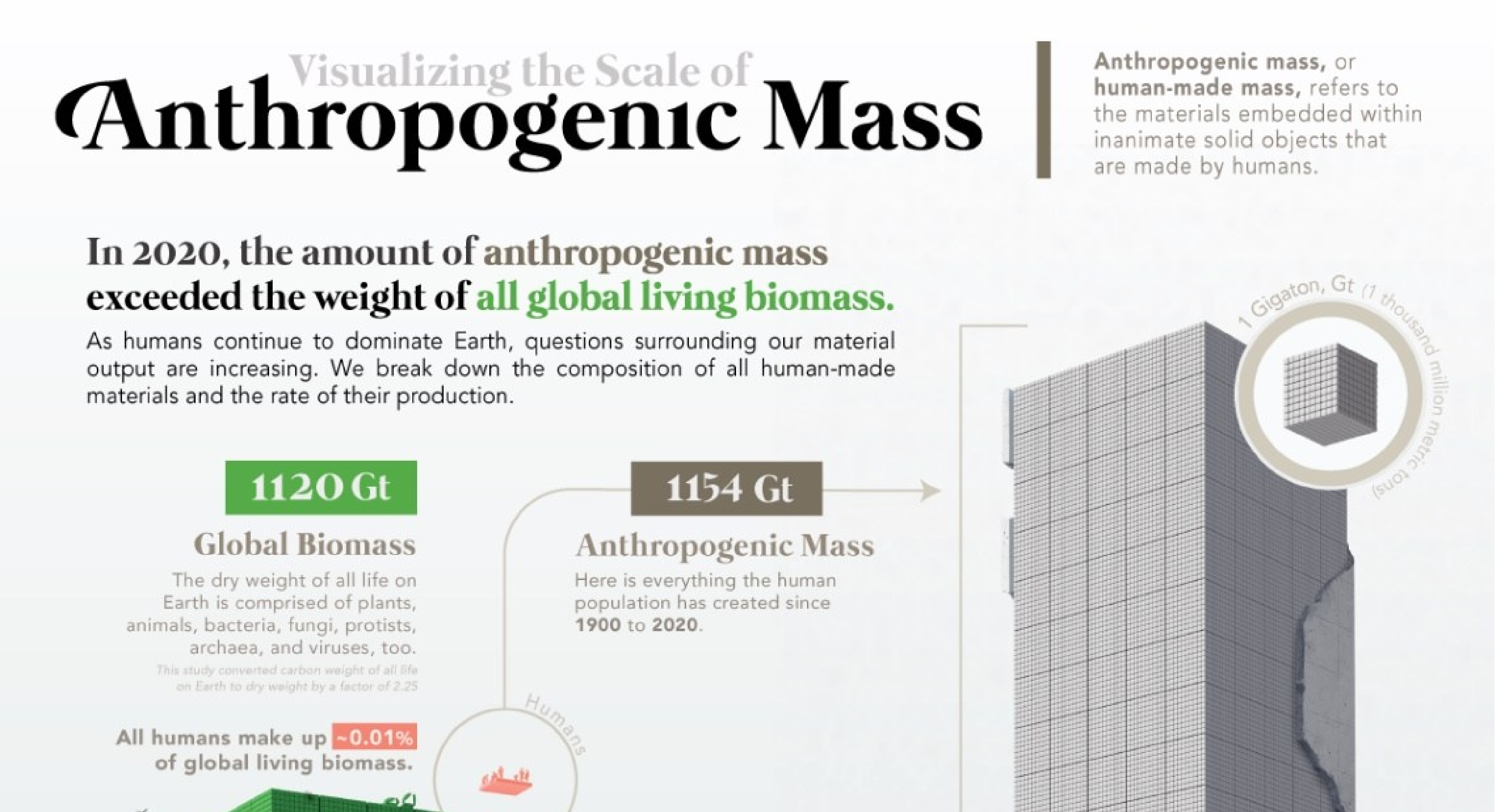


Sample breakdown for midrise residential building

Carbon impact

$$\frac{\text{Carbon intensity of material} \times \text{Amount of material used}}{\text{Lifespan of structure}}$$

Why concrete?



Visualizing the Scale of

Anthropogenic Mass

Anthropogenic mass, or **human-made mass,** refers to the materials embedded within inanimate solid objects that are made by humans.

In 2020, the amount of anthropogenic mass exceeded the weight of all global living biomass.

As humans continue to dominate Earth, questions surrounding our material output are increasing. We break down the composition of all human-made materials and the rate of their production.

1120 Gt

Global Biomass

The dry weight of all life on Earth is comprised of plants, animals, bacteria, fungi, protists, archaea, and viruses, too.

This study converted carbon weight of all life on Earth to dry weight by a factor of 2.25

All humans make up ~0.01% of global living biomass.

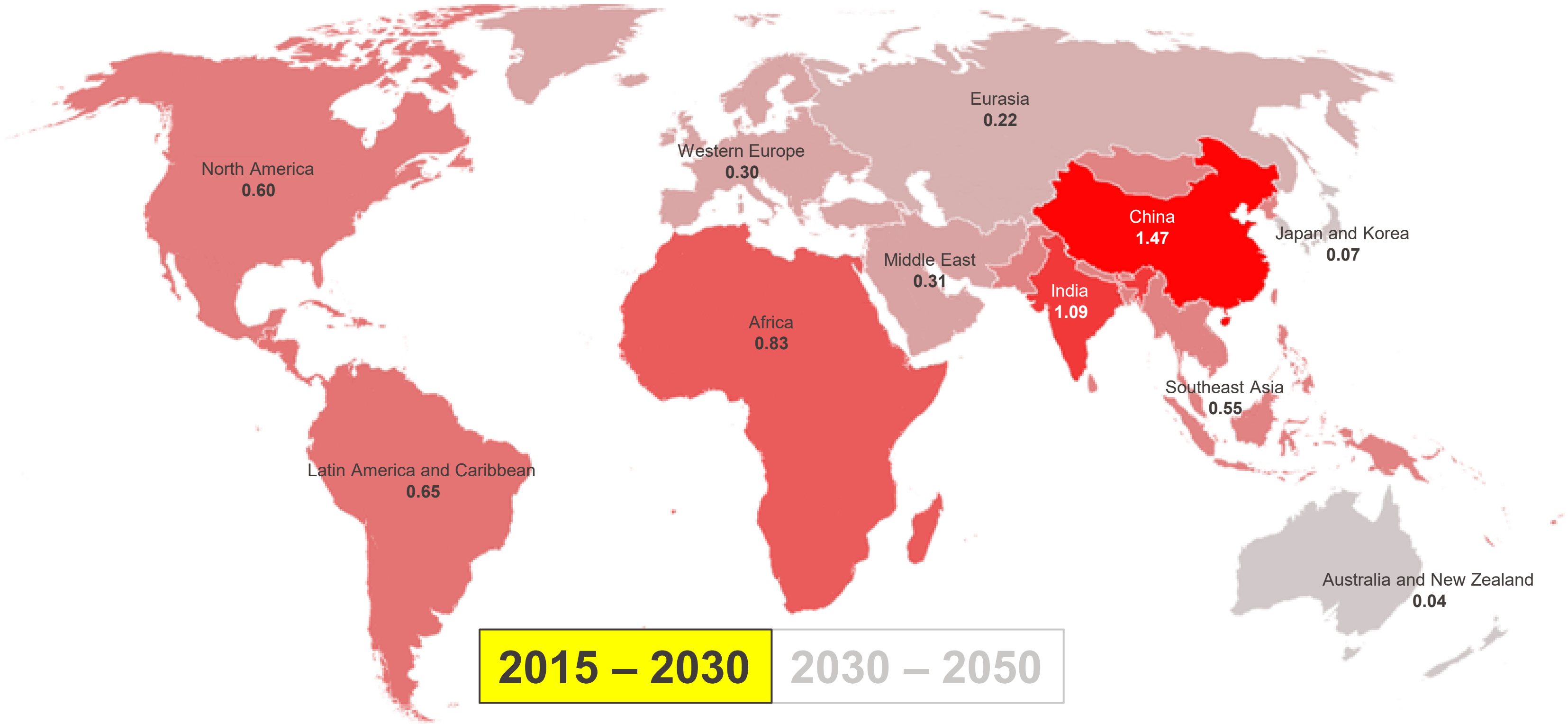
1154 Gt

Anthropogenic Mass

Here is everything the human population has created since **1900** to **2020**.

Visual Capitalist

Global demand for net increase in floor area

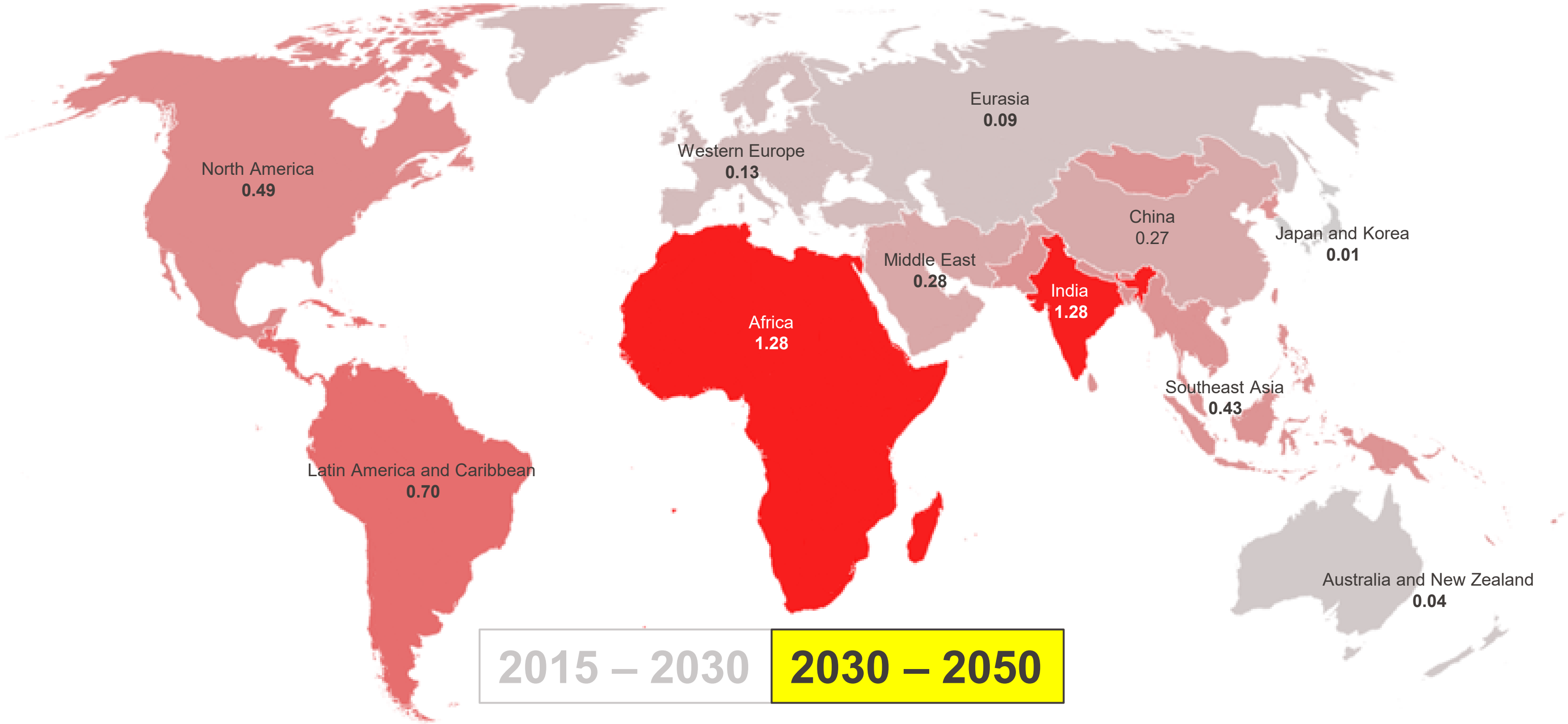


2015 – 2030 2030 – 2050

Average projected demand in billion m² per annum

UNEP, 2016, United Nations Environment Programme, *Towards zero-emission efficient and resilient buildings, Global Status Report 2016*

Global demand for net increase in floor area



2015 – 2030 | **2030 – 2050**

Average projected demand in billion m² per annum

UNEP, 2016, United Nations Environment Programme, *Towards zero-emission efficient and resilient buildings, Global Status Report 2016*

> By one estimate, the world will add 2 trillion square feet of buildings by 2060—the equivalent of putting up another New York City every month for the next 40 years.

Bill Gates

Gates Notes, “Buildings are bad for the climate”, 2019
Photo: The Guardian

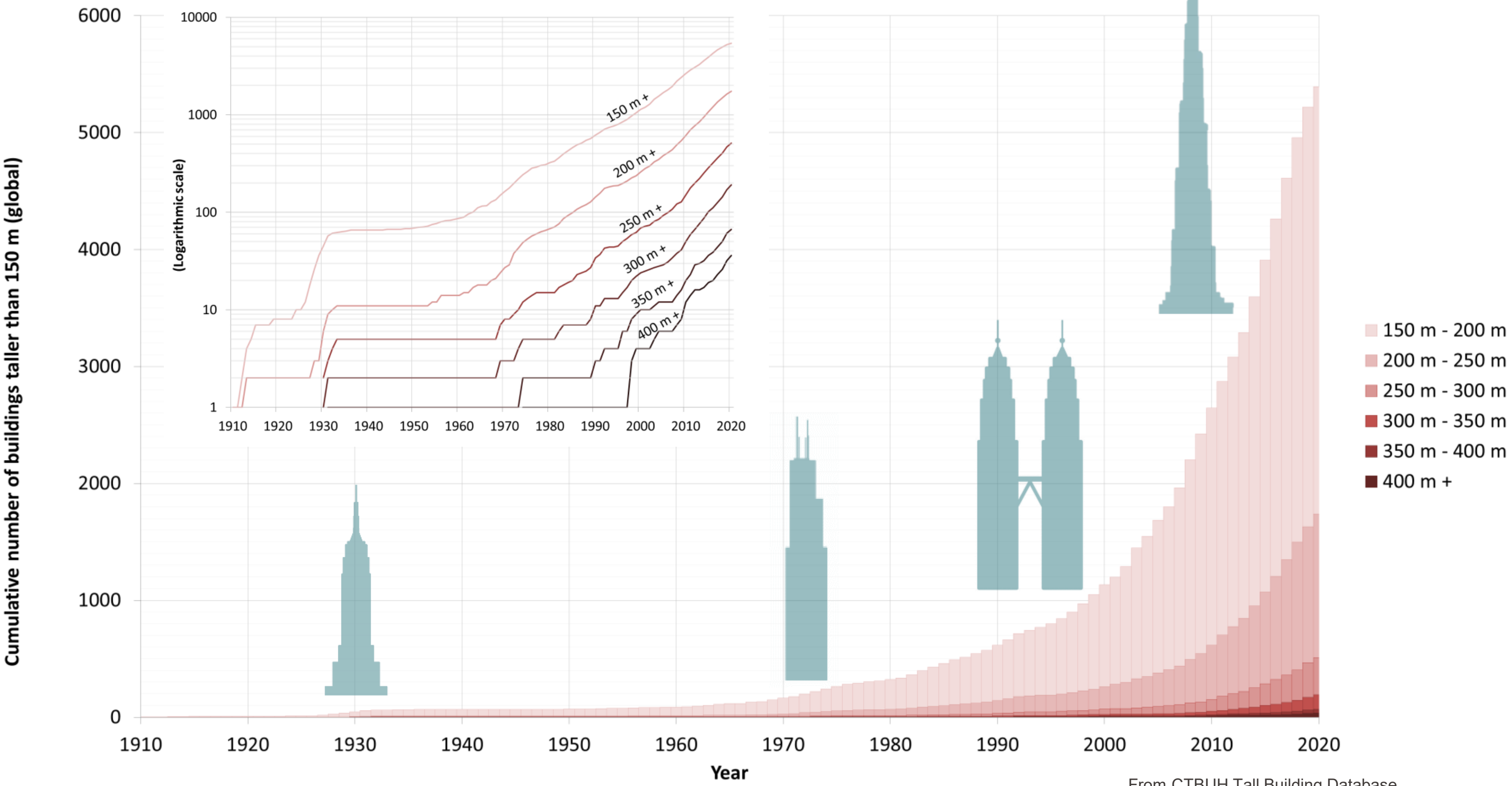
Toronto, Canada – 1972

City of Toronto Archives, Fonds 1526, File 46, Item 20

Toronto, Canada – 2022

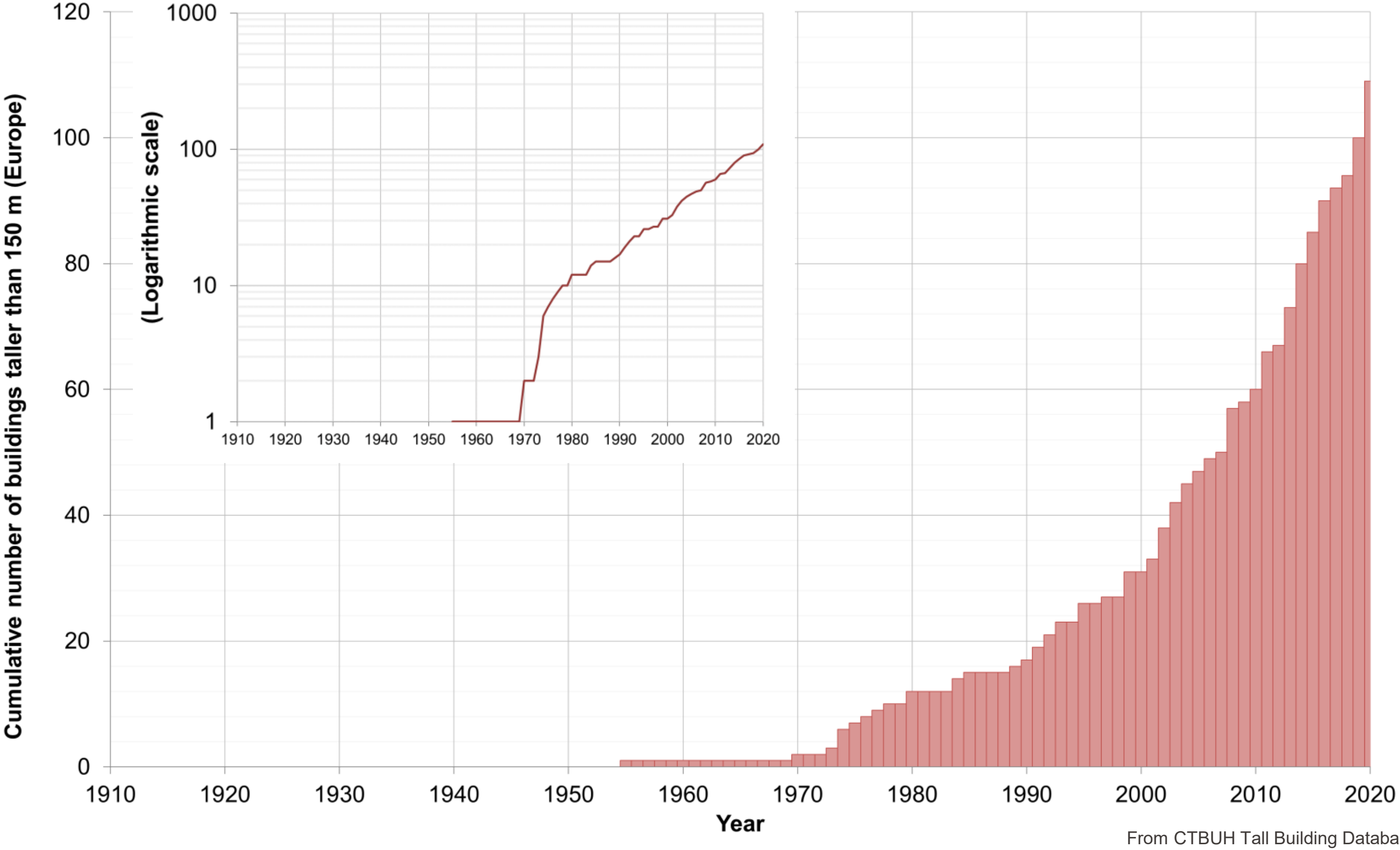
Toronto, Canada – 2030?

Skyscraper proliferation



From CTBUH Tall Building Database

Skyscrapers in Europe



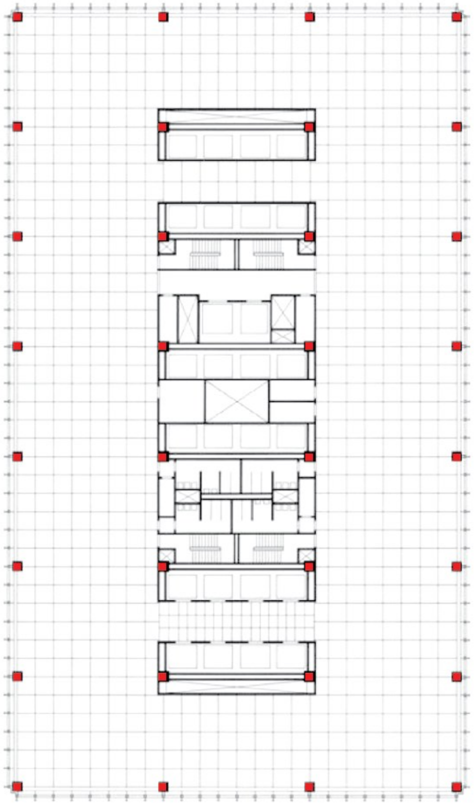
From CTBUH Tall Building Database

Then …

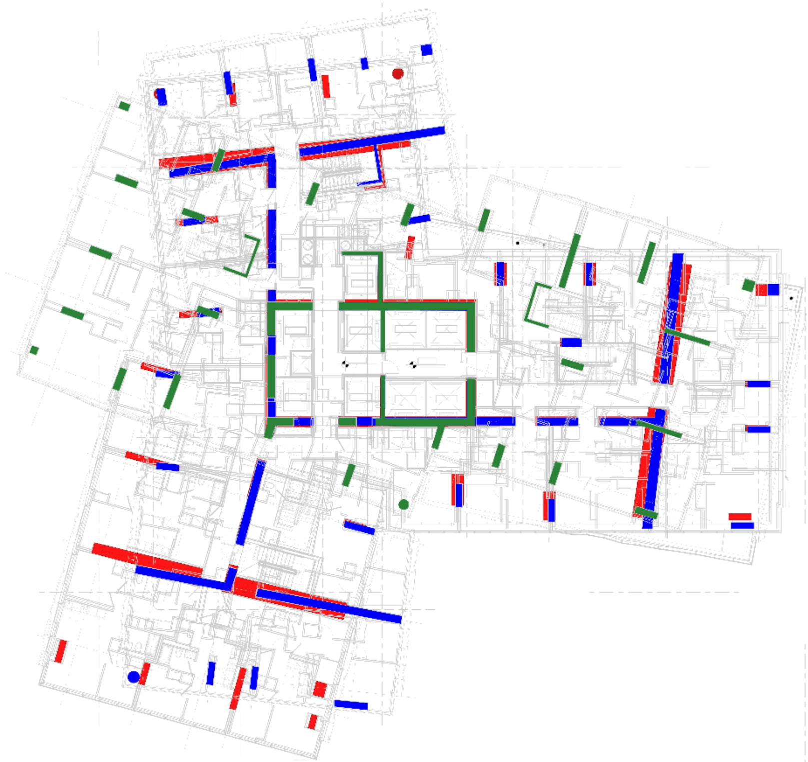
… and now

Sora/Gehry Partners

Then …



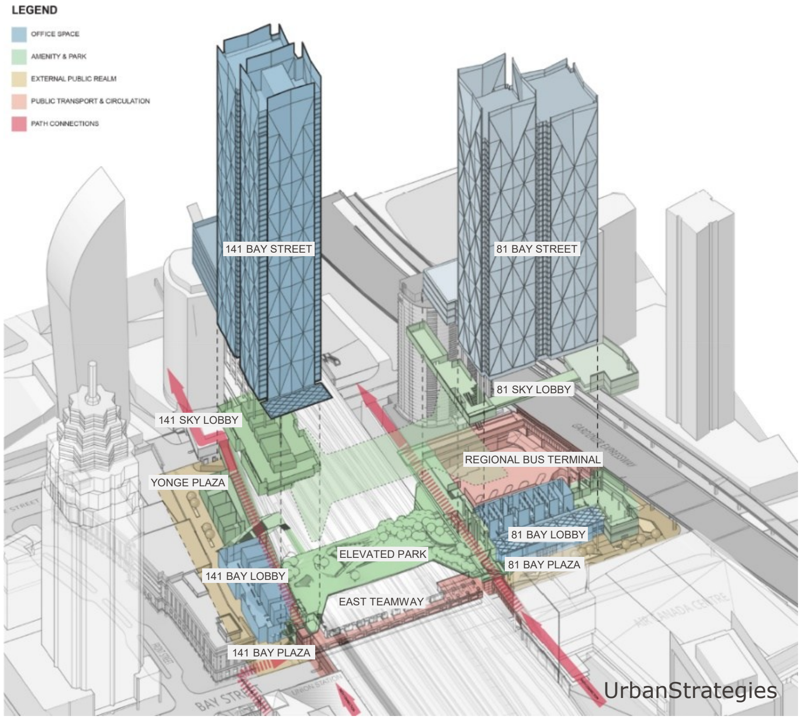
… and now

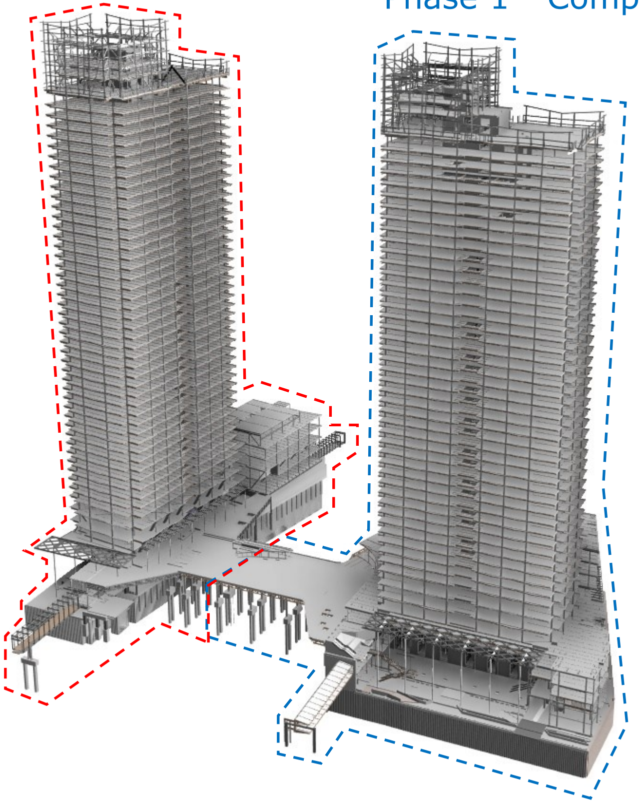


CIBC Square, Toronto

DBOX, WilkinsonEyre

Complex program, constrained site





Phase 2 – Under Construction

Phase 1 - Complete

David Ruggiero

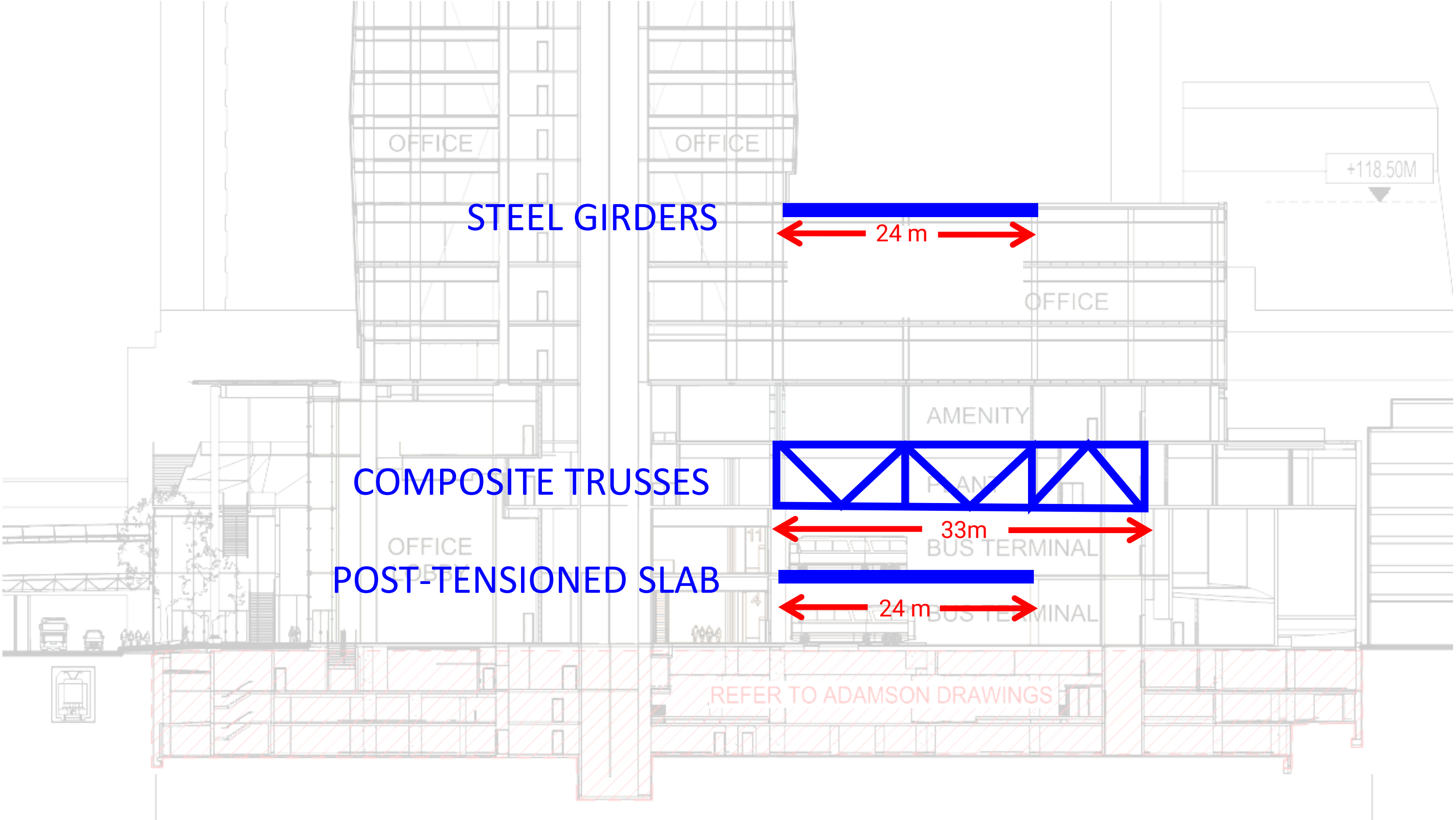
SUSTAINABILITY AT THE STRUCTURAL SCALE

Tower columns

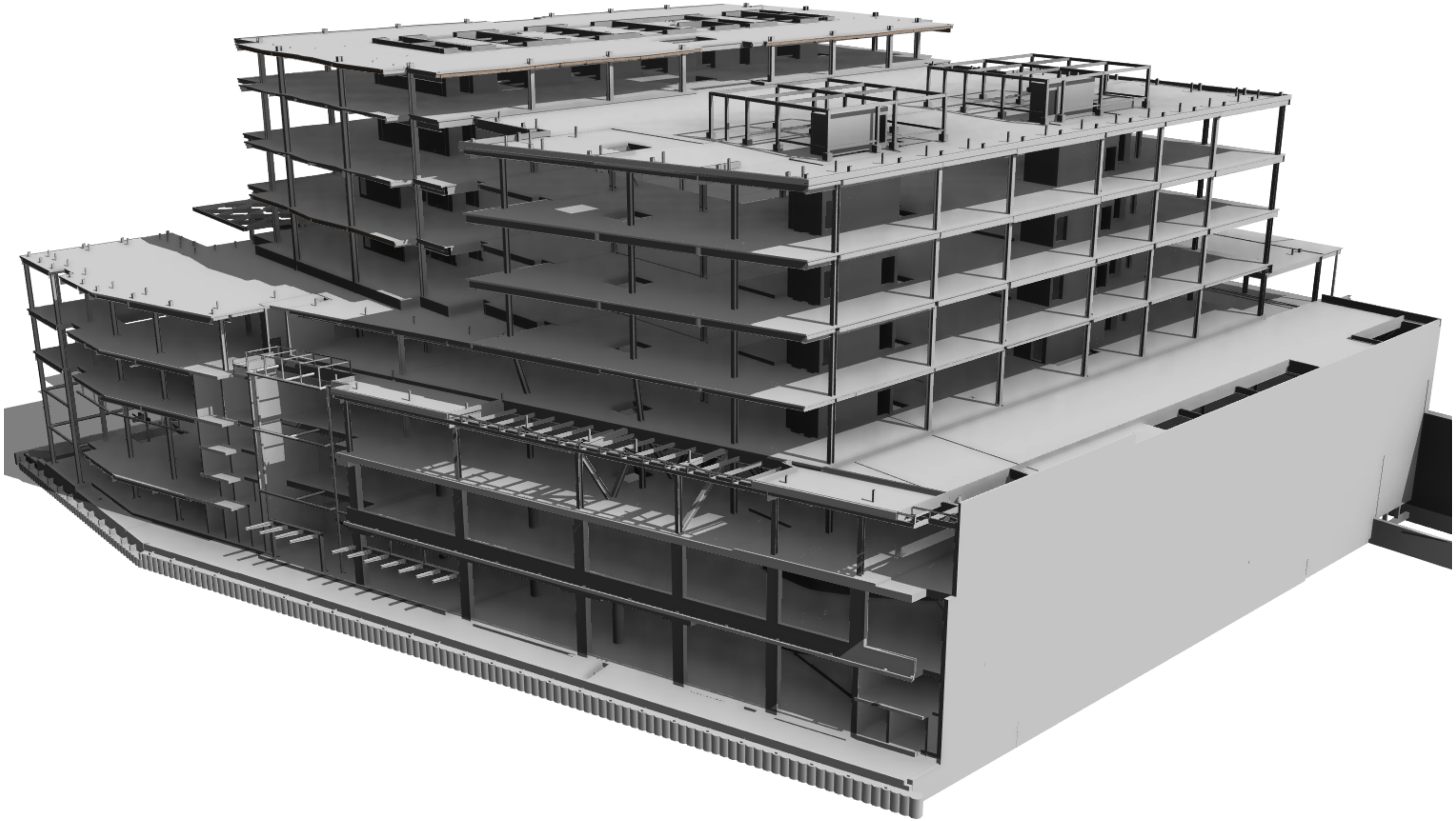
David Ruggiero

Tower columns

Podium


OFFICE
OFFICE
+118.50M
STEEL GIRDERS
24 m
OFFICE
AMENITY
COMPOSITE TRUSSES
PLANT
33m
OFFICE
BUS TERMINAL
POST-TENSIONED SLAB
24 m
BUS TERMINAL
REFER TO ADAMSON DRAWINGS

Podium



Composite trusses

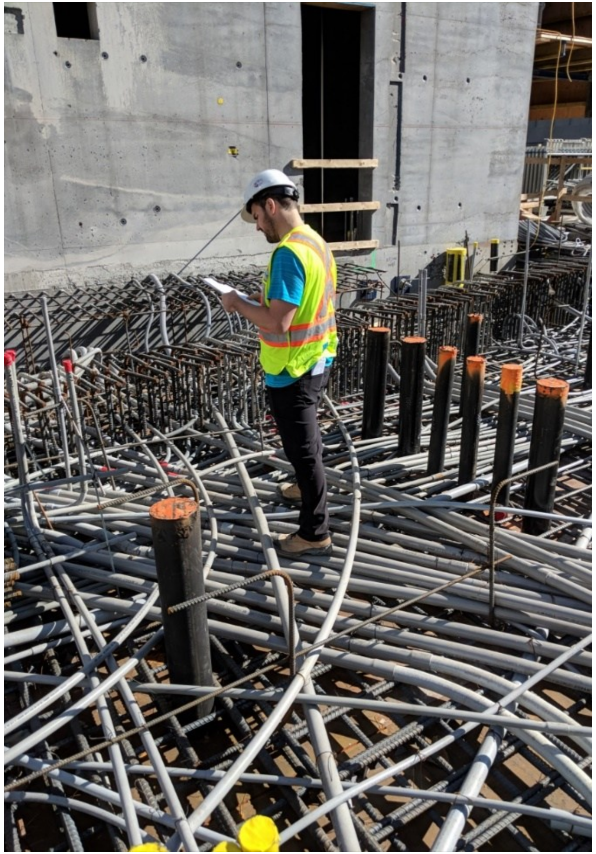
Composite trusses

Composite trusses

Composite trusses

Composite trusses

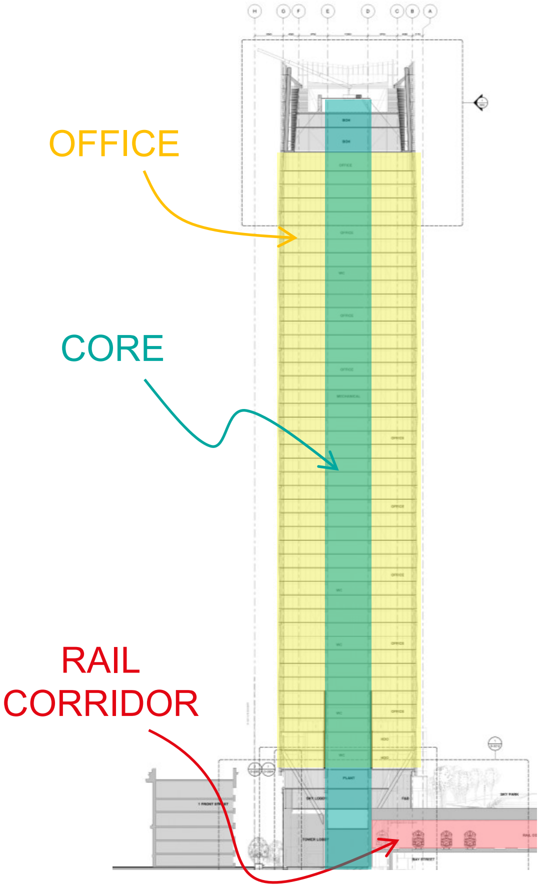
Electrical conduit

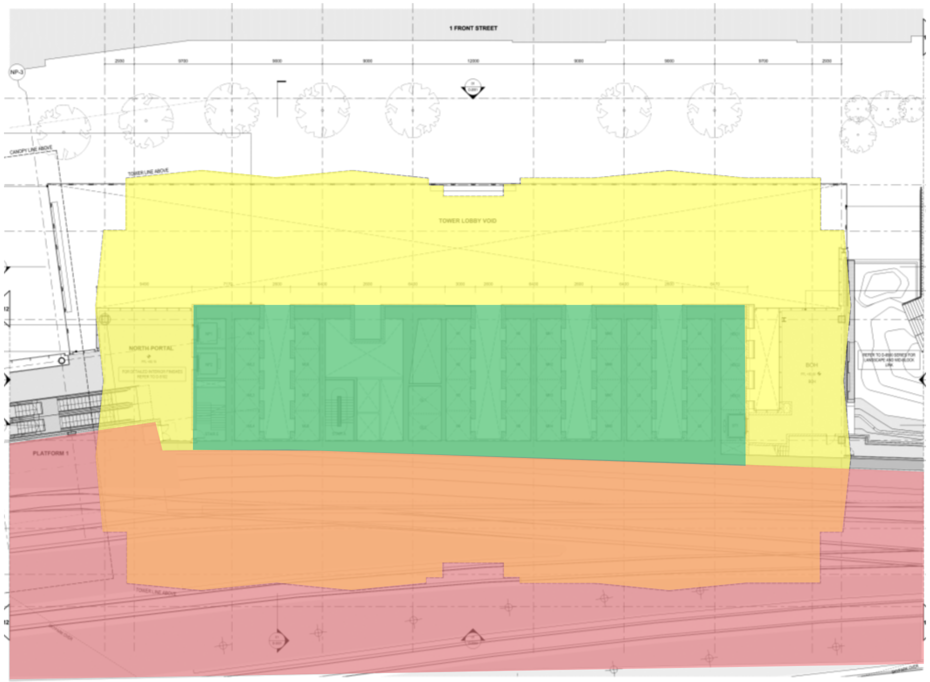


Phase I complete

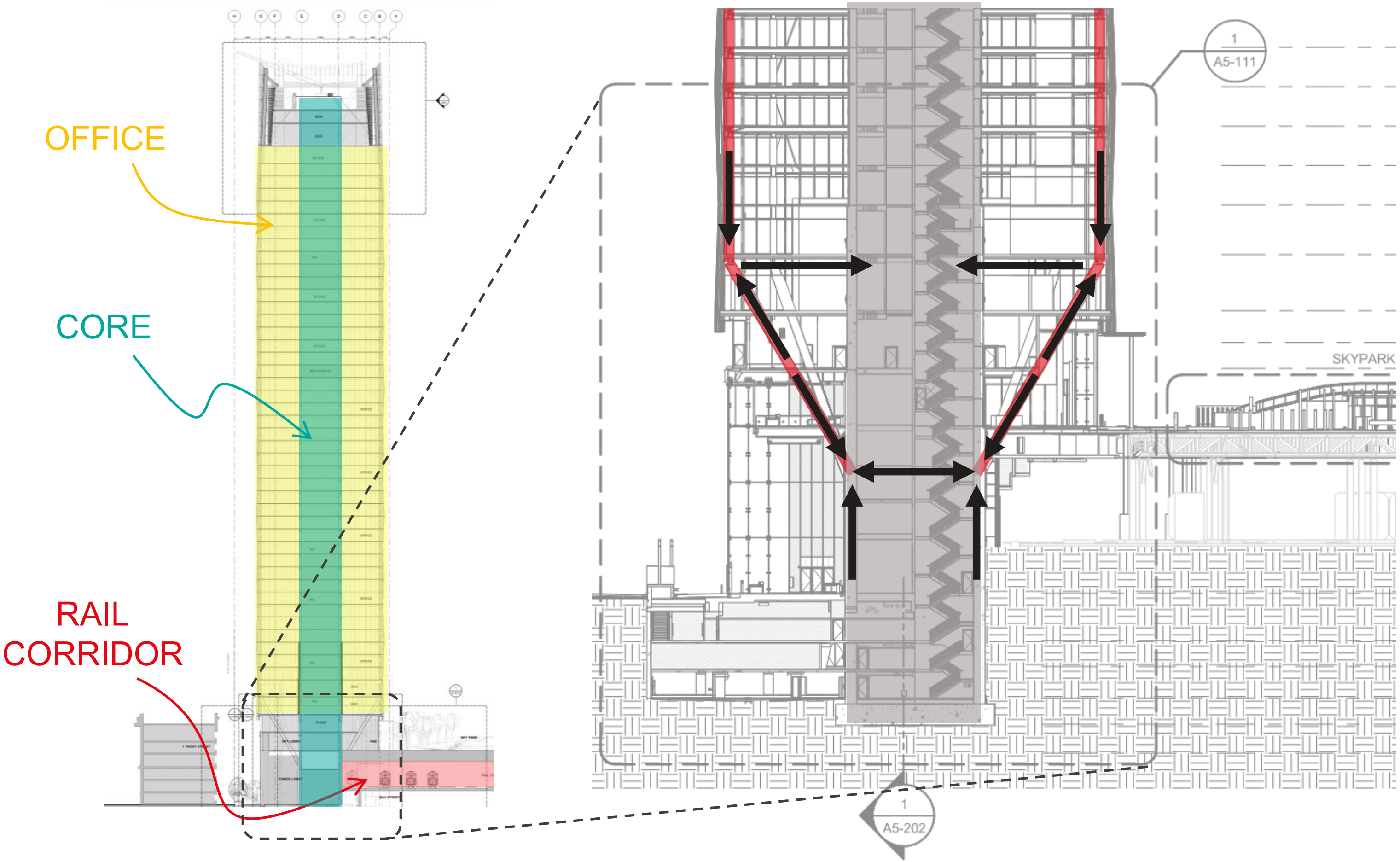
DBOX, WilkinsonEyre, RJC

Phase II


OFFICE
CORE
RAIL
CORRIDOR


1 FRONT STREET
TOWER LOBBY VOID
NORTH PORTAL
PLATFORM 1

Phase II

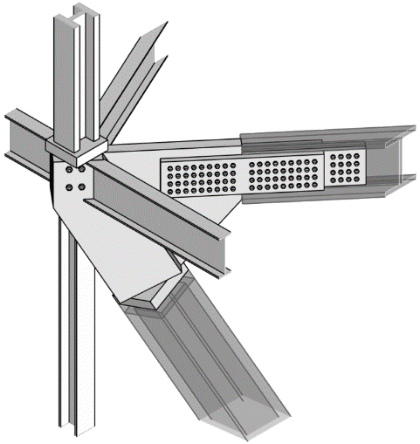


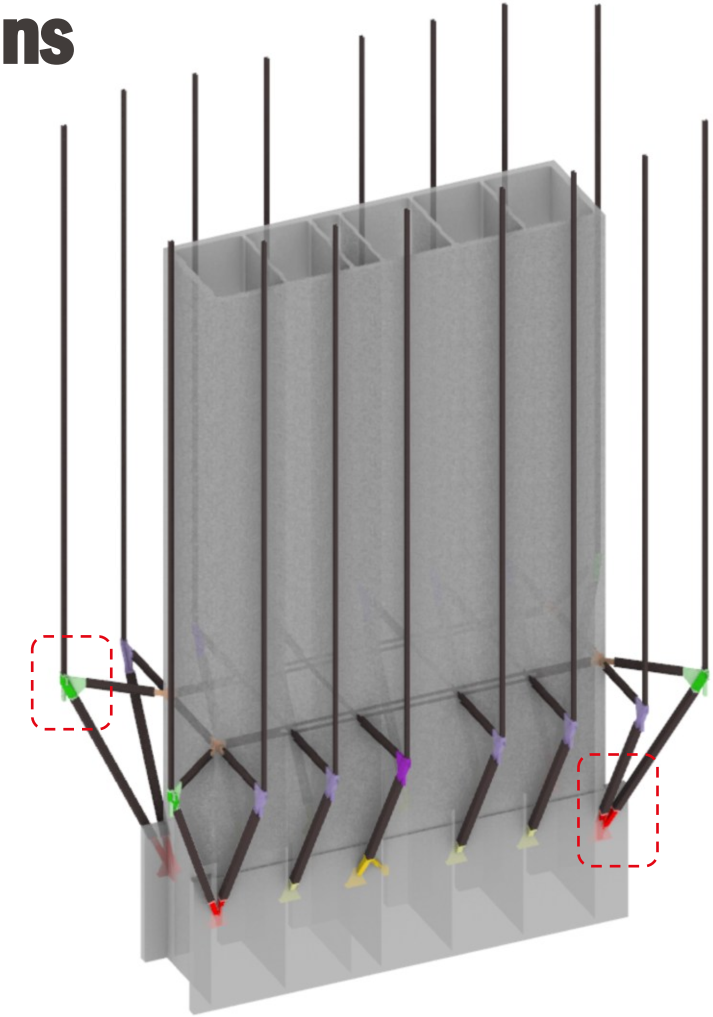
OFFICE

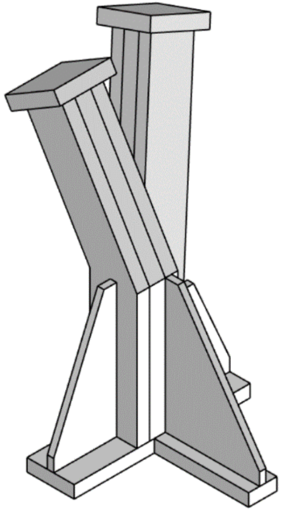
CORE

RAIL CORRIDOR

Sloping columns







Cast steel nodes

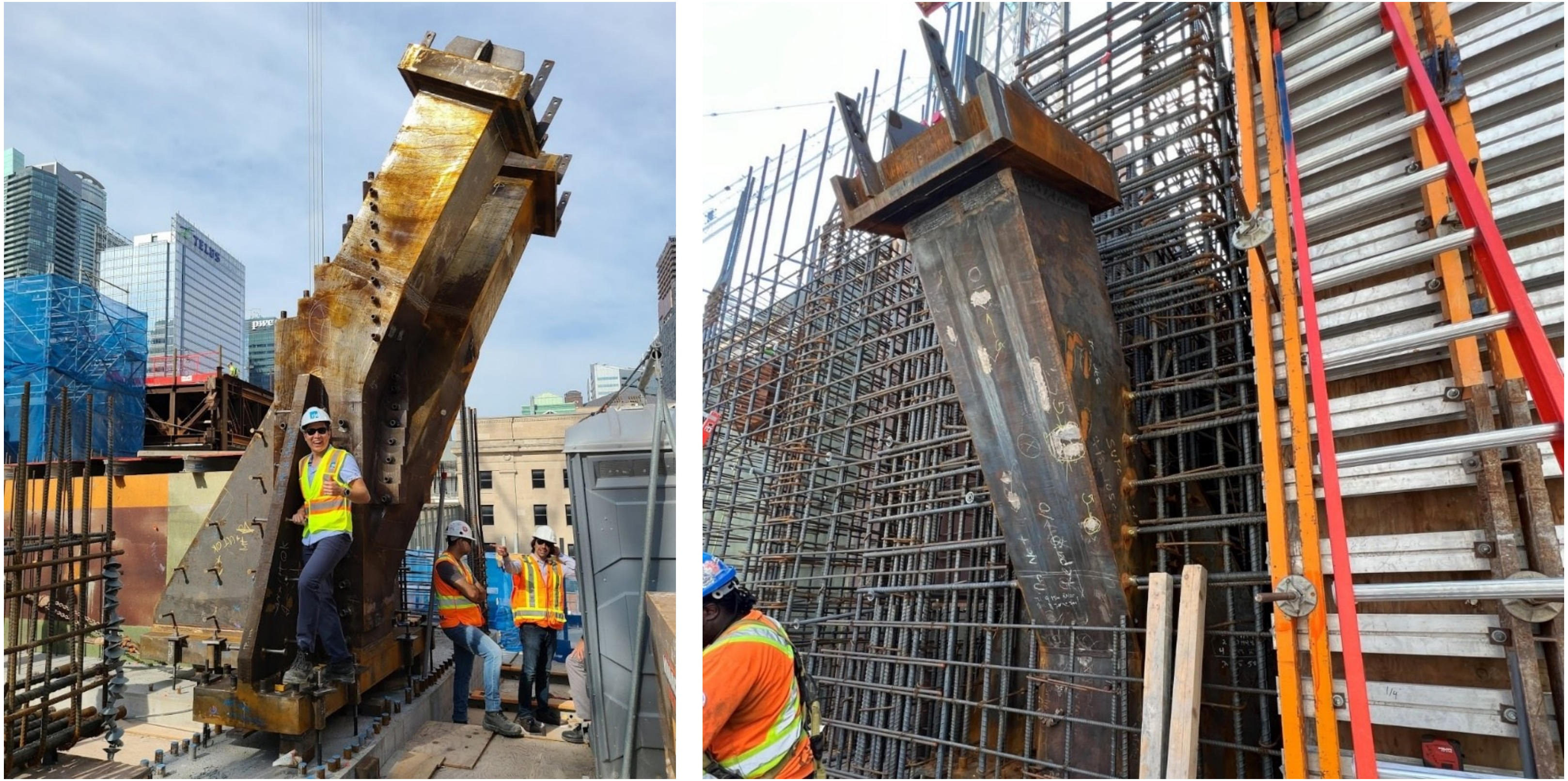
CastConnex

Cast steel nodes

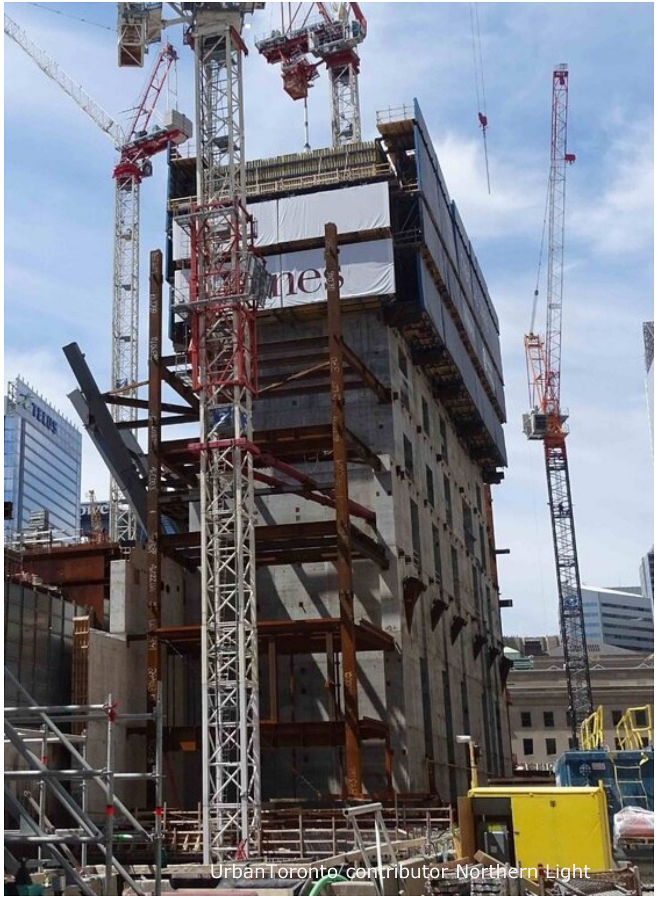
Cast steel nodes

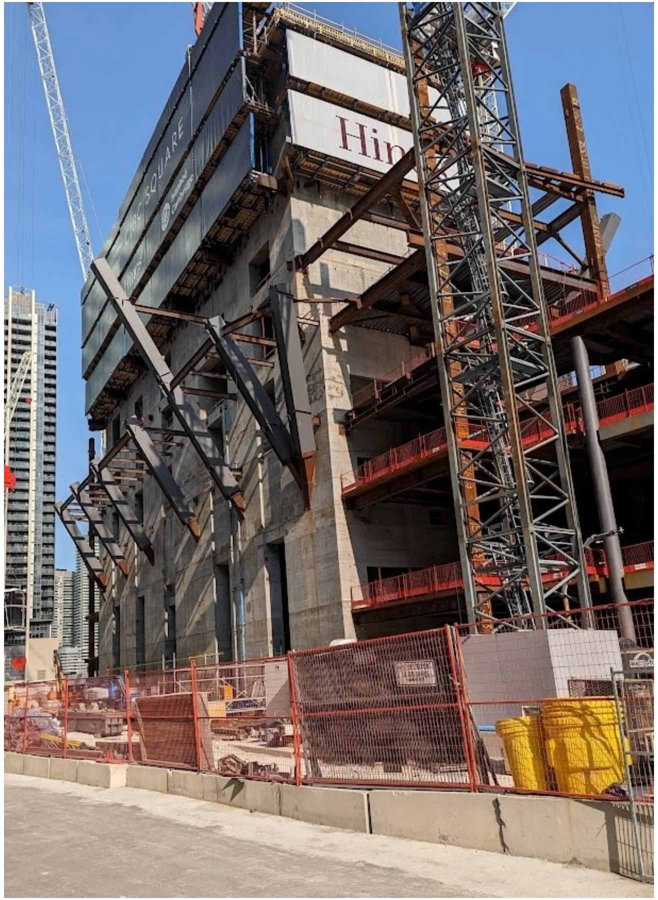
Cast steel nodes

David Ruggiero

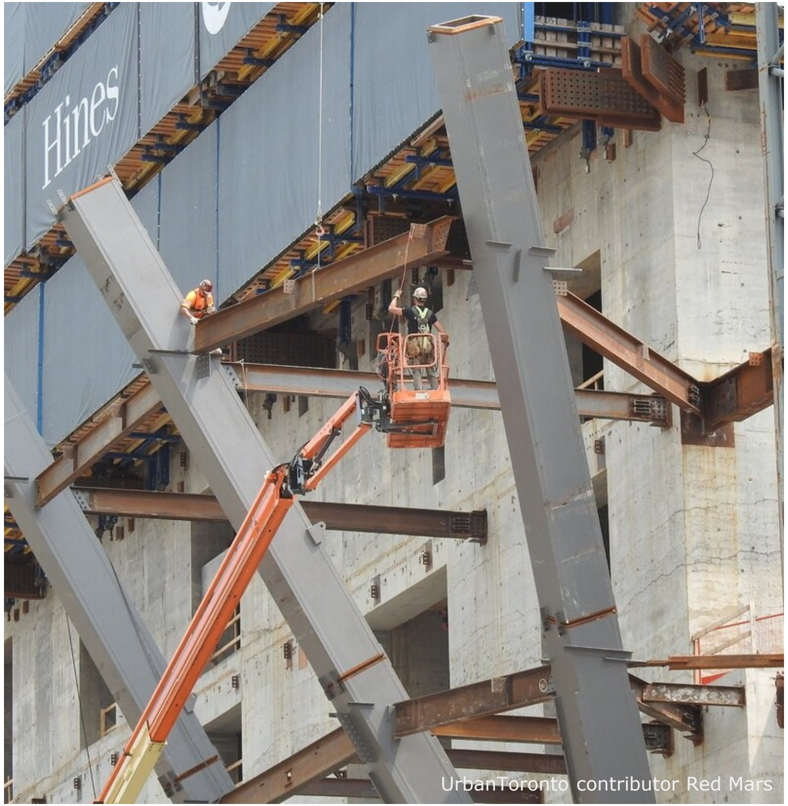


Sloping columns


UrbanToronto contributor Northern Light



Sloping columns



UrbanToronto contributor Red Mars

Sloping columns

SuperMetal

Construction progress

Construction progress

Construction progress

Construction progress

Construction progress

Phil Quach

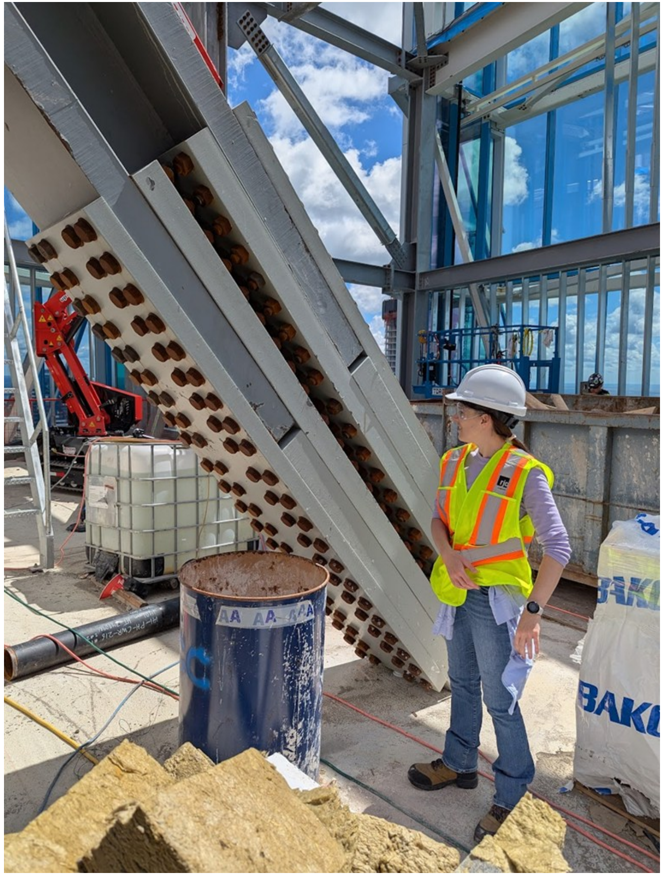
Construction progress

Hines/Ivanhoé Cambridge

Construction progress

Hines/Ivanhoé Cambridge

Construction progress

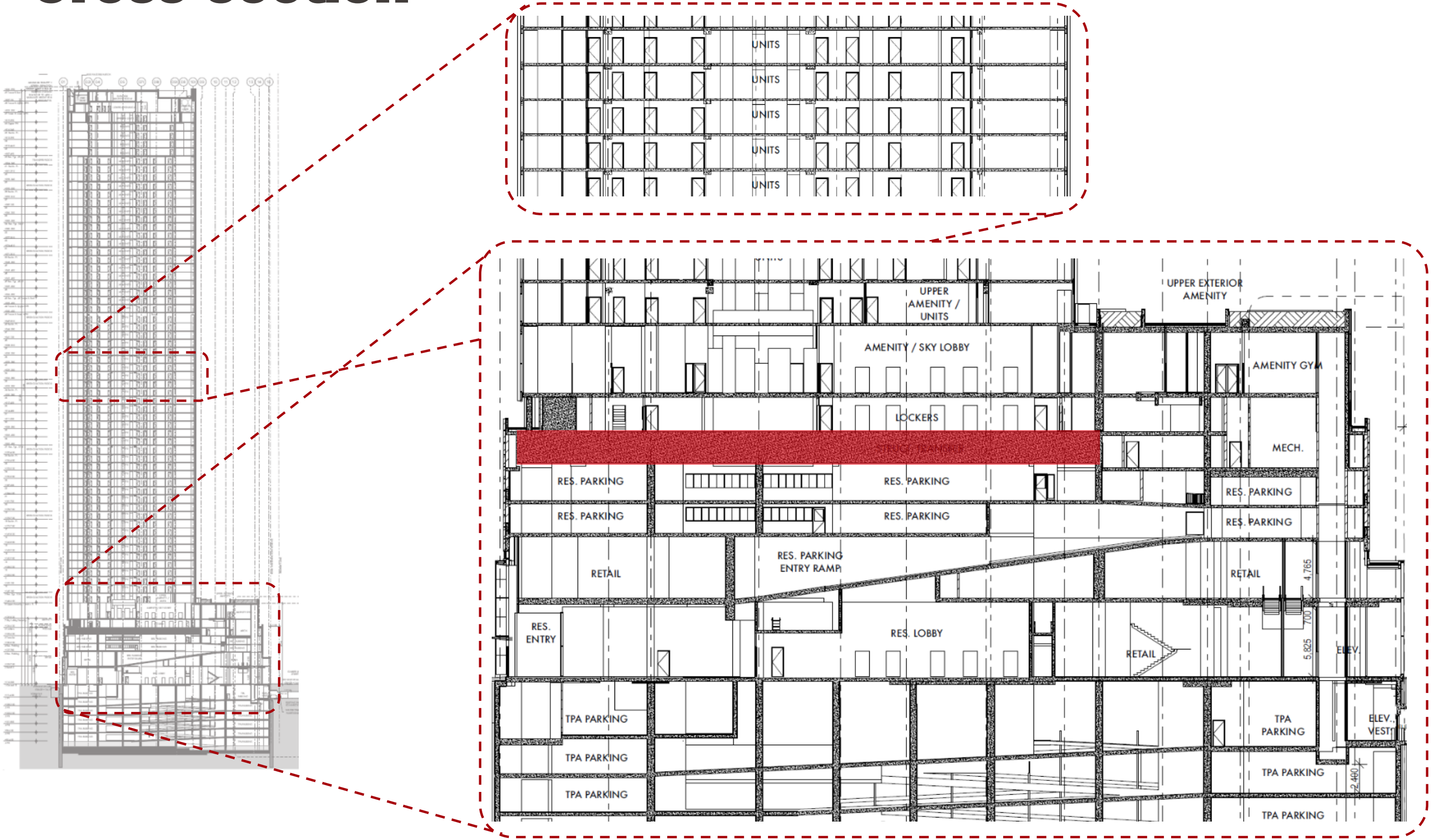


Construction progress

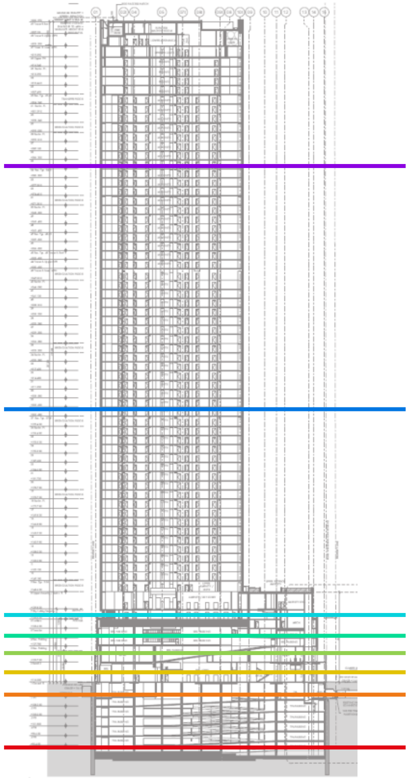
flickr: Drone Alone

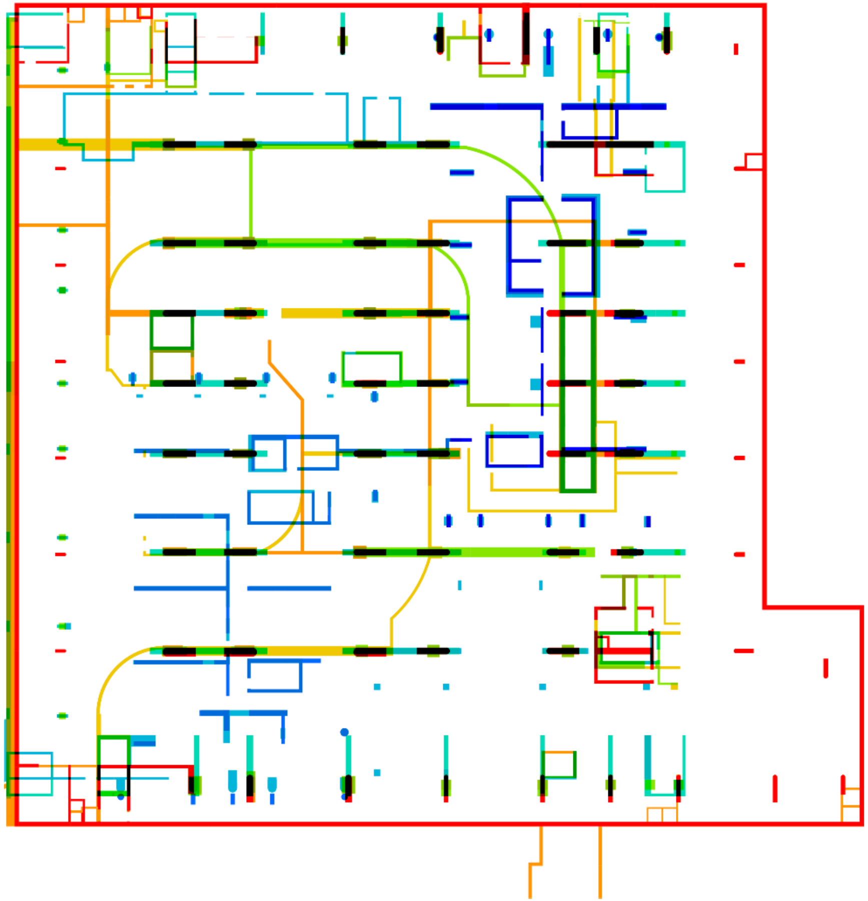
68-storey residential

Cross-section

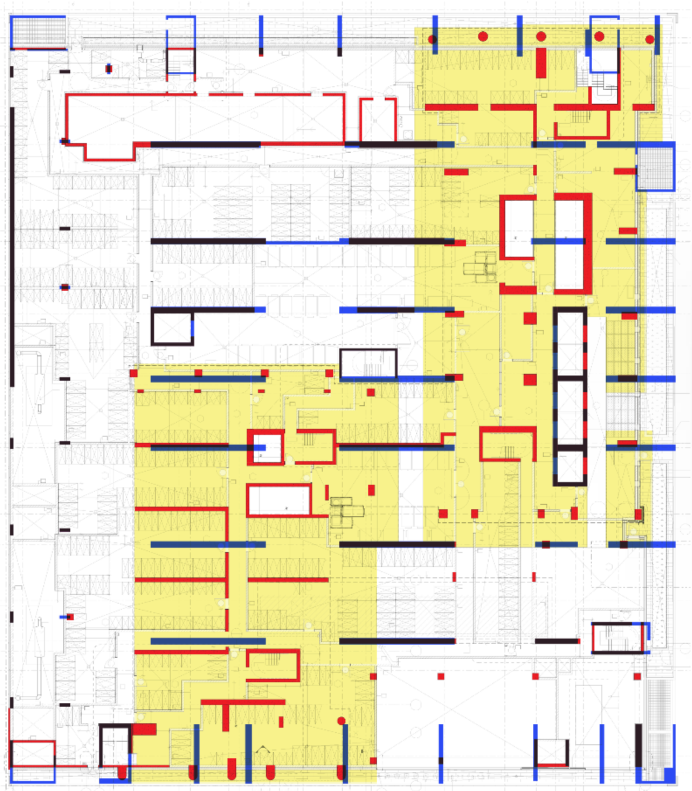


Floorplans

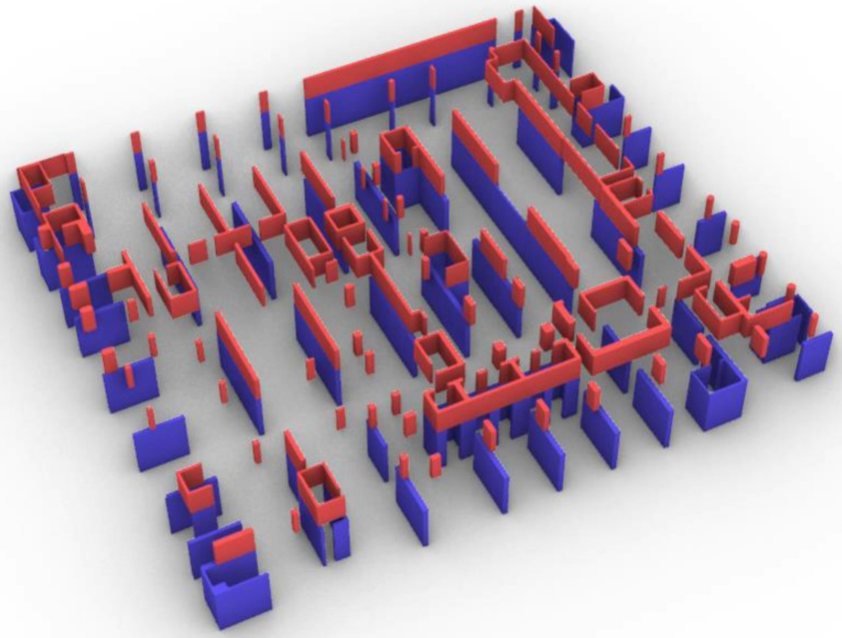




Transfer slabs



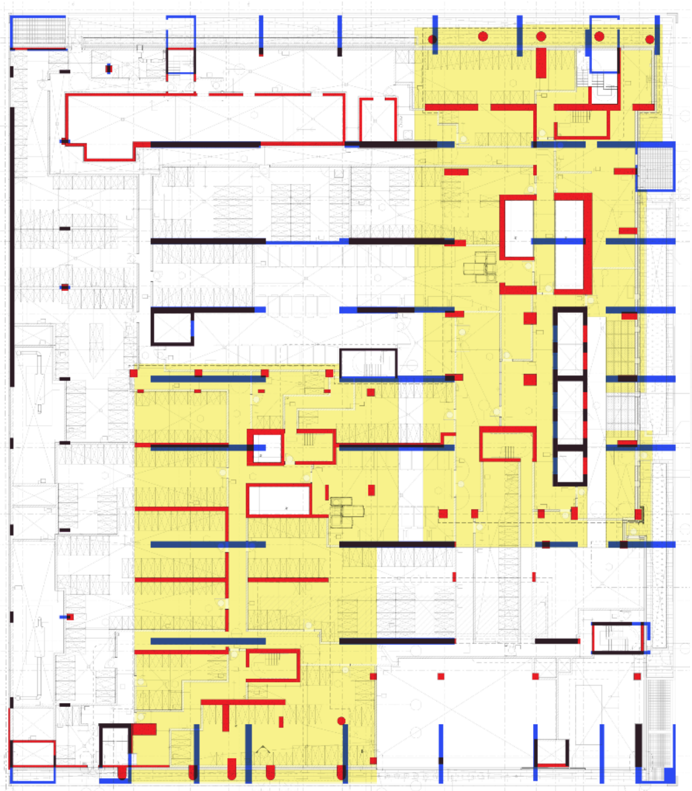
🟥 Above 🟦 Below 🟨 Transfer slab



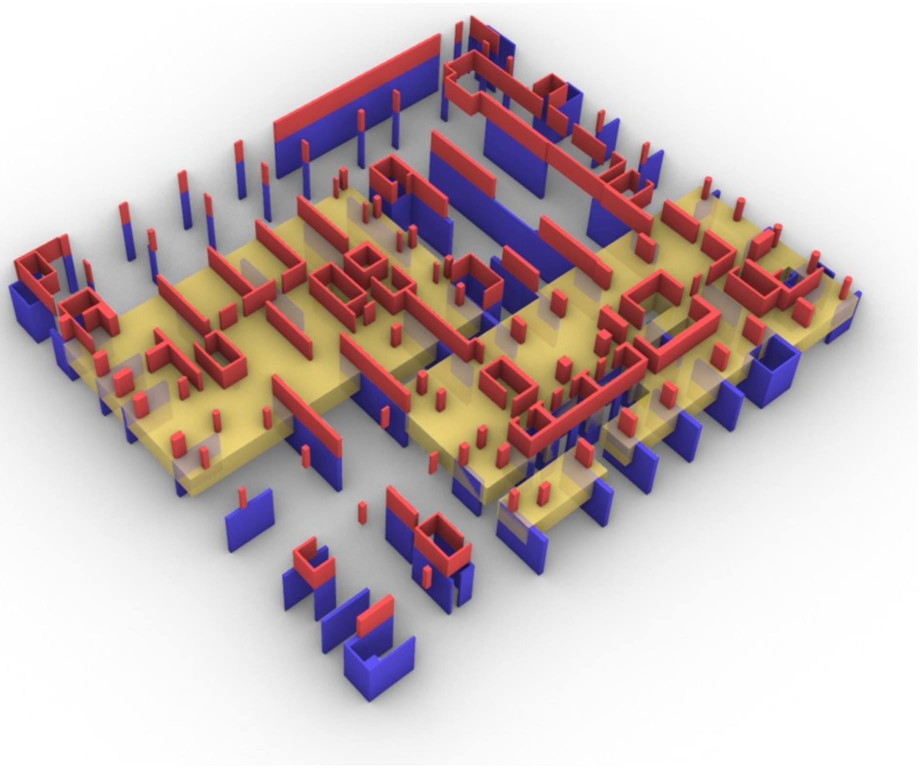
David Ruggiero

SUSTAINABILITY AT THE STRUCTURAL SCALE

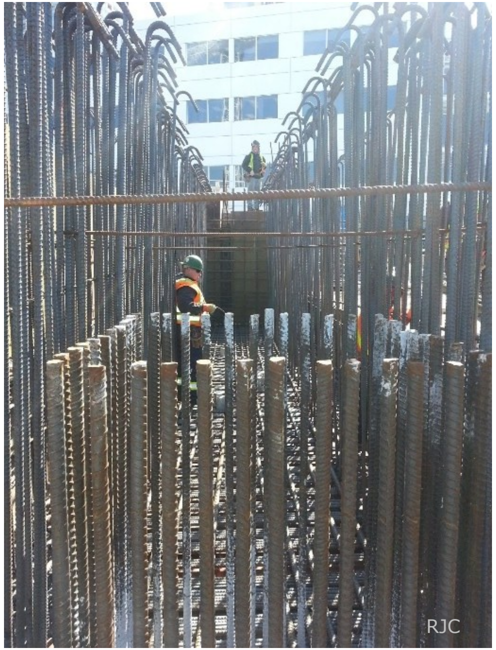
Transfer slabs



🟥 Above 🟦 Below 🟨 Transfer slab



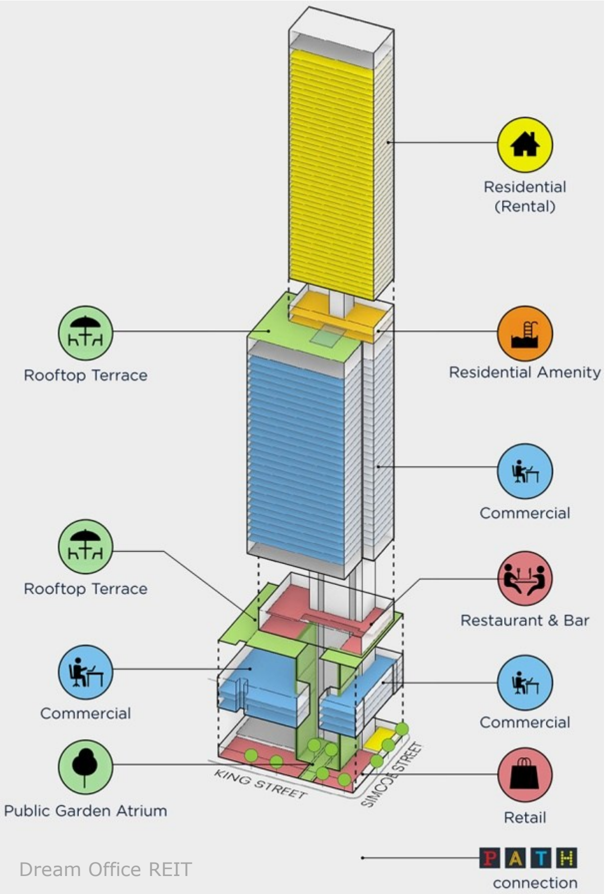
Transfer slabs


RJC

Transfer slabs

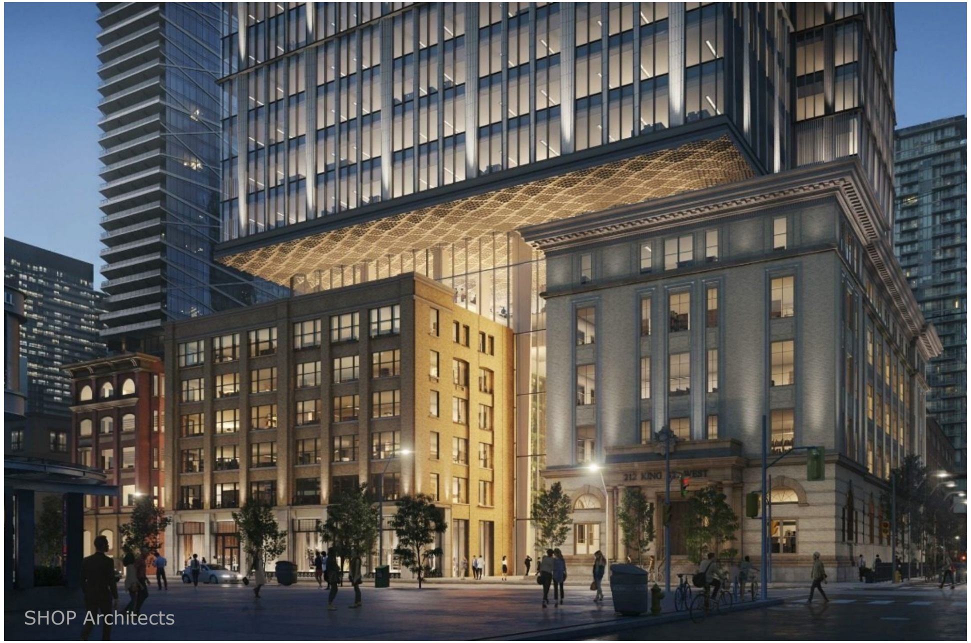
80-storey mixed use


SHOP Architects

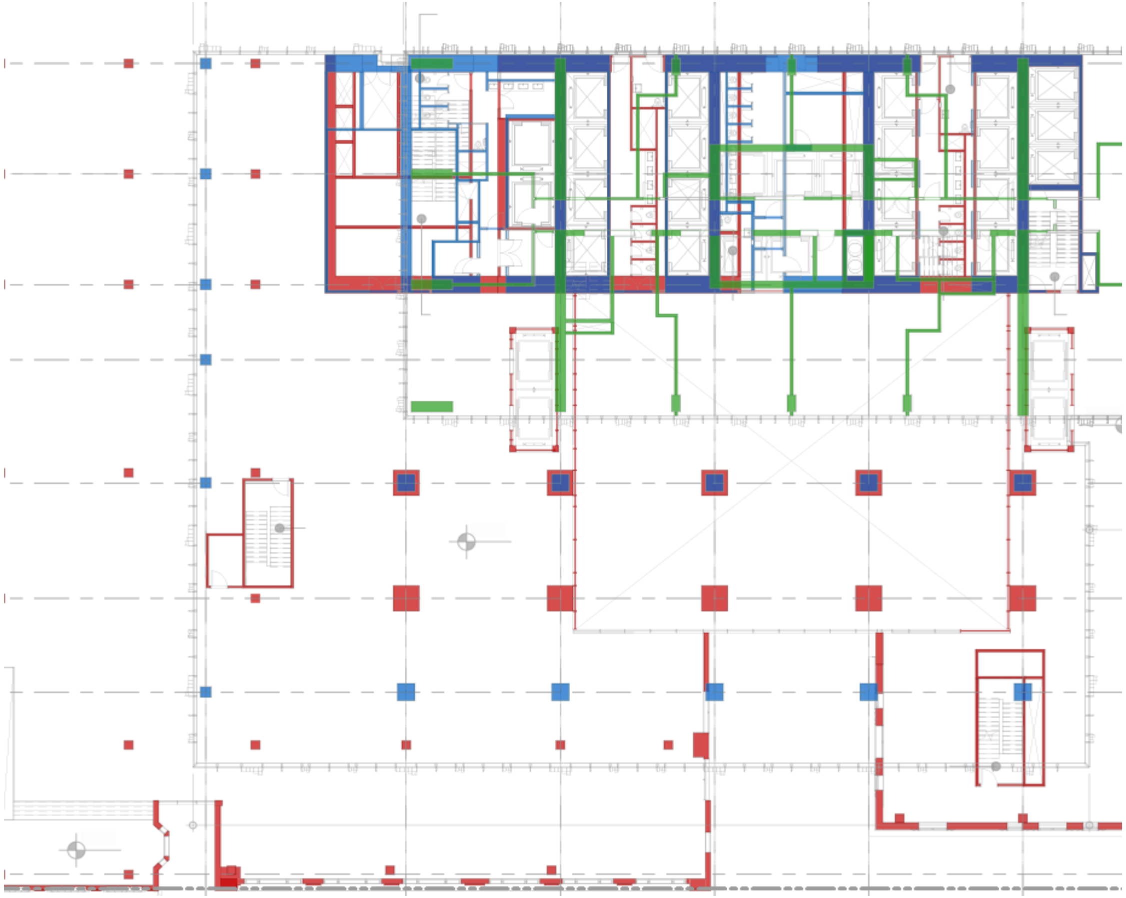


Dream Office REIT

80-storey mixed use


SHOP Architects

Plan

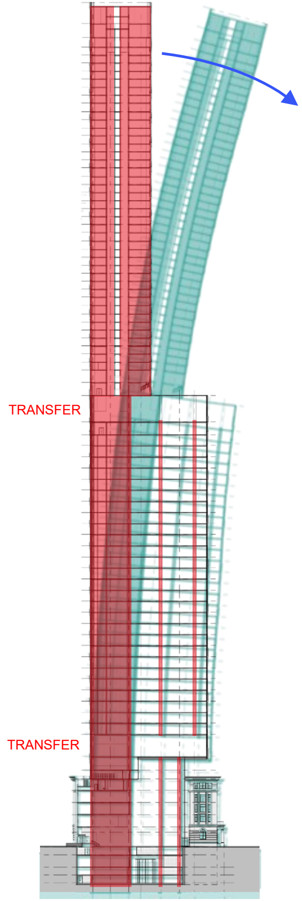


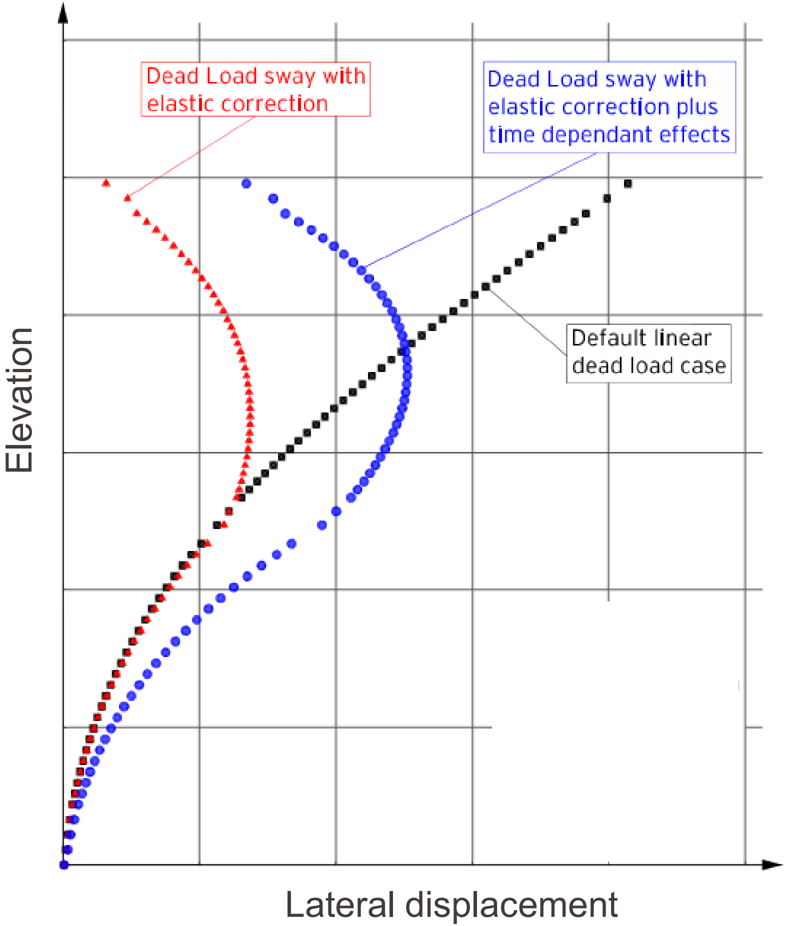
PODIUM

OFFICE

RESIDENTIAL

Cross-section

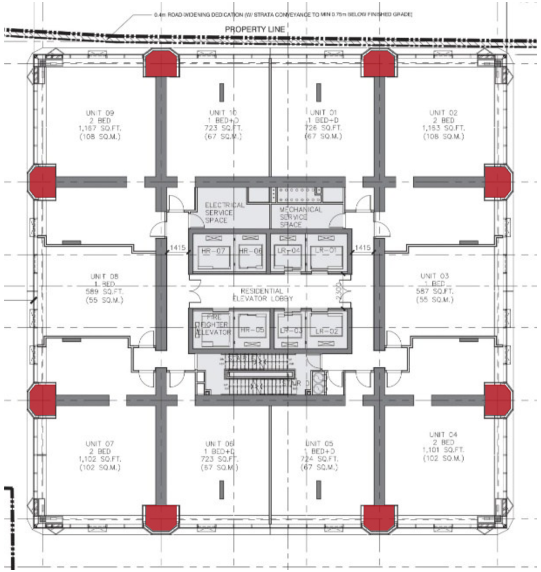




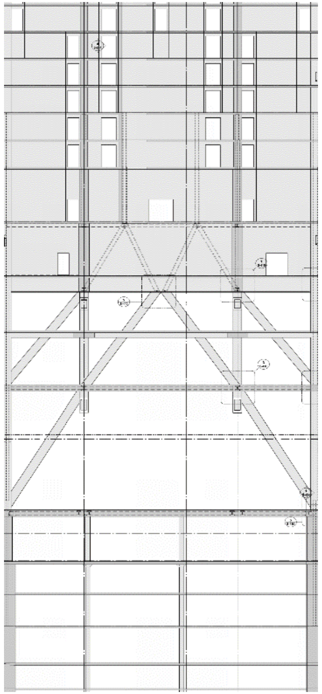
1 Bloor St W

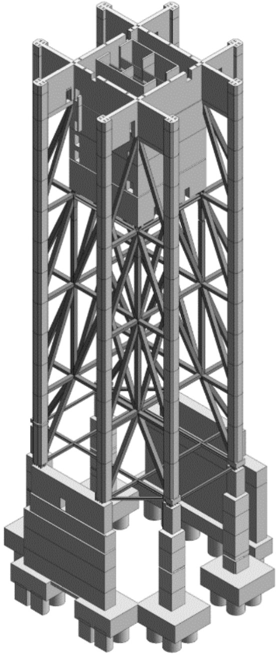
Mizrahi Developments

1 Bloor St W



MEGACOLUMNS





RJC Engineers

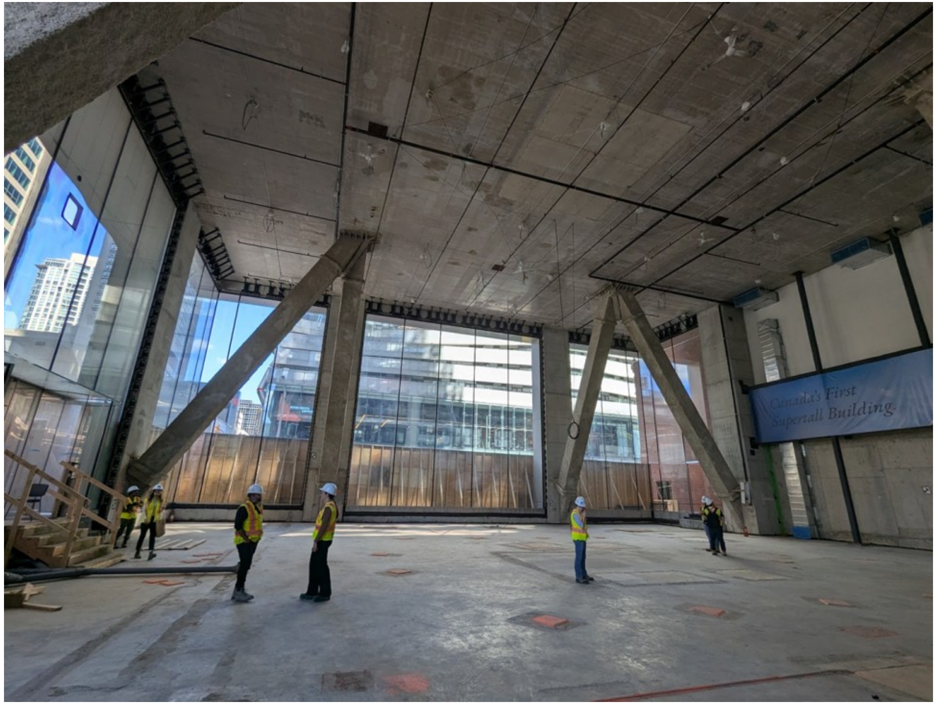
1 Bloor St W

RJC

UrbanToronto contributor AdamsS

1 Bloor St W

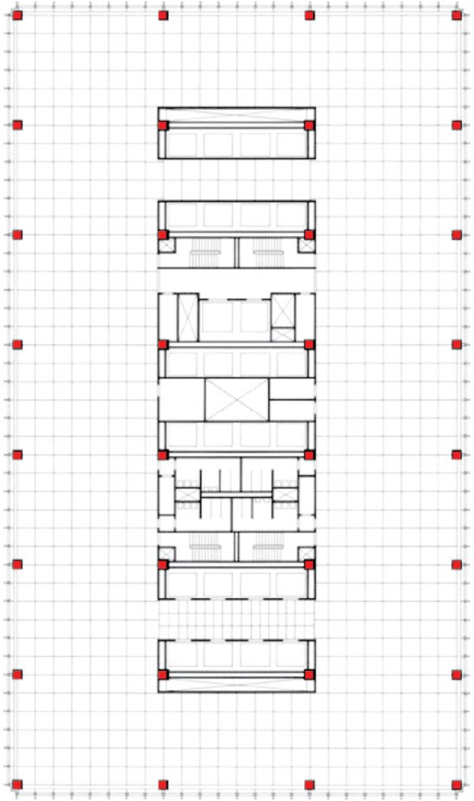
1 Bloor St W


Canada's First
Supertall Building


TRIDEL
ONE BLOOR WEST
Yonge

1 Bloor St W

Increasing complexity



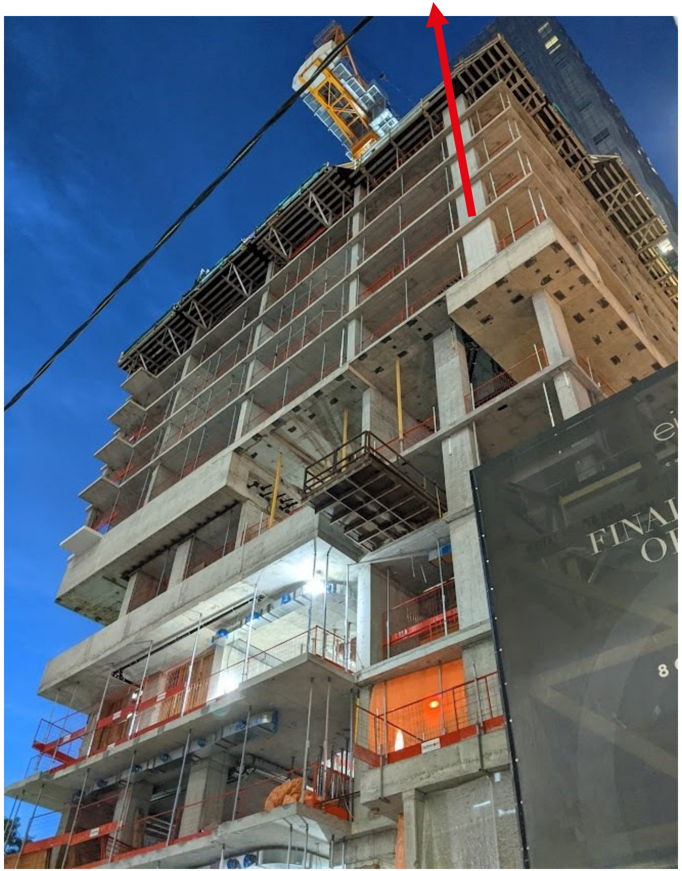
Increasing complexity

UrbanToronto contributor Rascacielo

UrbanToronto contributor Red Mars

Increasing complexity

45 STOREYS



Increasing complexity

UrbanToronto contributor Solaris

Increasing complexity

Increasing complexity

2 m thick transfer slab
Supports 90 storeys

UrbanToronto contributor wmedia

Increasing complexity


UrbanToronto contributor Red Mars

Increasing complexity

Increasing complexity


UrbanToronto contributer AHK

Increasing complexity

Phil Quach

Increasing complexity

Phil Quach

Increasing complexity

Increasing complexity

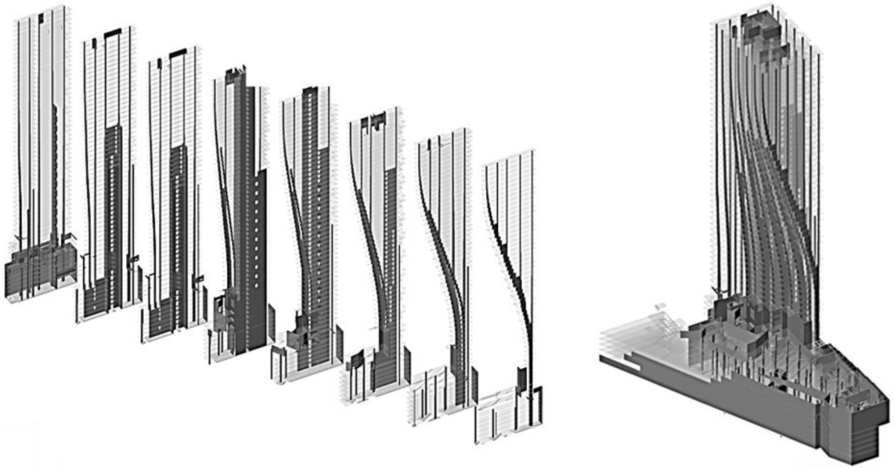
4.5 m deep transfer grillage

UrbanToronto contributor Jeff Morgan

Increasing complexity

Increasing complexity

Increasing complexity

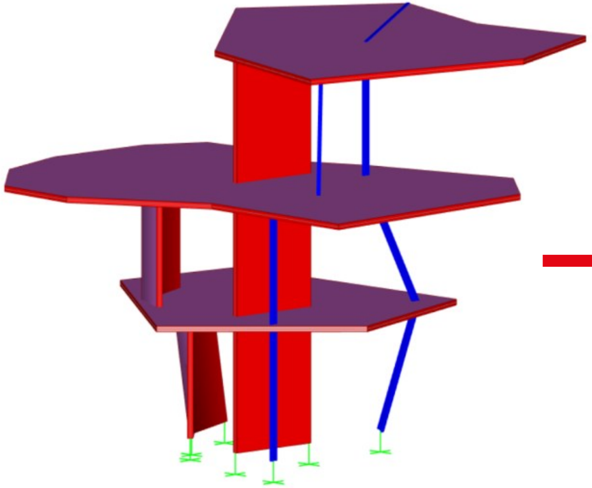


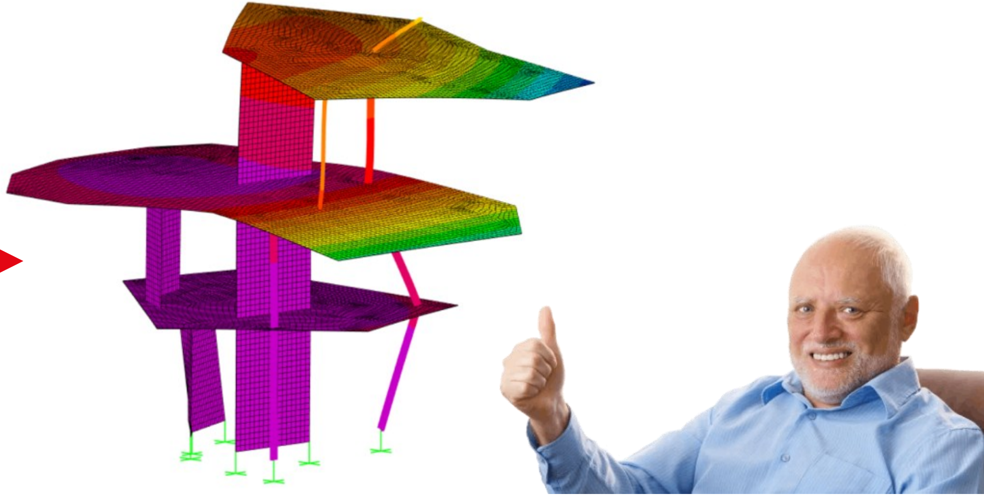
STRUCTURE Magazine

Westbank

Increasing complexity

Computer software

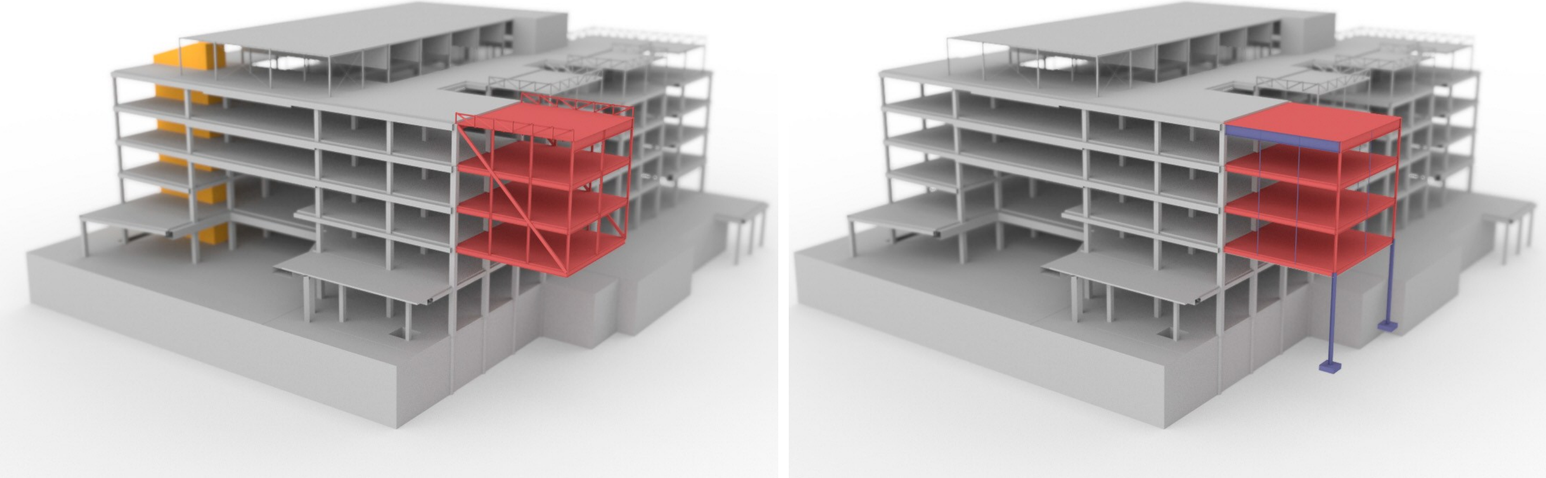




Garbage in …

… Garbage out

Carbon cost of cantilevers



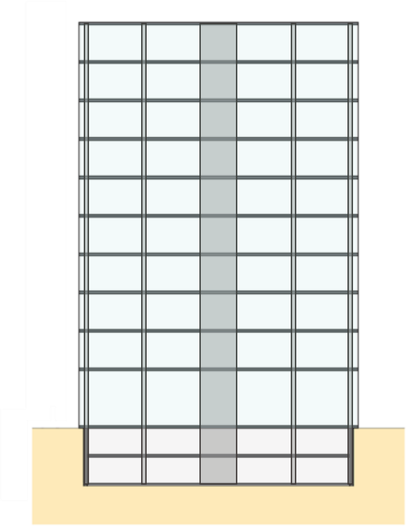
Helal, J.; Trabucco, D.; Ruggiero, D.; Miglietta, P.; Perrucci, G. Embodied Carbon Premium for Cantilevers. *Buildings* **2024**, *14*, 871. https://doi.org/10.3390/buildings14040871

~50% higher embodied carbon associated with cantilever floor area

David Ruggiero

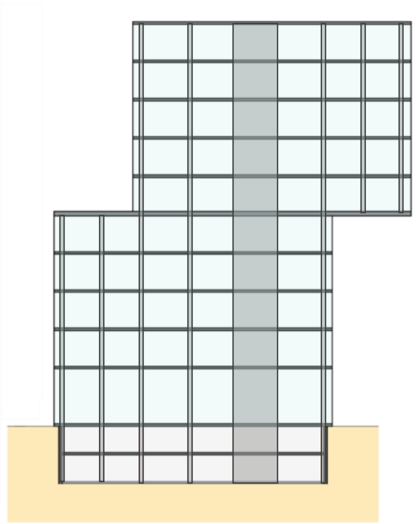
SUSTAINABILITY AT THE STRUCTURAL SCALE

Carbon cost of irregularity



~138 $kgCO_2e/m^2$

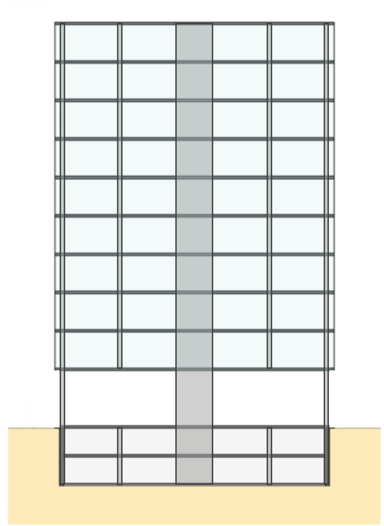
(8 designs)



~154 $kgCO_2e/m^2$

(4 designs)

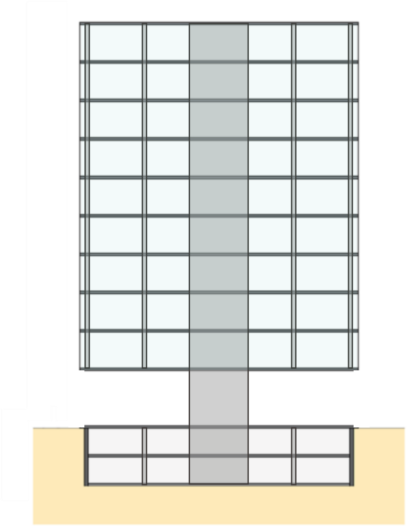
+11%



~198 $kgCO_2e/m^2$

(6 designs)

+37%

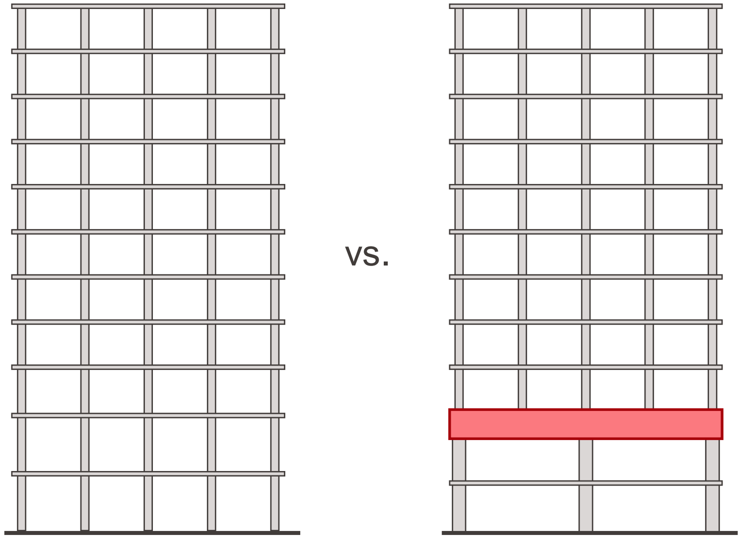


~291 $kgCO_2e/m^2$

(1 design)

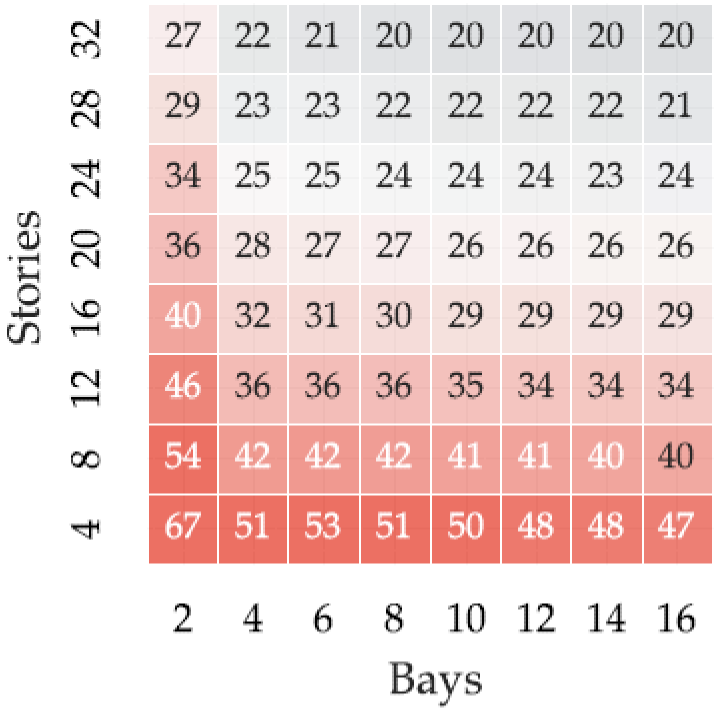
+110%

Carbon cost of transfers



Source: Enrico Pinelli (MSc project)

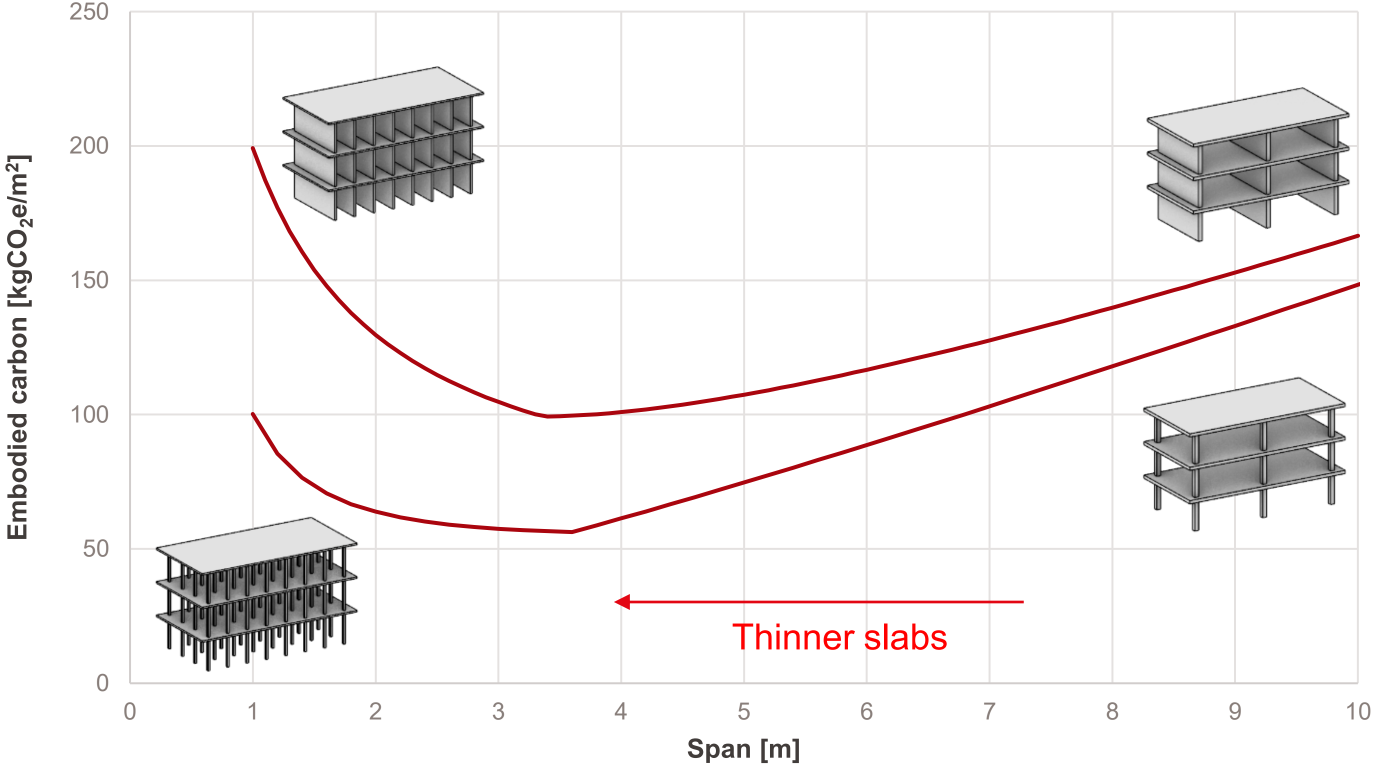
Additional CO$_2$e, %



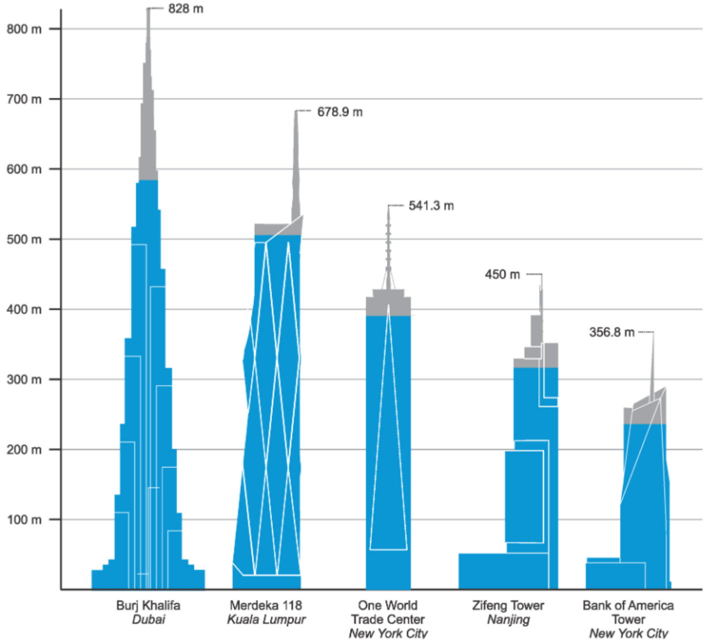
Stories \ Bays	2	4	6	8	10	12	14	16
32	27	22	21	20	20	20	20	20
28	29	23	23	22	22	22	22	21
24	34	25	25	24	24	24	23	24
20	36	28	27	27	26	26	26	26
16	40	32	31	30	29	29	29	29
12	46	36	36	36	35	34	34	34
8	54	42	42	42	41	41	40	40
4	67	51	53	51	50	48	48	47

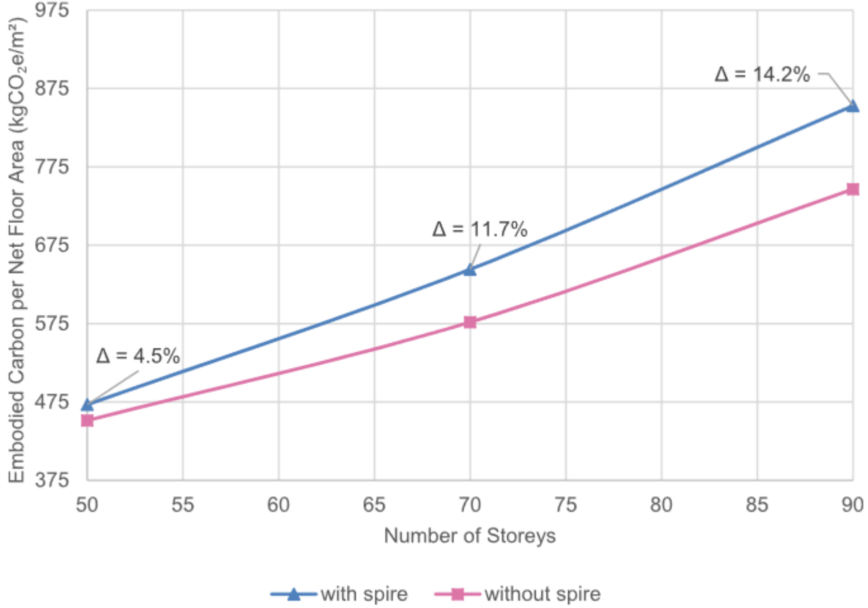
(A) Frame embodied carbon

Carbon cost of long spans



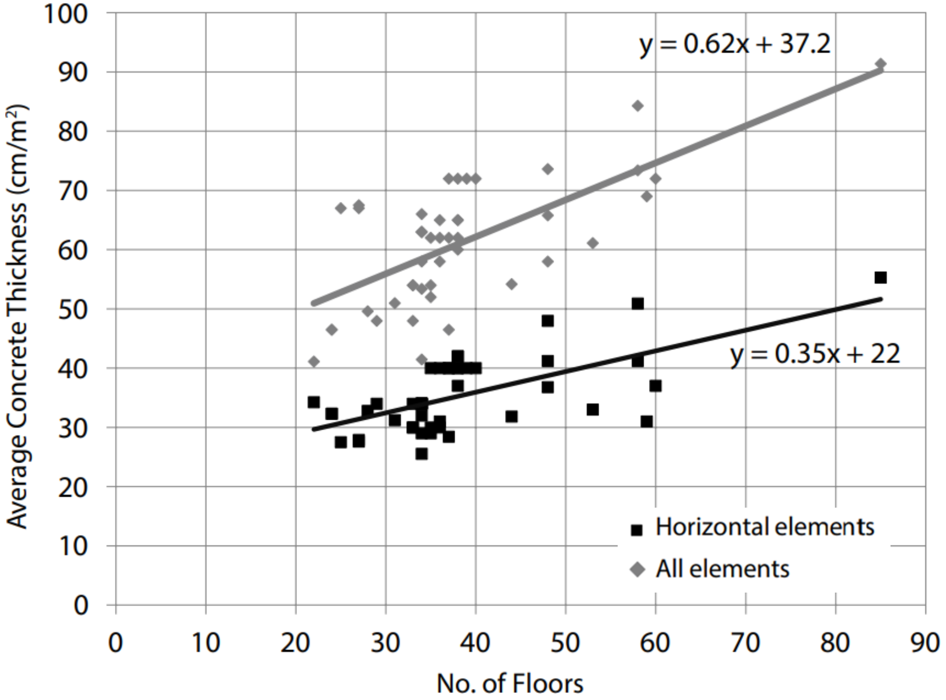
Carbon cost of vanity spires





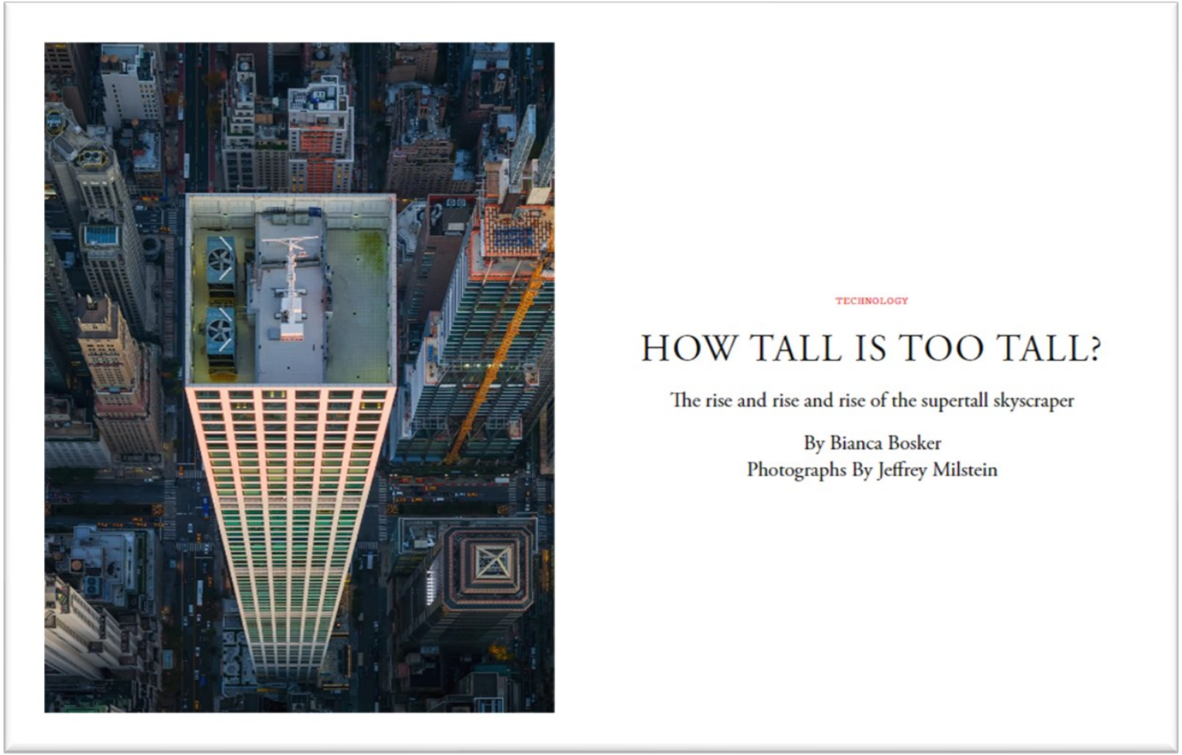
Helal, James, Dario Trabucco, and Dalibor Savovic. 2024. ‘Embodied Carbon Premium for Vanity Height: A Case for the Exclusion of Decorative Spires in the Design of Tall Buildings’. Journal of Cleaner Production 456 (June):142334.

Carbon cost of height



Ali Sherif S. Rizk Director, Dar al-Handasah Shair and Partners (2010). “Structural Design of Reinforced Concrete Tall Buildings”. In: CTBUH Journal.

How tall is too tall?



TECHNOLOGY

HOW TALL IS TOO TALL?

The rise and rise and rise of the supertall skyscraper

By Bianca Bosker
Photographs By Jeffrey Milstein

The Atlantic

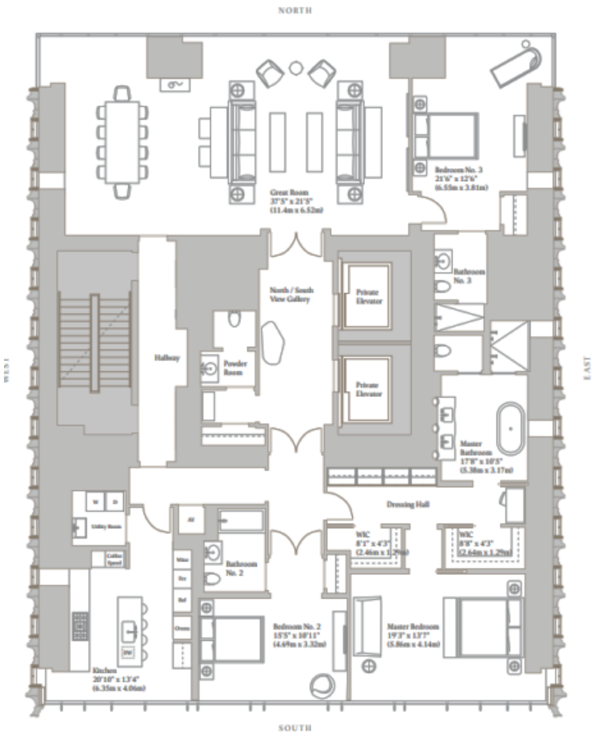
January/February 2023 Issue

Vanity projects – 11th century

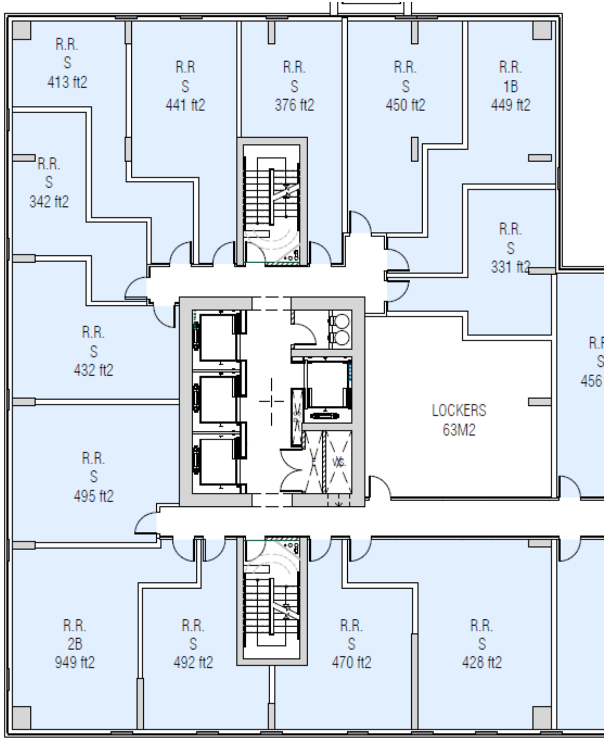
Vanity projects – 21^{st} century

The Guardian

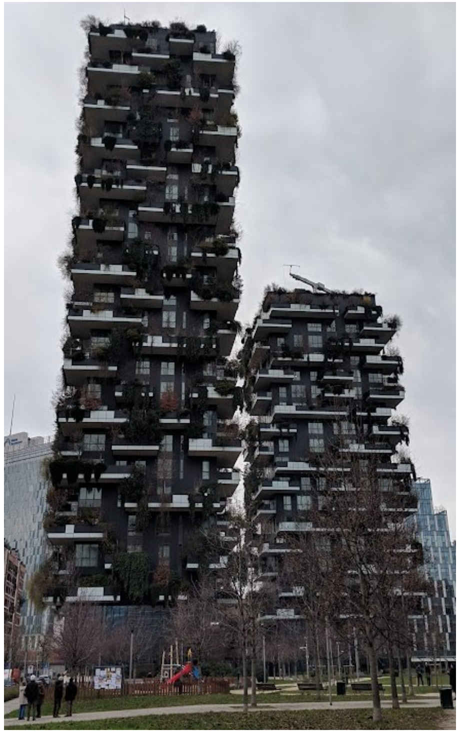
Structural inequity



JDS Development Group



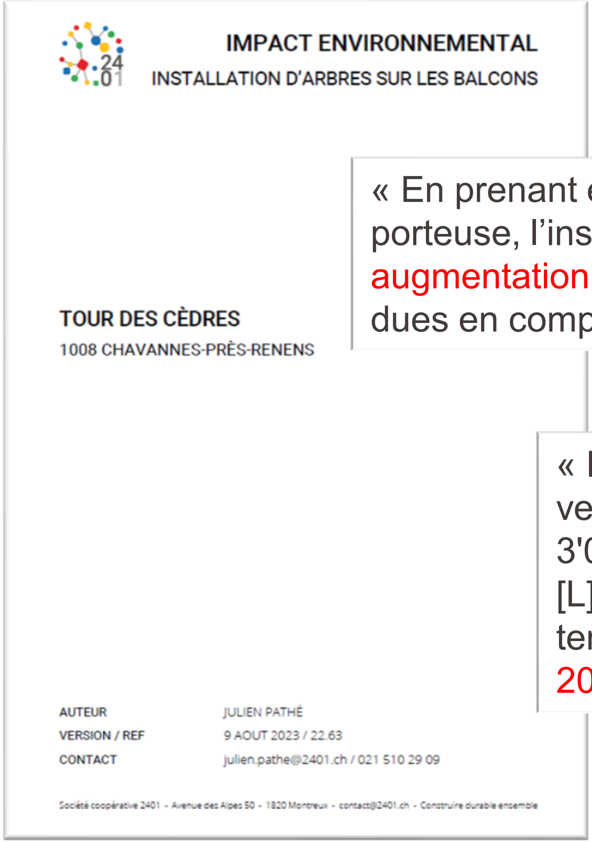
Greenwashing



Greenwashing

Stefano Boeri

Greenwashing



IMPACT ENVIRONNEMENTAL
INSTALLATION D'ARBRES SUR LES BALCONS

TOUR DES CÈDRES
1008 CHAVANNES-PRÈS-RENENS

AUTEUR	JULIEN PATHÉ
VERSION / REF	9 AOUT 2023 / 22.63
CONTACT	julien.pathe@2401.ch / 021 510 29 09

Société coopérative 2401 - Avenue des Alpes 50 - 1820 Montreux - contact@2401.ch - Construire durable ensemble

« En prenant en compte les éléments analysés de la structure porteuse, l'installation d'arbres sur les balcons représente une augmentation ... de 65.9 % l'émission de gaz à effet de serre dues en comparaison d'une variante sans arbres. »

« En effet, les promoteurs du projet mettent en avant les vertus environnementales de l'installation de 80 arbres et 3'000 m^2 d'arbustes sur le projet de la Tour des Cèdres ... [L]a compensation des émissions de CO_2 sur un horizon temporel de 60 ans nécessiterait de planter environ 20'000 arbres au moment de la construction. »

Julien Pathé – Societé cooperative 2401

The future?

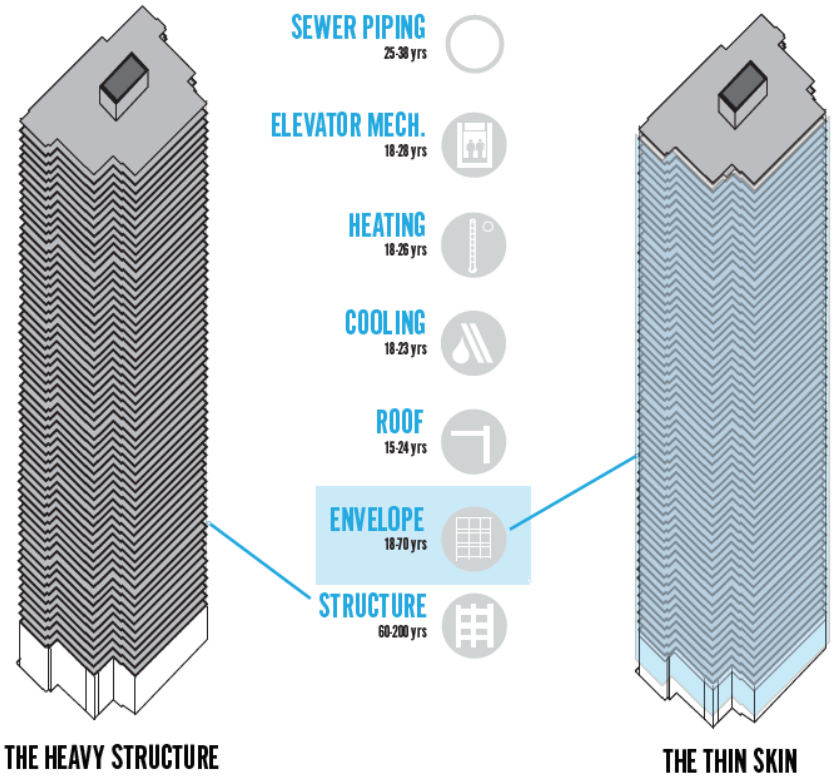
Matthew Borrett

The present

Iwan Baan

Wikipedia

Life-cycle



Building resilience in condoland, SPACING magazine

Life-cycle

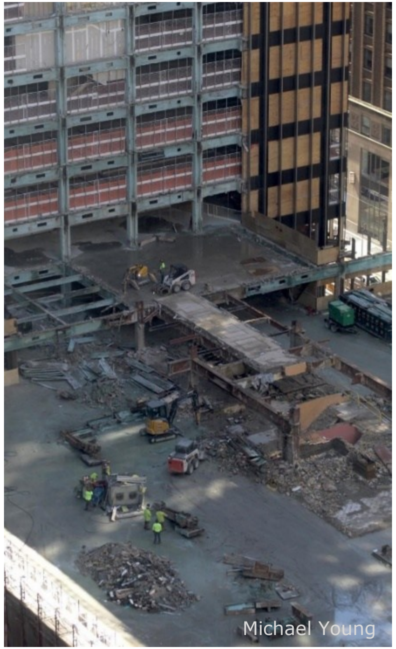
39 years old

1900 years old

Skyscraper demolition

Google Earth

Wikimedia Commons



Michael Young

Michael Young

Skyscraper demolition

Vincent Cheang - YouTube

Mathias Beinling - Wikimedia

Skyscraper demolition

”

[Skyscrapers] need to be designed to be never taken down, such that their life cycle is as close to forever as you can get... No-one's talking about when the pyramids are going to come down.

Antony Wood, Executive Director of the Council on Tall Buildings and Urban Habitat (CTBUH)

Problems

Complexity	Inefficient structures
Materials	High cement content
Decommissioning	No plan for demolition
Obsolescence	Lack of adaptability

Solutions

Policymakers

- Specify baseline requirements for life cycle assessments
- Review building setback requirements
- Establish maximum parking ratios
- Focus on number of units rather than height limits
- Review maximum floor plate sizes
- Prioritize projects which incorporate adaptive reuse

Developers

- Design beyond code minimums to allow for longer life span
- Incorporate longer cure times in concrete elements
- Lay out suites to reduce horizontal span distances
- Reinvent the lobby/retail space to avoid double height, open lobbies

Designers

- Quantify embodied carbon
- Advocate for responsible building practices as professionals
- Refine and optimize the scheme to minimize transfers
- Employ adaptive reuse rather than reconstruction

adapted from "Embodied Carbon in Residential Structures: A Toronto based case study"
RJC Engineers & BDP Quadrangle, 2023

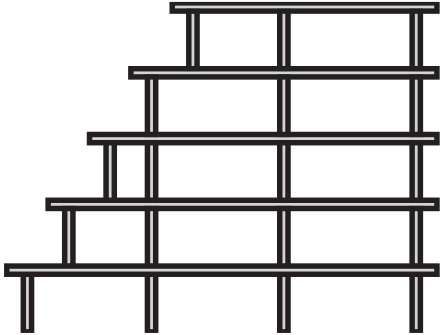
Solutions

- Estimating embodied carbon from bottom-up quantities
- Statistically predicting embodied carbon
- Exploring or optimizing the parametric design space
- Comparing design concepts, case studies, and benchmarks
- Using less material
- Using low-carbon and carbon-sequestering materials

- Designing for reuse and reusing structural elements
- Adaptively reusing whole structures and designing for longevity
- Reducing construction and demolition waste
- Reducing load demands
- Exploiting standardization and/or customization
- Implementing active structures
- Integrating systems

from Fang et al., *Reducing embodied carbon in structural systems: A review of early-stage design strategies*. Journal of Building Engineering, 2023.

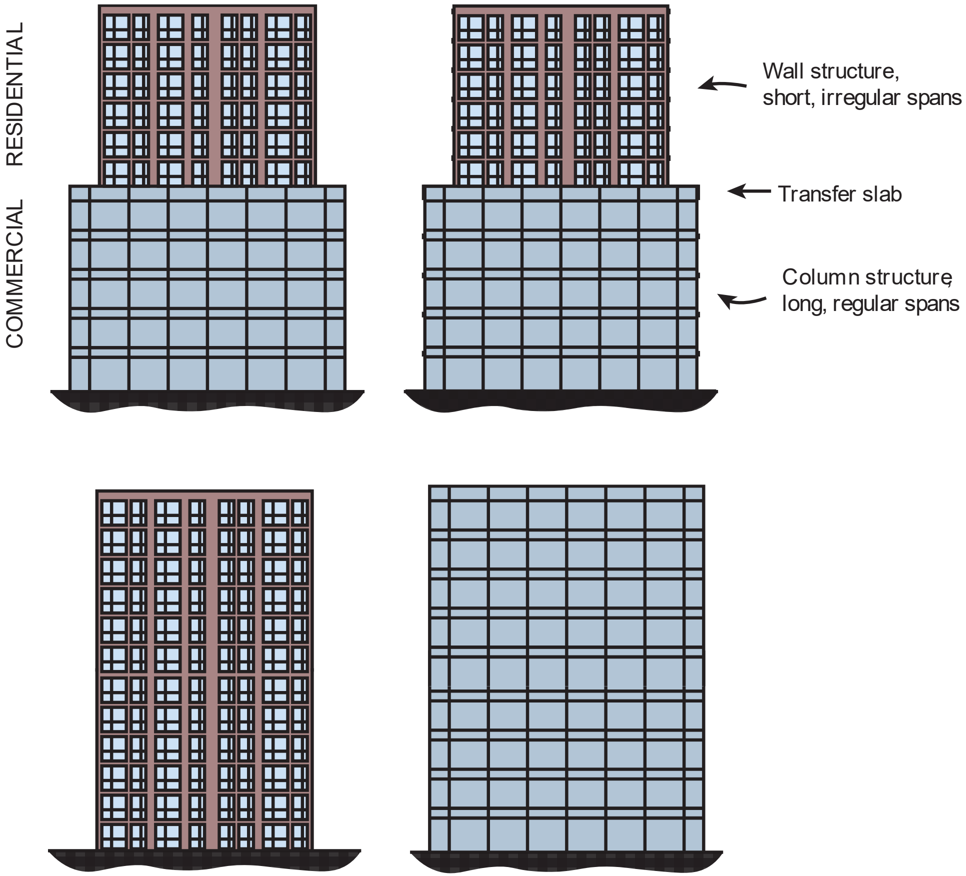
Minimize transfers




RioCan

UrbanToronto contributer AHK

Minimize transfers



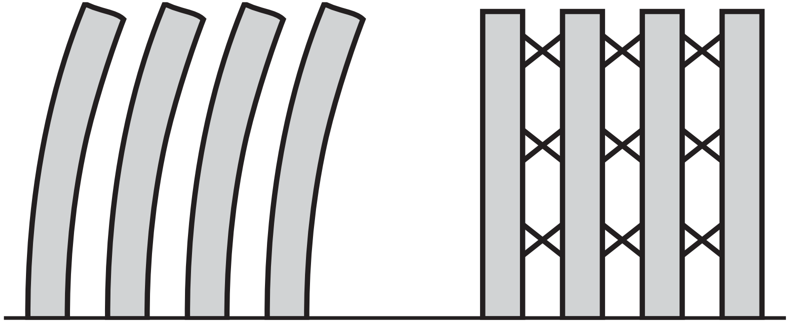
Wall structure,
short, irregular spans

Transfer slab

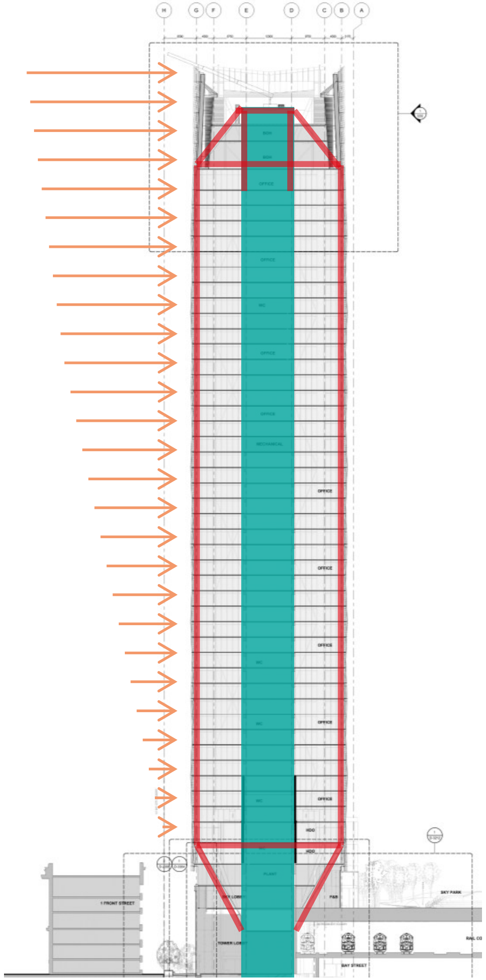
Column structure,
long, regular spans

Largescale structural efficiency


Bing Image Creator



Outriggers


H
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PLANT
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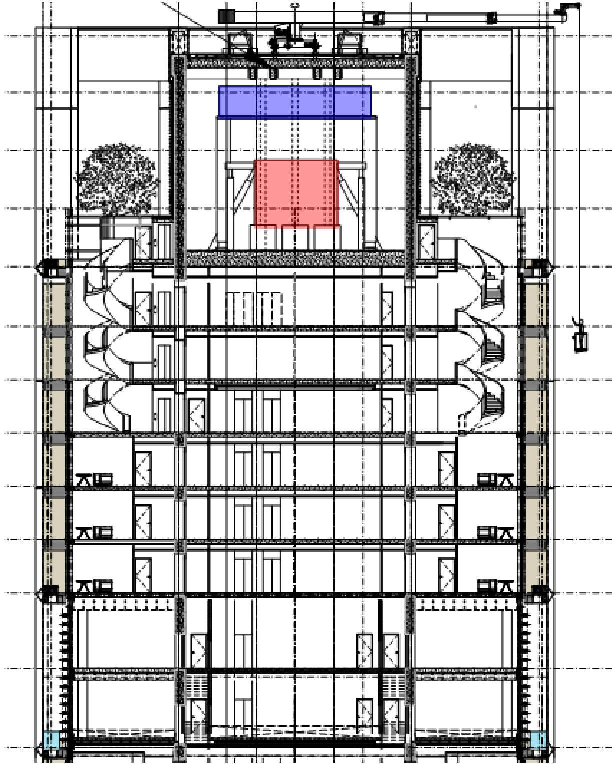
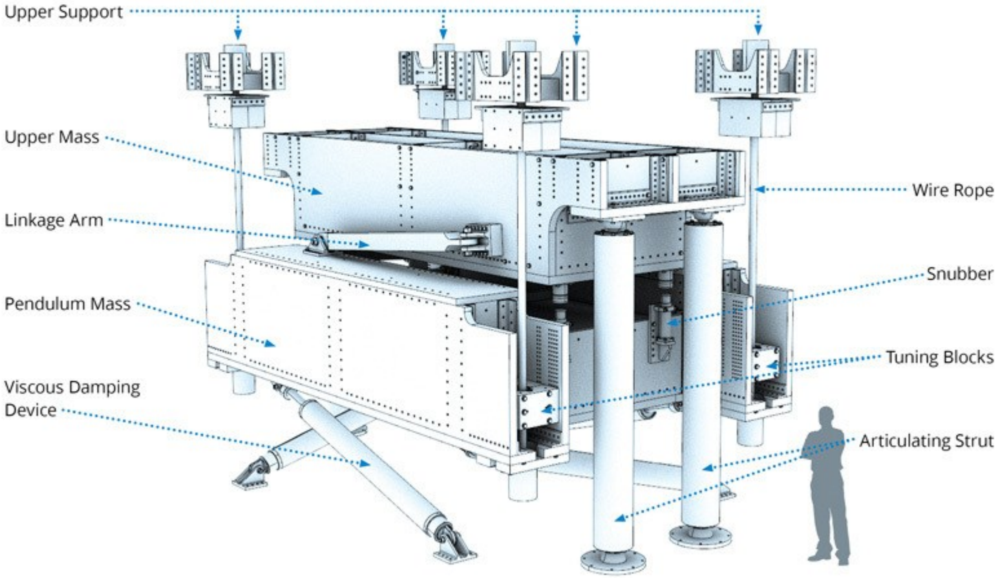
F&B
SKY PARK
1 FRONT STREET
TOWER LOBBY
RAIL CO
BAY STREET

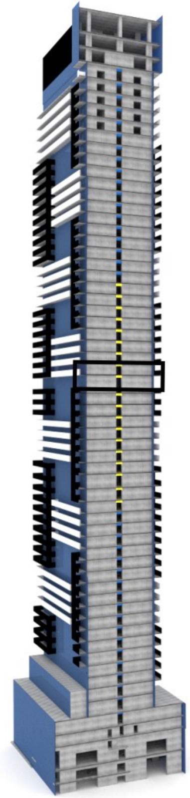
Tuned mass dampers

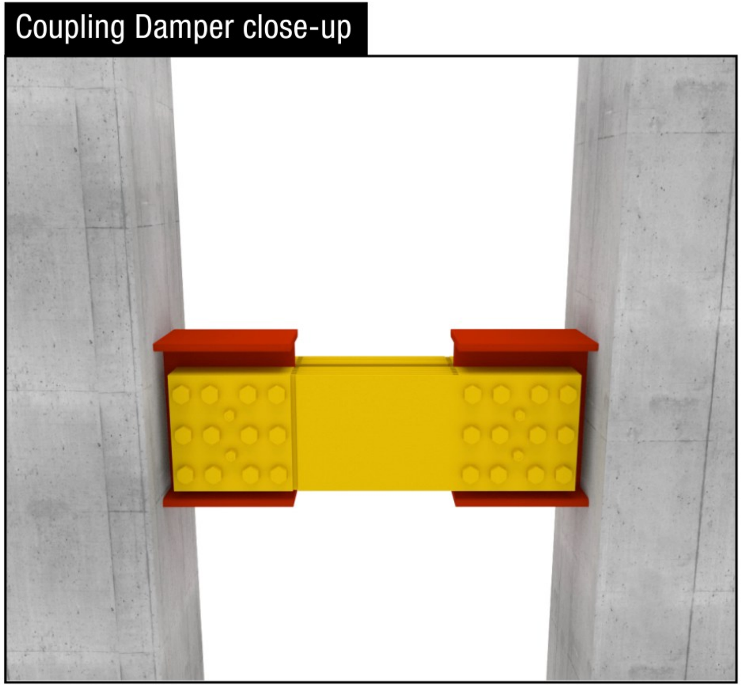




RWDI

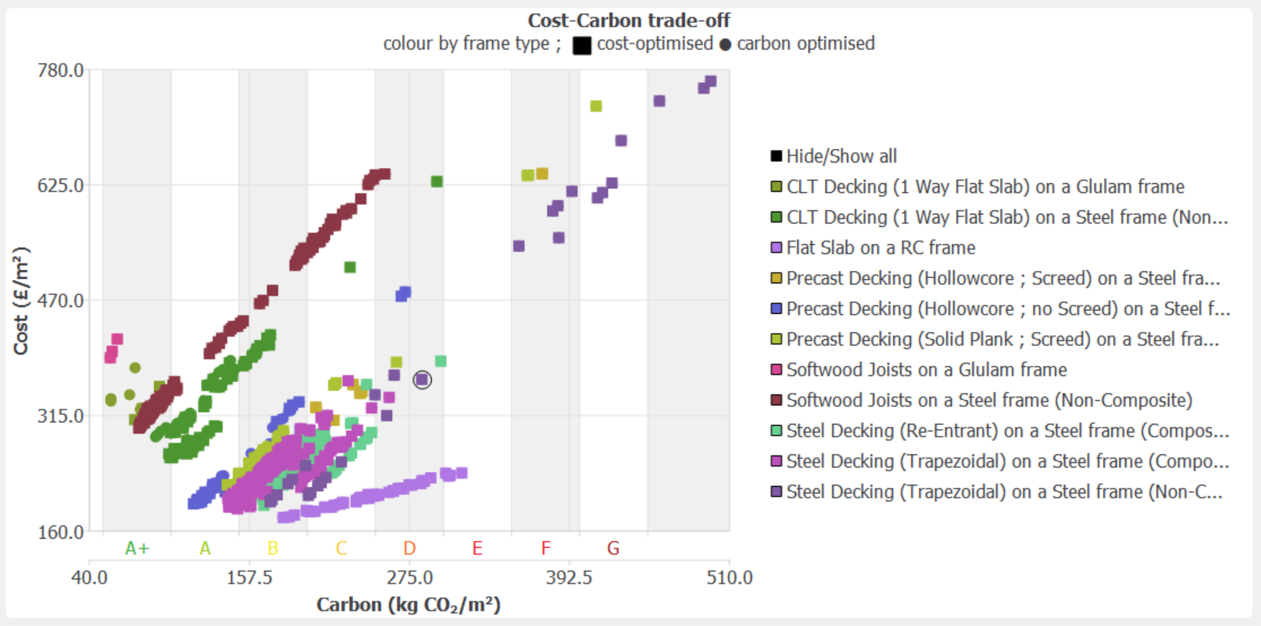
Viscoelastic coupling dampers





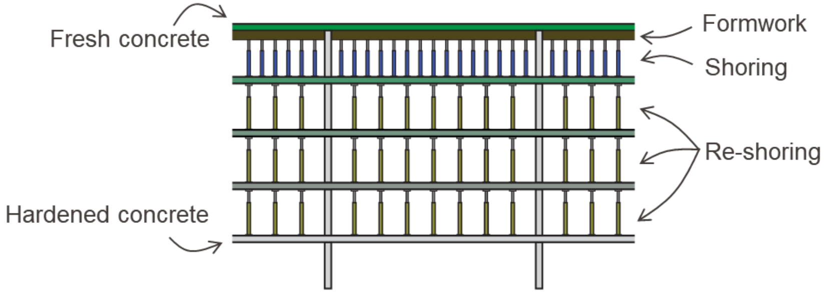
Kinetica

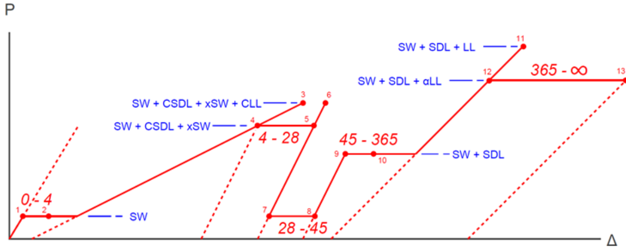
Material optimization



Structural PANDA

Delayed loading





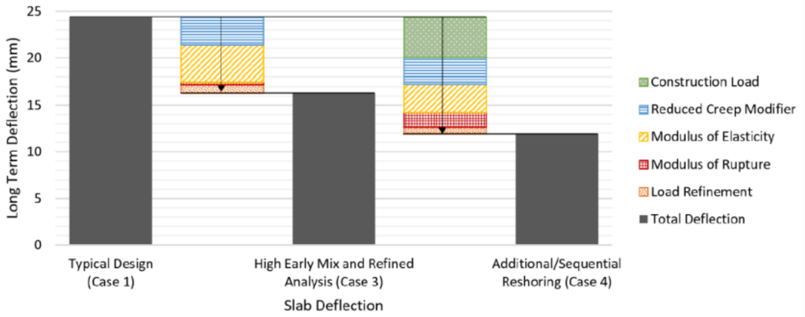
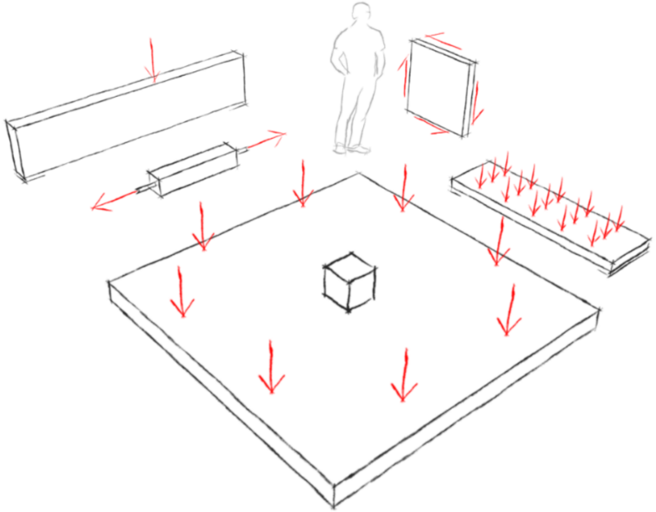
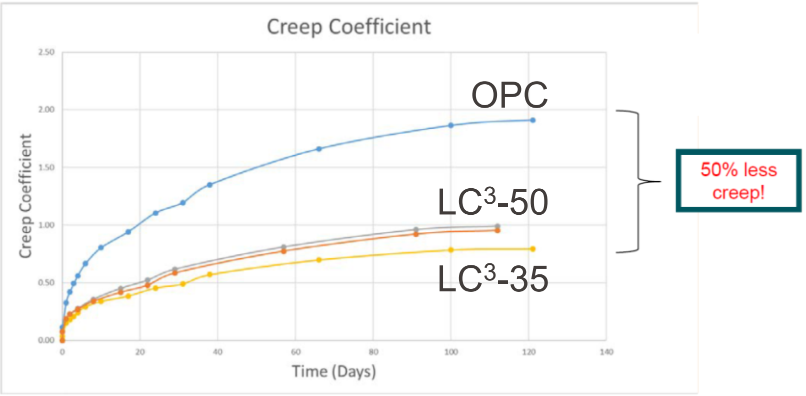


Fig. 6 Influence of different design variables on slab deflection. From the originally predicted displacement of 24 mm, the deflection is reduced by 33% in Case 3, and 50% in Case 4.

Snodgrass D, Ruggiero D. Finding carbon and cost efficiencies in the design of RC slabs made from high early strength concrete. In: *Proceedings of the fib Symposium 2025*. Antibes, France, 2025.

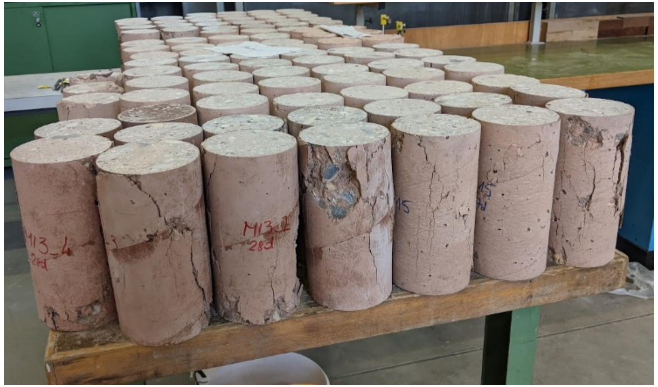
Limestone Calcined Clay Cement (LC^3)



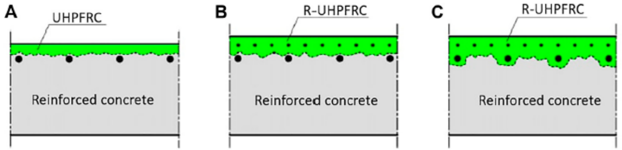


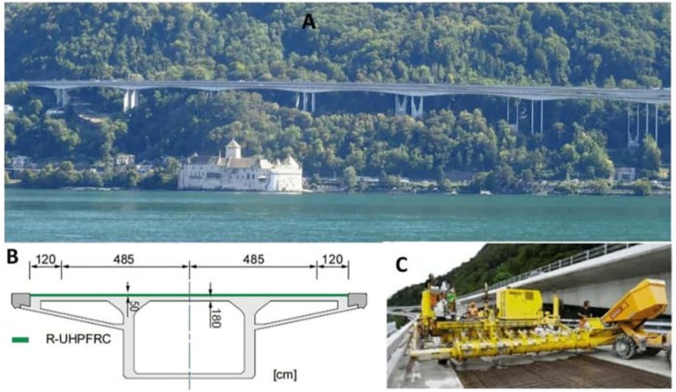
50% less creep!

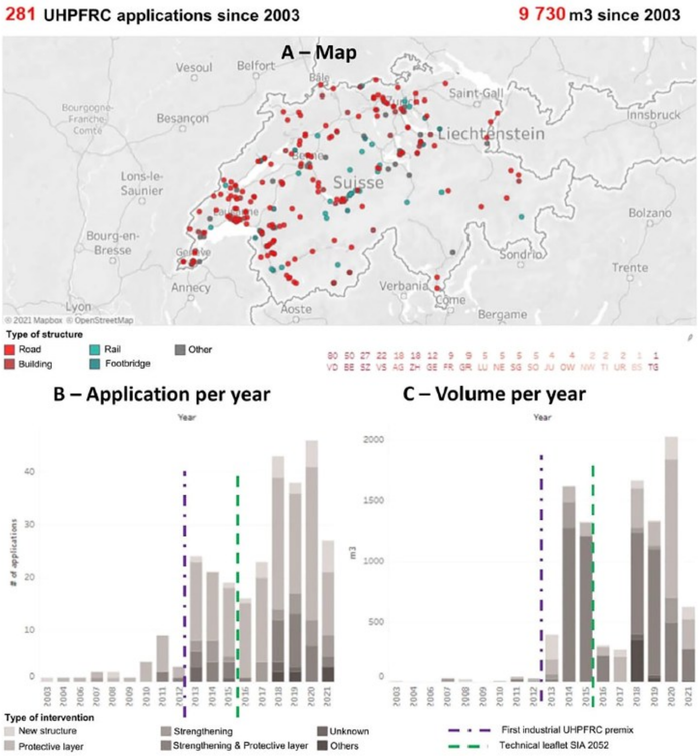
Ömer Behçet
Ph.D. candidate
(joint LMC)

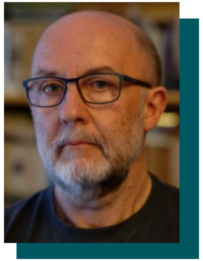


Ultra-High Performance Fibre-Reinforced Concrete









Emmanuel Denarié
Adjunct Professor

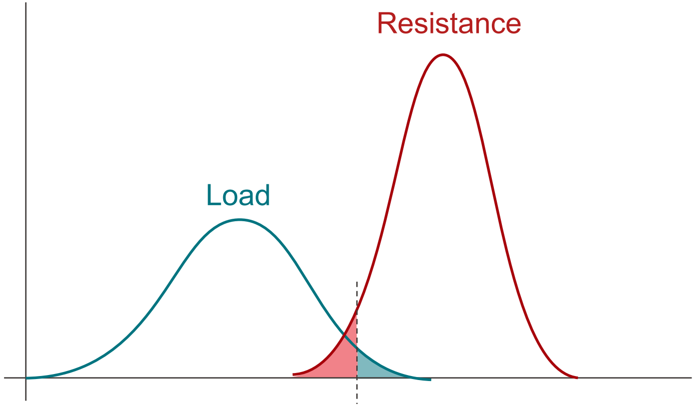
[1] Bertola N, Schiltz P, Denarié E, Brühwiler E. A Review of the Use of UHPFRC in Bridge Rehabilitation and New Construction in Switzerland. Front Built Environ 2021; 7: 769686.

Reduce overdesign

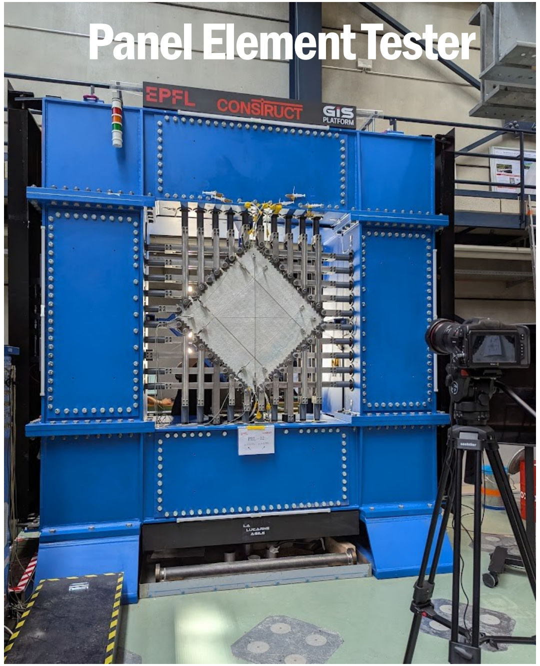
Table 3.3-5: Recommended target reliability indices β for structures to be designed, related to the specified reference periods

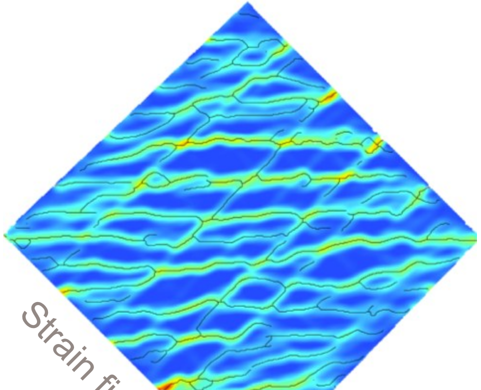
Limit states	Target reliability index β	Reference period	
Serviceability			
reversible	0.0	Service life	
irreversible	1.5	50 years	
irreversible	3.0	1 year	
Ultimate			
low consequence of failure	3.1	50 years	← 1 in 1000
	4.1	1 year	
medium consequence of failure	3.8	50 years	← 1 in 14000
	4.7	1 year	
high consequence of failure	4.3	50 years	← 1 in 120000
	5.1	1 year	

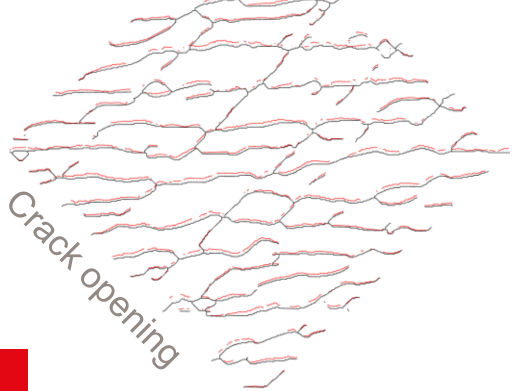
fib Model Code for Concrete Structures 2010

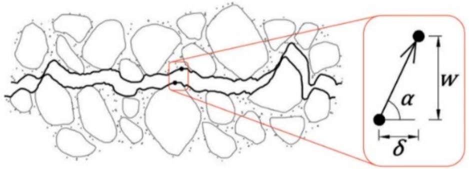


Mechanical behaviour of cracked concrete





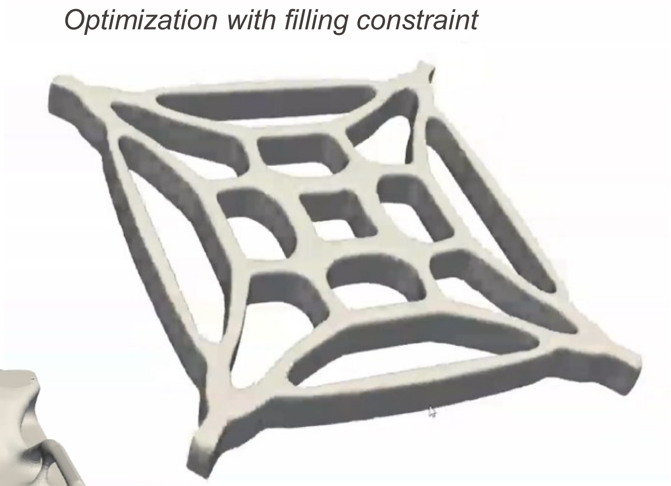


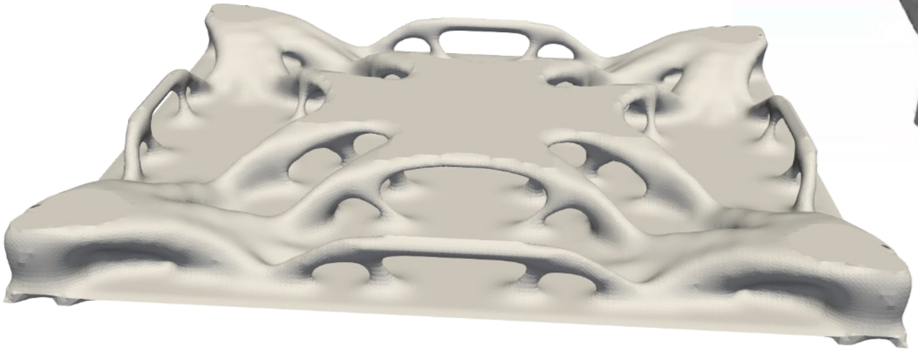


Elias Merhi
Ph.D. candidate

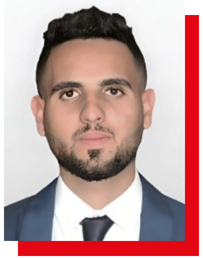
Structural optimization of slabs

Optimization with filling constraint





Freeform 3D optimization

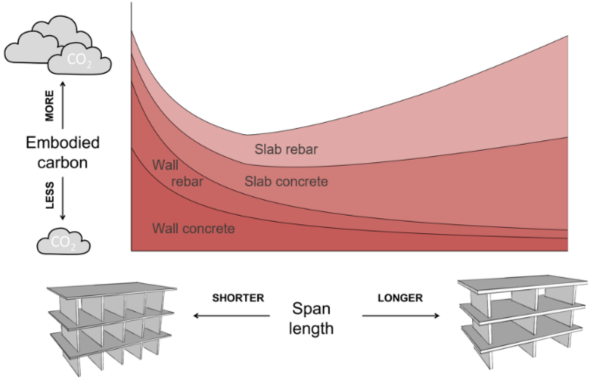


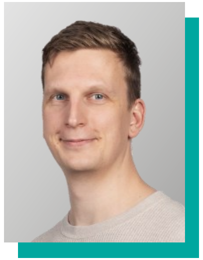
Ahmad Majdouba
Ph.D. candidate

Reuse of structural components

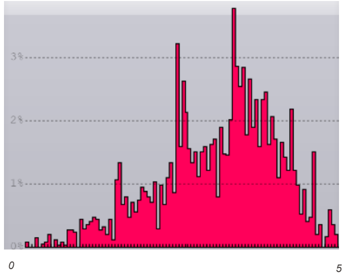
Design for adaptability

David Ruggiero

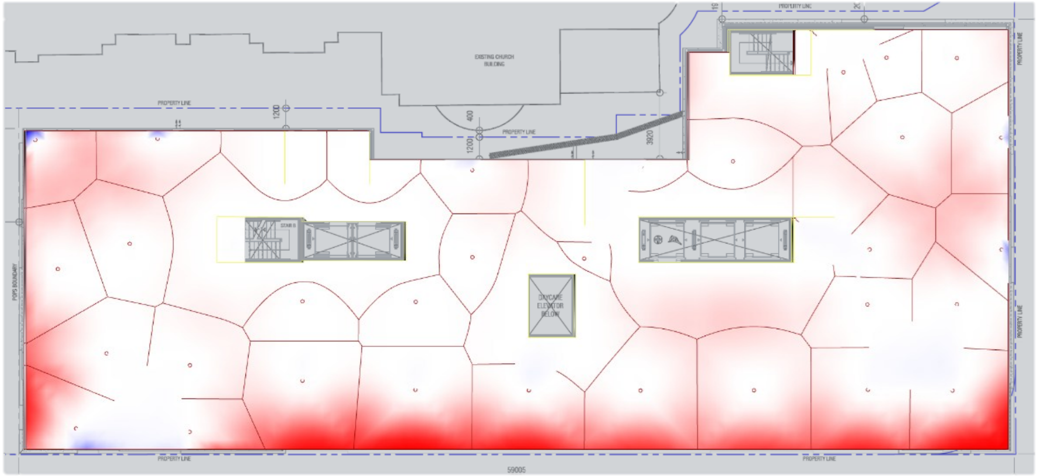




Sjonnie Boonstra
Former postdoctoral researcher



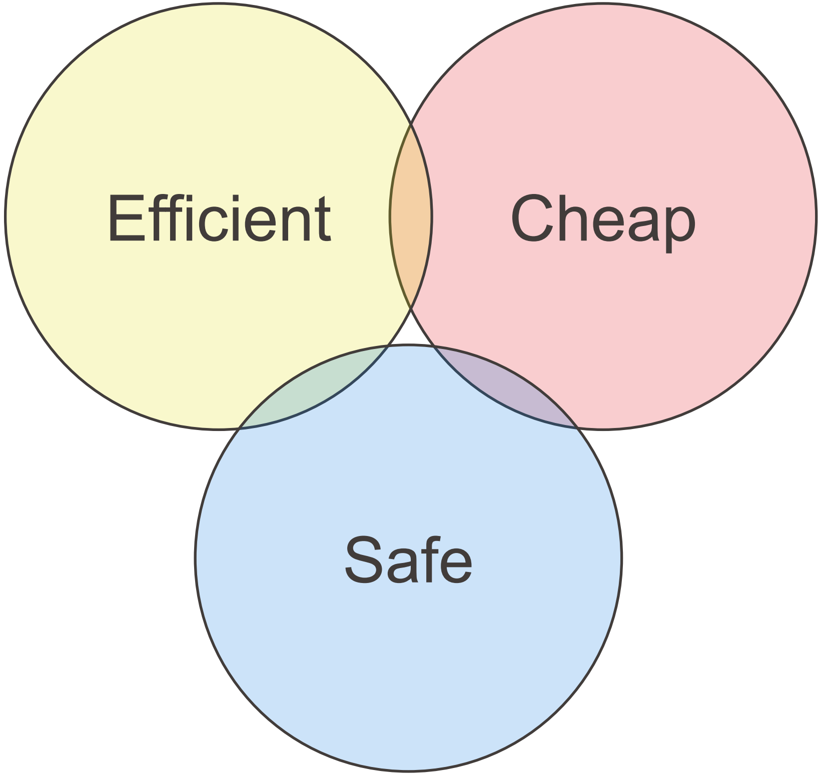
Span length distribution



Deflection/span ratio

SUSTAINABILITY AT THE STRUCTURAL SCALE

Value in structural design



Efficient

Cheap

Safe

A Promise to Future Generations

All appropriate measures shall be taken to ensure that the rights of future generations are protected and not sacrificed for the expedience and convenience of the present generation.

Oath for graduating Civil Engineering students at the University of Toronto

Questions?