Reducing Carbon Footprint with High Performance Steel - Concrete Composite Construction

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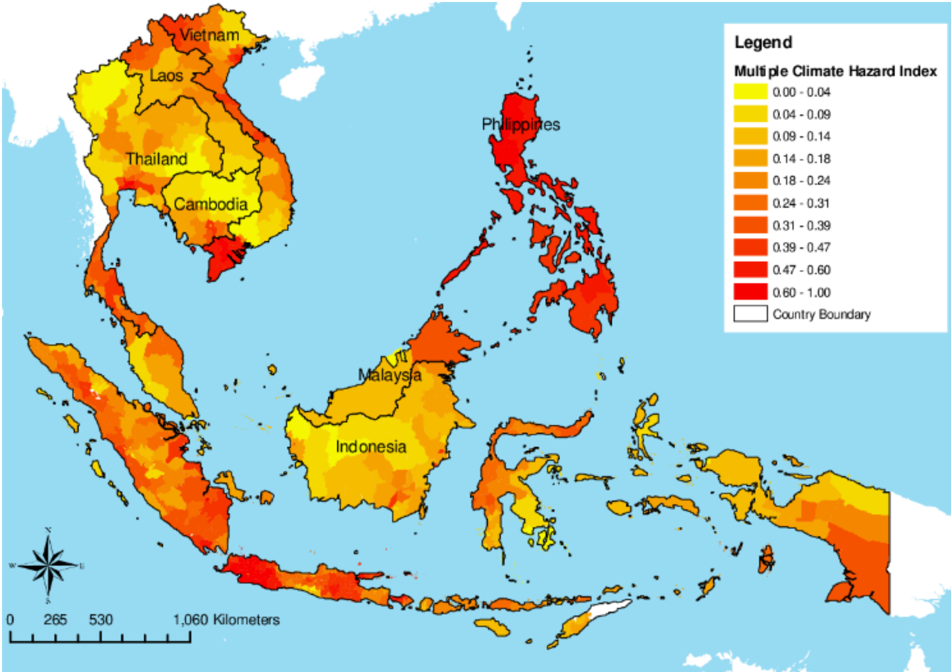
Sustainability in the Built Environment

Minimize the Consequence of Climate Change

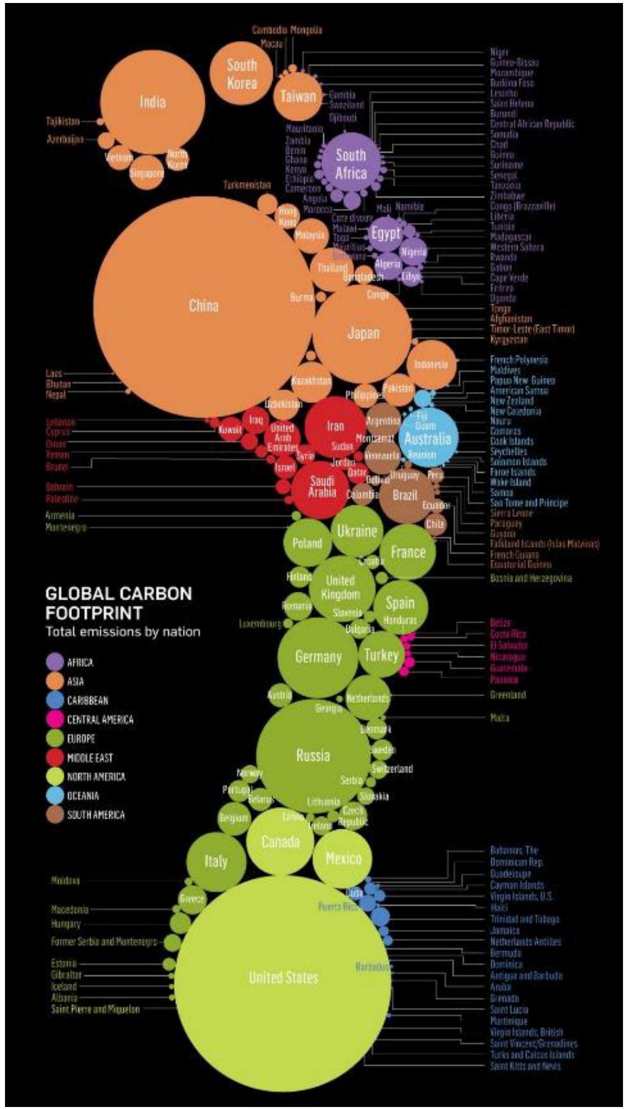
The Paris Agreement sets a goal to limit global average temperature increase to ‘well below 2°C above preindustrial levels’ and to ‘pursue efforts’ to limit it to 1.5°C.

- **Greenhouse gas removal**
- **Rapid decrease in carbon emissions**



Southeast Asia is on the frontlines of efforts to counter climate change and its impacts.

- mean temperature increased by 0.1 to 0.3 °C per decade between 1951 and 2000
- rainfall trended downward from 1960 to 2000
- sea levels have risen 1 to 3 mm per year.
- Heat waves, droughts, floods, and tropical cyclones have also become more intense and frequent.



Source: *1. Yusuf, A., & Francisco, H. (2009). Climate change vulnerability mapping for Southeast Asia.*
2. Environment Division of the ASEAN Secretariat
3. Venngage.com

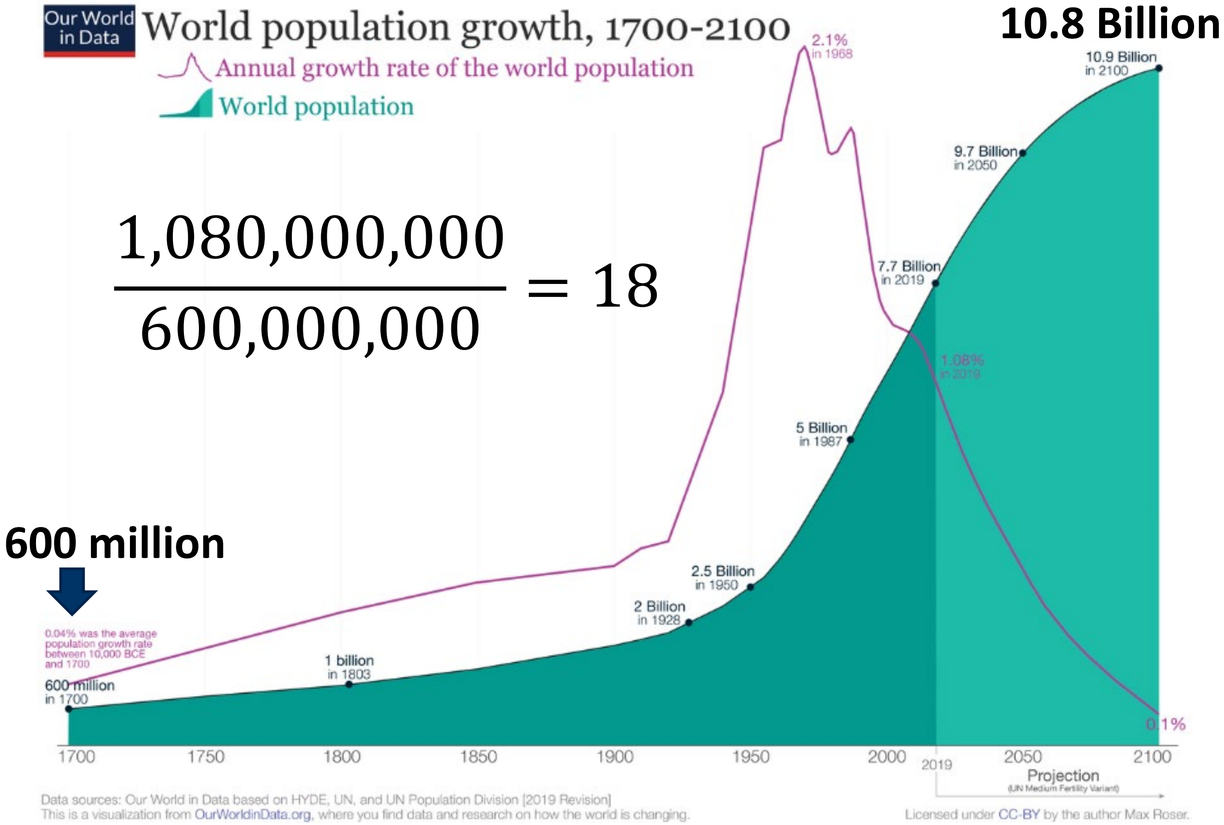
What Has Changed from 17th Century to 21st Century?

1. Living quality shall not be sacrificed

Cooler Times: A depiction of Frost Fair at Temple Stairs on London's River Thames in 1684

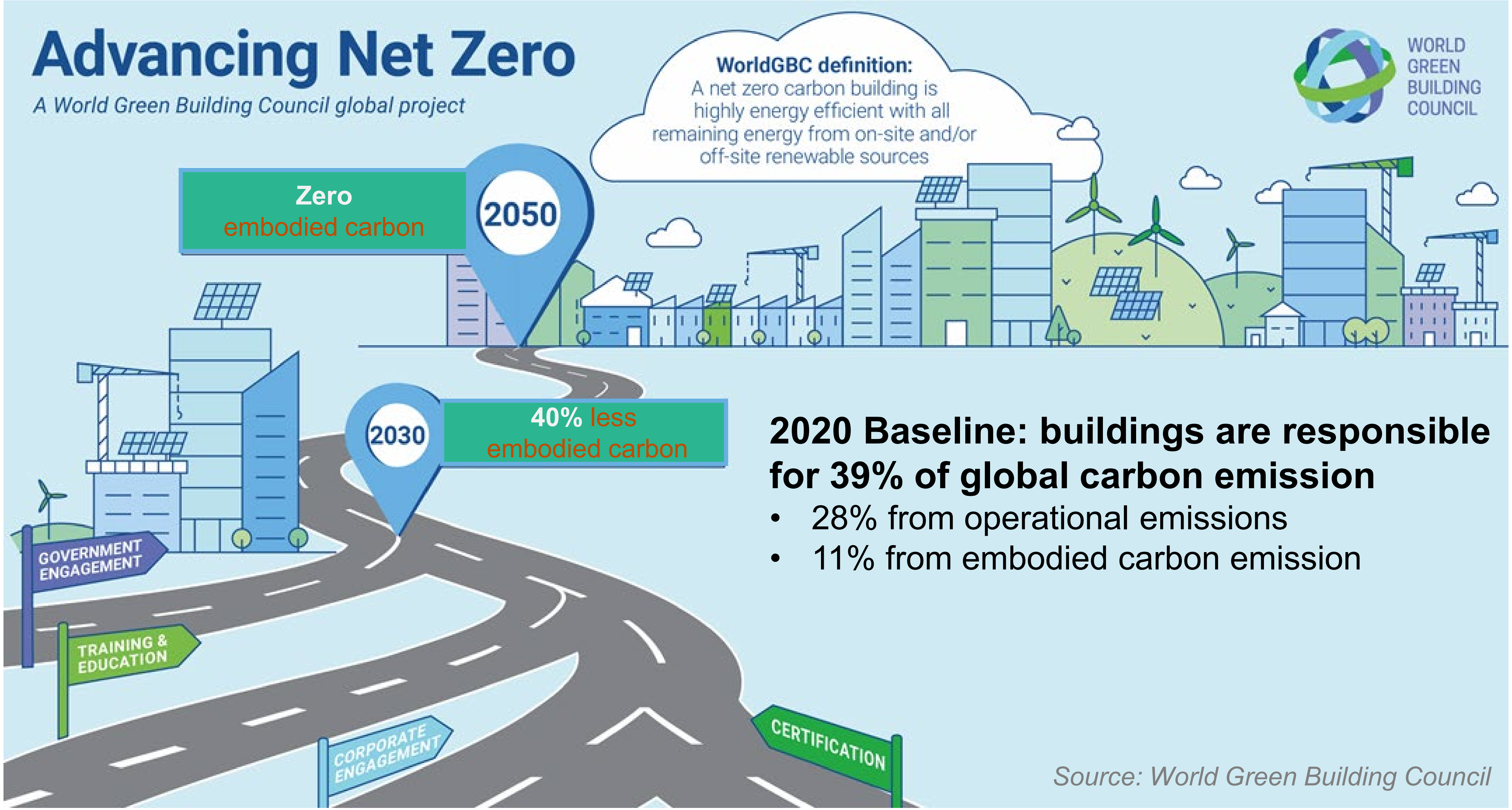
https://www.museumoflondon.org.uk/discover/frost-fairs

2. Significant increase in emissions / person



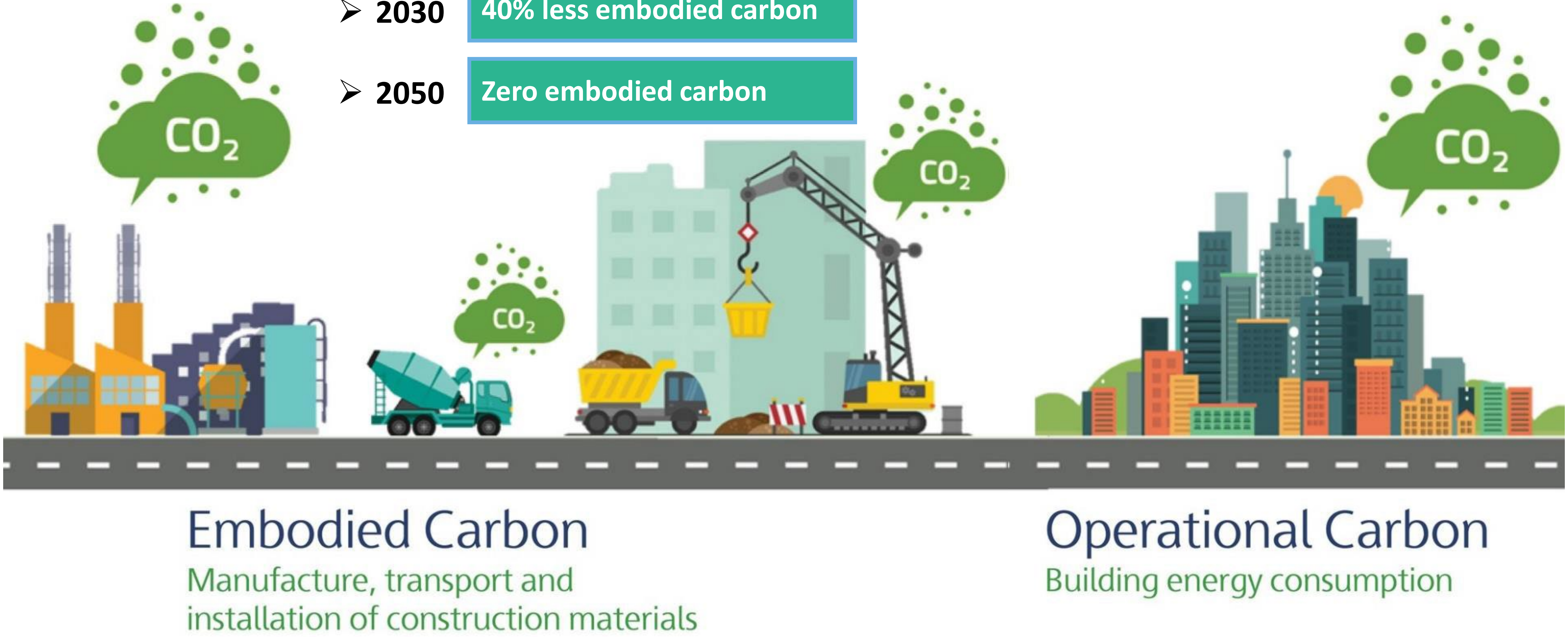
$$\frac{1{,}080{,}000{,}000}{600{,}000{,}000} = 18$$

Sustainability in the Built Environment



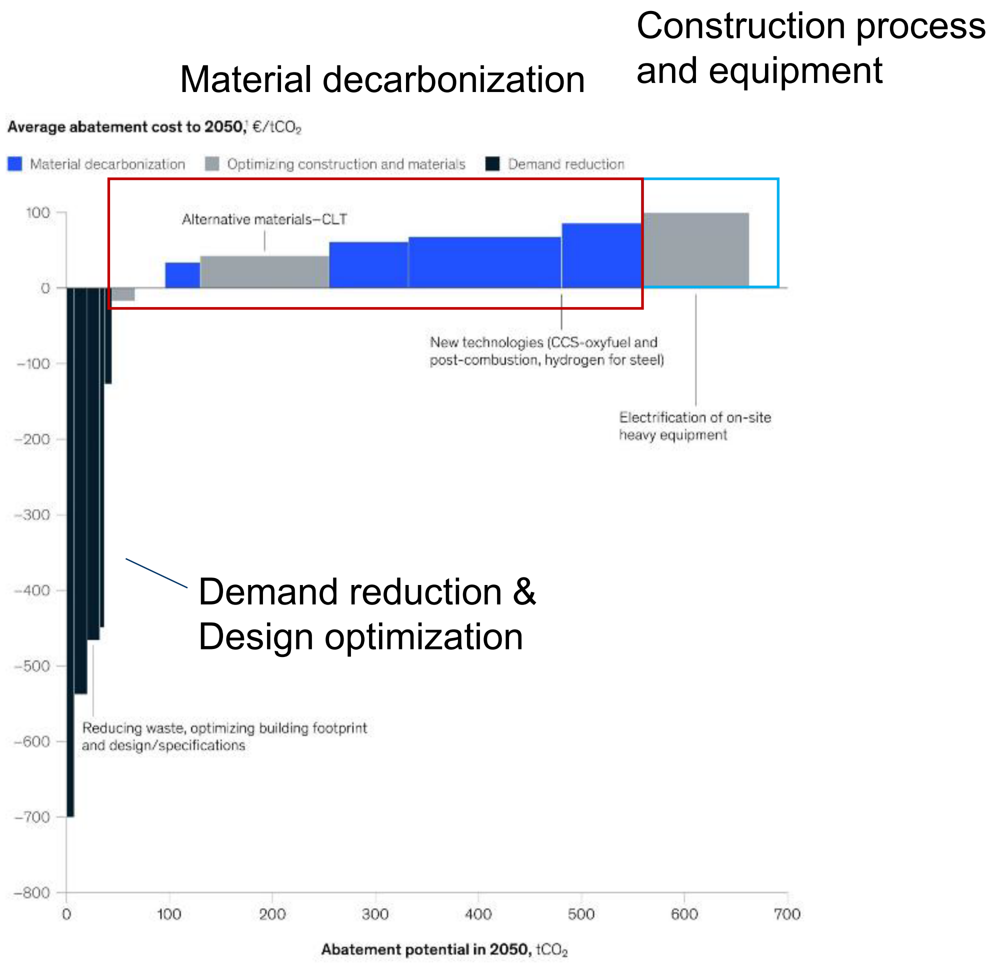
What is Embodied Carbon

- **2030** 40% less embodied carbon
- **2050** Zero embodied carbon



Source: Skanska

Reducing the Emissions Impact of New Builds



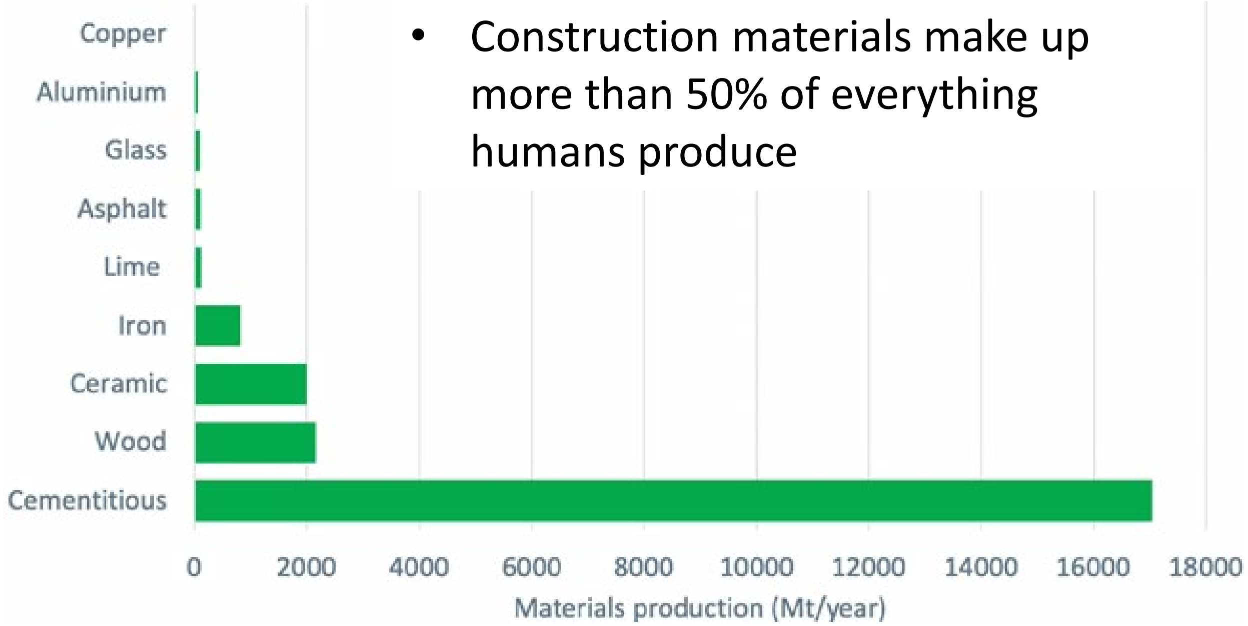
Source: McKinsey & Company

❑ **Demand reduction and circularity**
- Design and process optimization
- Increasing closed-loop circularity for materials and components

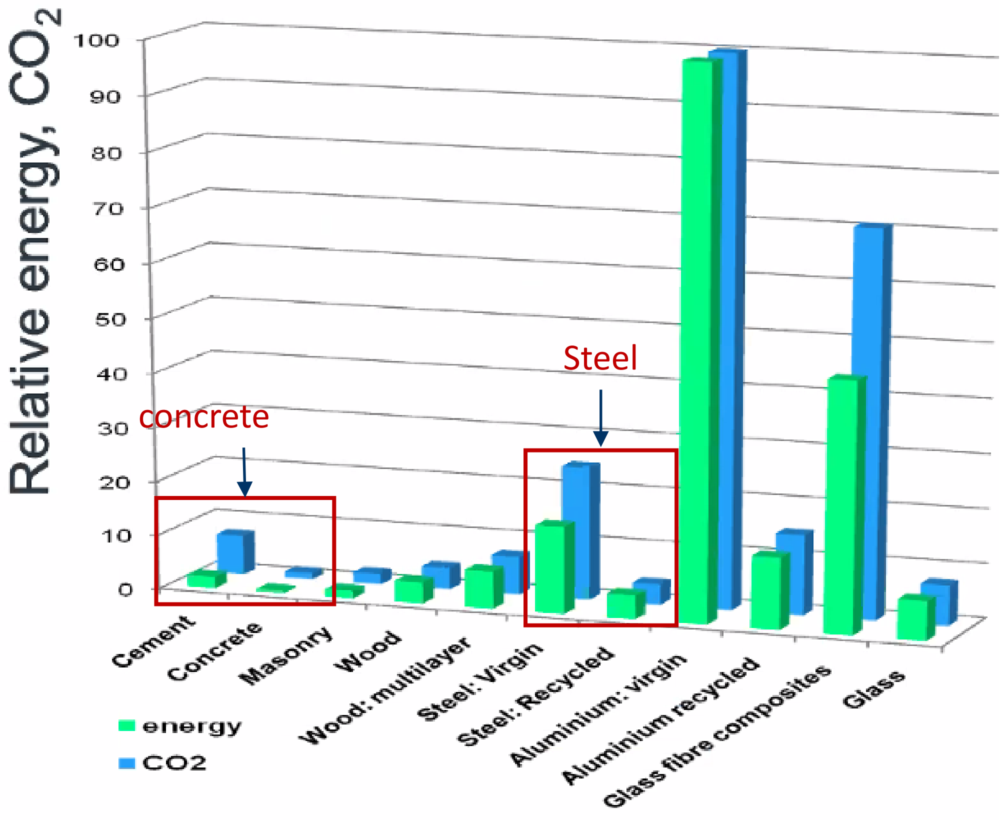
❑ **Material decarbonization**
- Reducing emissions during production of materials

➢ **High performance material and construction**
- Energy efficient materials *(e.g., low-carbon materials, higher-performing materials)*
- Modularization and off-site construction *(e.g., lower consumption onsite and electrification of heavy equipment)*

Towards 2030: What is Available?



- Construction materials make up more than 50% of everything humans produce



Source: ICE version 1.6a
Hammond G.P. and Jones C.I.
2008 Proc Instn Civil Engineers

Current Status

Concrete and Steel can not be replaced by alternatives in a short time

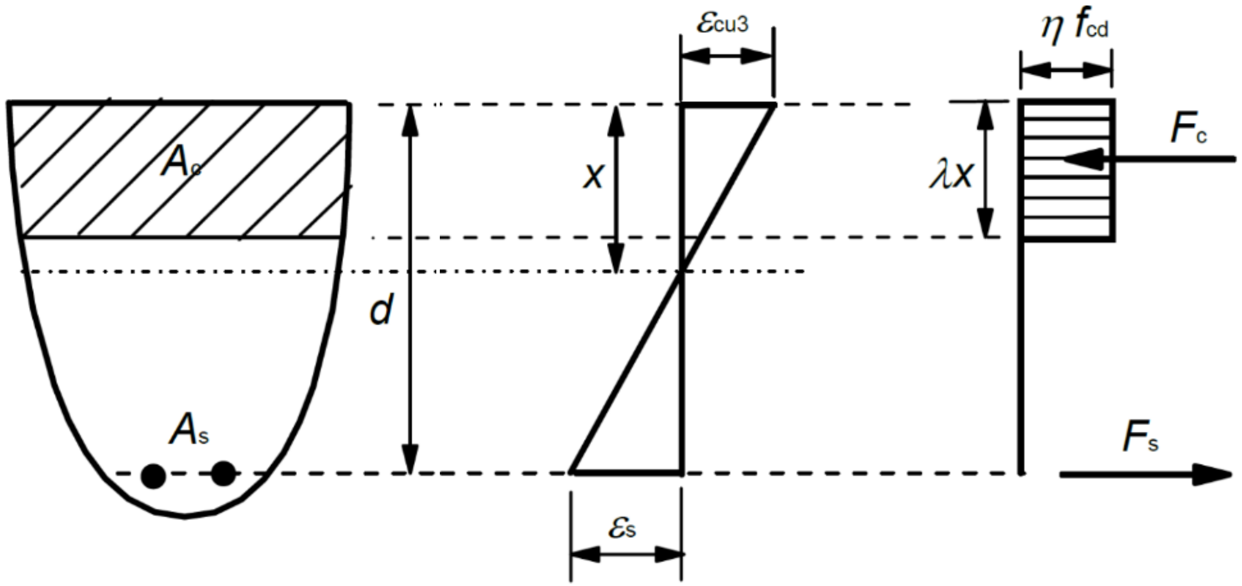
Solutions:
1. Use less and better materials
2. Improve structural efficiency
3. Use recycled materials

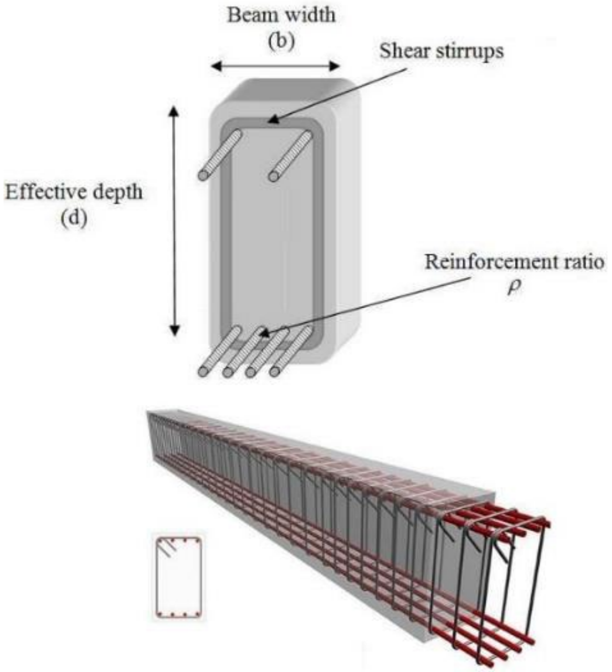
Structural Optimization

EC2: Rectangular stress distribution for RC beams subjected to bending

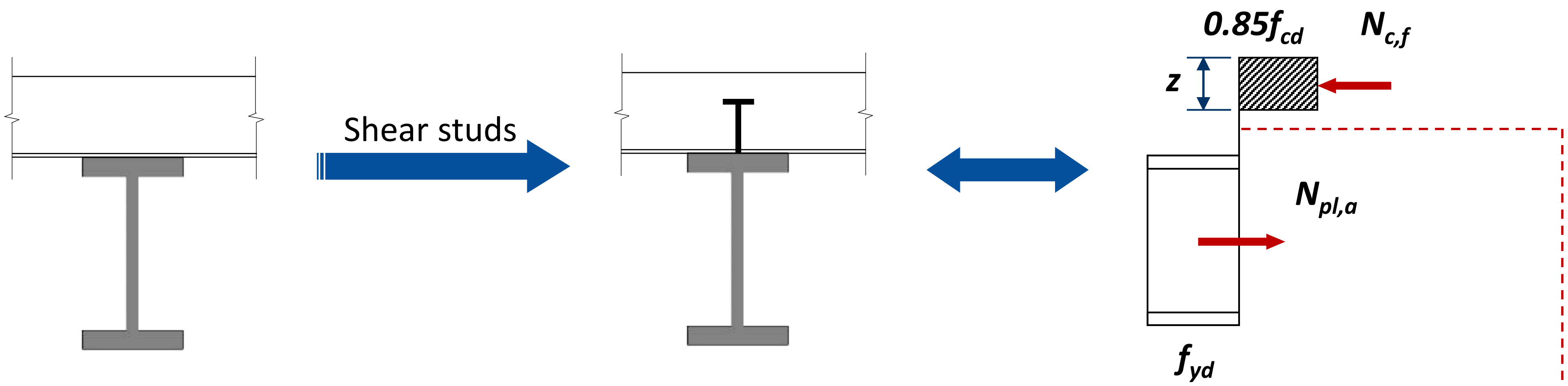
$x \leq 0.45\text{d}$

$\geq 0.55\text{d}$ NOT contributing to bending moment resistance





From EC2&EC3 to EC4: Enhanced Efficiency

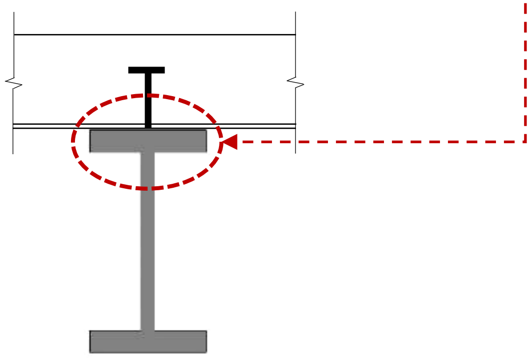


Composition action

Ideal situation:

- Concrete is taking compression and steel is taking tension.
- LTB of steel is restrained by concrete.

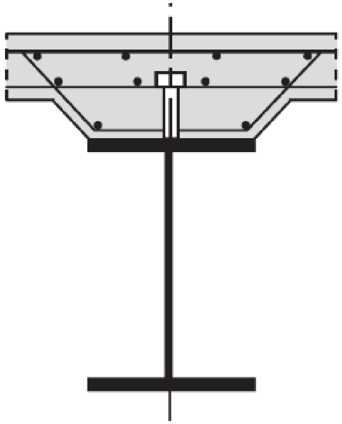
However… something is not working



In the case of 762 x 267 UB173, top flange contribute to ***45.3 kg/m (26.2% of total weight)****.*

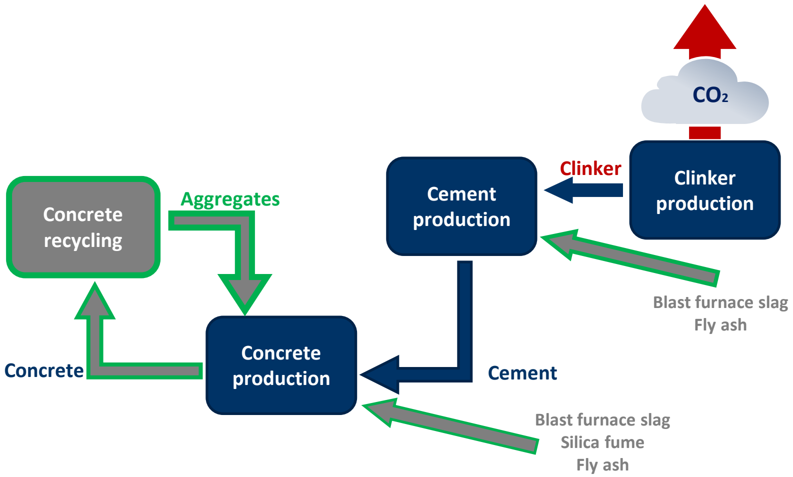
High Performance Pre-Engineered Steel-Concrete Composite Beams (HPB) for Sustainable Construction

Concrete 200mm



UB 914x419x343

Conventional Design



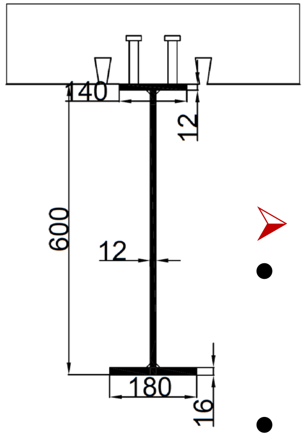
Performance improvement & eCO2 control

Conventional UB

TTJ HISTEEL (high strength)

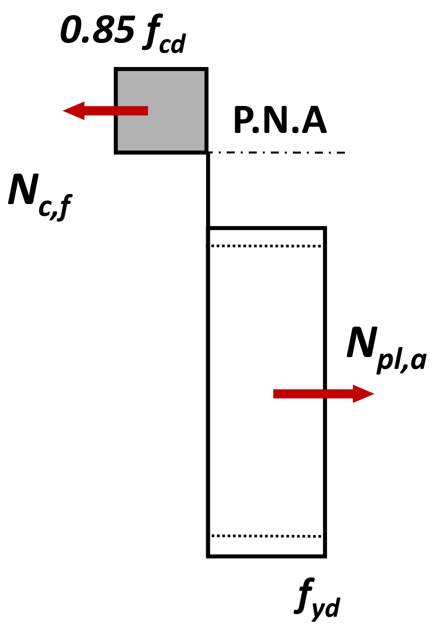
High performance pre-engineered sections

Maximized structural efficiency

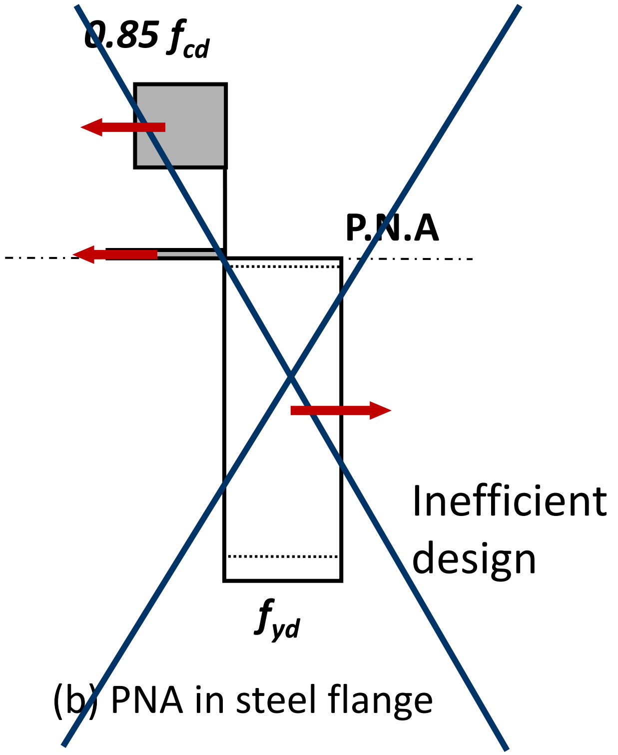


- **Ideal situation:**
  - Concrete taking compression and steel taking tension only.
  - LTB of steel is restrained by concrete.

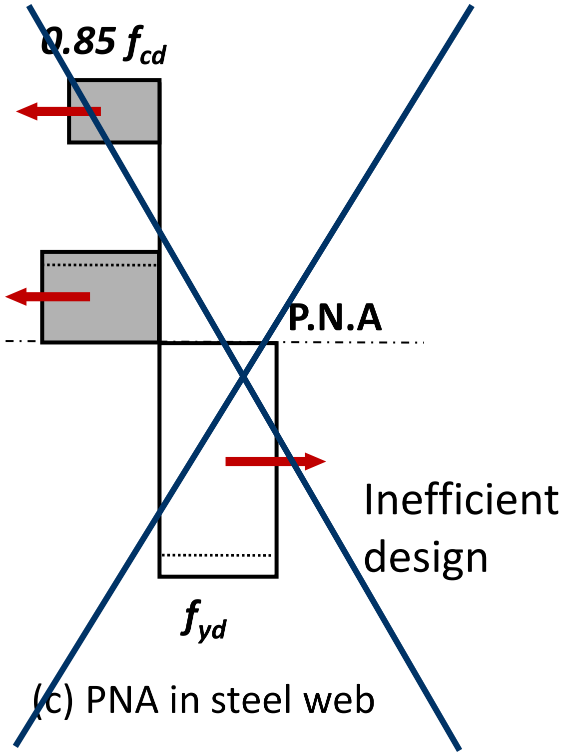
Positions of the P.N.A.



(a) PNA in slab



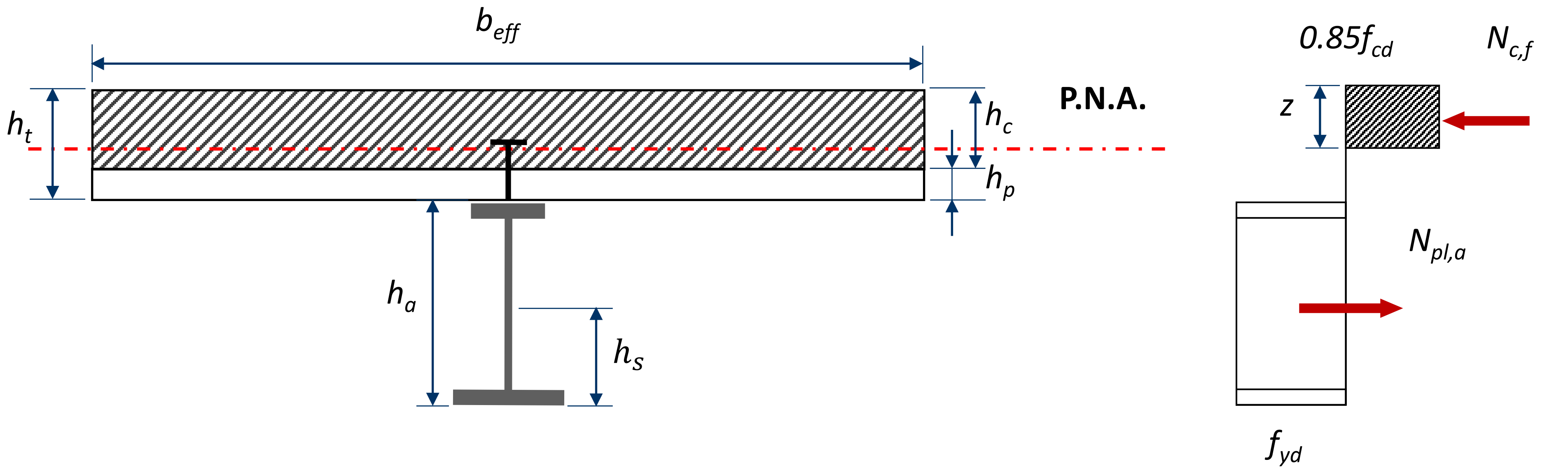
(b) PNA in steel flange



(c) PNA in steel web

Steel section in tension!

P.N.A in Concrete Slab (ULS)



The compressive resistance of concrete slab is:

$$N_{c,f} = h_c b_{eff} \left(0.85 f_{cd}\right)$$

The tensile resistance of steel beam is:

$$N_{pl,a} = A_a f_y / \gamma_a$$

Design Moment Resistance $M_{pl,Rd}$

The depth of the plastic neutral axis z measured from the upper surface of the slab is obtained from force equilibrium:

$$z = N_{pl,a}/(b_{eff} \cdot 0.85 f_{cd}) \quad < h_c$$

Centroid of the pre-engineered section from the edge of the bottom flange:

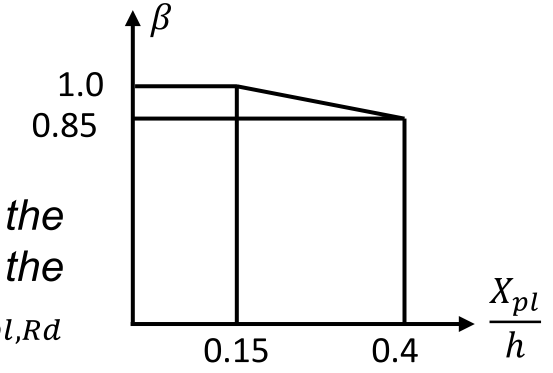
$$h_s = \frac{\sum A_i y_i}{A_a} = \frac{b_{f1} t_{f1}\left(h_a - 0.5 t_{f1}\right) + h_w t_w\left(0.5 h_w + t_{f2}\right) + 0.5 b_{f2} t_{f2}^2}{A_a}$$

The moment resistance is:

$$M_{pl,Rd} = N_{pl.a}(h_a - h_s + h_c + h_p - 0.5z)$$

or

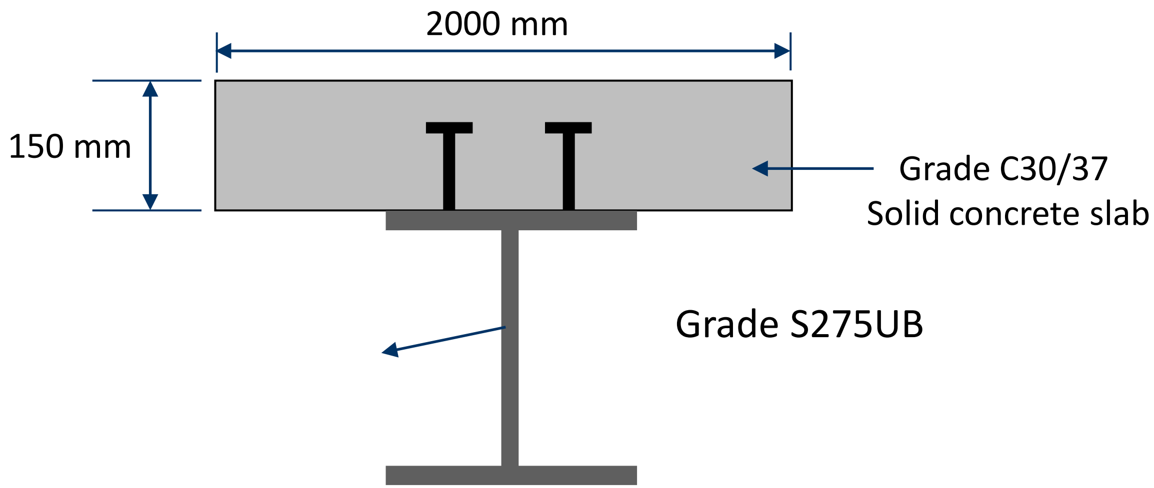
$$M_{pl,Rd} = N_{pl.a}(h_a - h_s + h_c + h_p - \frac{N_{pl,a}}{N_{c,f}} \frac{h_c}{2})$$

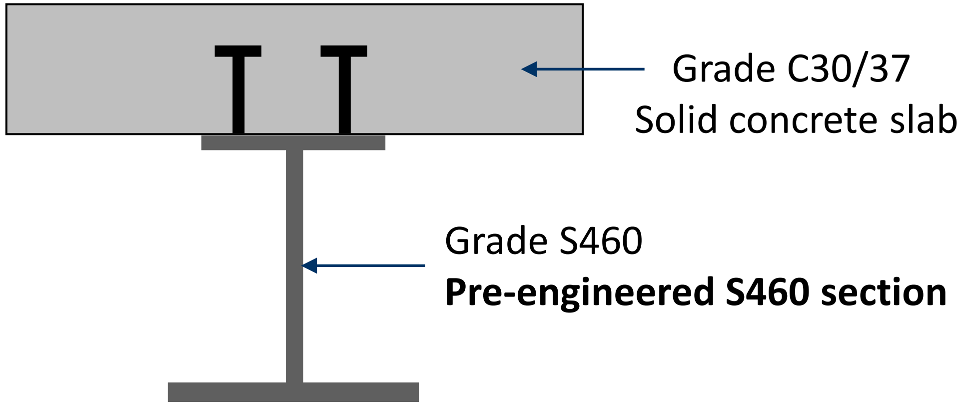


Note: *for composite cross-section with structural steel S420 or S460, where distance z between the plastic neutral axis and the extreme fibre of the concrete slab in compression exceeds 15% of the overall depth h of the member, the design resistance moment* M_{Rd} *should be taken as* $\beta M_{pl,Rd}$ *where* β *is a reduction factor.*

Worked Example

The simply-supported composite beam with an effective cross-section shown in the figure is subjected to an ultimate factored design uniformly distributed action of 40 kN/m acting along its entire span of 12m. For simplicity, assume full shear connection and ignore self-weight.





The mid-span design bending moment is:

$$M_{Ed} = \frac{qL^2}{8} = 40 \times \frac{12^2}{8} = 720\ kNm$$

Concrete slab resistance and neutral axis

Conventional UB design

Effective width of compression flange of the composite beam

$$b_{eff} = 2000\ mm$$

Compression resistance of the concrete slab

$$N_{c,f} = h_c b_{eff}(0.85 f_{cd}) = 5100\ kN$$

Tensile resistance of the steel section

$$N_{pl,a} = A_a f_{yd} = 2351.25\ kN$$

If $N_{c,f} > N_{pl,a}$, PNAis in concrete slab
If $N_{c,f} < N_{pl,a}$, PNA is in the flange of steel beam
If $N_{pl,a} - N_{c,f} > 2 b_f t_f f_{yd}$, PNA in the web of steel beam

Pre-engineered S460 section design

Effective width of compression flange of the composite beam

$$b_{eff} = 2000\ mm$$

Compression resistance of the concrete slab

$$N_{c,f} = h_c b_{eff}(0.85 f_{cd}) = 5100\ kN$$

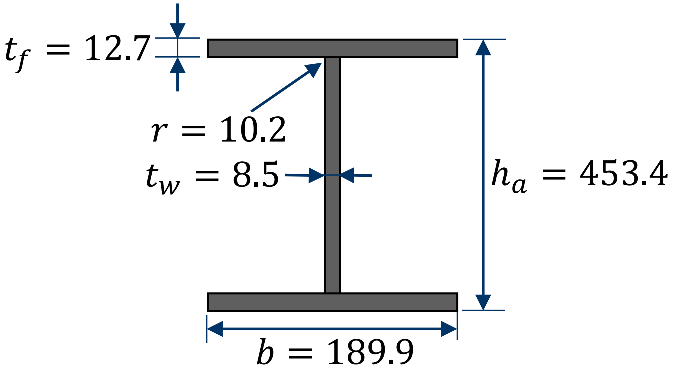
Design the pre-engineered section
$z = N_{pl,a}/(b_{eff} \cdot 0.85 f_{cd}) < h_c$ and $z < 0.15h$

Check position of the plastic N.A. v.s. Design the position of the plastic N.A.

Section properties

Conventional UB design

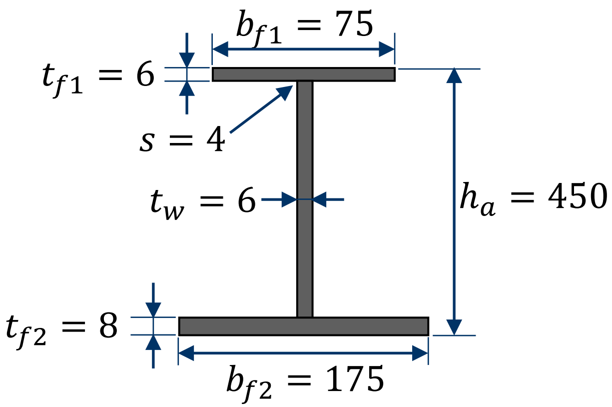
457×191 UB67 Grade S275



$$A_a = 8550\,mm^2$$
$$N_{pl,a} = 2351.25\,kN$$
$$h_s = 0.5h_a = 226.7\,mm$$

Pre-engineered S460 section design

S460 design:



$$A_a = t_{f1}b_{f1} + t_w(h_a - t_{f1} - t_{f2}) + t_{f2}b_{f2} = 4466\,mm^2$$
$$N_{pl,a} = A_a f_{yd} = 2054.4\,kN$$
$$h_s = \frac{\sum A_i y_i}{A_a}$$
$$= \frac{b_{f1}t_{f1}(h_a - 0.5t_{f1}) + h_w t_w(0.5h_w + t_{f2}) + 0.5b_{f2}t_{f2}^2}{A_a}$$
$$= 178.7\,mm$$

Bending resistance

Conventional UB design

$$z = \frac{N_{pl,a}}{b_{eff} \cdot 0.85 f_{cd}} = 69.2\ mm < h_c = 150\ mm$$

The moment resistance is:

$$M_{pl,Rd} = N_{pl,a}(0.5h_c + h_c - 0.5z)$$
$$= 2351.25 \times \frac{0.5 \times 453.4 + 150 - 0.5 \times 69.2}{1000}$$
$$= 803\ kNm > M_{Ed}$$

Bending resistance of the composite section is adequate.

Pre-engineered S460 section design

$$z = \frac{N_{pl,a}}{b_{eff} \cdot 0.85 f_{cd}} = 60.4\ mm < h_c$$

The moment resistance is:

$$M_{pl,Rd} = N_{pl.a}\left(h_a - h_s + h_c + h_p - 0.5z\right)$$
$$= 2054.4 \times \frac{(450 - 178.7 + 150 - 0.5 \times 60.4)}{1000}$$
$$= 804\ kNm > M_{Ed}$$

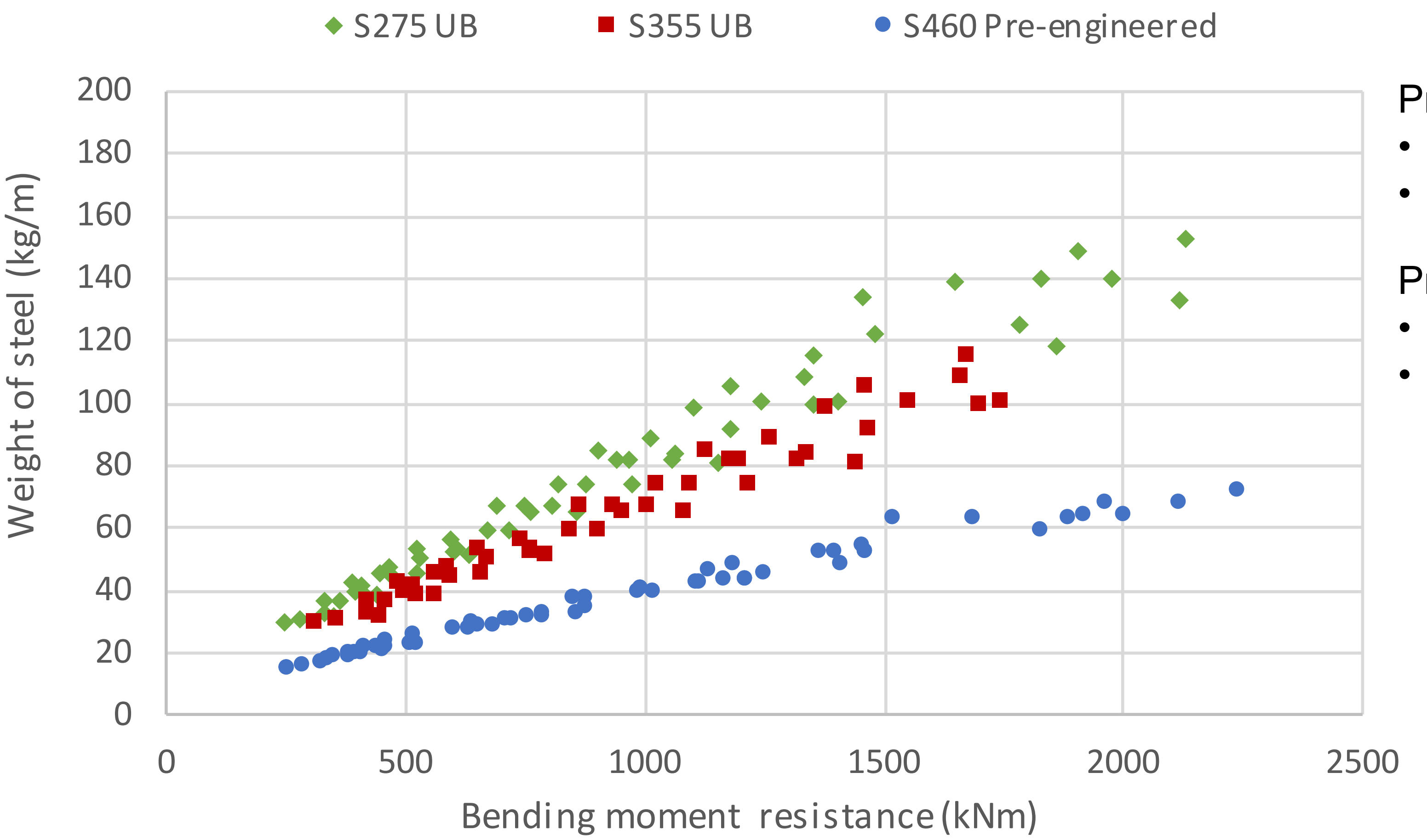
Bending resistance of the composite section is adequate.

Pre-engineered S460 section design v.s. Conventional UB design

$M_{pl,Rd}$ + 0.71%

Weight - 47.8%

Bending Moment Resistance vs. Weight of steel



Pre-engineered S460 v.s. S275UB

- 41.7% to 56.6% weight saving
- Average = 50.0%

Pre-engineered S460 v.s. S355UB

- 24.9% to 41.9% weight saving
- Average = 35.8%

Note: assuming a 150mm solid concrete slab, Grade C30/37, $b_{eff} = 2000\ mm$

Case Study: Long Span Industrial Buildings

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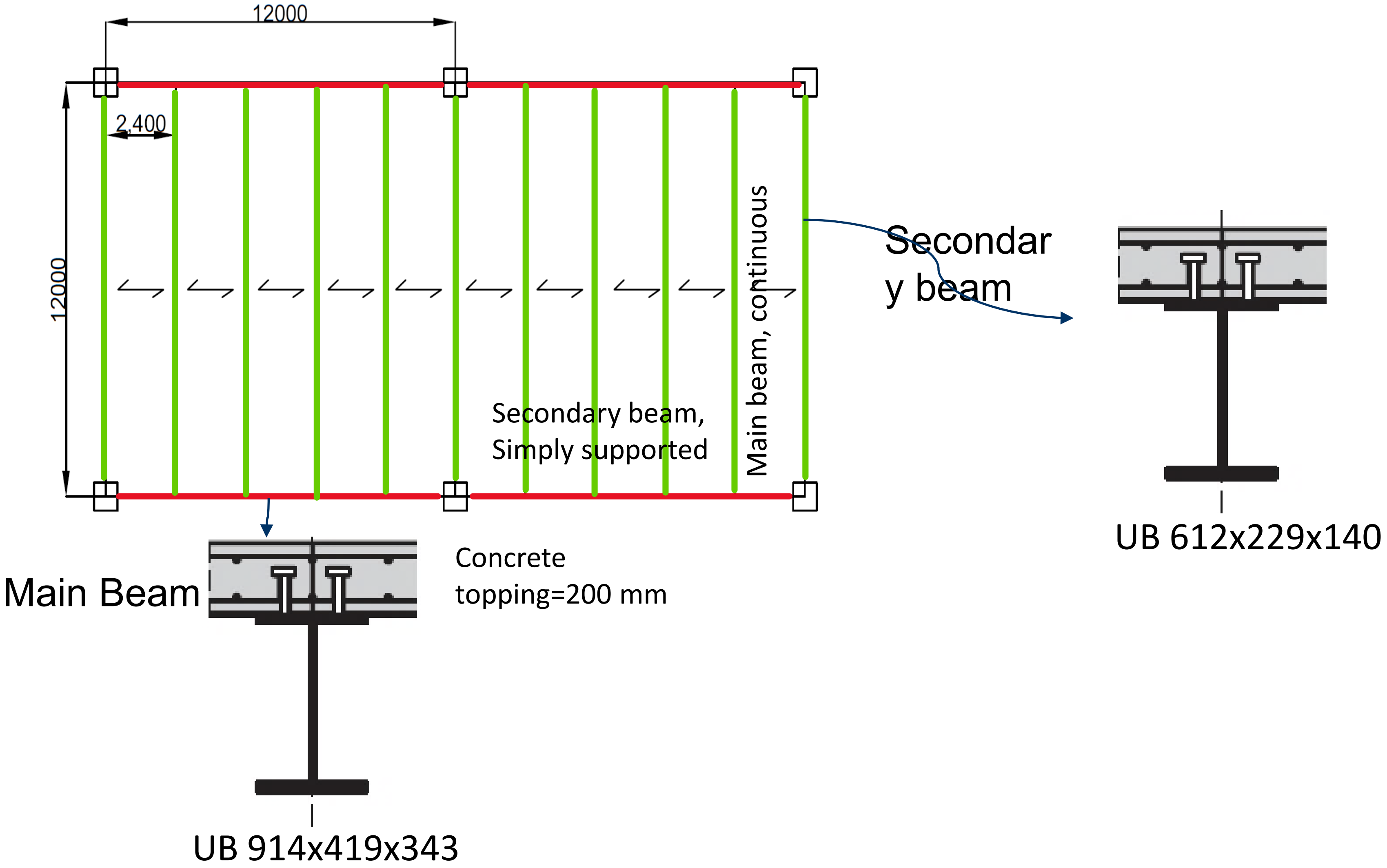
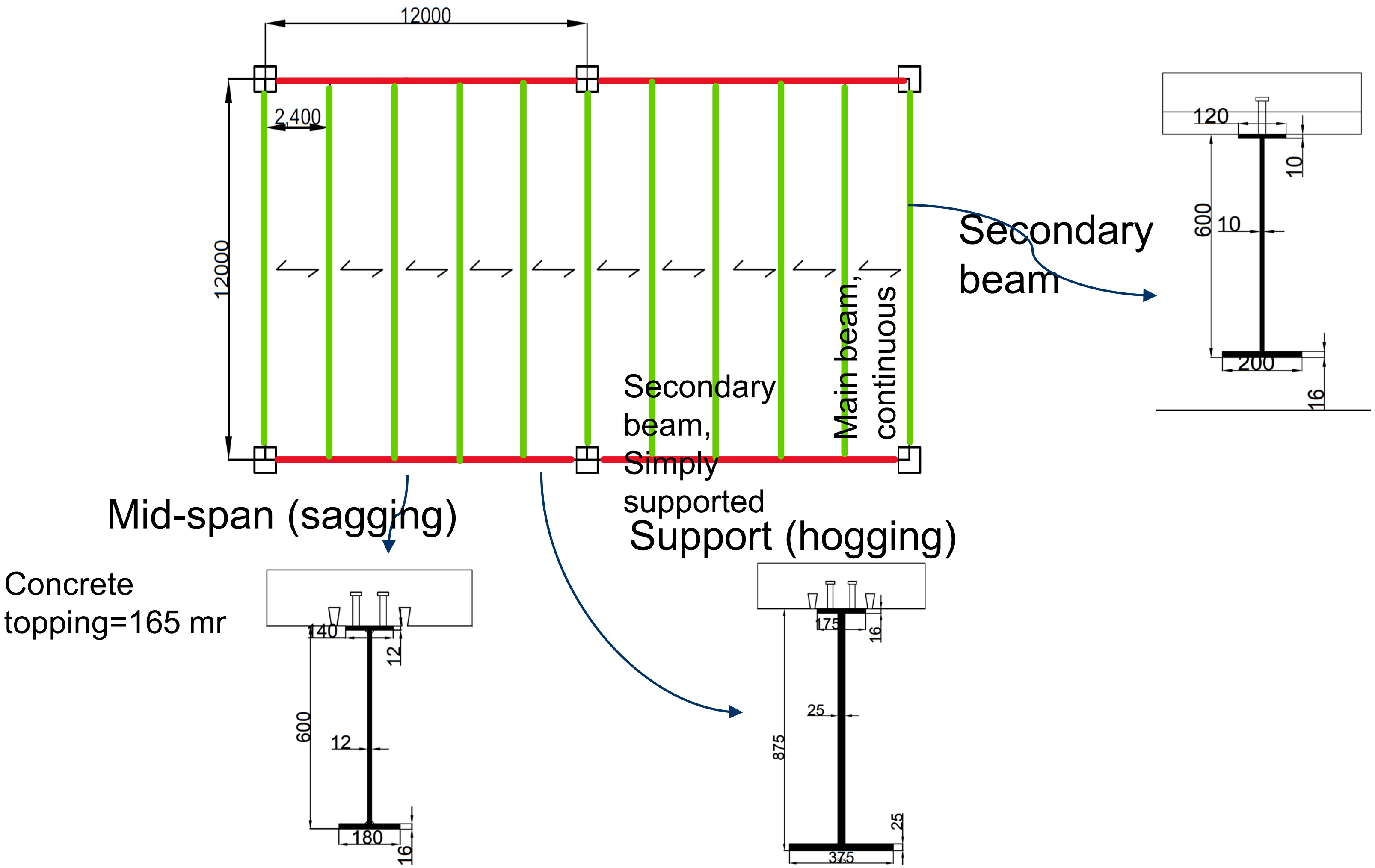
Live Load
- 15 kN/m^2

Conventional design
- **C355+C32/40**
- MB-column: fixed joint
- MB-SB: pinned joint



High Performance Beam (S460M+C60/75)



BCA Green Mark 2021 Carbon Calculator

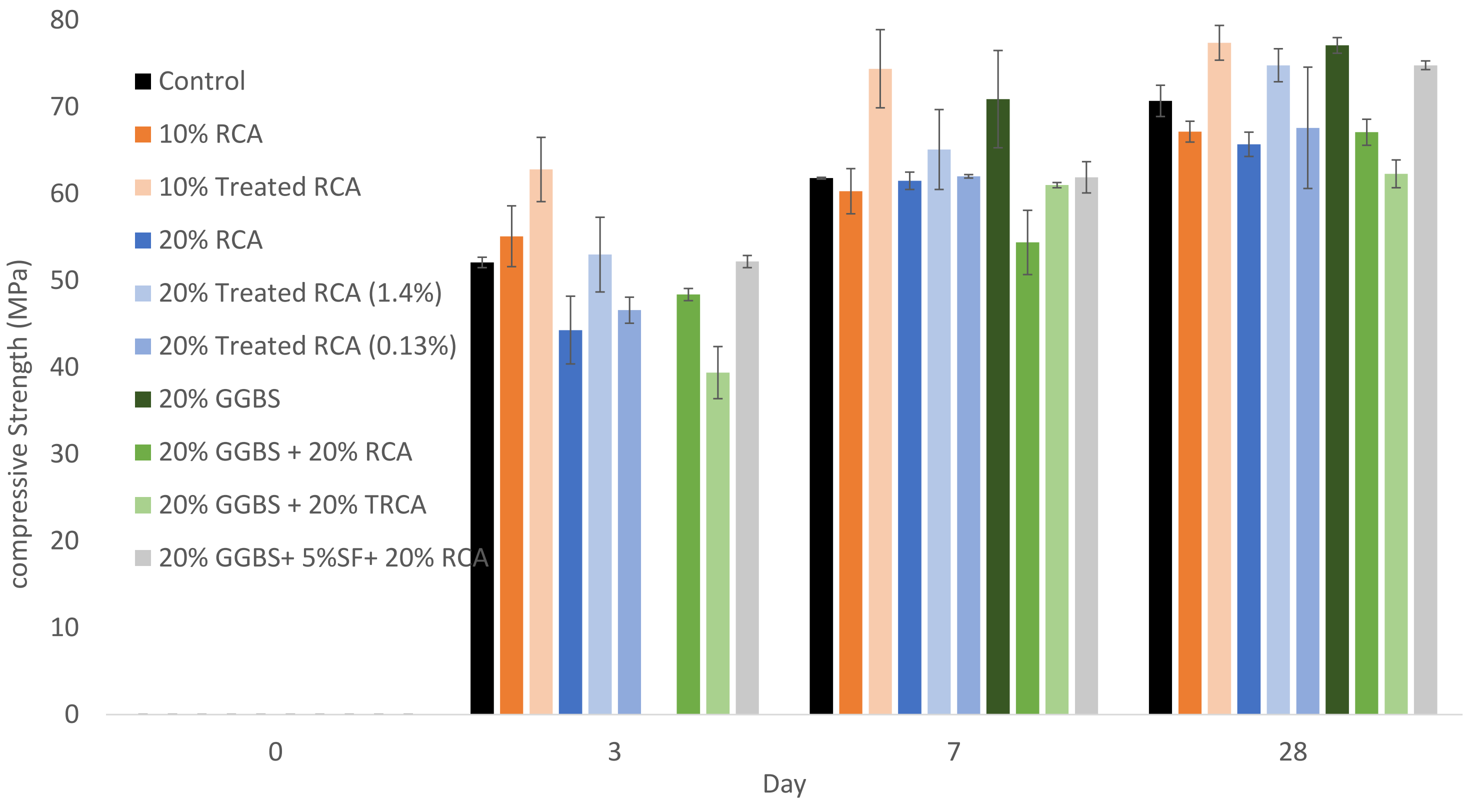
Concrete Type
Concrete (Natural)
Eco Concrete (15% Fly Ash Replacement)
Eco Concrete (30% Fly Ash Replacement)
Eco Concrete (25% GGBS Replacement)
Eco Concrete (50% GGBS Replacement)
Precast Concrete (Natural)
Precast Eco Concrete (15% Fly Ash Replacement)
Precast Eco Concrete (30% Fly Ash Replacement)
Precast Eco Concrete (25% GGBS Replacement)
Precast Eco Concrete (50% GGBS Replacement)
Glass
Glass
Steel
Primary/Secondary Steel
Others
Aluminium
Timber
Tiles
Paint
Bricks
Waterproofing
Carpet
Copper
Mineral Wool
Paper
Plaster
Plastic
Sealant
For Self-Inputs
Total Quantit 24.00 kg

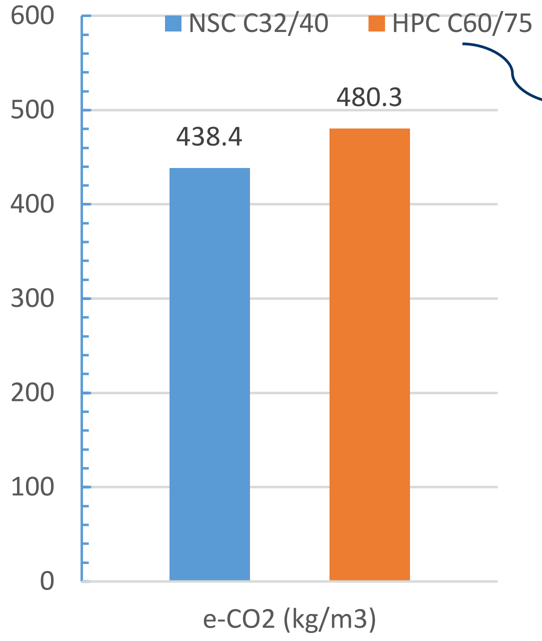
- Estimate the total upfront carbon emissions of the project based on materials declared.
- Has a built-in database for equivalent CO2 (CO2e) for common materials

For Super Sturcture - Material Details:					
Material / Grade	Quanity	Units	Source of product	Transport Emissions	Total Carbon (kgCO2e)
Concrete (Breakdown into components)					
Admixture					
Admixture	1.00	kg	Thailand	0.020974057	1.69 kg CO2e
Air entrainers	1.00	kg	Thailand	0.020974057	0.55 kg CO2e
Hardening Accelerators	1.00	kg	Thailand	0.020974057	2.30 kg CO2e
Plasticisers and	1.00	kg	Thailand	0.020974057	1.90 kg CO2e
Retarders	1.00	kg	Thailand	0.020974057	1.33 kg CO2e
Set Accelerators	1.00	kg	Thailand	0.020974057	1.35 kg CO2e
Water Resisting	1.00	kg	Japan	0.069700071	2.74 kg CO2e
Cement					
Cement (OPC)	1.00	kg	Vietnam	0.025397566	0.94 kg CO2e
Fly Ash	1.00	kg	Vietnam	0.025397566	0.07 kg CO2e
Ground-Granulated	1.00	kg	Malaysia (west)	0.0622832	0.13 kg CO2e
Limestones	1.00	kg	Malaysia (west)	0.0622832	0.15 kg CO2e
Limestones Fines	1.00	kg	Malaysia (west)	0.0622832	0.14 kg CO2e
Coarse Aggregates					
egates_(RCA)	1.00	kg	Singapore	0.0047152	0.01 kg CO2e
Granite	1.00	kg	Myanmar	0.030087943	0.04 kg CO2e
Aggregates	1.00	kg	Myanmar	0.030087943	0.03 kg CO2e
Fine Aggregates					
Washed_Copper_Slag_(	1.00	kg			
Sand	1.00	kg	Cambodia	0.019635821	0.02 kg CO2e
Water					
Water	1.00	m3			0.01 kg CO2e

Material + Transport Emissions

e-CO2 of Materials

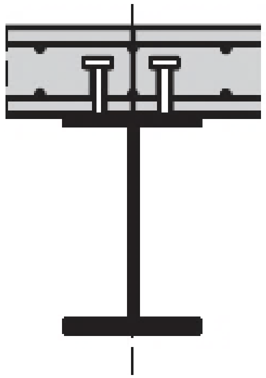


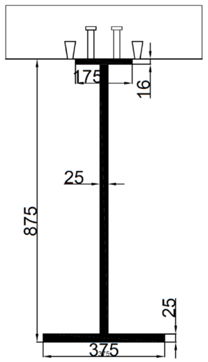


20% GGBS
5% Silica Fume
20% RCA

CO2 sequestration and utilization in concrete could further reduce the e-CO2

Weight and Carbon Analysis for the 12mx12m Floor



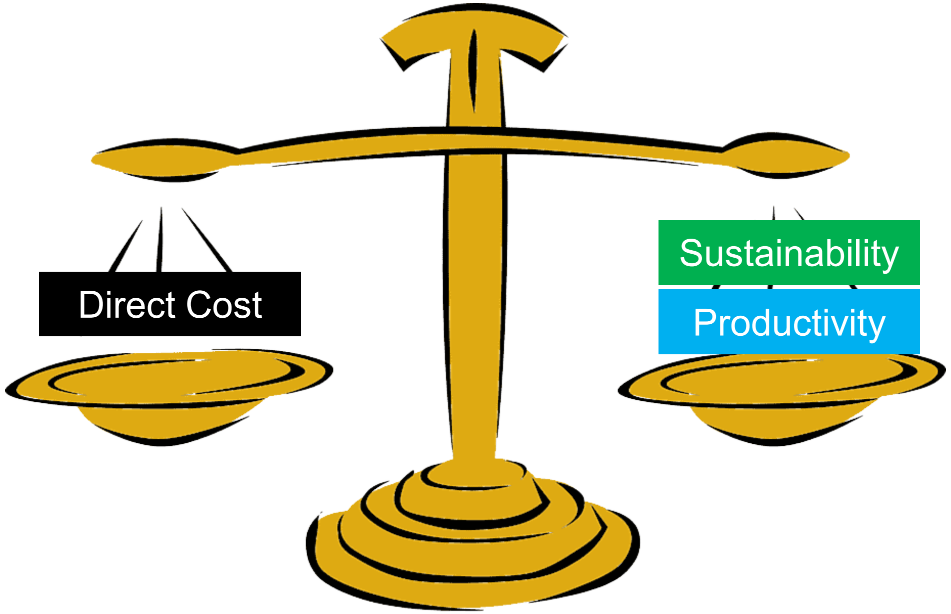


		e-CO2 (kg/kg)	Weight (tons)	e-CO2 (tons)
Conventional design	C32 (+2% rebar)	0.246	72.0	22.26
	S355 (SB)	2.89	10.1	29.13
	S355 (MB)	2.89	8.2	23.79
	Deck	2.53	1.6	4.01
	Total		91.9	79.19
HPB design	C60 (+2% rebar)	0.263	46.8	15.20
	S460 (SB)	3.76	5.9	21.99
	S460 (MB)	3.76	3.5	13.22
	Deck	2.53	1.6	4.01
	Total		57.8	54.42
Reduction			**37.1%**	**31.3%**

e-CO2 includes materials and transport

Concluding Remarks
- How to achieve 40% reduction in embodied carbon by 2030?

Time to change?



Q1: How to achieve 40% reduction in embodied carbon by 2030?

The proposed HPB system achieved 30% reduction on embodied carbon and 35% reduction on self-weight for long-span industrial and commercial buildings from:

- Reduced amount of raw materials used, especially OPC
- Improved structural efficiency

Q2: How much additional cost are we willing to pay for higher sustainability and productivity?