



**UHPFRC 2024**  
October 21-23  
Menton (France)



# NON-LINEAR FINITE ANALYSIS OF RIBBED VAULTED FLOOR MADE OF ECOLOGICAL UHPFRC



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UNIVERSITÉ  
LAVAL



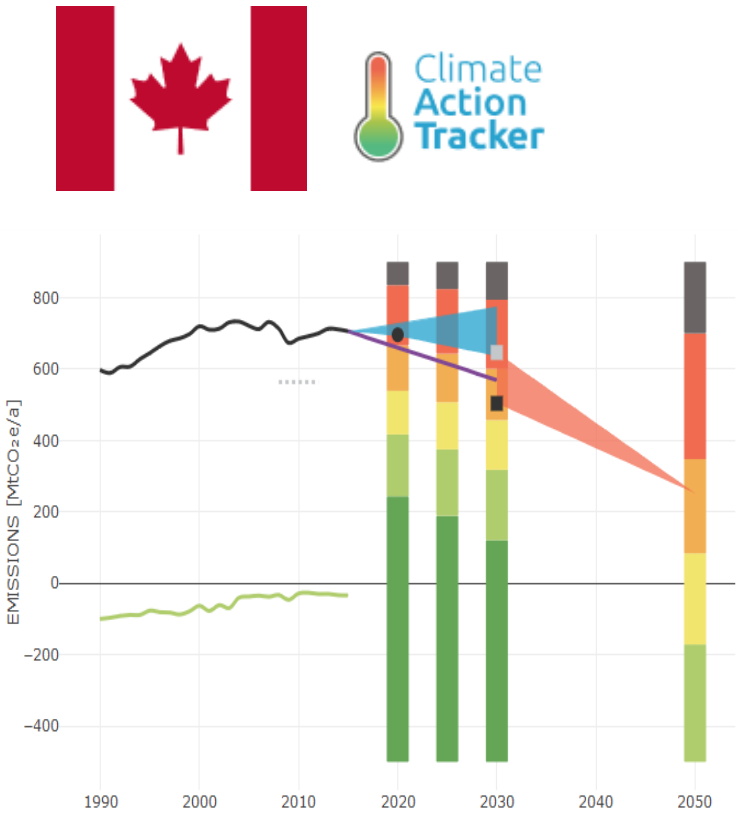
Salle Amphitheatre 16h00

# Agenda

- Industrial Problem
- Research problem : Objectives
- Methodology
- Finite Element Model
- Scenarios of Fiber Distribution
- Results
- Conclusions



# Industrial Problem



Canadian GHG emissions by sector in 1990 and 2018  
After (ECCC (Environment and Canada 2021));



# Industrial Problem



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et al.

UHPC  
ribbed  
vaulted



Education

## Defending the Most Sustainable Construction Material: Response to CNN



BY AALI R. ALIZADEH

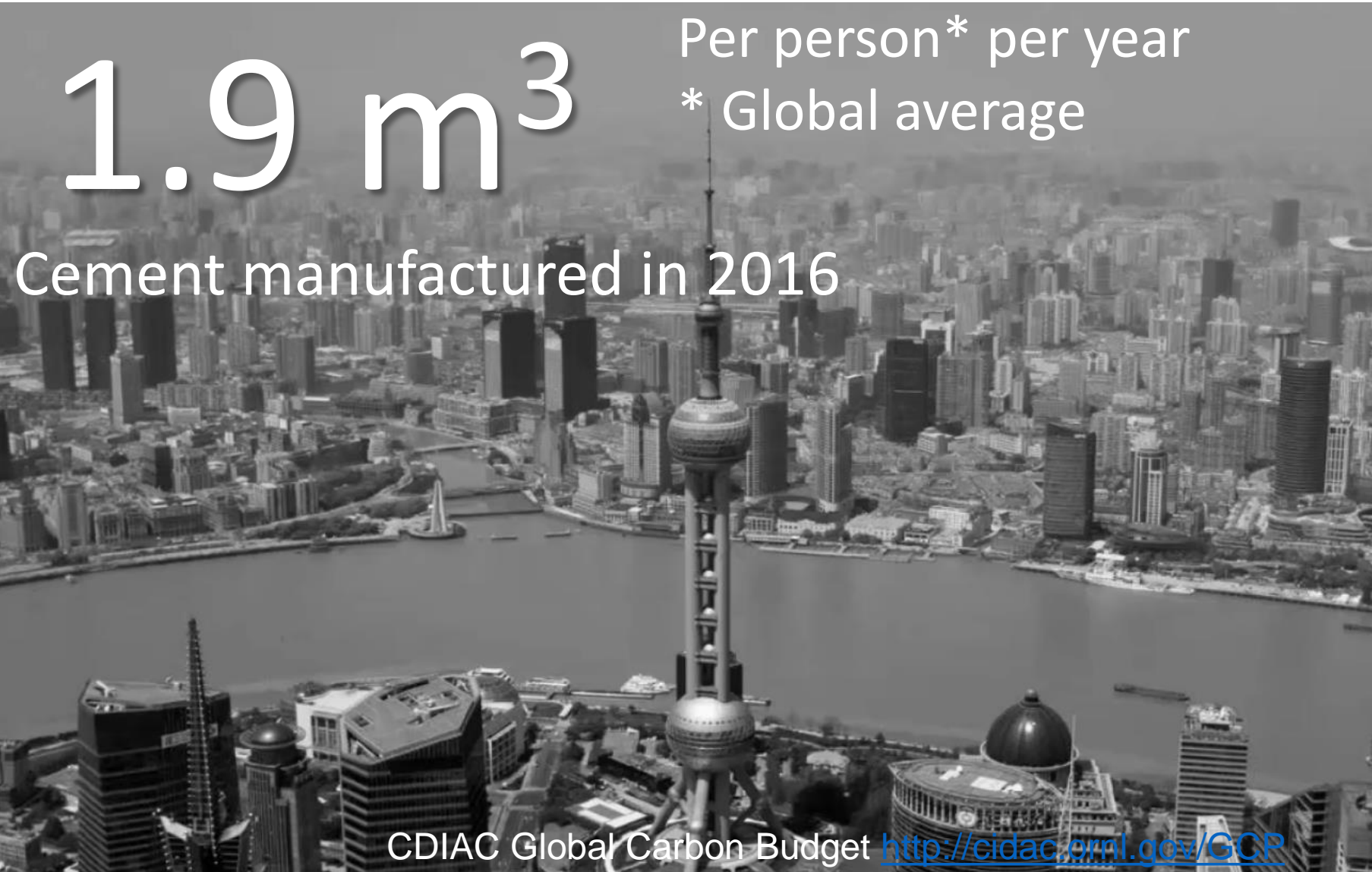
MAY 8, 2018



Material	Embodied Energy (MJ/kg)	Produced CO <sub>2</sub> (kg CO <sub>2</sub> / kg)
Concrete	0.95	0.13
Fired Clay Bricks	3	0.22
Wood (Platin Timber)	8.5	0.46
Wood (Multi-Layer Board)	15	0.81
Steel	35	2.8

<https://www.giatecscientific.com/education/defending-concrete-most-sustainable-construction-material/>

# Industrial Problem



UHPC  
ribbed  
vaulted



# Industrial Problem



 John Orr 2016  
50% more than necessary

## Environmentally inefficient design structures

1. Overdesigned structures
2. Structural grid spacing and regularity
3. Optimized element shape
4. Codes are imposing minimum limits for material

# Industrial Problem



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UHPC ribbed vaulted

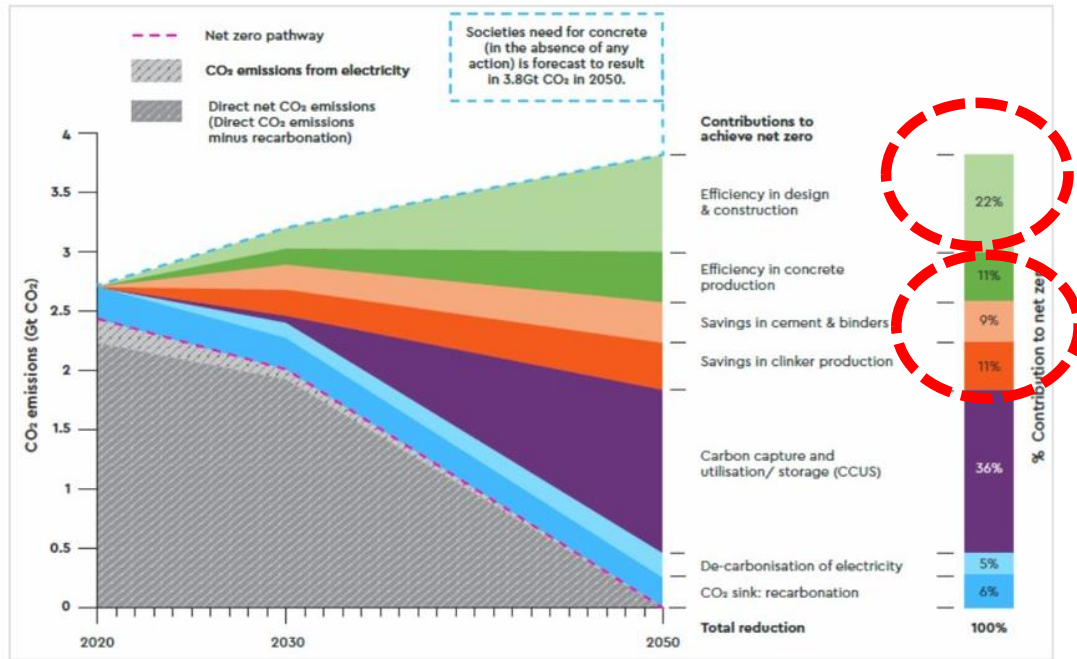
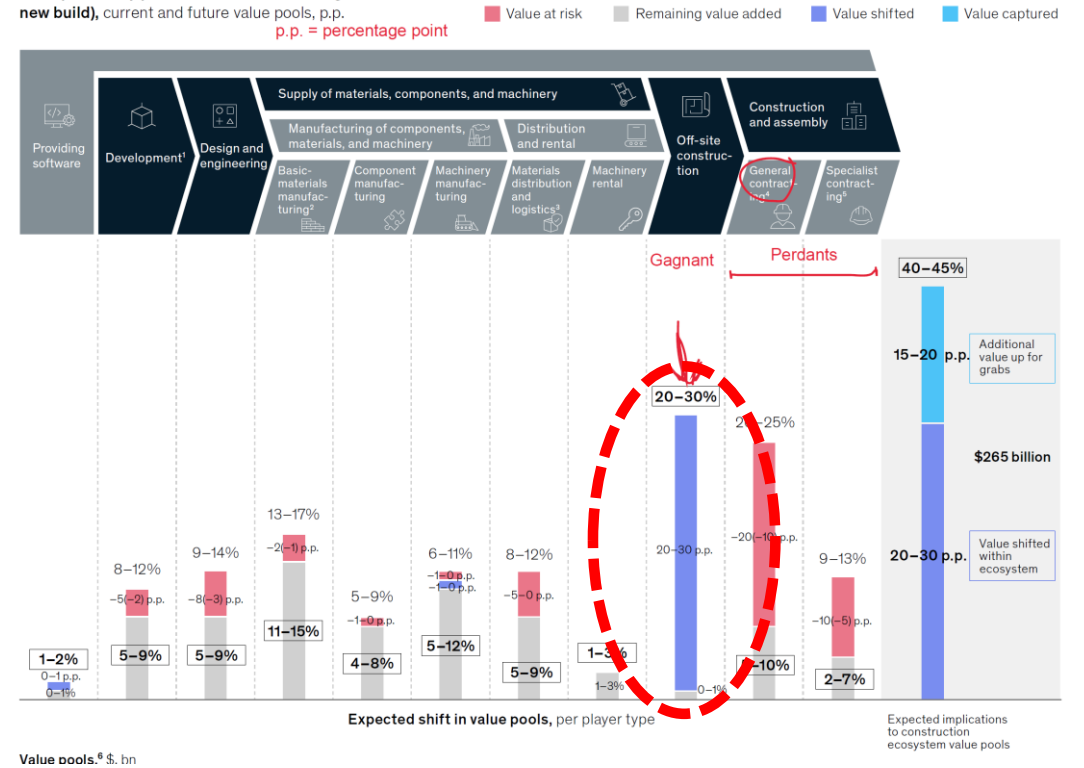


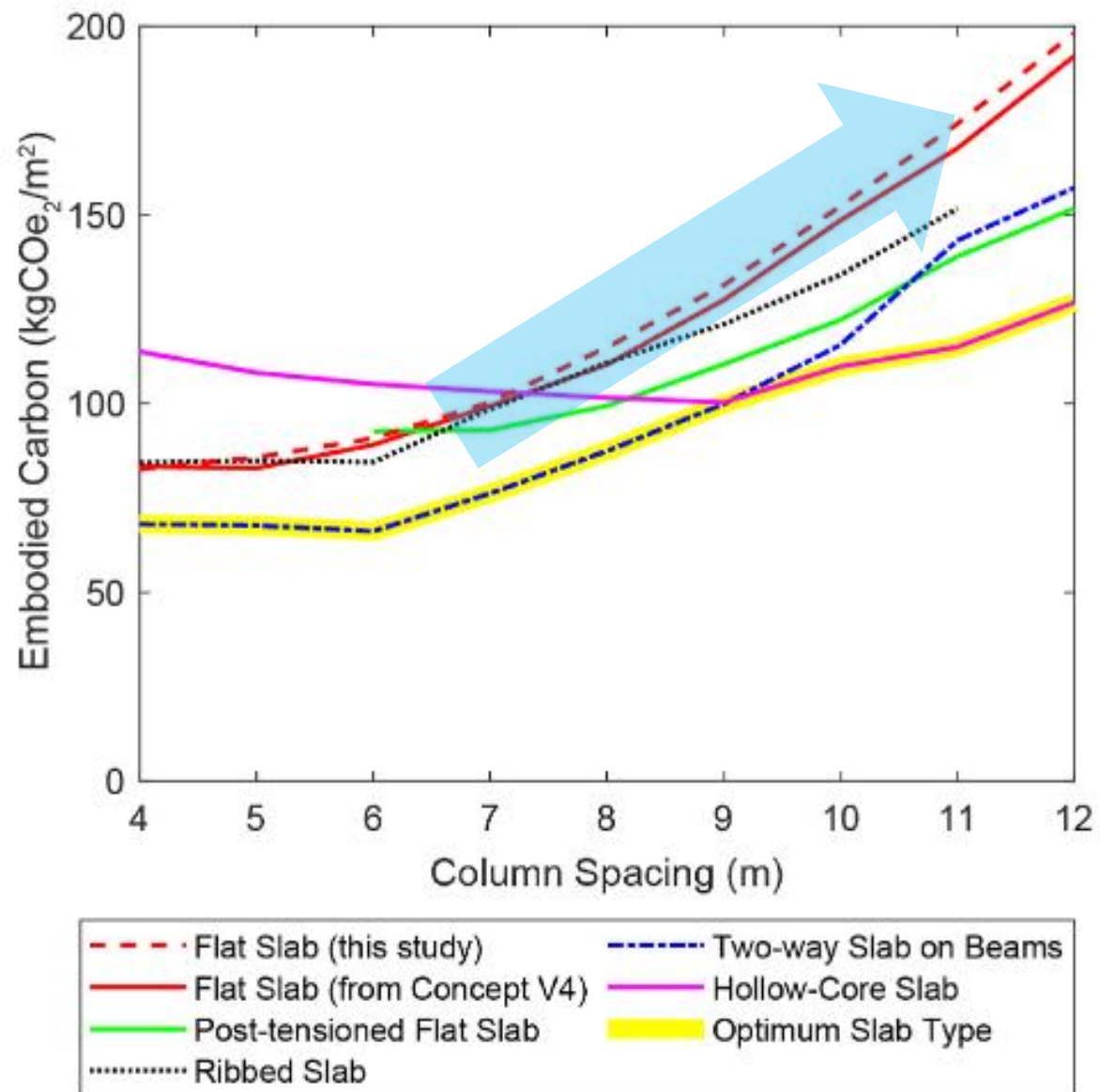
Figure 25 CO2 reductions along the EU cement value chain between 1990 and 2050

Example of fully productized value chain (eg, real estate new build), current and future value pools, p.p.  
p.p. = percentage point





# The crux is minimizing embodied carbon but keeping a long span



# Industrial Problem



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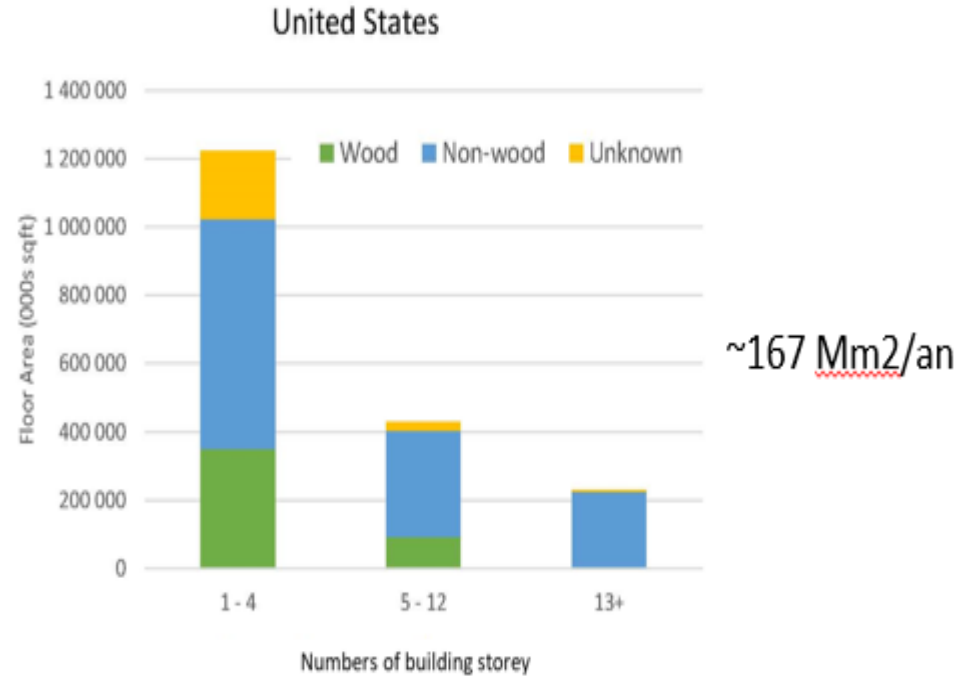
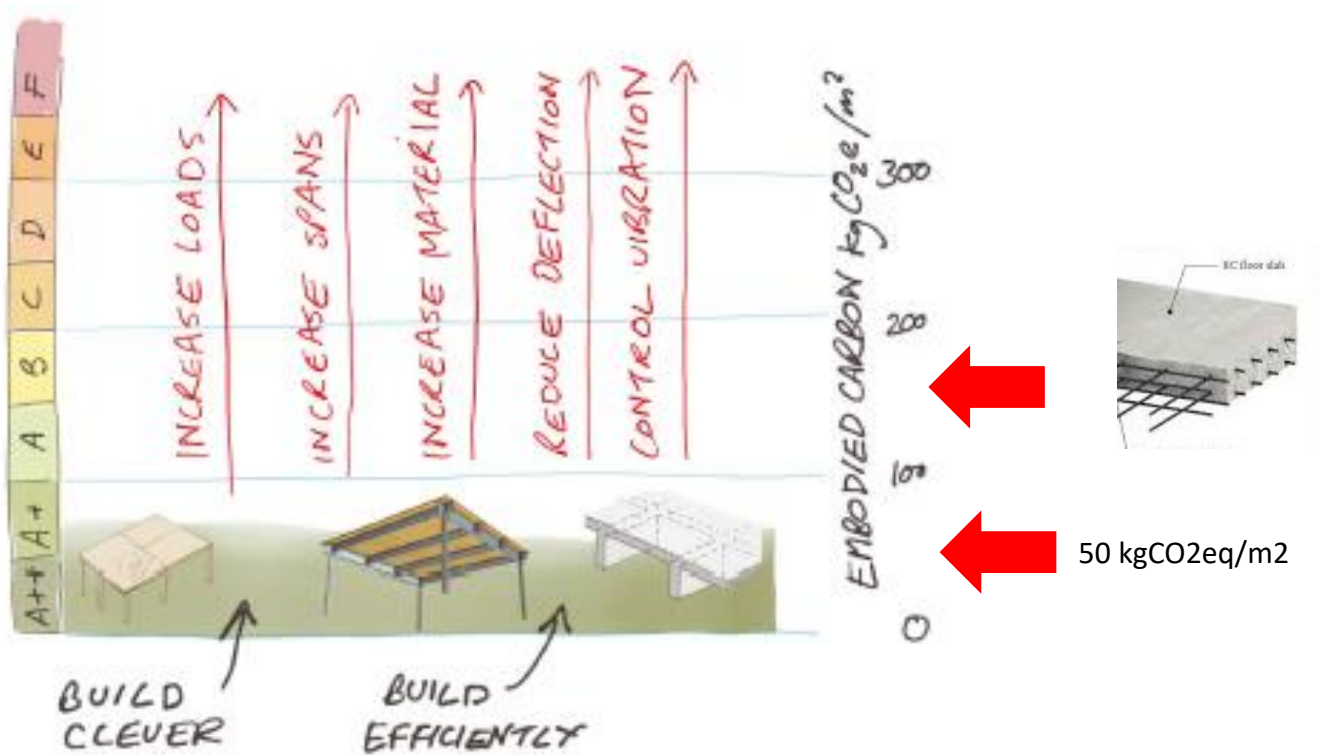
Technical Carbon-driven design

## What if carbon drives our IStructE design from the outset?

JAMES NORMAN  
MEng, PhD, CEng, MICE, FHEA  
Professor of Sustainable Design, University of  
Bristol, UK

### SYNOPSIS

This article considers the implications of adopting a carbon-driven design approach – with the express intent of



# Literature survey

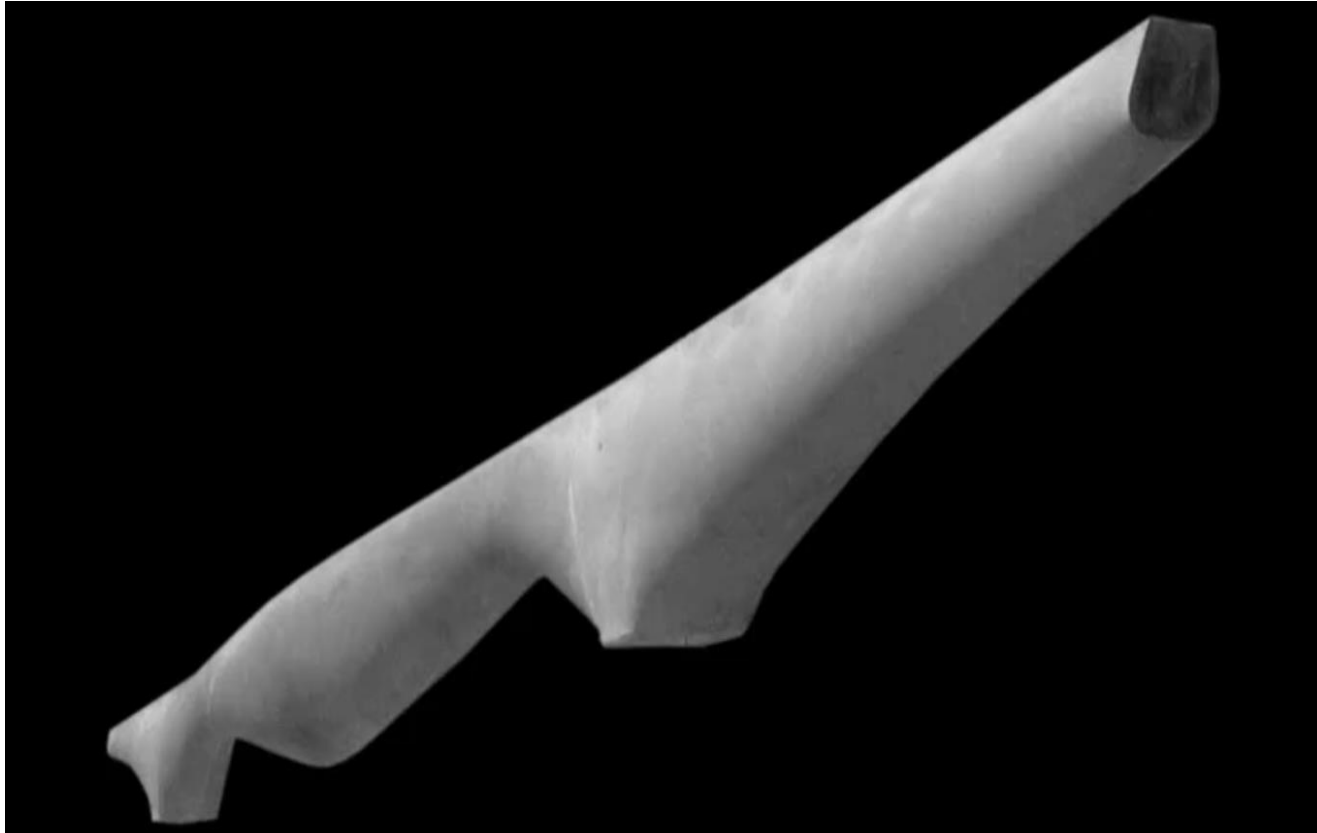


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-30-40%

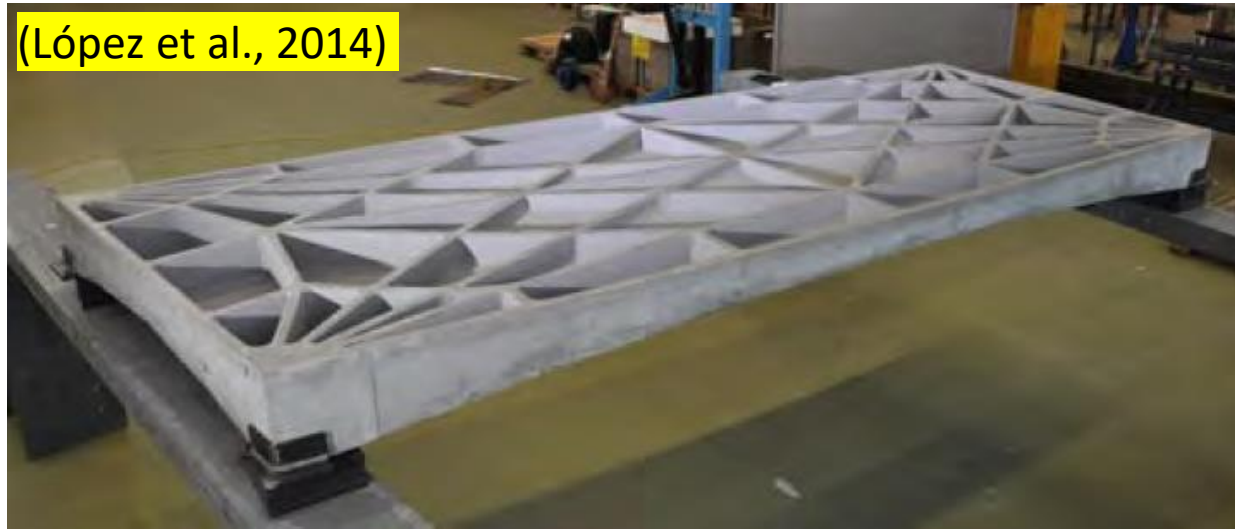
Orr et al 2021

# Literature survey

Prof. Philippe  
Block



(López et al., 2014)



**Material:** High-performance, self-compacting fiber-reinforced concrete (SCFRC)

**Slenderness** = 20

**Mass** = 119 kg/m<sup>2</sup>

(Liew et al., 2017)



**Material:** UHPFRC

**Slenderness** = 17.5

**Mass** = 119 kg/m<sup>2</sup>



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vaulted



# RESEARCH : OBJECTIVES

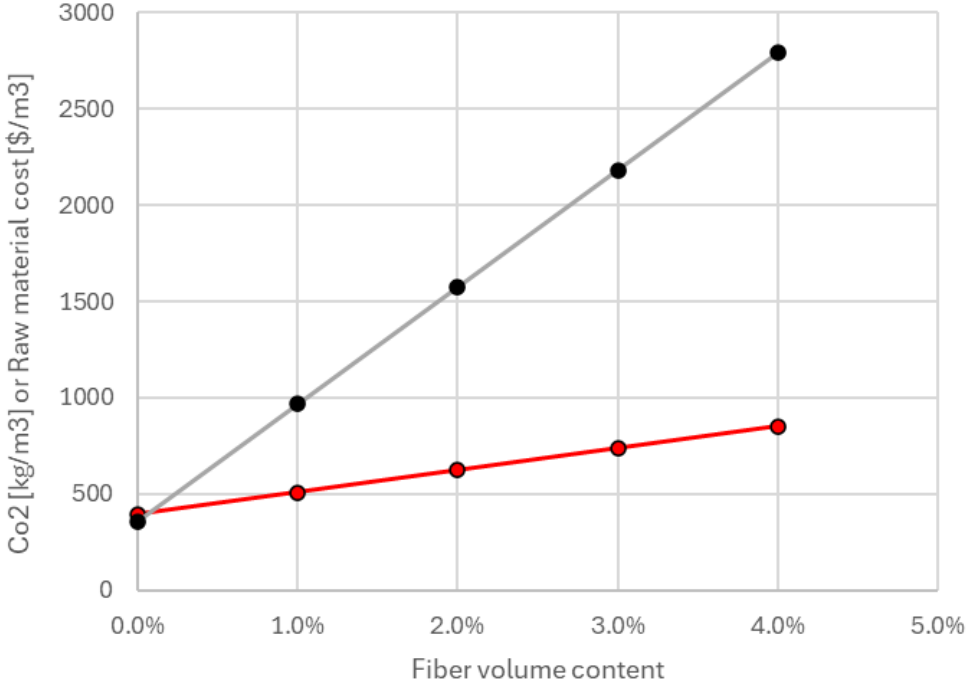


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● CO<sub>2</sub>  
● \$

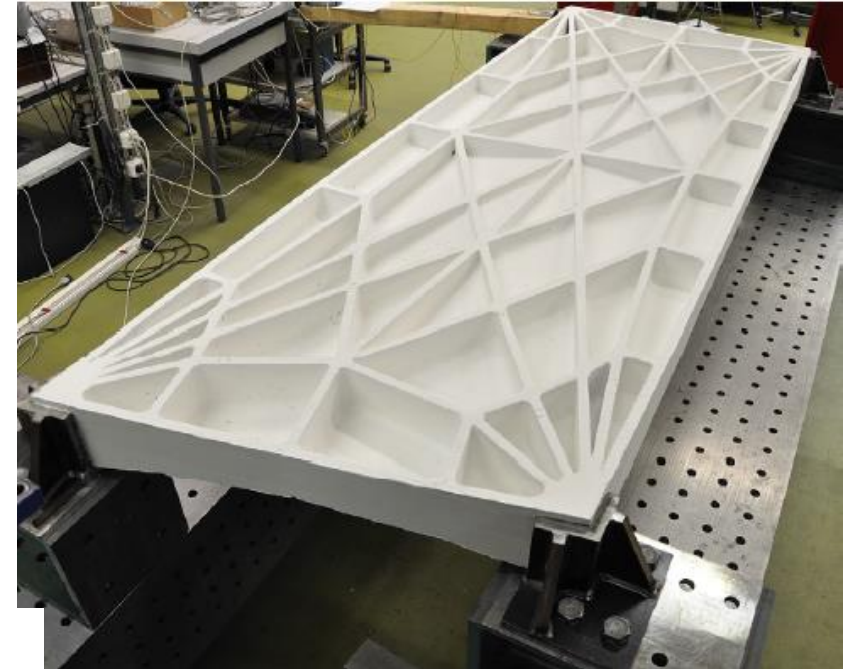
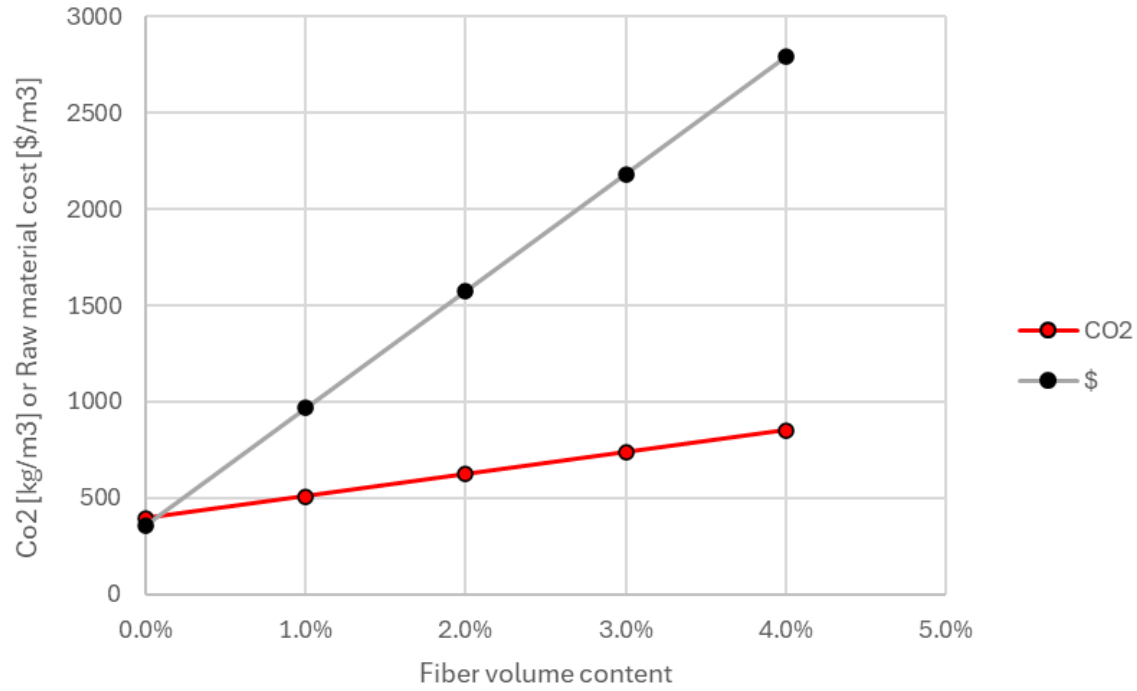
	Eco-UHPFRC without fibers	Steel fibers
Cost	<b>359 \$/m<sup>3</sup></b>	<b>8000 \$/ton</b>  For 1 % of fibers: Mass = 76 kg/m <sup>3</sup> <b>608 \$</b>
Embodied CO <sub>2</sub>	<b>395 kgCO<sub>2</sub>/m<sup>3</sup></b>	<b>1.5 kgCO<sub>2</sub>/kg</b>  For 1 % of fibers: Mass = 76 kg/m <sup>3</sup> <b>114 kgCO<sub>2</sub></b>

Material cost and embodied carbon, estimated

(Bouchard et al. 2022)



# RESEARCH : OBJECTIVES





# Wu et al., 2020

- An anti-funicular vaulted unreinforced concrete floor
- Geometry optimized using Thrust Network Analysis (TNA) (Block & Ochsendorf, 2007)
- 70% reduction in volume compared to solid slabs
- Max. deflection = 1/500 of the span
- ~2 kPa selfweight

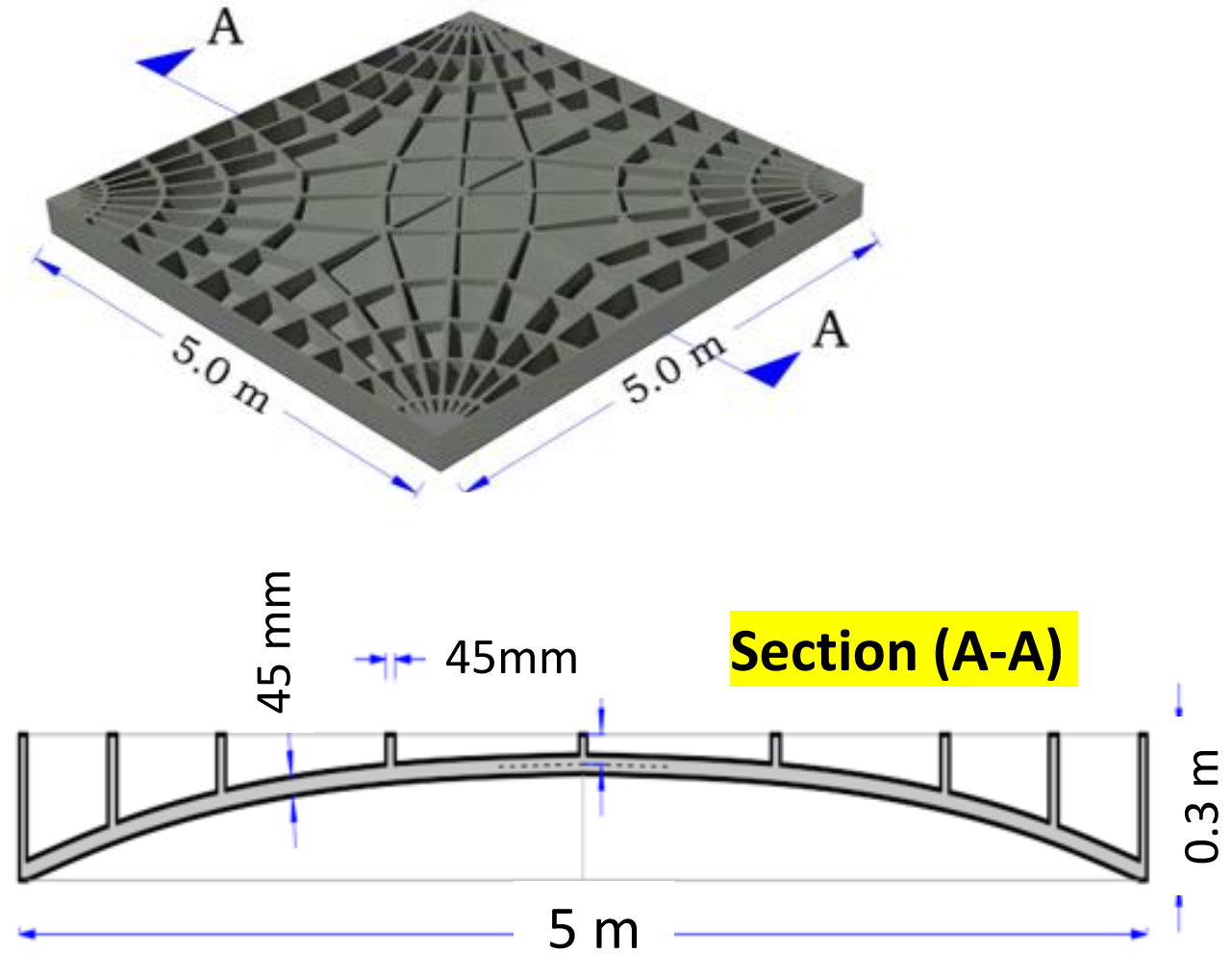
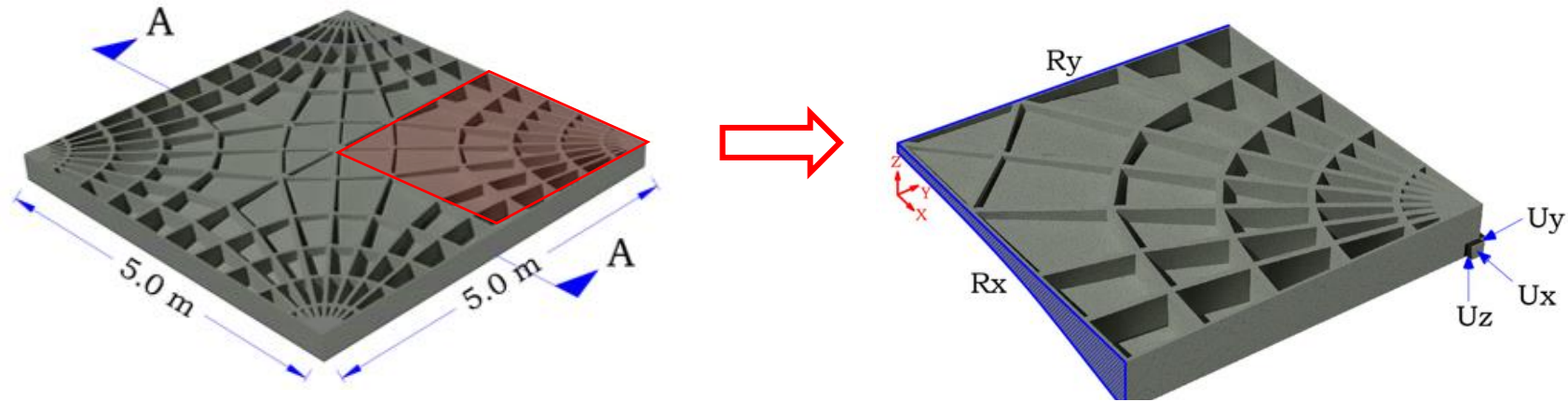
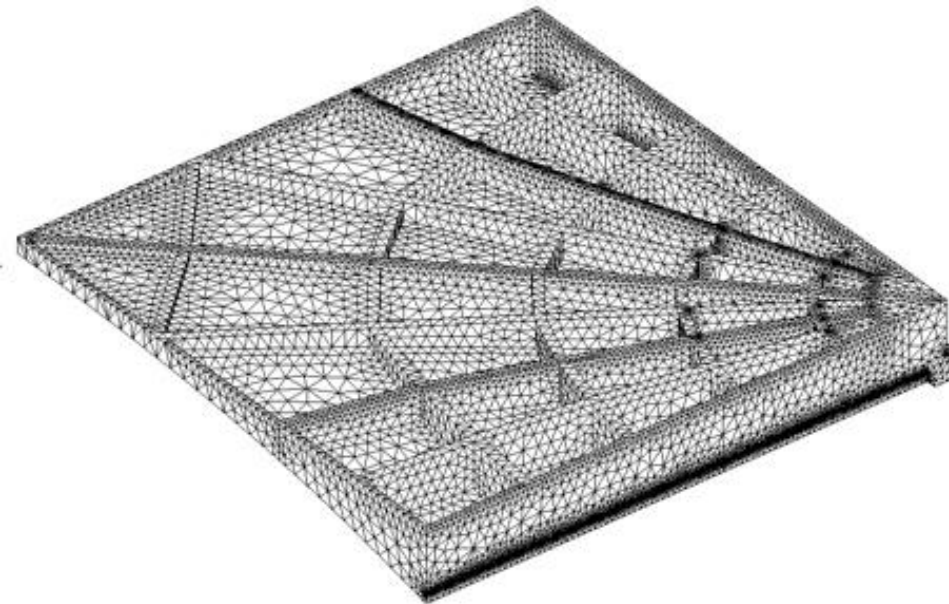


Fig. 1: Layout and dimensions of the studied floor

# Finite Element Model

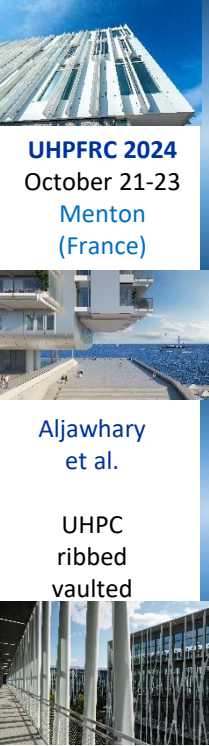


**Fig. 2:** Geometrical model with constraints



**Fig. 3:** Finite element mesh

- 4-noded solid tetrahedrons
- Mesh size = 5-300mm



# Finite Element Model

## Considers:

- Matrix-fiber properties
- Spatial fiber distribution

## Strain-hardening:

Weibull-based stochastic approach

## Fluendo Fiber

Non-linear finite element model implemented in Cast3m



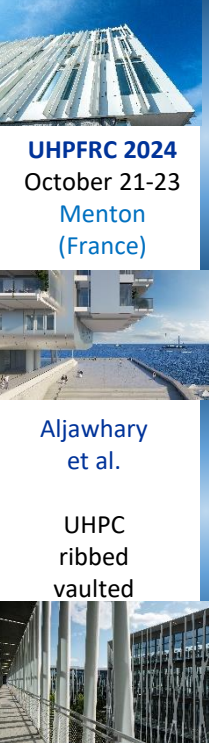
## Tensile law:

- Pull-out model
- Fiber orientation

Prediction of narrow crack widths

## Fiber pull-out mechanisms:

- Abrasion
- Particles accumulation
- Fiber end anchorage



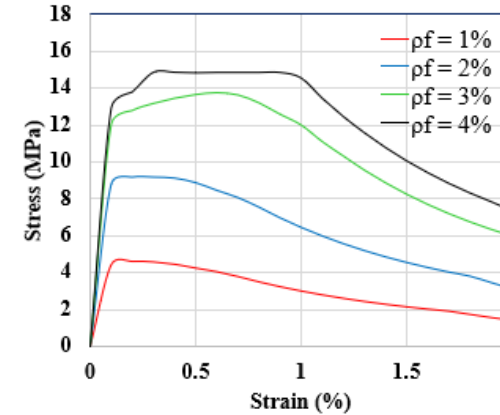
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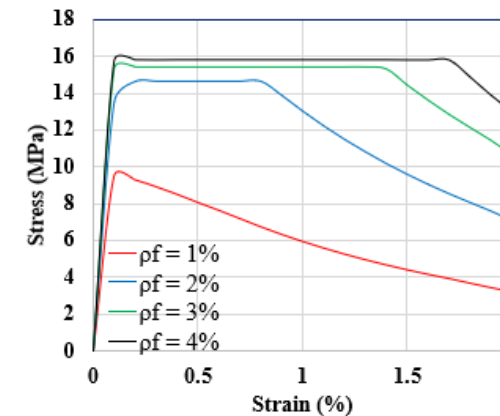
UHPC  
ribbed  
vaulted

# Finite Element Model

Properties of Eco-UHPFRC	
Modulus of elasticity ( $E_u$ )	38.5 GPa
Elastic limit stress ( $f_{Ute}$ )	8.2 MPa
Elastic limit strain ( $\epsilon_{Ute}$ )	0.021%
Ultimate tensile strength ( $f_{Utu}$ )	12.1 MPa
Ultimate hardening strain ( $\epsilon_{Utu}$ )	0.14%
Ultimate compressive strength ( $f'_c$ )	120 MPa
Properties of fibers	
Shape	Straight
Section	Circular
Length	13 mm
Diameter	0.2 mm
Tensile strength	2860 MPa

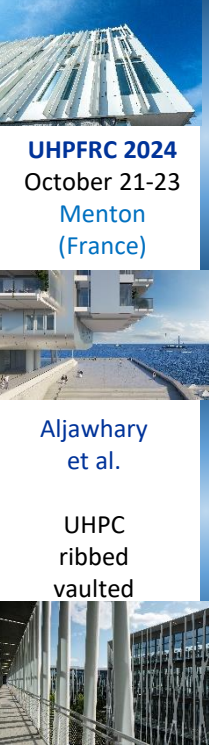


(a) Randomly oriented fibers



(b) Uniformly oriented fibers in the direction of tension

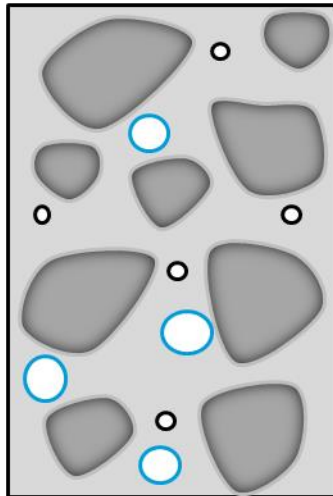
**Fig. 4:** Tensile law by Fiber Fluendo – Cast3m



# Materials properties

Standard UHPC

UHPC with  
unreacted cement

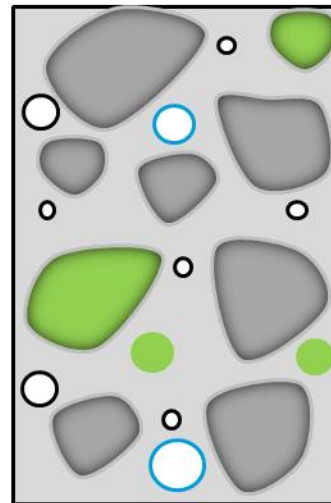


$w/c \sim 0.2$

$w/f \sim 0.2$

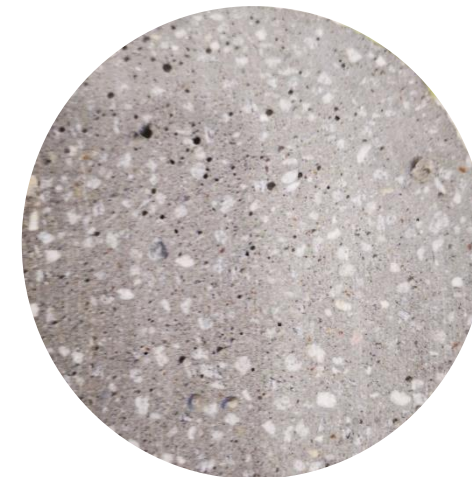
eco<sup>2</sup>-UHPC

Filler replacement

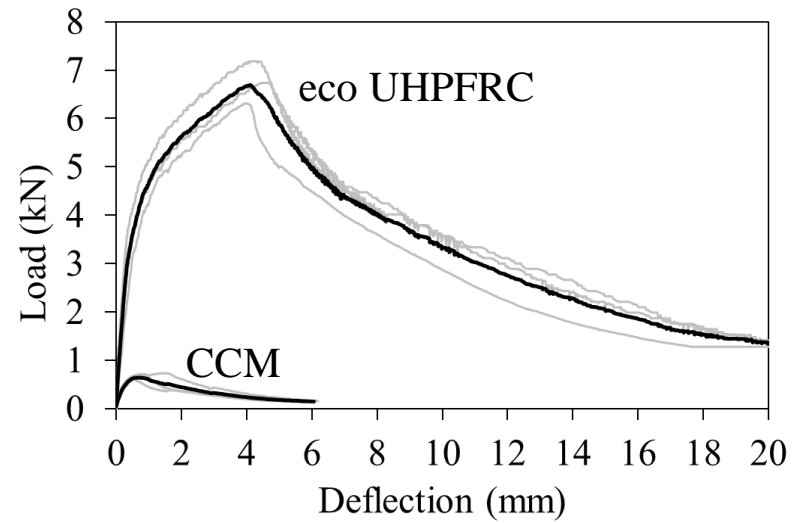
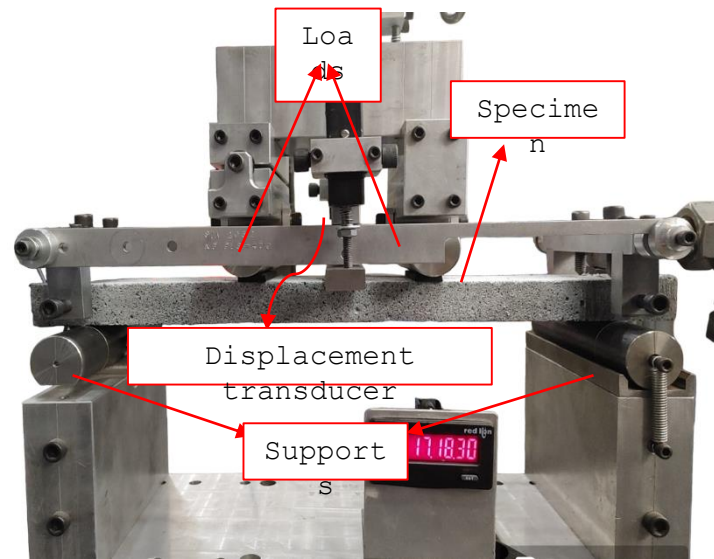


$w/c \sim 0.45$

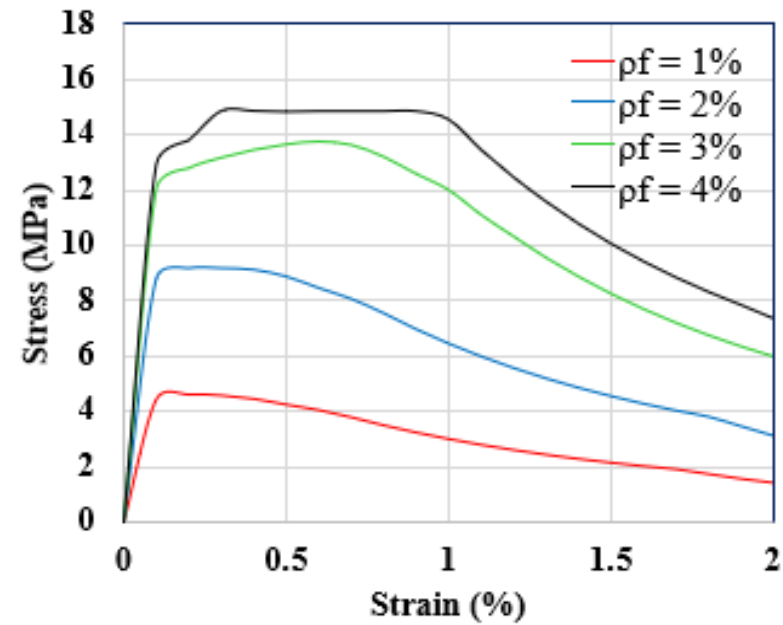
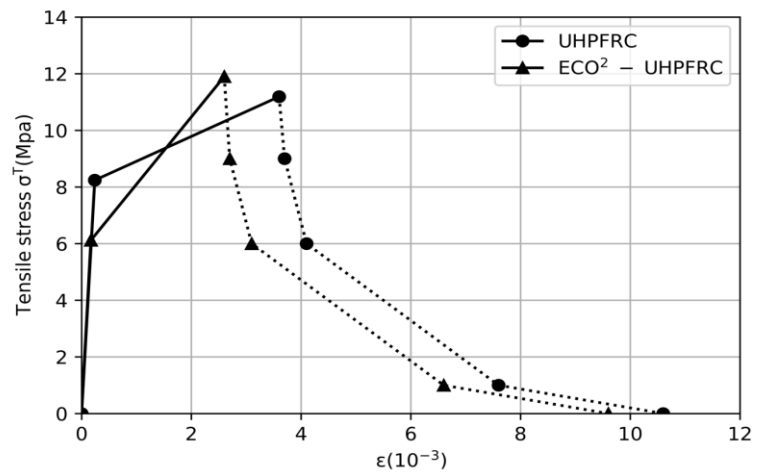
$w/f \sim 0.2$



Tran, Sorelli et al. 2023b



20



# Effect of ribs

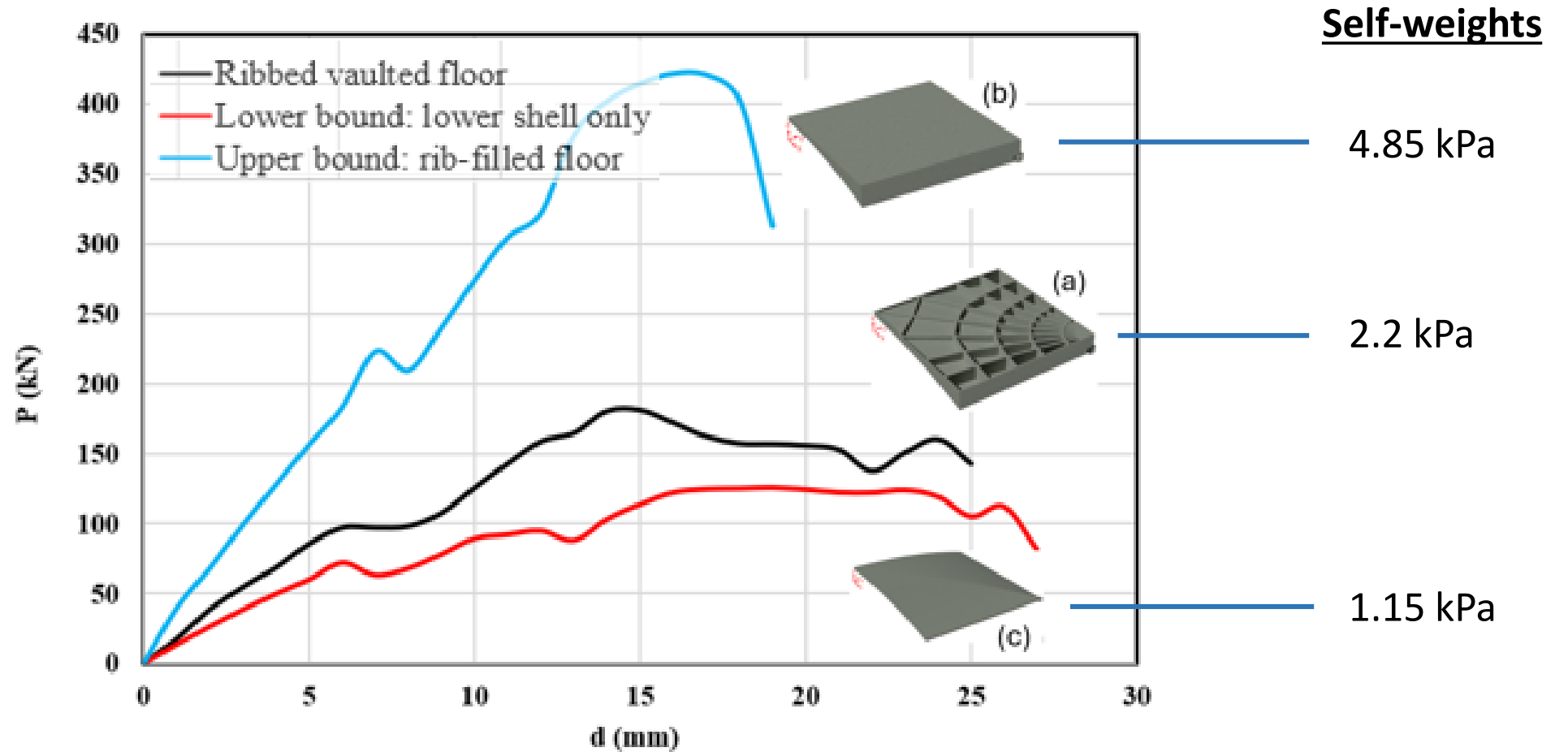
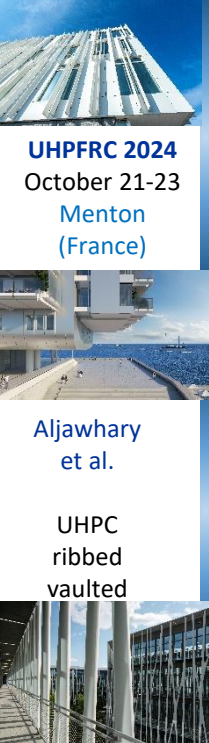
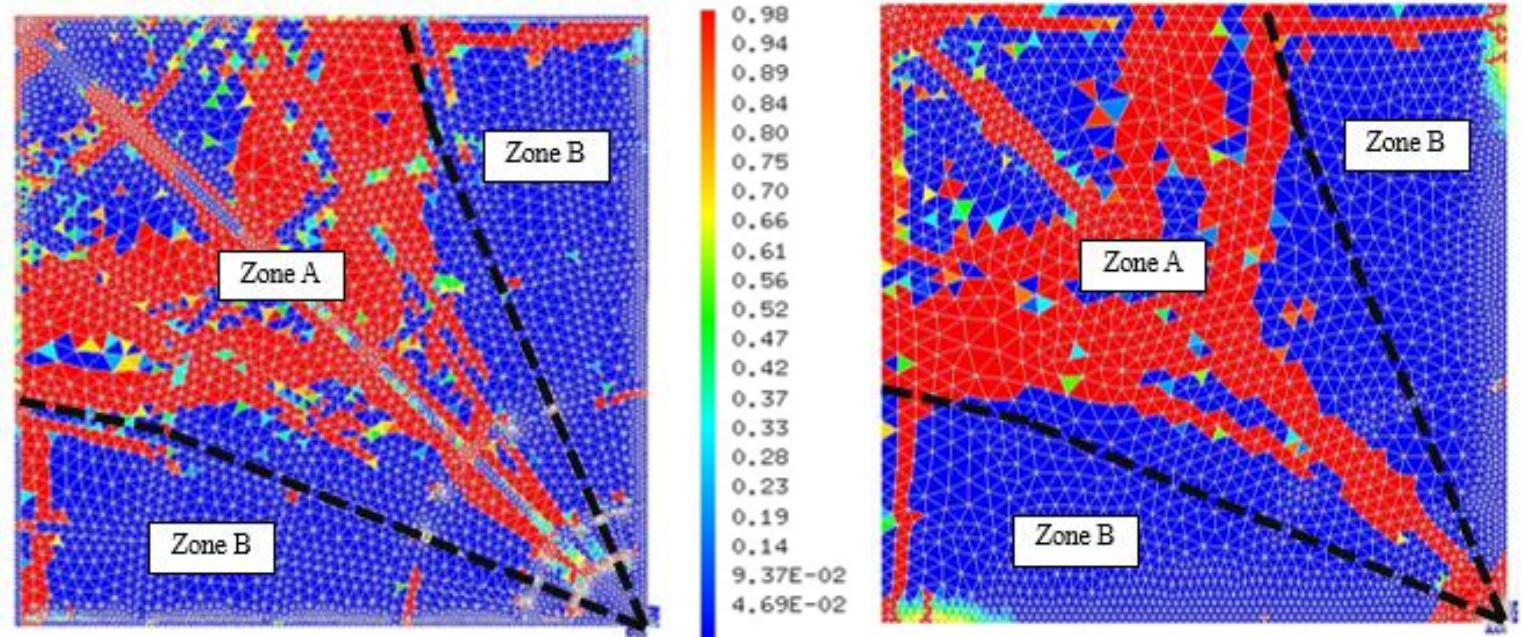


Fig. 5: Load-displacement curves of the 3 slab geometry forms



# Scenarios of Fiber Distribution

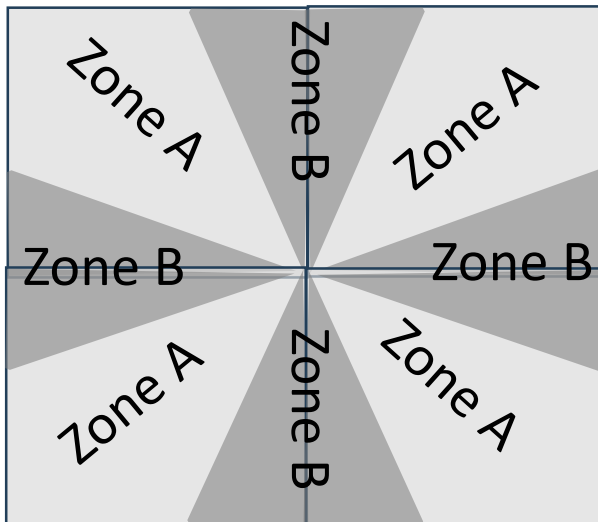
- Zone A: Severely damaged
- Zone B: Slightly damaged



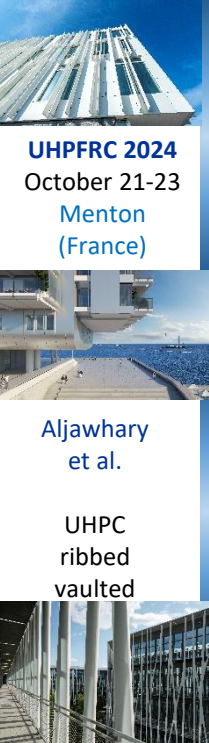
(a) Bottom view

(b) Top view

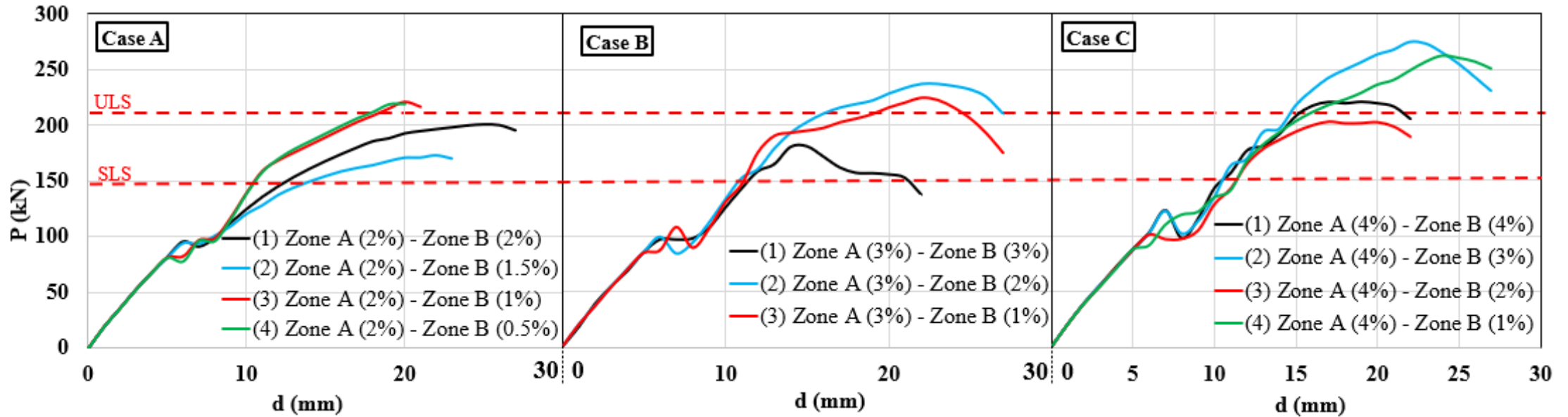
**Fig. 7:** Tensile damage contours just before failure (uniform fiber content = 2%)



	Cases A				Cases B			Cases C			
Case	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(1)	(2)	(3)	(4)
Zone A	2%	2%	2%	2%	3%	3%	3%	4%	4%	4%	4%
Zone B	2%	1.5%	1%	0.5%	3%	2%	1%	4%	3%	2%	1%

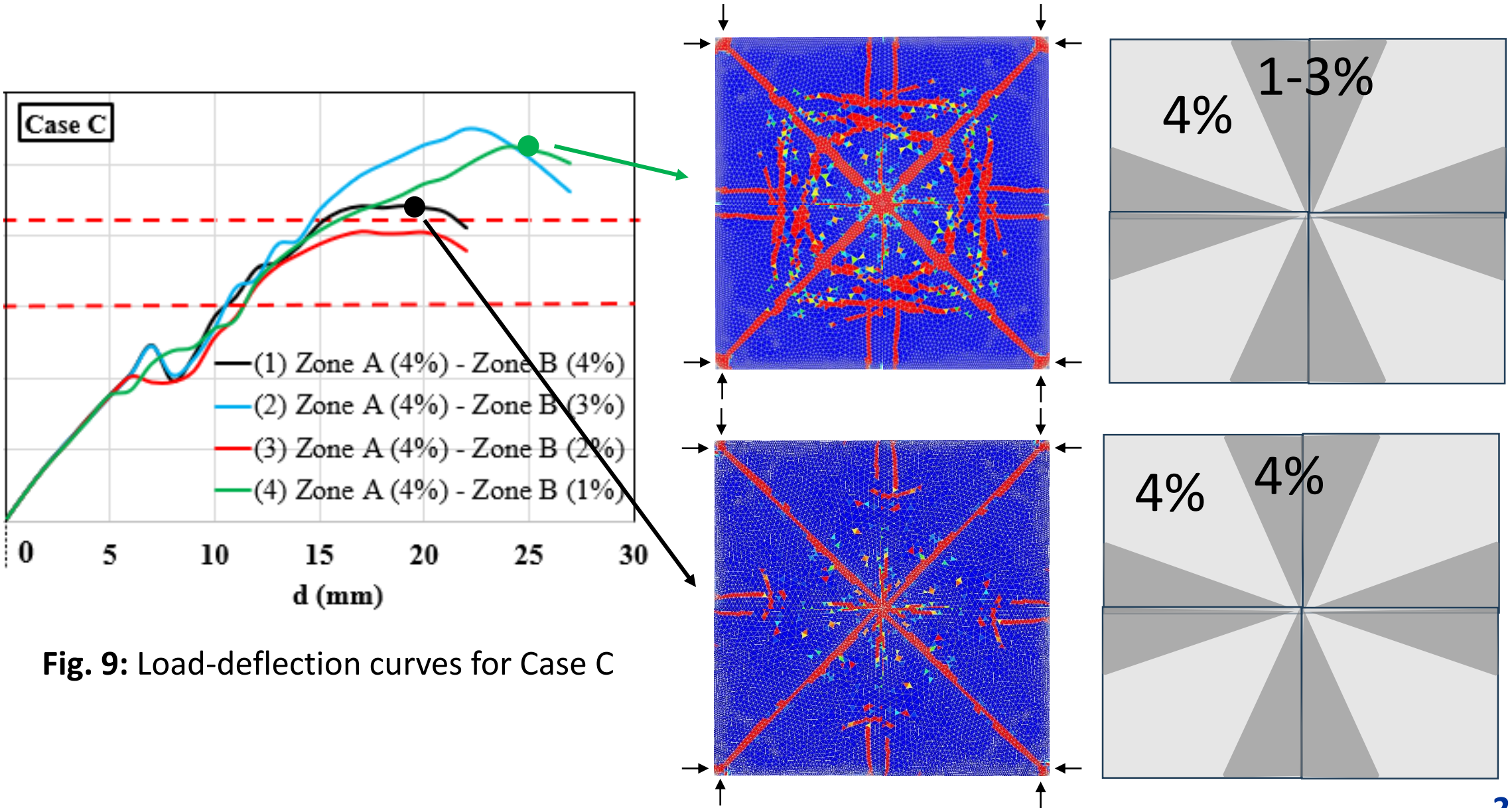


# Results: Load-deflection curves

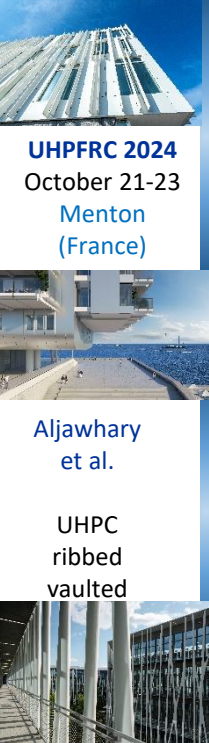


**Fig. 8:** Load-deflection curves for all cases

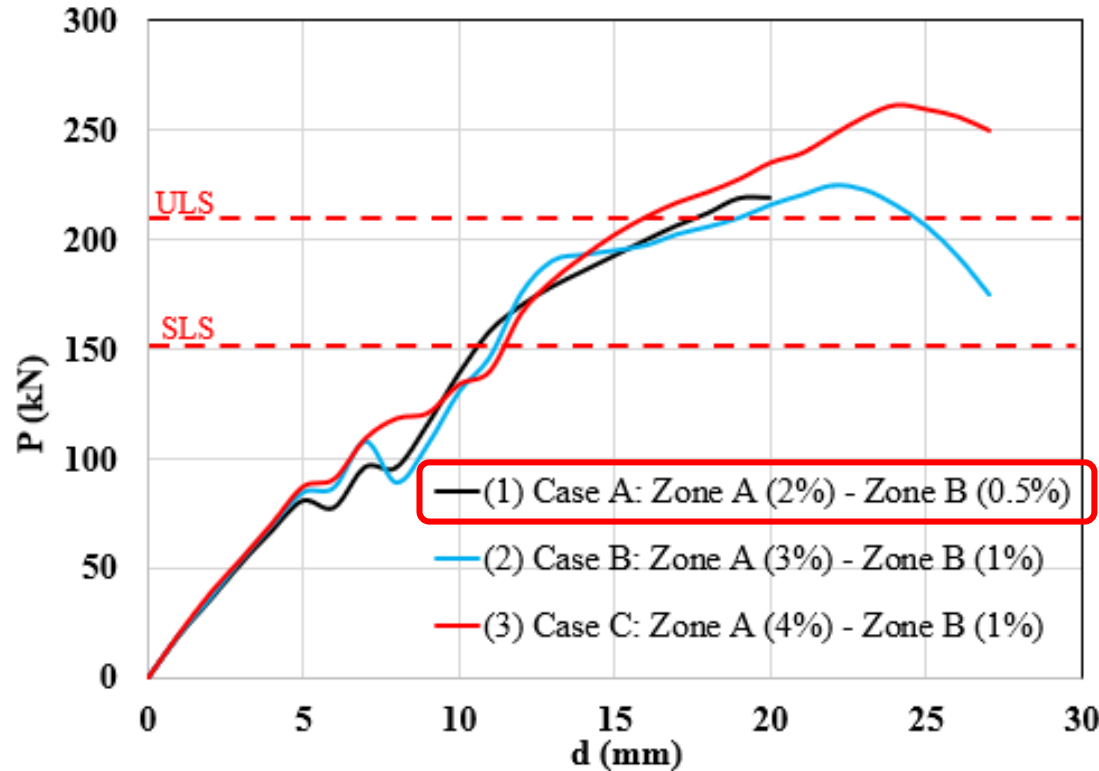
# Why load increased at lower fiber content?



**Fig. 9:** Load-deflection curves for Case C



# Results: Optimum cases



**Fig. 10:** Load-deflection curves for the optimum cases

## Optimum selection criteria:

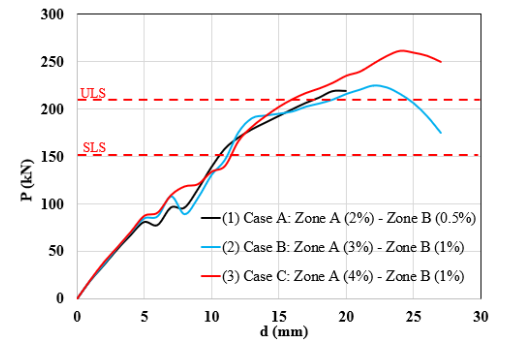
1. Max crack width at SLS < maximum allowed (0.4mm)
2. Max. deflection at SLS <  $L/360 = 13.9\text{mm}$  (live load)  
Max. deflection at SLS <  $L/250 = 20\text{mm}$  (total load)
3. ULS safety factor for ultimate capacity > 1.0

## Most optimum case:

Case A with zone A (2.0%) and zone B (0.5%)  
(Least factor of safety = 1.04 for the ultimate capacity which indicates that it provides the necessary strength without being overdesigned)



# Results: Comparison

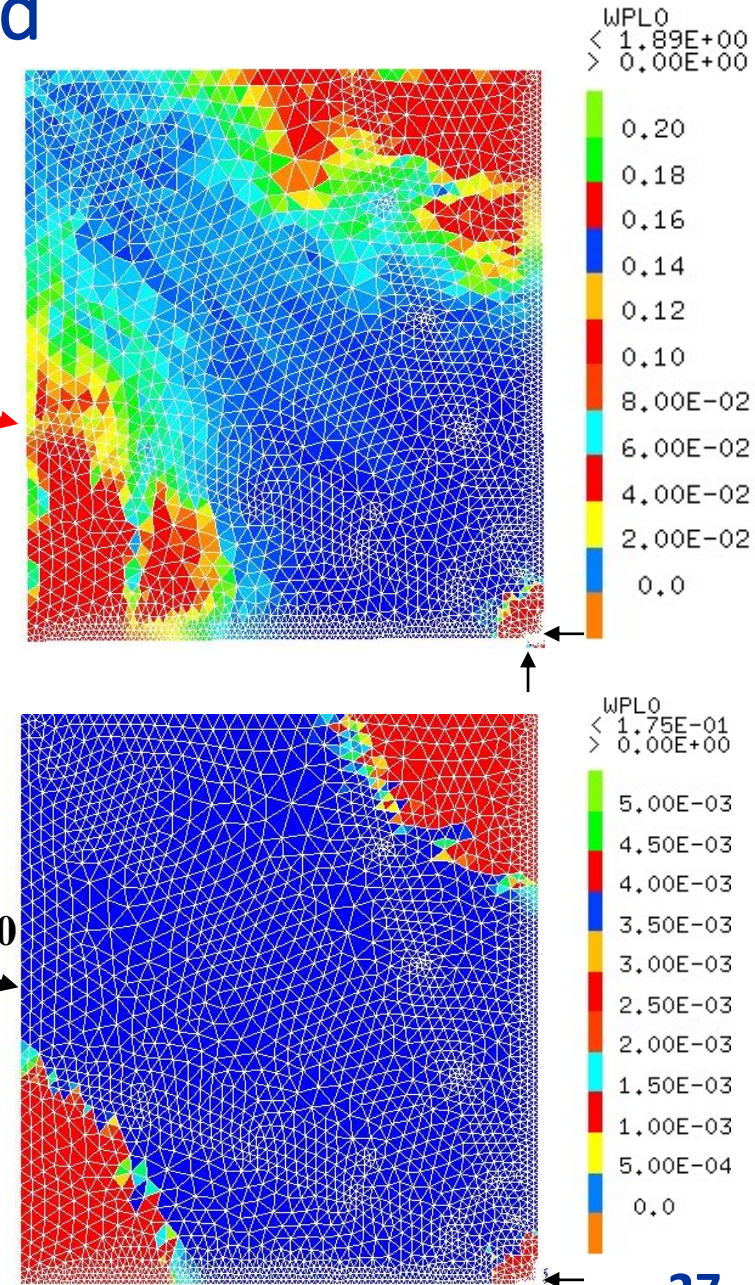
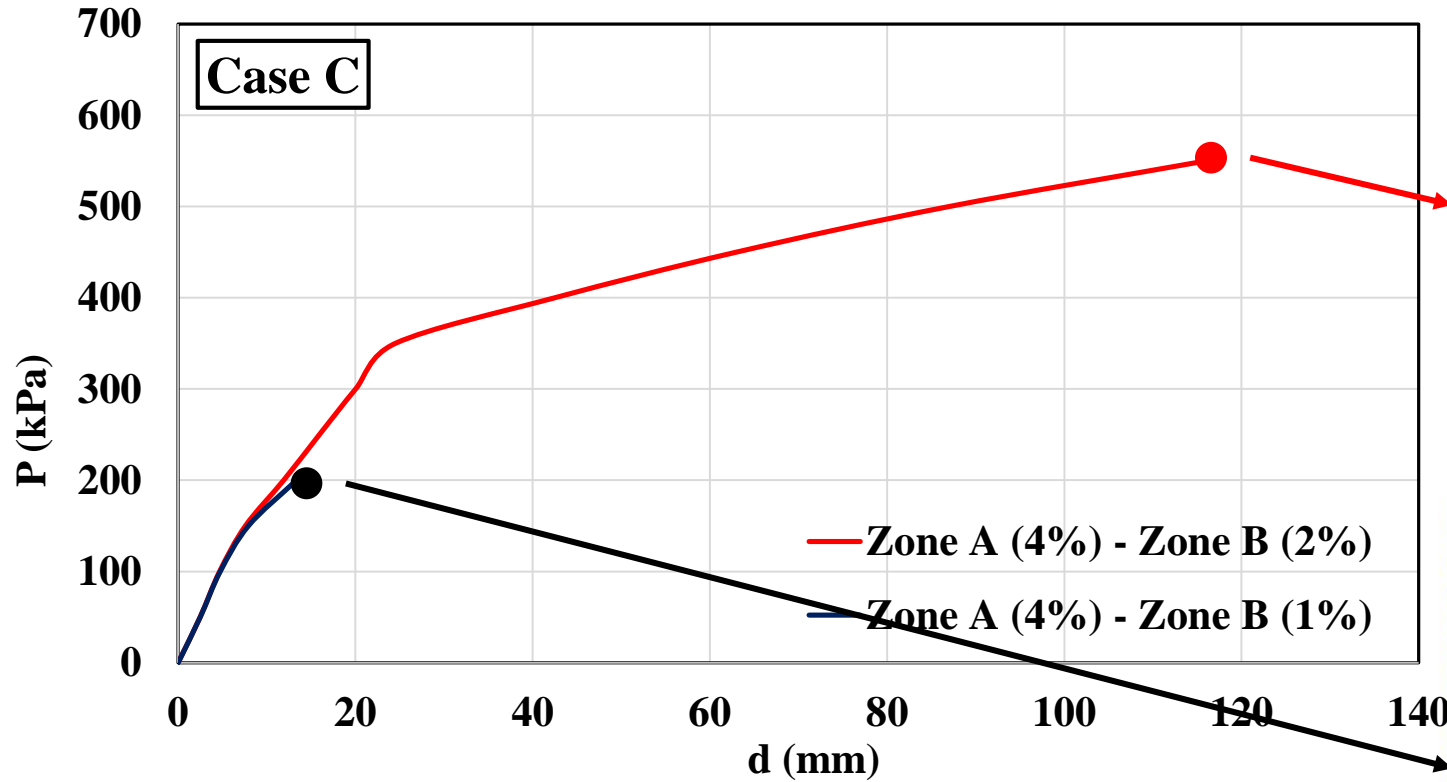


**Table 2:** Estimation of material cost and embodied carbon for all cases

	Case A (Zone A=2%)			Case B (Zone A=3%)			Case C (Zone A=4%)		
Case	Cost (\$/m <sup>2</sup> )	Embodied CO <sub>2</sub> (kg/m <sup>2</sup> )	Vf-avg (%)	Cost (\$/m <sup>2</sup> )	Embodied CO <sub>2</sub> (kg/m <sup>2</sup> )	Vf-avg (kg/m <sup>3</sup> )	Cost (\$/m <sup>2</sup> )	CO <sub>2</sub> (kg/m <sup>2</sup> )	Vf-avg (kg/m <sup>3</sup> )
(1)	130	52	2	181	61	3	231	71	4
(2)	119	49	1.8	157	57	2.5	208	66	3.5
(3)	107	47	1.5	134	52	2.1	184	62	3.1
(4)	<b>95</b>	<b>45</b>	<b>1.3</b>				<b>161</b>	<b>57</b>	<b>2.6</b>



# Results: Uniformly distributed load



**Fig. 11:** Load-deflection curves for the optimum cases and crack width contours (crack width in mm)

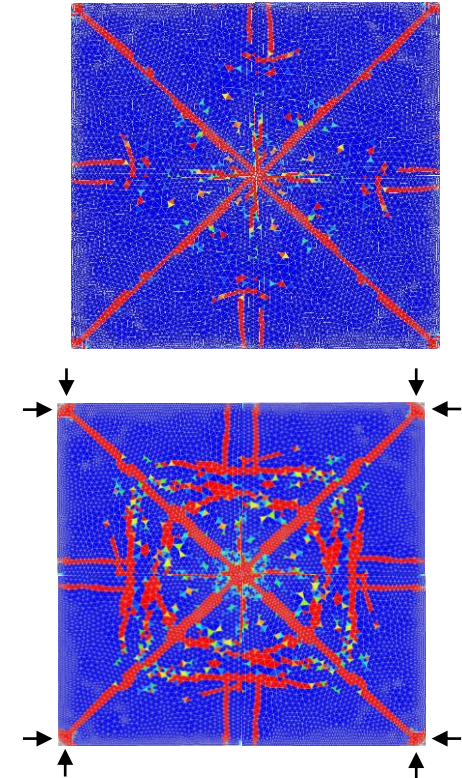


# Conclusions

Optimizing cost and carbon by using UHPFRC with varying fiber content within the structures enables:

- A significant reduction in both cost (by 40-60%) and embodied carbon (by 20-40%) compared to a uniform fiber distribution.
- Interestingly, it also increases load capacity by promoting the formation of additional crack lines at collapse (yield lines).

Future work will focus on updating the results under uniform loads, optimizing the shape and fiber content for different elements (ribs, slabs, zones).



# Acknowledgements



Romain Gontero pour conseils sur FLUENDO FIBER

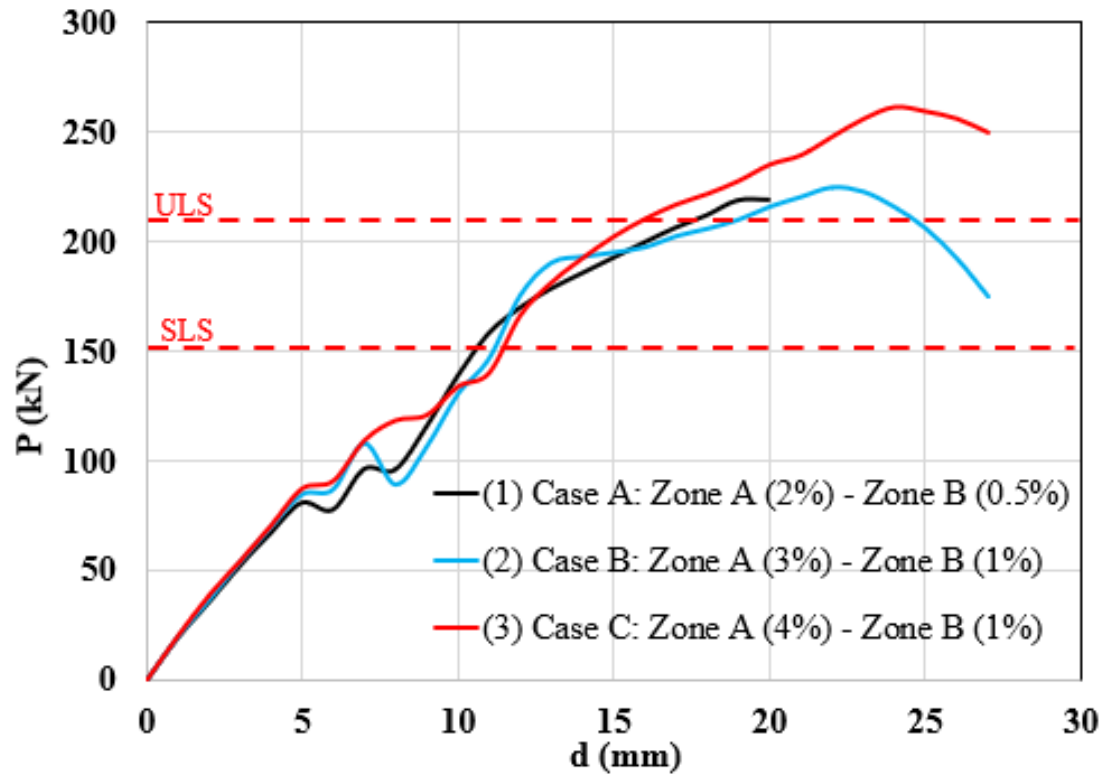


## References

- Block, Philippe, and John Ochsendorf. 2007. 'Thrust Network Analysis: A New Methodology for Three-Dimensional Equilibrium'. *Journal of the International Association for Shell and Spatial Structures* 48 (3): 167–73.
- Bouchard, D., Sanchez, T., Sorelli, L., & Conciatori, D. (2022). Development of Eco-Efficient UHPC and UHPFRC by Recycling Granite Waste Powder (GWP). In *Fibre Reinforced Concrete: Improvements and Innovations II: X RILEM-fib International Symposium on Fibre Reinforced Concrete (BEFIB) 2021* 10 (pp. 903-914). Springer International Publishing.
- Gontero, R. (2022). *Modélisation du comportement mécanique des structures en bétons fibrés à ultra-hautes performances* [Doctoral dissertation, Université Toulouse III - Paul Sabatier & Université Laval].
- Liew, A., López, D. L., Van Mele, T., & Block, P. (2017). Design, fabrication and testing of a prototype, thin-vaulted, unreinforced concrete floor. *Engineering Structures*, 137, 323-335.
- López, D. L., Veenendaal, D., Akbarzadeh, M., & Block, P. (2014, September). Prototype of an ultra-thin, concrete vaulted floor system. In *Proceedings of IASS annual symposia* (Vol. 2014, No. 15, pp. 1-8). International Association for Shell and Spatial Structures (IASS).
- Wu, H., Liew, A., Van Mele, T., & Block, P. (2020). Analysis and optimisation of a rib-stiffened vaulted floor for dynamic performance. *Engineering Structures*, 213, 110577.



# Why load increased?



Case	Material cost (\$/m <sup>2</sup> )	CO <sub>2</sub> (kg/m <sup>2</sup> )	Max. crack width at SLS (mm)	Max. Deflection at SLS (mm)	FS for ultimate capacity
(1)	389	182	0.289	10.5	1.04
(2)	549	212	0.340	11.0	1.07
(3)	660	232	0.221	11.5	1.25

ADD A PLOT OF CRACK WIDTH WITH LEGEND INDICATING THE LOAD WHEN IS TAKEN FOR CURVE RED AND BLUE (AT HE SAME DEFLECTION IF POSISBLE)