Cradle-to-grave life-cycle assessment of ultra-high-performance concrete (UHPC) beams based on real-time monitoring data

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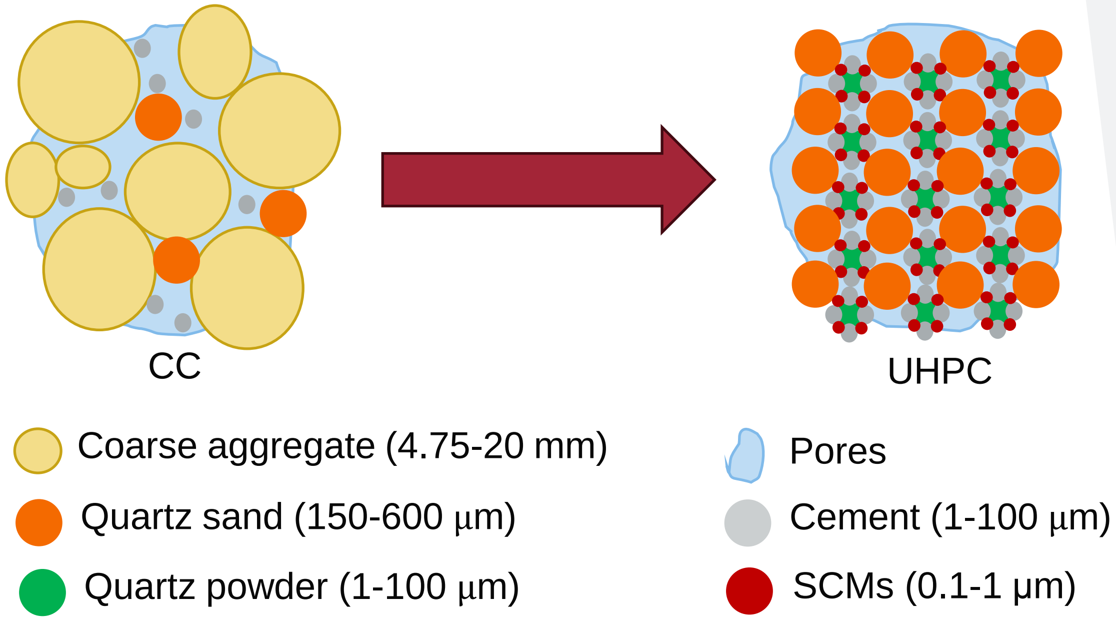
Design of Sustainable UHPC

- To achieve the superior materials properties, UHPC mixtures are designed to achieve high particle packing density:
  - Elimination of coarse aggregates
  - Low water to cement ratio (0.15-0.25)
  - High content of cementitious materials



- Replacement of cement by solid wastes (e.g., SCMs) is the major way to reduce the cost and carbon emissions of UHPC mixtures.

Slag

Silica fume

Glass microsphere (GM)

Fly ash

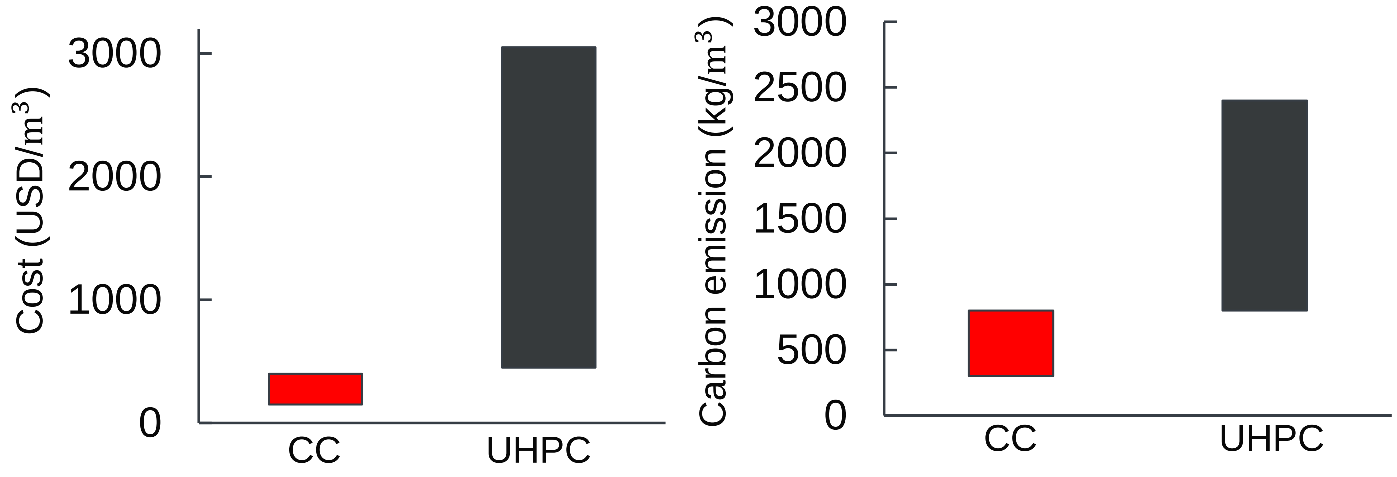
Off-specification fly ash (OSFA)

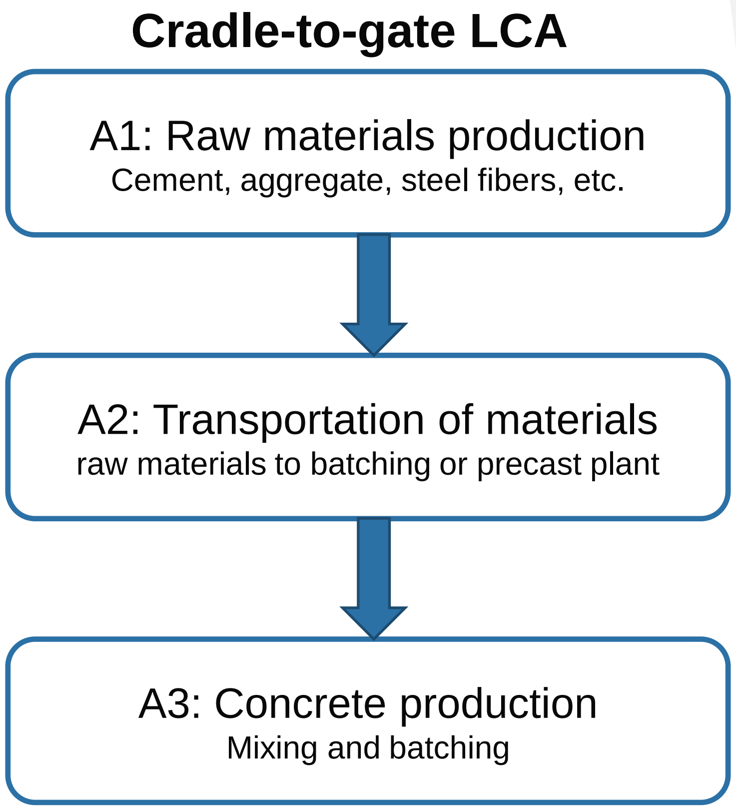
[2] Du, J., Meng, W., et al. 2021. New development of ultra-high-performance concrete (UHPC). Composites Part B: Engineering, 224, p.109220.
[3] Du, J., Liu, Z., Christodoulatos, C., Conway, M., Bao, Y. and Meng, W., 2022. Utilization of off-specification fly ash in preparing ultra-high-performance concrete (UHPC): Mixture design, characterization, and life-cycle assessment. Resources, Conservation and Recycling, 180, p.106136.
[4] Guo, P., Meng, W., et al. 2023. Lightweight ultra-high-performance concrete (UHPC) with expanded glass aggregate: Development, characterization, and life-cycle assessment. Construction and Building Materials, 371, p.130441.

CO_2 emission of UHPC v.s. conventional concrete (CC)

- However, due to the use of high cementitious content and steel fibers, in materials level (cradle-to-gate LCA), UHPC emits significantly higher CO_2 compared with CC in unit volume and raises significant concerns regarding the cost.

- **Cradle-to-gate** life-cycle assessment (LCA) is commonly used for assessing the cost and emission of UHPC mixtures.
  - UHPC has higher cradle-to-gate cost and CO_2 compared with CC.



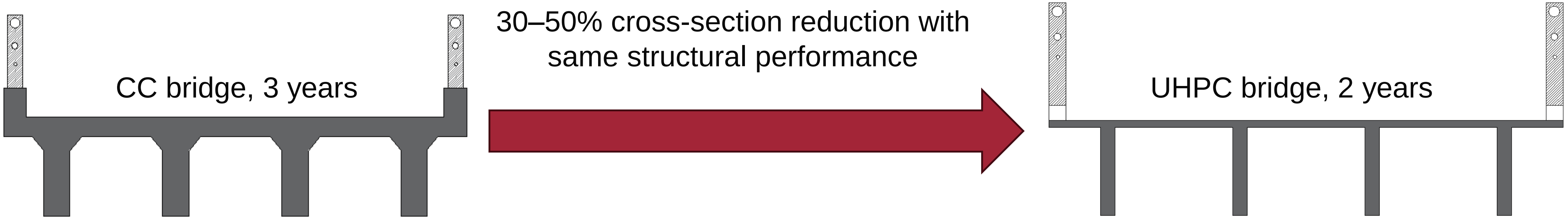


[5] Li et al. 2023. Cement and Concrete Composites.

Limitations of current cradle-to-gate LCA

- Current cradle-to-gate method does not consider:

1. Structural design
   - The higher mechanical strength of UHPC allows for a reduction in cross-section size and shorter project duration.



2. Maintenance costs and emissions over the service life

Preventive maintenance (seal joints and cracks)

Every **10 years** for CC beams

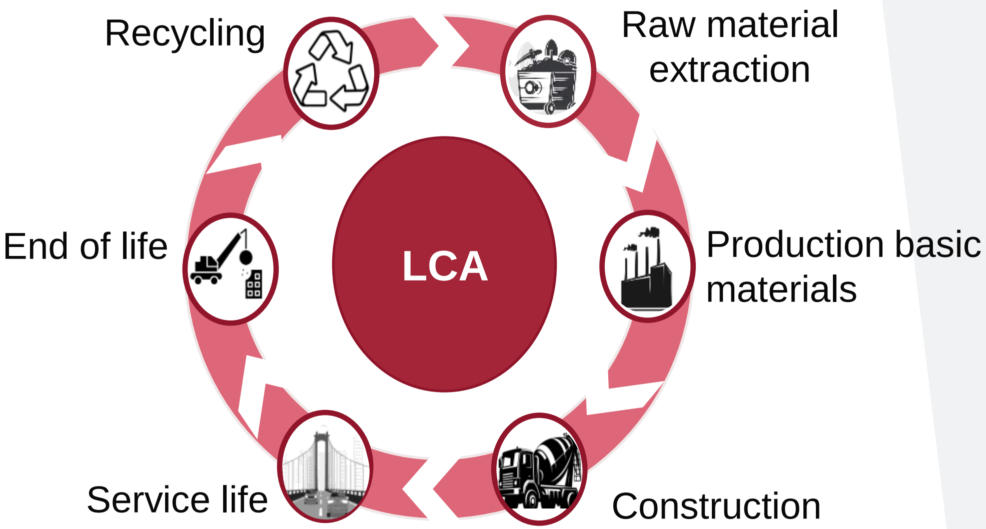
Essential maintenance (replacement of damaged parts)

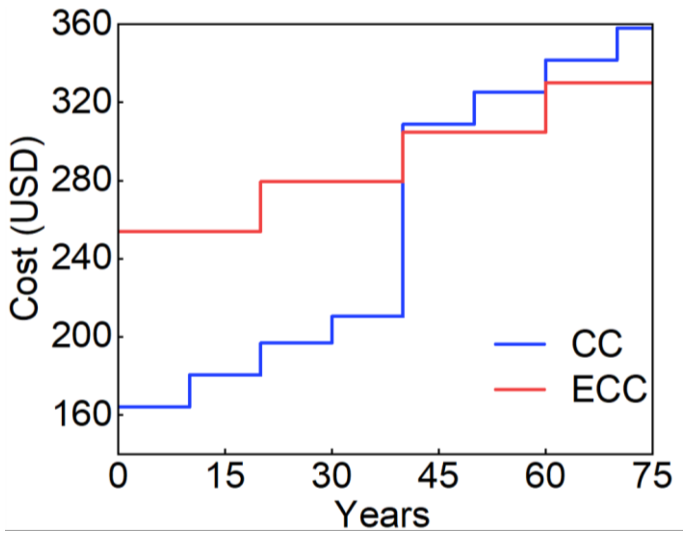
Every **40 years** for CC beams

[6] Kien. 2023. Journal of Science and Technology in Civil Engineering.
[7] Dong. 2018. Construction and Building Materials Journal.
[8] Fan et al. 2024. Engineering Structures.

Cradle-to-grave LCA

- To better understand the performance of UHPC, the LCA should be extended to include the service and end-of-life stages, known as "**cradle-to-grave**".
- Maintenance has a significant impact on cradle-to-grave cost and emissions:
  - For more durable concretes, preventive and essential maintenance intervals were **20** and **80** years.
  - Although the initial fabrication cost of ECC is higher than CC, the more frequent maintenance required for CC increases its cost over time. After 40 years, the total cost of CC exceeds that of ECC.
- In cradle-to-grave LCA, **preventive** and **essential** maintenance account for approximately **10%** and **50%** of the fabrication stage cost and emissions, respectively.





CC requires more frequent maintenance, raising service costs and resulting in a higher overall cost after 40 years compared with ECC.

[7] Dong. 2018. Construction and Building Materials Journal.
[9] Li, X., Lv, X., Zhou, X., Meng, W. and Bao, Y., 2022. Upcycling of waste concrete in eco-friendly strain-hardening cementitious composites: Mixture design, structural performance, and life-cycle assessment. Journal of Cleaner Production, 330, p.129911.

Challenge and research objective

Challenges

- While the maintenance intervals for CC beams are well-documented for LCA evaluation, the maintenance interval for UHPC beams remains unclear.
- How do solid wastes affect both the maintenance and structural performance, and therefore the LCA outcomes of UHPC beams remains unknown.

Objectives:

- Assess the influence of solid waste on the structural performance of UHPC beams.
- Develop a framework for evaluating the maintenance intervals of various UHPC beams.
- Investigate impacts of solid wastes on the cradle-to-grave life-cycle performance of UHPC beams.

Experimental method: Mix design

- Conventional concrete and different UHPC mixtures were investigated
  - The UHPC mixtures were cost-effective formulations developed in our previous research.
  - Slag, off-specification fly ash (OSFA), and glass microspheres (GM) were utilized as cement replacements.

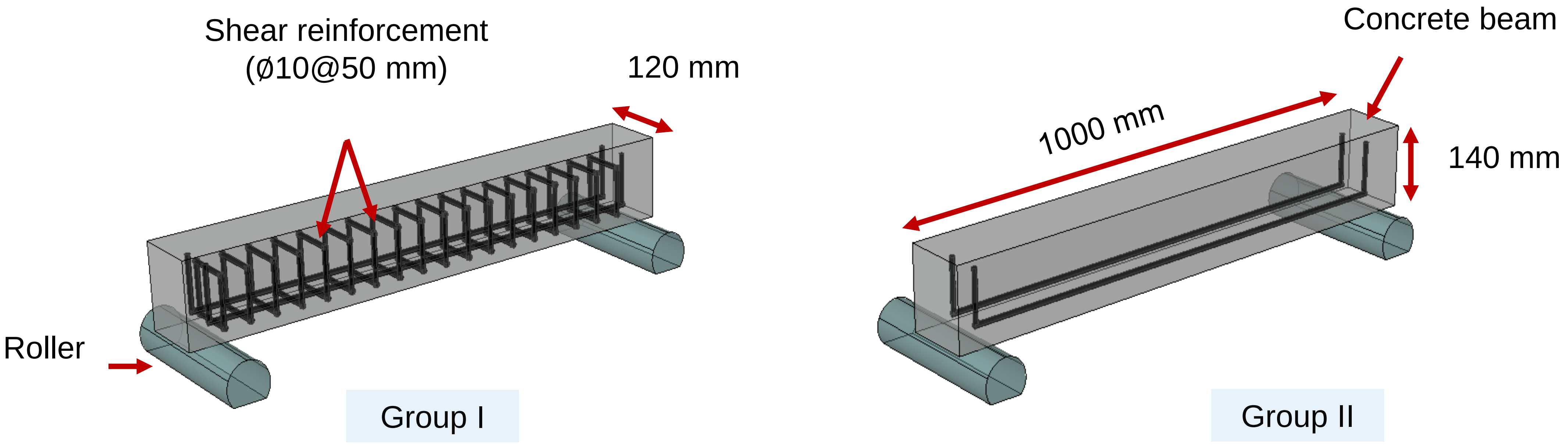
Mixture	C	CA	OSFA	GM	Slag	RS	QS	Water	HRWR	SF	PEF	Density
CC	320	879	-	-	-	891	-	202	-	-	-	2354
UHPC	471	-	-	-	634	980	-	244	10	156	-	2464
UHPC-OSFA	471	-	108	-	433	990	-	232	10	156	-	2377
UHPC-L	565	-	-	41	520	-	780	225	34	-	10	2155

C= cement, CA= coarse aggregate, GM= glass microsphere, RS= river sand, QS= quartz sand, SF= steel fiber, PEF= Polyethylene fiber

[3] Du, J., Liu, Z., Christodoulatos, C., Conway, M., Bao, Y. and Meng, W., 2022. Utilization of off-specification fly ash in preparing ultra-high-performance concrete (UHPC): Mixture design, characterization, and life-cycle assessment. Resources, Conservation and Recycling, 180, p.106136.
[4] Guo, P., Meng, W., et al. 2023. Lightweight ultra-high-performance concrete (UHPC) with expanded glass aggregate: Development, characterization, and life-cycle assessment. Construction and Building Materials, 371, p.130441.

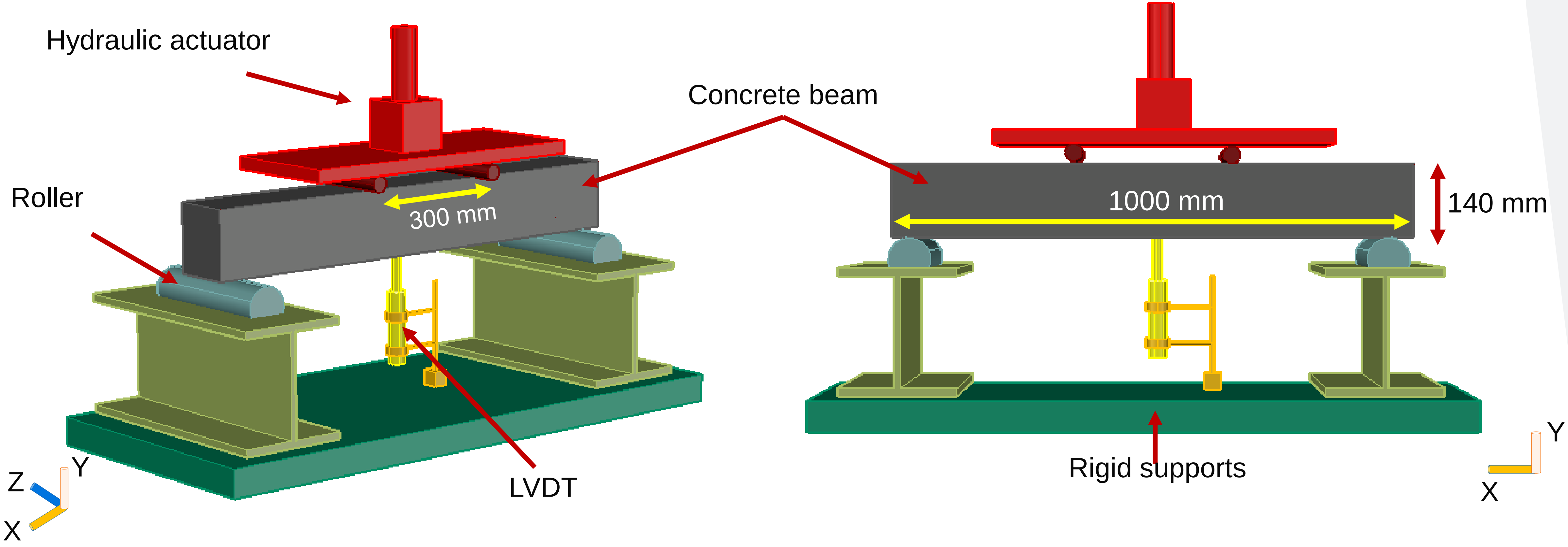
Experimental method: Steel reinforcement schemes

- Investigated **steel reinforcement schemes:** with stirrups (Group I) and without (Group II)
  - Conventional UHPC has high shear capacity, allowing for a reduction in stirrup quantity.
  - In the Group II, all stirrups were removed to assess the effect of solid waste incorporation on the shear capacity of UHPC beams.



Experimental method: Test setup

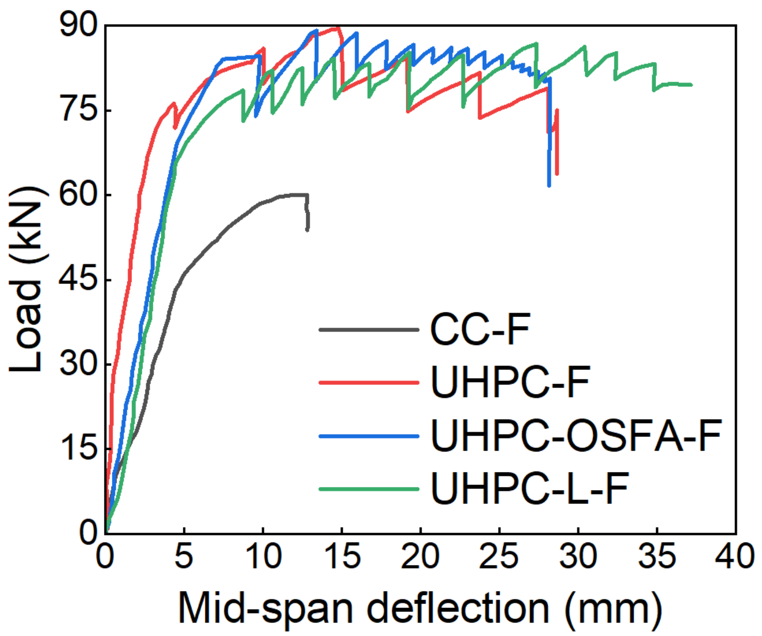
- The four-point bending test setup was used for all beams.
  - Beams were designed according to ACI 318
  - Loading rate of 1 mm/min was applied



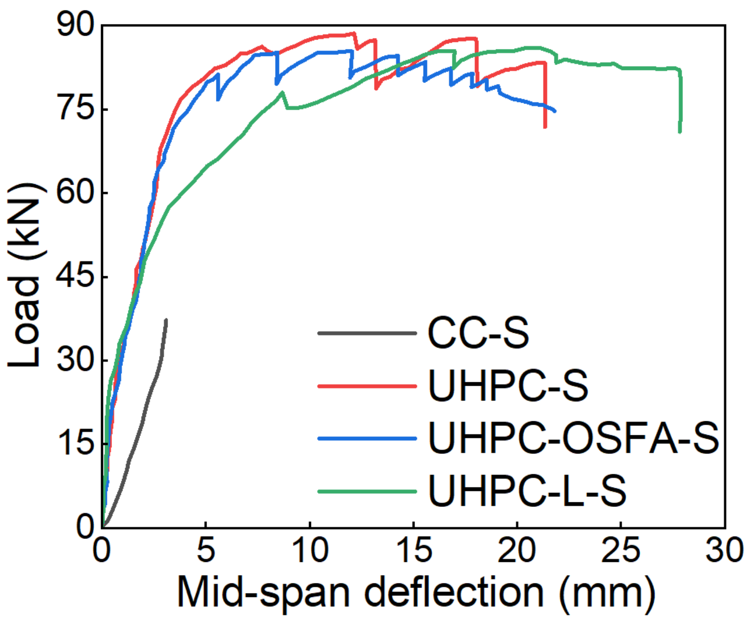
Effect of solid wastes on structural performance of UHPC

- Solid wastes did not negatively impact the flexural capacity of UHPC beams.
- UHPC-L-F exhibited greater mid-span deflection due to the presence of PE fibers in the mixture.
- Removing shear reinforcement did not significantly reduce load-carrying capacity of UHPC.

Beams with shear reinforcement



Beams without shear reinforcement



Label Definitions:
CC = Conventional Concrete
UHPC= reference UHPC
UHPC-OSFA = UHPC with OSFA
UHPC-L = UHPC with glass microspheres

Reinforcement details:
F = Samples with both flexural and shear reinforcement
S = Samples without shear reinforcement

Cradle-to-grave LCA methodology in this study

- The cradle-to-grave LCA in this study is structured to cover three stages: fabrication, operation, and end-of-life.

1. Fabrication

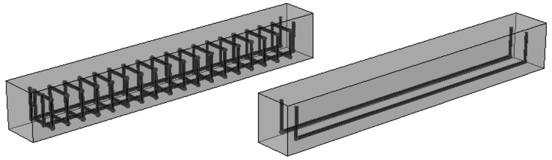
Raw materials

↓

Transportation of materials

↓

Construction



2. Operation and maintenance

Crack width affects the maintenance interval

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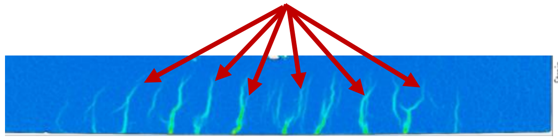
Evaluation of crack width using DIC and DFOS

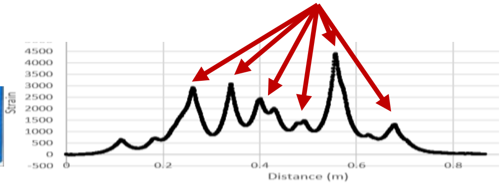
↓

Cracks



DIC

Cracks



DFOS

3. End-of-life

Demolition of structure

↓

Transportation of wastes

↓

Landfill wastes

Recycling wastes

[7] Dong. 2018. Construction and Building Materials Journal.

LCA Stage 1: Fabrication

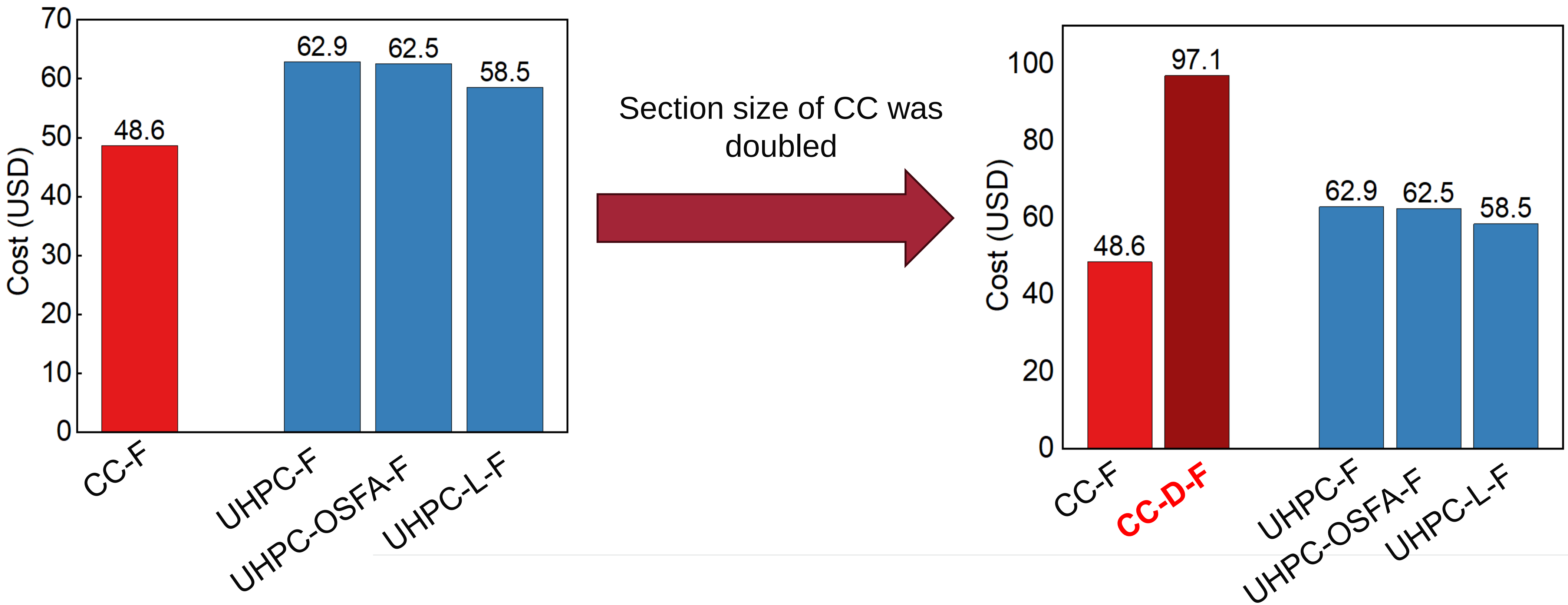
- The cost and carbon emission during the fabrication stage can be assessed using the inventory data and the volume of concrete beam.

Ingredients	Cost		Carbon emission		References
	Value	Unit	Value	Unit	
Cement	0.11	USD/kg	0.83	kg/kg	[3, 4]
Slag	0.10	USD/kg	0.02	kg/kg	[3, 4]
OSFA	0.00	USD/kg	0.00	kg/kg	[3, 10]
River sand	0.02	USD/kg	0.01	kg/kg	[3, 4]
Quartz sand	0.03	USD/kg	0.10	kg/kg	[4]
Coarse aggregate	0.01	USD/kg	0.002	kg/kg	[11]
Glass microsphere	5.92	USD/kg	0.30	kg/kg	[12]
Water	0.037	USD/kg	0.01	kg/kg	[4]
HRWR	3.60	USD/kg	0.72	kg/kg	[3, 4]
Steel fiber	4.76	USD/kg	1.49	kg/kg	[3, 4]
PE fiber	16.20	USD/kg	4.08	kg/kg	[4]
Steel rebar	3.99	USD/kg	3.03	kg/kg	[9]
Transportation (truck)	0.04	USD/ton-km	0.06	kg/ton-km	[12]
Landfill solid waste	0.059	USD/kg	0.007	kg/kg	[13]
Labor	16.31	USD/h	-	-	[14]
Recycling waste concrete	0.012*	USD/kg	0.014	kg/kg	[9]

[3] Du, J., Liu, Z., Christodoulatos, C., Conway, M., Bao, Y. and Meng, W., 2022. Utilization of off-specification fly ash in preparing ultra-high-performance concrete (UHPC): Mixture design, characterization, and life-cycle assessment. Resources, Conservation and Recycling, 180, p.106136.
[4] Guo, P., Meng, W., et al. 2023. Lightweight ultra-high-performance concrete (UHPC) with expanded glass aggregate: Development, characterization, and life-cycle assessment. Construction and Building Materials, 371, p.130441.
[9] Li et al. 2022. Journal of Cleaner Production.
[10] Liu, Z., J. Du, C. Christodoulatos, W. Meng, and Y. Bao, Recycling Off-Specification Fly Ash for Producing Strain-Hardening Cementitious Composites. Journal of Materials in Civil Engineering, 2024. 36(1): p. 04023531.
[11] Wang et al. 2021. Renewable and Sustainable Energy Reviews.
[12] Guo, P., Y. Bao, and W. Meng, Review of using glass in high-performance fiber-reinforced cementitious composites. Cement and Concrete Composites, 2021. 120: p. 104032.
[13] Mah et al. 2018. Journal of Cleaner Production.
[14] https://www.ziprecruiter.com/Salaries/General-Labor-Salary--in-New-Jersey#:~:text=As%20of%20Apr%2025%2C%202024,Jersey%20is%20%2416.31%20an%20hour.%202024.

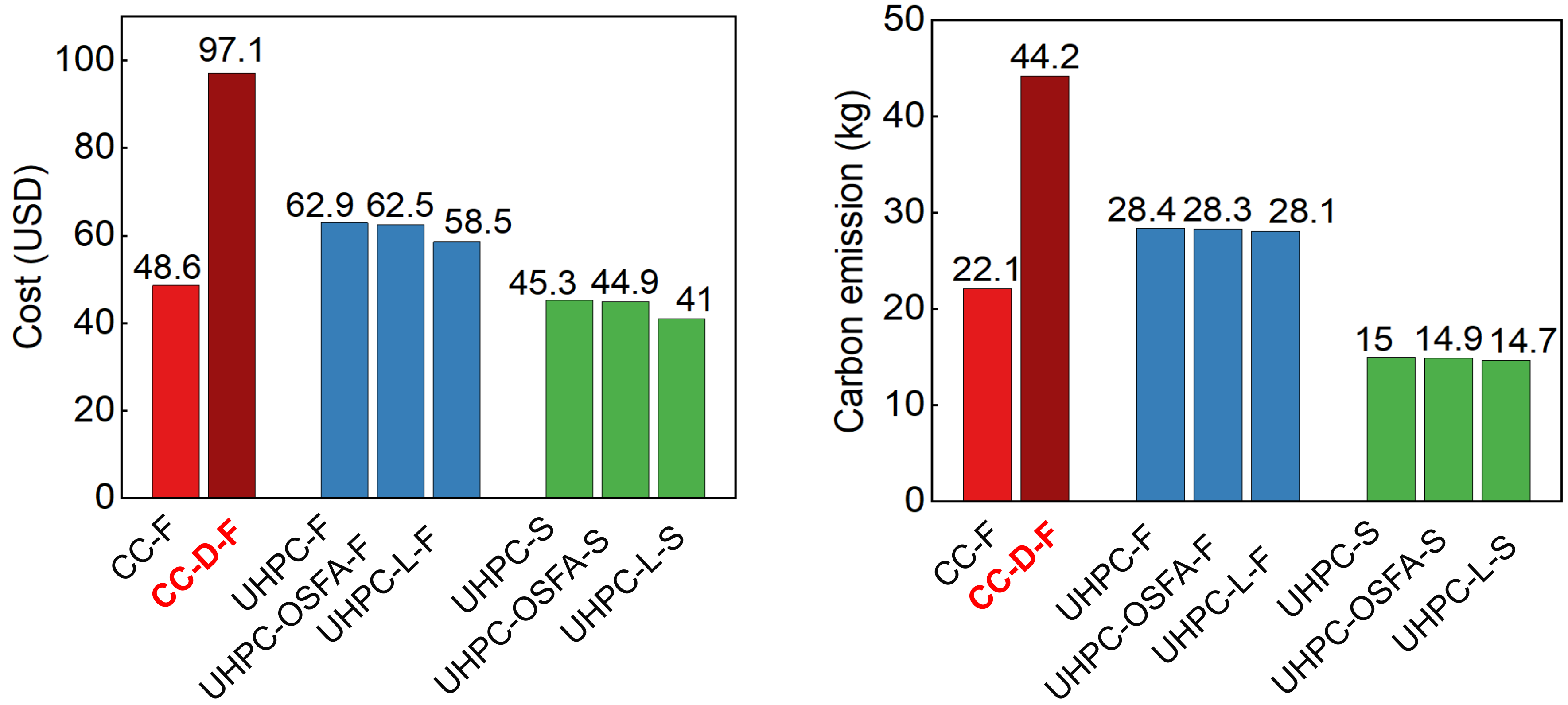
LCA Stage 1: Fabrication

- Due to its lower mechanical strength, the CC beam requires a larger cross-sectional size in real-world application compared to UHPC beams:
  - The cross-sectional size of CC beams was doubled (referred to as CC-D).
  - After adjusting the cross-section, the cost of the CC beam becomes higher than UHPC beams, highlighting the importance of incorporating structural design requirements into LCA.



LCA Stage 1: Fabrication

- The fabrication cost and emission of UHPC beams were **40%** and **36%** lower than CC beam.
- After removing shear reinforcement, the cost and emission of UHPC beams were further reduced by up to **58%** and **67%** compared with CC beam.

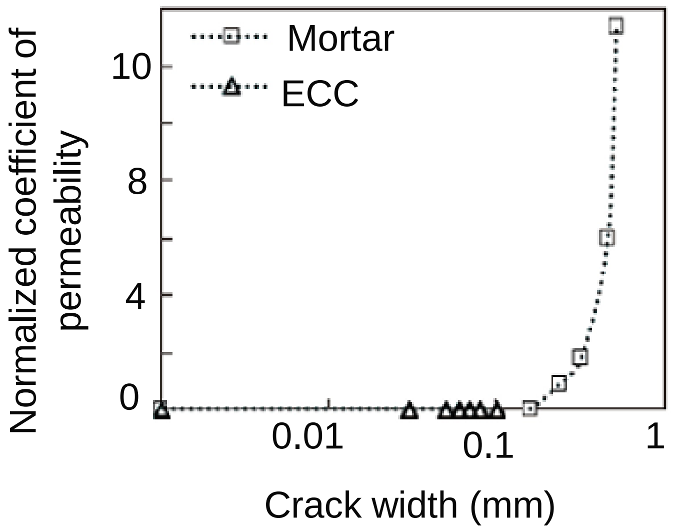


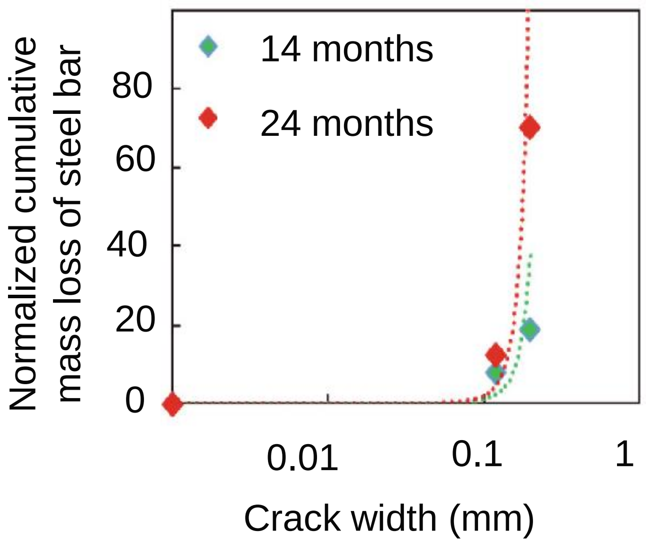
Label Definitions:
CC = Conventional Concrete
CC-D= CC with doubled section size
UHPC= reference UHPC
UHPC-OSFA = UHPC with OSFA
UHPC-L = UHPC with glass microspheres

Reinforcement details:
F = Samples with both flexural and shear reinforcement
S = Samples without shear reinforcement

LCA Stage 2: Operation and maintenance

- Maintenance intervals are influenced by durability of concrete and considered in the LCA.
- Cracks adversely affect durability and are associated with maintenance intervals.
  - ✓ Cracks wider than **0.1 mm** can result in reinforcement corrosion.
  - ✓ Cracks under service load should be detected.
  - ✓ Cracks under service loads are invisible to the naked eye.



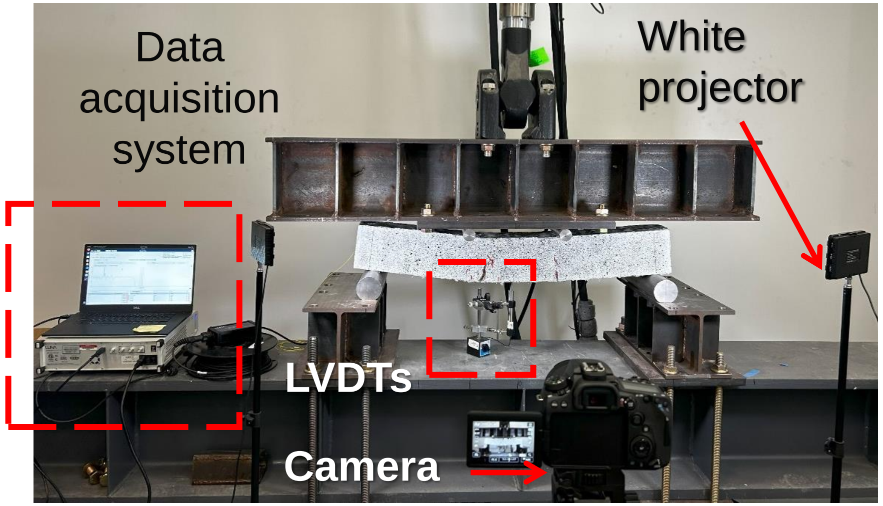


Corrosion of steel reinforcement
(crack width>0.1 mm)

[7] Dong. 2018. Construction and Building Materials Journal.
[15] Fan, L., Teng, L., Tang, F., Khayat, K.H., Chen, G. and Meng, W., 2021. Corrosion of steel rebar embedded in UHPC beams with cracked matrix. Construction and Building Materials, 313, p.125589.
[16] Li. 2019. Engineering.

Crack detection by advanced monitoring technologies

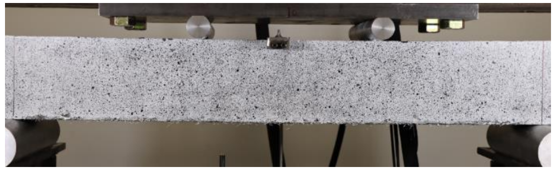
- Distributed fiber optic sensors (DFOS) and digital image correlation (DIC) were utilized to assess crack width.



Testing set up

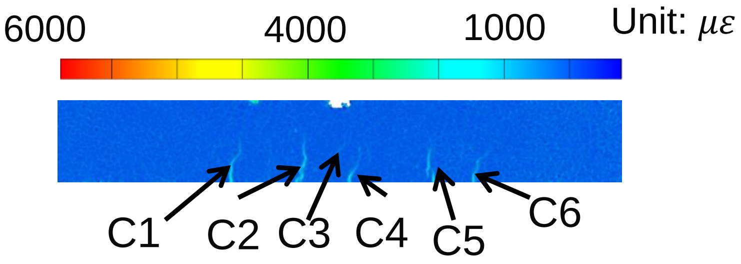
Surface preparation for DIC

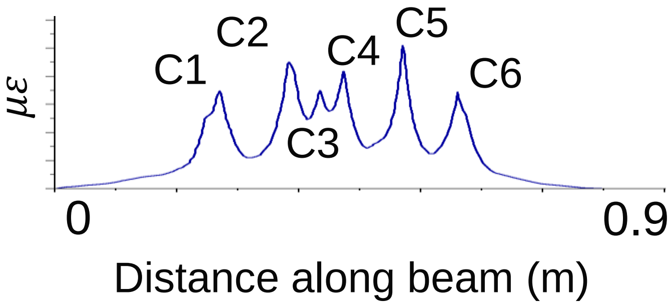
DFOS



UHPC-OSFA-F beam

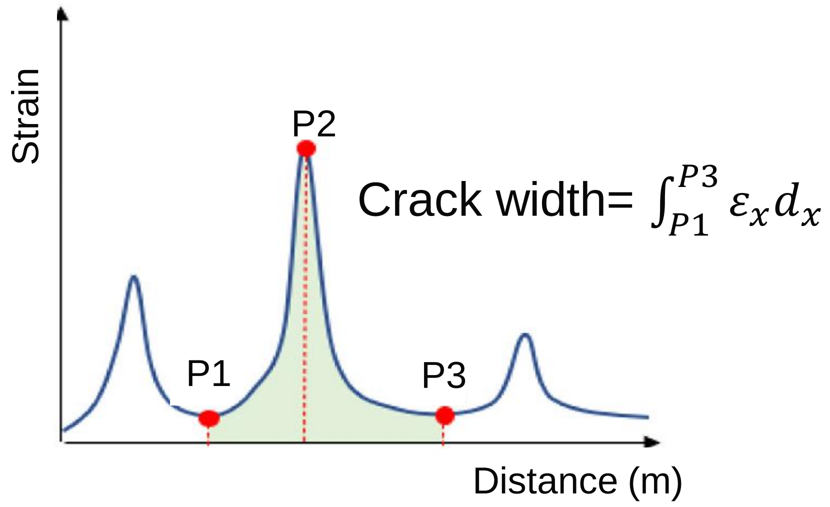
Load: 21 kN



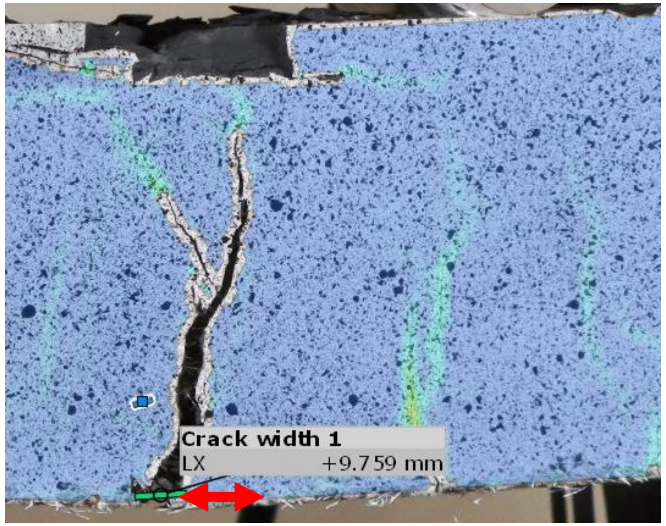


DFOS and DIC for crack width measurement

- For DFOS:
  - First, the strain at service load was detected, and diagram was drawn.
  - The peak strain is associated with the crack width.
  - Integration of the strain distribution across the crack zone gives the crack width.



- For DIC:
  - First, two points on either side of the widest crack are selected at maximum load.
  - Then, the analysis is repeated at the service load level (60% of maximum load) to measure crack width under service conditions.



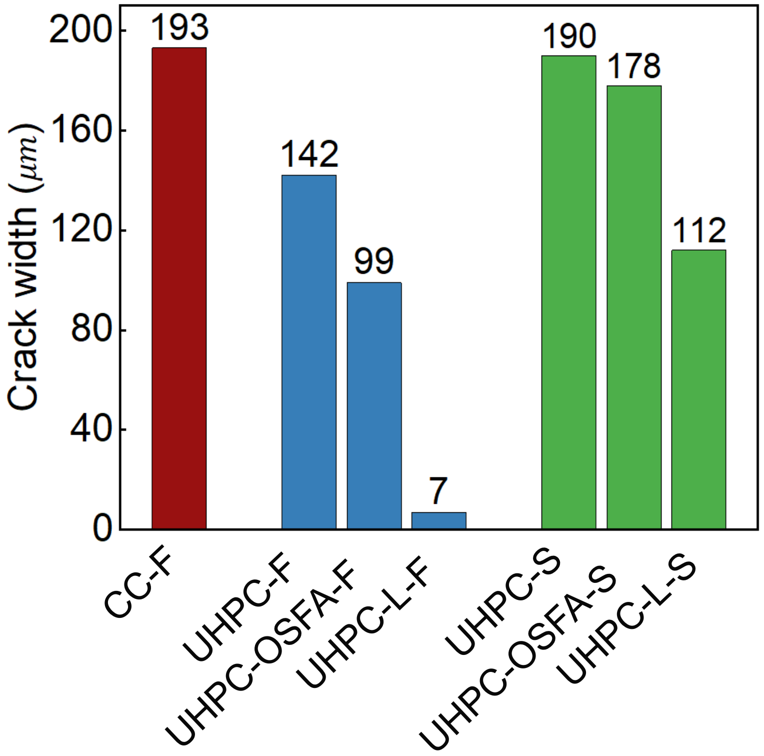
Defining two points on either side of widest crack at maximum load

Tan et al. 2021. Automation in Contruction

Determination of maintenance intervals

- UHPC beams exhibited smaller crack widths compared with CC beams, suggesting a reduction in maintenance needs.

- The removal of shear reinforcement led to an increase in crack width in UHPC beams.



- Based on previous studies:
  - For CC beams, preventive and essential maintenance intervals are **10** and **40 years**.
  - UHPC is more durable than CC, these intervals are extended to **20** and **80 years** for UHPC-F.

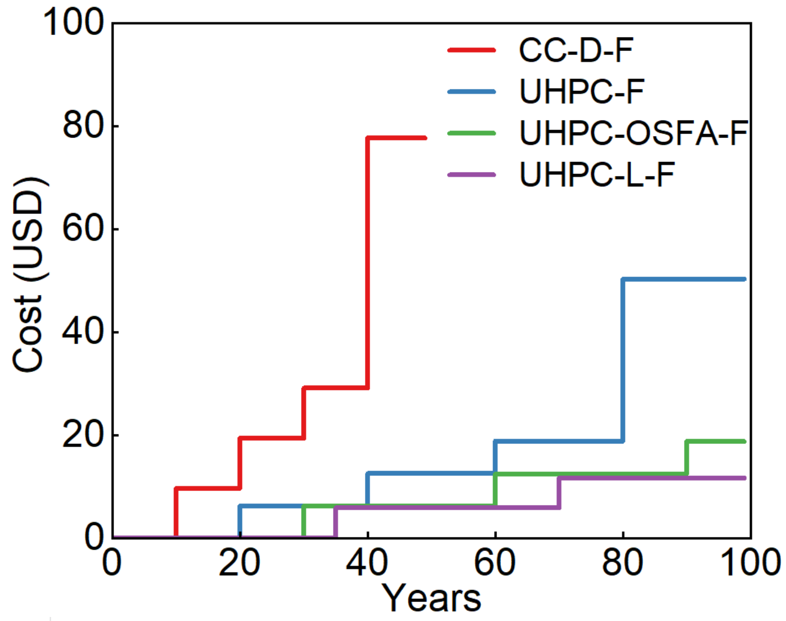
- For UHPC-OSFA-F beams, a crack width of 0.099 mm (lower than the 0.142 mm observed in UHPC-F) allowed for further extension of maintenance intervals to **30** and **120** years.

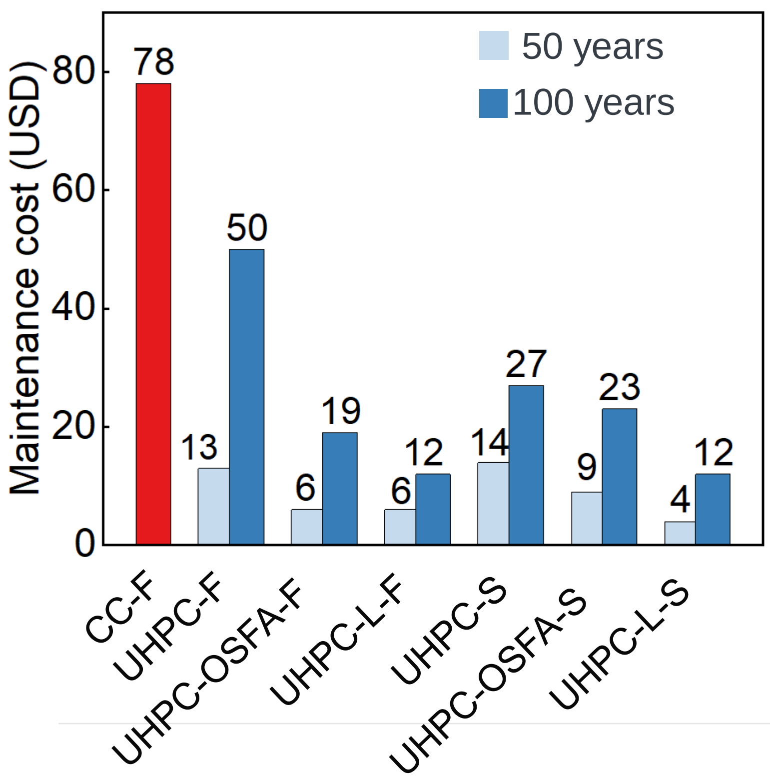
- For UHPC-L-F, a crack width of 0.007 mm allowed for further extension of maintenance intervals to **35** and **140** years.

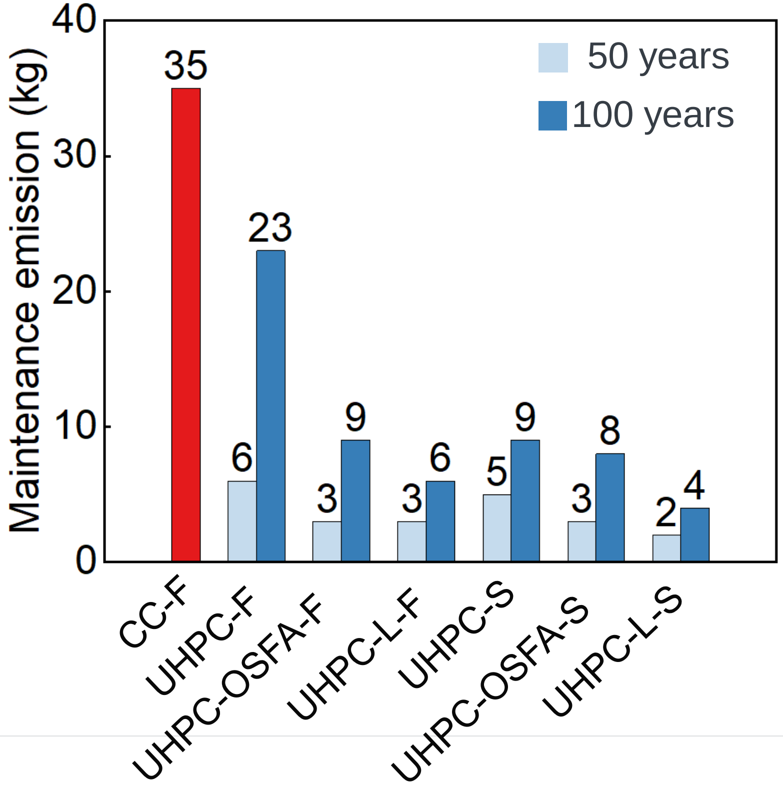
Dong. 2018. Construction and Building Materials Journal.

LCA Stage 2: Maintenance cost and emission

- Maintenance cost and emission of each beam was calculated based on a service life of 50 years for CC and 100 years for UHPC. At the end of service life:
  - Maintenance cost of UHPC beams was reduced up to **92%** at 50 years and **85%** at 100 years compared with CC beam.
  - Maintenance carbon emission of UHPC beams was reduced up to **94%** at 50 years **89%** at 100 years compared with CC beam.



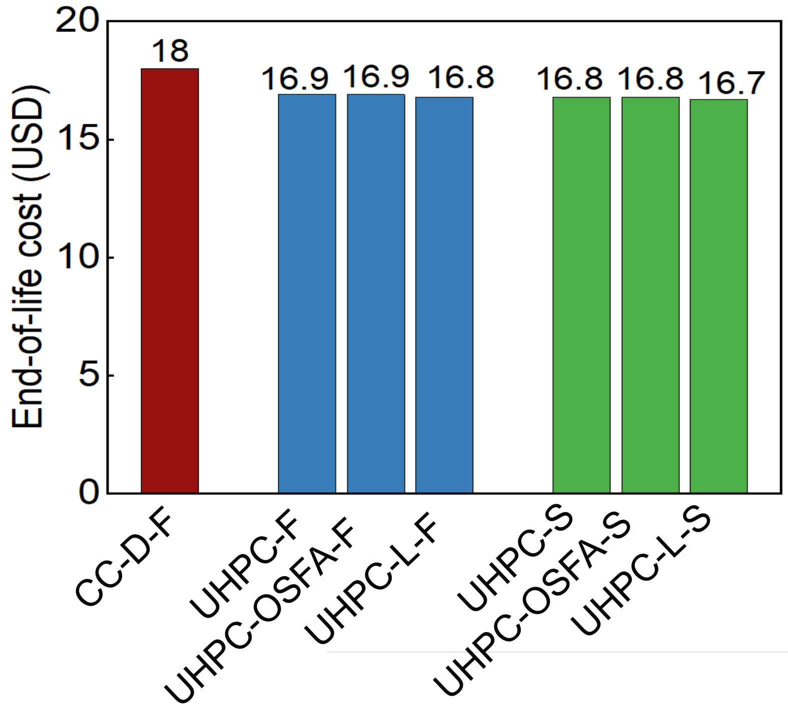


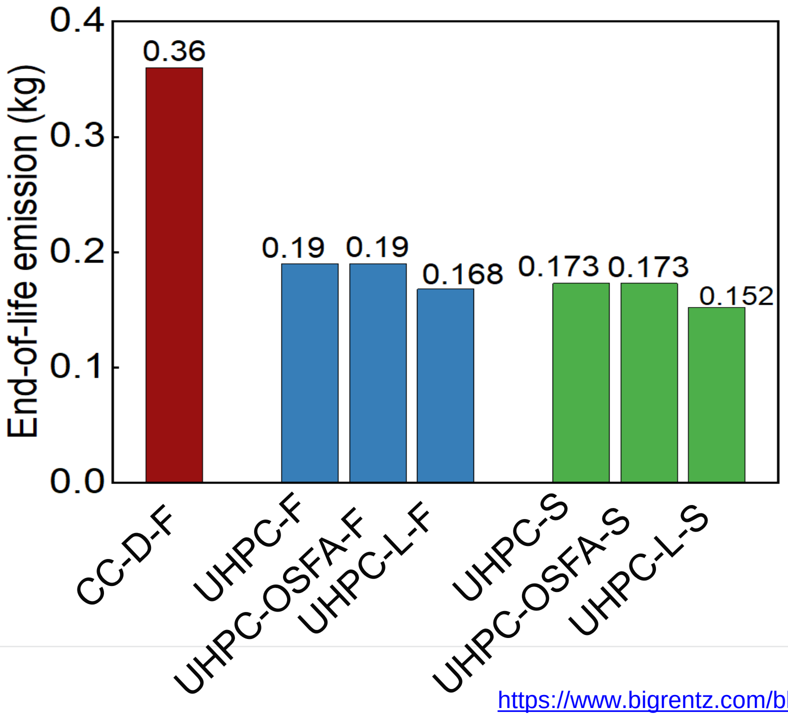


[7] Dong. 2018. Construction and Building Materials Journal.

LCA Stage 3: End-of-life cost and emission

- This study assumed 90% of waste concrete will be recycled after 50 years (for CC beams) in the U.S., and 100% after 100 years (for UHPC beams).
- Assumed cost and emission associated with demolition machinery and transportation of CC and UHPC are the same.
- The end-of-life cost of CC beams (50 years) was 6-7% higher than UHPC beams (100 years).
- The end-of-life carbon emission of CC beam is 47-58% higher than UHPC beams.

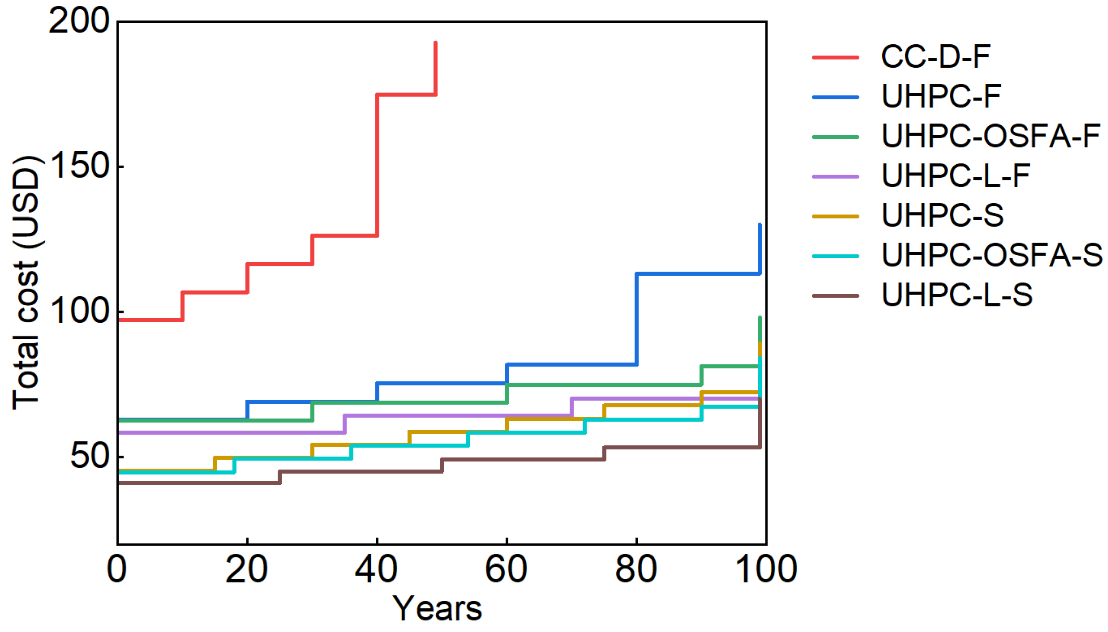


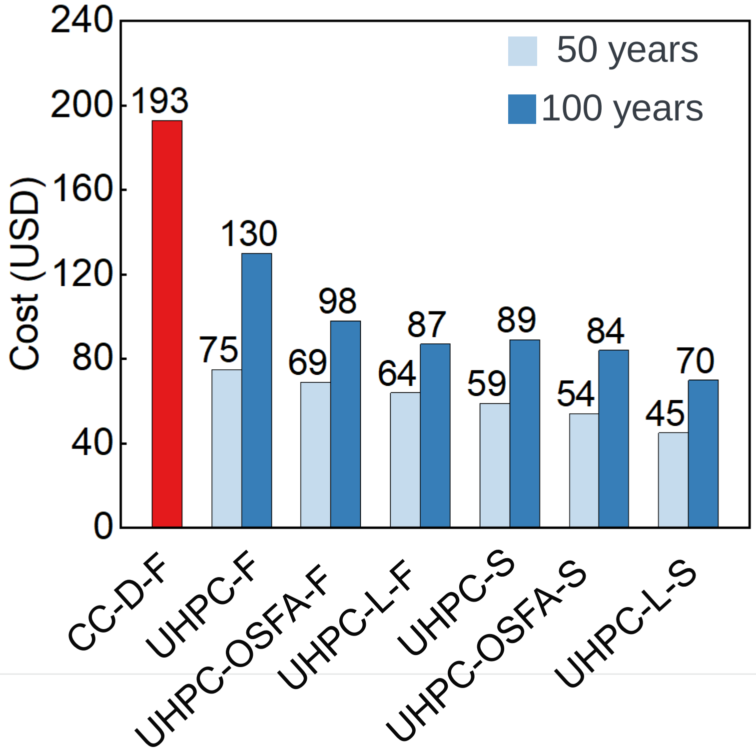


https://www.bigrentz.com/blog/construction-waste-statistics

Overall cradle-to-grave LCA cost

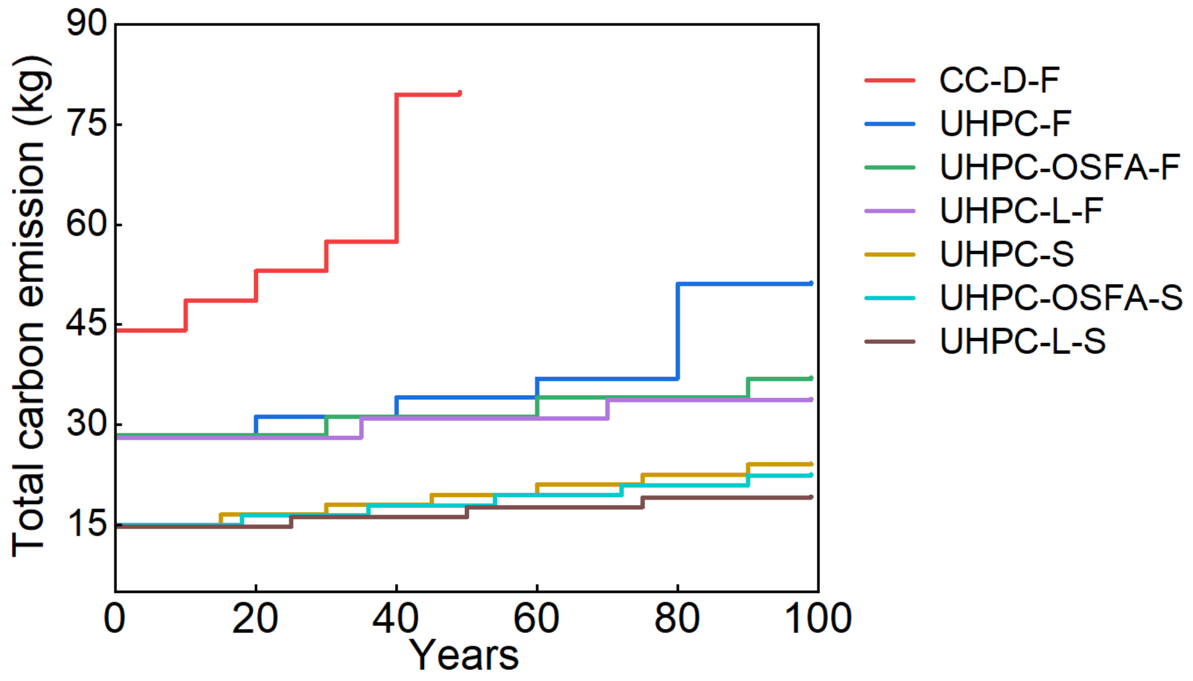
- The overall cradle-to-grave analysis encompasses the combined impacts of the fabrication, maintenance, and end-of-life stages
- The use of UHPC materials reduced the life-cycle cost by up to **67%** at 50 years and **55%** at 100 years compared with the CC beam.
- Removing shear reinforcement further reduced the cost by up to **77%** at 50 years and **64%** at 100 years compared with CC beam.

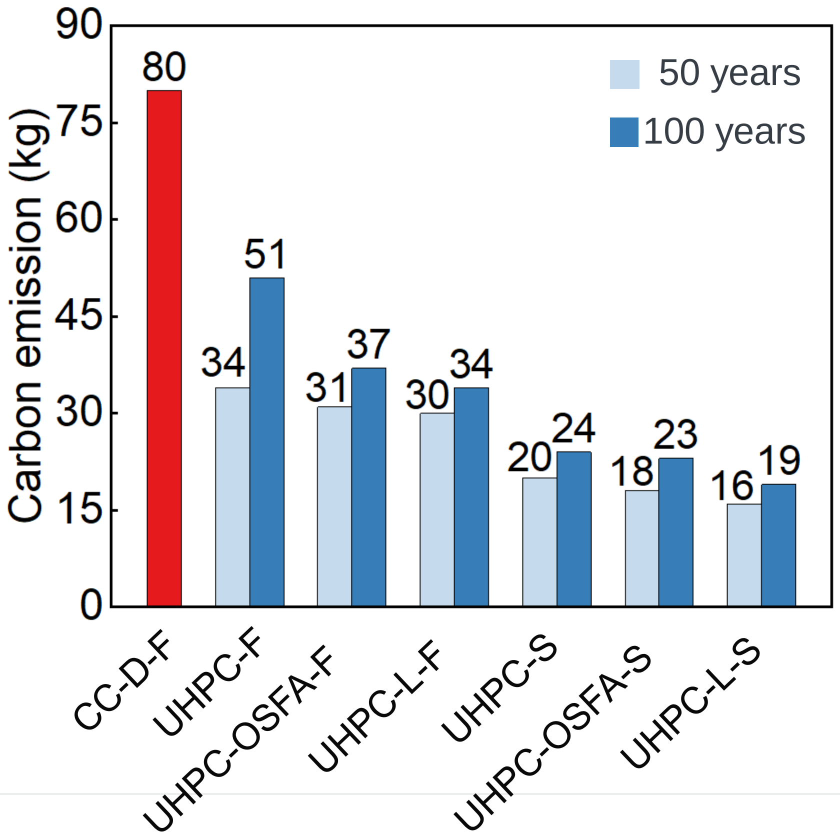




Overall cradle-to-grave LCA carbon emission

- The use of UHPC materials reduced the life-cycle carbon emissions by up to **63%** at 50 years and **58%** at 100 years compared with CC beams.
- Removing shear reinforcement further reduced the emission by up to **80%** at 50 years and **76%** at 100 years compared with CC beam.





Conclusions

- This research presents a comprehensive framework for the cradle-to-grave LCA of UHPC beams utilizing advanced monitoring technologies.
- The integration of **DIC** and **DFOS** for **crack monitoring** enabled a predictive approach to assess the **maintenance intervals** of concrete beams.
- **Structural design** and **maintenance** strategies demonstrated substantial impacts on LCA outcomes.
- The incorporation of solid wastes into UHPC resulted in life-cycle cost and emission reductions of up to **64%** and **76%**, respectively, relative to CC beams.

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