Life-cycle assessment of ultra-high-performance concrete (UHPC) beams using advanced monitoring technologies

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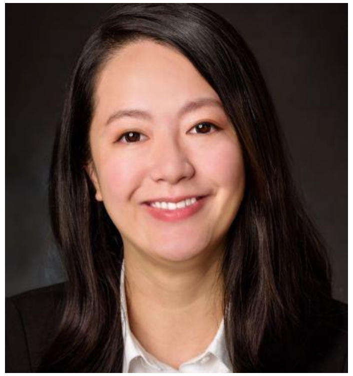
Acknowledgment

- Thanks to my advisors, Professors Yi Bao and Weina Meng, for their strong supports and supervision throughout this research.
- Thanks to Professors Christos Christodoulatos and Qinghua Zhang for their important inputs.
- Thanks to my colleagues, Mr. Sina Poorghasem, Mr. Hammad Ahmed Shah, and Mr. Pengwei Guo, for their supports.
- This research was funded by the National Science Foundation (NSF) and the US Army Corps of Engineers.
- The presented contents only reflect the authors' opinions and do not reflect the sponsors' endorsement.

Prof. Yi Bao



Prof. Weina Meng

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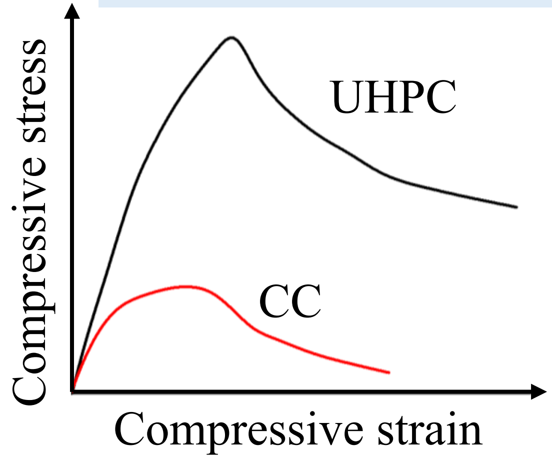
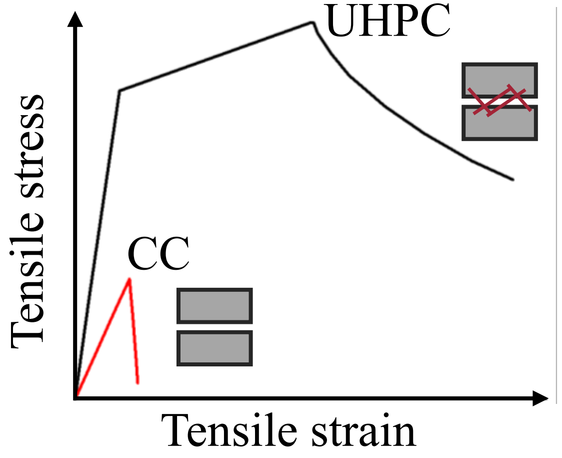
Benefits of UHPC

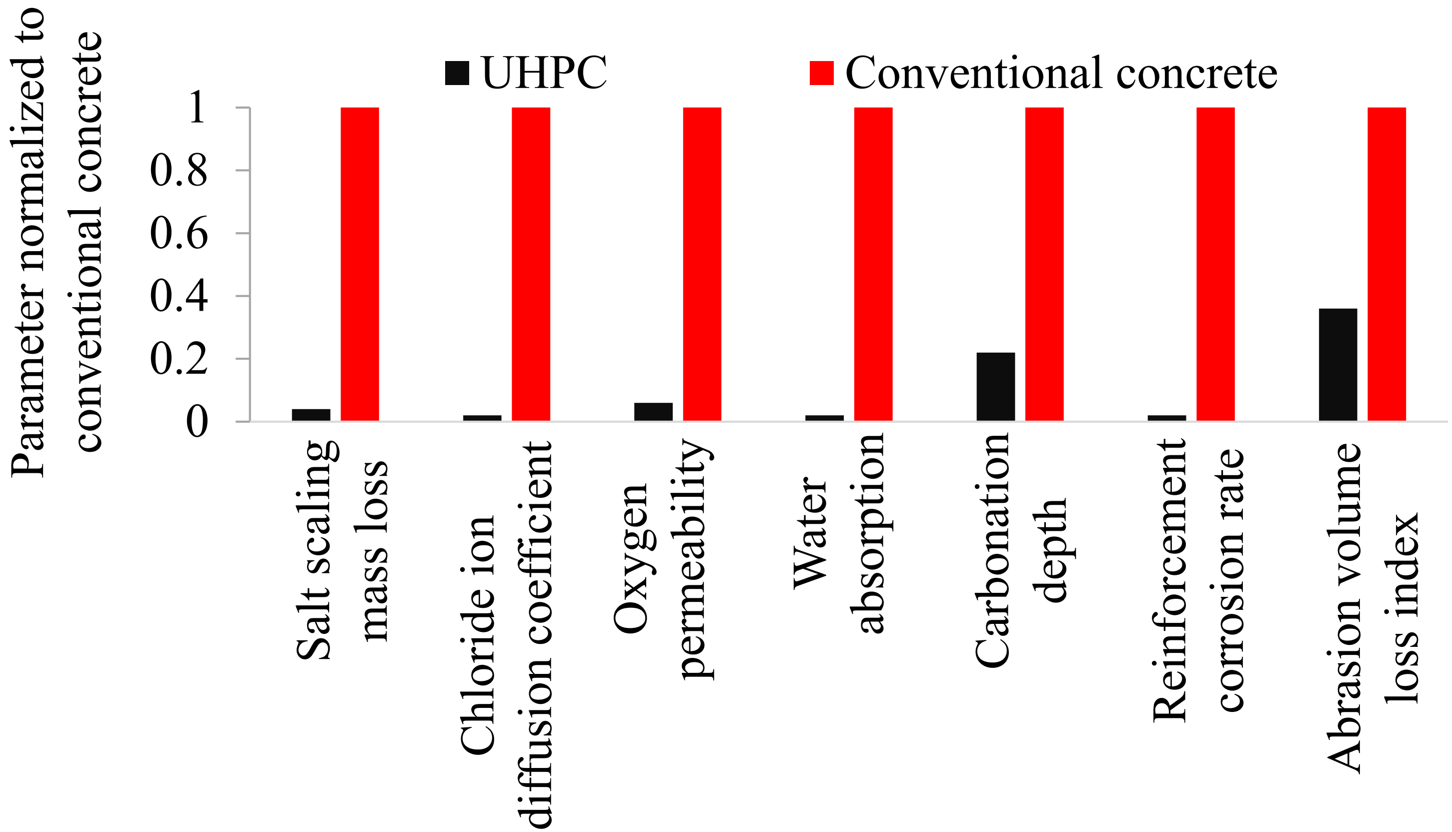
UHPC has attracted strong interests owing to remarkable material properties:

High strength



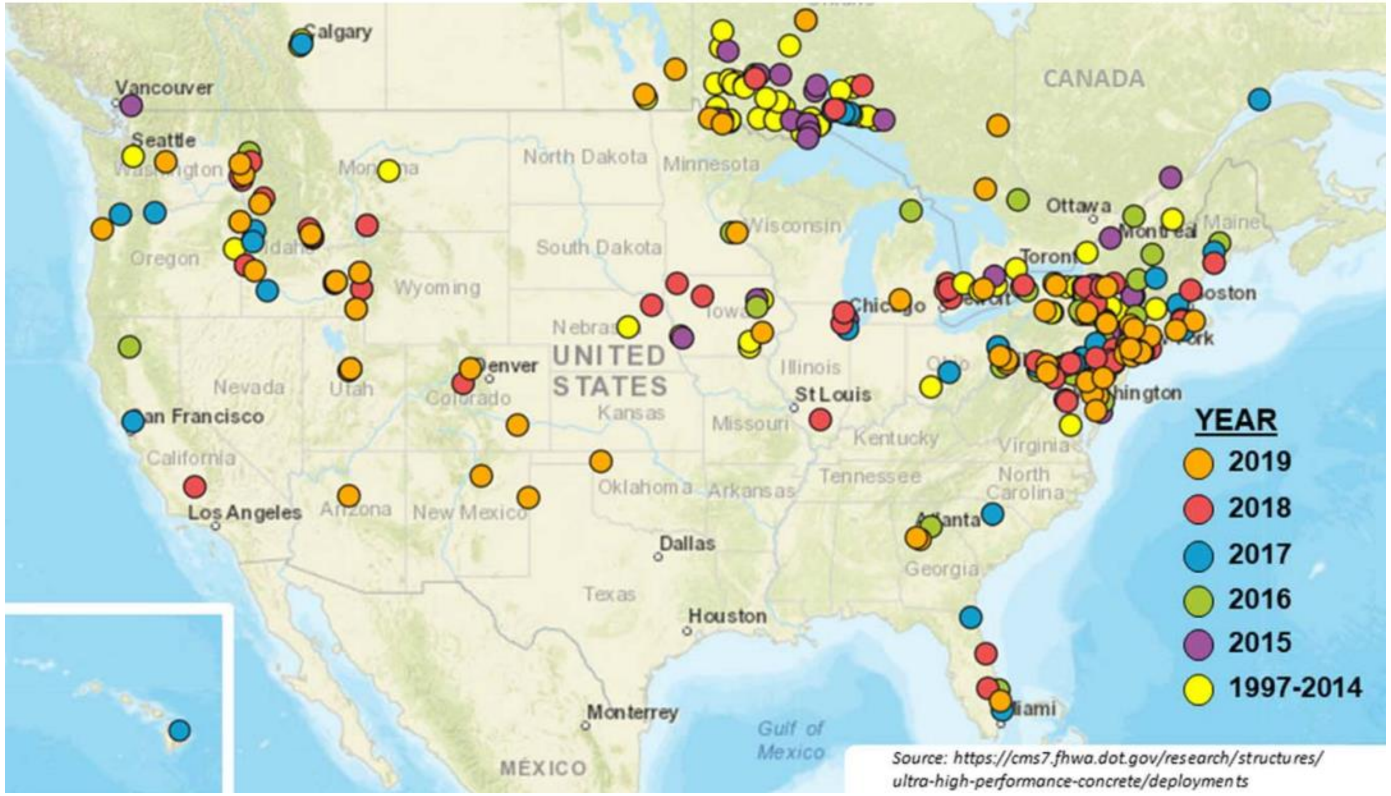


Excellent durability



Application of UHPC

UHPC is an appealing choice for bridge construction.



UHPC bridges in the U.S. and Canada through 2019. (Map data from Esri, HERE, Garmin, NGA, USGS.)

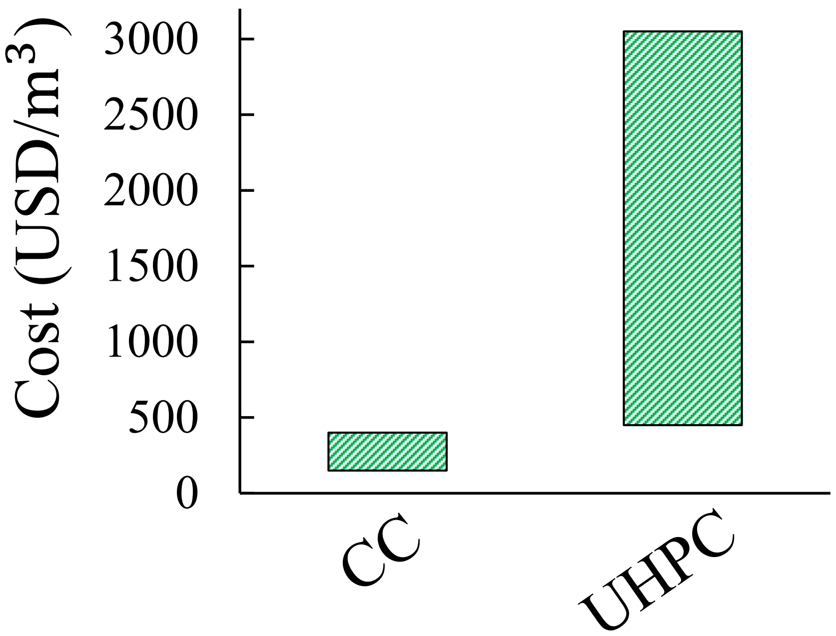
Mars Hill Bridge, Iowa

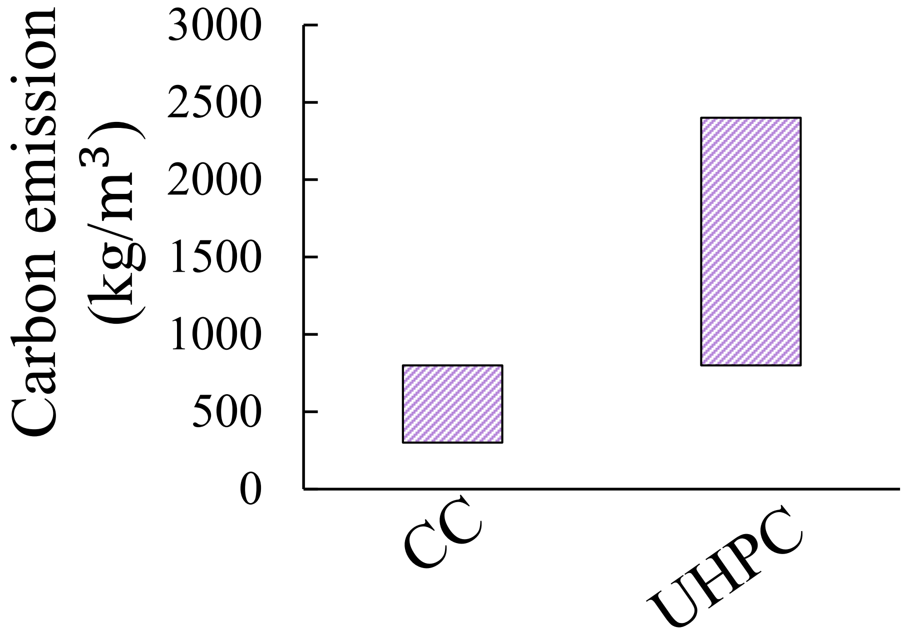
Cat Point Creek Bridge, Virginia

Graybeal, B., 2011. UHPC in the US Highway Infrastructure. *Designing and Building with UHPFRC*, pp.221-234.

High upfront cost and emission of UHPC

To achieve the superior materials properties, UHPC contain substantial cement and steel fibers.





Development of sustainable UHPC

Incorporating waste materials in UHPC mixture:

- Industrial waste, e.g., slag, off-specification fly ash (OSFA)
- Municipal solid waste, e.g., glass

Slag

OSFA

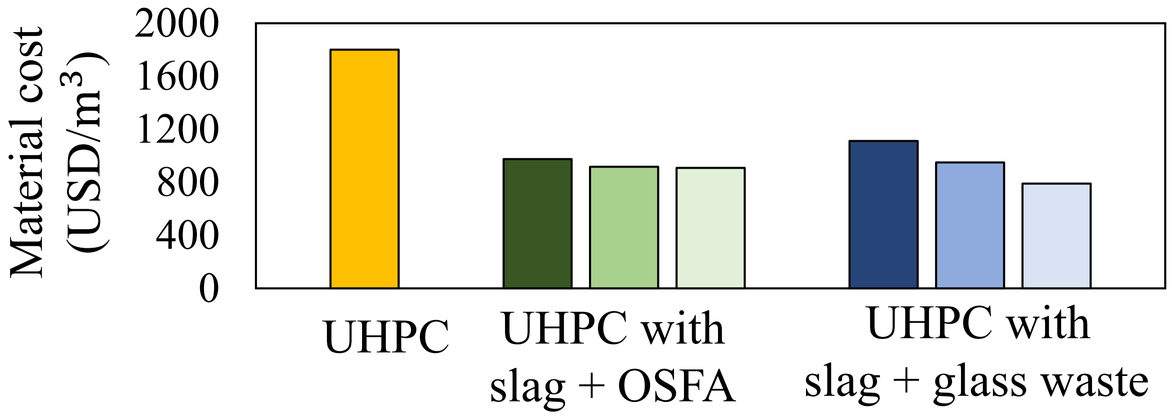
Glass microsphere

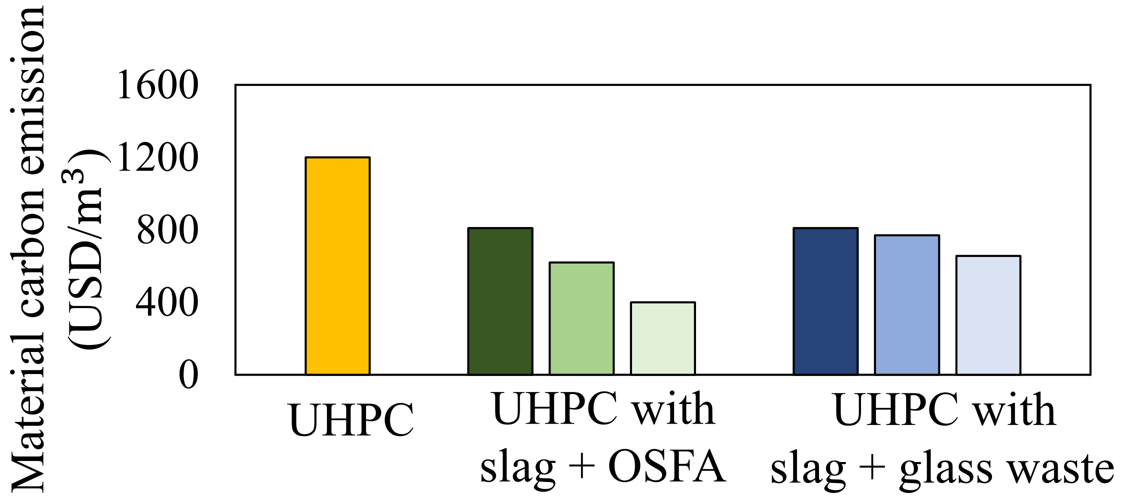
Du, J., Liu, Z., Christodoulatos, C., Conway, M., Bao, Y. and Meng, W., 2022. Utilization of off-specification fly ash in preparing ultra-high-performance concrete (UHPC): Mixture design, characterization, and life-cycle assessment. *Resources, Conservation and Recycling*, *180*, p.106136.
Guo, P., Meng,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

Cradle-to-gate life cycle assessment (LCA)

- The previous LCA of UHPC was primarily focused on the production stage, known as cradle-to-gate LCA.

- Cradle-to-gate LCA does not involve the complexity of structural design.



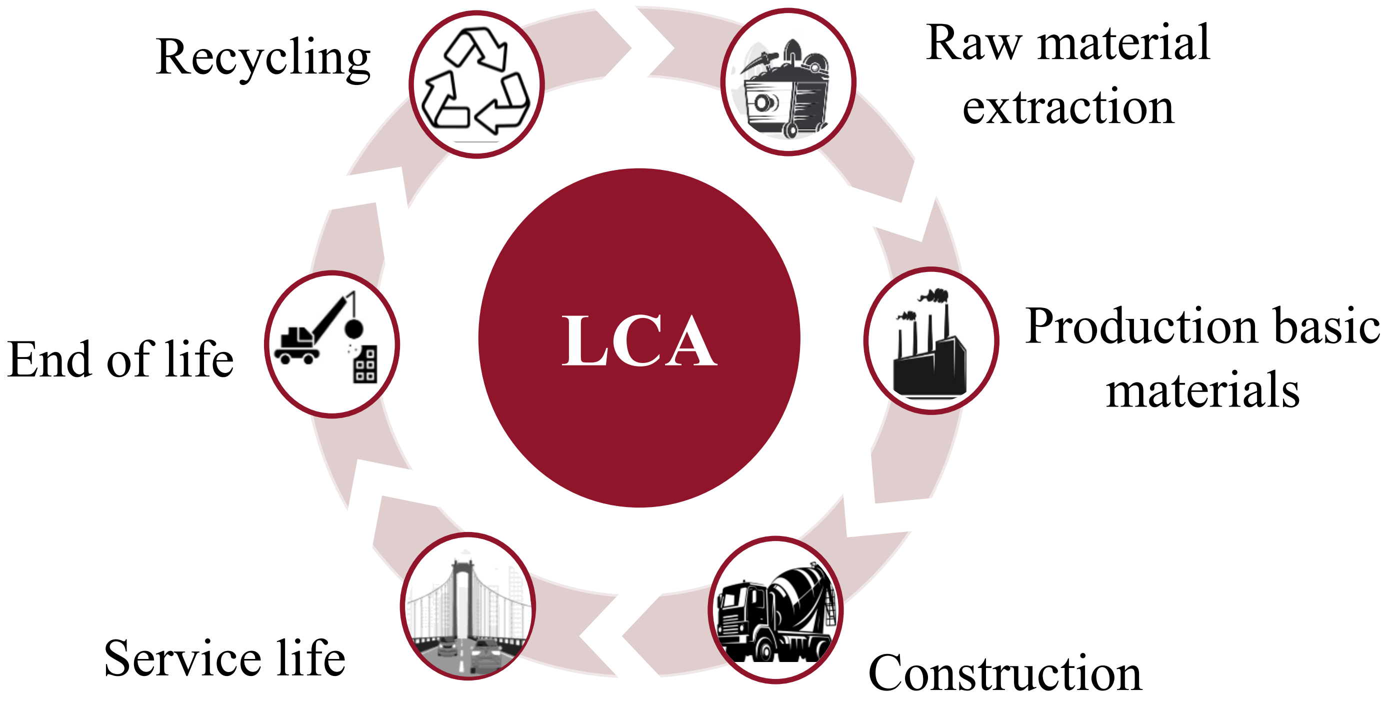


Du, J., Liu, Z., Christodoulatos, C., Conway, M., Bao, Y. and Meng, W., 2022. Utilization of off-specification fly ash in preparing ultra-high-performance concrete (UHPC): Mixture design, characterization, and life-cycle assessment. *Resources, Conservation and Recycling*, *180*, p.106136.

Guo, P., Meng, W., Du, J., Stevenson, L., Han, B. and Bao, Y., 2023. Lightweight ultra-high-performance concrete (UHPC) with expanded glass aggregate: Development, characterization, and life-cycle assessment. *Construction and Building Materials*, *371*.

Cradle-to-grave LCA

The LCA system boundary can be extended to include the service and end-of-life stages, known as "cradle-to-grave" analysis.



Maintenance intervals in LCA

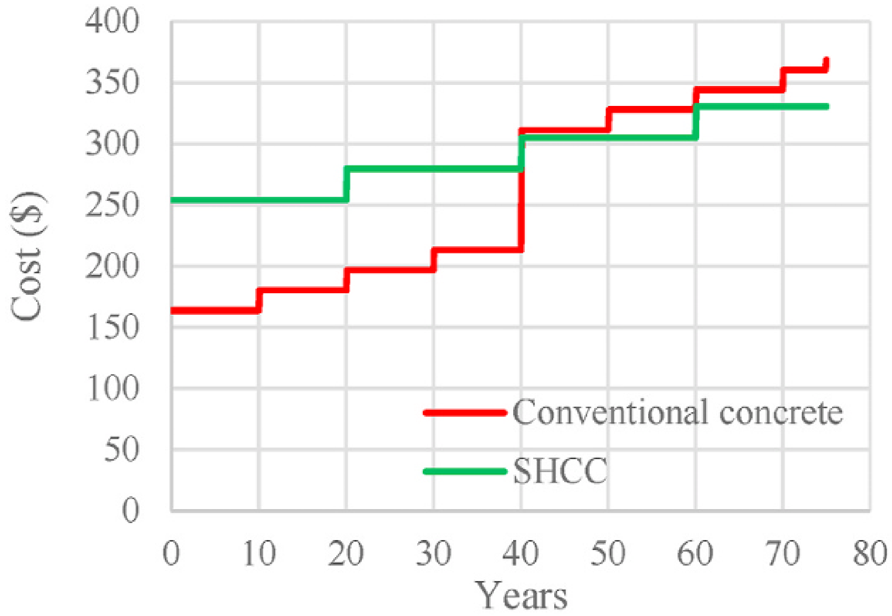
Maintenance frequency is a key factor that significantly affects costs and emissions during the service life.

Preventive maintenance like seal joints and cracks

Every **10 years** for CC beams

Essential maintenance like repairing or replacement of damaged parts

Every **40 years** for CC beams



Effects of different maintenance interval on life-cycle cost

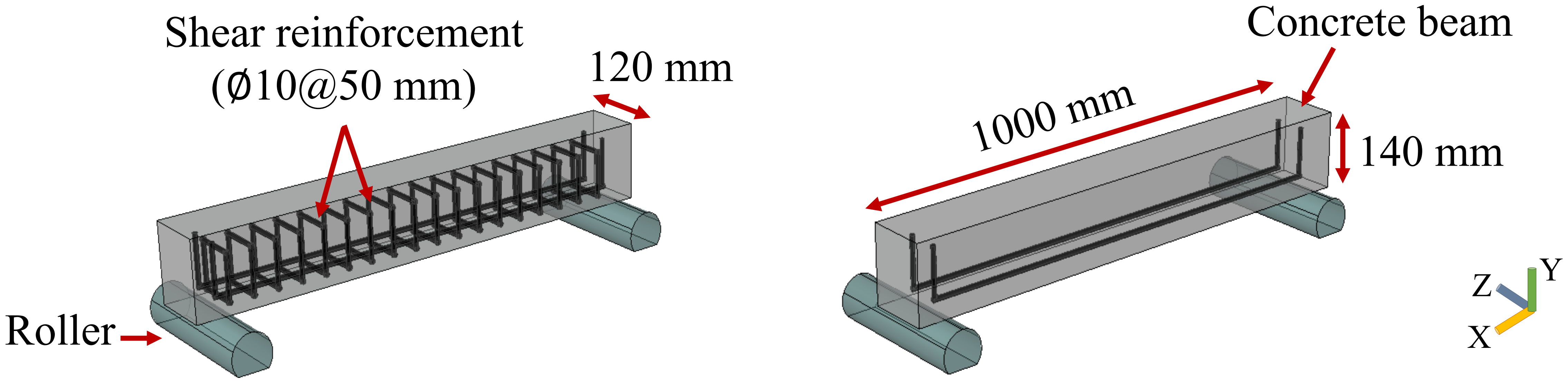
Li, X., Lv, X., Zhou, X., Meng, W. and Bao, Y., 2022. Upcycling of waste concrete in eco-friendly strain-hardening cementitious composites: Mixture design, structural performance, and life-cycle assessment. *Journal of Cleaner Production*, *330*, p.129911.

Research objective and novelties

- **Knowledge gap**: Although the incorporation of solid wastes into UHPC can reduce the **cradle-to-gate** life-cycle cost and emission while retaining the mechanical strength of UHPC, it is unknown how the use of solid wastes impacts the **cradle-to-grave** life-cycle performance of UHPC structures.
- We **aim to** understand the impacts of using solid wastes in UHPC on the life-cycle performance of UHPC beams.
- **Primary novelties**
  - A cradle-to-grave life-cycle analysis of UHPC beams was performed
  - Distributed fiber optic sensors and digital image correlation were used
  - Different steel reinforcement schemes were compared

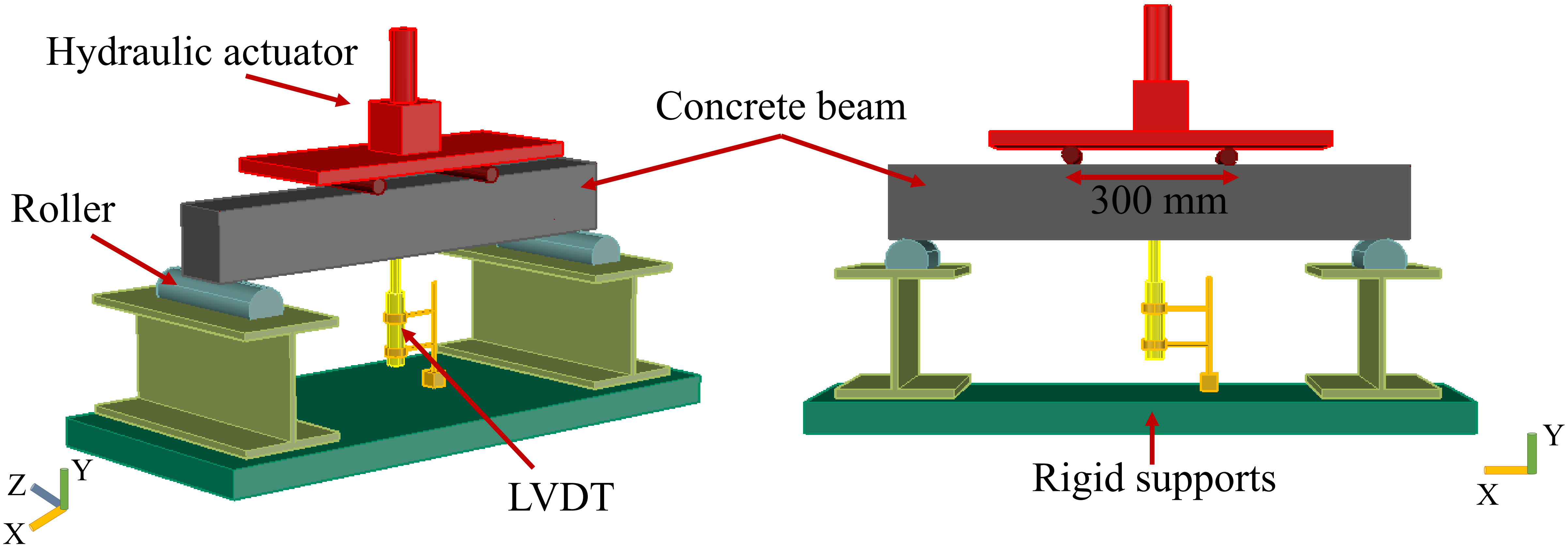
Design of UHPC beams

- Investigated variables
  - ➢ Steel reinforcement schemes: with stirrups and without stirrups
  - ➢ Materials: conventional concrete and different UHPC mixtures



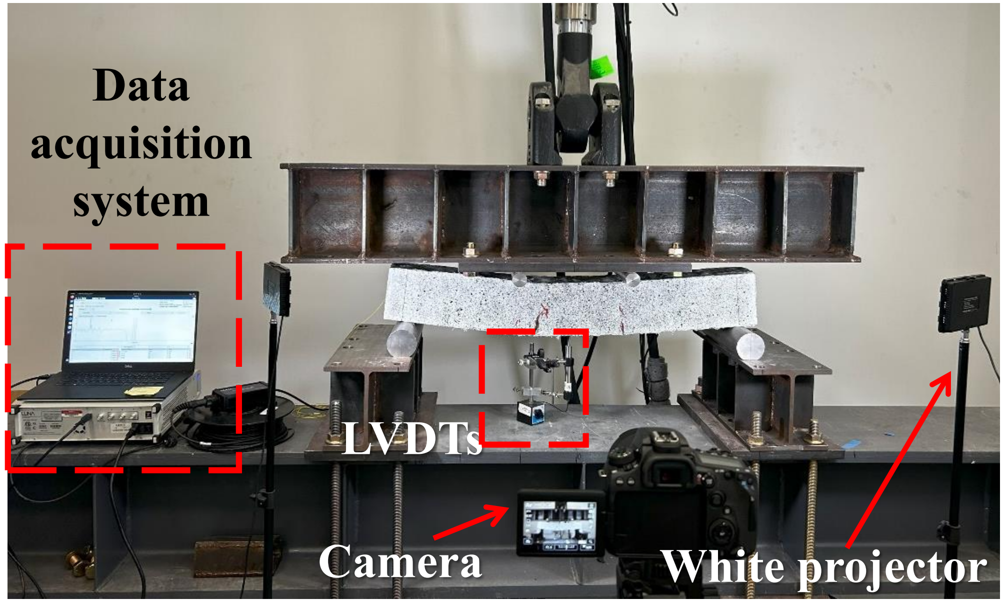
Four-point bending test

The same four-point bending test setup was used for all beams.



Utilizing advanced monitoring technologies for crack detection

- Distributed fiber optic sensors (DFOS) and digital image correlation (DIC) were utilized to assess crack width.
- This assessment aids in determining the maintenance intervals for various UHPC beams.

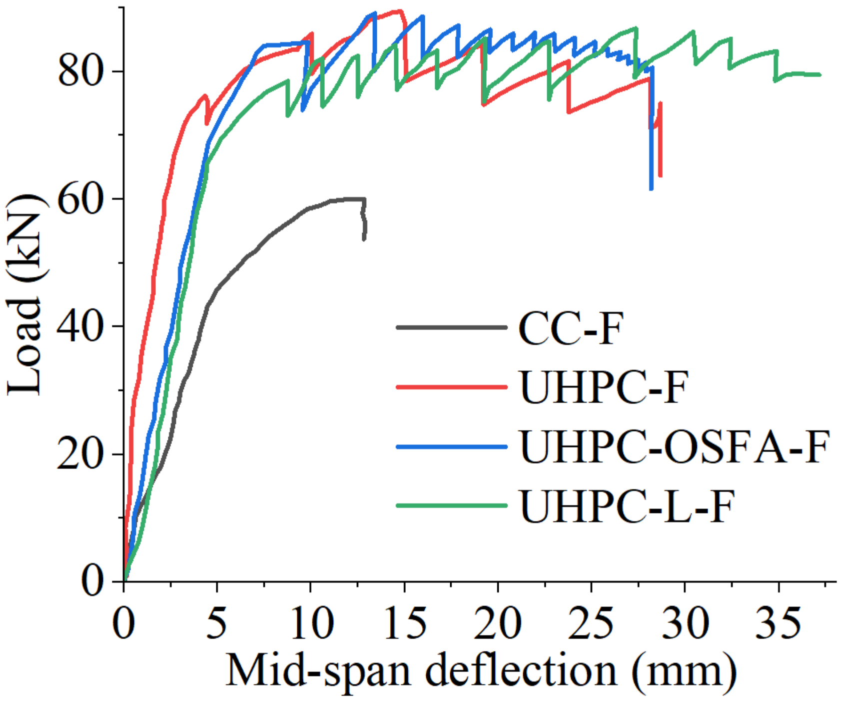


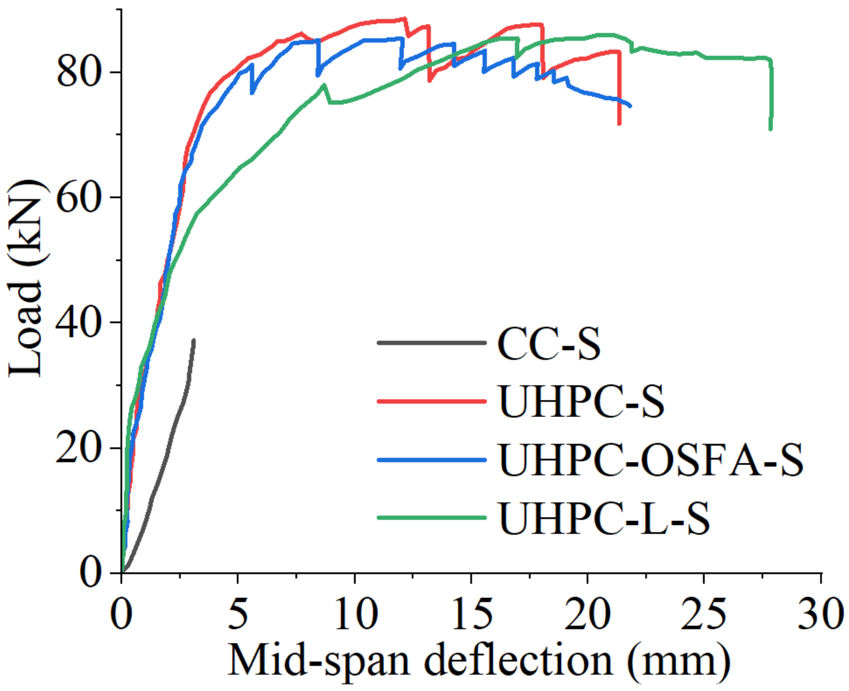
Surface preparation of concrete beams for DIC

Distributed fiber optic sensors (DFOS)

Effects of solid wastes on structural performance of UHPC

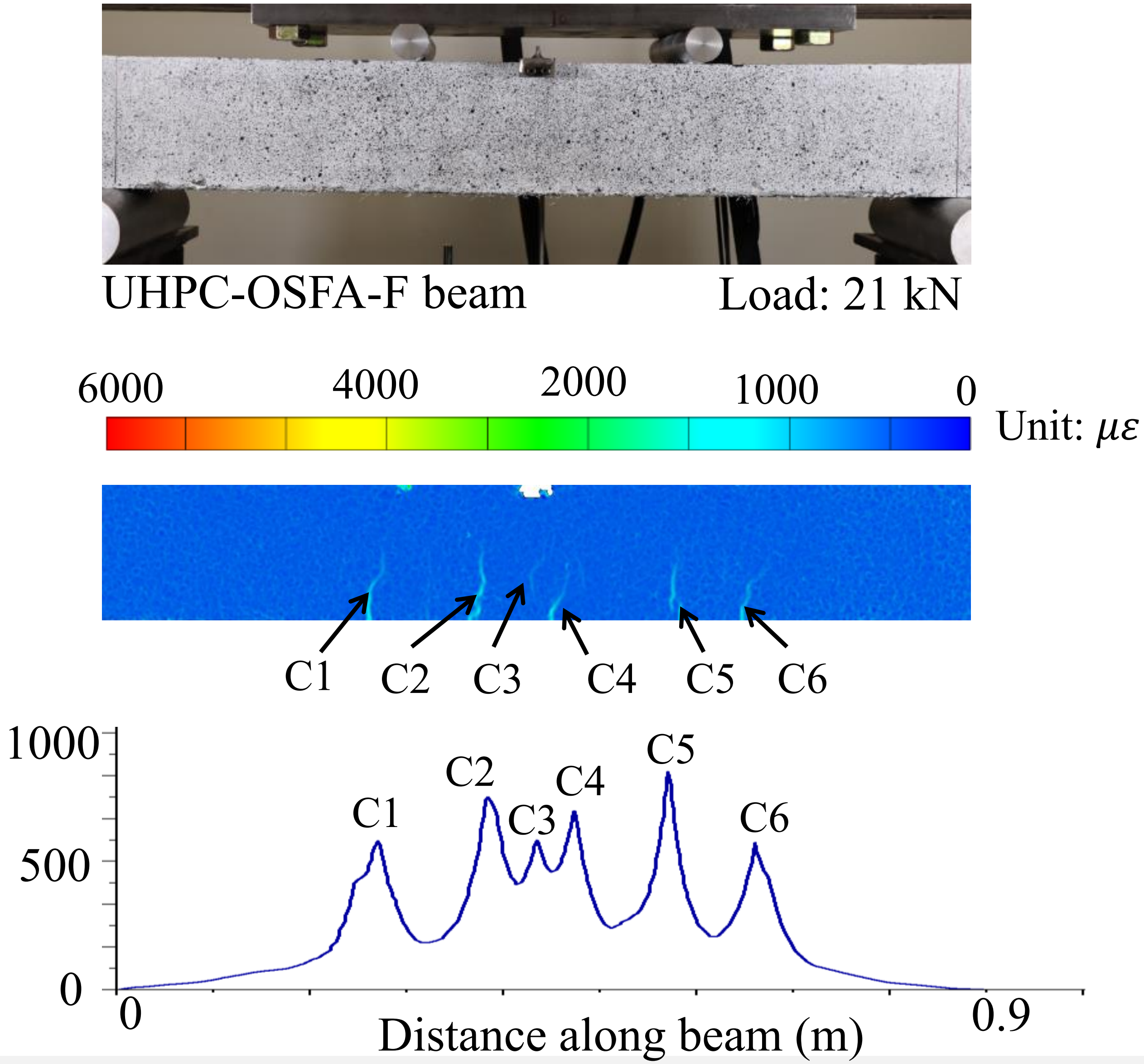
Solid wastes did not negatively impact the flexural and shear capacities of UHPC beams.





Crack detection by advanced monitoring technologies

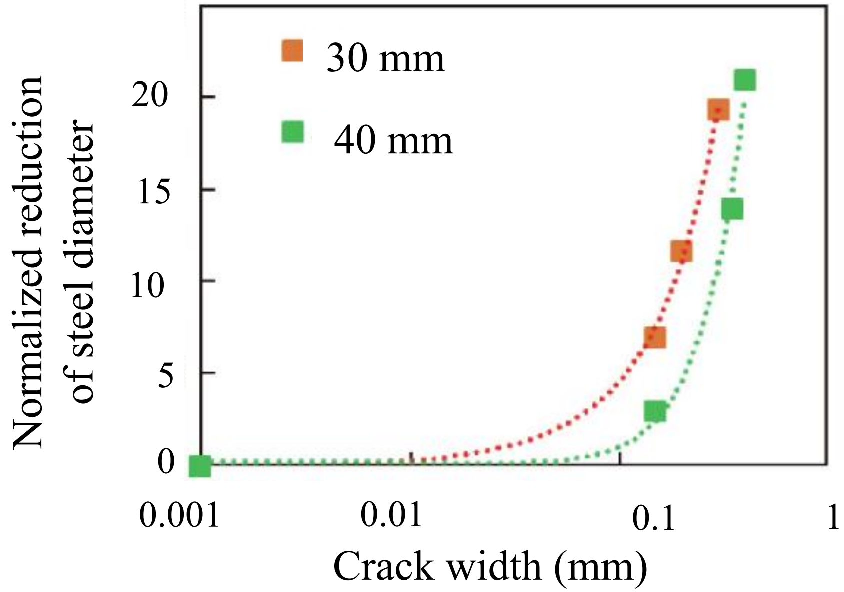
DIC and DFOS are effective methods for detecting micro-cracks that are not visible to the naked eye.

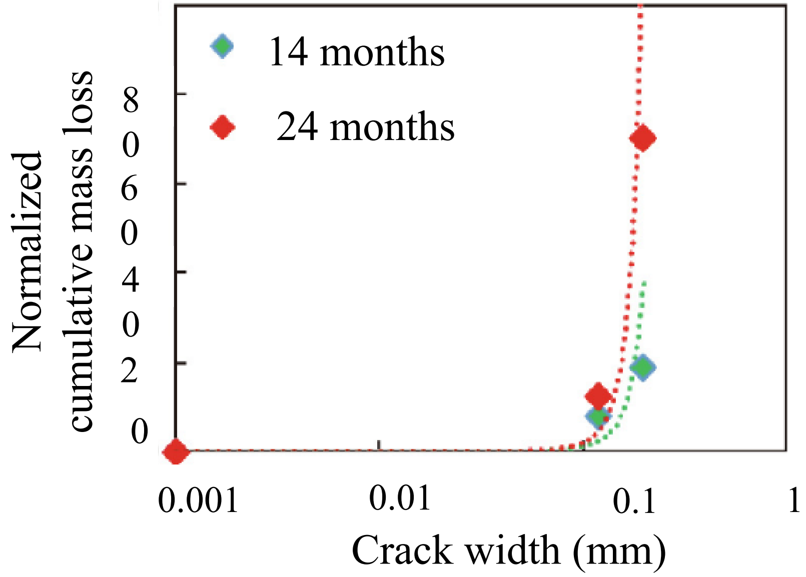


Effects of crack width on maintenance cost and emission

- Crack with has significant effect on durability and maintenance of concrete structures.

- The maintenance intervals for UHPC beams incorporating solid waste materials remain unknown.

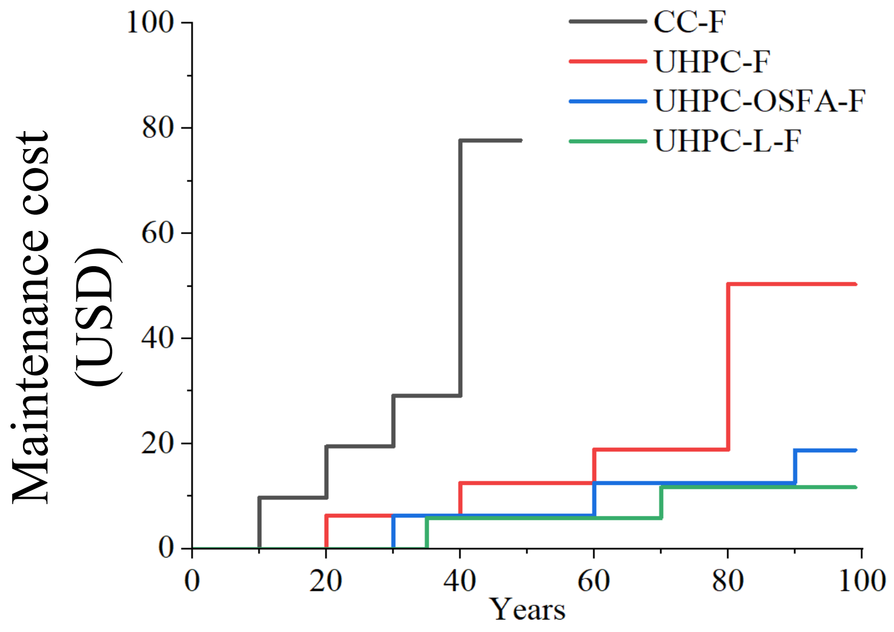




Li, V.C., 2019. High-performance and multifunctional cement-based composite material. *Engineering*, *5*(2), pp.250-260.

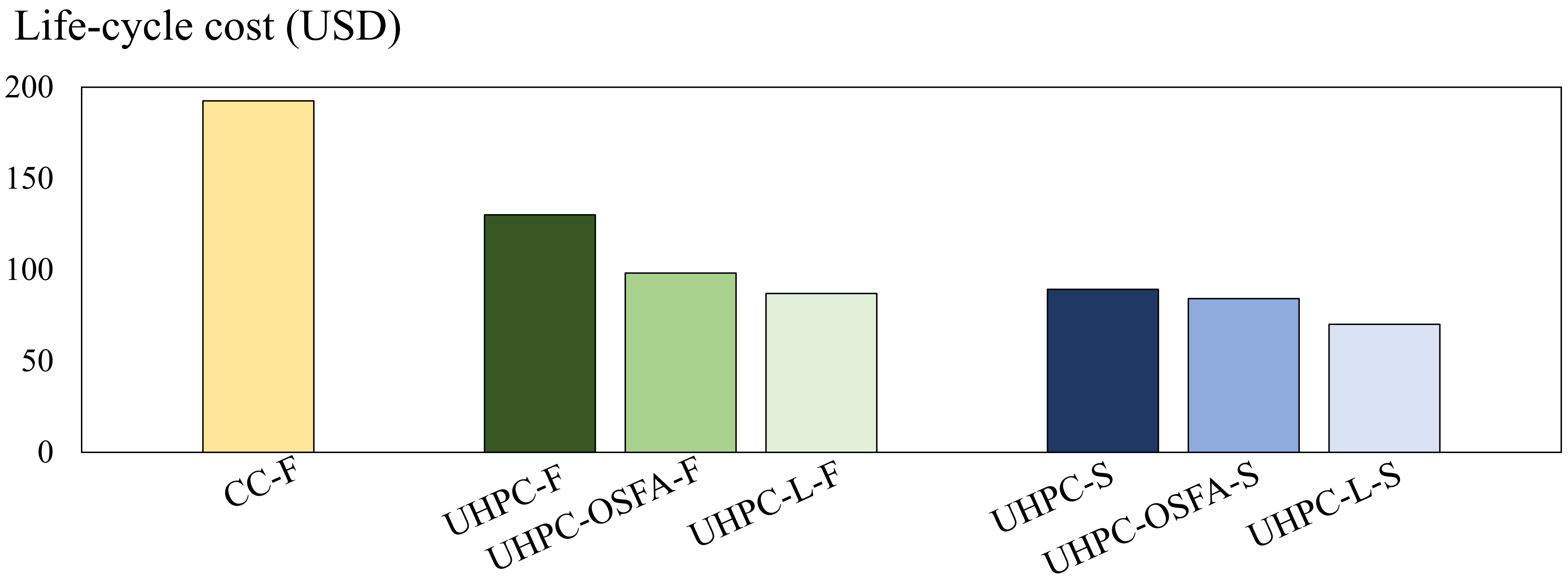
Effects of crack width on maintenance intervals

- Crack widths of concrete beams were measured using DIC and DFOS.
- UHPC beams exhibited lower crack widths than CC beams, indicating reduced maintenance frequency.
- Based on the correlation between crack width and durability, maintenance intervals for various UHPC beams were estimated.



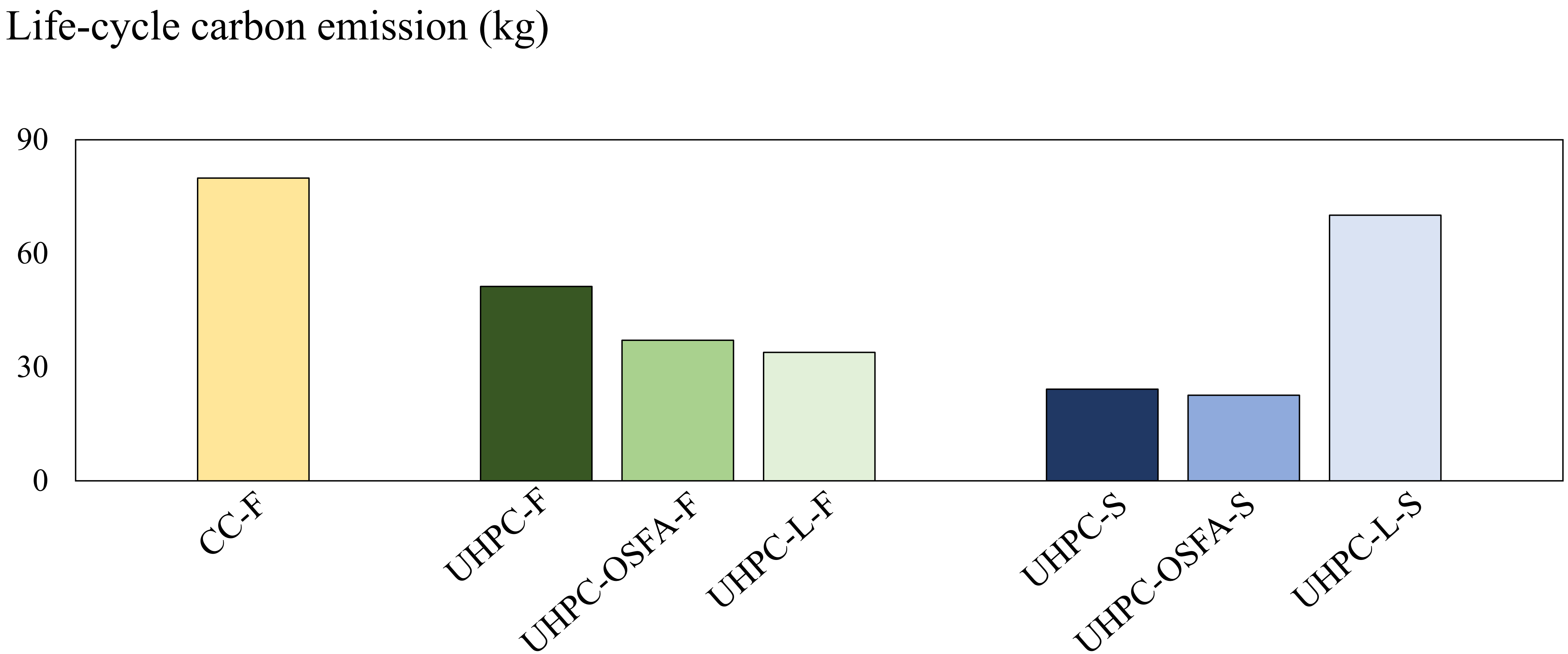
Overall cradle-to-grave LCA cost

The use of UHPC materials reduced the life-cycle cost by up to 64% compared with the conventional concrete beams.



Overall cradle-to-grave LCA carbon emission

The use of UHPC materials reduced the life-cycle carbon emissions by up to 76% compared with CC beams.



Conclusions

- Incorporating solid wastes (OSFA and glass microsphere) did not negatively affect the flexural and shear performance of UHPC beams.

- The use of UHPC materials reduced the life-cycle cost and emission by up to 64% and 76%, respectively, compared with conventional concrete beams.

- By using DIC and DFOS to monitor cracks, this study provides a method for predicting the durability and maintenance intervals of concrete beams.

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