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TriDurLE
National Center for Transportation Infrastructure Durability & Life-Extension

Improving bridge resilience and sustainability through optimizing high-performance fiber-reinforced cementitious composites (HPFRCC)

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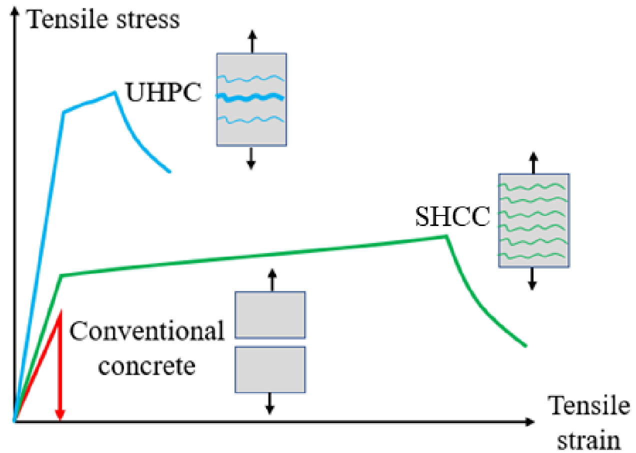
Background

- Compared with conventional concrete, high-performance fiber-reinforced cementitious composites (HPFRCC):
  - ➢ Improving the mechanical performance of engineering structures.
  - ➢ Involving concerns in sustainability:
    - ✓ High material costs
    - ✓ High carbon footprint



Comparison of UHPC and SHCC against conventional concrete in tension

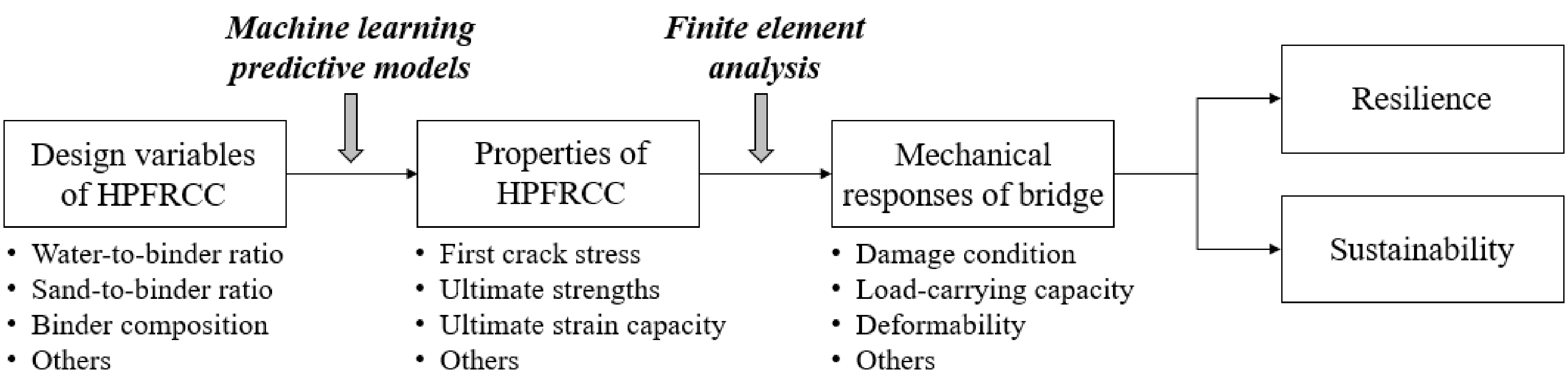
Estimation of Material Costs

Concrete type		Unit cost ($/m^3) [1]
Conventional concrete (CC)		102
Commercial UHPC	Ductal	2022
	BSI	2216
	CEMTEC	3218
	Cor-Tuf	2067

[1] Ngo, T. (2016). "Application of UHPC in Long Span Bridge Design." *Doctoral dissertation*. http://resolver.tudelft.nl/uuid:128b5606-28b3-46ec-bb78-4830f7319eee

Goal and objectives

- To develop a framework to improve both resilience and sustainability of bridges by
  - ➢ Optimized material designs of HPFRCC:
    - ✓ SHCC (Strain hardening cementitious composites)
    - ✓ UHPC (Ultra-high performance concrete)



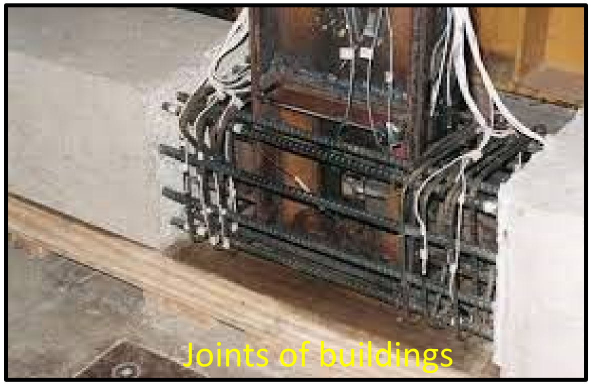
Contents

- Existing methods for improving resilience and sustainability
- Current challenges
- Proposed framework
- Results
- Conclusions

Existing methods

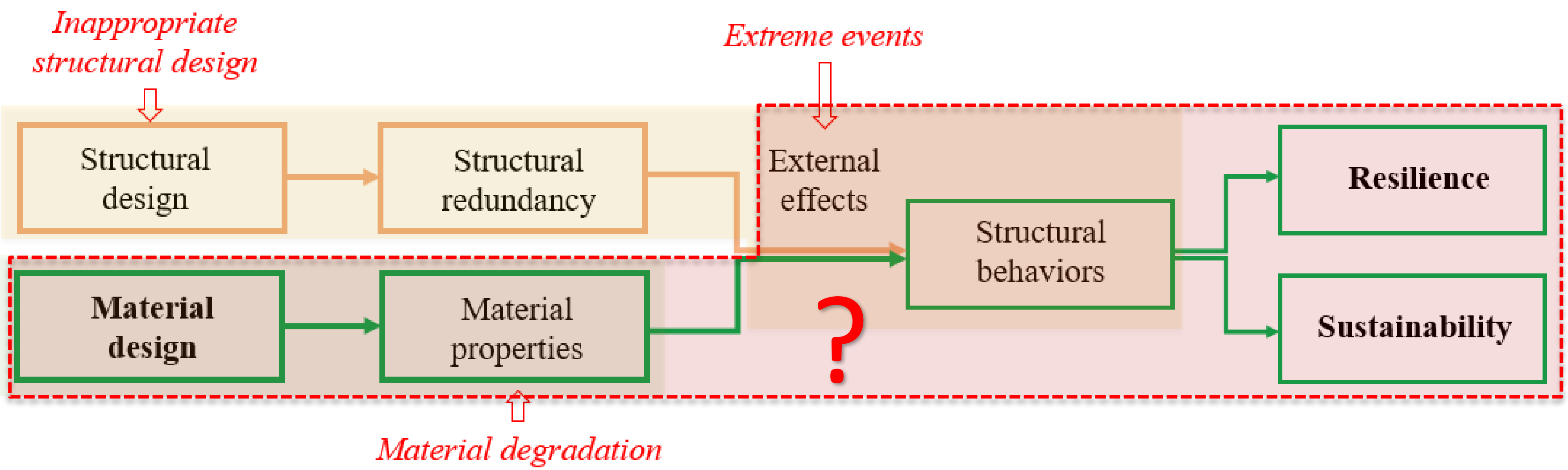
- Green raw materials:

➢ Only using HPFRCC at critical positions:



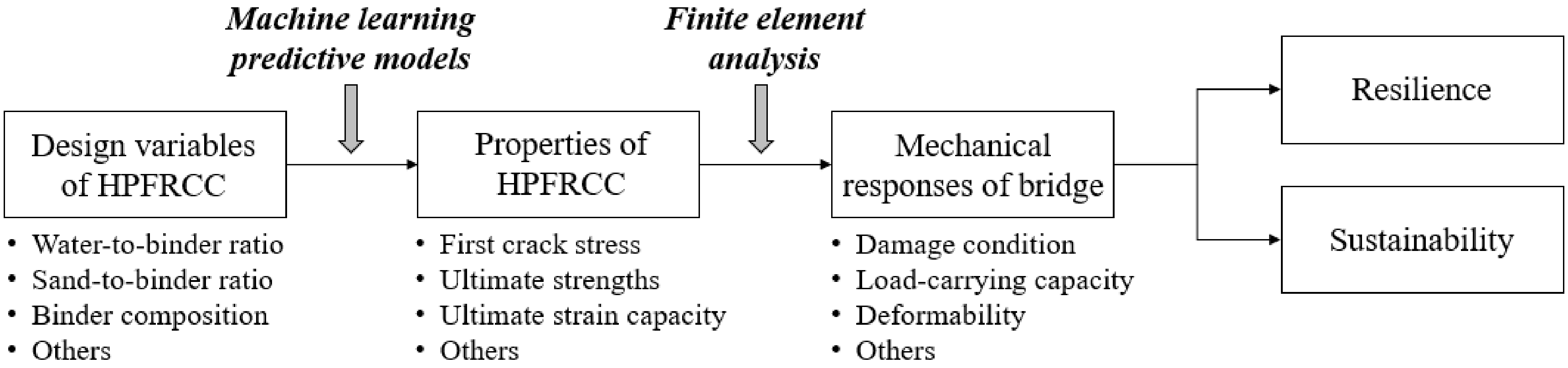
Current challenges

- It is unclear how the use of HPFRCC will influence the resilience and sustainability of structures.
- It is unknown how the mixture of HPFRCC should be engineered to achieve the optimal resilience and sustainability.



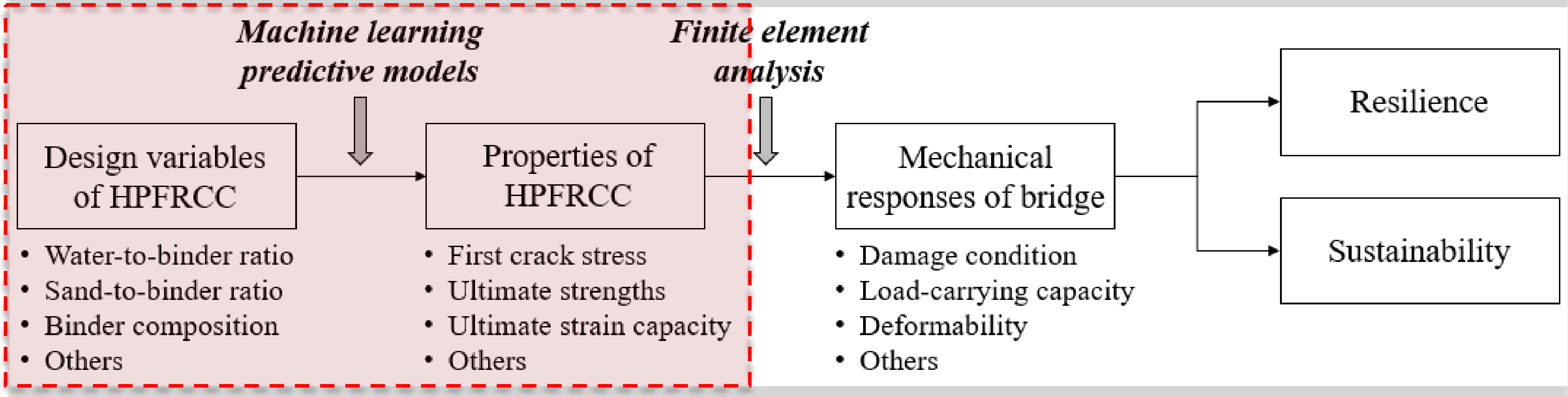
Proposed framework

- Specifically, this study has three objectives:
  - To evaluate the resilience of bridges incorporating HPFRCC with different properties
  - To develop an effective and efficient approach to enhance material sustainability by optimizing the mixture design of HPFRCC
  - To evaluate the effects of key mechanical properties of HPFRCC on the mechanical responses of bridges



Proposed framework

- Machine learning predictive models:
  - ➢ XGBoost [1,3]
  - ➢ LightGBM [2]
  - ➢ Extremely randomized trees [3]



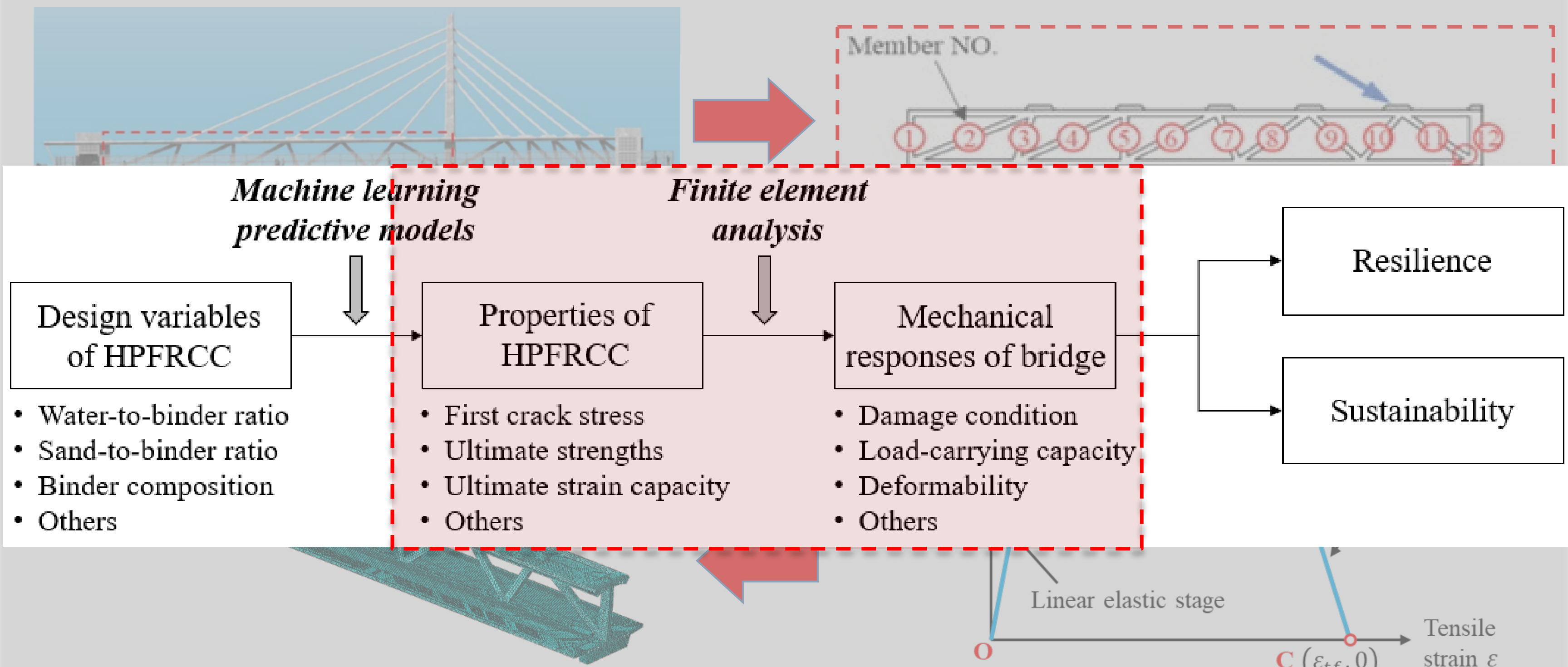
[1] Mahjoubi, S., Barhemat, R., Guo, P., Meng, W., and Bao, Y.* (2021). "Prediction and multi-objective optimization of mechanical, economical, and environmental properties for strain-hardening cementitious composites (SHCC) based on automated machine learning and metaheuristic algorithms." Journal of Cleaner Production, 329, p.129665. https://doi.org/10.1016/j.jclepro.2021.129665

[2] Mahjoubi, S., Meng, W., and Bao, Y.* (2022). "Auto-tune learning framework for prediction of flowability, mechanical properties, and porosity of ultra-high-performance concrete (UHPC)." Applied Soft Computing, 115, p.108182. https://doi.org/10.1016/j.asoc.2021.108182

[3] Mahjoubi, S., Barhemat, R., Meng, W., and Bao, Y.* (2023). “AI-guided auto-discovery of low-carbon cost-effective ultra-high performance concrete (UHPC).” Resources, Conservation and Recycling, 189, p. 106741. . https://doi.org/10.1016/j.resconrec.2022.106741

Proposed frame

- Finite element analysis
  - ➢ Tensile σ - ε relation: Strain hardening model
  - ➢ Tensile damage: $DAMAGET = (\varepsilon - \varepsilon_e)/(\varepsilon_{tf} - \varepsilon_e)$

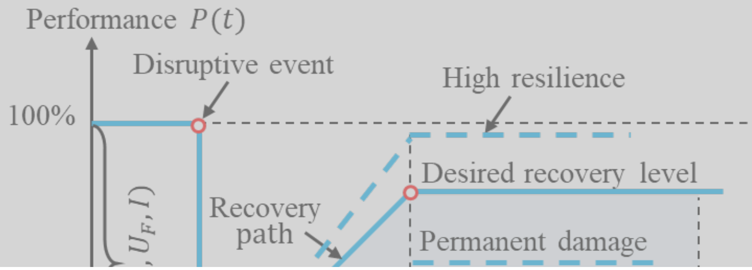


Finite element model

Tensile stress-strain relation of HPFRCC

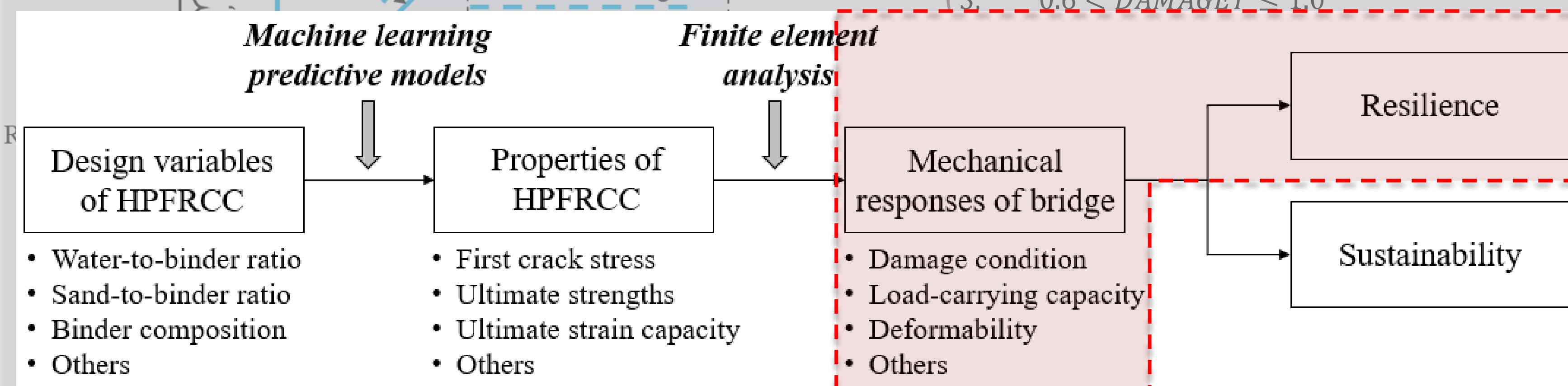
Proposed framework

- Resilience evaluation



$$P_R = 100\% - f(H, V, U_F, I) = 100\% - \max(9.259 \times H \times V \times U_F) \times I \geq 0\% \quad [1]$$

$$V = \begin{cases} 1, & 0 < DAMAGET \leq 0.25 \\ 2, & 0.25 < DAMAGET \leq 0.6 \\ 3, & 0.6 < DAMAGET \leq 1.0 \end{cases}$$



where: P_R is Robustness; H is the hazard value; V is the vulnerability value related to damages in bridges; U_F is the uncertainty factor; I is the importance factor of the bridge; T_{rec} is the recovery time; T_{res} is the basic restoration time; α_1, α_2, and α_b are adjustment factors; $P(t)$ is the performance of the bridge; $P(100\%)$ is the performance of the bridge at 100% level (non-interrupted); T_0 is the time (unit in days) when extreme or disruptive events take place.

[1] Minaie, E., and Moon, F. (2017). "Practical and simplified approach for quantifying bridge resilience." *Journal of Infrastructure Systems*, 23(4), p.04017016. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000374

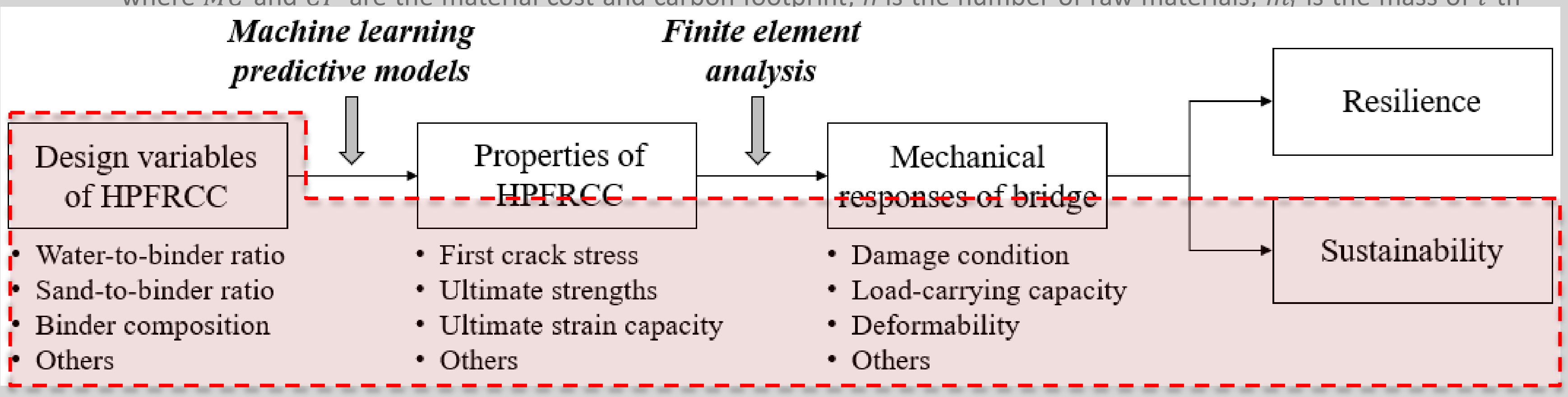
Proposed framework

- Sustainability evaluation

  - Material cost & the carbon footprint of HPFRCC:

$$MC = \sum_{i=0}^{n} m_i \times c_i \qquad CF = \sum_{i=0}^{n} m_i \times \mathrm{CO_2}-eq_i$$

where MC and CF are the material cost and carbon footprint; n is the number of raw materials; m_i is the mass of i-th



where EI_i is the sustainability index of the i-th mix design; CF_i and MC_i are the carbon footprint and materials cost of the i-th mix design. The sustainability index is between 0 to 1.

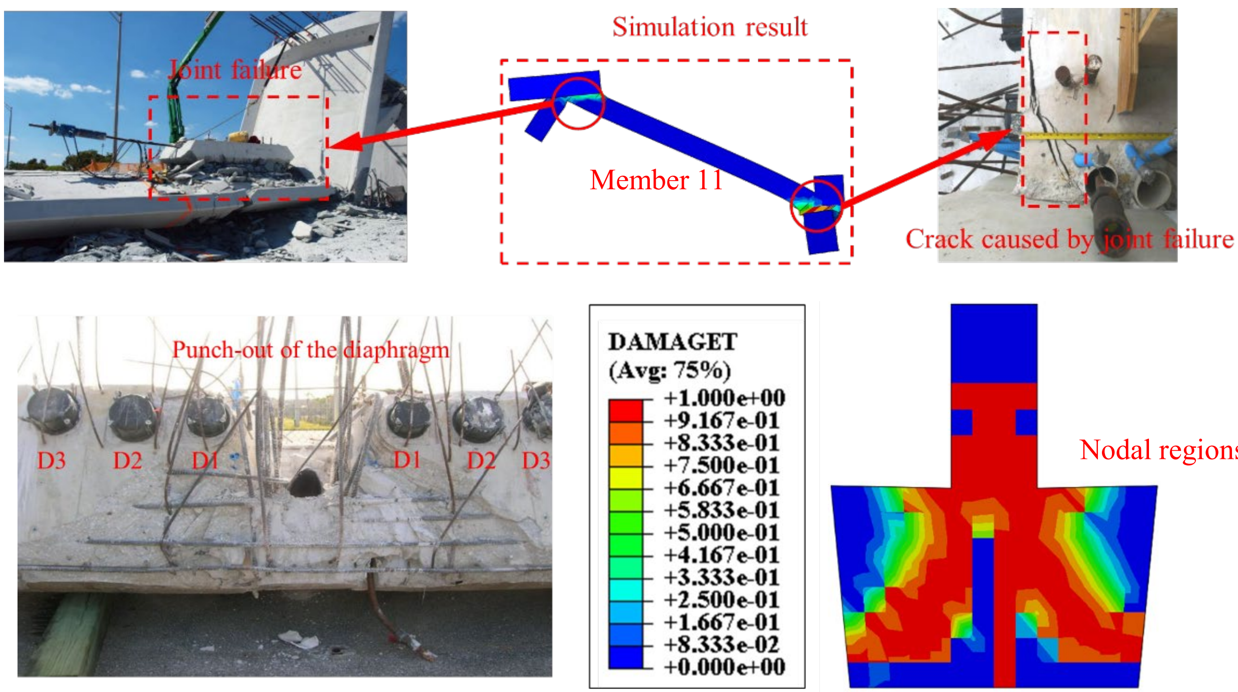
Proposed framework

- Multi-objective optimization
  - ➢ Objective functions:
    - ✓ Min. material cost
    - ✓ Min. carbon footprint
  - ➢ Design constraints: High bridge resilience
    - ➢ The lowest compressive strength, first crack stress, ultimate tensile strength, and ultimate tensile strain of HPFRCC
  - ➢ Non-dominated Sorting Genetic Algorithm II (NSGA-II) [1]
    - ✓ Best trade-off between competing objectives
    - ✓ High resilience vs high sustainability
    - ✓ Ranking of the design solutions (*EI*)

[1] Deb, K., Pratap, A., Agarwal, S. and Meyarivan, T.A.M.T. (2002). "A fast and elitist multiobjective genetic algorithm: NSGA-II." *IEEE transactions on evolutionary computation*, 6(2), pp.182-197. https://doi.org/10.1109/4235.996017

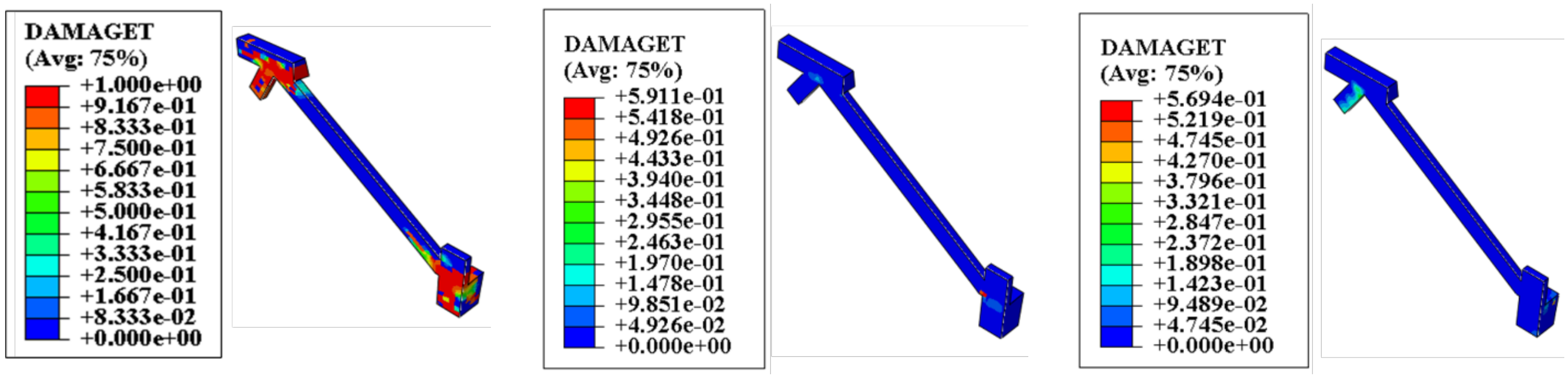
Results and discussions

- Results validation
  - The failure of the bridge is closely related to the tensile damage in member 11 and its nodal regions.
  - Low-resilience class, which is aligned with the identified level of damage



Results and discussions

- Parametric study results
  - Conventional concrete: the two joints of member 11 are severely damaged.
  - SHCC: damage significantly alleviated.
  - UHPC: Only minor damage in member 11



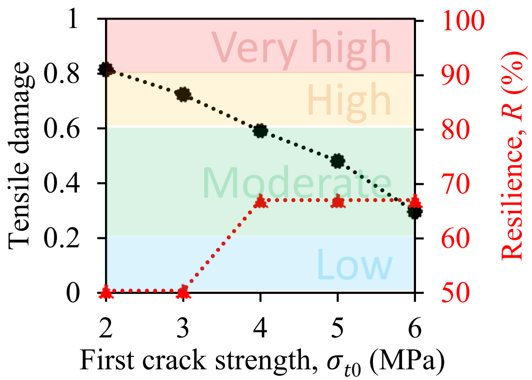
(a) (b) (c)

Contours of tensile damage distributions of member 11 made using different materials: (a) conventional concrete; (b) SHCC (σ_{t0} = 4 MPa; ε_{tu} = 4%; σ_{tu} = 8 MPa); and (c) UHPC (σ_{t0} = 10 MPa; ε_{tu} = 0.3%; σ_{tu} = 14 MPa).

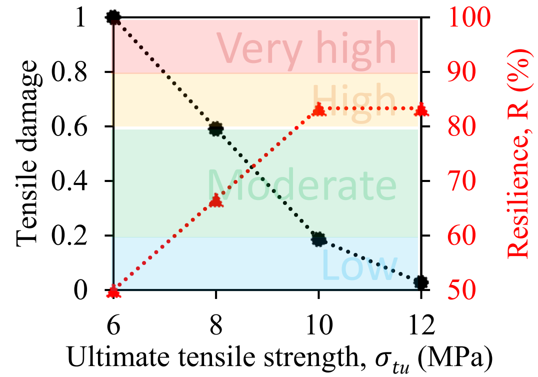
Results and discussions

- Parametric study results
  - ➢ Effect of first crack strength, ultimate tensile strength, ultimate tensile strain:

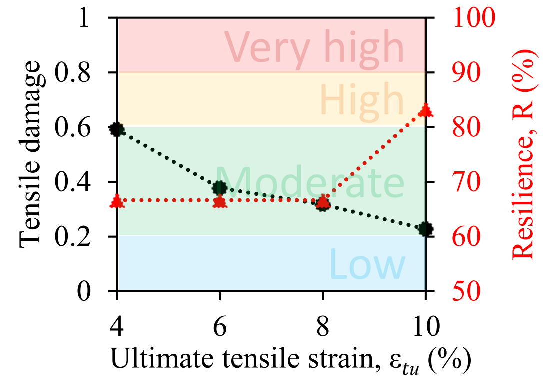
SHCC:



SHCC (ε_{tu} = 4% and σ_{tu} = 8 MPa)

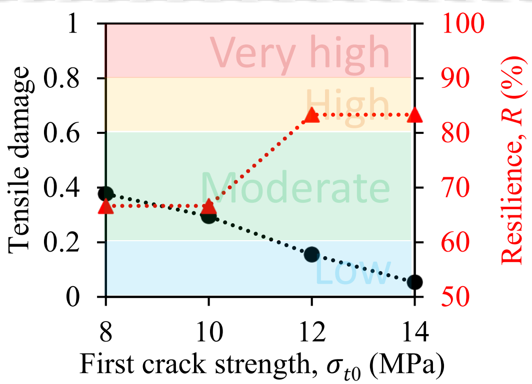


SHCC (σ_{t0} = 4 MPa and ε_{tu} = 4%)

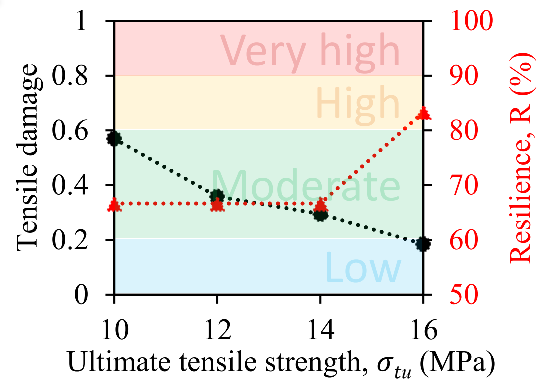


SHCC (σ_{t0} = 4 MPa and σ_{tu} = 8 MPa)

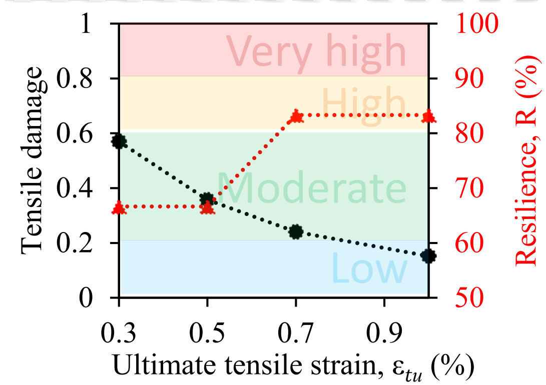
UHPC:



UHPC (ε_{tu} = 0.3% and σ_{tu} = 14 MPa)



UHPC (σ_{t0} = 10 MPa and ε_{tu} = 0.3%)



UHPC (σ_{t0} = 10 MPa and σ_{tu} = 10 MPa)

Results and discussions

- Optimization results

Mix design	S1	S2	S3	S4	S5	S6	S7	S8	S9
Design variables									
Cement-to-binder ratio	14.4	25.0	25.0	11.8	16.1	16.1	11.8	24.9	25.0
Fly ash-to-binder ratio	27.1	28.4	28.4	20.5	30.8	30.8	27.2	27.0	28.4
Slag-to-binder ratio	7.2	7.2	7.3	7.5	6.8	6.8	6.6	7.4	7.1
Rice husk-to-binder ratio	5.2	9.5	9.4	6.0	17.2	17.2	5.4	16.9	9.3
Limestone-to-binder ratio	40.4	7.2	7.2	43.1	9.0	9.0	43.1	1.6	7.2
Metakaolin-to-binder ratio	4.7	4.9	4.9	9.4	12.5	12.5	3.8	5.1	4.9
Silica fume-to-binder ratio	1.0	17.0	16.8	0.3	6.7	6.7	0.5	16.3	16.8
Sand-to-binder ratio	0.8	0.7	0.8	1.3	0.6	0.6	1.4	0.4	1.4
Water-to-binder ratio	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.1
Superplasticizer content (%)	2.0	1.9	1.3	2.0	2.6	2.6	1.8	1.9	1.4
Fiber volume (%)	2.7	2.7	2.8	1.7	2.7	2.7	2.6	2.7	2.7
Fiber length (mm)	18	12	11	27	12	12	27	12	27
Fiber diameter (μm)	24	17	17	40	16	16	40	17	40
Young's modulus of fibers (GPa)	100	6	6	200	6	6	200	6	200
Fiber type	PE[1]	PP[2]	PP	Steel	PP	PP	Steel	PP	Steel
Output variables									
Compressive strength (MPa)	59.1	62.5	67.3	93.1	103.3	103.2	70.9	114.1	102.6
First crack strength (MPa)	4.8	4.9	5.1	5.6	5.7	5.7	4.9	5.0	5.3
Ultimate tensile strength (MPa)	16.6	14.0	17.2	9.4	10.0	10.0	14.1	11.6	13.2
Ultimate tensile strain (%)	6.0	7.1	4.2	8.5	10.0	10.0	6.1	4.2	8.0
Carbon footprint (kg/m^3)	745	1142	1207	895	1943	1990	1010	2249	1485
Cost (USD/m^3)	633	456	458	872	566	579	1143	610	1292
Sustainability index (EI)	0.89	0.87	0.84	0.7	0.54	0.51	0.5	0.41	0.25

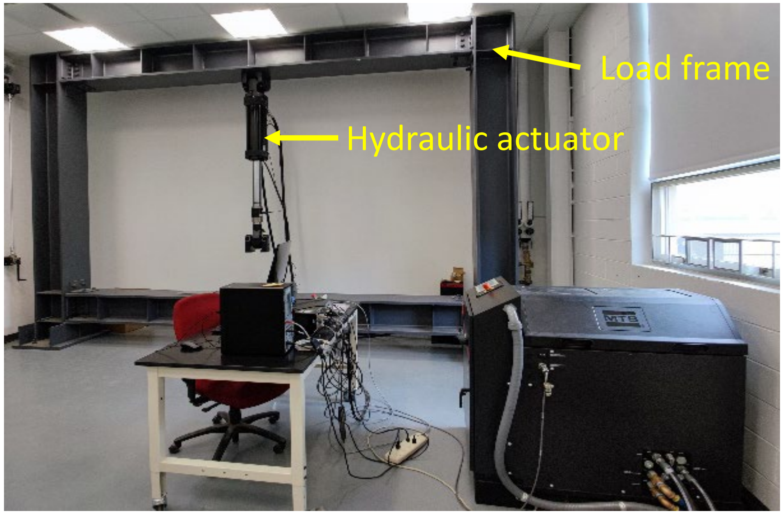
[1]PE stands for Polyethylene fiber; [2]PP stands for Polypropylene fiber.

Conclusions

- The presented framework can be used for enhancing bridge resilience and sustainability simultaneously by optimized mixture design of HPFRCC.
- The optimization of material mix design enables HPFRCC to achieve minimized material cost and carbon footprint while remaining high resilience of bridges.
- The tensile properties of HPFRCC have significant effects on the damage condition and resilience of the bridge. The parametric study provides data guide for the design of structures made using HPFRCC.

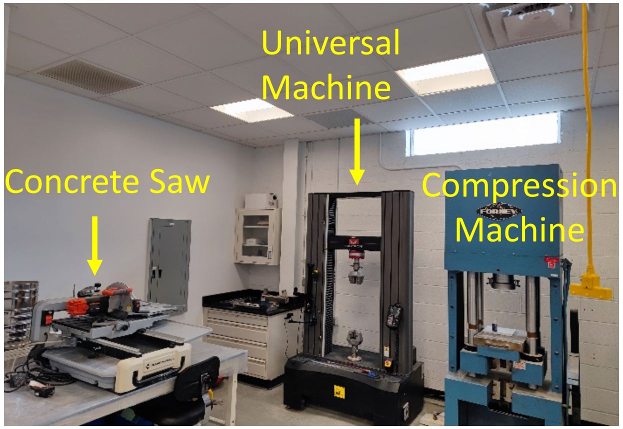
Smart Infrastructure Laboratory

- The newly-upgraded Smart Infrastructure Lab is equipped for large-scale structural testing.
  - ➢ MTS high-capacity hydraulic actuator (static & fatigue tests)
  - ➢ Advanced instruments (optic cameras, fiber optic sensors, etc.)
  - ➢ Robots for bridge condition assessment



Advanced Concrete Technology (ACT) Lab

- The newly-upgraded ACT Lab is well-equipped for large mixing, testing, and multi-scale characterization of concrete.
  - ➢ Six mixers (volumes: 340 L, 19 L, and 5L)
  - ➢ Load frames and environmental chambers (temperature & humidity)
  - ➢ Characterization instruments (isothermal calorimeter, TGA, MIP, etc.)



Q & A

Thank you!

Further works

- It remains unclear how the use of ductile materials affects the lifecycle cost and long-term durability.
- Self-healing properties of UHPC and SHCC should be considered in future studies.
- It is unclear whether collapse can occur at operation stage. The whole lifecycle safety and resiliency of bridges needs to be considered in future research.

Proposed method

Hazards considered	Hazard values (H)		
	1	2	3
Scour; debris and ice; vessel collision; seismic liquefaction; settlement; flood	• Outside of a 500-year flood plain. • Seismic design category A (low probability of earthquake leading to liquefaction). • Low hurricane risk [3 s gust wind speed less than 145 kph]. • Over a non-navigable channel. • Located more than 800 km from coast. • No potential for scour. • No records of significant earthquake, floods, or storm surge.	• Outside of a 100-year flood plain. • Seismic design category B, C (moderate probability of earthquake leading to liquefaction). • Moderate hurricane risk [3 s gust wind speed within 145 ~ 210 kph]. • Navigable channel for mid-sized vessels. • Located more than 80 km from coast. • A rating of NBI Item 113 (scour) of 5 or higher. • Records of moderate earthquake, floods or storm surge.	• Within a 100-year flood plain. • Seismic design category D, E, F (high probability of earthquake leading to liquefaction). • Moderate hurricane risk [3 s gust wind speed more than 210 kph]. • Navigable channel for large vessels. • Located within 80 km from coast. • A rating of NBI Item 113 (scour) of 4 or lower. • Observed drift and debris at piers/abutment history of ice flows in waterway.
Seismic; fatigue; vehicle collision; overload; fire	• Seismic design category A (low probability of seismic damage). • No records of significant earthquake. • ADTT less than 5,000 (low probability of fatigue failure). • Not spanning over a roadway. • Located more than 32 km from heavy industry. • No history of overloads, collision, fire under the bridge.	• Seismic design category B, C (moderate probability of seismic damage). • Records of moderate earthquake. • ADTT less than 10,000 (moderate probability of fatigue failure); • Spanning over a roadway with ADTT less than 1,000. • Located more than 16 km from heavy industry. • History of moderate level of overloads, collision, fire under the bridge.	• Seismic design category D, E, F (high probability of seismic damage). • Records of significant earthquake. • ADTT more than 10,000 (high probability of fatigue failure). • Spanning over a roadway with ADTT more than 1,000. • Located less than 16 km from heavy industry. • History of high level of overloads, collision, fire under the bridge.
Note: ADTT = annual average daily truck traffic.			

[1] Minaie, E., and Moon, F. (2017). "Practical and simplified approach for quantifying bridge resilience." *Journal of Infrastructure Systems*, 23(4), p.04017016. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000374

Proposed method

Bridge importance factor (I)	Criteria
0.75	• Bridge is located on local routes. • Replacement costs less than 5% of the total agency budget. • Bridge does not carry utility lines. • Average daily traffic is less than 10,000. • Detour length less than 5 km, or level of service on detour is A or B.
1.0	• Bridge is located on National Highway System (NHS) or state routes. • Replacement costs more than 5% and less than 25% of agency budget. • Bridge carries utility lines such as fiber optics, communication lines, or other low-risk utilities (colocation). • Average daily traffic is more than 10,000 and less than 50,000. • Detour length more than 5 km and less than 16 km, or level of service on detour is C or D.
1.25	• Bridge is located on evacuation routes, critical infrastructure, the Strategic Highway Network, or national network for trucks. • Replacement costs more than 25% of the agency budget. • Bridge carries utility lines such as electricity, gas, or other high-risk utilities (colocation). • Average daily traffic is more than 50,000. • Detour length more than 16 km, or level of service on detour is E or F.

Affected area	Basic restoration time (T_{res}) depending on severity of the hazard			
	Low	Moderate	Severe	Catastrophic
Isolated	1 day	2 weeks	6 months	N/A
Local	3 days	6 months	9 months	N/A
Regional	1 week	9 months	12 months	24 months

Resilience value, R (%)	Resilience class
0 ~ 20	Non-resilient
21 ~ 40	Extremely low
41 ~ 60	Low
61 ~ 80	Moderate
81 ~ 90	High
91 ~ 100	Very high

Proposed method

Adjustment factor, α_1	Disaster management practices
0.8	At least three of the following criteria: • Public extreme event preparedness educational programs, scheduled test, and drill programs. • Designated evacuation routes. • Designated shelters. • Extreme event management plans and designated centers. • First responders equipped with necessary tools and equipment to manage the post extreme event conditions. • On-call emergency contractors for incident management. • Local access to equipment, goods, and materials for minimal restoration. • Available modes of transportation for individuals: > 2 [8-km radius around the bridge]. • Access to number of emergency facilities (including emergency, hospital, gas stations): ≥ 20 [8-km radius around the bridge]. • A Level III or higher emergency response management (ERM)*.
1.0	Not meeting the above criteria
*** Emergency response management levels [S3]: Level I = police officers directing traffic; Level II = traffic signals; Level III = dynamic traffic signal timing and ramp metering; Level IV = traffic cameras and variable message signs; Level V = intelligent transportation systems and advanced traveler information systems.**	

Adjustment factor, α_2	Agency's contracting practices
1.0	No history of disruptive events
1.1	History of low event
1.2	History of moderate event
1.4	History of severe event
1.6	History of catastrophic event

Adjustment factor, α_b	Type of bridge*
1.00	Single-span bridges [up to 15-m span], or multiple simply supported spans.
1.15	Medium-size bridges [up to 50-m span], multiple continuous spans, movable bridges.
1.30	Large-span bridges [from 50-m to 150-m span].
1.50	Complex bridges [generally longer than 150-m span]
*** Bridge categories from Pennsylvania Department of Transportation (2015) [S4].**	