University of South Australia

Next Generation Design of Sustainable, Durable, Multi-hazard Resistant, Resilient and Smart (SDuMuRS) Civil Engineering Structures

Thong Pham

Associate Professor and Enterprise Fellow

UniSA STEM

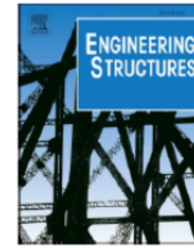
University of South Australia

Engineering Structures 277 (2023) 115477

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct



Review article

Towards next generation design of sustainable, durable, multi-hazard resistant, resilient, and smart civil engineering structures

Hong Hao, Kaiming Bi, Wensu Chen, Thong M. Pham *, Jun Li *

Centre for Infrastructural Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, WA 6102, Australia

Prof. Jie Yang, Chief Editor of Engineering Structures

Handling editor and reviewers.

Acknowledgement

Dist. Prof., ARC Laureate Fellow, Hong Hao (FTSE)

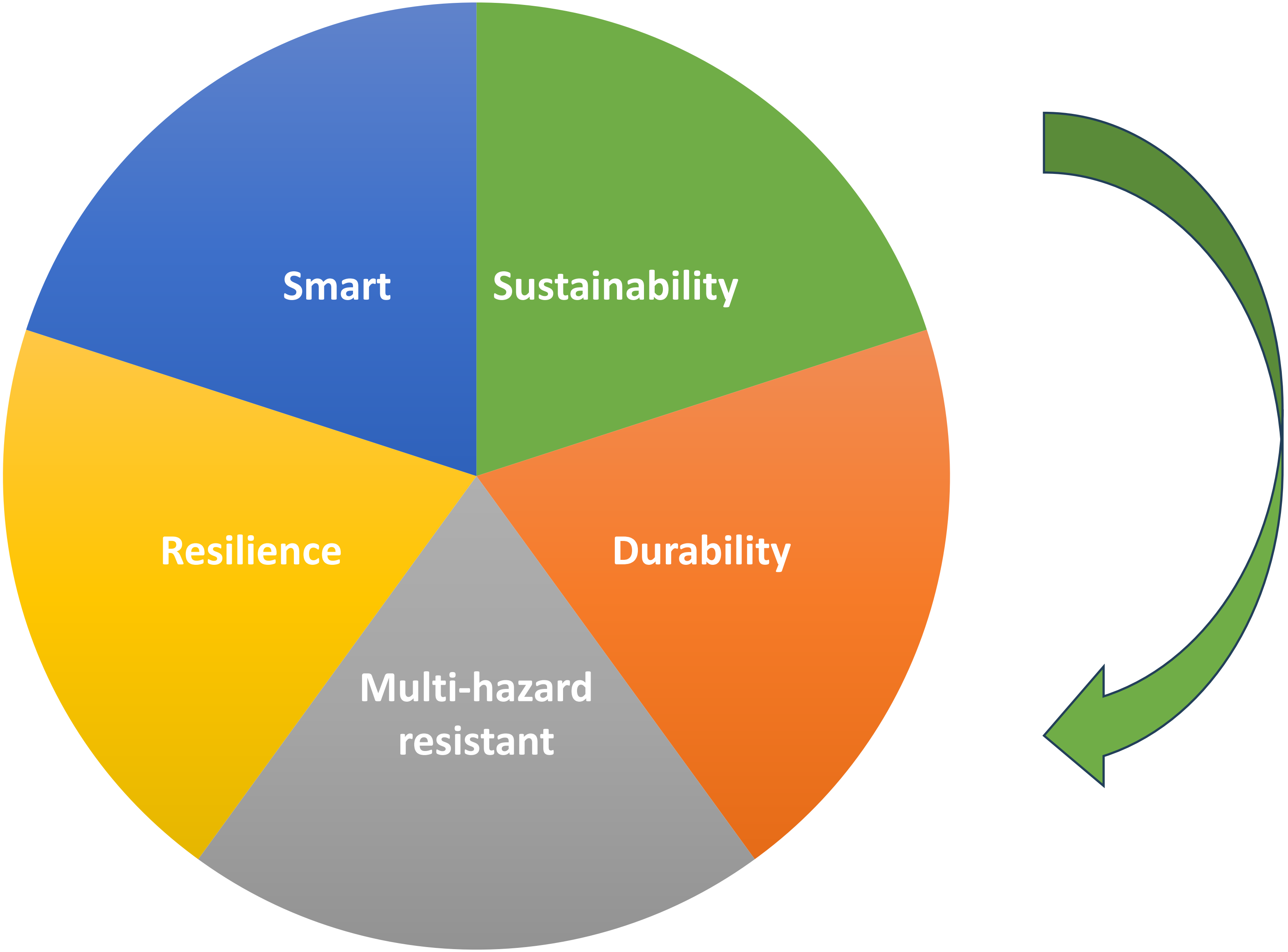
A/P Kaiming Bi

A/P Wensu Chen

Prof. Jun Li

Australian Research Council

Key contents



Evolving of design philosophy

Evolving of design philosophy

Structural design philosophy has also been evolving from Strength-based, to Limit State-based and Performance-based designs.

Strength-based designs consider the load-carrying capacity of structural components and structure. The design analysis mainly focuses on the structural strength and loading capacity.

Performance-based designs consider the predefined structural performance. Displacement and risk are the most common performance criteria.

Structural components and structure-based

Time – independent analysis

Other time – independent analysis methods include:

1) Deterministic design; 2) Reliability-based design; 3) Risk-based design; 4) Sustainability-based design; 5) Multi-hazards resistance design; 6） Optimization design, and 7) Intelligent design, 8) remaining load-carrying capacity based design, etc.

Time-dependent systematic analysis

The current intensively researched resilience-based design is a new design philosophy as it considers not only structural safety (strength), but also considers the impact of loss of functionality, time and cost required to restore the functionality with respect to the targeted extreme event

Lifecycle performance-based design is also a time-dependent design method as it considers structural deterioration, maintenance and lifecycle structural performances.

Because failure of civil engineering structures often leads to catastrophic consequences, significant loss of economy, loss of life, and impacts to the society, **SAFETY** is the primary concern in the design of civil engineering structures.

However, to meet the societal need, the next generation design should also consider sustainability, durability, multi-hazard resistance, resilience and smart monitoring and maintenance.

SDuMuRS

Sustainability in construction

Sustainability

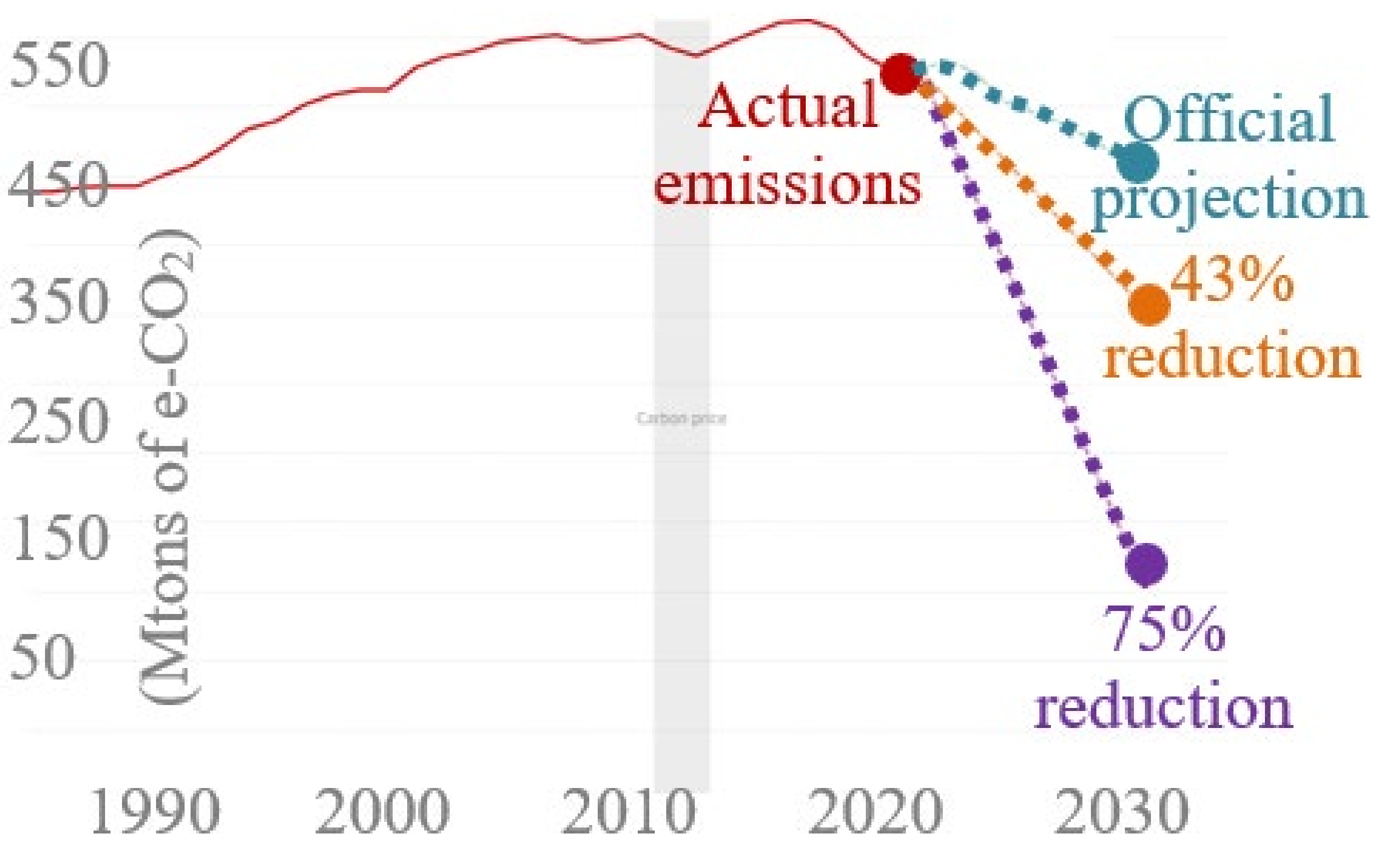
The earliest definition of sustainability can be attributed to Brundtland who stated 'sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs'.

The simple definition of sustainability is: **Supply > Demand**

1) Economic growth (increased demand);
2) Natural resources (depletion);
3) Environmental protections (pollution);
4) Energy supply;
5) Infrastructure;
6) Technology development;
7) etc

Sustainable development

Where are we now?

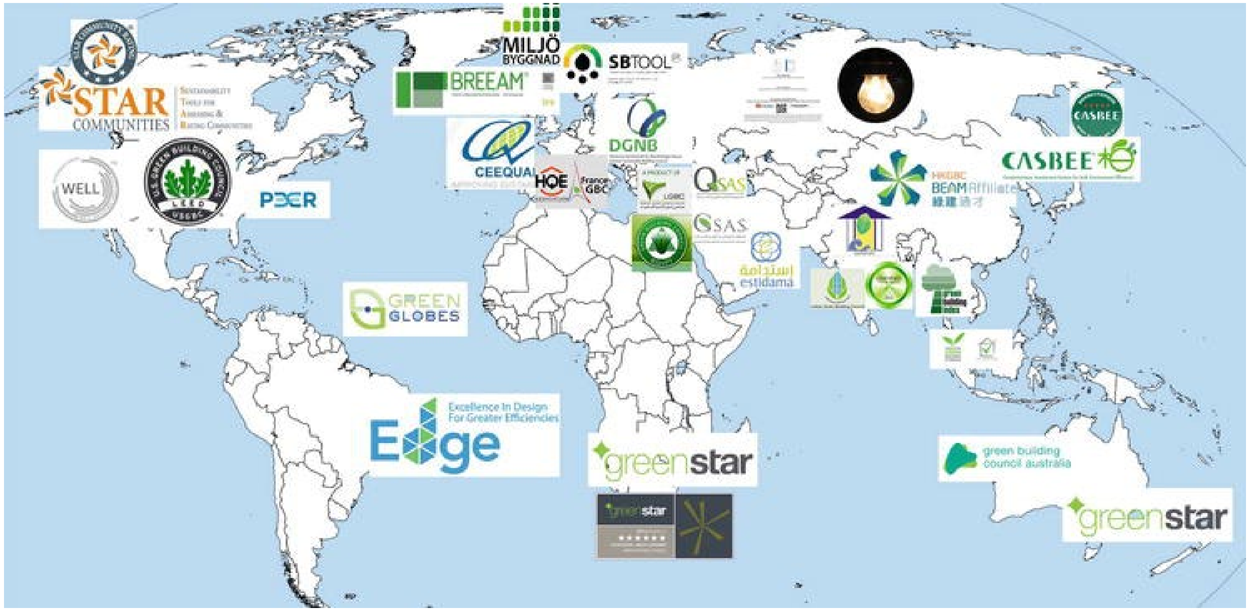


The Australian government has legislated targets of cutting emissions to 43% below 2005 levels by 2030 and reaching net zero by 2050. The live update on 06/05/2024 shows the projected eCO_2 (452 Mtons) is significantly higher than our 2030 target (355 Mtons)

Source: https://www.theguardian.com/

Many countries have published Green Star Rating system

Different green rating approaches



Green Building Council Australia

Green Building Council of Australia (GBCA), up to 6 star with maximum score of 100

Four tools:

1) Green Star Building,
2) Green Star - Communities,
3) Green Star - Performance,
4) Green Star - Interiors,

- Different methods proposed to evaluate development sustainability, e.g. Green Star, LEED, BREEAM, CASBEE, DGNB, HQE, etc.

- Criteria and weighting vary between rating systems. Examples: Green Star 1-6 stars (max 100), CASBEE (scale of 10), BREEAM (max 134), ITACA/LEED (100 points)

- Need for more research to unify the rating systems

- Green rating formula:

Green rating = $G = \sum_{i=1}^{k}(f_i)$, where k = number of factors, f_i = score for each factor.

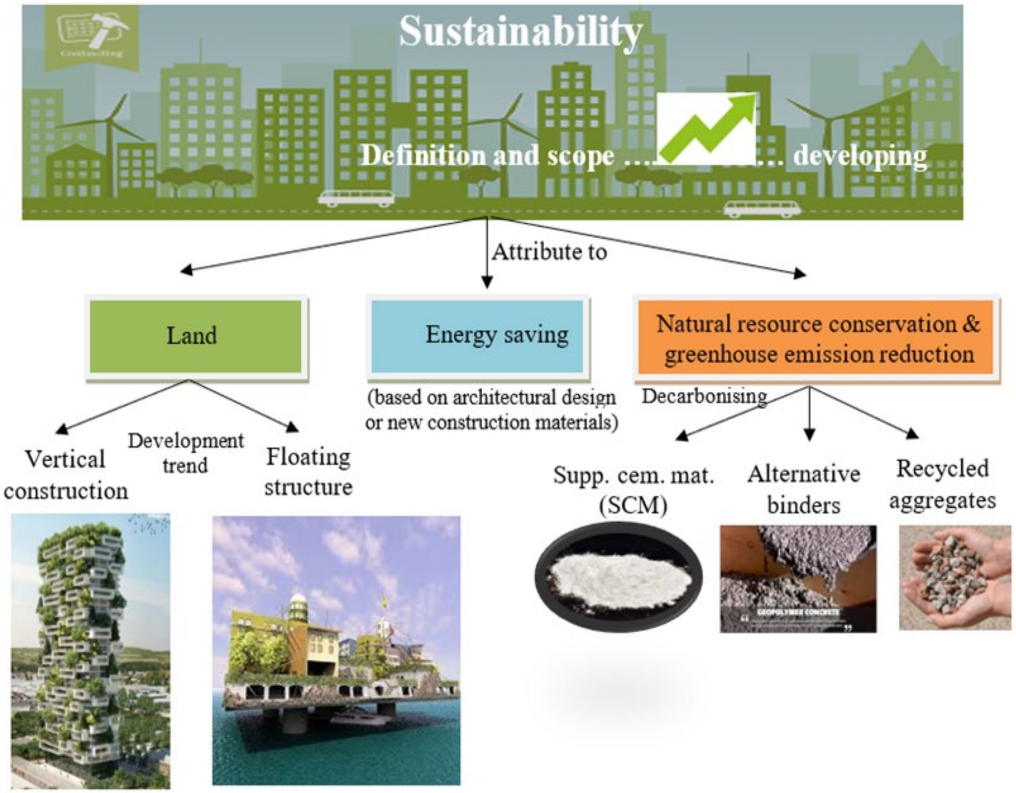
Sustainability

In civil engineering, there are primarily three aspects that affect the sustainable development

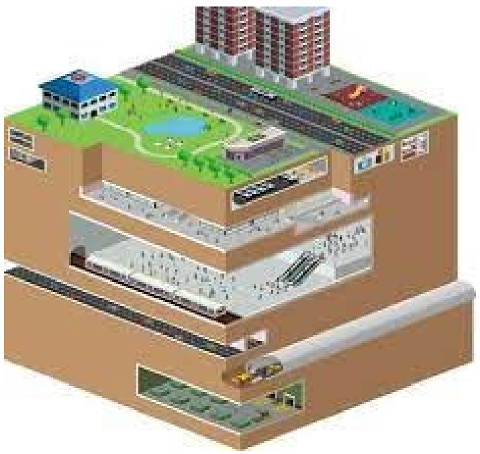
1) Land availability for structure development – vertical construction vs horizontal construction, floating structures

2) Energy consumption – Minimizing energy required in construction and operation of structures, e.g., cement production requires heating up limestone and clays to about 1,450°C, significant amount of energy and is responsible for 5-7% CO_2 emission in the world

3) Depletion of Natural Resources – Recycle industry, household wastes, and construction materials










Build taller, deeper and floating structures with greener construction materials and proper architectural designs to save energy for lifecycle operation and maintenance

Sustainable Structures (netzero or netpositive)

1) Built with low upfront carbon emissions
2) Offset with positive activities in the natural environment
3) Reuse/recycle materials in construction to minimize depletion of natural resources
4) Minimize or zero fossil fuel energy consumption during operation (green energy, minimize energy consumption with proper architecture and use of building materials, e.g., phase changing materials, insulation, etc)





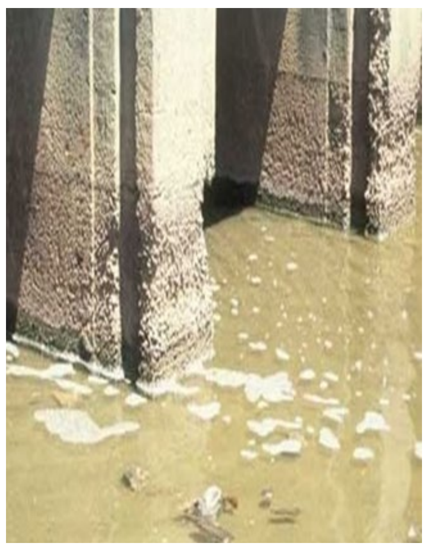

Durability of structures

Durability

Various factors affect the structural durability, proper considerations at the design stage the durability problem can significantly reduce the lifecycle maintenance costs of structures, prolong structural service life

Primary sources that affect structural durability: Corrosion, Sulfate attack, Frost action (freeze-thaw cycles), Alkali-aggregate reaction, etc

Corrosion



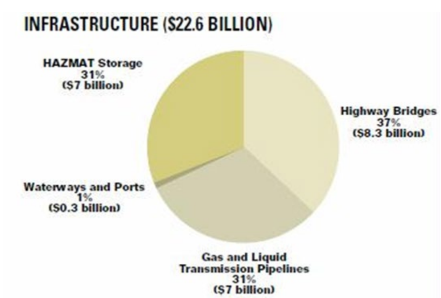
Sulfate attack

Frost action

Alkali-aggregate reaction

Corrosion damage

Use stainless steel and fiber-reinforced polymer (FRP) in construction



Sulfate attack

Use supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag, silica fume, and metakaolin can improve Sulfate resistance

Frost damage

Reduce permeability and void ratio of concrete

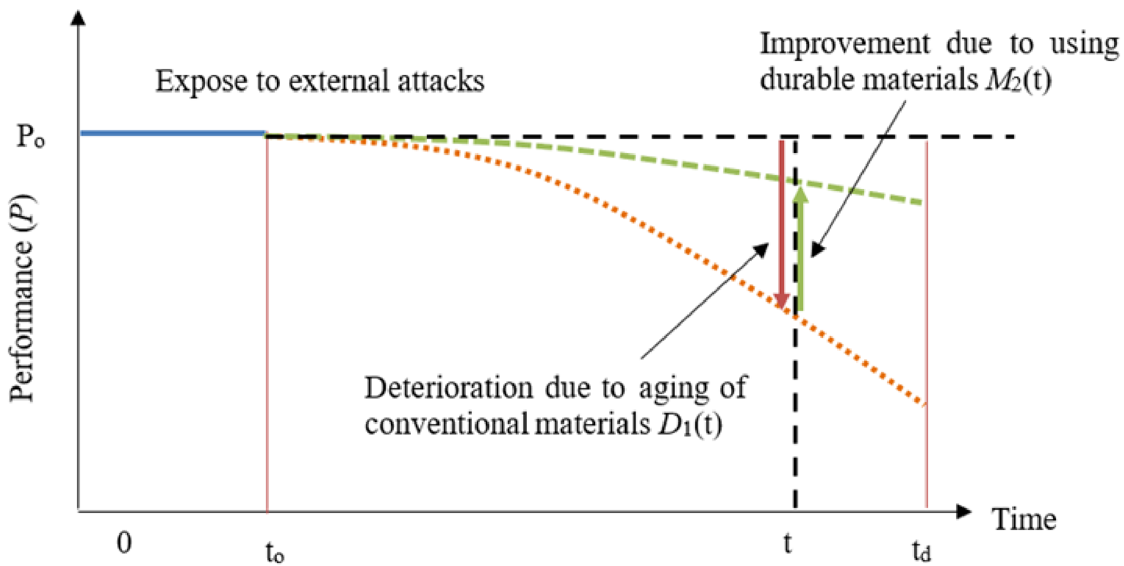
Alkali-Aggregate Reaction (AAR)

Fig. 1.1-1 Typical deterioration in concrete barrier

Control AAR by using low-alkali Portland cement, non-reactive aggregates, and controlling moisture in concrete

Various measures have been and are still being studied to enhance structural durability, e.g.,

- increase concrete cover depth
- Use supplementary cementitious materials (SCMs)
- use nanoconcrete, functionally graded graphene concrete to reduce or prevent air and moisture penetration to steel reinforcement
- use stainless steel or use FRP materials.



The performance (P) of a structure can be quantified:

$$P(\mathrm{t}) = P_{\mathrm{o}} - D_2(\mathrm{t})$$

$$M_2(\mathrm{t}) = D_1(\mathrm{t}) - D_2(\mathrm{t})$$

Despite many researches have been conducted and reported, which are fragmented. In normal practice durability is not explicitly considered in structural design and construction. There is no specific guide either. Considering durability in structural design could bring enormous benefits, enhancing structural safety, prolonging structural service life and reducing lifecycle maintenance costs, therefore should be explicitly considered in the design of structures.

Multi-hazard resistance

Multi-hazard resistance

During the service life of a structure, it is inevitable it will be subjected to multi-hazards. The extreme multi-hazards may occur simultaneously, in sequential or independently. For example:

earthquake-land sliding, earthquake-tsunami, earthquake-fire, earthquake-impact, fire-blasting, impact-blasting, impact-fire, etc

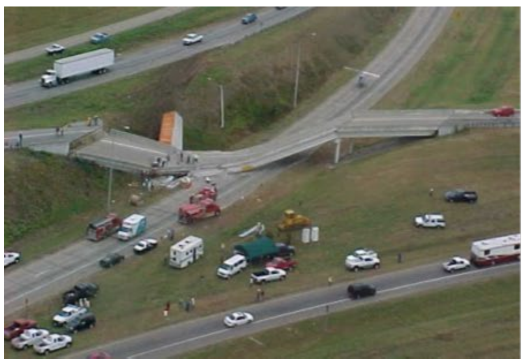
Different hazards may have different effects (e.g., earthquake vs blasting and impact)

Current design practices: load combination, response superposition may lead to unreasonable/inaccurate structural response predictions and design

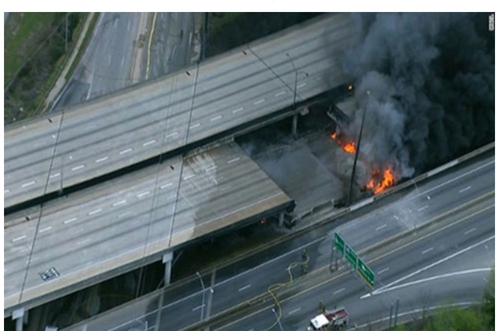
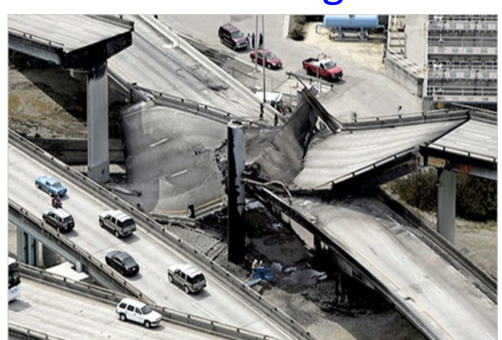
Multi-hazards – simple load combination does not lead to effective structural designs



Earthquake – global responses caused by inertia force and large relative displacement



Vehicle impact – local responses and damage which may induce total collapse


Blast – localized response and damage

Structural Response Analysis – some fundamentals

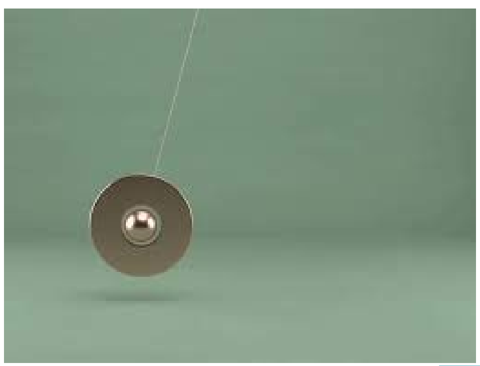
Wave propagation. Mass govern	Dynamic, damping critical	Quasi-static, stiffness govern
small	Intermediate	large

t_d/T →

$$m\ddot{v} = P(t)$$

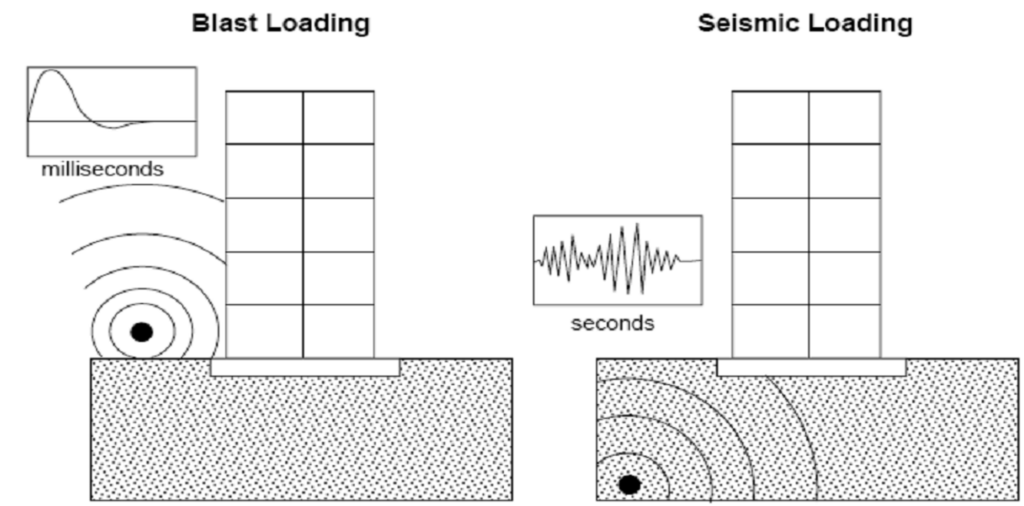
$$kv = P(t)$$

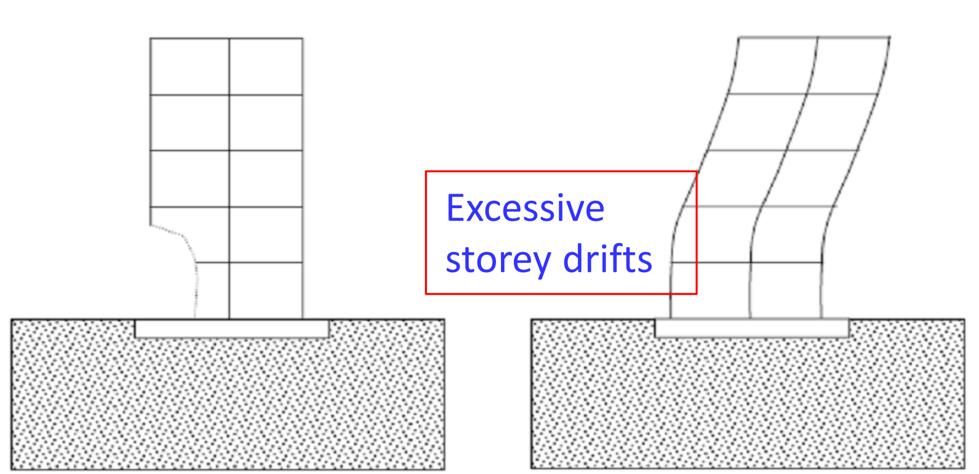
$$m\ddot{v} + c\dot{v} + kv = P(t)$$



Equivalent static analysis methods in most design guides give good predictions only when t_d/T is large and quasi-static response governs

Structural response to earthquake and blast loading – similarity and differences

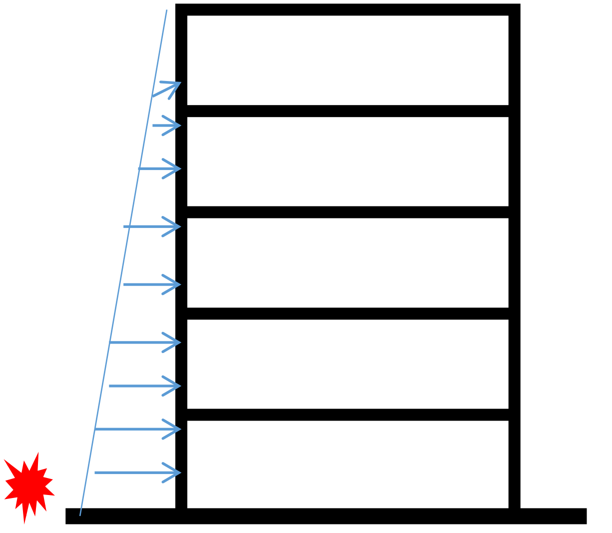
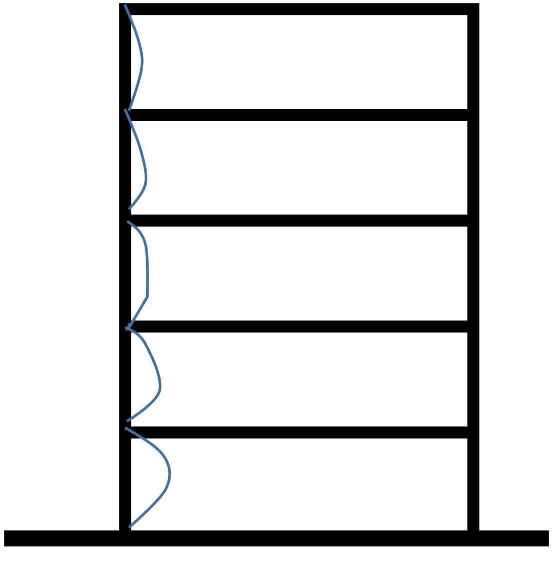




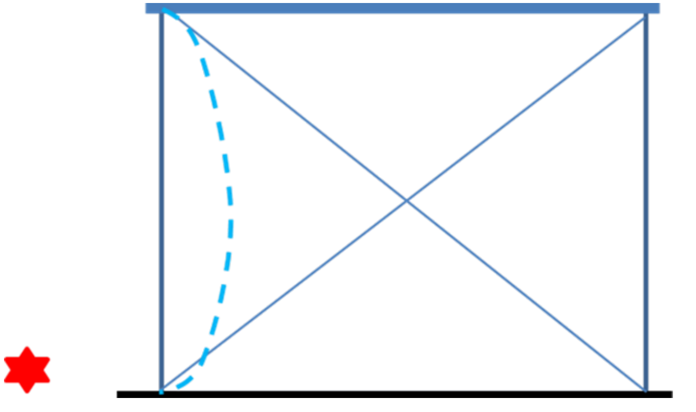
Excessive storey drifts

Loss of key load-carrying members that induce progressive collapse



Under blast loading, owing to large floor mass and thus large inertial resistance at floor level, structural deformation is governed by local column deformation, there are very small storey drifts



Structural response to earthquake and blast loading – similarity and differences

Above-deck detonation

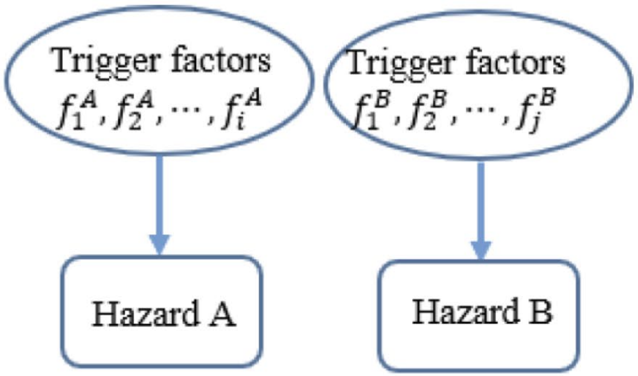
Below-deck detonation

Cross bracing, base isolation, tuned mass damper that are effective to mitigate seismic responses of structures are not effective to resist blast and impact loads

Increasing structural mass enhances blast and impact resistance, but may have adverse effects on seismic safety of the structure

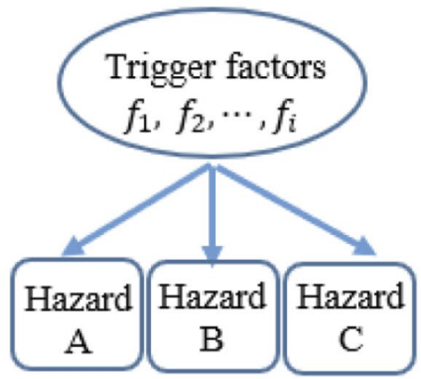
Classifications

✓Based on hazard occurrence



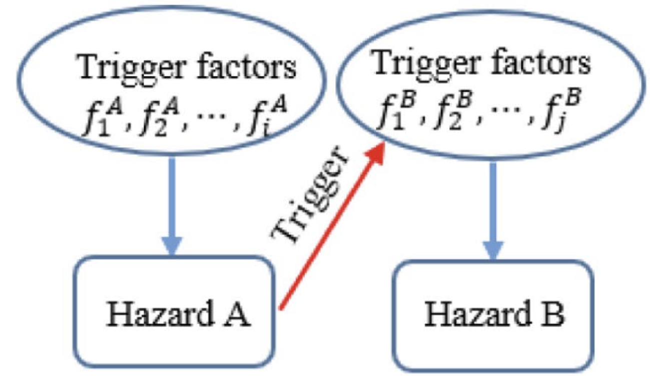
Non-concurrent
Independent

Earthquake + flood
Earthquake + Scour
Earthquake + hurricane



Concurrent
Correlated

Mainshock + after shock
Hurricane + wave + surge



Cascading

Earthquake trigged: landslides, liquefaction, tsunami, Fire, Impact

Fire + blast, impact + blast

✓**Based on influence on fragility and risk**

- Amplifying hazards (scour + earthquake)
- Diminishing hazards (truck load + earthquake)

✓**Based on influence on design parameter selection**

- Competing hazards (earthquake + hurricane + flood on bridge column height selection)
- Complementary hazards (improving the ductility might be benefit for seismic + collision)

Ageing (corrosion, fatigue, etc)

Discussions

- ✓ **Extensive research works have been carried out** to assess the performances of engineering structures subjected to multi-hazards, which are normally carried out **based on the performance-based design method** in the probabilistic framework with the fragility curve and fragility surface as the assessment index. Most of such studies are related to earthquake and wind loads, blast and fire, etc.

- ✓ The corresponding study on the **multi-hazard resilience assessment is very limited**. More comprehensive studies are required to better understand the performances of structures subjected to multi-hazards, and also more refined resilience-based assessment frameworks are needed.

Resilience based analysis and design

Resilience is an 'in-word' that is very commonly used in every aspect, not only in engineering structures, which mainly refers to the disaster resilience of engineering infrastructure.

It could be a political word or a technical word. It becomes so fashionable and fuzzy that some people simply use it to impress others without properly defining the meaning of 'resilience'.

When used as a technical term in structural engineering, we need and should at least clearly define the specific meaning of resilience, e.g., how to measure the resilience of a structure? how can or can it be quantified? how much can the resilience of a structure be improved after the specific engineering design actions? before conducting the 'resilience analysis and design'.

What is resilience?

Resilience Definition

Latin word 'resiliens' means rebound

- **First English use in 1620**
- **In 1800's mainly used in relation to elasticity, means recovery**
- **In 1900's commonly applied to people**
- **In 2000's has become an in-word**

-applied to everything and especially disaster risk management

Although Resistance may Contribute to Resilience, Resilience is about Recovery from Impact

Not about Resistance to Impact (Strength)

A common confusion is to mix Resistance with Resilience

Resilience can refer to a particular structure, a community, a city and a region, or a system

Different definitions of resilience

Absorb/Adapt to changes; Continue/keep functioning; Quick recovery to minimize disruption

Recently it has further extended from Absorb/Adapt changes, quick recovery to Transform the designs

recover from deliberate attacks, accidents, or naturally occurring threats or incidents.' **PPD-21 (2013) Presidential Policy Directive/PPD-21, Obama Administration, 2013**.

'A resilient infrastructure network is designed and constructed to accommodate hazard-related damage with ability to continue providing services or limit service outage times tolerable for community recovery efforts.' **Davis, C. A. et al, 2015**

Resilience of a Structure is measured by how quickly functionality can be restored if resistance is exceeded and loss of functionality occurs

Resistance of a Structure indicates capacity of structure to resist defined event without loss of functionality

Therefore, defining resilience of a structure must be accompanied with the impact due to the loss of functionality and the time required to recover to full functionality.

Resilience analysis therefore is a probabilistic and systematic analysis.

Enhancing structural resistance (strength) increases structural resilience
Prefabrication construction also enhances structural resilience
SHM, management and retrofitting also enhances structural resilience

Not structural resilience analysis

Resilience analysis

- Resilience has four attributes, i.e., **four Rs**: **robustness, redundancy, resourcefulness, and rapidity of recovery.**
- Resilience is built on four pillars including **economic, environmental, social and cultural impacts** besides structural safety.
- Resilience can be considered at the **structural, system, community, urban and regional** levels.
- Resilience analysis (Systematic and Probabilistic-based analysis),

  1) Identify and quantify hazards (loading predictions);
  2) Vulnerability analysis against multi-hazards;
  3) Determine acceptance levels of disruptions;
  4) Establish resilience target;
  5) Estimate the time and cost required to recover the functionality after damage;
  6) Require iteration in design analysis to balance the need for initial investments, maintenance costs, impact and cost due to out of functionality, and cost to recover, etc.

Resilience-based design (RBD)

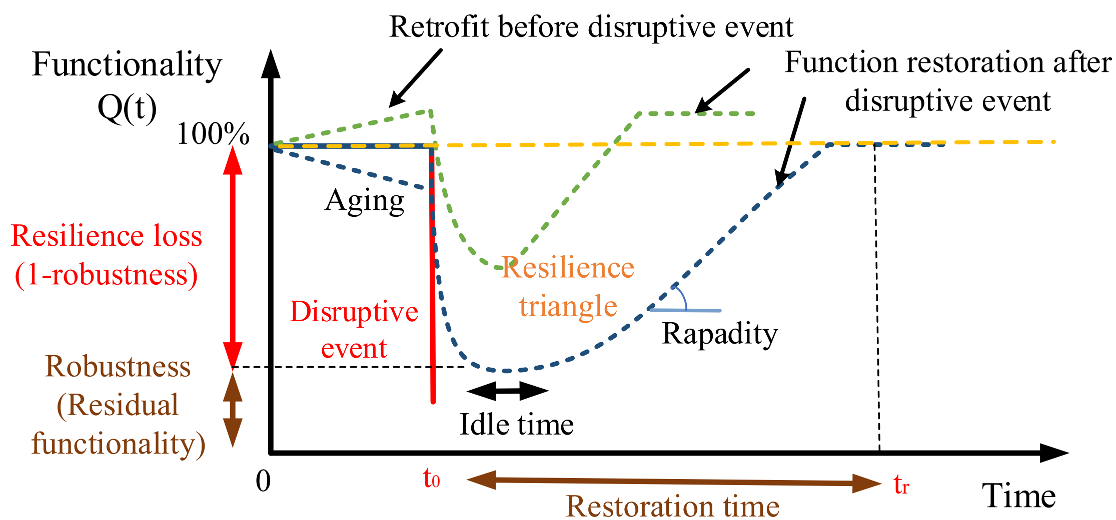


Fig. Resilience curve and indices

- The "**resilience triangle**" was introduced by Bruneau et al. [109]
- The total time for functionality restoration $t_r - t_0 = \frac{1 - Robustness}{Rapidity}$
- Resilience loss (the area of resilience triangle) $R_L = \int_{t_0}^{t_r} [100 - Q(t)]dt$
- Resilience index (R) $R = \frac{\int_{t_0}^{t_r} Q(t)dt}{t_r - t_0}$
- The direct cost $C^s_{dir} = P^s \cdot C^c \cdot \sum_{d=1}^{5} P_d \cdot D_d$
- The indirect cost $C^s_{ind} = P^s \cdot \int_{t=0}^{t_r} \left[1 - Q(t)\right] \cdot c_{ind} \cdot dt$

* Require to define a resilience criterion for iterative design analysis.

Smart Civil Engineering Structure

No universal definition yet exactly what is intelligent construction and asset management

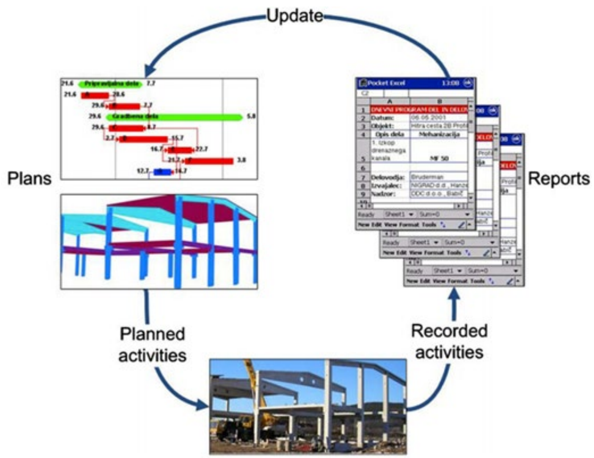
Challenges: Construction industry has the legacy of being labour intensive, low efficiency, high pollution, high energy consumption and high environment disruption

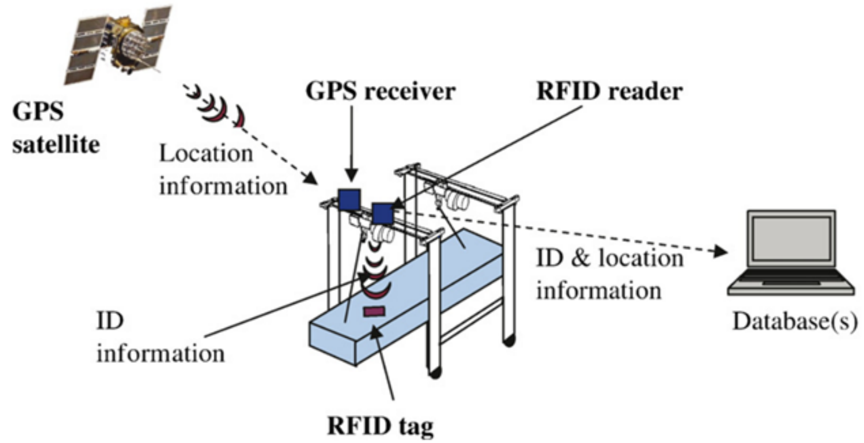
Smart management and maintenance certainly contribute to the structural designs, e.g., resilient design, but how?

Take advantage of the significant developments and advancements in other professions

Intelligent construction and asset management is to integrate these new advancement in computer science, computer technology, information technology, sensor, automation, control, manufacturing, AI, network, big data analytics and material science together with the traditional construction technology to develop the optimized design, construction, monitoring and maintenance of civil engineering structures.

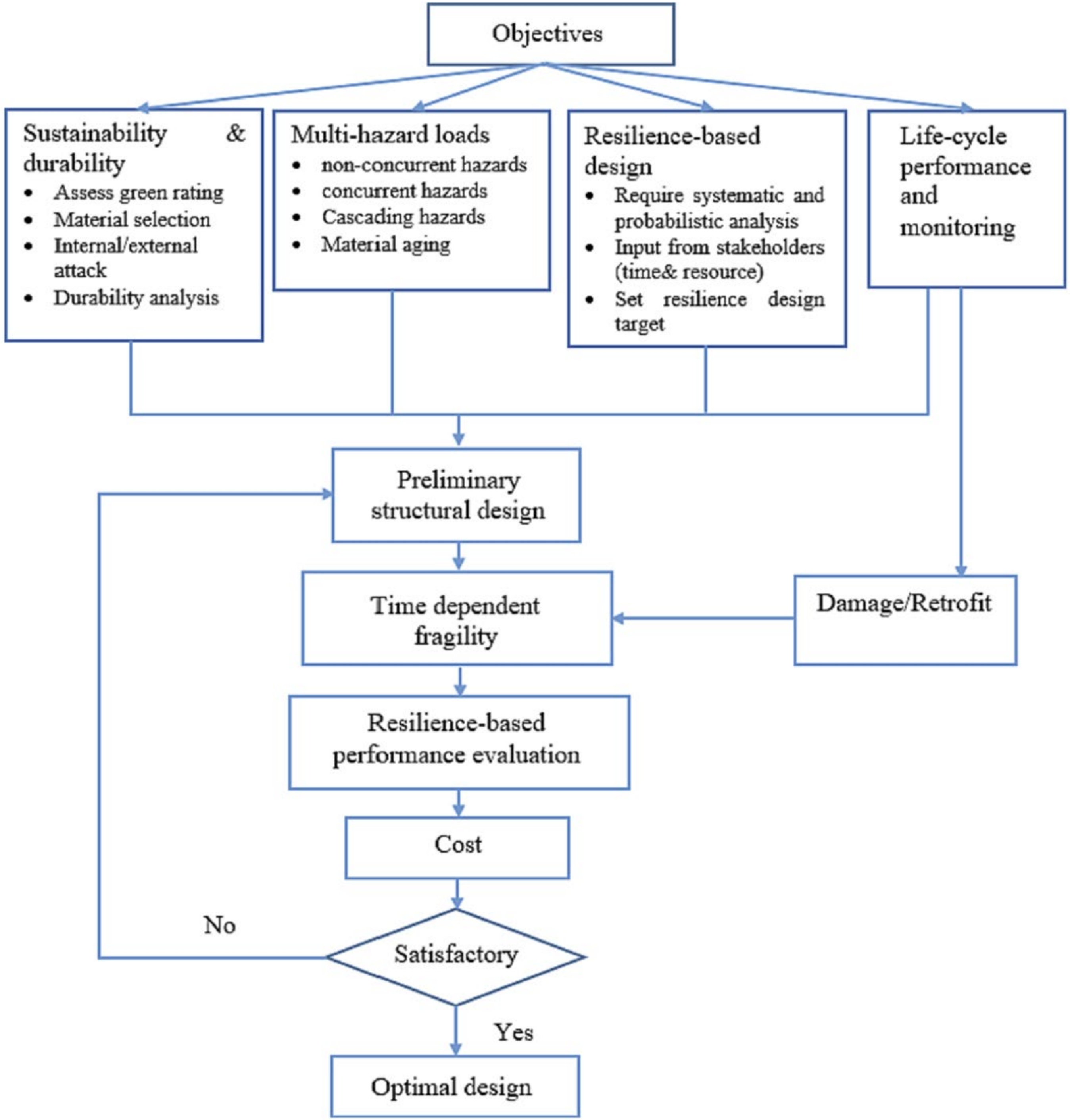
Construction process monitoring, Structural Health Monitoring and Engineering Asset Management





Sensors: accelerometers, FBG, strain gauges, LVDT, GPS, PZT, wired and wireless Camera/imagining processing

Proposed framework for SDuMuRS Analysis



For more information, please read

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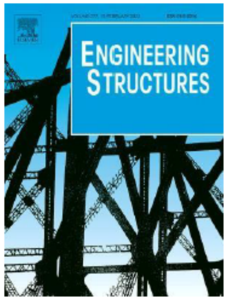

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Volume 277, 15 February 2023, 115477

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