Fall-2023 Convention of American Concrete Institute (ACI)
Saturday, October 28, 2023
Wednesday, November 01, 2023

Quantification, Damage Mitigation, and Preservation of Concrete Bridges and Structures under Natural and Man-Made Hazards, Part 2 of 2

Moderators: Dr Hyeon Jong Hwang and Dr Yail Jimmy Kim

Achieving Multi-Hazard Resilience of Bridge Infrastructure under Extreme Loading

Professor Dr Vasant Matsagar
(Professor and Dogra Chair)

Multi-Hazard Protective Structures (MHPS) Laboratory
Department of Civil Engineering
Indian Institute of Technology (IIT) Delhi
India

Monday, October 30, 2023

11:00 a.m. - 01:00 p.m., W-Marina Ballroom I, Westin Boston Seaport District, Boston Convention and Exhibition Center, USA

Agenda

- ✓ Failures of Lifeline Structures: Bridge and Bridge Failures at Deck or Piers
- ✓ Multi-Hazard Protective Structures
  - Need for Multi-Hazard Studies in Structural Engineering
  - Need : Multi-Hazard Assessment of Structures
  - Global Overview of Hazard Scenario
  - Why Study Multi-Hazard Effects?
- ✓ **Multi-Hazard Assessment under Earthquake and Scour**
- ✓ **Hazards During Design Life of Structure**
  - **Losses due to Multi-Hazard (Extreme?) Events**
  - **Different (Multi-) Hazards for Structures**
  - **Multi-Hazard Assessment under Independent Hazards**
  - **Historical Overview of Multi-Hazard Scenario**
- ✓ **Multi-Hazard Assessment under Earthquake and Wind**
- ✓ **Assessment Methodology for Global MHA Scenario**
  - **Assessment Methodology - An Example of MHA**
- ✓ General Framework for Multi-Hazard Scenario
- ✓ Multi-Hazard Scenario-Based Analysis
- ✓ Probabilistic Assessment Methodology - Independent Hazards
- ✓ **Other Code/Specifications/Standards**
- ✓ Dynamic Response Control under MH-Scenarios in Bridges
- ✓ **Experience from the USA**
- ✓ Future Vision and Outlook
- ✓ Concluding Remarks

Communication (Lifeline) Network

Failures of Lifeline Structures: Bridge

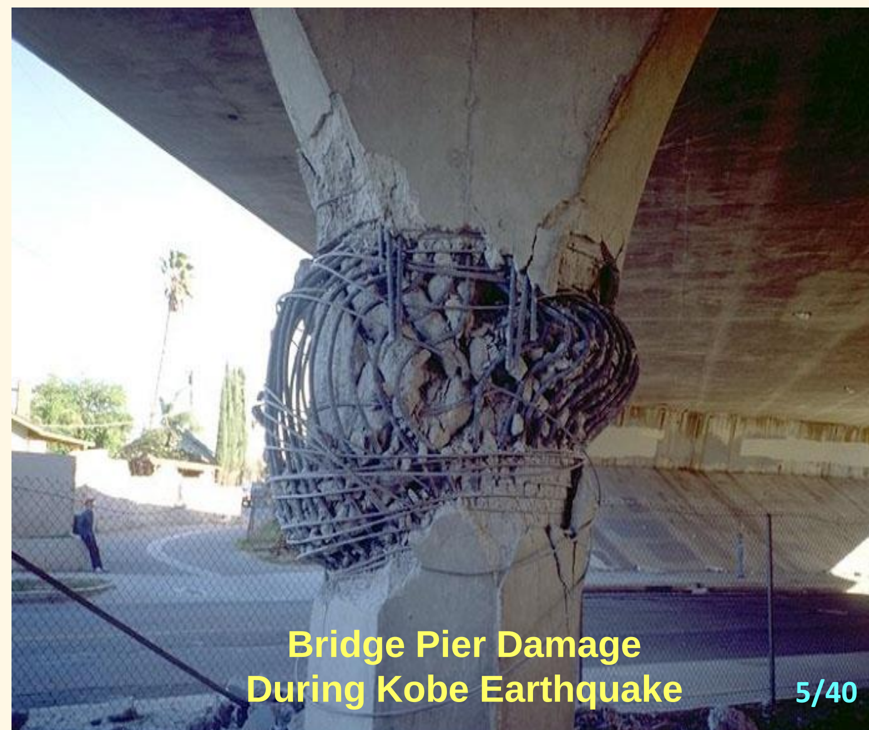
**Damage of Bridges
During
Earthquakes**

Bridge Failures at Deck or Piers

Bridge Failures at Deck or Piers

Pounding of Deck Girders (2001 Bhuj Earthquake, India)

Bird Nest Failure!

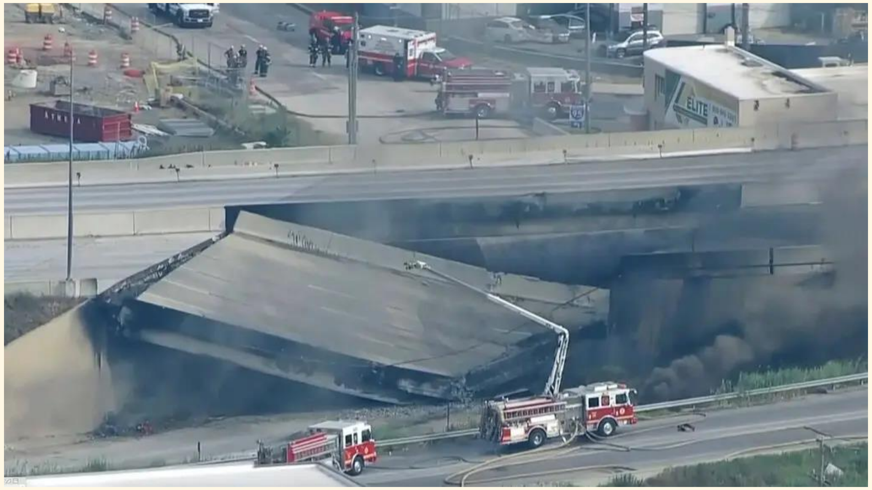


Bridge Pier Damage During Kobe Earthquake

Bridge Failures at Deck or Piers

Accidental/ Manmade Hazards

I-95 Overpass Collapses in Philadelphia After a Tanker Fire



Multi-Hazard Protective Structures

1. Dynamic Phenomena, Vibrations, and Response Control
2. Earthquake Engineering
3. Wind Engineering
4. Fire Engineering
5. Blast Engineering and Protective Structures
6. Advanced Engineered Materials and their Composites:
   Fibre Reinforced Polymers (FRP) in Prestressed Concrete Structures

Earthquake

Wind

Advanced Engineered Materials

↓

Novel Structural Systems

↓

Multi-Hazard Protection of Structures

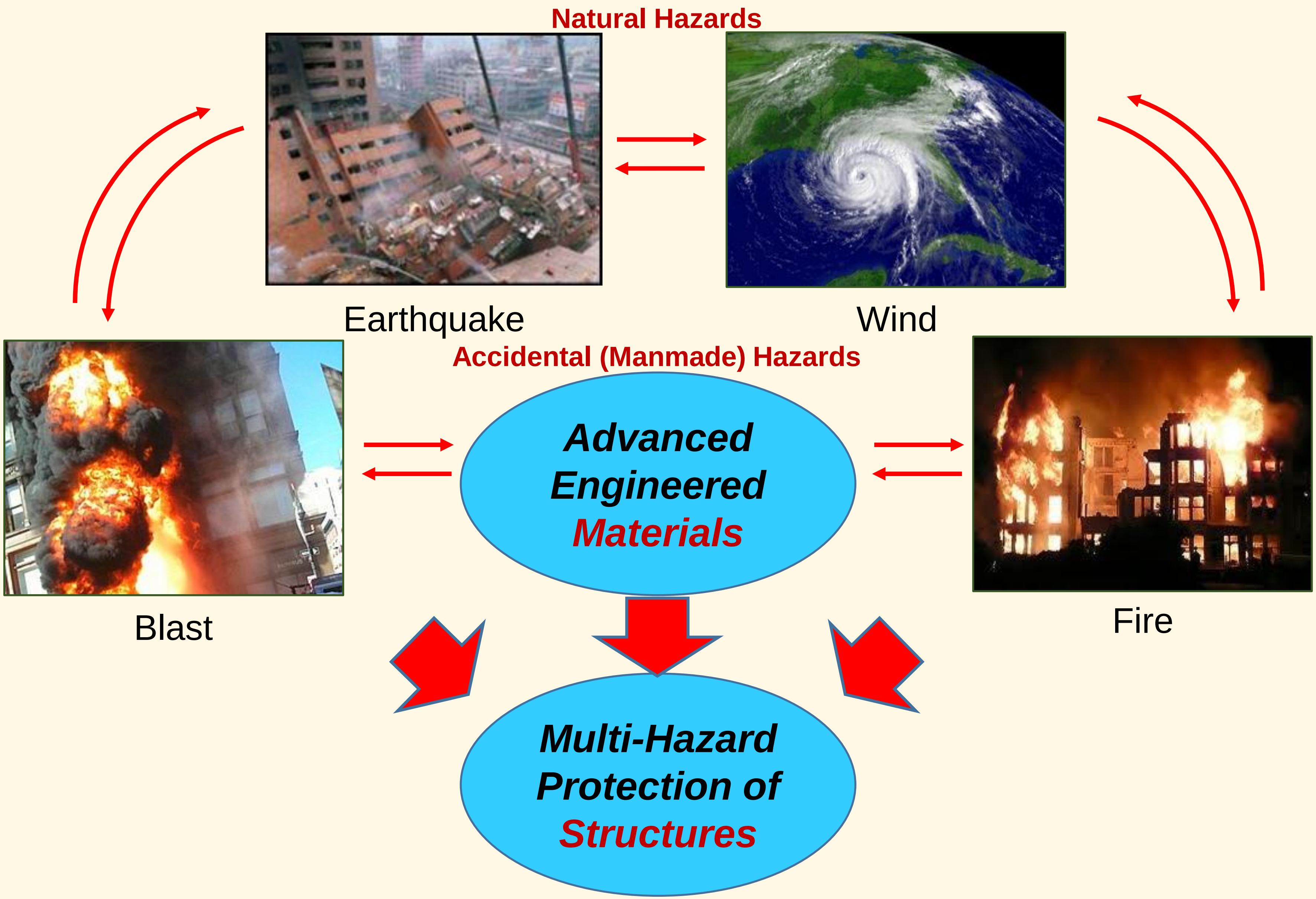
↓

Blast

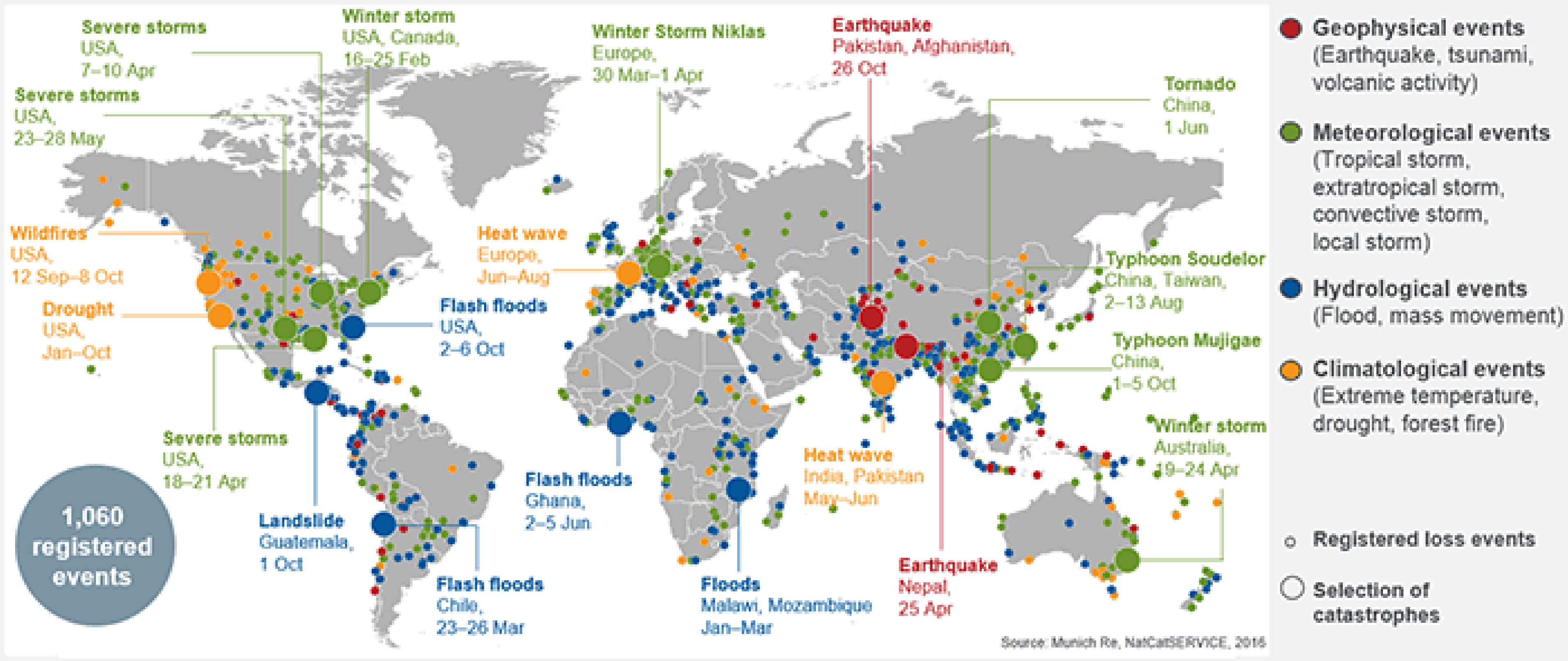
Fire

(a) Deterministic/ Possibilistic Approach; (b) Probabilistic/ Stochastic Approach; (c) Experimental Approach

Need for Multi-Hazard Studies in Structural Engineering



Global Overview of Hazard Scenario



2016 Munich Re, Geo Risks Research, NatCatSERVICE (As of March 2016).

Why Study Multi-Hazard Effects?

I-10 Bridge Collapse in Arizona, 2015

Heavy rain causing scouring with wash away of riverbed materials

30' × 50' chunk of the bridge collapse

- ➢ Event type - Heavy Rains after Hurricane Dolores.
- ➢ Major set-back as ~20,000 cars pass everyday connecting California and Arizona.

Why Study Multi-Hazard Effects?

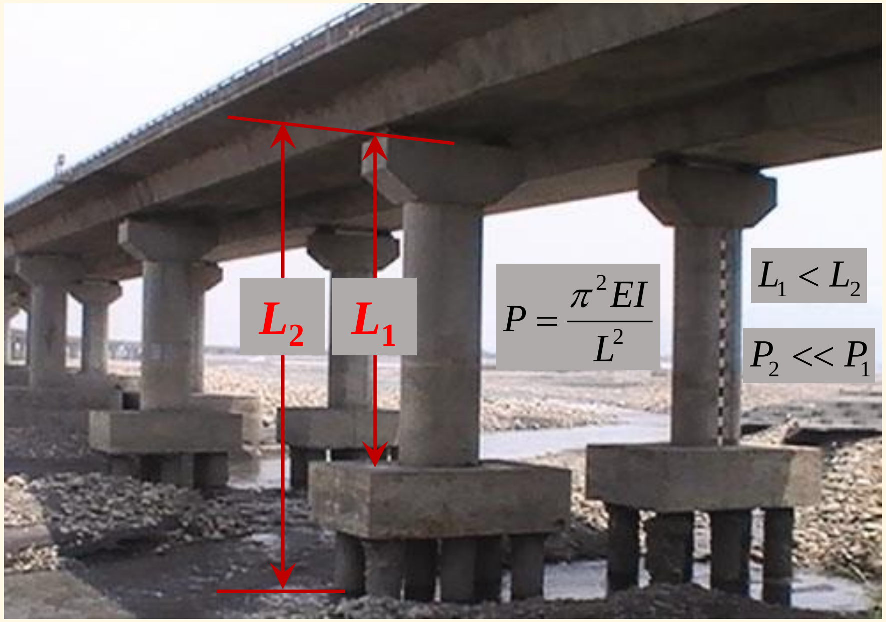
Hurricane Matthew, 2016

Storm surges have caused major flooding in St Augustine, Florida

Hurricane Matthew washes away parts of A1A in Flagler County

- Event type - Heavy Wind, Storm Surge, and Flood with rages of Fire.
- > 1650 fatalities.
- Insured losses - > 10 billion US$.

Multi-Hazard Assessment under Earthquake and Scour



- Earthquakes and flood-induced scouring -major concern for the **lifeline bridge engineering research communities**.
- **Simultaneous occurring events**.

- Examples:

✓ Countless Weir Bridge, England, 1968
✓ Schoharie Creek Bridge, USA, 1987
✓ I-5 Bridge, Coalinga, USA, 1995
✓ Walnut Street Bridge, USA, 1996
✓ Malahide Viaduct, Ireland, 2009
✓ Railway Bridge RDG1 48, England, 2009
✓ CPR Bonnybrook Bridge, Canada, 2013
✓ I-10 Bridge, 2015, USA

Why Study Multi-Hazard Effects?

Multiple hazards - Earthquakes, Strong Winds, Blasts, Fire Outbreaks, Floods, Tsunamis, Landslides, Storm Surge, etc.

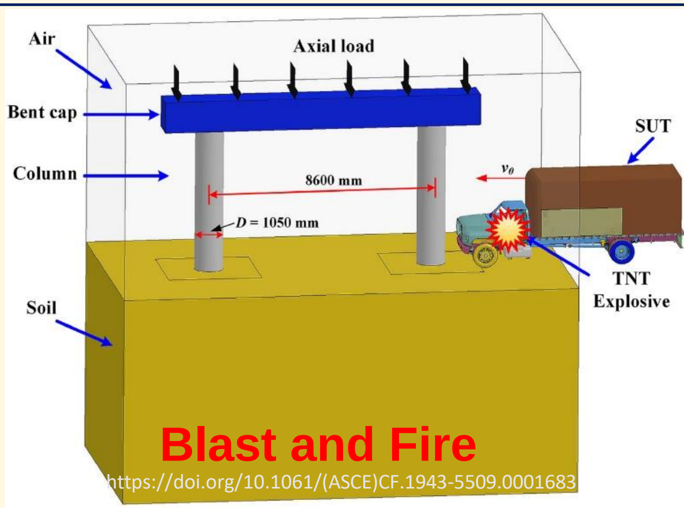
Global devastations in terms of physical and socio-economic losses.

Multi-hazard has been coined in the broader context of *risk reduction*.

Limited progress in ***protection of structures*** against the multiple hazards

This is neither simple and straightforward nor commonly undertaken at present.

Multi-Hazard Resilient Society



Hazards During Design Life of Structure

Natural Hazards	2015 (Original figures)	2014 (Original figures)	Average of the last 10 years 2005-2014 (Losses adjusted to inflation based on country CPI)	Average of the last 30 years 1985-2014 (Losses adjusted to inflation based on country CPI)	Significant Year 1985 -2014
Number of events	1,060	980	870	670	980 (2014)
Overall losses in US$ m	90,000	110,000	180,000	130,000	424,000 (2011, e.g. EQ Japan)
Insured losses in US$ m	27,000	31,000	56,000	34,000	132,000 (2011, e.g. EQ Japan)
Fatalities	23,000	7,700	68,000	54,000	296,000 (2010, e.g. EQ Haiti)

	Number of incidents	Deaths	Insured loss ($ millions)
All manmade disasters	**155**	**6,994**	**$8,983**

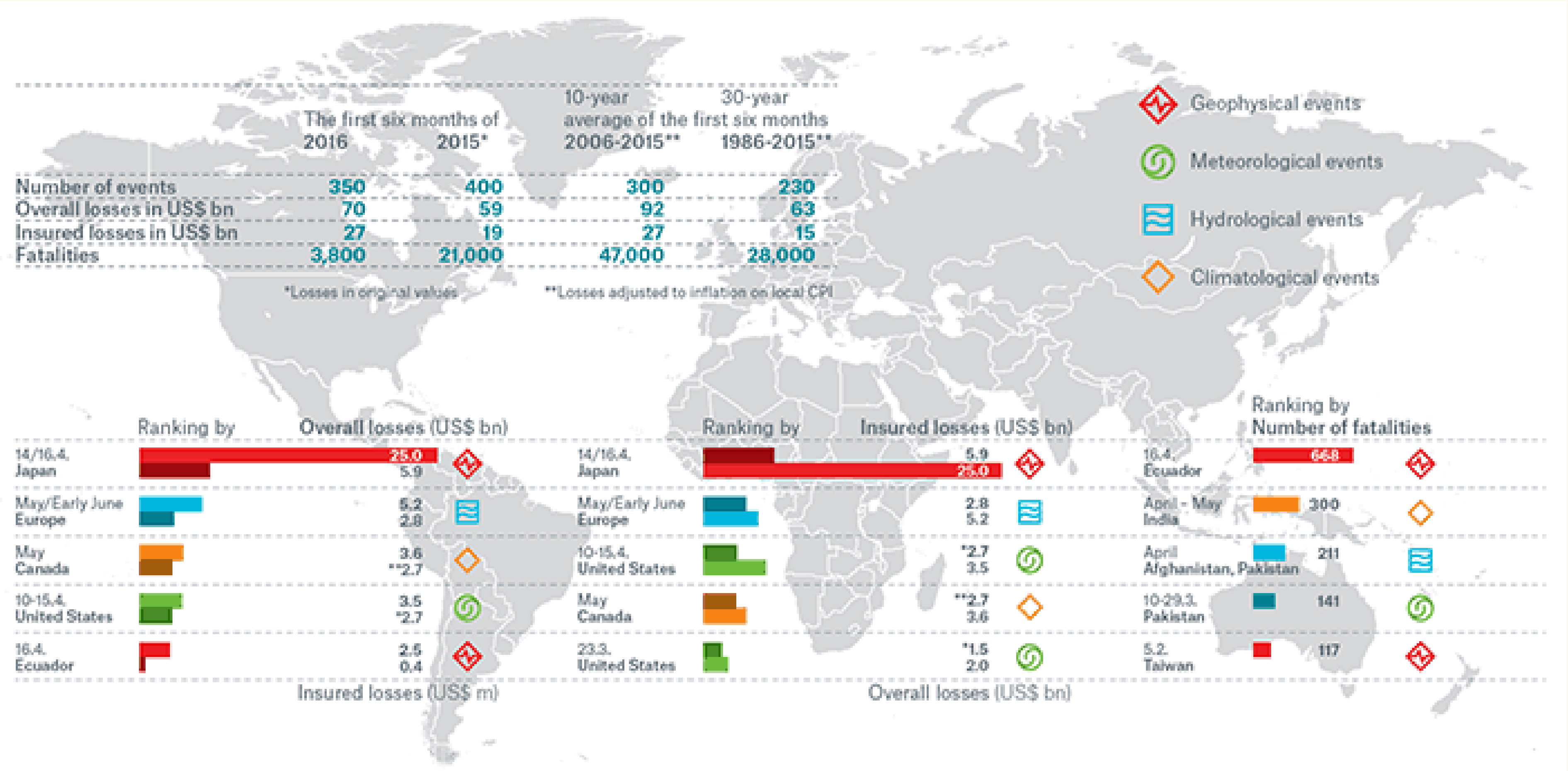
World Natural and Manmade Catastrophes, 2015 (2016 Munich Re, Geo Risks Research, NatCatSERVICE) (As of January 2016)

Losses due to Multi-Hazard (Extreme?) Events

Rank	Date	Country	Events : Multi-Hazard … ??	Insured loss
1	Aug. 25, 2005	U.S., Gulf of Mexico	Hurricane Katrina, storm surge, damage to oil rigs	$79,663
2	Mar. 11, 2011	Japan	Earthquake (Mw 9.0) triggers tsunami	36,865
3	Oct. 24, 2012	U.S., Caribbean, Canada	Hurricane Sandy, massive storm surge	36,115
4	Aug. 23, 1992	U.S., Bahamas	Hurricane Andrew, floods	27,017
5	Sep. 11, 2001	U.S.	Terror attacks on WTC, Pentagon and other buildings	25,129
6	Jan. 17, 1994	U.S.	Northridge earthquake (Mw 6.7)	24,455
7	Sep. 6, 2008	U.S., Gulf of Mexico, Caribbean	Hurricane Ike	22,343
8	Feb. 22, 2011	New Zealand	Earthquake (Mw 6.1), aftershocks	16,853
9	Sep. 2, 2004	U.S., Caribbean, Venezuela	Hurricane Ivan, damage to oil rigs	16,180
10	Jul. 27, 2011	Thailand	Heavy monsoon rains, extreme flooding	15,799

Top 10 Costliest World Insurance Losses,1970-2015 (2016 Swiss Re)

Losses due to Multi-Hazard (Extreme?) Events



World Natural Catastrophe Losses First Half, 2016 (2016 Munich Re, NatCatSERVICE)

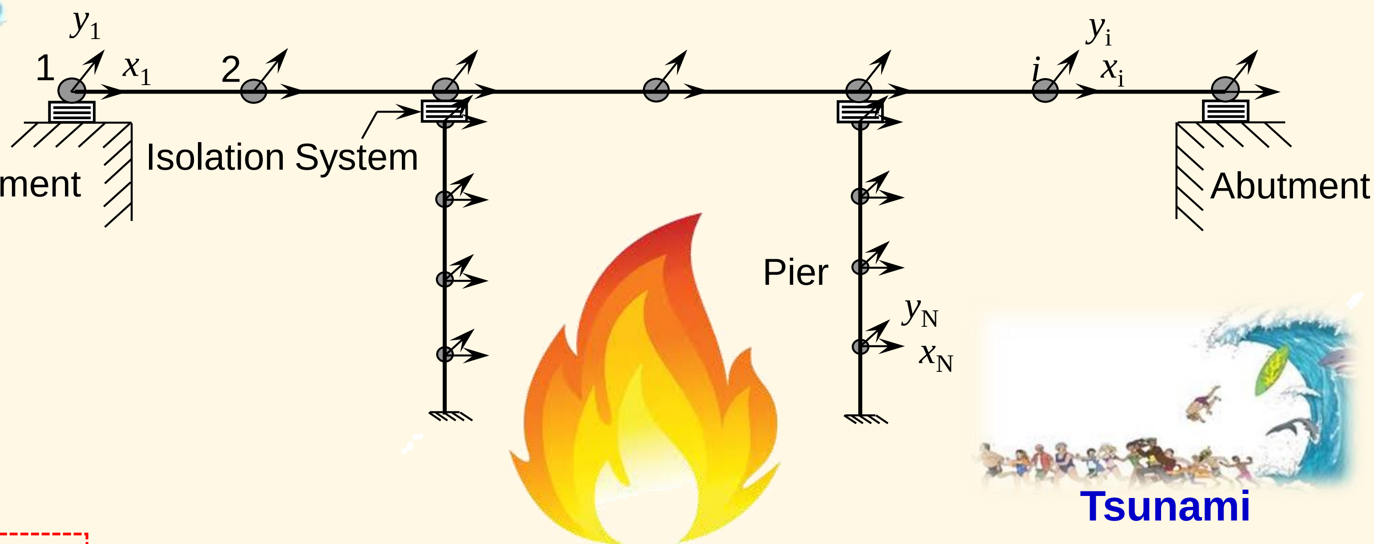
Different (Multi-) Hazards for Structures

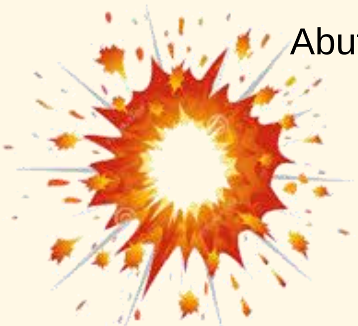
- **Natural hazards**
- **Manmade or accidental hazards**

Earthquake
- Random
- Duration is few seconds to minutes
- Presence of acceleration and velocity pulse (at near-fault location)
- Travels through soil/ rock below the ground

Blast
- Impulsive in nature
- Duration is in mili-seconds
- Travels through air, ground surface, and through soil/ rock below the ground (BIGM)

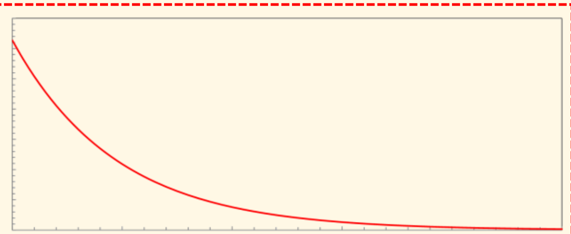

Wind

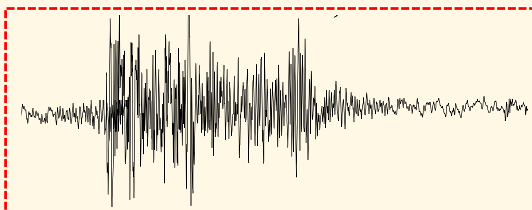



Blast

Fire

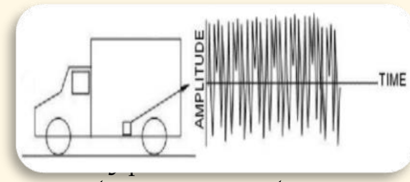
Tsunami

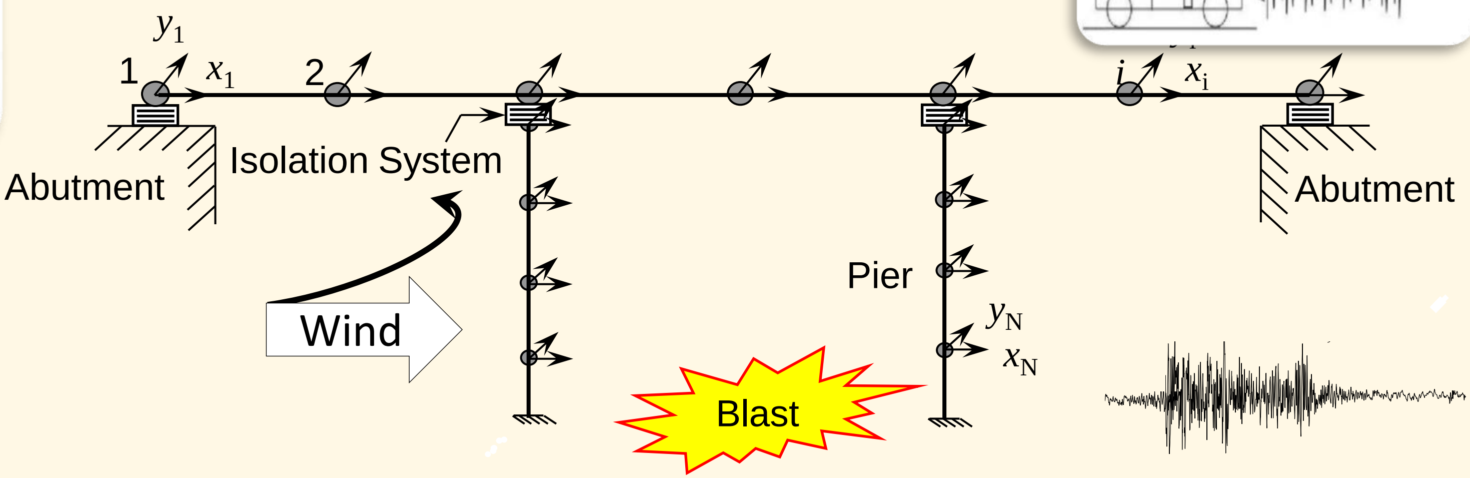

Blast Induced Ground Motion (BIGM)


Earthquake

Different (Multi-) Hazard for Structures : Requirement → Analysis and Design Procedures.

Different (Multi-) Hazards for Structures





- **Main Objective of Control Systems**
  - **To minimize the energy imparted to a structure, thereby reduce damage**
- **Source of other forces / excitations:**
  - **Underground rail/ vehicular movement (noise)**
  - **Earthquake (seismic)-induced loads**
  - **Wind-induced vibration (low frequency)**
  - **Blast (shock/ impact)**
  - **Vibrating equipment (may match modal frequency or frequencies)**

Loads
- **Combinations**
- **Multi-Hazard Effects**

Hazards During Design Life of Structure

~ 19% of the world's land cover
> 50% of the population
SINGLE hazard

~ 4 million km^2 area land cover
> 800 million people
At least TWO hazards

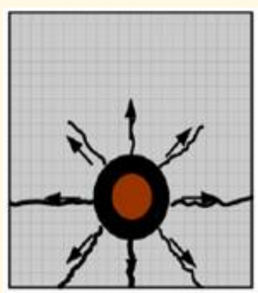
~ 0.5 million km^2 area land cover
> 105 million people
> THREE hazards

Interacting or cascading effects on the structures, inflicting additional destructions.

Multi-Hazard Risk Assessment

Risk-Based Decision Making

Service (design) life deterioration



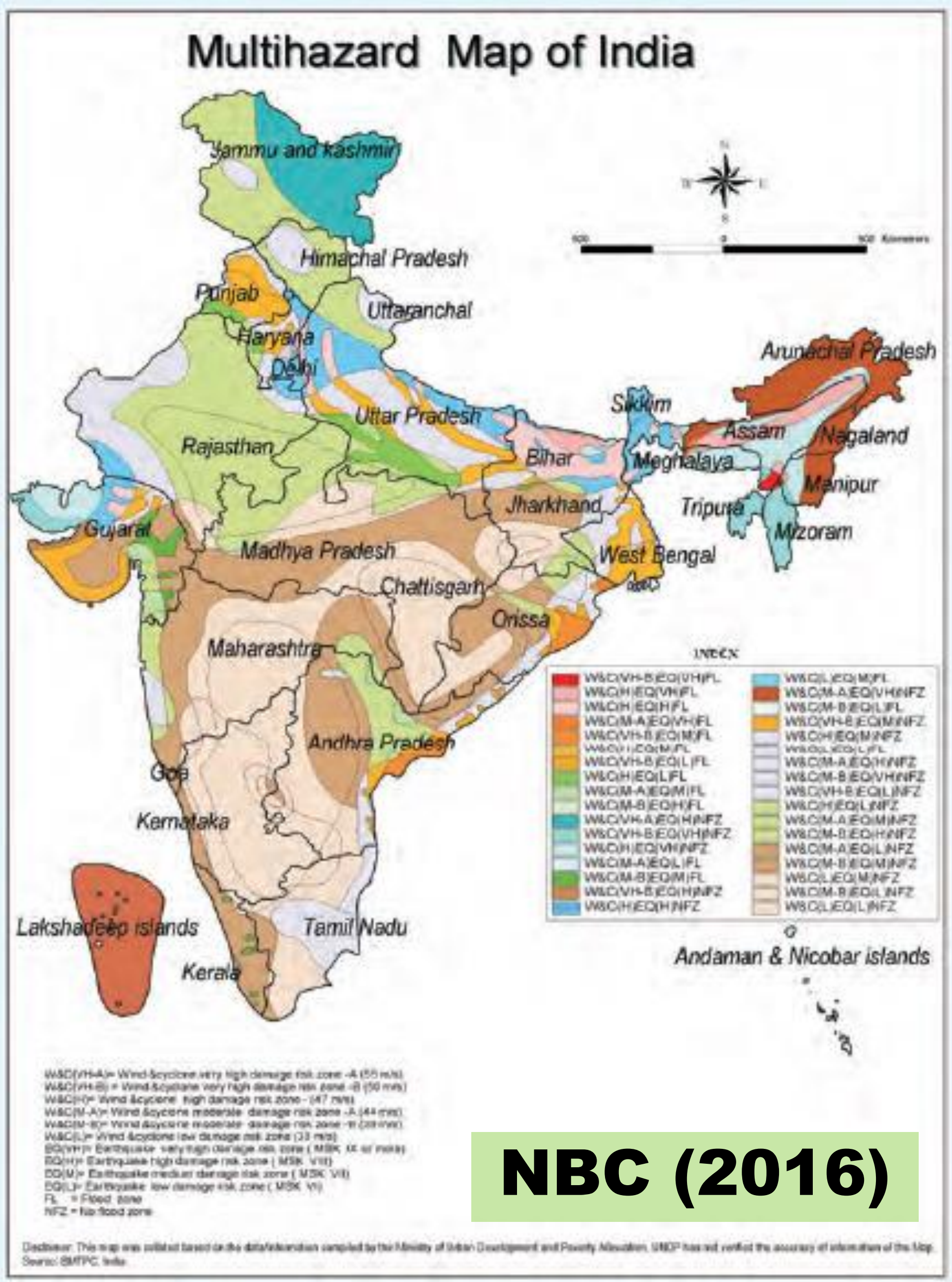
Concrete cracking

Challenges in Multi-Hazard Risk Assessment

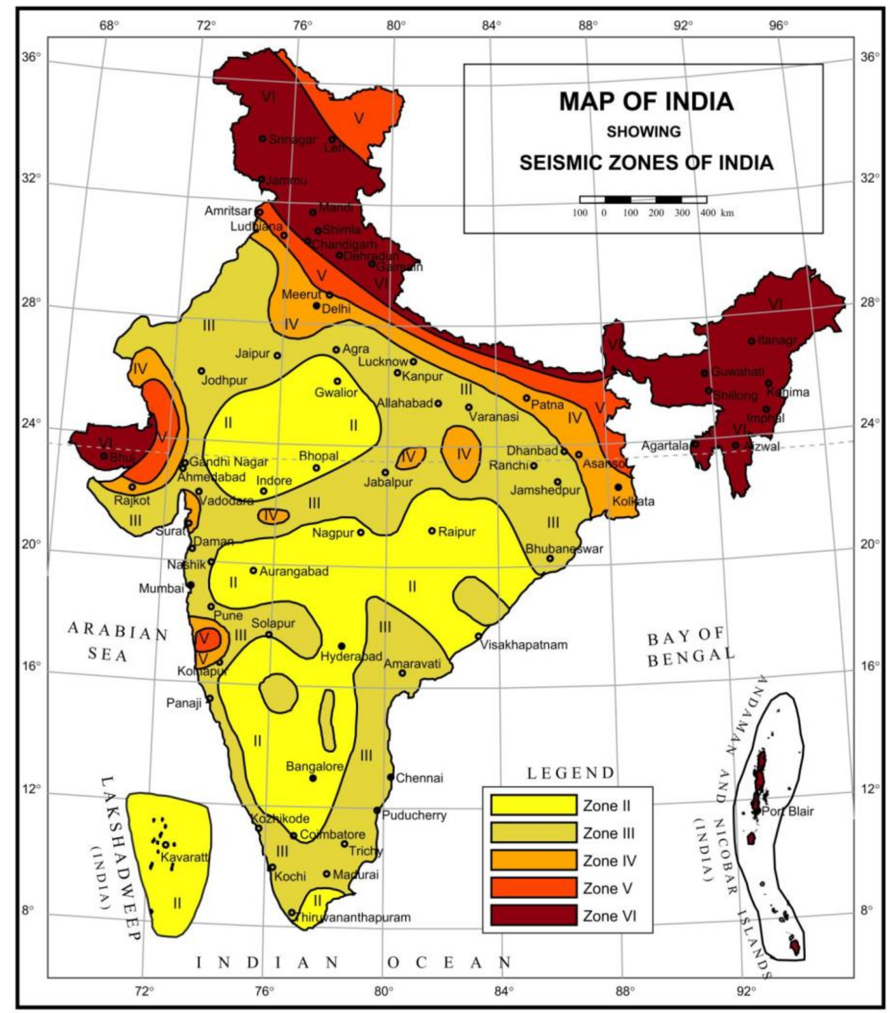
- Differences in hazard processes
- Different assessment models for different hazards
- Complex interaction between different hazards
- Non-availability of sufficient data multi-hazard scenarios
- Requirement of huge amount of data for accurate assessment

Multi-hazard risk evaluation of communities ⇨ **System-Level Approach**

Other Code/ Specifications/ Standards



NBC (2016)



New earthquake zone map based on mean horizontal peak ground acceleration (PGA) values expected at the ground surface estimated by probabilistic seismic hazard assessment (PSHA) corresponding to a return period of 2,475 years.

Multi-Hazard Assessment under Independent Hazards

Characteristics of specific region

Independent hazards → Geophysical environment factors

Independent and Mutually Exclusive

 $\cap$  = Φ

Intersection → Null-set

Proper methodology → New design codes and guidelines

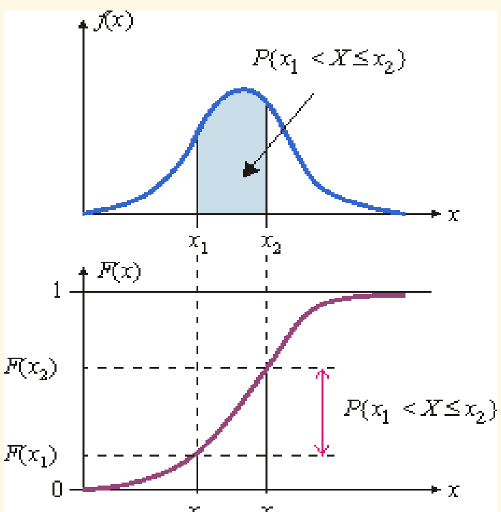
Historical Overview of Multi-Hazard Scenario

Early experimentation in dams, bridges, offshore structures, etc.

The 1995 Oklahoma City bombing - triggered effects of fire after explosion.

Seismic provision under blast ?

New Socio-Political Scenario



Vulnerable for bridge systems due to additional secondary hazards (flood, scour, ageing)

Recent use of **statistical / probabilistic** tools to quantify failure

MULTI-HAZARD RESILIENT COMMUNITY

General Framework for Multi-Hazard Scenario

1. Identify challenges
2. Mitigate challenges

Interaction and inter-relation effects

Personnel involved:
Structural designers, code-writers, builders, developers, policy-makers, key stakeholders, etc.

Structural safety on innovation scale

- Few recent examples of multi-hazard:

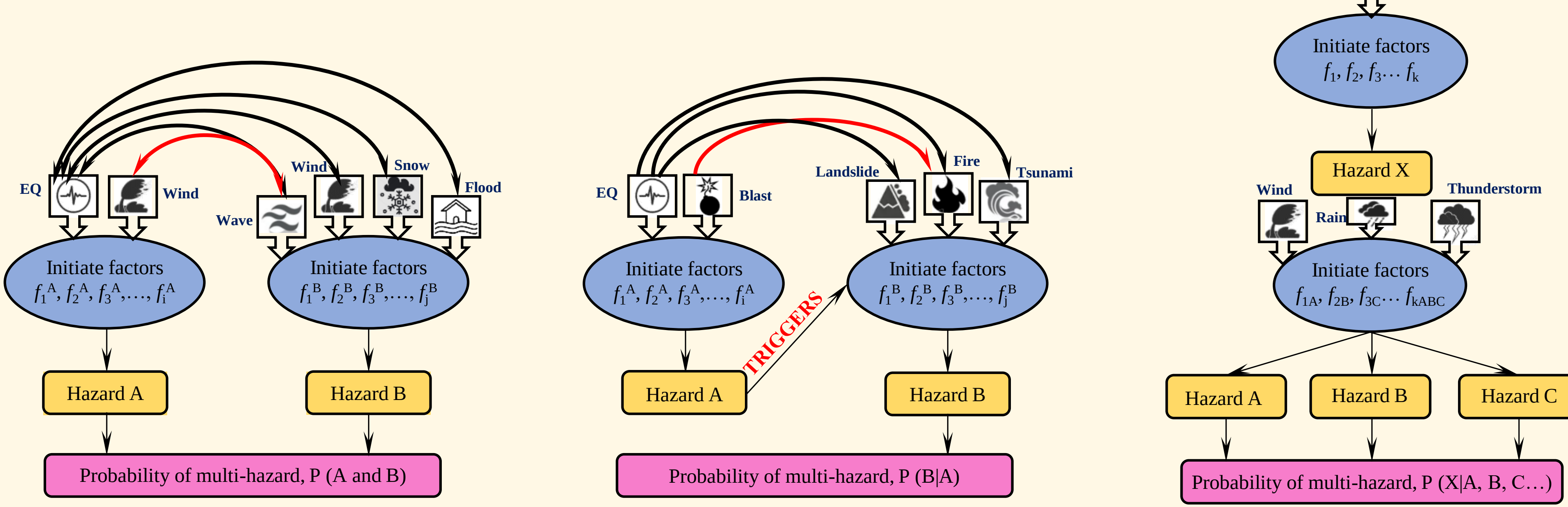
✓ Cyclone and Flood - Myanmar (Bay of Bengal), 2008
✓ Earthquake and Tsunami - Sumatra, 2004 and Japan, 2011
✓ Earthquake and Fire - Sendai, Japan, 2011
✓ Hurricane Sandy and Massive Storm - USA, Caribbean, Canada, 2012
✓ Petrochemical Fire and Explosion - Louisiana, USA, 2013
✓ Thunderstorm, Tornadoes, and Flash Floods - USA, April 7th 2015

HYPOTHESIS

Multi-hazard (risk) analyses are **NOT** just the sum of single hazard (risk) analyses.

Assessment Methodology for Global MHA Scenario

General Classification and Probability of Occurrence for Multi-Hazard Scenarios



Multi-Hazard Analysis (MHA) Scenario and Achieving Multi-Hazard Resilience of Bridge Infrastructure under Extreme Loading

Resilience (R) : capacity to withstand and recover from the effects of a hazard.

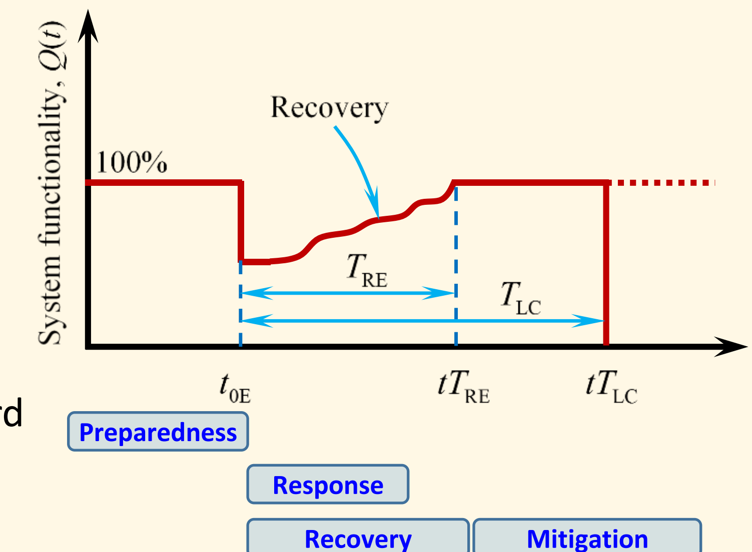
$$R = \int_{t_{0E}}^{tT_{LC}} \frac{Q(t)}{T_{LC}} \mathrm{d}t$$

$Q(t) \rightarrow$ system functionality

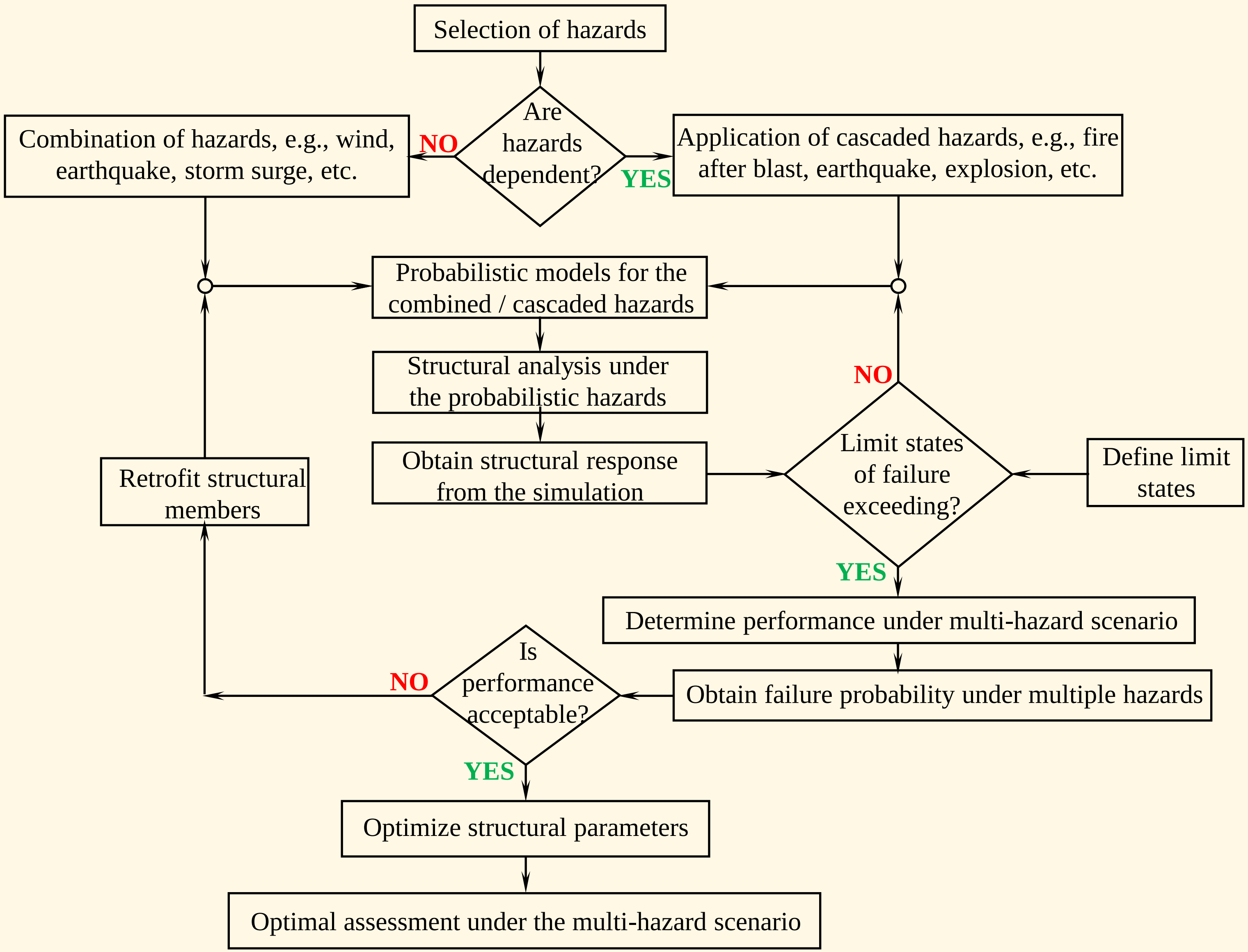
$t_{0E} \rightarrow$ time of occurrence of a hazard

$T_{RE} \rightarrow$ recovery time

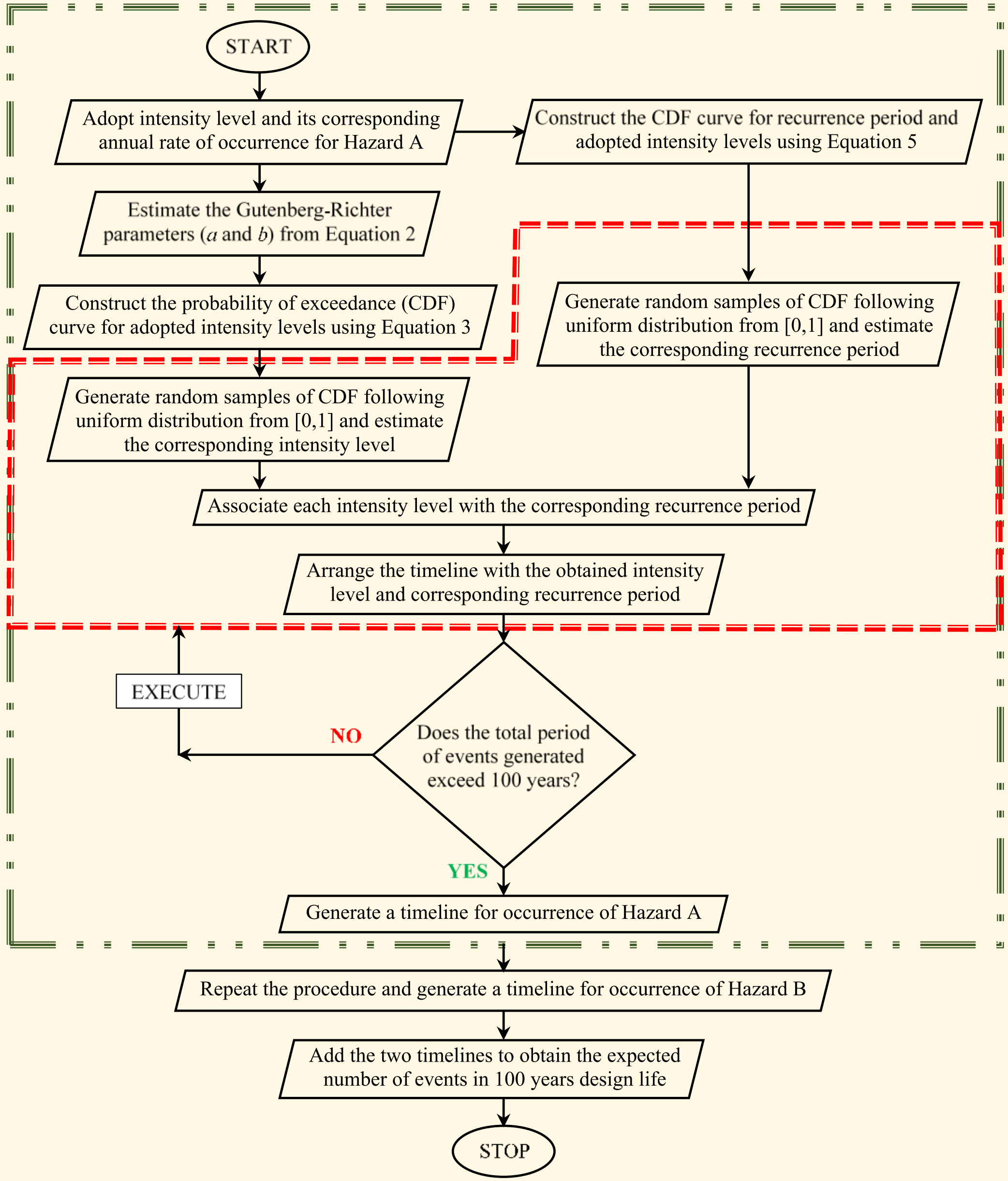
$T_{LC} \rightarrow$ control time



Assessment Methodology - An Example of MHA

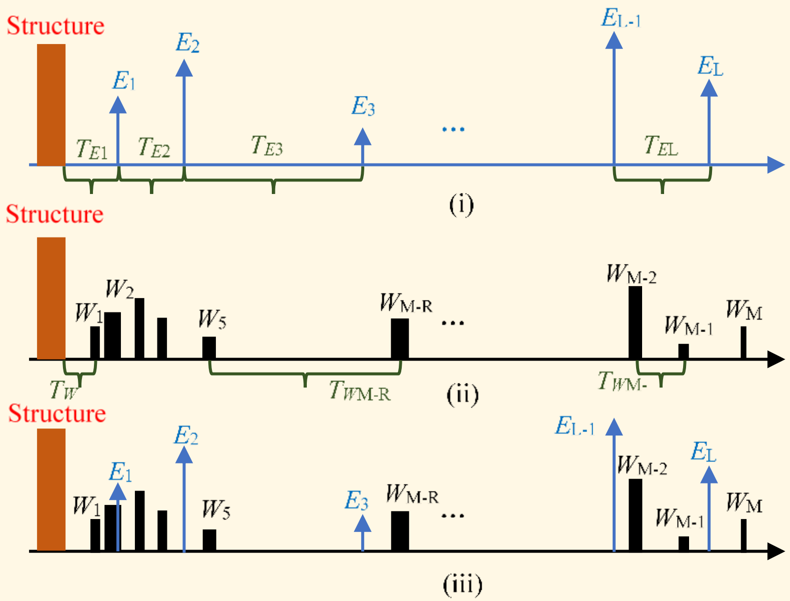


Assessment Methodology - An Example of MHA

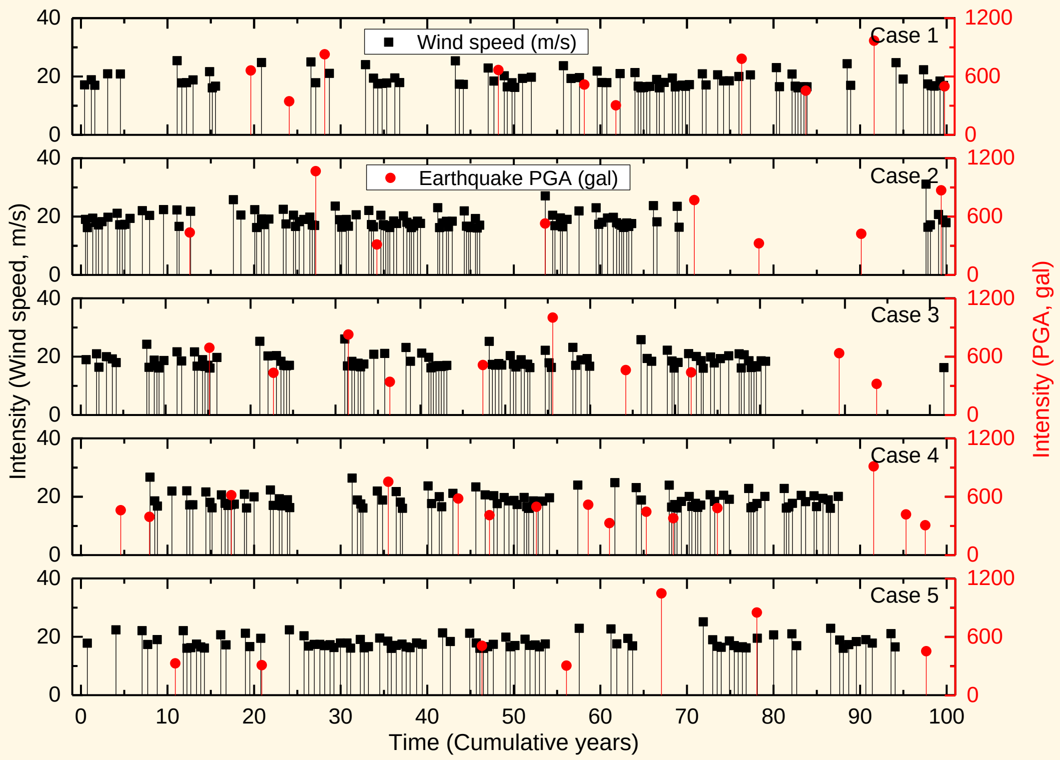


Framework for generating timeline for earthquake and wind during design life of a structure

Assessment Methodology - An Example of MHA



Generating timelines for earthquake and wind during design life of a structure



Timelines of earthquakes and winds generated through the proposed methodology

Life-Cycle Multi-Hazard Assessment

Multi-Hazard Scenario-Based Analysis

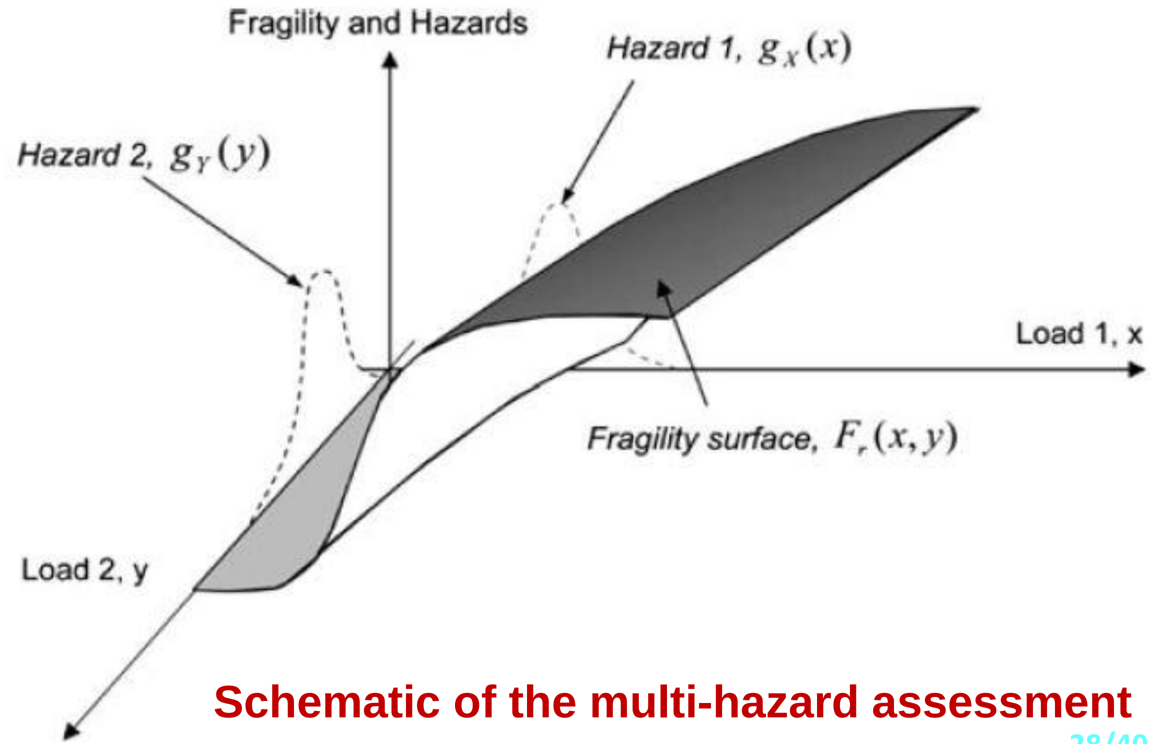
Determination of the study area, identification of the relevant hazards and acquisition of hazard information

Determination of vulnerability indicators and collection of the data

Weighting of factors and vulnerability assessment (including the display of vulnerabilities)

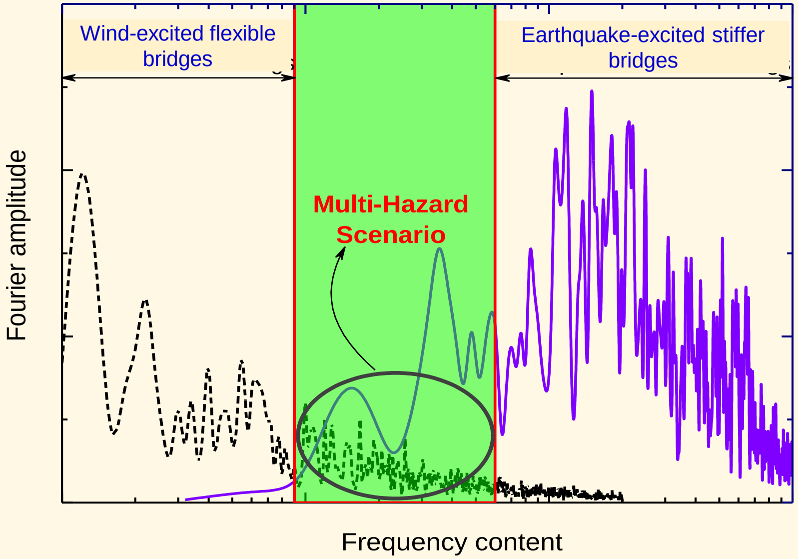
Effect of hazard interactions on the overall vulnerability

Roy, T. and Matsagar V. "**Multi-Hazard Analysis and Design Guidelines: Recommendations for Structure and Infrastructure Systems in the Indian Context**", *Current Science*, Volume 121, Number 1, July 2021.



Schematic of the multi-hazard assessment

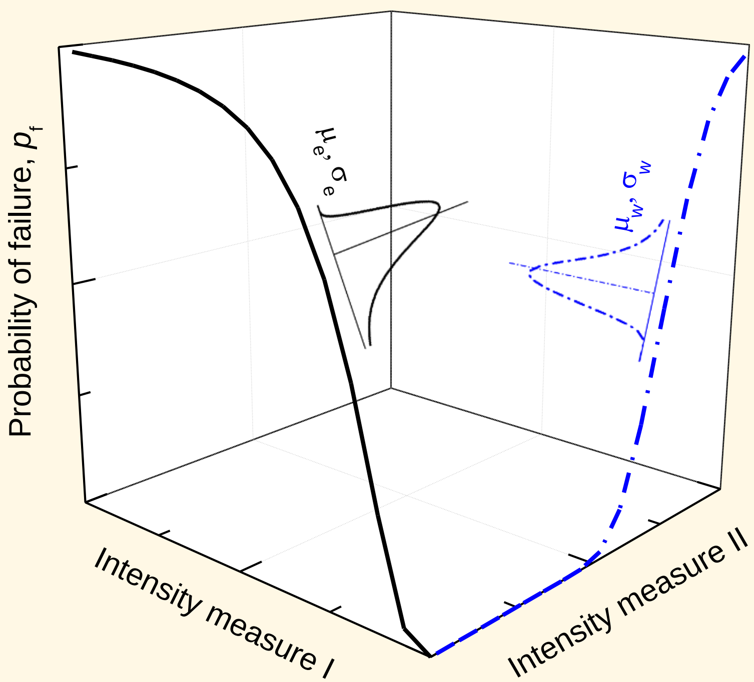
Probabilistic Assessment Methodology - Independent Hazards



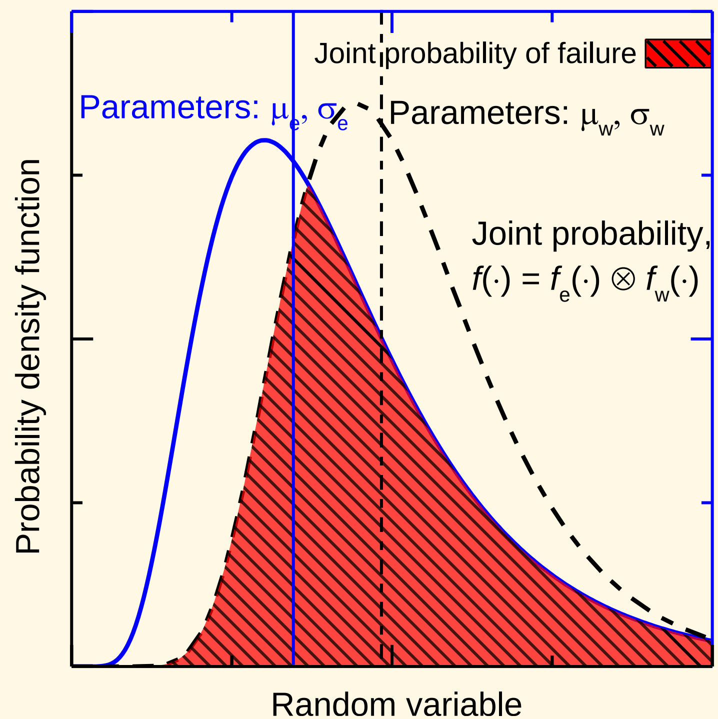
Multi-Hazards: Wind and Earthquake

Comparison of FFT spectrum for typical earthquake and wind scenario:

- Overlapped frequency band showing multi-hazard dominance.
- Structure subjected to excitation within this overlapped band is vulnerable against multiple hazards.
- It becomes important to characterize the modal properties of the structure.



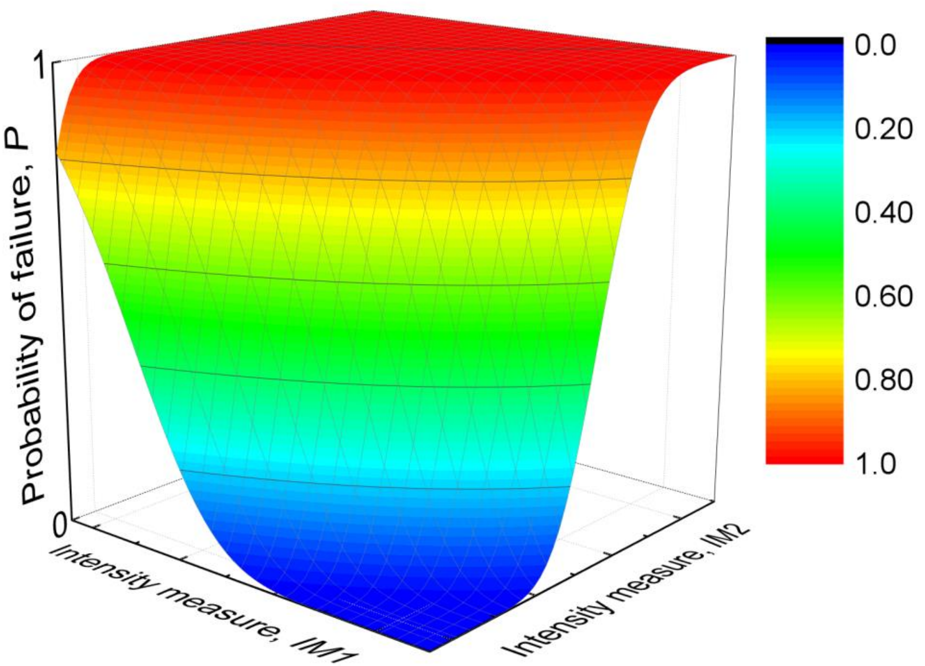
Probability of failure under two hazards



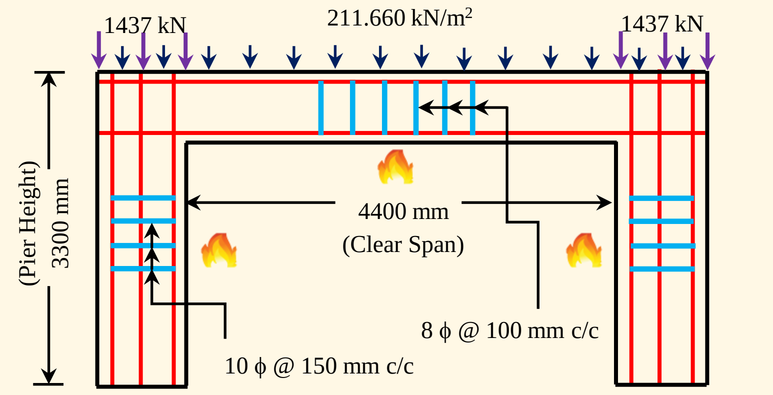
Joint probability of failure

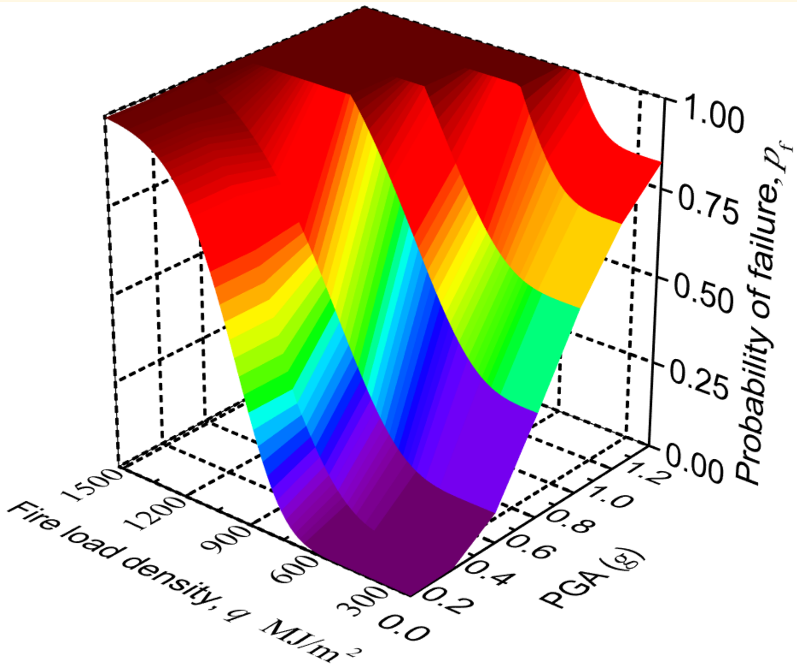
Probabilistic Assessment Methodology - Cascading Hazards

POST-EARTHQUAKE FIRE (PEF) SCENARIO



Fragility surface showing combination of failure for *IM1* and *IM2*





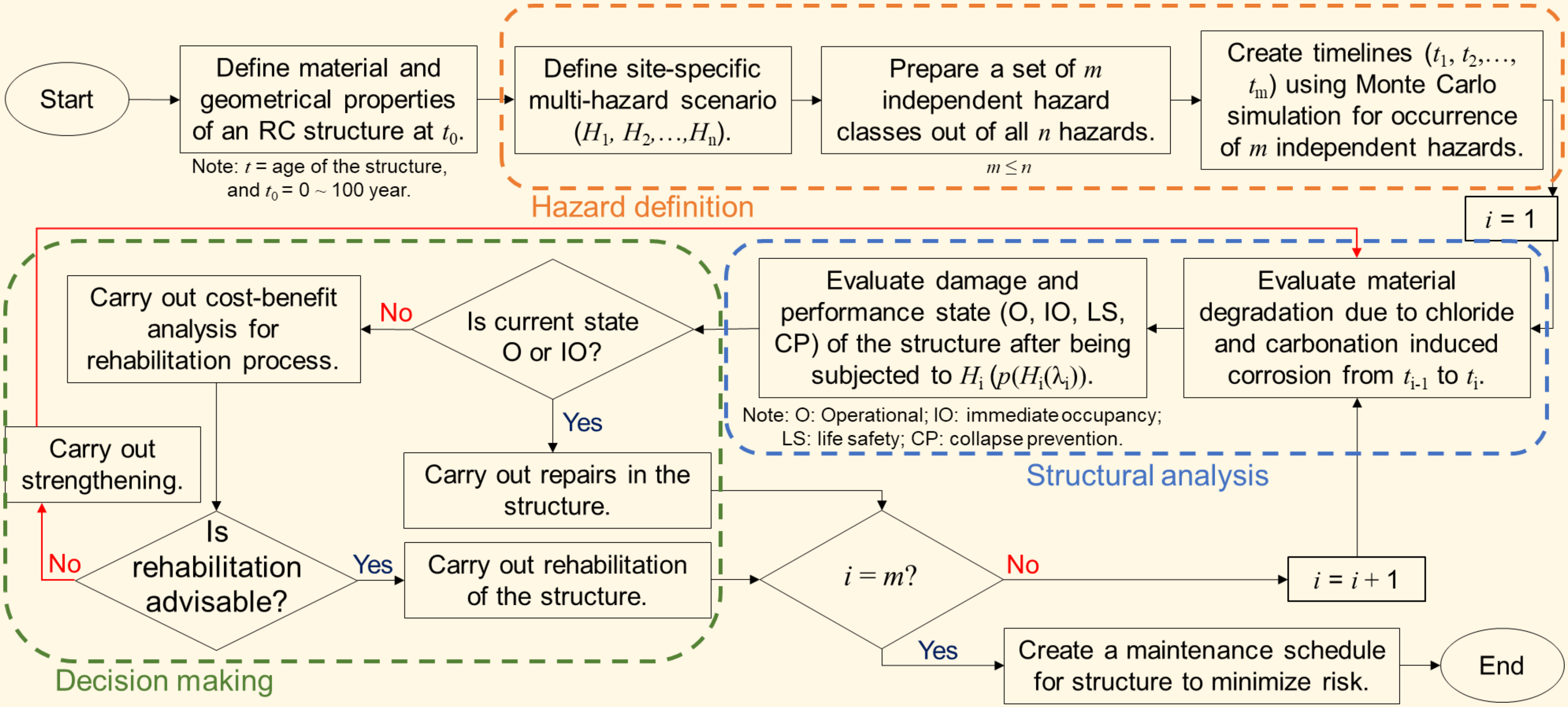
Fragility curve for the RC structure under post-earthquake fire scenario

Bridge Portal Analysis:

Overall, the increase in the response is in the range of 40 % to 60 %, indicating significant reduction of fire resistance rating of the structure due to the cascading effect of PEF.

Assessment Methodology - An Example of MHA

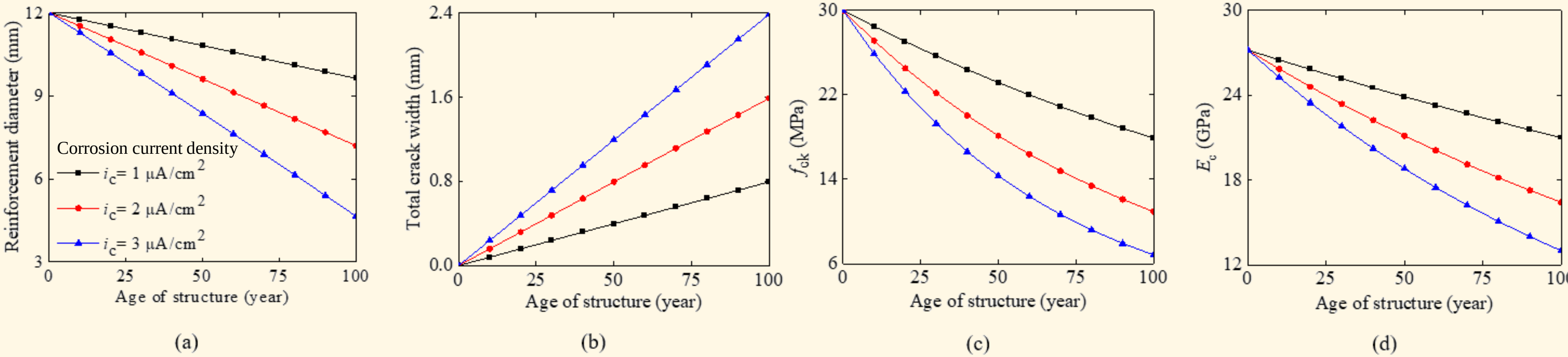
EARTHQUAKE AND FIRE SCENARIO

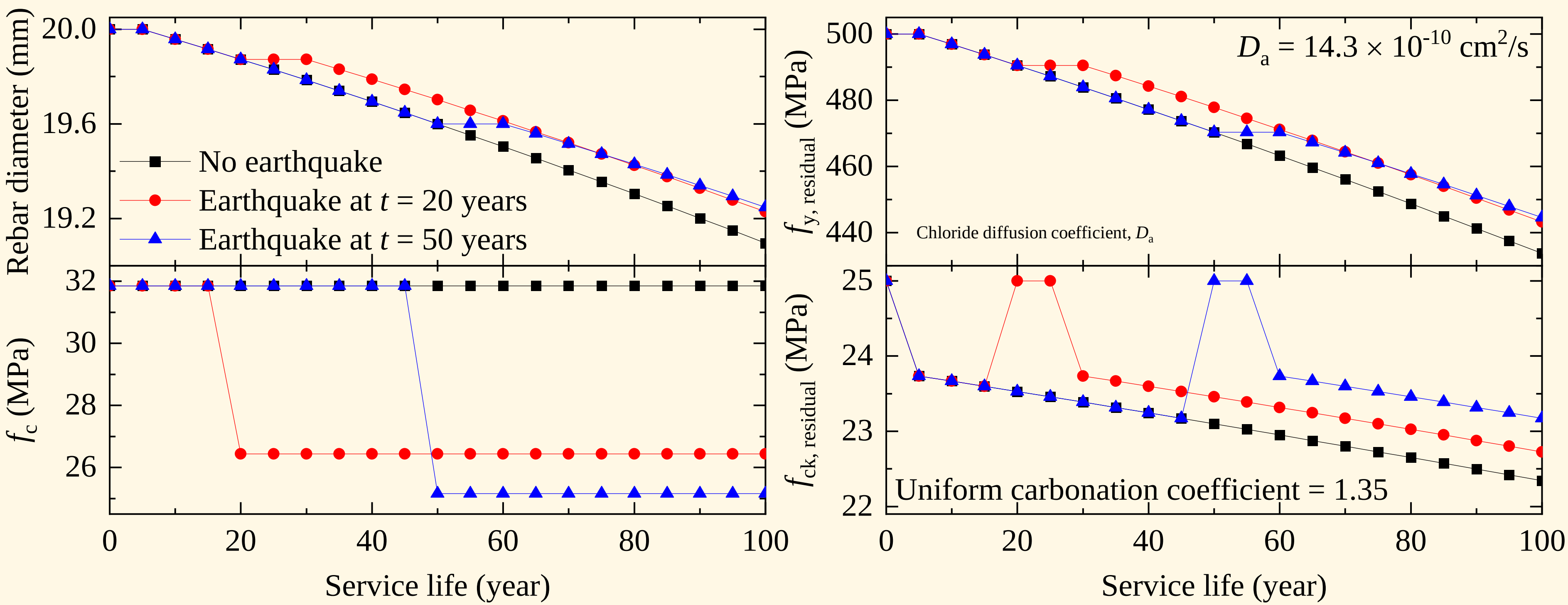


Framework for assessment of the RC structures under INDEPENDENT site-specific earthquake and fire scenarios (i.e., uncorrelated events)

Pratik Bhaskar, Akshay Baheti, and Vasant Matsagar*, "**Service-Life Damage Assessment of a Reinforced Concrete Structure under Multi-Hazard Seismic and Wind Actions**", *Transactions of the Indian National Academy of Engineering*, *Springer*, Volume 7, No. 3, pp. 1017-1031, 2022, https://doi.org/10.1007/s41403-022-00344-0

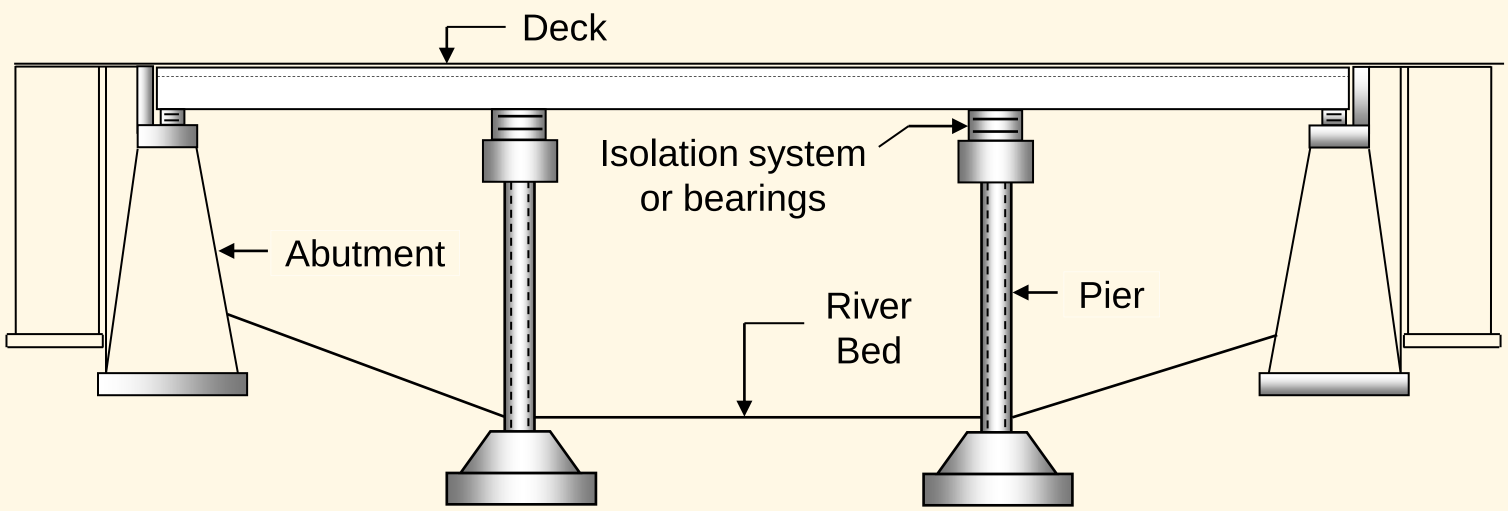
Assessment Methodology - An Example of MHA



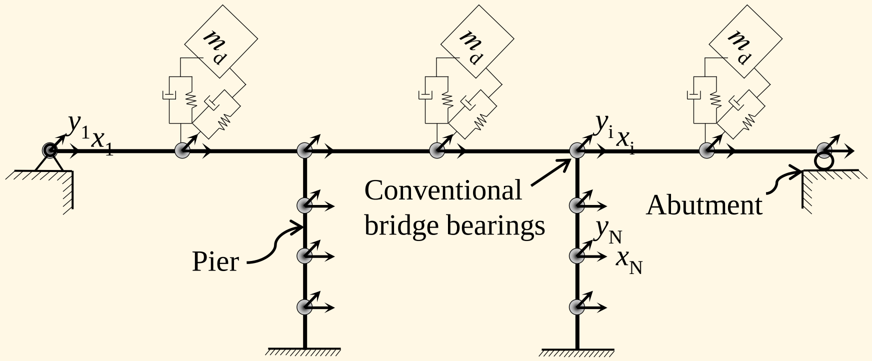


Continuous structural deterioration due to (1) carbonation and (2) chloride-induced corrosion in damaged reinforced concrete (RC) structure

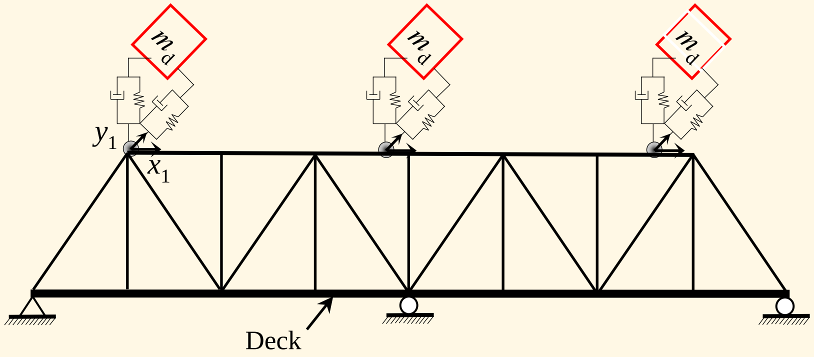
Dynamic Response Control under MH-Scenarios in Bridges



Bridge Deck (Base) Isolation using Bearing (Seismic + Thermal + Wind)

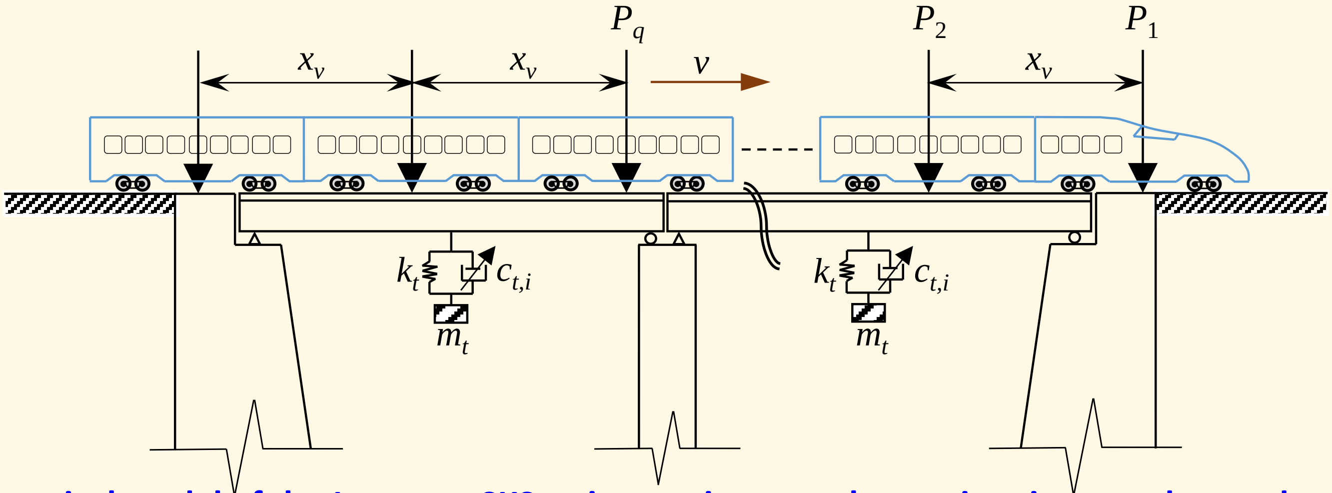


Concrete Bridge with d-MTMDs
(Seismic + Wind)

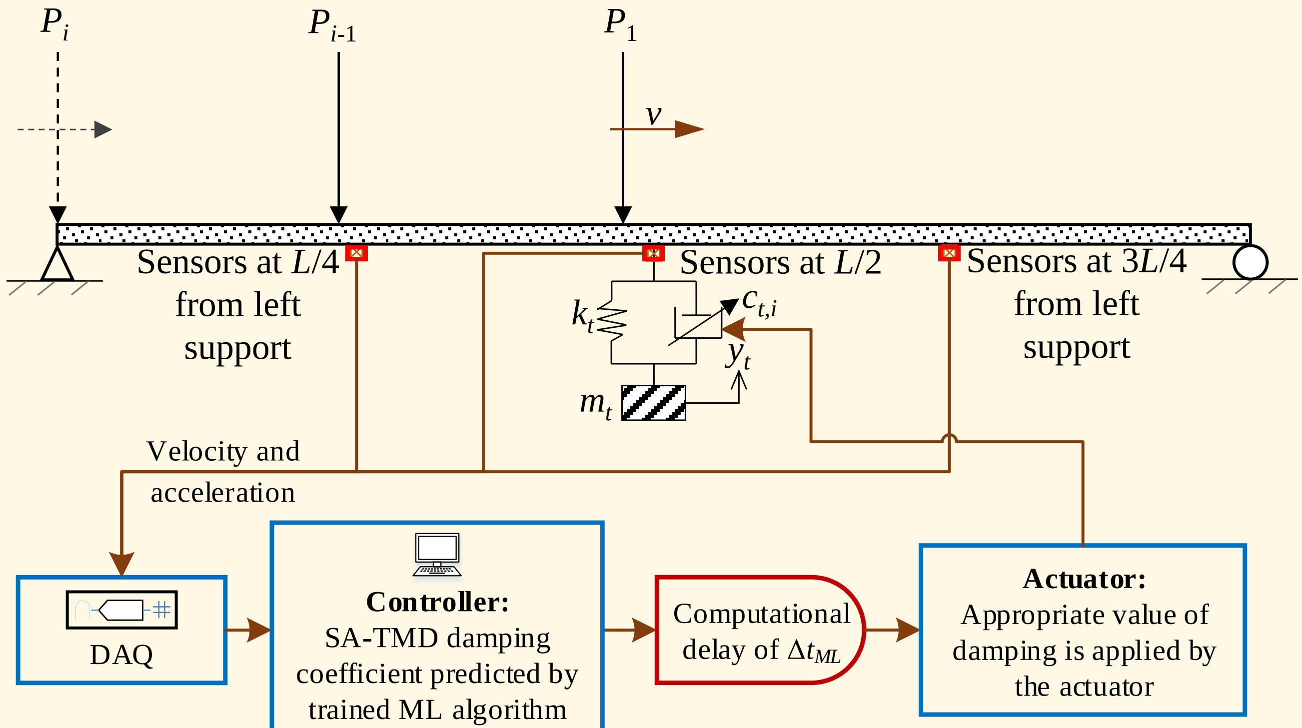


Steel Bridge with d-MTMDs
(Seismic + Wind)

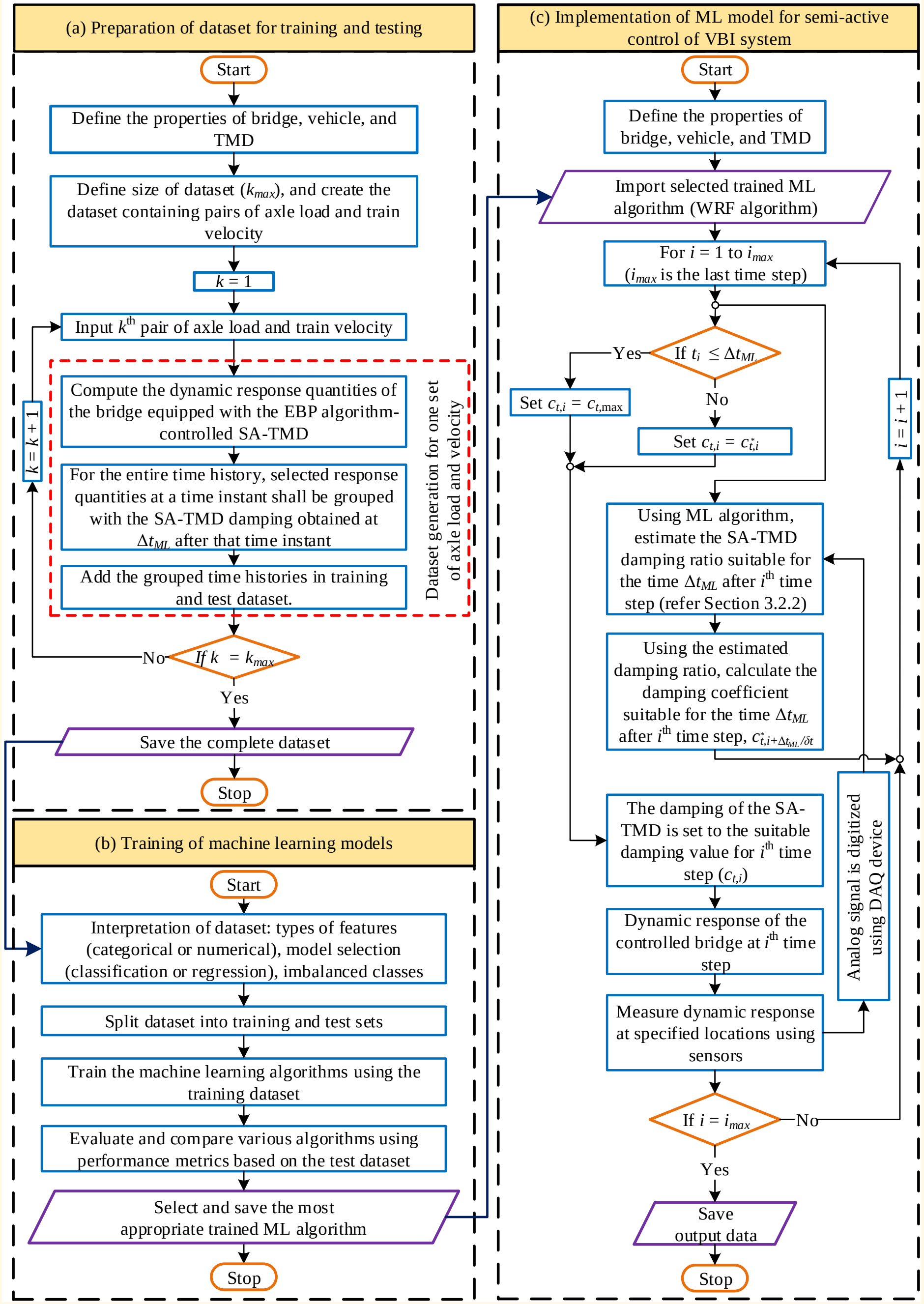
Dynamic Response Control under MH-Scenarios in Bridges

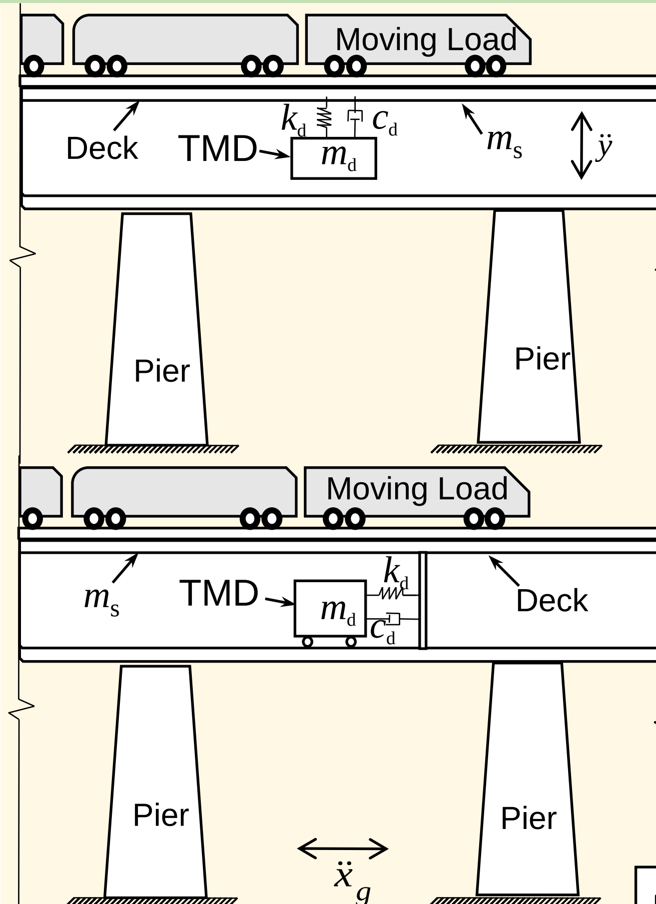


Idealized mathematical model of the Japanese SKS train crossing over the semi-active tuned mass damper (SA-TMD)-controlled THSR bridge

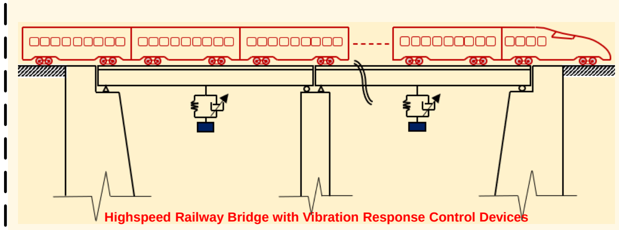


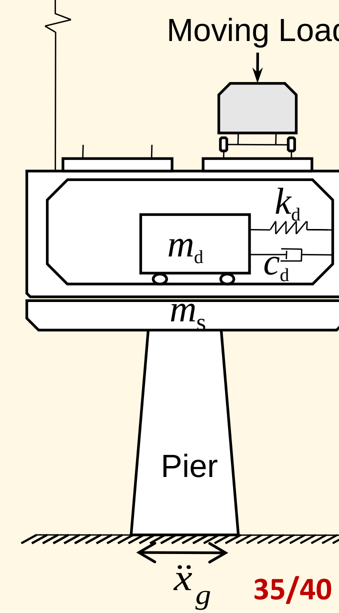
Dynamic Response Control under MH-Scenarios in Bridges





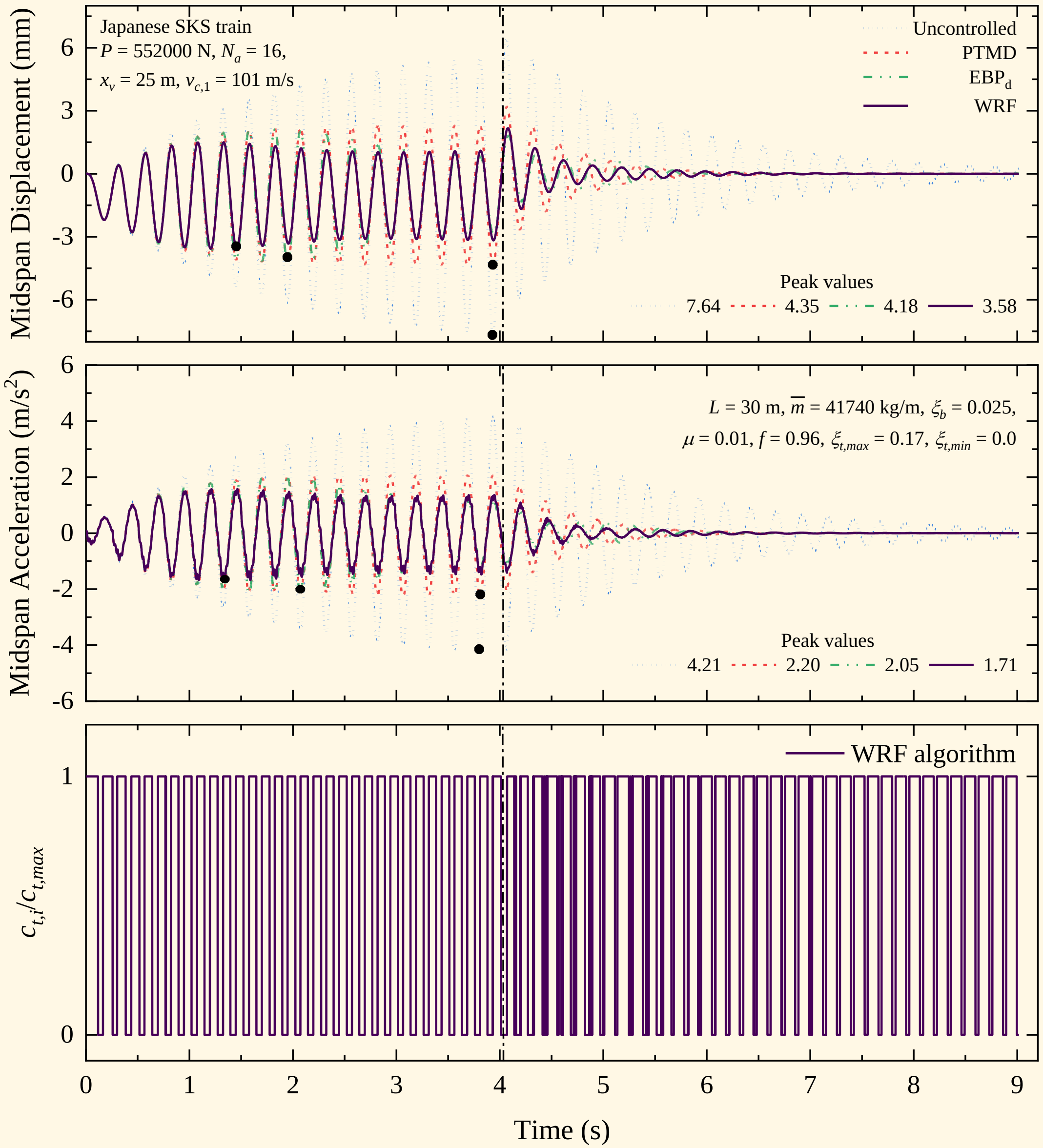
One Horizontal Component

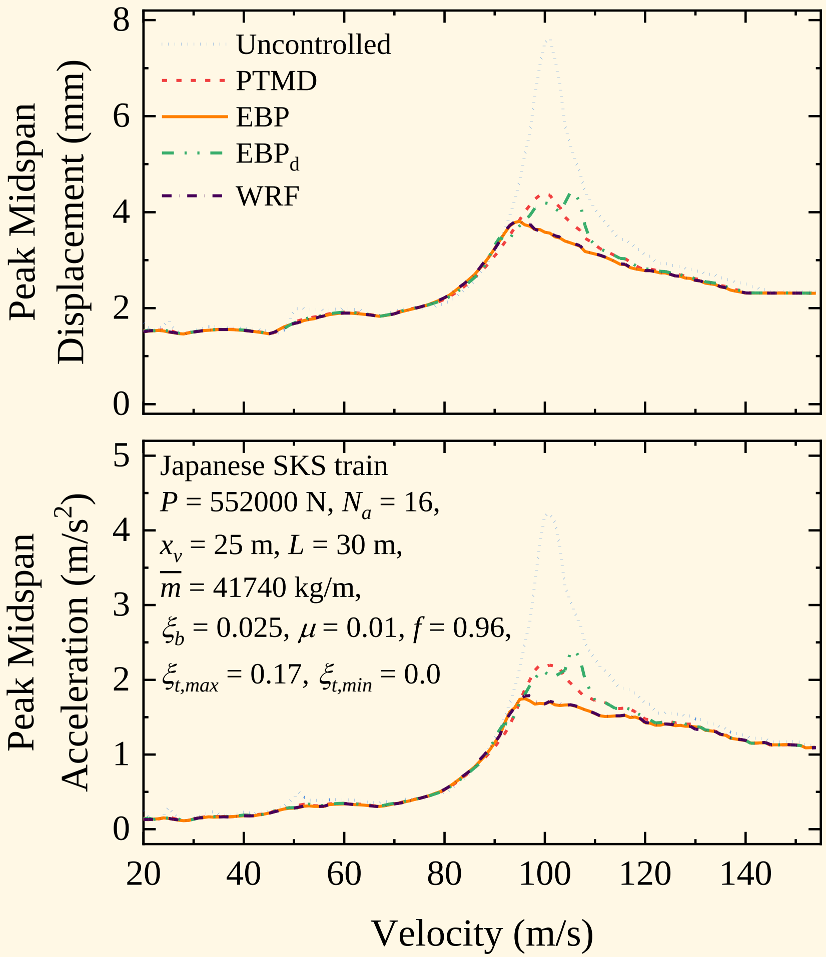




Second Horizontal Component

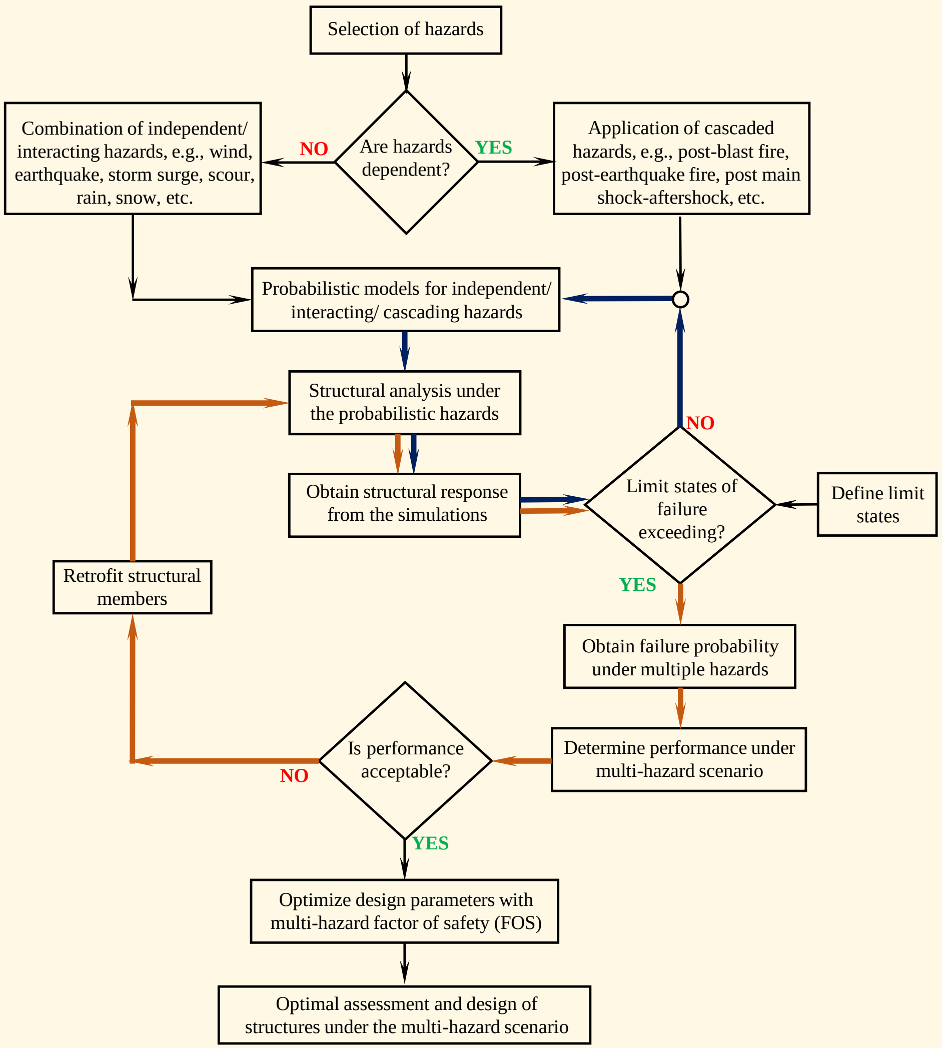
Dynamic Response Control under MH-Scenarios in Bridges



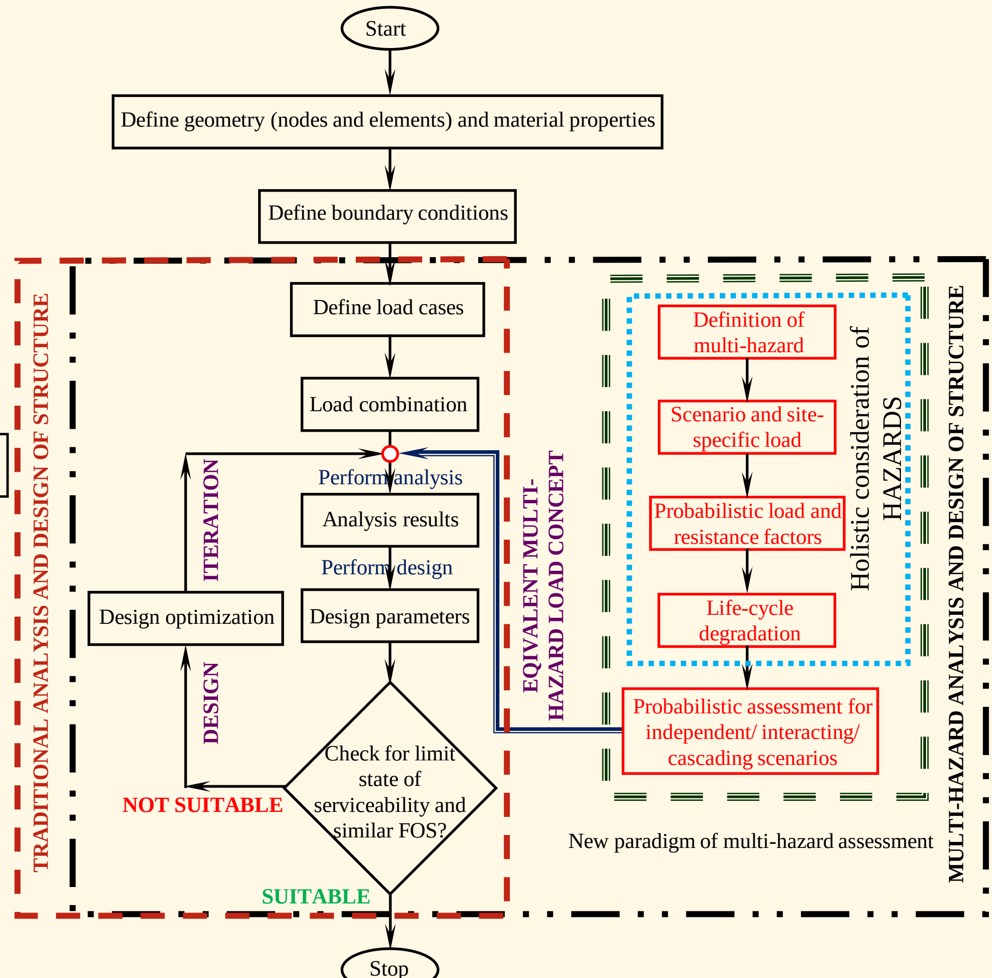


Bridge with no-control (uncontrolled), PTMD, EBPd, and WRF algorithm-controlled SA-TMD – the smart device → optimization of the design parameters for multi-hazard risk reduction !

Assessment Methodology - An Example of MHA



Technical framework for optimal assessment of the structures under multiple hazard scenarios in entirety



Proposed generalized multi-hazard analysis and design technique for structures and infrastructure systems

Other Code/Specifications/Standards

NBC (2016)

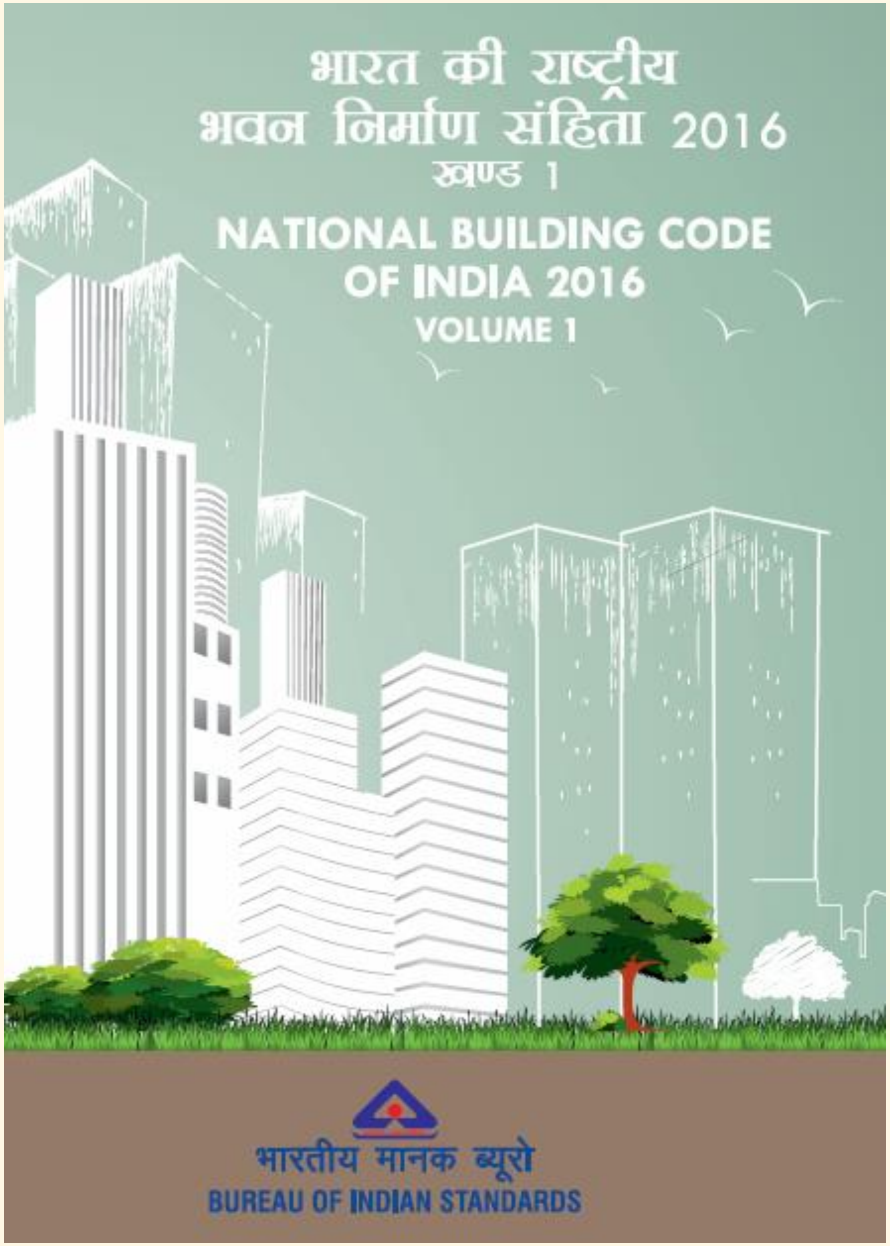
1. Member of National Building Code (NBC) committee for standardisation in the area of building construction norms in India by the Bureau of Indian Standards (BIS) →

Condition of acting all extreme loading together in terms of 'Multi-Hazard Risk Concept' and 'Multi-Hazard Prone Area', in Sections 9.1 and 9.2, respectively.

According to NBC, the commonly encountered hazards are:

1. Earthquake,
2. Cyclone,
3. Windstorm,
4. Floods,
5. Landslides,
6. Liquefaction of soils,
7. Extreme winds,
8. Cloud bursts, and
9. Failure of slopes.

1. **Multi-Hazard Analysis and Design of Structures.**
2. **Prescriptive Approach.**



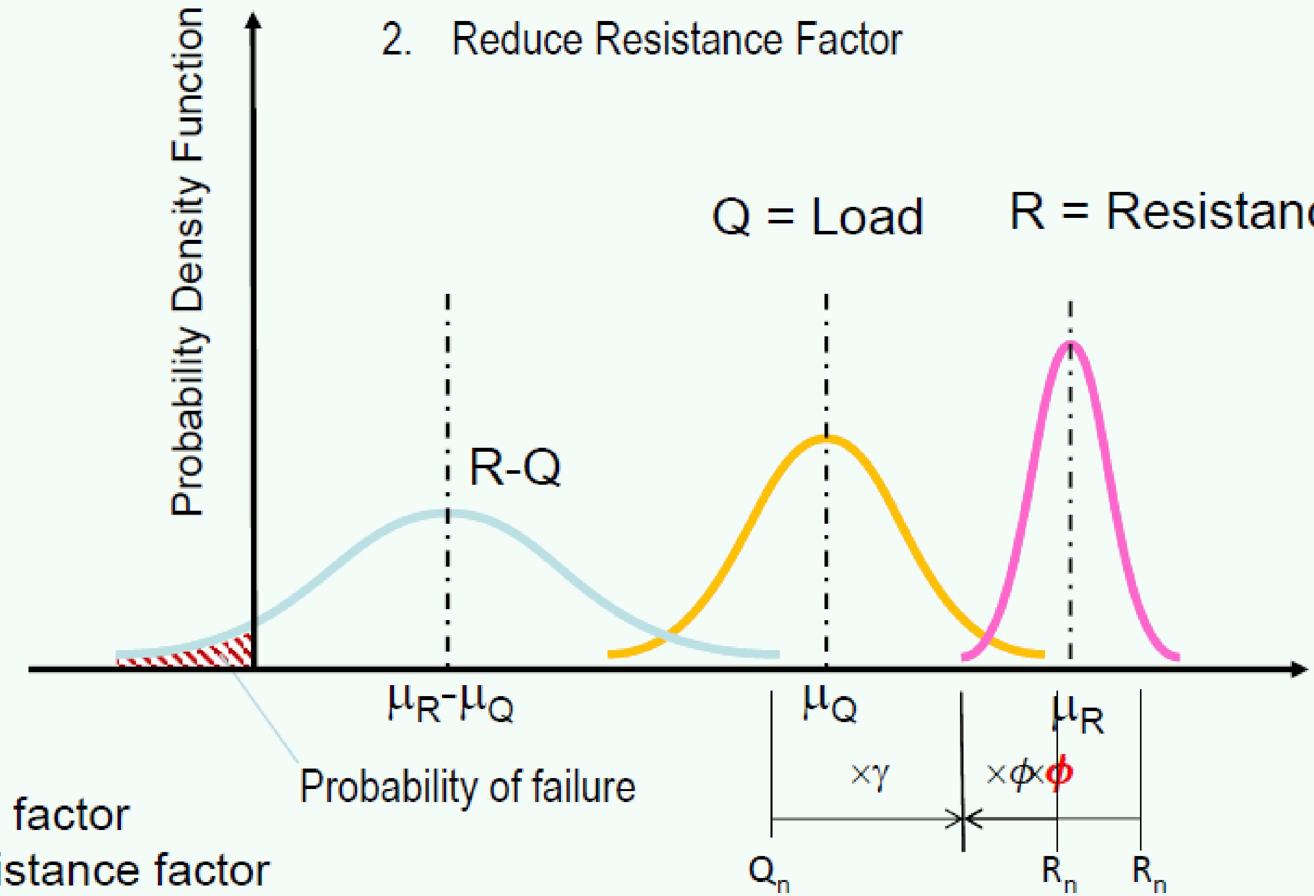
Experience from the USA

AASHTO LRFD Design Limit State Equations

$\phi R_n = \gamma Q_n$

To increase bridge reliability, i.e., reduce probability of failure

1. Increase Load Factor
2. Reduce Resistance Factor



γ: Load factor

ϕ: Resistance factor

Future Vision and Outlook

Evolution of Traditional Structural Design Philosophies

1. **Working stress method (WSM)**
2. **Ultimate load method (ULM)**
3. **Limit state method (LSM)**

Current State-of-the-Art in Structural Design

1. **Performance-based engineering (PBE)**
2. **Risk-based structural design**

Upcoming Trends in Structural Design Philosophies

1. **Multi-hazard risk-based structural design**
2. **Service-life risk-based structural design**

<u>Codes/ Standards</u> → <u>Course of Action</u>

- Limit State Design of Structures.
- Performance-Based Design of Structures.
- Prescriptive Approach → **Multi-Hazard Protection of Structures**.

Roy, T., and Matsagar, V.A.*, "**Multi-Hazard Analysis and Design of Structures: Status and Research Trends**", *Structure and Infrastructure Engineering, Taylor & Francis* , Volume 19, Number 6, 2023.

Concluding Remarks

Conventional Structural Analysis and Design

Load scenario
- Gravity load
- Equivalent seismic/ wind/ blast load
- Combinations

(Worst load combination)

INITIAL → FOS

Structural design
- Buildings
- Bridges
- Critical infrastructures, etc.

Structural Design
- Buildings
- Bridges, etc.

Site-Specific
- Region
- Zone
- Climate, etc.

Scenario-Based
- Probability
- Interaction

Conventional Approach
- Loads
- Combinations

Multi-Hazard Approach:
Analysis & Design

Multi-Hazard Structural Analysis and Design

New Sustainable Construction Materials

LOAD SCENARIO

Gravity load

Site-specific consideration
- Region, Zone, Climate, Environment, etc.

Scenario-based consideration
- Probability, Uncertainty
- Hazard interaction

MULTI-HAZARD → FOS

Structural design
- Buildings
- Bridges
- Critical infrastructures, etc.

Augmentation of multi-hazard analysis and design in the conventional design approach for structure and infrastructure systems

Acknowledgements

Thank You

Discussion