Infrastructure resilience and structural integrity in construction

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Infrastructure Resilience and Structural Integrity in Construction

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National Research Council Canada

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Canada

Built Environment

- Human-made places and spaces to support quality of life
  - Houses, buildings , parks
  - Infrastructures: roads, bridges, railways, dams, water systems, energy networks
  - Provide core services: shelter, transportation, water, energy
  - Critical to economy and quality of life of communities and cities

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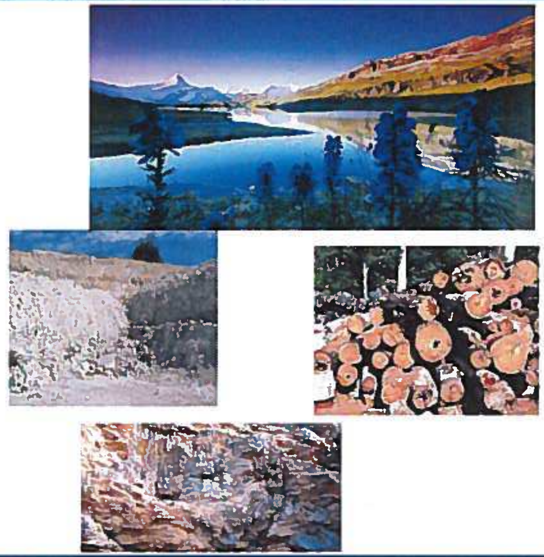
Natural Environment

- Encompasses all living and non-living things on earth
- Components
  - Ecological units: atmosphere, rocks, vegetation, wood, micro-organisms
  - Natural resources: air, water, soil , iron, wood, coal, limestone, oil, gas…



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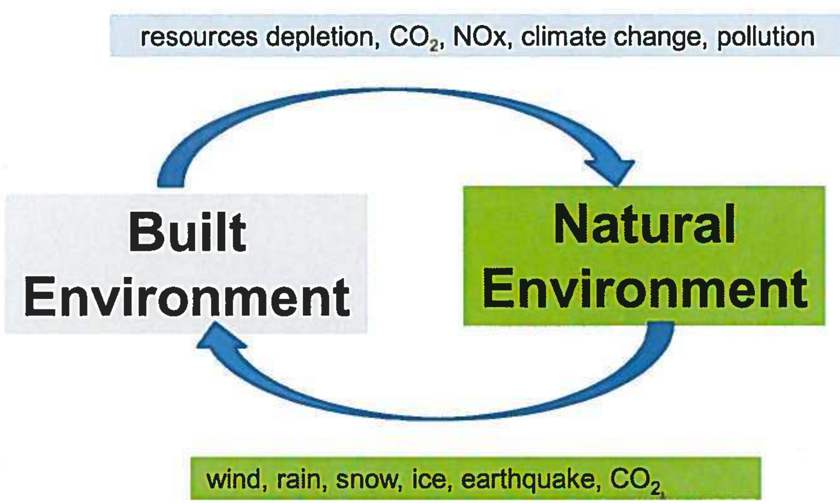
Interactions between Built Environment & Natural Environment



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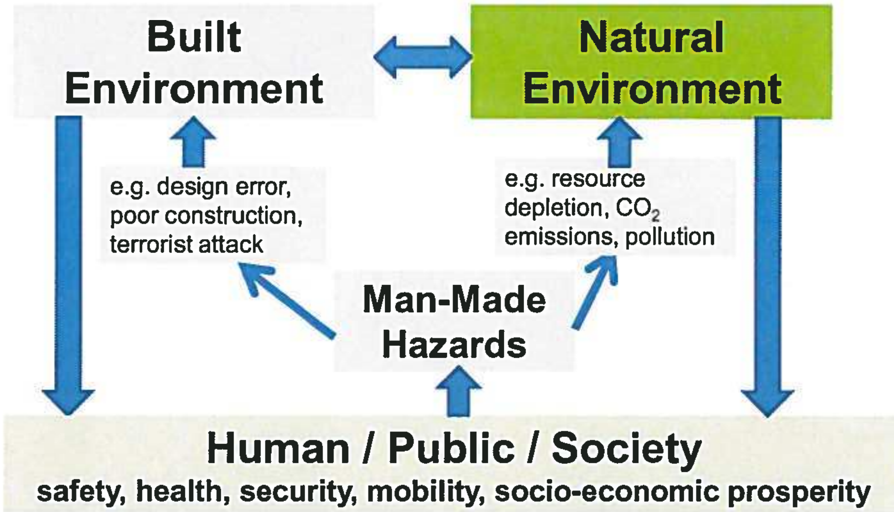
Interactions between Human with Built Environment & Natural Environment



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Impacts of cumulative damage / perturbations

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Challenges

- Growing concerns for extreme natural & man-made hazards in many countries
- Extreme/abnormal loads with low likelihood of occurrence and high consequences of failure
  - Weather extremes
  - Terrorist attacks
  - Accidental events
- Limited available funds for protection of BE

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Impacts of extreme shocks

Challenges

- Current design codes/standards/asset management systems
  - Performance-based design for safety and serviceability
  - Prescriptive rules for durability
  - Brittle materials and systems – vulnerable to small, unforeseen perturbations
  - Limited modeling of the interactions between built and natural environments

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Challenges

- Current design codes/standards/asset management systems
  - Prescriptive rules for inspection and maintenance
  - Qualitative condition assessment measures
  - Inadequate life cycle performance forecast models
  - Limited consideration for sustainability and resilience

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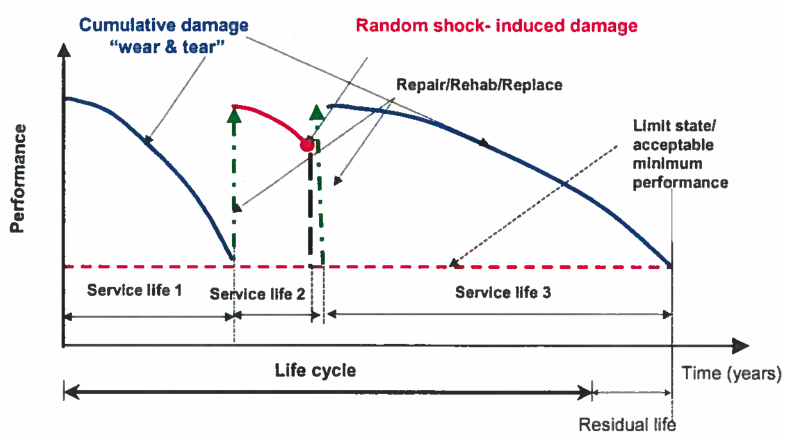
Life Cycle Performance of Built Environment



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Definitions of Failure

- **Loss of structural integrity**

Failure is the inability of a structural system or one of its primary load-carrying components to no longer perform its intended function.

- **Loss of functionality/ level of service**

Failure is the inability of a built environment to provide the level of functionality or service it was designed for.

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Challenges

- Considerable uncertainty in loads, material properties, environment, consequences with high noise-to-signal ratios
- Model uncertainty associated with BE performance
  - Considerable variability from mean values of key parameters
  - Uncertainty of physical models

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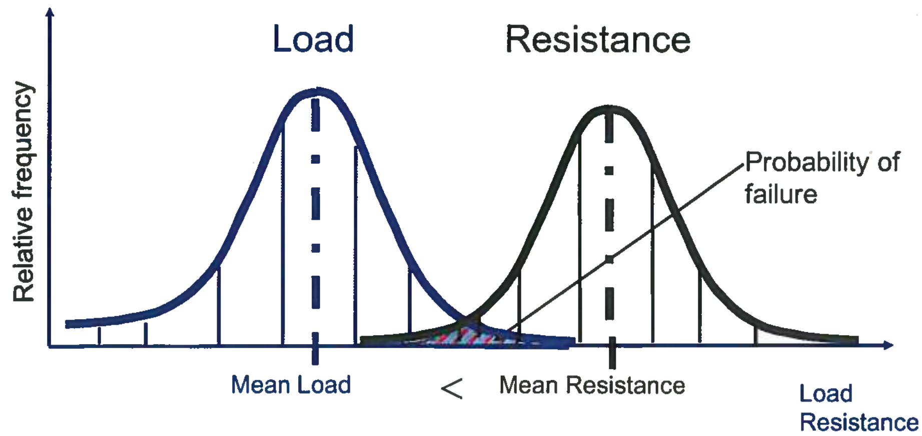
Modeling Uncertainty



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Challenges

- Need appropriate stochastic models to predict life cycle performance of concrete infrastructure
- Need to develop risk-based decision-making approaches for
  - Design
  - Inspection
  - Rehabilitation
  - Monitoring
  - Protection/hardening

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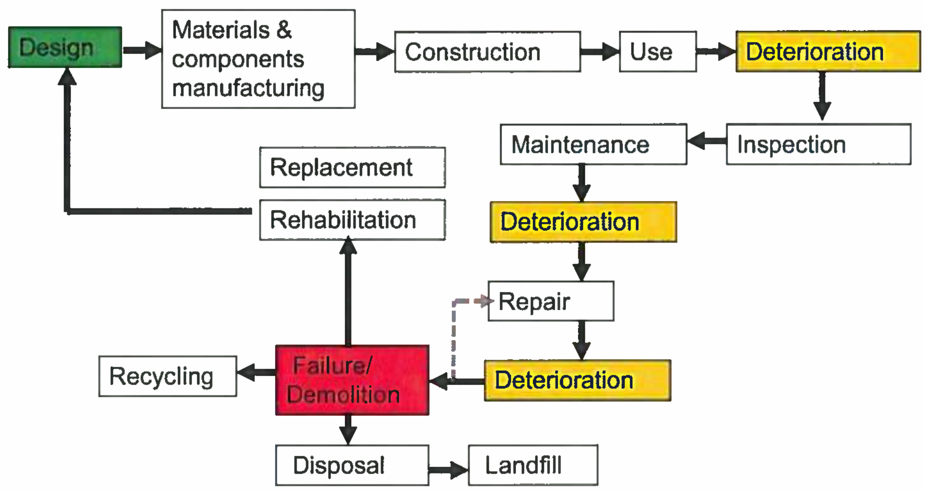
Life Cycle of Built Environment



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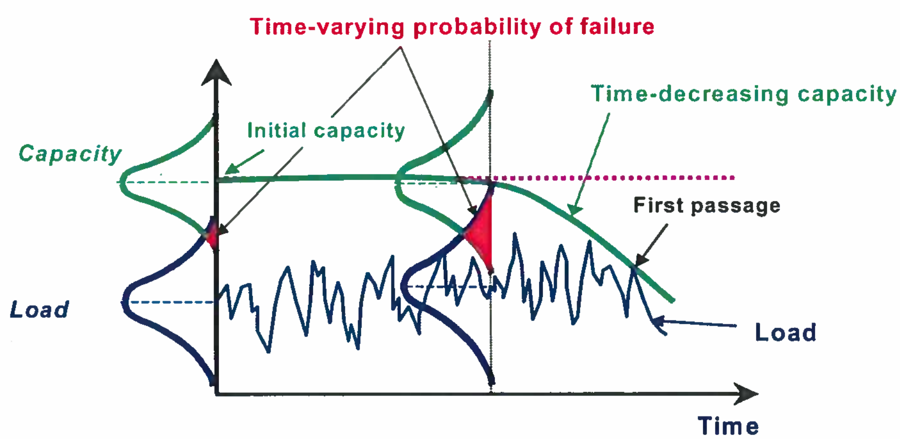
Time-Varying Probability of Failure



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Towards a Resilient Built Environment

Enhance resilience of existing and new built through effective design, rehabilitation, protection and management to ensure:

- Structural integrity
  - Acceptable levels of structural safety
  - Acceptable levels of serviceability
- Acceptable levels of service/ functionality
- Long service life
- Minimum life cycle costs

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Resilience: Concepts & Definitions

- Ability of a system, community or society exposed to hazards to **resist, absorb, accommodate to and recover** from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.
- Resilience means the ability to "resile from" or "spring back from" a shock.
- Ability to withstand extreme events and human error, without being damaged to an extent disproportionate to the original cause' (ISO 2390:1998)
- Resilience is the essence of sustainability : ability to resist disorder (Fiksel 2003)

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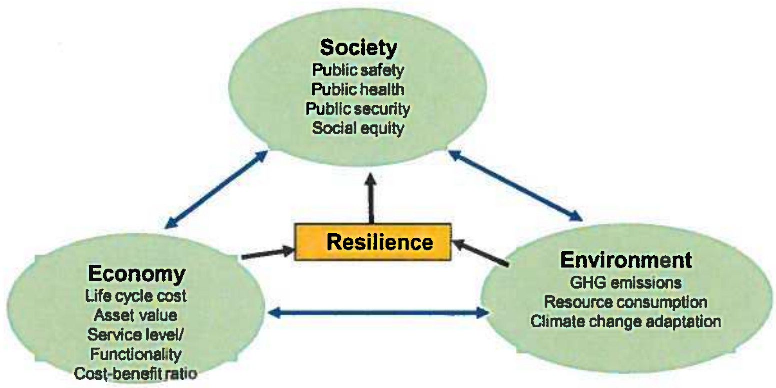
Resilient and Sustainable Built Environment



(Model Framework NRTSI/NRC 2009)
http://www.nrtsi.ca/documents/Framework.E.pdf

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Risk-based Decision-Making for Resilient Infrastructure

- Risk of failure = $P_f \times C_f$
- Probability of failure
  - Natural & man-made hazards: H_i, n_H
  - Damage D_j, n_D
  - Structural behaviour S_k, n_S

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Consequences of Failure

- Social impacts
  - fatalities, injuries, illnesses
- Economic impacts
  - maintenance, rehab/replacement costs
  - liability costs
  - loss of functionality /disruption of services
  - recovery time
- Environmental impacts
  - CO_2 emissions
  - Contamination of water/ soil
  - waste materials

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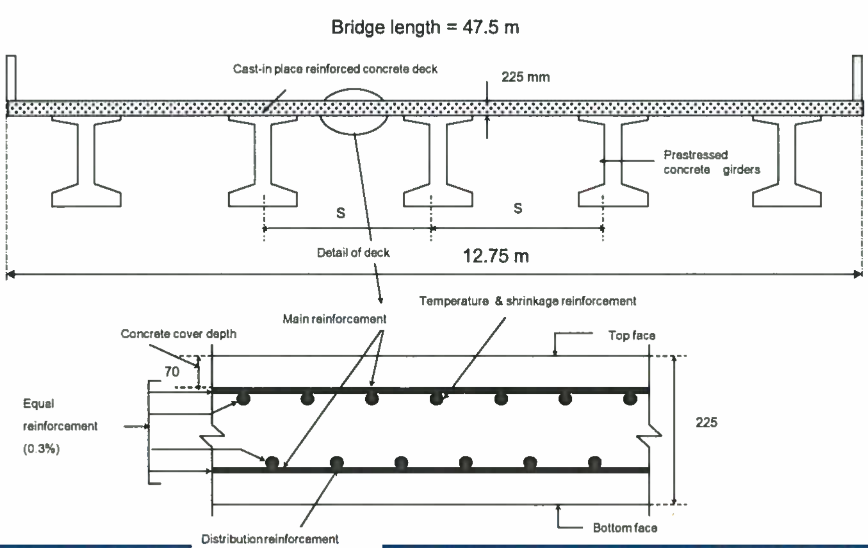
Case Study 1: Design of Resilient Highway Bridge Deck



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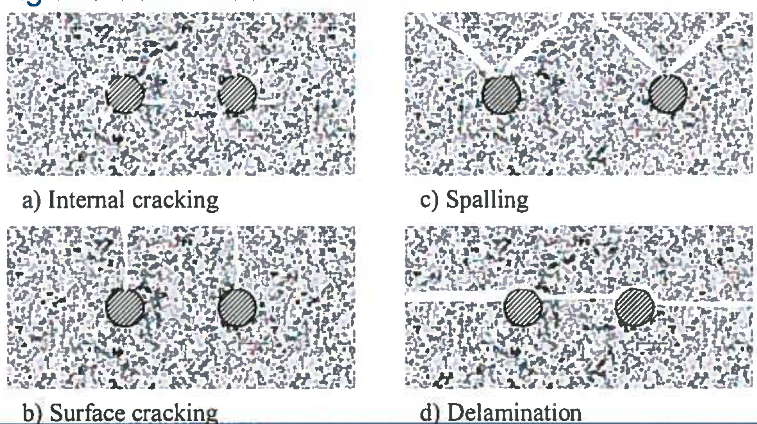
Failure Modes

- Corrosion of reinforcing steel
- Internal cracking
- Spalling and delamination of deck



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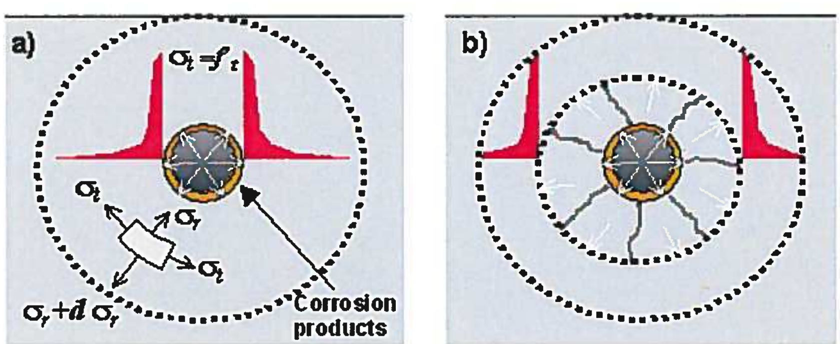
Failure Mode: Concrete Deck Spalling



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Case Study 1: Highway Bridge Deck Subjected to Corrosion

Initial Resilience enhancement strategies:

- Use high performance concrete
- Use corrosion-resistant steel
- Increase concrete cover depth
- Patch repairs of damaged deck
- Rehabilitation of chloride-contaminated concrete cover
- Replacement of deck

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Case Study 1: Highway Bridge Deck Subjected to Corrosion

•Focus on 2 resilience enhancement strategies:

i. Rehabilitation and replacement with conventional normal performance concrete (NPC) deck reinforced with carbon steel

ii. Replacement with high performance concrete (HPC) deck reinforced with carbon steel

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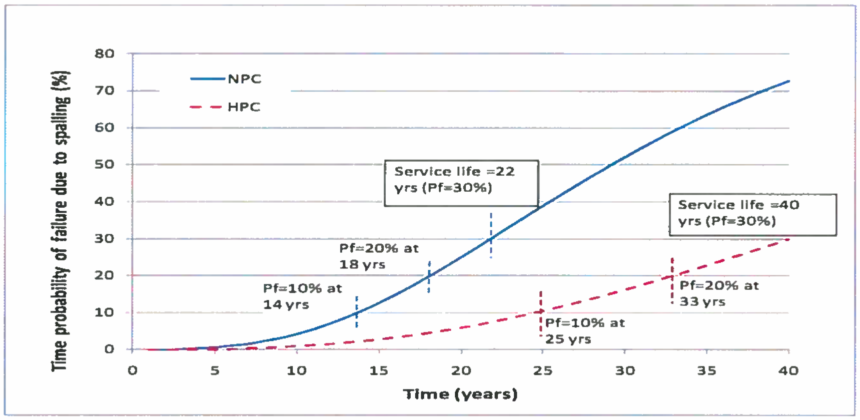
Time-Varying Probability of Failure



Expected ServiceL ife

- Maximum probability of failure (30% spalling)
  - After 22 years for conventional concrete bridge deck (NPC)
  - After 40 years for high performance concrete bridge deck (HPC)

Travel Delay Costs

Travel Delay Costs

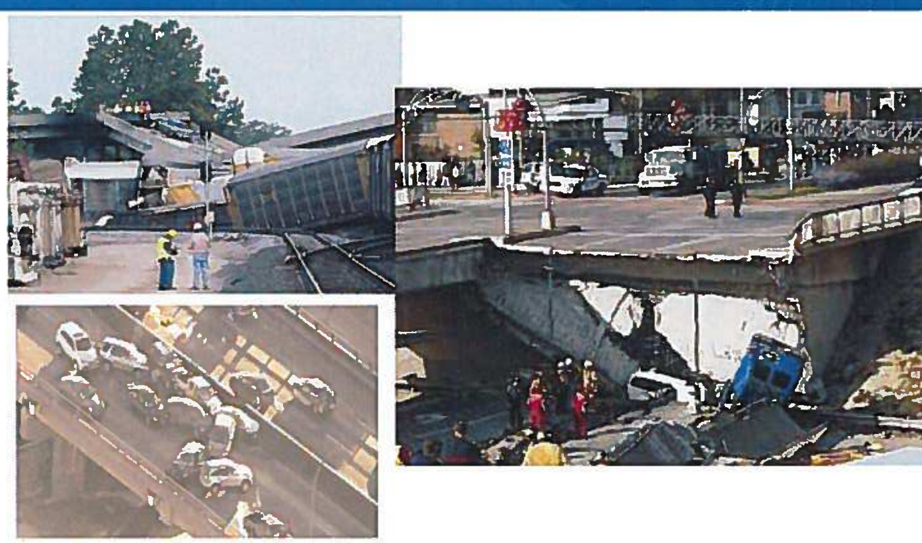
Maximum speed:100km/h

Actual average speed: 20km/h

Travel Delay Costs

- Length of highway affected by activity
- Traffic speed during activity
- Normal traffic speed
- Durations of maintenance, rehabilitation, and replacement activities
- Annual average daily traffic (AADT)
- Annual average daily truck traffic (AADTT)
- Average values of automobile and truck drivers time
  - $12/hr for automobile drivers
  - $20/hr for truck drivers

Traffic Accidents due to Failure



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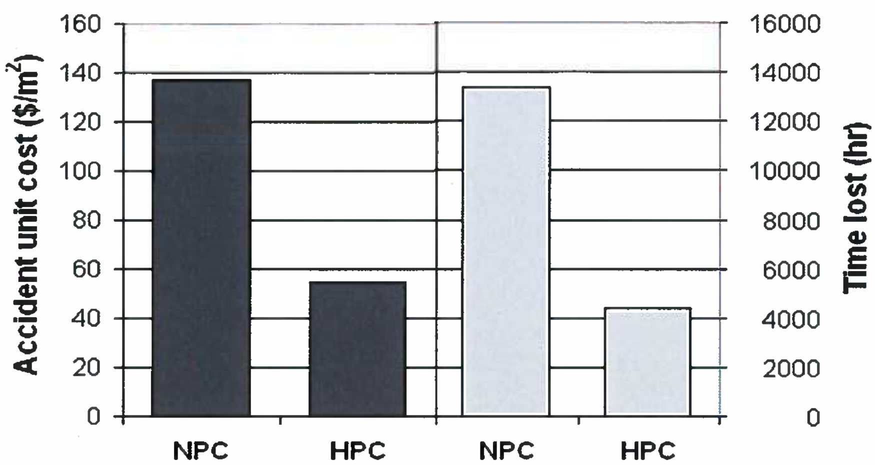
Travel Delay and Accident Costs



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Total Costs

- Life cycle= 40 years
- Discount rate= 3%
- Present value life cycle costs:
  - Initial construction costs
  - Discounted cost of inspections
  - Discounted costs of repairs and rehabilitation
  - Discounted costs of replacement
  - Discounted salvage value
  - Discounted travel delay and accident costs

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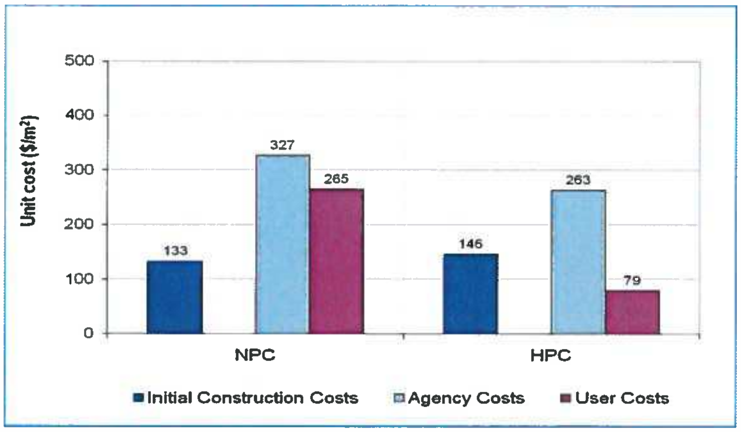
TotalL ife Cycle Costs



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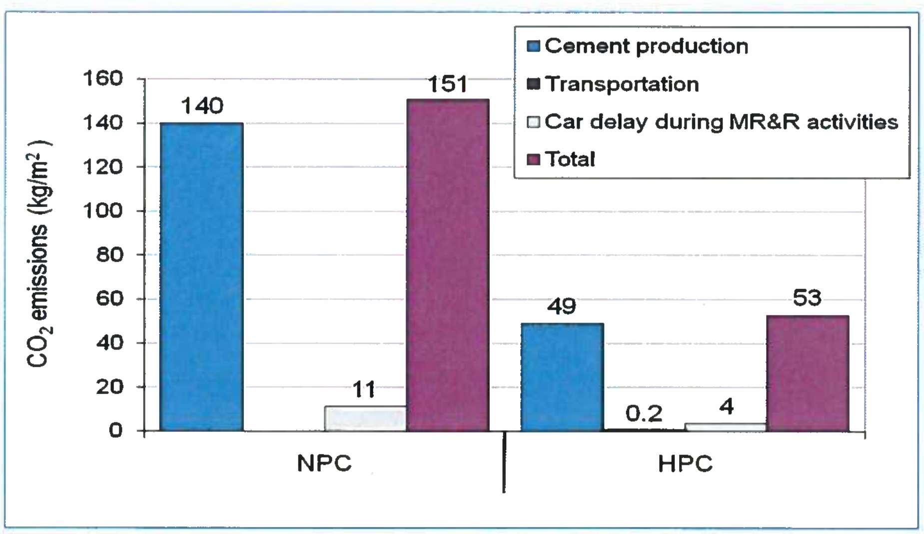
Life Cycle CO_2 Emissions



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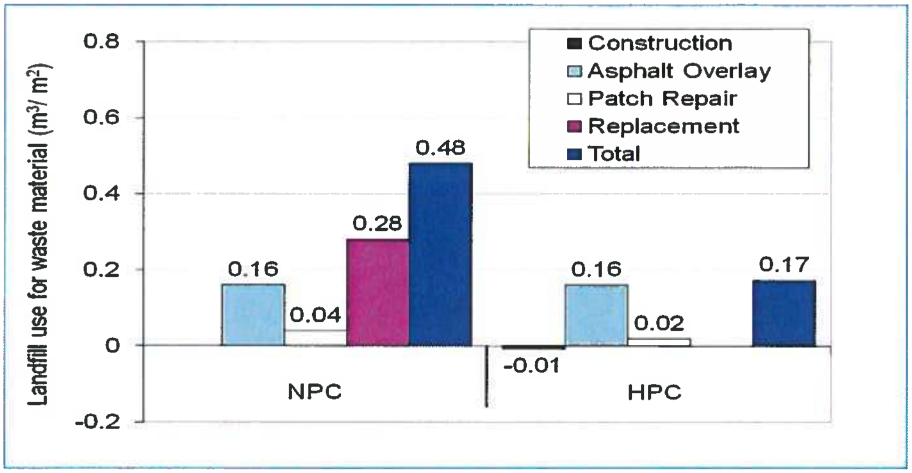
Life Cycle Waste Materials Production



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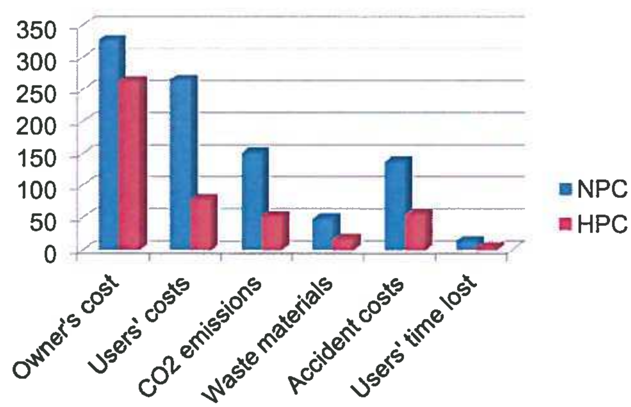
Resilient Design of Highway Bridge Decks



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Case Study 2: Building under Blast

- Blast loads resulting from explosions, triggered during a terrorist attack on a concrete column
- Resilience enhancement of concrete column using carbon fibre-reinforced polymers (3,000 MPa tensile strength)

Unprotected column

S-NoFRP-Axial400kN .avi

Resilient column

NS-CFRP-Axial400kN HS prod1.avi

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Case Study 3: Aging Bridge under Heavy Traffic

Osmos Zoubir.avi

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Conclusions

- Resilience of critical built environment needs to be considered at the design stage for new ones and at the management stage for existing ones.
- Simplified risk-based design and management approaches to enhance the resilience of structural systems are proposed , considering :
  - All potential hazards
  - All direct and indirect consequences
  - Relevant measures of resilience
  - Uncertainty and time/space dependence in parameters and physical models captured by stochastic models

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Epilogue

To achieve resilient built environment there is a need to develop comprehensive risk-based design and management technologies that enable the structural systems to provide :

- High resistance and functionality under small perturbations
- High shock absorption capacity and acceptable resistance and functionality under extreme shocks
- Remote and continuous monitoring of high risk built environment
- Consideration of socio-economic, and environmental impacts of built environment

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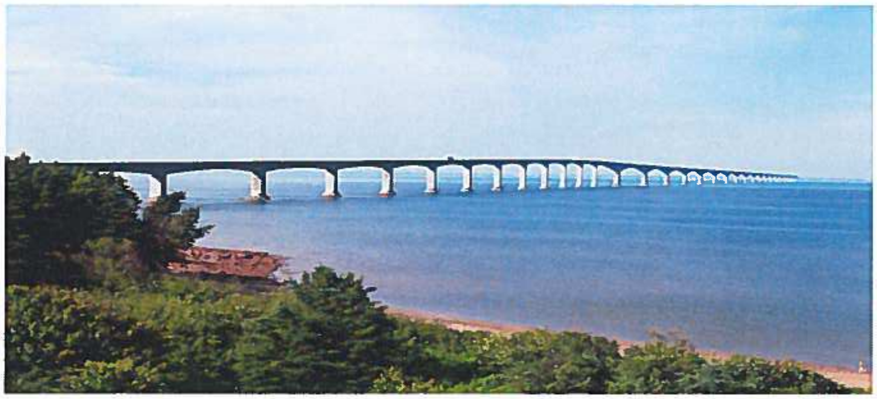
Longest (12.9 km) *bridge* over ice covered waters in the world, joining *Borden-Carleton, Prince Edward Island & Cape Jourimain*, New-Brunswick. Completed in 1997. Total construction cost= $1B. Service Life =100 years.



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Thank you

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