IBRACON

53º CONGRESSO BRASILEIRO DO CONCRETO

IBRACON 2011

Integrated Reliability-Based Life-Cycle Framework for Design, Inspection, Maintenance and Monitoring of Structures: Applications to Bridges

November 2, 2011

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Federal Highway Administration

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INTRODUCTION

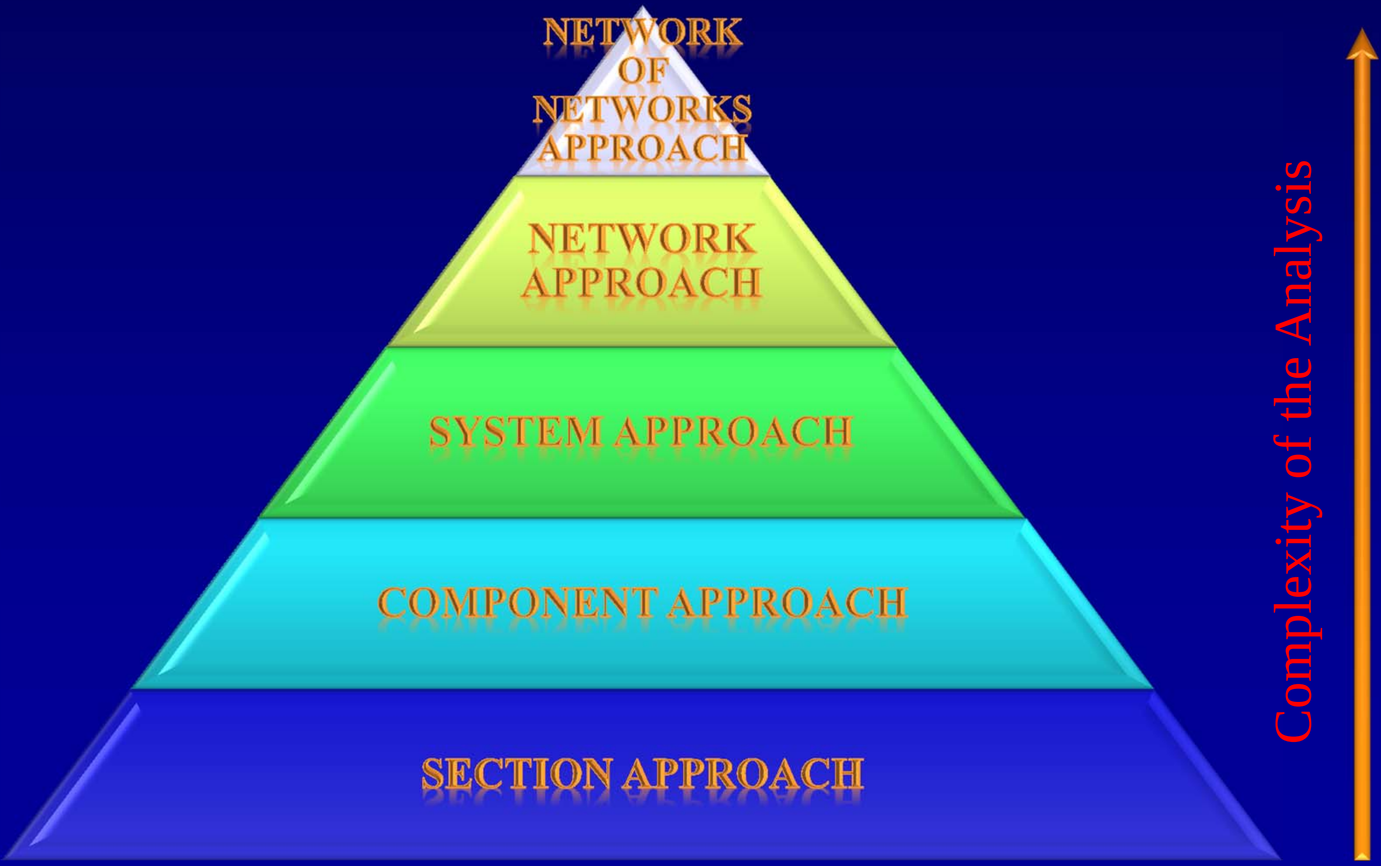
OUR KNOWLEDGE

Model, Analyze, Design, Maintain,
Monitor, Manage, Predict,
and Optimize the life-cycle performance
of structures and infrastructures

"Under Uncertainty"
Aleatory
Epistemic

USE OF PROBABILISTIC METHODS
in Life-Cycle Analysis

LEVELS OF PERFORMANCE QUANTIFICATION



APPLICATIONS

Integration of System-Based Performance Measures and Structural Health Monitoring for Optimized Structural Management Under Uncertainty

OBJECTIVES

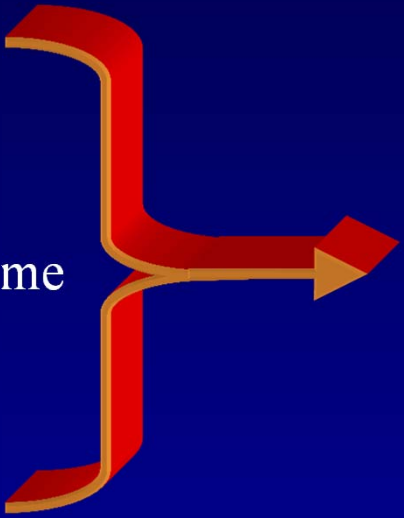
- Investigate the system-based performance and its quantification with advanced tools.
- Develop an approach for using SHM data in updating the life-cycle performance.
- Develop approaches for the life-cycle structural maintenance.
- Develop a detailed life-cycle management framework.

Outline:

Civil Infrastructure

- *System-Based Performance Prediction*
- *Updating the Performance with SHM Data*
- *Maintenance Optimization*
- *Management Framework*

System-based performance prediction

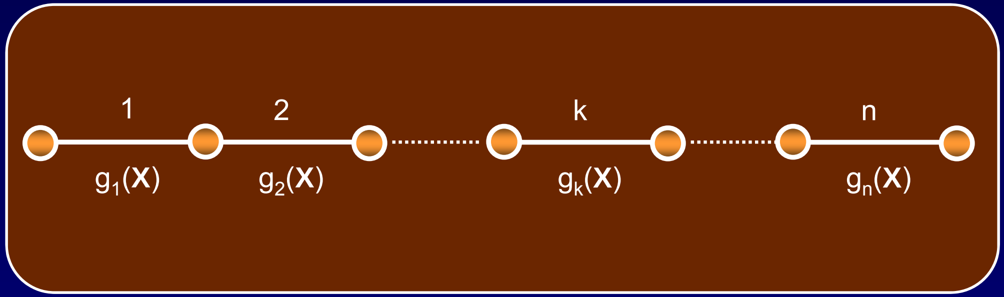


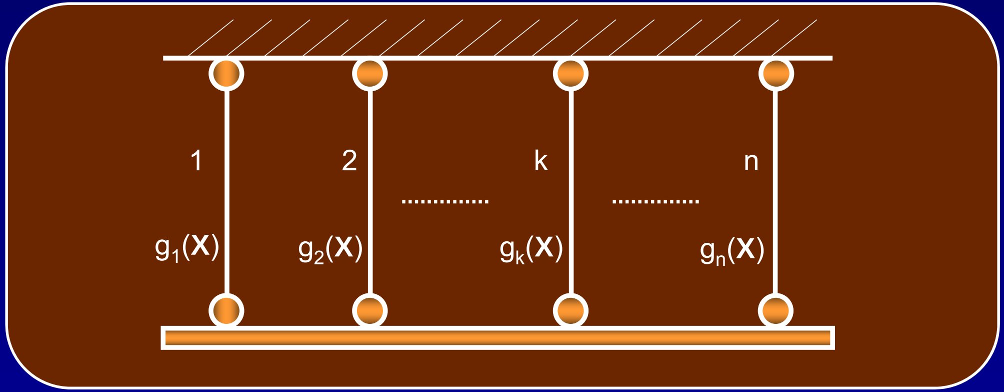
- Instantaneous system reliability
- System cumulative-time failure probability
- Lifetime functions
- System redundancy

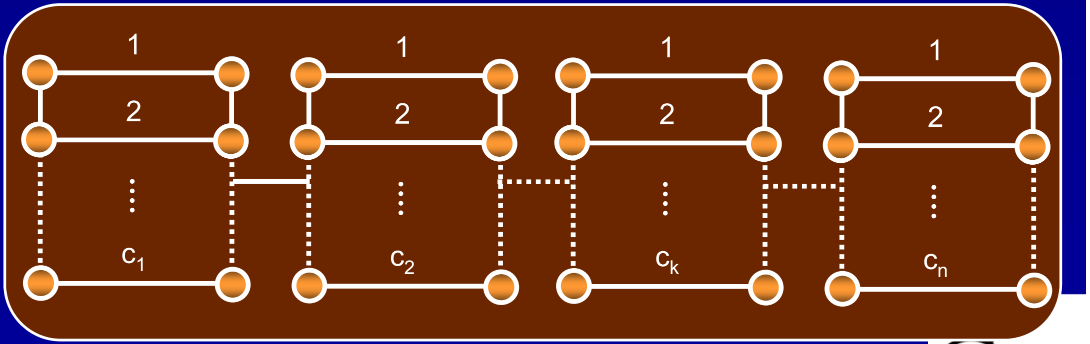
- Safety (ultimate)
- Safety (first failure)
- Serviceability

LEVELS OF PERFROMANCE QUANTIFICATION

System Approach

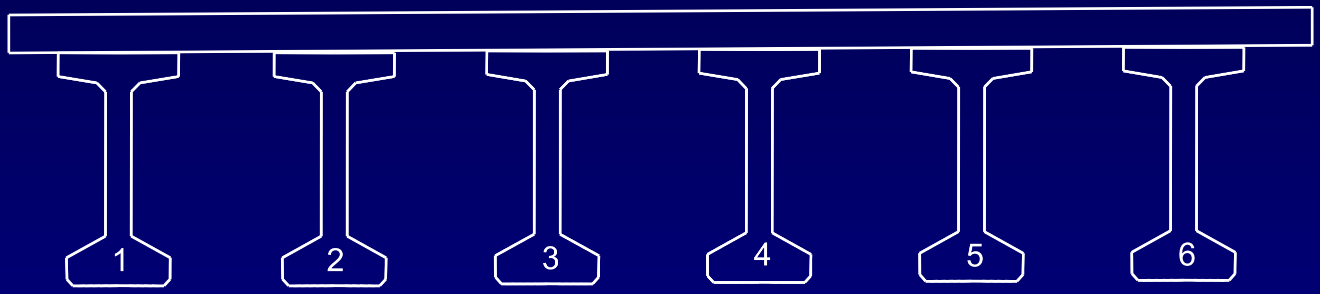

Series System


Parallel System


Series-Parallel System

LEVELS OF PERFROMANCE QUANTIFICATION

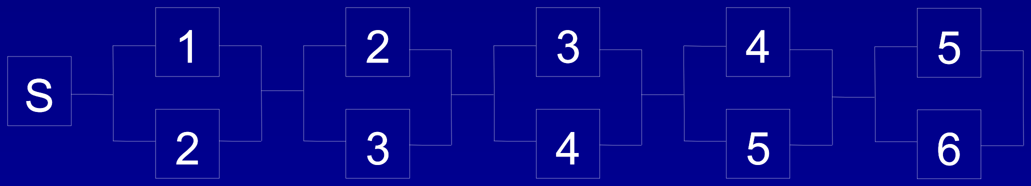
Reliability of a system



- Considering only flexure
- Failure of slab

  or failure of any two adjacent girder

  → System failure



S: Flexure of Slab

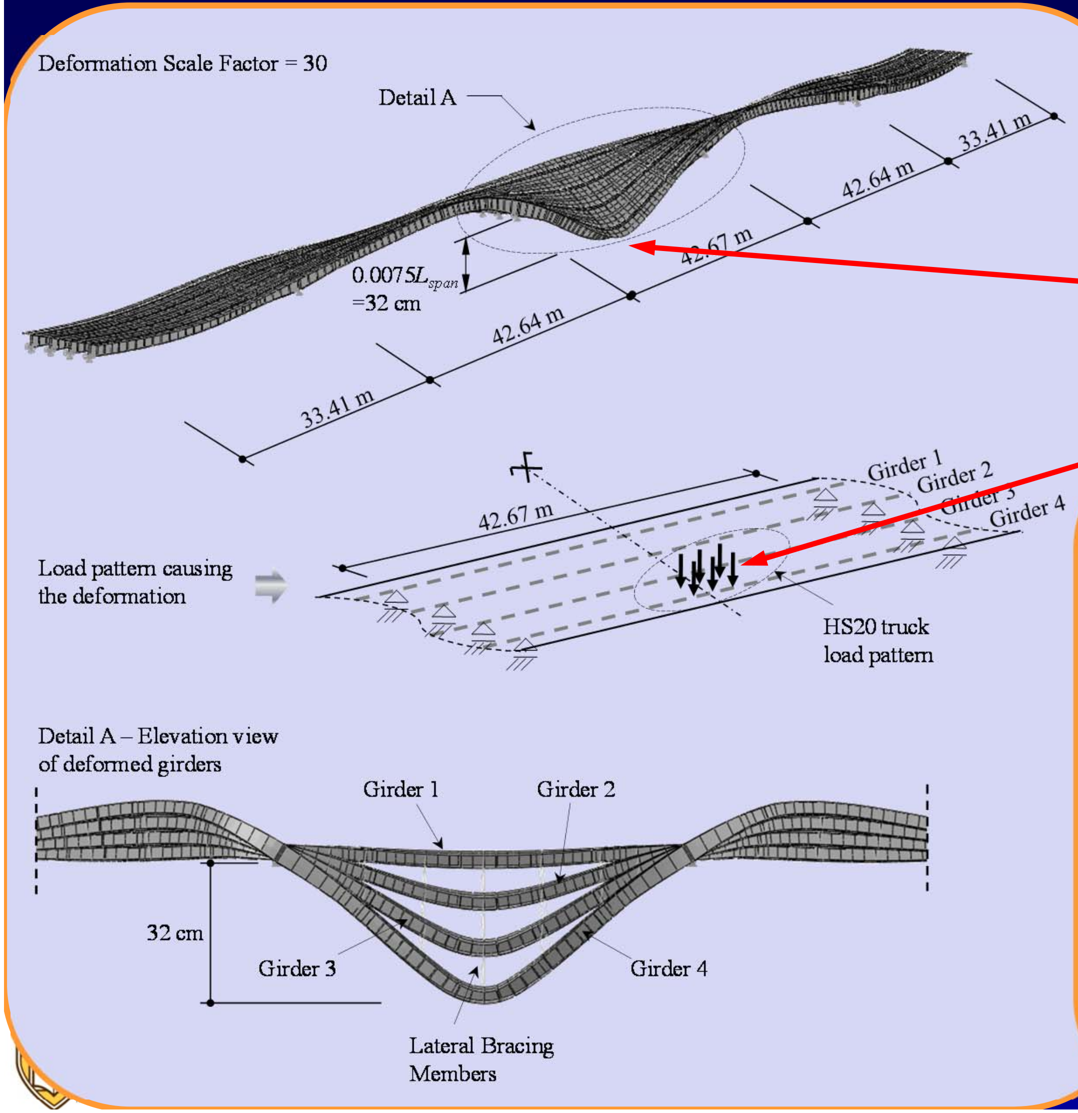
i: Flexure of Girder i

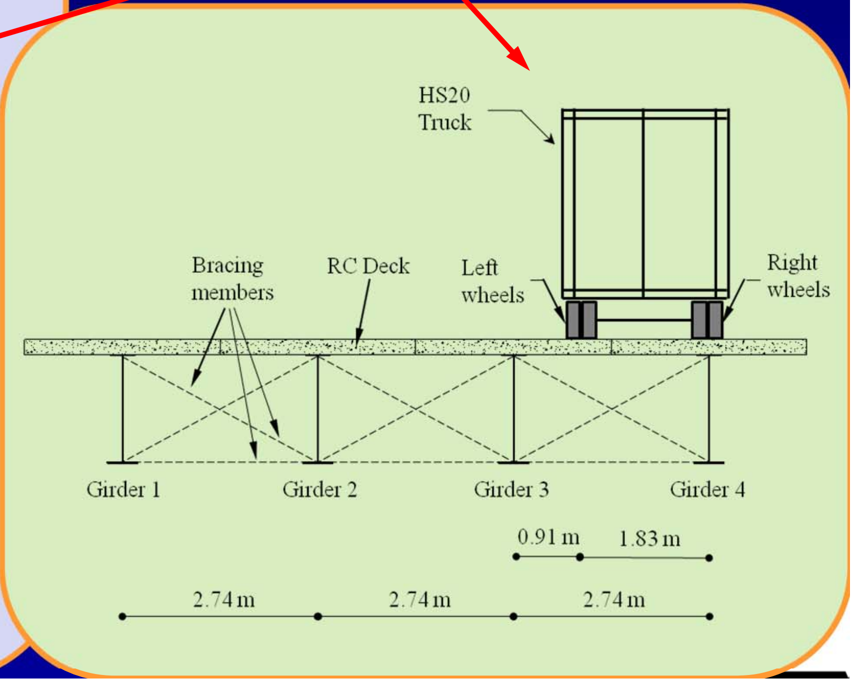
Alternative Approach to Model System Behavior

Finite Element Modeling

I-39 Northbound
Wisconsin River Bridge
- 4 steel girders
- Composite with RC deck

Displacement
- At critical locations
- Under critical loading





SYSTEM PERFORMANCE ASSESSMENT AND PREDICTION

Cumulative-time member failure probability

- Time-variant resistance of a structural member

$$\boxed{R(t) = R_0 \cdot g(t)}$$

$R(t)$ = time-variant resistance,
R_0 = initial resistance,
$g(t)$ = resistance degradation function

- **Cumulative-time failure probability of "a member"** subjected to two statistically independent load processes with intensities S_1 and S_2

$$P_f(t_L)_{mem} = 1 - \int_0^\infty \int_0^\infty \exp\left(-\lambda_{S_1} t_L \left\{1 - \frac{1}{t_L}\int_0^{t_L} F_{S_1}\left[r \cdot g(t) - s_2\right] dt\right\}\right) \cdot f_{S_2}(s_2)\, f_{R_0}(r)\, ds_2\, dr$$

Probability of member failure over a duration $[0, t_L]$ → "Cumulative-time failure probability"

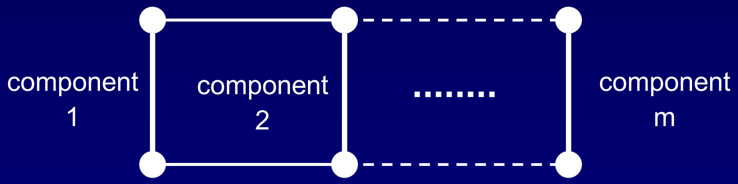
S_1 = time-variant (live) load
S_2 = time-variant (dead) load
λ_{S_1}, F_{S_1} = mean load occurrence rate and CDF of time-variant (live) load
f_{S_2} = PDF of S_2
f_{R_0} = PDF of R_0

Mori, Y., and Ellingwood, B.R. 1993. Reliability-based service life assessment of aging concrete structures. J. Struct. Engrg., ASCE, 199(5).

SYSTEM PERFORMANCE ASSESSMENT AND PREDICTION

Cumulative-time member failure probability

- **Cumulative-time failure probability of "a parallel system"** of *m* components subjected to the live load process with intensity S_1



$$\underbrace{P_f\left(t_L\right)_{par}}_{} = \underbrace{\int_0^{\infty}\cdots\int_0^{\infty}}_{\text{m-fold}}\left[1-\exp\left(-\lambda_{S_1} t_L\left\{1-\frac{1}{t_L}\int_0^{t_L} F_{S_1}\cdot\min_{k=1}^{m!}\left[\max_{i=1}^{m}\left(\frac{r_i\cdot g_i(t)}{RSF_i^d}+\sum_{j=1}^{i}\eta_j\cdot r_j\right)\right]dt\right\}\right)\right]\cdot f_{\underline{R}_0}\left(\underline{r}\right)d\underline{r}$$

Probability of the system failure over a duration [0, t_L] → "Cumulative-time failure probability"

RSF_i^d = resistance sharing factor of member I in the damage state $\left(DS\right)_k^{q_i}$

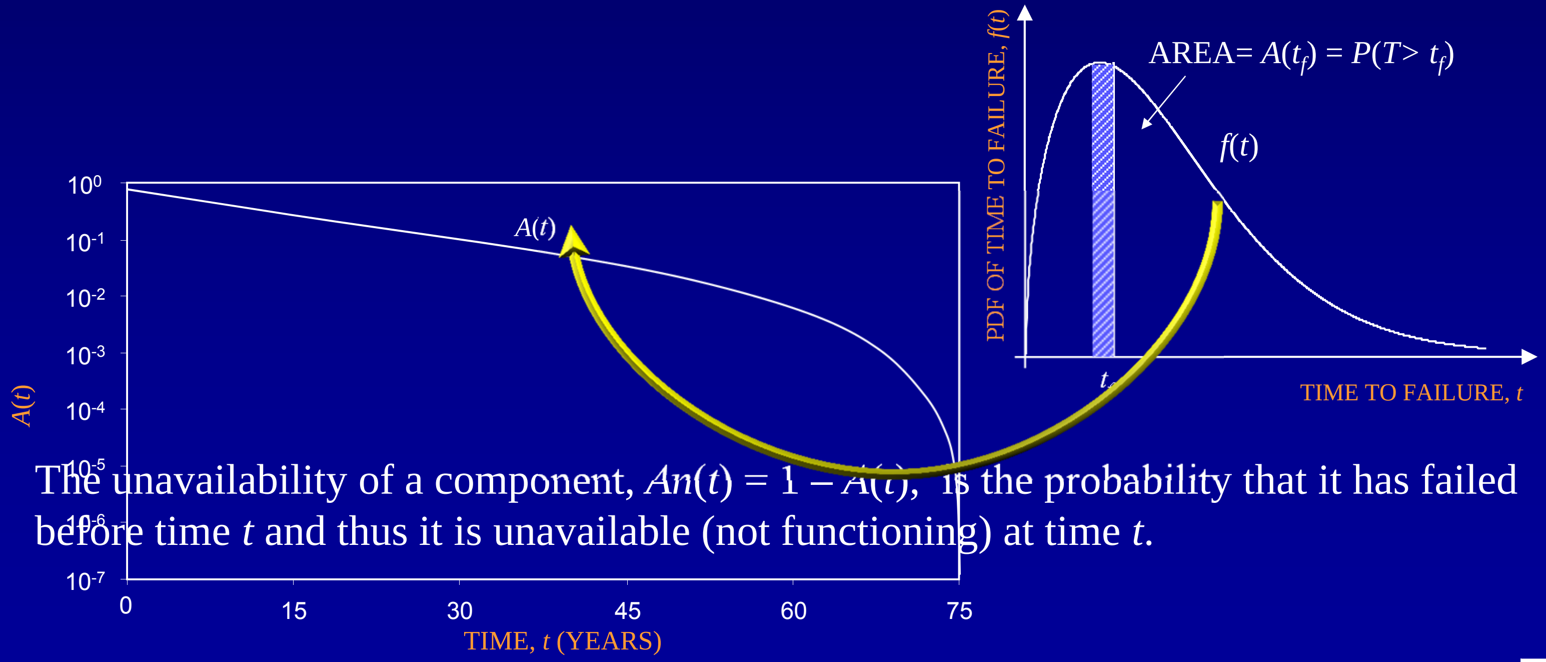
q = the sequence of *l* failed members $\left(0\le l< m\right)$

Enright and Frangopol1998. Failure time prediction of deteriorating fail-safe structures. J. Struct. Engrg., ASCE, 124(12).

Lifetime functions

•Availability *A*(*t*)

A component is available at time *t* if it is functioning at time *t*.



The unavailability of a component, $An(t) = 1 - A(t)$, is the probability that it has failed before time *t* and thus it is unavailable (not functioning) at time *t*.

SYSTEM PERFORMANCE ASSESSMENT AND PREDICTION

System Redundancy

- Time-dependent redundancy indices (Okasha and Frangopol, Structural Safety , 2009)

$$RI_1(t) = \frac{P_{y(sys)}(t) - P_{f(sys)}(t)}{P_{f(sys)}(t)}$$

$P_{y(sys)}(t)$ = probability of first member failure occurrence at time t

$P_{f(sys)}(t)$ = probability of system failure occurrence at time t

……

$$RI_2(t) = \beta_{f(sys)}(t) - \beta_{y(sys)}(t)$$

$\beta_{y(sys)}(t)$ = probability of first member failure occurrence at time t

$\beta_{f(sys)}(t)$ = probability of system failure occurrence at time t

……

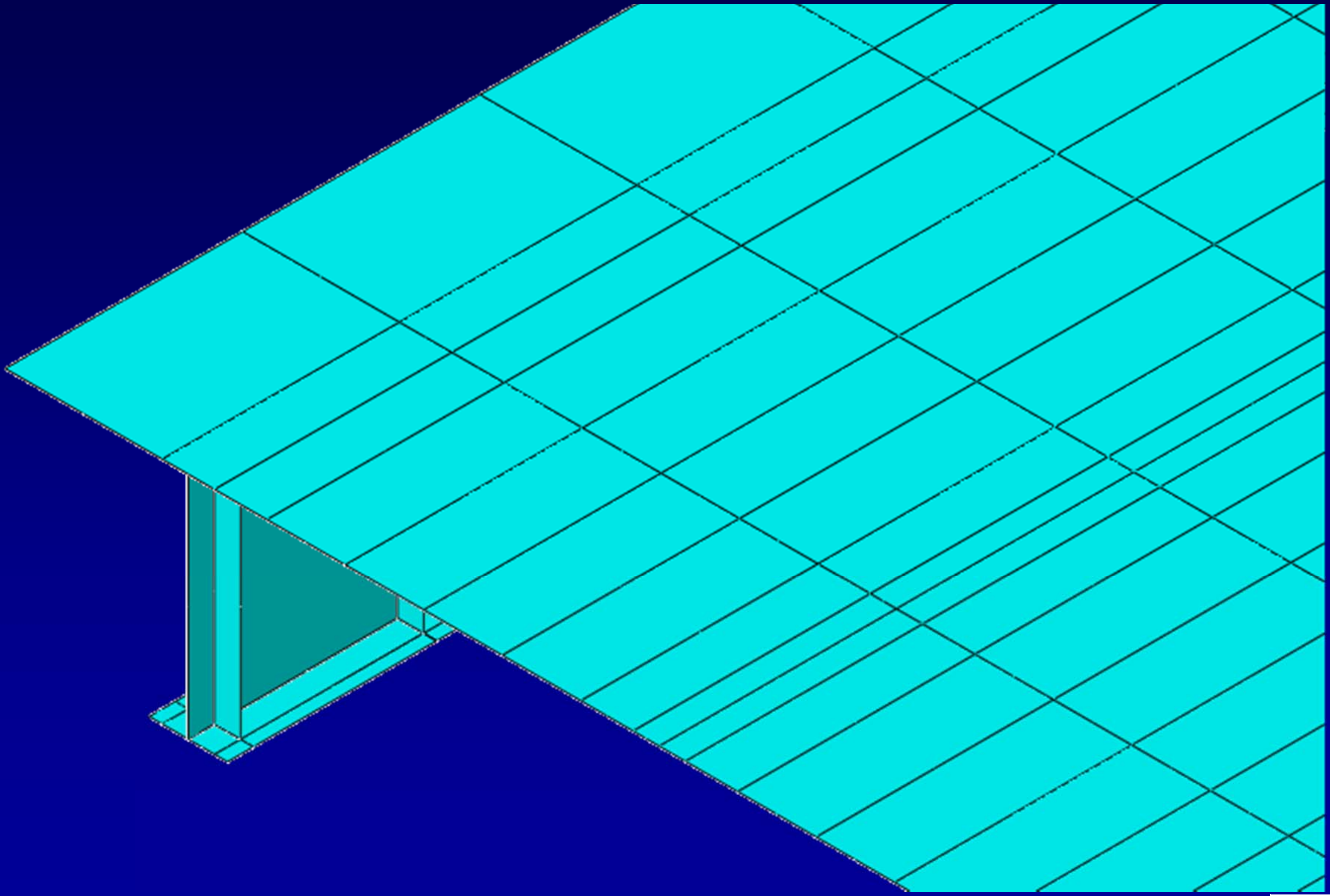
$$RI_3(t) = \frac{An_{wc}(t) - An_s(t)}{An_s(t)}$$

$An_s(t)$ = unavailability of the system at time t

$An_{wc}(t)$ = unavailability of the weakest component at time t

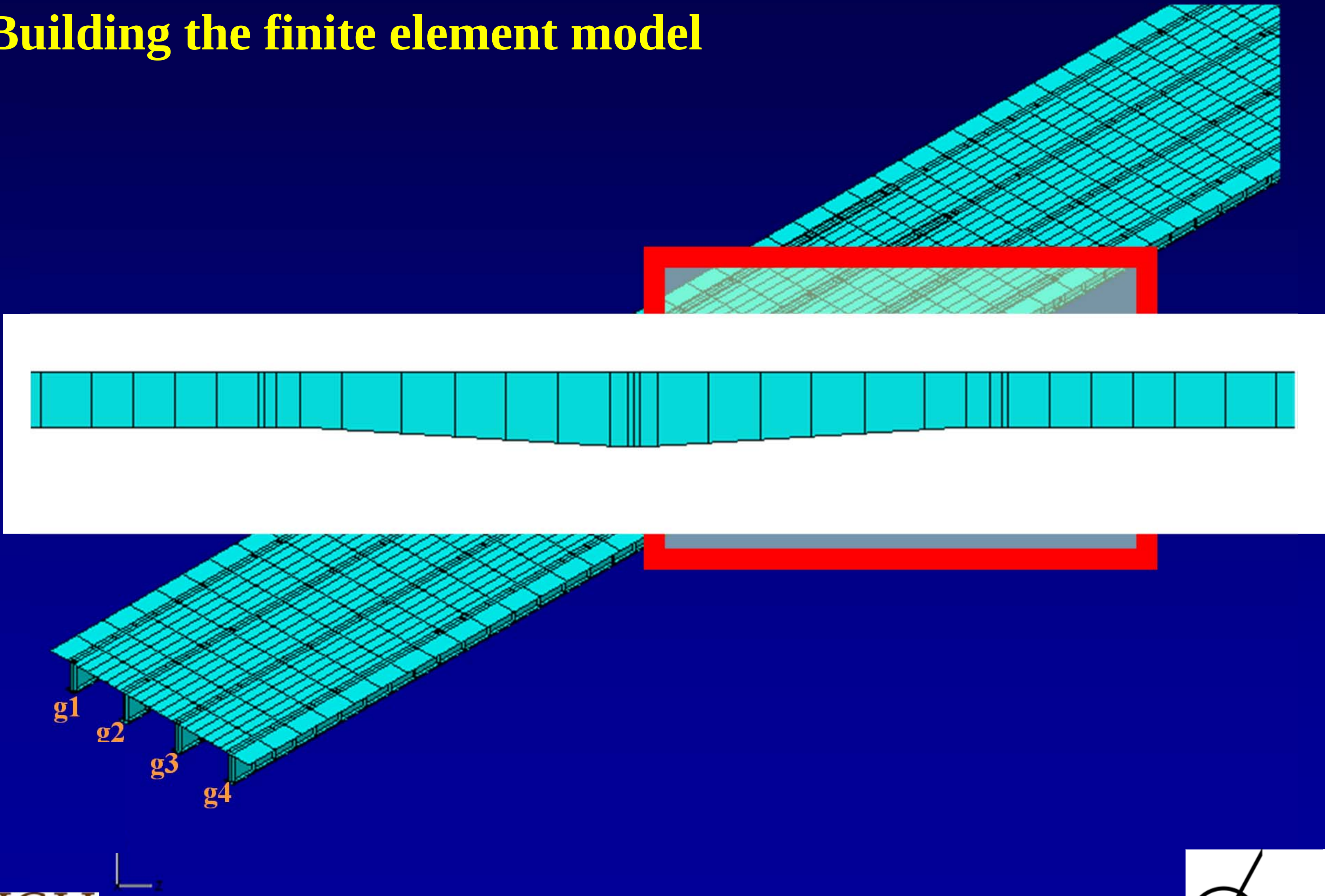
I-39 Northbound Bridge over the Wisconsin River

Building the finite element model



Okasha, N.M. and Frangopol, D.M. (2010). Advanced modeling for the life-cycle performance prediction and service-life estimation of bridges. *Journal of Computing in Civil Engineering*, ASCE, (in press).

Building the finite element model



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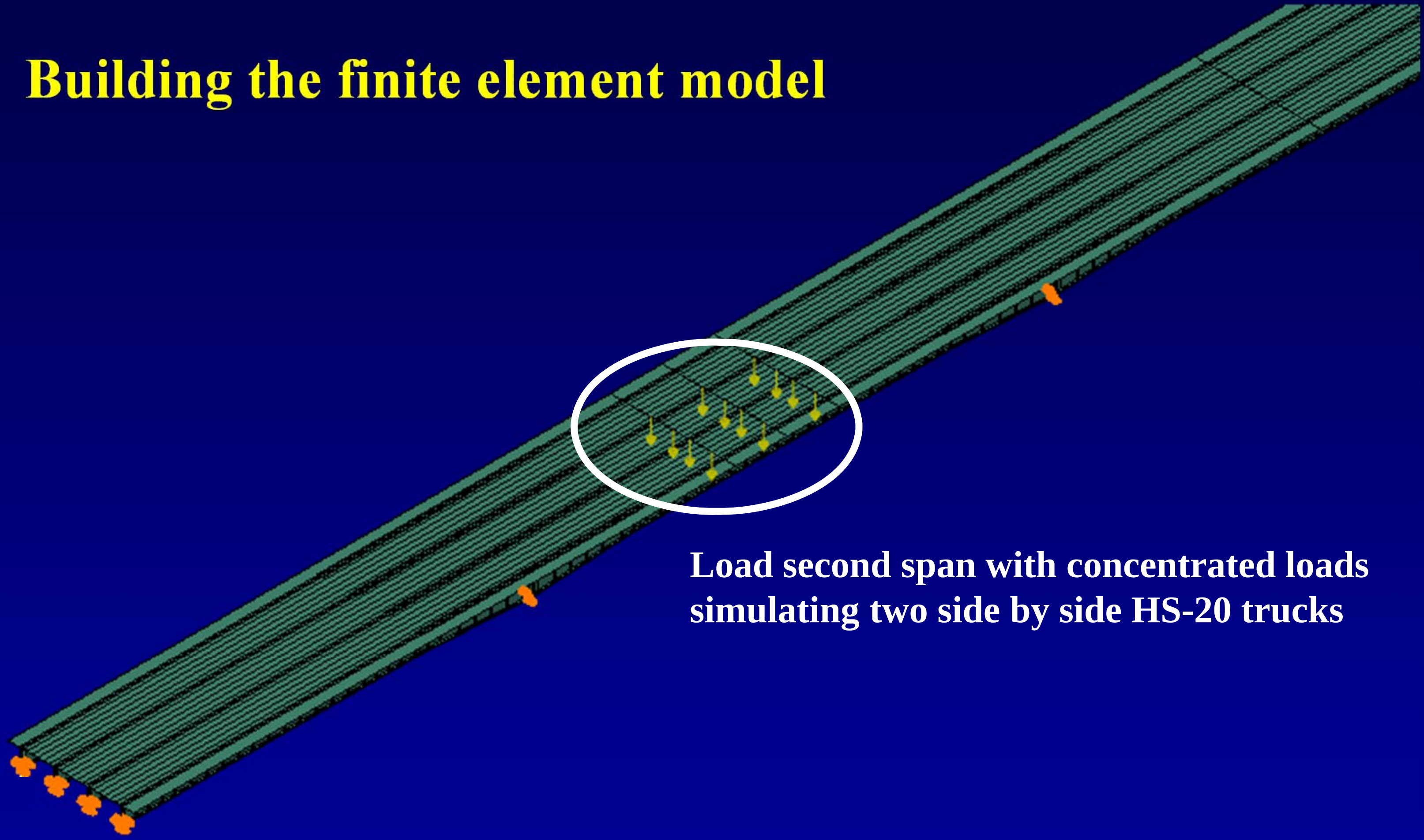
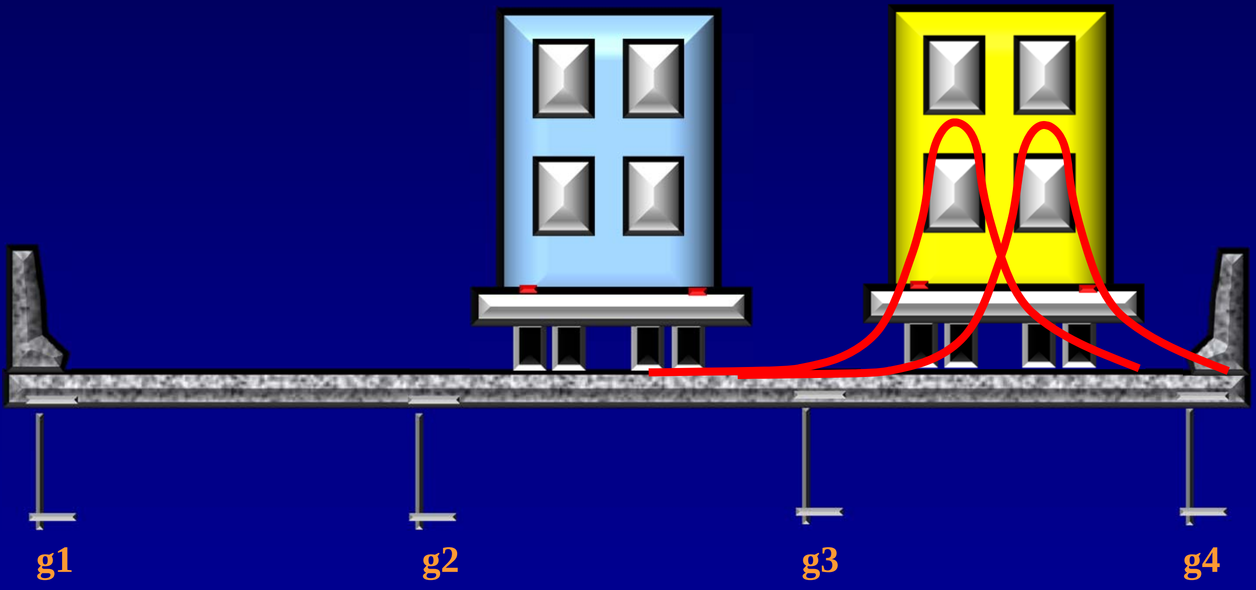
Building the finite element model



Load second span with concentrated loads simulating two side by side HS-20 trucks

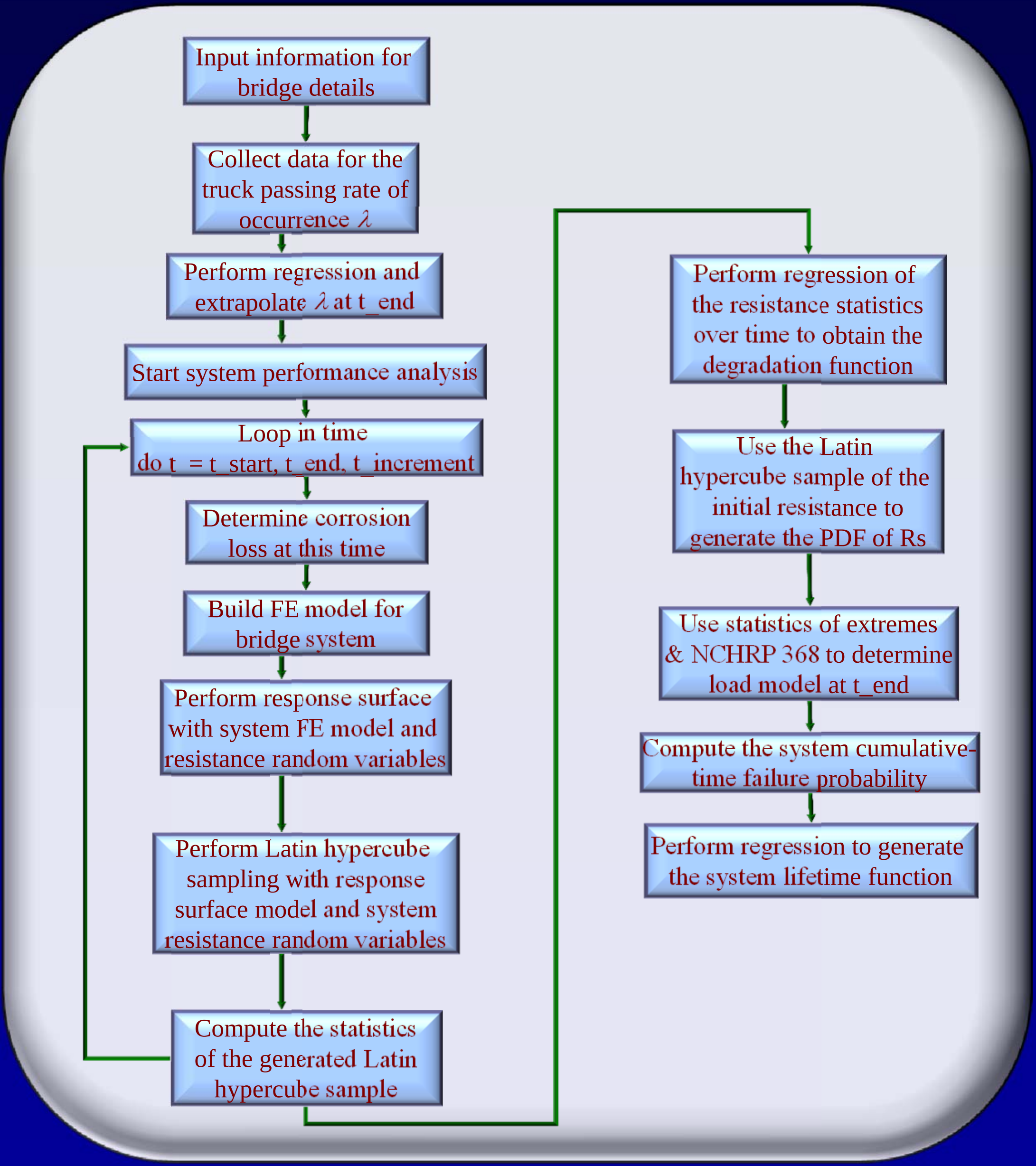
Okasha, N.M. and Frangopol, D.M. (2010). Advanced modeling for the life-cycle performance prediction and service-life estimation of bridges. *Journal of Computing in Civil Engineering*, ASCE, (in press).

Building the finite element model



Okasha, N.M. and Frangopol, D.M. (2010). Advanced modeling for the life-cycle performance prediction an
service-life estimation of bridges. *Journal of Computing in Civil Engineering*, ASCE, (in press).

Performance prediction



Input information for bridge details

Collect data for the truck passing rate of occurrence λ

Perform regression and extrapolate λ at t_end

Start system performance analysis

Loop in time
do t = t_start, t_end, t_increment

Determine corrosion loss at this time

Build FE model for bridge system

Perform response surface with system FE model and resistance random variables

Perform Latin hypercube sampling with response surface model and system resistance random variables

Compute the statistics of the generated Latin hypercube sample

Perform regression of the resistance statistics over time to obtain the degradation function

Use the Latin hypercube sample of the initial resistance to generate the PDF of Rs

Use statistics of extremes & NCHRP 368 to determine load model at t_end

Compute the system cumulative-time failure probability

Perform regression to generate the system lifetime function

Okasha, N.M. and Frangopol, D.M. (2010). Advanced modeling for the life-cycle performance prediction and service-life estimation of bridges. *Journal of Computing in Civil Engineering*, ASCE, Vol. 24, No.6.

Outline:

Civil Infrastructure (This lecture)

- *System-Based Performance Prediction*
- *Updating the Performance with SHM Data*
- *Maintenance Optimization*
- *Management Framework*

Combining SHM & LCM

Combining SHM and LCM has the benefit that each method's advantages complement the other's disadvantages

Structural Health Monitoring

Actual Structural Data

Predictive in nature?
Actionable Information?

Life-Cycle Management

Predictive Management Tool

Accuracy of random variables?
Limited use of structure-specific structural data

Combined Approach

Predictive Tool

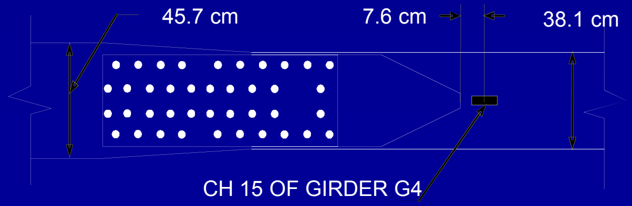
Actual Structural Data

Actionable Information for the bridge manager

Frangopol and Messervey "Maintenance Principles for Civil Structures," Chapter 89 in Encyclopedia of Structural Health Monitoring, John Willey & Sons, 2009

TOP VIEW

DETAIL 1 (PLAN VIEW)



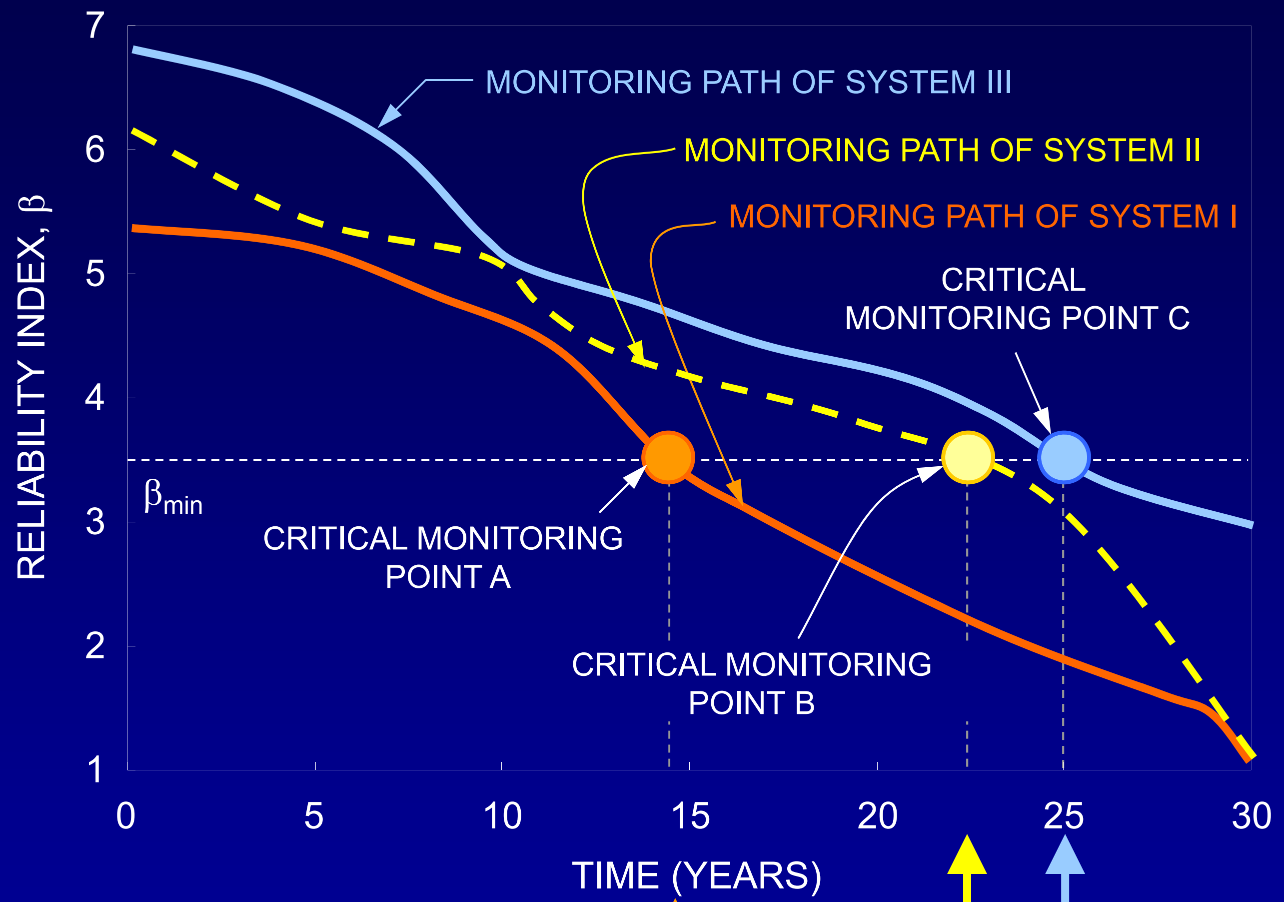
CH 15 OF GIRDER G4
CH 16 OF GIRDER G3
STRAIN GAGES

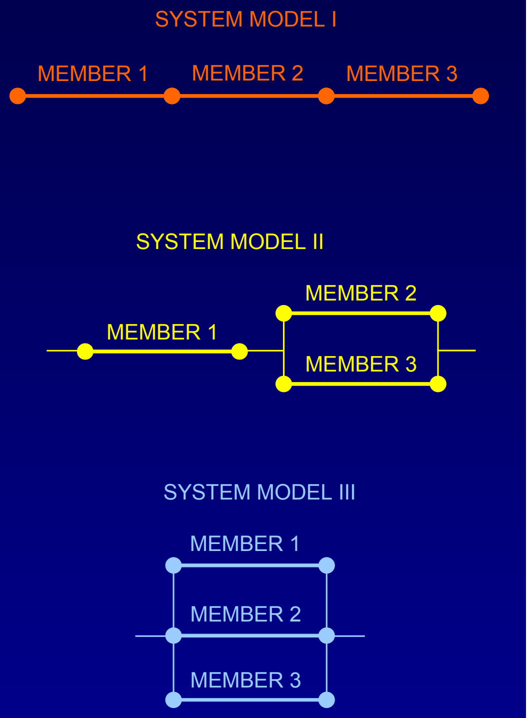
SHM design considerations: System Reliability

How a component functions in a system may give insight on where to focus monitoring priorities during time.

Which element should receive monitoring priority for each system at any point in time ?

TIME-DEPENDENT MONITORING PATHS





CRITICAL MONITORING POINTS

SYSTEM I

SYSTEM II

SYSTEM III

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Outline:

Civil Infrastructure (This Lecture)

- *System-Based Performance Prediction*
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ROLE OF OPTIMIZATION

OPTIMUM SHM PLANS

- **Continuous long-term monitoring** of an entire structural system can prevent unexpected failure through accurate assessment of its structural performance.

- **Cost-efficient placement of sensors and effective use of recorded data** are required by using probabilistic and statistical methods

- **Optimal planning of SHM**
  → Bi-objective problem

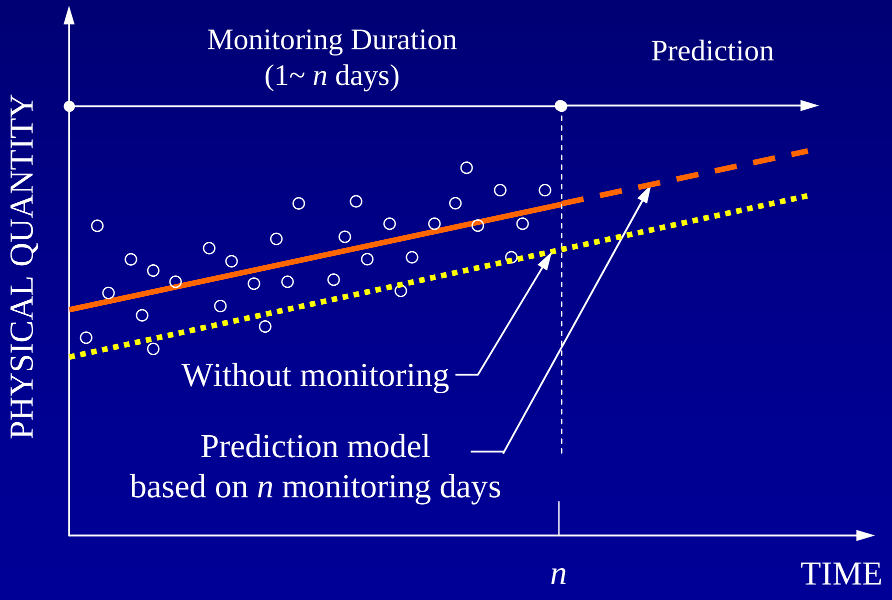
maximization of **availability of monitoring data**
for prediction of structural performance

minimization of **total monitoring cost**

BALANCE OF COST AND AVAILABILITY OF SHM

▲ MONITORING

- Monitoring provides additional information about the state of a system at a point in time or over a period of time
- Monitoring data can be used for prediction of the state of a system in the future



▲ AVAILABILITY OF MONITORING DATA FOR PREDICTION

- **Probability** that the prediction model based on monitoring data is used in the future

BI-OBJECTIVE PROBLEM (FORMULATION)

▲ OBJECTIVES

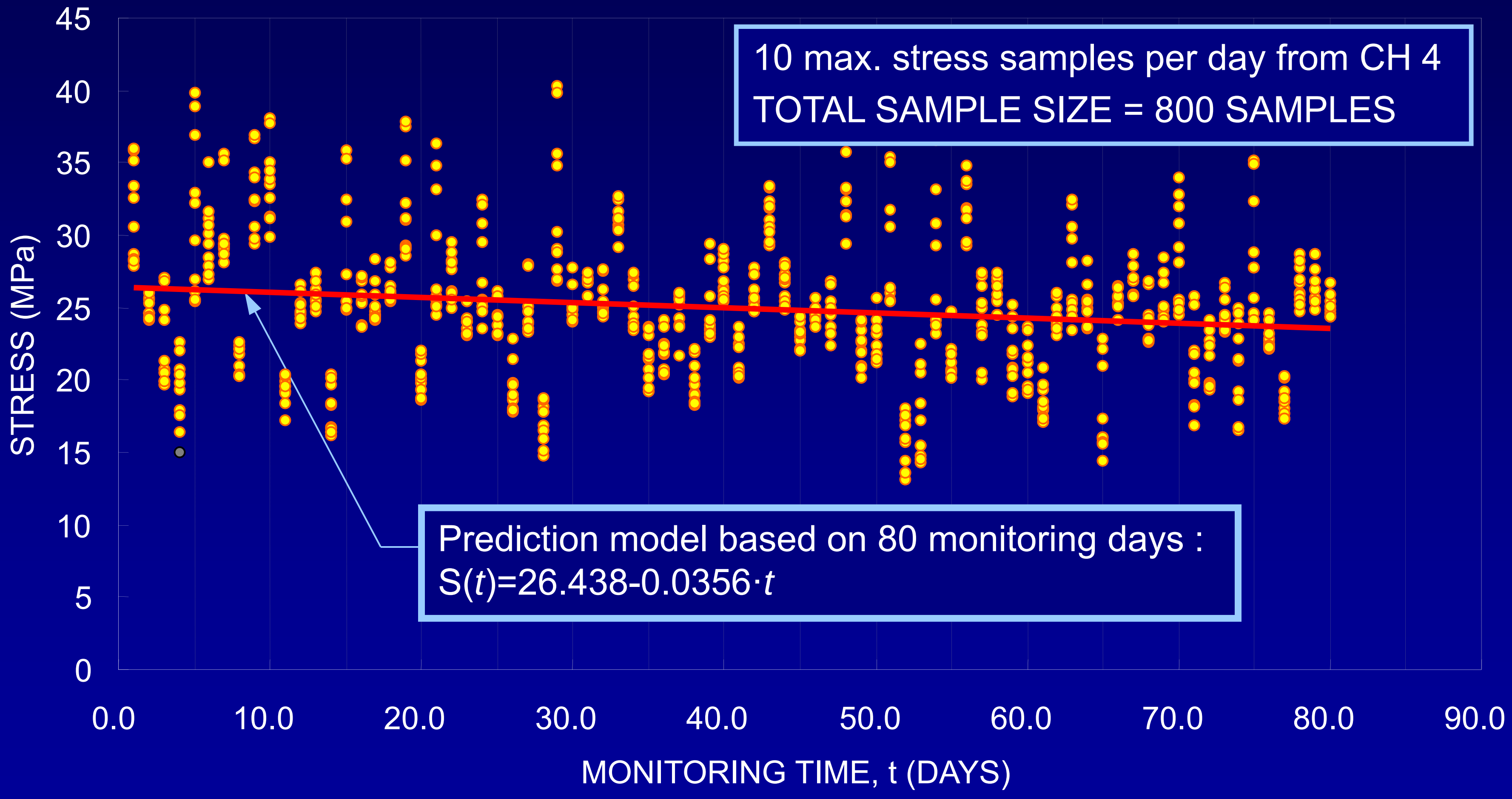
Expected average availability of monitoring data for prediction	$E\left(\bar{A}\right)$	**Maximize**
Cumulative total monitoring cost for a given life	$C_{Tcm} = \left(\frac{\tau_m}{\tau_{mo}} \cdot C_o\right) \cdot \sum_{i=1}^{n+1} \left(\frac{1}{\left(1+r\right)^{(i-1)(\tau+\tau_m)}}\right)$	**Minimize**

▲ VARIABLES

- **τ (non-monitoring duration)**
- **τ_m (monitoring duration)**

MULTI-OBJECTIVE PROBLEM (APPLICATION)

- **Monitoring of the I-39 Northbound Bridge over the Wisconsin River**



10 max. stress samples per day from CH 4
TOTAL SAMPLE SIZE = 800 SAMPLES

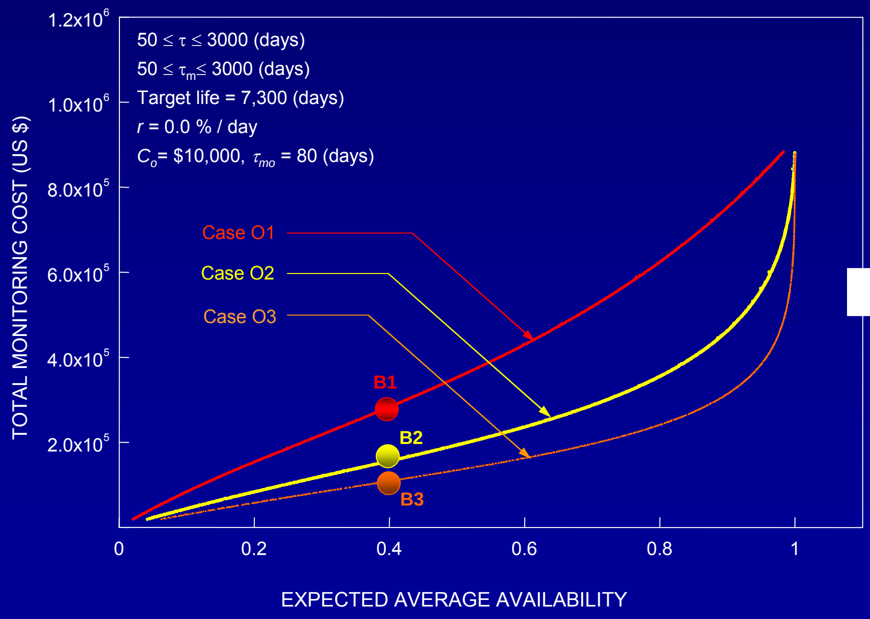
Prediction model based on 80 monitoring days :
$S(t)=26.438-0.0356\cdot t$

ROLE OF OPTIMIZATION

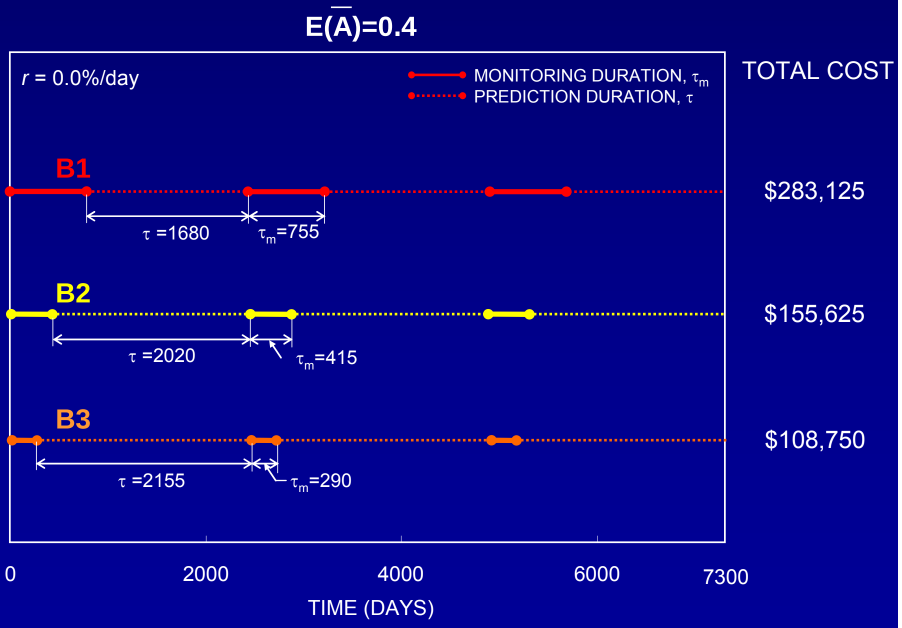
OPTIMUM SHM PLANS (Kim and Frangopol, Probabilistic Eng. Mech. 2010)

Bi-objective problem ⇨ **maximization** of **availability of monitoring data** for prediction of structural performance
minimization of **total monitoring cost**

Pareto Optimal Set



Monitoring Period



Movable Bridges (with UCF)

- Bridges which can move, rotate, or lift in order to alternatively allow intersecting traffic
  - Bascule Bridges
  - Vertical Lift Bridges
  - Swing Bridges


Miami River

BASCULE

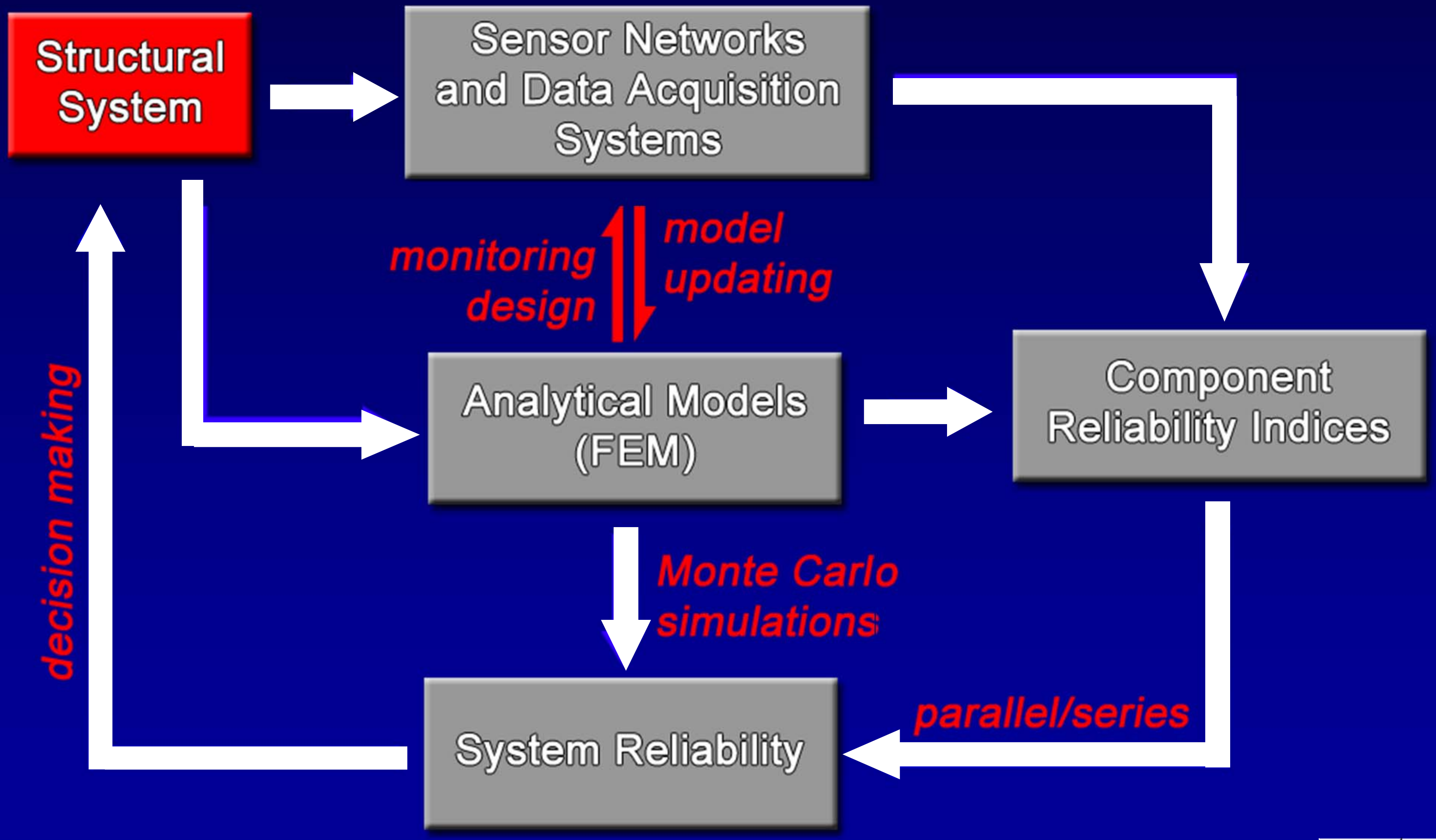

Vilano Beach

LIFT


SWING

Lake Okeechobee

Basic Framework



Structural System

Sensor Networks and Data Acquisition Systems

monitoring design

model updating

Analytical Models (FEM)

Component Reliability Indices

Monte Carlo simulations

System Reliability

parallel/series

decision making

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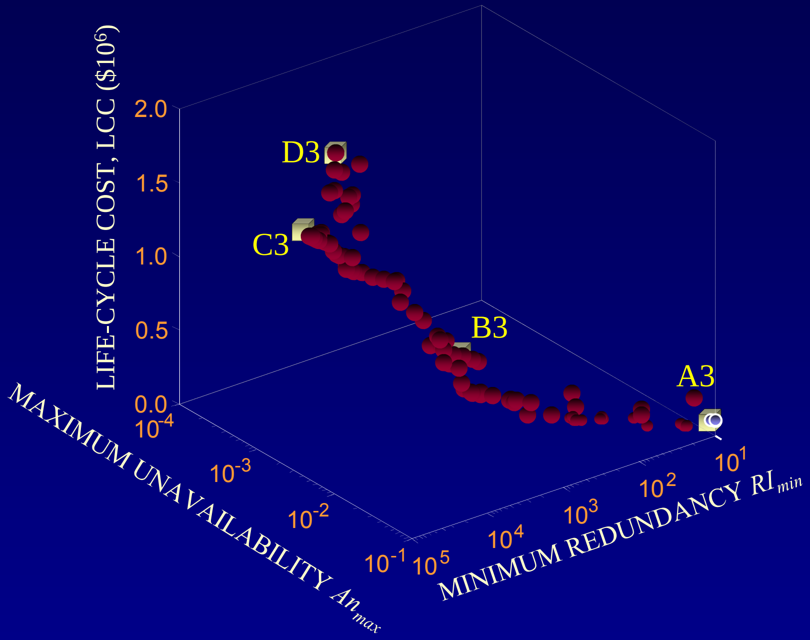
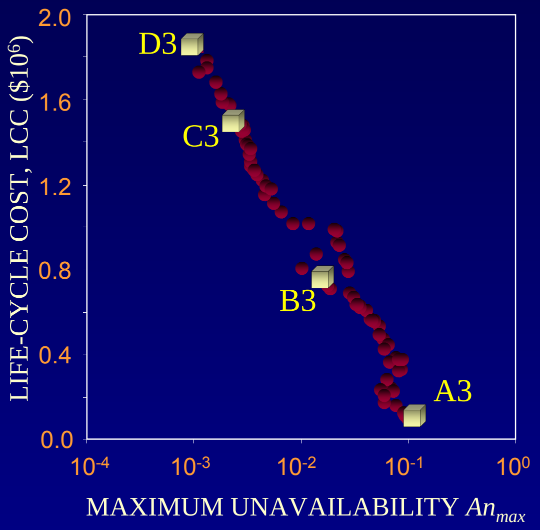
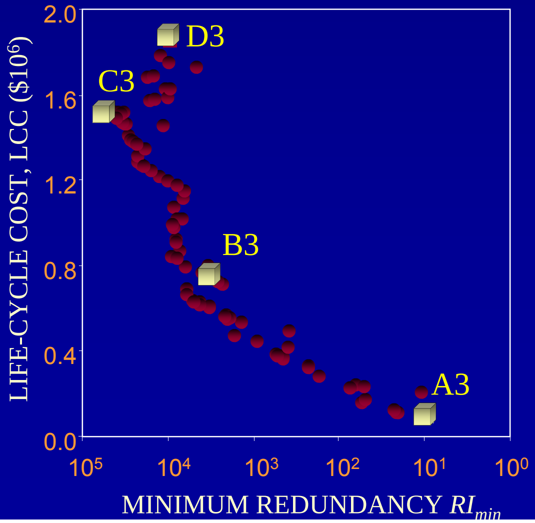
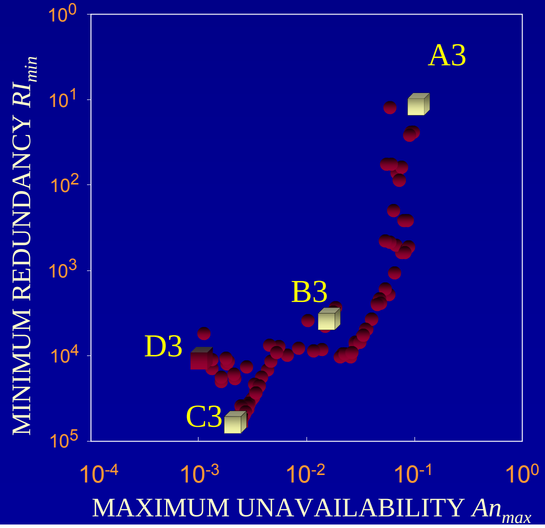
NUMERICAL MULTI-OBJECTIVE OPTIMIZATION

Multi-objective life cycle probabilistic optimization with conflicting criteria by means of **Genetic Algorithms**









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RESILIENCE OF BRIDGES IN TRANSPORTATION NETWORKS

(with Dr. Paolo Bocchini)

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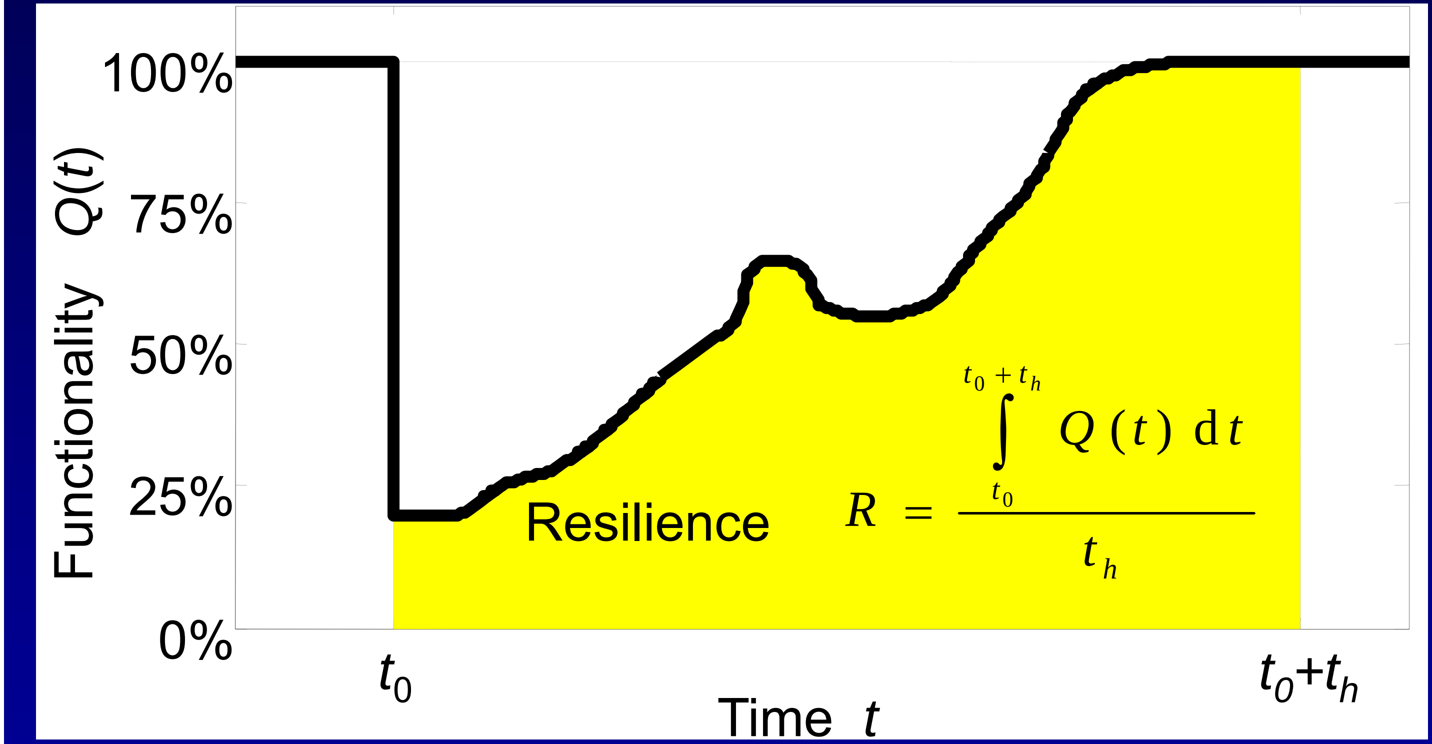
RESILIENCE OF BRIDGE NETWORKS

An extreme event has damaged a group of bridges

What is the most efficient and economical plan to restore them ?



Resilience is a measure of the promptness and efficiency of the restoration after the occurrence of an extreme event.

Resilience is used as objective of the optimization

Optimal resilience- and cost-based post-disaster intervention prioritization for bridges in a transportation network.

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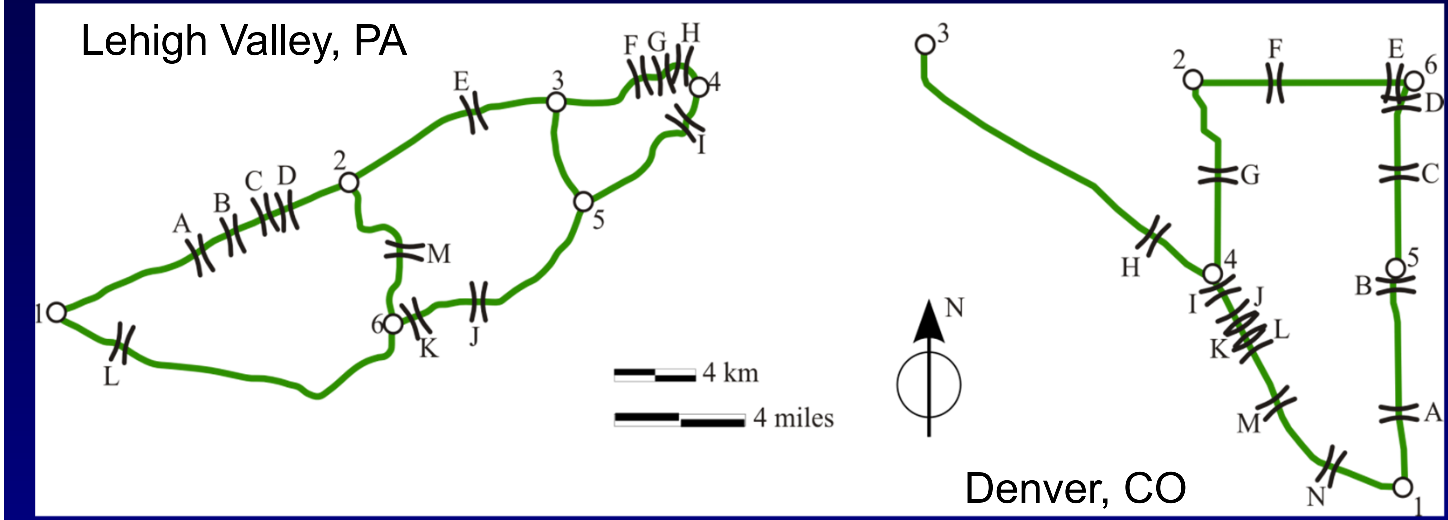
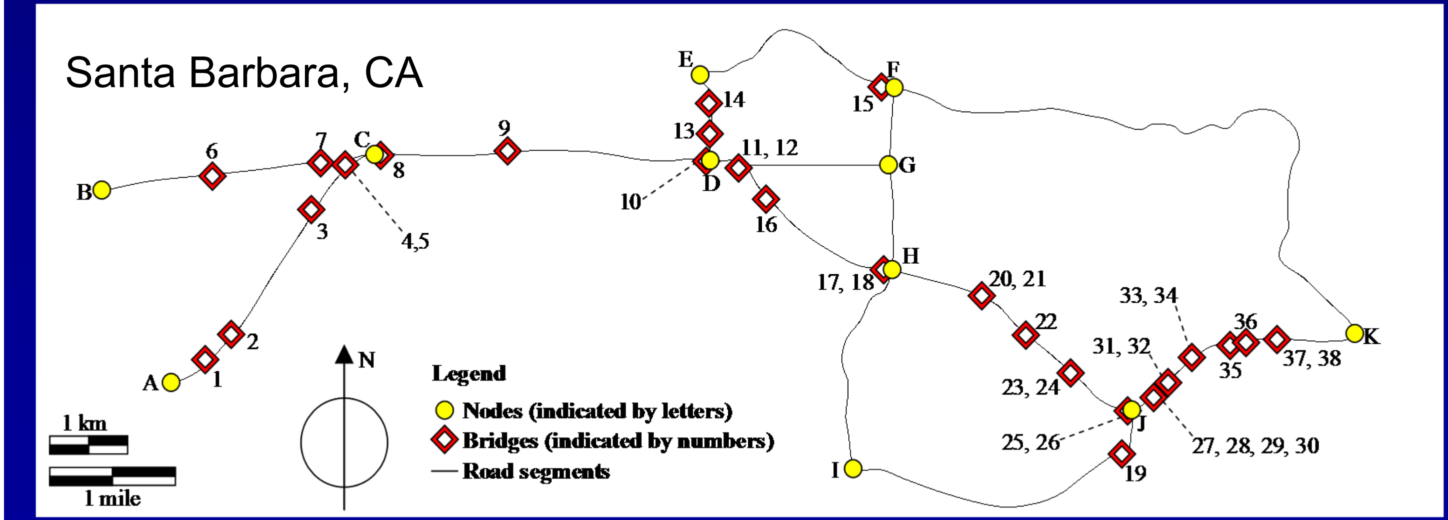
BRIDGE NETWORKS



Lehigh Valley, PA
13 bridges
8 road segments

Denver, CO
14 bridges
6 road segments



Santa Barbara, CA
38 bridges
14 road segments

LATEST APPLICATION: SANTA BARBARA

CONCLUSIONS

1. **Effective and practical methods** for capturing system performance including **redundancy and robustness in a time-dependent context** will continue to present an important challenge.

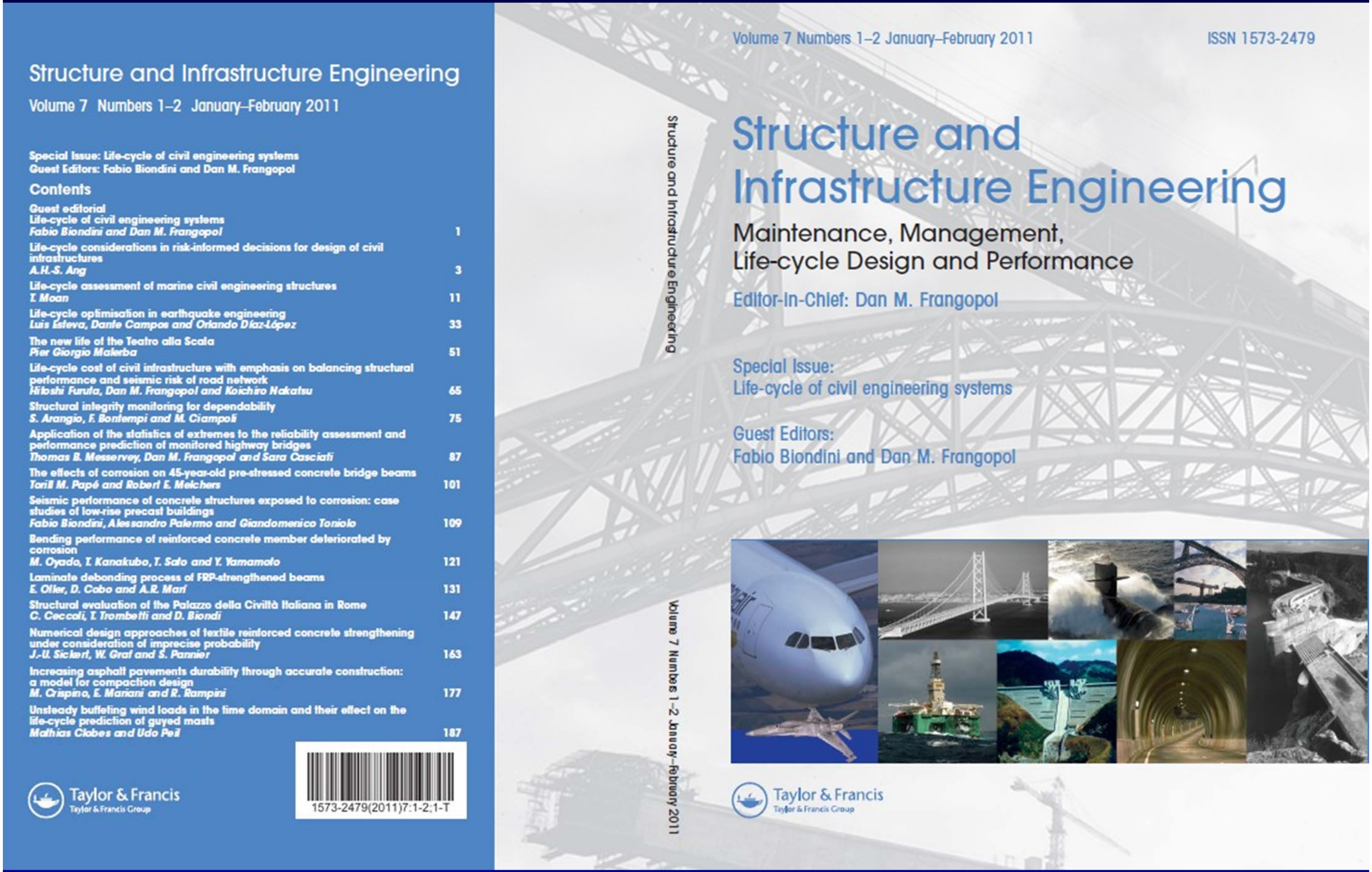
2. Development of prediction models for the structural performance assessment and prediction with **higher accuracy** will **improve the results** of any optimization process. **Incorporation of SHM** in this process is a field in its infancy.

3. **Improvements** in probabilistic and physical models for evaluating and comparing the risks and benefits associated with various alternatives for **maintaining or upgrading the reliability of existing structures** are needed.

Future challenges

Acquire reliable data and develop advanced computational tools in order to :

- PROVIDE BETTER KNOWLEDGE ON DEGRADATION AND PERFORMANCE OF CIVIL AND MARINE INFRASTRUCTURE SYSTEMS
- SUPPORT BETTER DESIGN METHODS AND PERFORMANCE PREDICTIVE MODELS
- SUPPORT ADVANCED MANAGEMENT DECISION-MAKING TOOLS



Structure and Infrastructure Engineering

Volume 7 Numbers 1–2 January–February 2011

Special Issue: Life-cycle of civil engineering systems
Guest Editors: Fabio Biondini and Dan M. Frangopol

Contents

1573-2479(2011)7:1-2;1-T

Taylor & Francis
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Structure and Infrastructure Engineering

Volume 7 Numbers 1–2 January–February 2011

Volume 7 Numbers 1–2 January–February 2011

ISSN 1573-2479

Structure and Infrastructure Engineering

Maintenance, Management, Life-cycle Design and Performance

Editor-in-Chief: Dan M. Frangopol

Special Issue:
Life-cycle of civil engineering systems

Guest Editors:
Fabio Biondini and Dan M. Frangopol

Taylor & Francis
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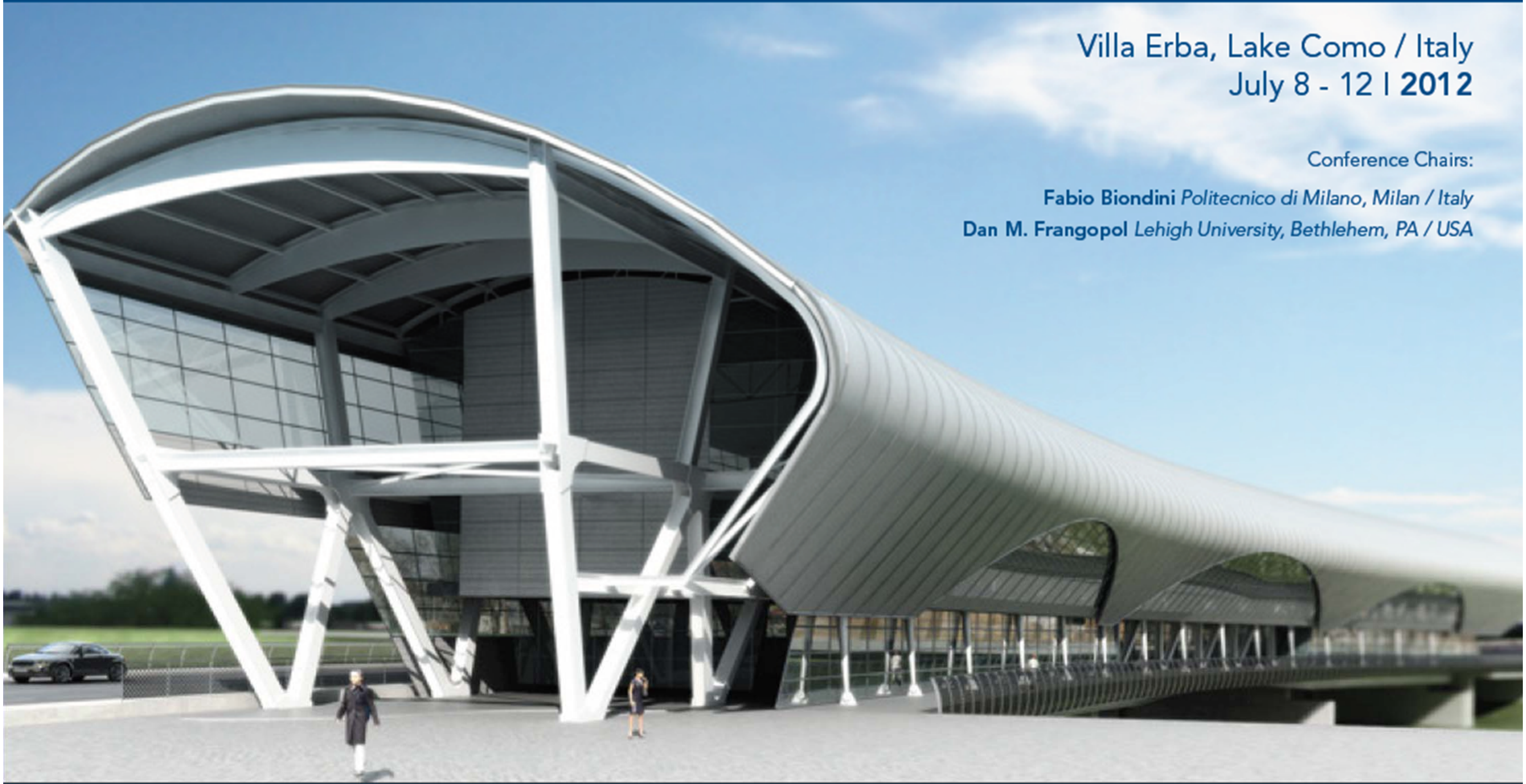
Life-Cycle of Civil Engineering Systems, Fabio Biondini and Dan M. Frangopol (Guest Editors), Volume 7, Numbers 1-2, January-February 2011 (15 articles, ~200 pages).

POLITECNICO
DI MILANO

IABMAS 2012

6th International Conference on
Bridge Maintenance, Safety and Management



Villa Erba, Lake Como / Italy
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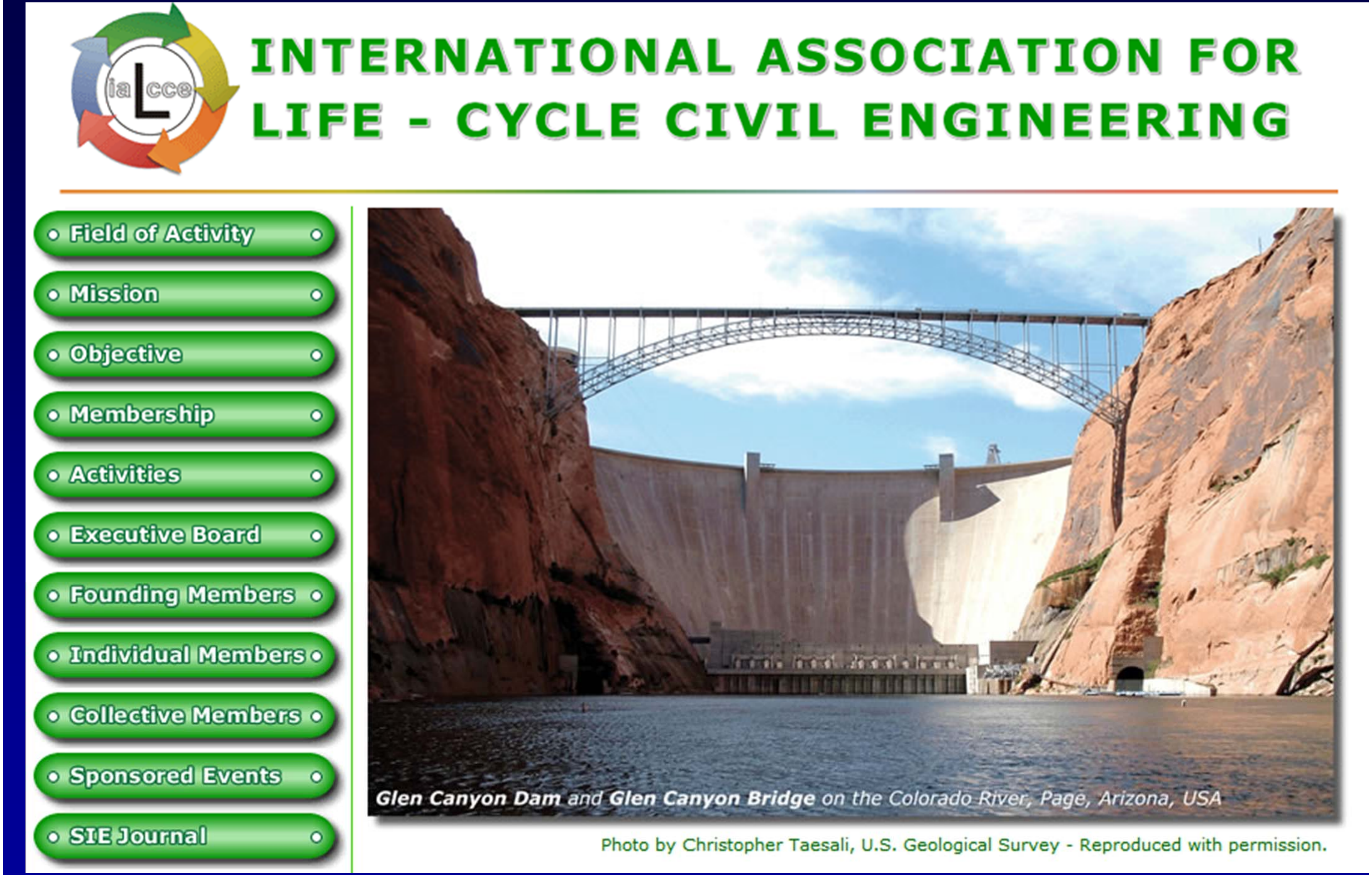
Fabio Biondini *Politecnico di Milano, Milan / Italy*
Dan M. Frangopol *Lehigh University, Bethlehem, PA / USA*

http://www.iabmas2012.org



INTERNATIONAL ASSOCIATION FOR LIFE - CYCLE CIVIL ENGINEERING

***Glen Canyon Dam** and **Glen Canyon Bridge** on the Colorado River, Page, Arizona, USA*

Photo by Christopher Taesali, U.S. Geological Survey - Reproduced with permission.

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AMERICAN SOCIETY OF CIVIL ENGINEERS

SEI
Structural Engineering Institute

SEI-ASCE Technical Council on
Life-Cycle Performance, Safety,
Reliability and Risk of
Structural Systems

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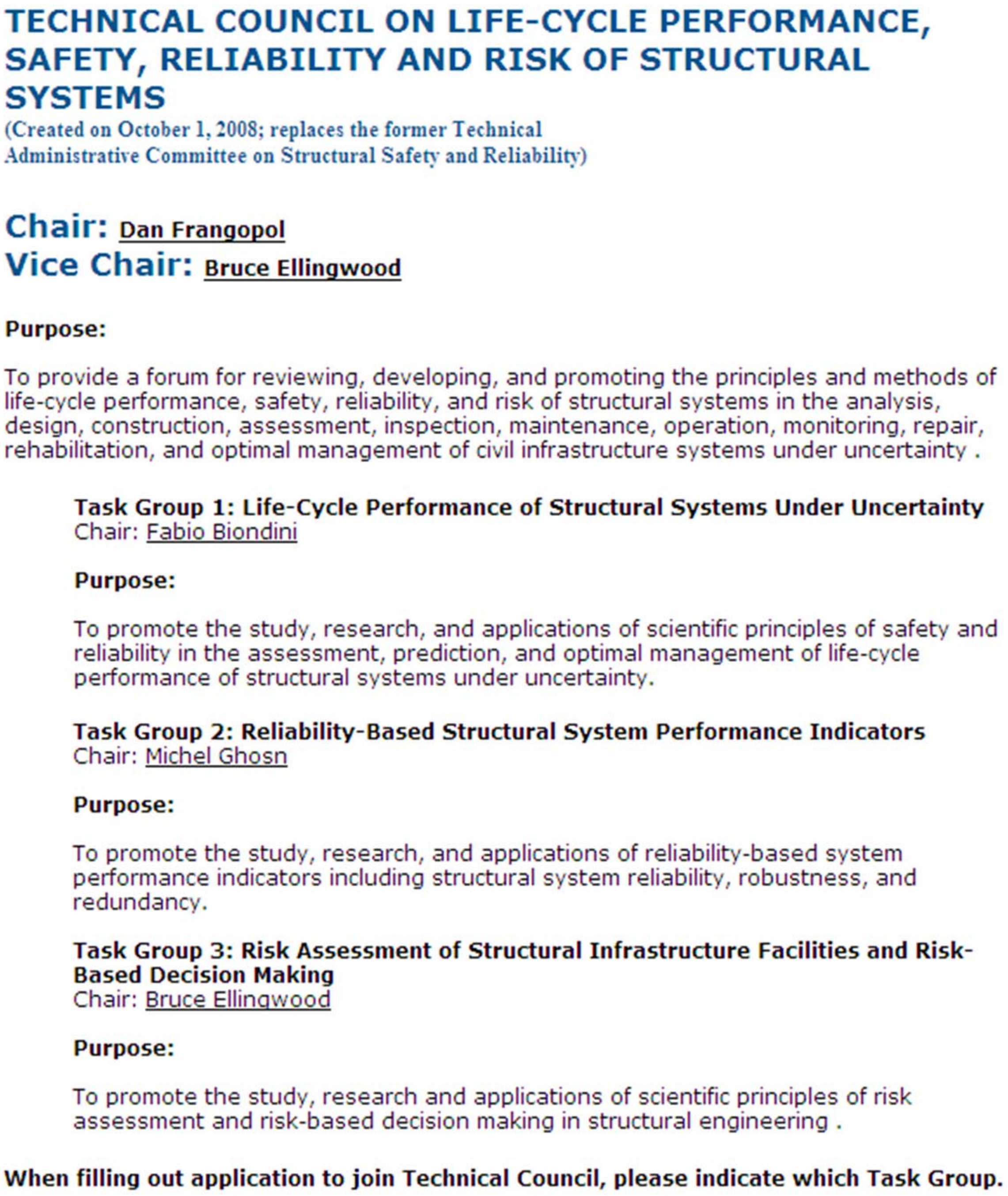

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Administrative Committee on Structural Safety and Reliability)

Chair: **Dan Frangopol**
Vice Chair: **Bruce Ellingwood**

Purpose:

To provide a forum for reviewing, developing, and promoting the principles and methods of life-cycle performance, safety, reliability, and risk of structural systems in the analysis, design, construction, assessment, inspection, maintenance, operation, monitoring, repair, rehabilitation, and optimal management of civil infrastructure systems under uncertainty .

Task Group 1: Life-Cycle Performance of Structural Systems Under Uncertainty
Chair: Fabio Biondini

Purpose:

To promote the study, research, and applications of scientific principles of safety and reliability in the assessment, prediction, and optimal management of life-cycle performance of structural systems under uncertainty.

Task Group 2: Reliability-Based Structural System Performance Indicators
Chair: Michel Ghosn

Purpose:

To promote the study, research, and applications of reliability-based system performance indicators including structural system reliability, robustness, and redundancy.

Task Group 3: Risk Assessment of Structural Infrastructure Facilities and Risk-Based Decision Making
Chair: Bruce Ellingwood

Purpose:

To promote the study, research and applications of scientific principles of risk assessment and risk-based decision making in structural engineering .

When filling out application to join Technical Council, please indicate which Task Group.

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THANK YOU !