Σχολή Πολιτικών Μηχανικών
School of Civil Engineering

INTEGRATED RELIABILITY-BASED LIFE-CYCLE OPTIMIZATION FRAMEWORK FOR MAINTENANCE AND MONITORING OF AGING STRUCTURES: APPLICATIONS TO BRIDGES AND NAVAL SHIPS

May 20 -2011

Dan M. Frangopol
Department of Civil and Environmental Engineering,
ATLSS Engineering Research Center,
Lehigh University, Bethlehem, PA, USA

LEHIGH UNIVERSITY

ATLSS

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

LEHIGH UNIVERSITY

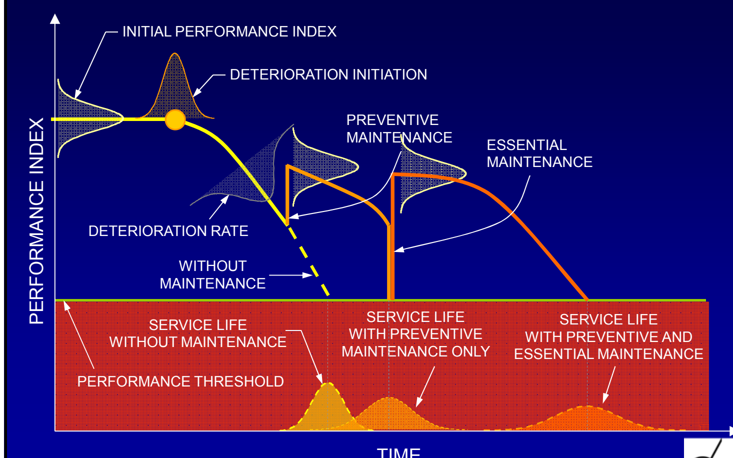
ATLSS

INTEGRATED RELIABILITY-BASED LIFE-CYCLE OPTIMIZATION FRAMEWORK FOR MAINTENANCE AND MONITORING OF AGING STRUCTURES: APPLICATIONS TO BRIDGES , BUILDINGS AND NAVAL SHIPS

LEHIGH UNIVERSITY

ATLSS

SERVICE LIFE UNDER UNCERTAINTY



LEHIGH UNIVERSITY

ATLSS

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.

LEHIGH UNIVERSITY ATLSS

Outline:

Civil Infrastructure

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

LEHIGH UNIVERSITY ATLSS

System-based performance prediction

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

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

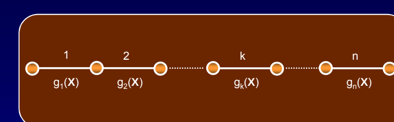
LEHIGH UNIVERSITY ATLSS

LEVELS OF PERFROMANCE QUANTIFICATION

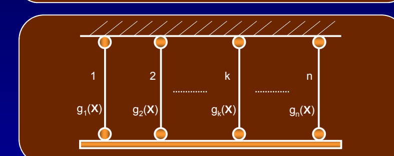
8

System Approach

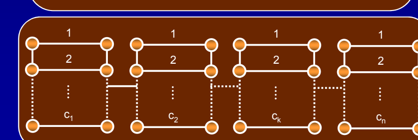
Series System



Parallel System

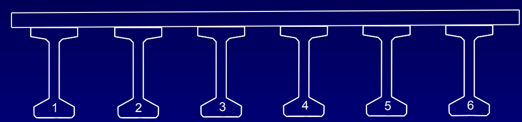


Series-Parallel System

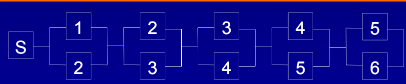


LEHIGH UNIVERSITY ATLSS

Reliability of a system



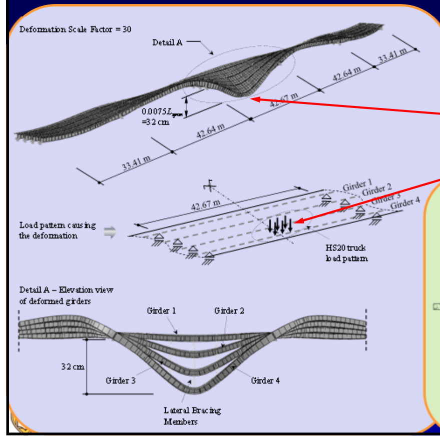
- Considering only flexure
- Failure of slab or failure of any two adjacent girder → System failure



S: Flexure of Slab
i: Flexure of Girder i

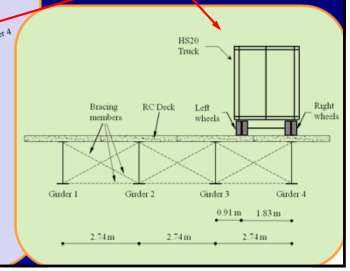
Alternative Approach to Model System Behavior

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"

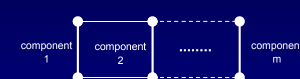
S_1 = time-variant (live) load $\quad$ S_2 = time-variant (dead) load
λ_{S_1}, F_{S_1} = mean load occurrence rate and CDF of time-variant (live) load
f_{S_2} = PDF of S_2 $\quad$ f_{R_0} = PDF of R_0

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



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

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 $(DS)_k^{q_i}$
q = the sequence of l failed members $(0 \le l < m)$

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

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

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

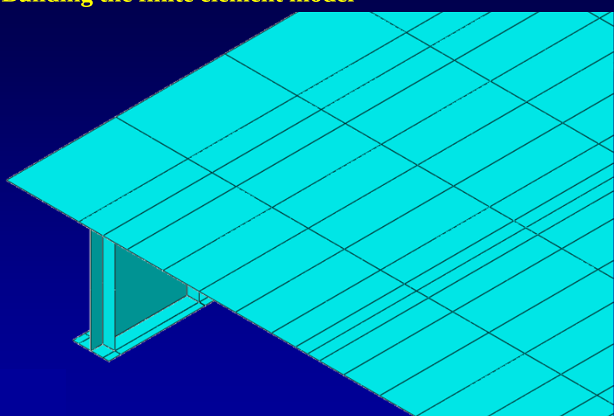
$\beta_{y(sys)}(t)$ = probability of first member failure occurrence at time t
$\beta_{f(sys)}(t)$ = probability of system failure occurrence at time t

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

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

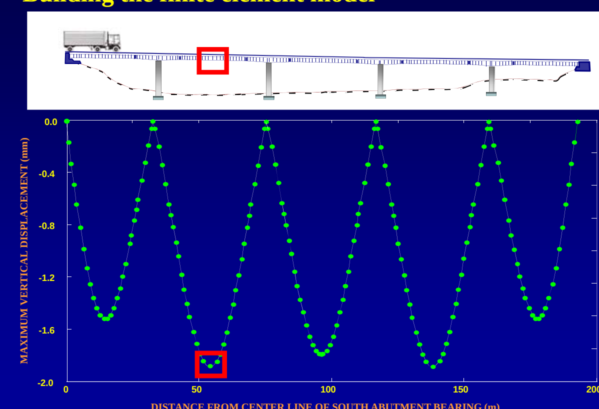
I-39 Northbound Bridge over the Wisconsin River

Building the finite element model



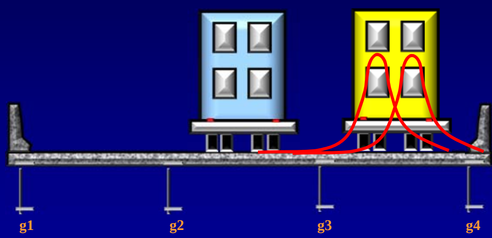
Okasha, N.M. and Frangopol, D.M. (2010). Advanced modeling for the life-cycle performance prediction and service-life estimation of bridges. *Journal of Computing in Civil Engineering*, ASCE, (in press).

Building the finite element model



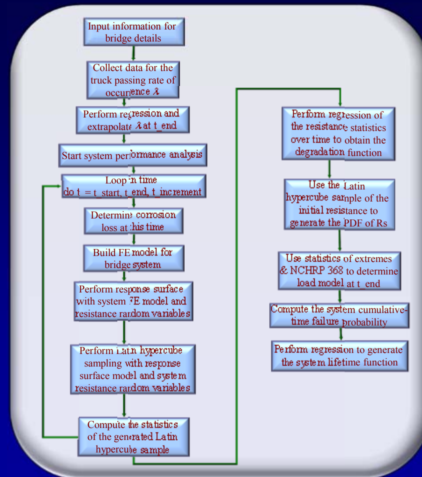
Okasha, N.M. and Frangopol, D.M. (2010). Advanced modeling for the life-cycle performance prediction and service-life estimation of bridges. *Journal of Computing in Civil Engineering*, ASCE, (in press).

Building the finite element model



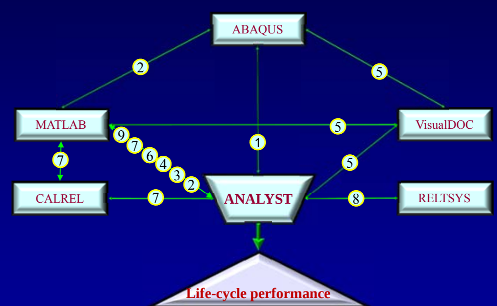
Okasha, N.M. and Frangopol, D.M. (2010). Advanced modeling for the life-cycle performance prediction and service-life estimation of bridges. *Journal of Computing in Civil Engineering*, ASCE, (in press).

Performance prediction



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).

Computational interaction



1) build the finite element model, (2) generate the response envelope, (3) forecast the average daily traffic, (4) perform statistics of extremes for finding the live load multiplier, (5) perform the response surface analysis, (6) perform the Latin hypercube sampling for resistance computations, (7) compute the point-in-time reliability, (8) compute the cumulative-time failure probability, and (9) compute the life-cycle performance (LCP) and the service life.

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

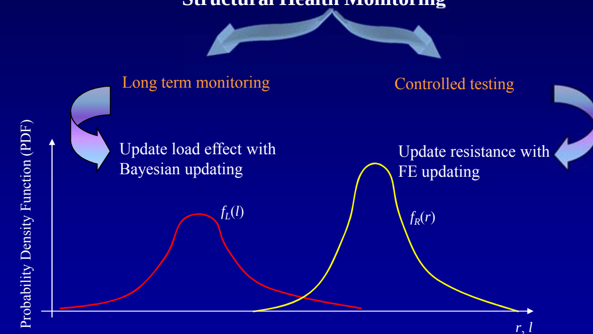
Predictive Tool

Actual Structural Data

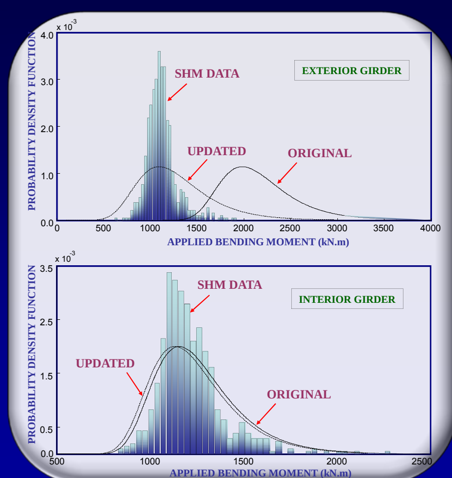
Actionable Information for the bridge manager

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

Updating the performance with SHM data



Load effect updating



Okasha, N.M. and Frangopol, D.M. (2010). Integration of structural health monitoring in a system performance based life-cycle bridge management framework. *Structure and Infrastructure Engineering*, Taylor & Francis, (in press).

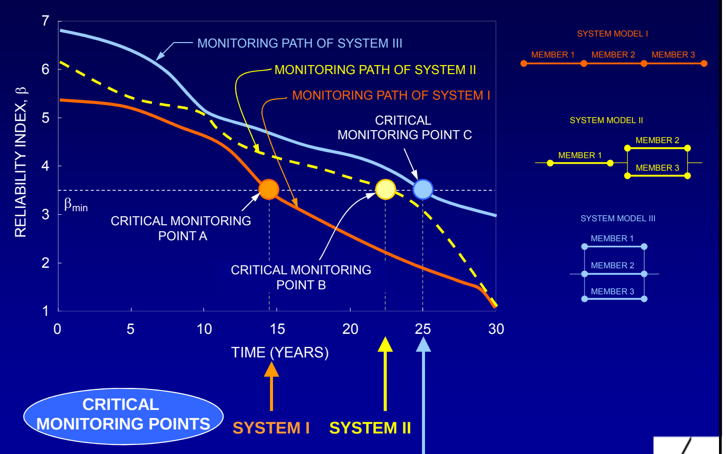
SHM design considerations: System Reliability

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 ?

24

TIME-DEPENDENT MONITORING PATHS



LEHIGH UNIVERSITY ATLSS

Outline:

Civil Infrastructure (This Lecture)

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

LEHIGH UNIVERSITY ATLSS

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**

LEHIGH UNIVERSITY ATLSS

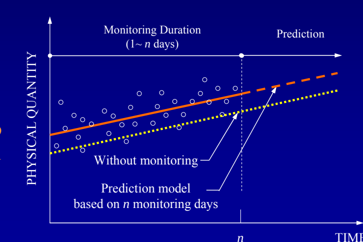
BALANCE OF COST AND AVAILABILITY OF SHM

▲ **MONITORING**

- Monitoring provides additional information about the state of a system at a point i n 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 D ATA FOR PREDICTION**

- **Probability** that the prediction mo del based on monitoring data is u sed in the future



LEHIGH UNIVERSITY ATLSS

COST EFFECTIVE MONITORING PLANNING

BI-OBJECTIVE PROBLEM (FORMULATION)

- OBJECTIVES

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

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

LEHIGH UNIVERSITY ATLSS

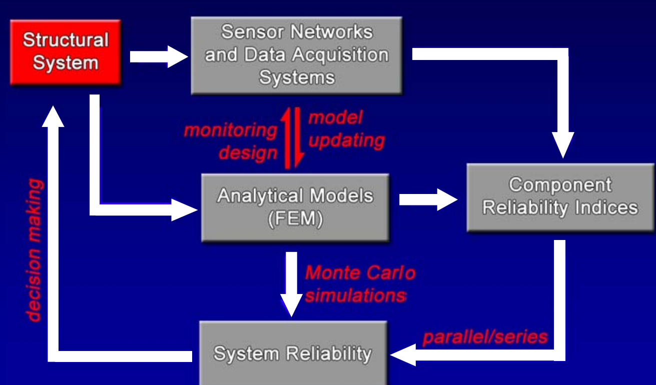
MULTI-OBJECTIVE PROBLEM (APPLICATION)

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

- The structural health monitoring (SHM) program on this bridge was conducted between July and November, 2004 by the personnel from the ATLSS Center with three main objectives
  (a) to assess the bridge serviceability through a complete fatigue evaluation for various fatigue prone details;
  (b) to estimate the remaining fatigue life of the details in question; and
  (c) to monitor the structural responses of the bridge under the actual traffic (uncontrolled load tests) for a relatively long period up to three or four months.
- There were 24 resistance strain gages and two linear variable differential transformers (LVDT) installed at 24 locations on the bridge

LEHIGH UNIVERSITY ATLSS

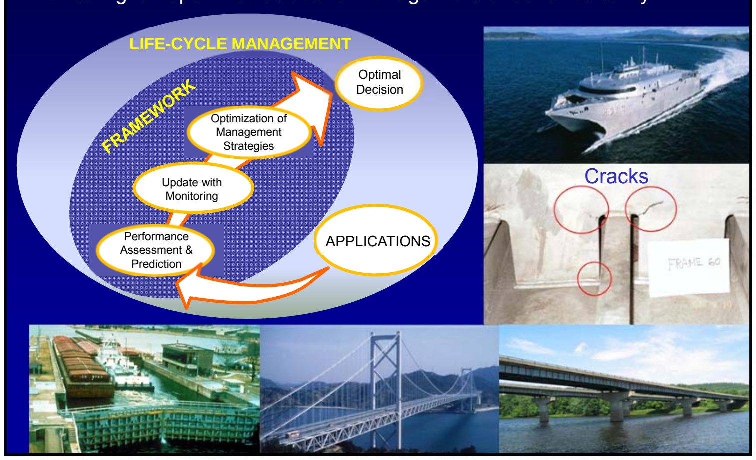
Basic Framework



LEHIGH UNIVERSITY ATLSS

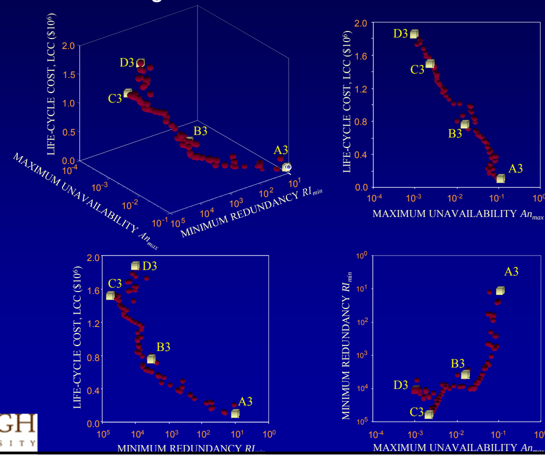
NUMERICAL MULTI-OBJECTIVE OPTIMIZATION

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



NUMERICAL MULTI-OBJECTIVE OPTIMIZATION

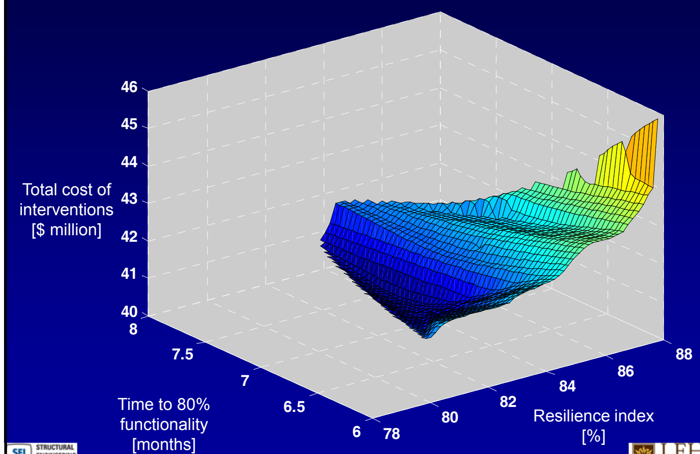
Multi-objective life cycle probabilistic optimization with conflicting criteria by means of **Genetic Algorithms**



LEHIGH UNIVERSITY

ATLSS

LATEST APPLICATION: SANTA BARBARA



SEI STRUCTURAL ENGINEERING INSTITUTE

LEHIGH UNIVERSITY

NAVAL SHIPS

SEI STRUCTURAL ENGINEERING INSTITUTE

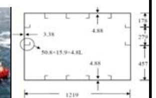
LEHIGH UNIVERSITY

ONR ATLSS LEHIGH UNIVERSITY

Applications

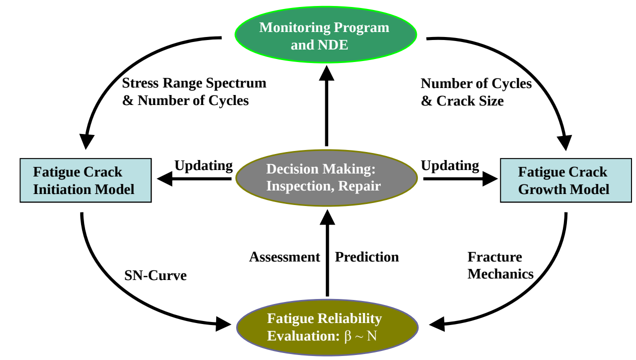
	HSV-2 (high speed naval craft, wave-piercing catamaran)	• Material: aluminum • Length: 98 m • Speed: 35 knots or greater Data from: Brady. Global structural response measurement of SWIFT (HSV-2) from JLOTS and blue game rough water trials. West Bethesda, MD: NSWCCD-65-TR-2004/33, Naval Surface Warfare Center, Carderock Division, 2004.
	JHSS Joint High-speed Sealift Ship	• Material: steel • Length: 299.45 m • Speed: 45 knots Data from: Devine. An overview of the recently-completed JHSS Monohull and Trimaran structural seaways loads test program. Naval Surface Warfare Center, Carderock Division (NSWCCD), PowerPoint Briefing, 30 October, 2009
	TANKER	• Material: steel • Length: 236 • Speed: 16 knots Data from: Soares & Garbatov. "Fatigue reliability of the ship hull girder". *Marine Structures*, Elsevier, 9(3-4), 495-516, 1996

Main Topics

[1] Marine Structures [2] J. of Ship Research [3] Struct. and Infr. Eng. [4] Struct. Health Monitoring [5] Int. J. of Fatigue				
Fatigue		[3]	[5]	
Damage detection	[4]		[5]	
Optimization			[5]	[2]
Reliability	[4]	[1, 3]		[2]
Redundancy		[1]		
SHM	[4]	[1, 3]	[5]	

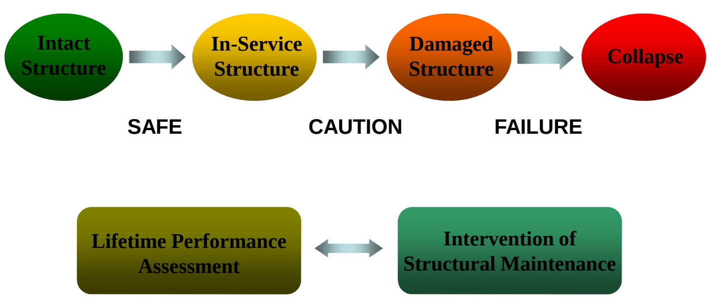
Progress

Overview of Ship Fatigue Evaluation

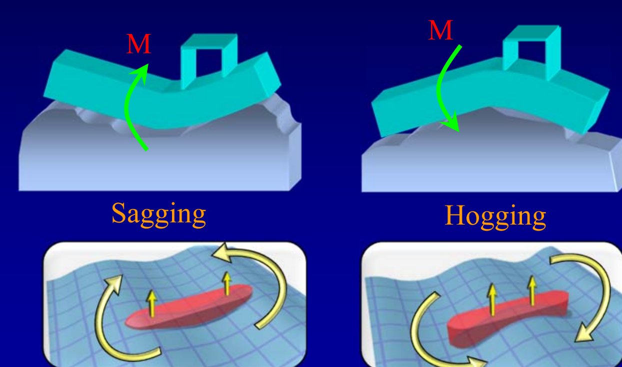


Progress

FATIGUE LIFE MANAGEMENT OF ALUMINUM SHIPS

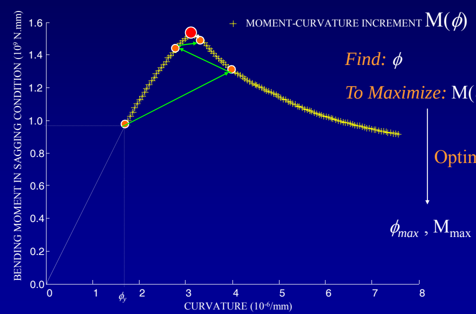


Bending strength of ships



Incremental-curvature method

THE USE OF OPTIMIZATION



Find: ϕ

To Maximize: $M(\phi)$

Optimization Search Methods

ϕ_{max} , M_{max}

Okasha, N.M. and Frangopol, D.M. (2010). Efficient method based on optimization and simulation for the probabilistic strength computation of the ship hull. *Journal of Ship Research*, SNAME, 54(4), 1-13.

OPTIMIZATION METHOD (Okasha and Frangopol, Journal of Ships Structures, 2010 (in press))

Time saving in computations:

Method	Number of increments or iterations	Number of function evaluations	Ultimate sagging moment (N.mm)	Computation time (sec)	5000 Simulation Time (hr)
Sagging Condition					
Incremental method	180	180	1.69186×10^{13}	20.58	28.58333
Golden Section	7	8	1.691691×10^{13}	2.91	4.041667
Quadratic Programing	2	9	1.690656×10^{13}	3.28	4.555556
Hogging Condition					
Incremental method	183	183	1.79254×10^{13}	22.59	31.375
Golden Section	5	6	1.792356×10^{13}	3.16	4.388889
Quadratic Programing	2	6	1.779753×10^{13}	4.35	6.041667

Outline:

PART I: Civil Infrastructure

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

PART II: Marine Structures

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

Frangopol, D.M. and Okasha, N.M. (2010). Life-cycle framework for maintenance, monitoring, and reliability of naval ship structures. *Proceedings of the Working conference on Reliability and Optimization of Structural Systems*, IFIP WG 7.5, Munich, Germany. (in press)

Outline:

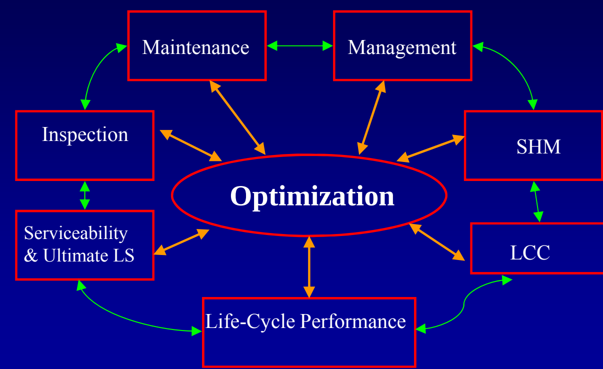
PART I: Civil Infrastructure

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

PART II: Marine Structures

- *System-Based Performance Prediction*
- *Updating the Performance with SHM Data*
- *Maintenance Optimization*
- *Management Framework*
- *Reliability Analysis and Damage Detection in High Speed Naval Crafts*

Optimization



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

ASCE AMERICAN SOCIETY OF CIVIL ENGINEERS

SEI Structural Engineering Institute

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

Founded 2008

http://content.seinstitute.org/committees/strucsafety.html

TECHNICAL COUNCIL ON LIFE-CYCLE PERFORMANCE, SAFETY, RELIABILITY AND RISK OF STRUCTURAL SYSTEMS

(Created on October 1, 2008; replaces the former Technical 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.

THANK YOU !