HAROSA KC WORKSHOP 2009
Castelldefels (Barcelona)
November, 9-11, 2009

IEMAE: Mathematics & Statistics Applied to Civil Engineering & Building

Carles Serrat
Director of IEMAE
Dept of Applied Mathematics I - EPSEB
UPC – Barcelona Tech

Aims

A. IEMAE Introduction

B. Structural Reliability Contribution:

USING DISCRETE-EVENT SIMULATION TO DESIGN RELIABLE AND COST EFFICIENT CIVIL-ENGINEERING STRUCTURES

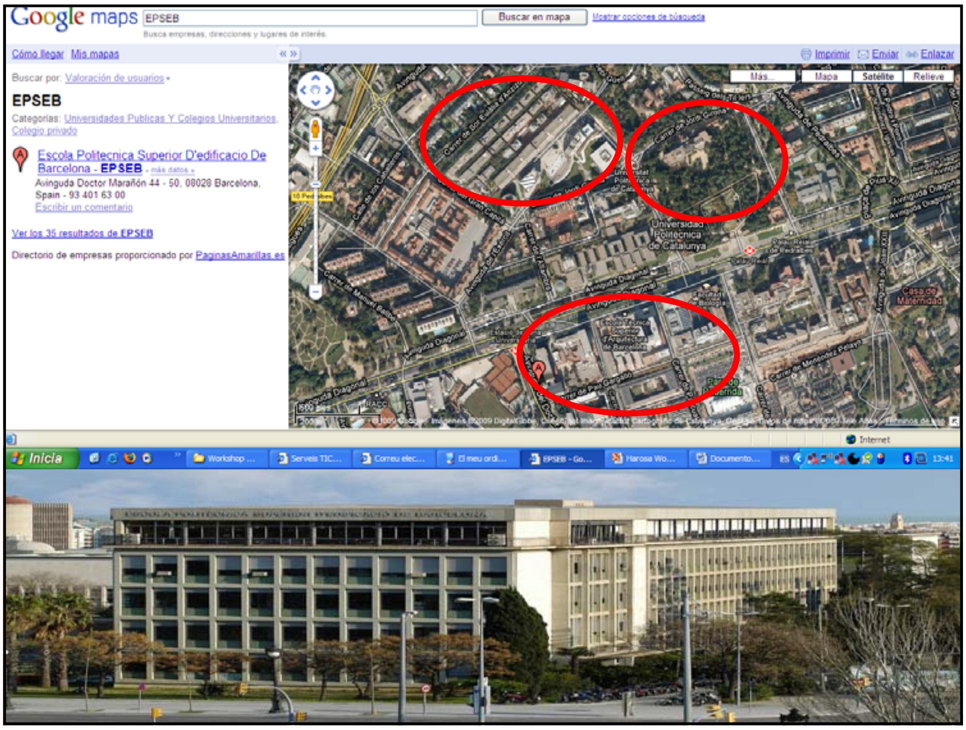
Outline A

1. IEMAE Presentation
2. Who we are?
3. Research fields
4. Academic projects
5. IEMAE Seminar

A. IEMAE Introduction

1. **IEMAE Presentation**

IEMAE (*Institut d'Estadística i Matemàtica Aplicada a l'Edificació* - Institute of Statistics and Mathematics Applied to the Building Construction) is an academic institution interested in solving Multidisciplinary problems in the civil and building engineering area by using statistics and mathematics disciplines.



A. IEMAE Introduction

2. **Who we are?**

   15 professors (5 depts) + 1 administrative staff

   In particular 10 + 1 involved in the HAROSA KC

3. **Research fields**
   - Structural Reliability
   - Survival Maintenance
   - Building Project Scheduling
   - Building Prevention and Safety
   - Related Areas

A. IEMAE Introduction

4. **Academic projects**
   Members of the IEMAE are involved in the promotion and supervision of
   - Degree Final Projects
   - Master Thesis
   - Doctoral Thesis

5. **IEMAE Seminar**
   The IEMAE Seminar is the periodically meeting point where members of the Institute share advances in their respective research topics and offer also the oportunity of inviting other researches .

USING DISCRETE-EVENT SIMULATION TO DESIGN RELIABLE AND COST EFFICIENT CIVIL-ENGINEERING STRUCTURES

A. Juan, A. Ferrer, C. Serrat, J. Faulin, J. Hester & P. Lopez

http://dpcs.uoc.es http://iemae.upc.edu

Members of the HAROSA Knowledge Community

www.uoc.edu

Outline B

1. Introduction

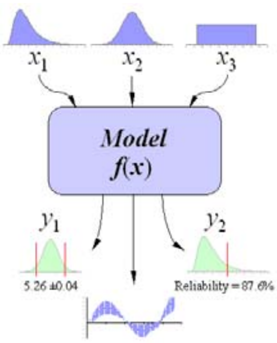
- Some building and civil engineering structures are exposed to natural forces → they suffer from age-related degradation (deterioration, fatigue, deformation, etc.) and also from the effect of external factors (corrosion, overloading or environmental hazards).
- The state of these structures should not be considered constant but rather as being variable through time.

Structural reliability analysis should consider the structure's evolution through time

- We propose the use of discrete-event simulation (DES) and fuzzy rule-based systems as the most natural way to deal with uncertainties in time-dependent structural reliability and availability (R&A) analysis.

Bridges, wind turbines, off-shore platforms, ... their reliability varies with time

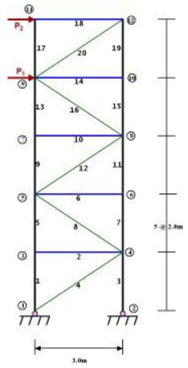
Simulation-based methods can be used in Structural R&A analysis



2. Structural Reliability

$$R(t) = 1 - F(t) = P(T > t)$$

- SR aims to predict and/or determine the R&A and safety of structures, both during their design stage and during their useful life.
- For a given structure, it is possible to consider a set of limit states (Melchers 1999). These limit states define the different types of structural failure or malfunction.
- SR is defined as the probability that a structure will not achieve each specified limit state (i.e. will not suffer a particular type of failure) during a specified period of time (Thoft-Christensen & Murotsu 1986).
- SR goal: to provide an assembly of components which, when acting together, will perform satisfactorily for some specified time period, either with or without maintenance policies (at component level).



Most structures can be seen as systems

No maintenance → Reliability
With maintenance → Availability

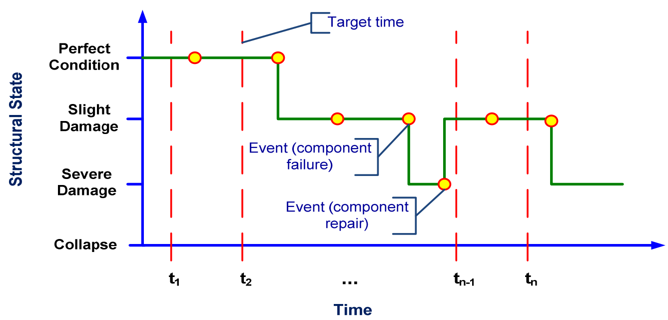
3. Describing the problem

- Consider a structure with several components linked together according to a well-defined logical topology. Assume that time-dependent reliability functions for each component are known (from historical records or survival analysis techniques).
- At any target-time the structure will be in one of the following 4 states: (a) perfect condition; (b) slight damage; (c) severe damage; and (d) collapsed, i.e. 3 types of structural failures.
- Goal: to estimate R/A functions for each type of struct. failure.

Survival analysis techniques, such as accelerated life-tests, can be used to obtain reliability information at component level.

Structural states:
a)Perfect condition
b)Slight damage
c)Severe damage
d)Collapsed

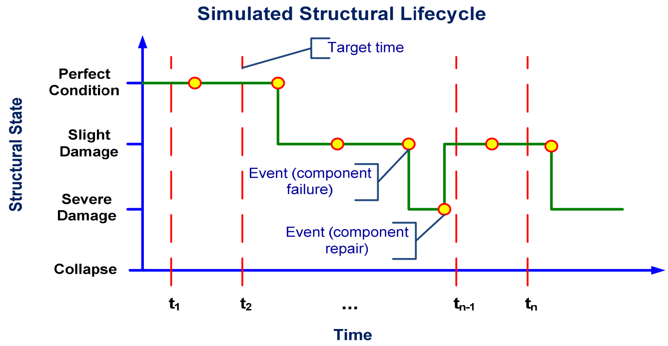
Simulated Structural Lifecycle



Given a logical topology and R&A information at component level, we want to infer R&A information at the system (structural) level.

4. Basic ideas of our approach

- Idea: DES can be used to generate a random sample of structural lifecycles, each providing a random observation of the structural state at each target-time. After running a large number of iterations, accurate point and interval estimates for the structural reliability function can be obtained (Juan et al. 2007; Faulin et al. 2008).
- Additional information: which components are more likely to fail?, which component failures are more likely to cause structural failures?, etc.
- (What-if analysis) effects of: a different logical topology, adding redundancies, improving components' reliability, maintenance policies, dependencies, etc.



We use DES to artificially generate random observations of the structural lifecycle.

Then we use statistical inference to obtain interval estimates for R&A levels at each target time.

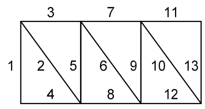
Additional parameters describing the structural behavior can also be estimated from the sample.

5. A reliability numerical example (1/2)

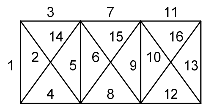
- 3 possible designs for a bridge: case A (original design), case B (redundant components) and case C (reinforced components). Which is the most appropriate design?
- A failure of one component in the case A and C bridges lead to a type 2 failure (severe damage), while it will only lead to a type 1 failure (slight damage) in the case B bridge.
- We assumed that the failure-time distributions associated with each individual truss are known:

Failure-time distribution for each of the trusses

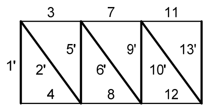
Component	Distribution	Shape	Scale	Component	Distribution	Shape	Scale
1	Weibull	4	22	9	Weibull	4	22
1'	Weibull	6	28	9'	Weibull	6	28
2	Weibull	6	18	10	Weibull	6	18
2'	Weibull	6	28	10'	Weibull	6	28
3	Weibull	5	30	11	Weibull	5	30
4	Weibull	5	30	12	Weibull	5	30
5	Weibull	4	22	13	Weibull	4	22
5'	Weibull	6	28	13'	Weibull	6	28
6	Weibull	6	18	14	Weibull	6	18
6'	Weibull	6	28	15	Weibull	6	18
7	Weibull	5	30	16	Weibull	6	18
8	Weibull	5	30	-	-	-	-



Case A:
Original base structure
(13-bar plane truss)



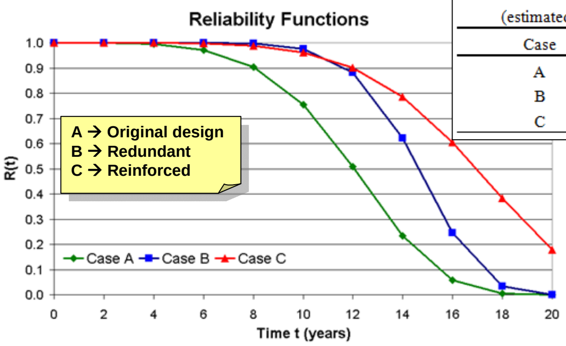
Case B:
Original structure with redundant components
(16-bar plane truss)



Case C:
Original structure with reinforced components
(13-bar plane truss)

5. A reliability numerical example (2/2)

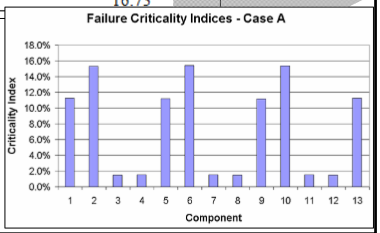
- We used the J-SAEDES software (Juan et al. 2008), which implements the algorithms described in our methodology.
- Each case was run for one million iterations using a standard PC (Intel Pentium 4 CPU 2.8GHz and 2GB RAM). The total computational time employed for running all iterations was below 10 seconds for the two tests related to Cases A and C, and below 60 seconds for the test related to Case B.
- Cases B and C represent more reliable structures than case A. Case B (redundant components) shows itself to be a design at least as reliable as case C (reinforced components) for some time period (about 11 years), after which case C is the most reliable.



Structural Mean Time To Type-2 Failure (estimated values from simulation)

Case	Years
A	11.86
B	14.52
C	16.73

Failure Criticality Indices help to identify key components in structural reliability.

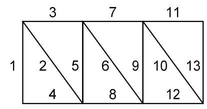


6. An availability numerical example (1/2)

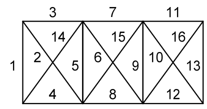
- With DES, we can also consider the effect of maintenance policies –modeled as random repair-times for each component– and track the structural availability function as well as the associated costs of those repairs.
- It is assumed that repair-time distributions for each of the trusses are known:

Repair-time distributions for each of the trusses

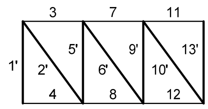
Component	Distribution	Shape	Scale	Component	Distribution	Shape	Scale
1	Weibull	2	0.5	9	Weibull	2	0.5
1'	Weibull	2	0.5	9'	Weibull	2	0.5
2	Weibull	1.8	0.5	10	Weibull	1.8	0.5
2'	Weibull	1.8	0.5	10'	Weibull	1.8	0.5
3	Weibull	1.8	0.3	11	Weibull	1.8	0.3
4	Weibull	1.8	0.3	12	Weibull	1.8	0.3
5	Weibull	2	0.5	13	Weibull	2	0.5
5'	Weibull	2	0.5	13'	Weibull	2	0.5
6	Weibull	1.8	0.5	14	Weibull	1.8	0.5
6'	Weibull	1.8	0.5	15	Weibull	1.8	0.5
7	Weibull	1.8	0.3	16	Weibull	1.8	0.5
8	Weibull	1.8	0.3	-	-	-	-



Case A: Original base structure (13-bar plane truss)

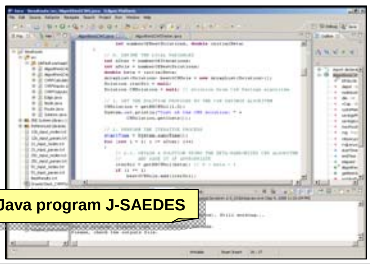


Case B: Original structure with redundant components (16-bar plane truss)



Case C: Original structure with reinforced components (13-bar plane truss)

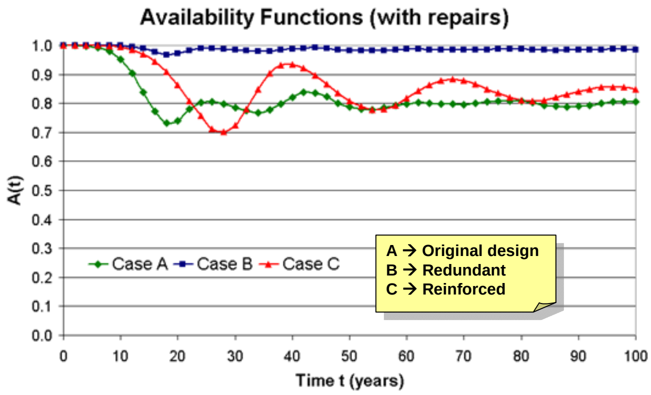
Which design alternative provides the highest availability levels?



Java program J-SAEDES

6. An availability numerical example (2/2)

- Results:
  - a) No significant differences between cases A and C: since we are now considering repairs at component level, reinforcing some components (case C) will basically shift the availability curve to the right, but not upwards.
  - b) Adding redundancies (case B) has shown to be more effective: since we are repairing components as they fail, and since repair times are much smaller than failure times, it is unlikely to suffer a structural type-2 failure in case C.

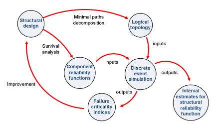


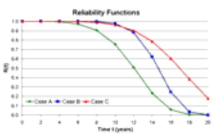
In this example, the design with redundancies is the one showing the highest availability (operability) levels.

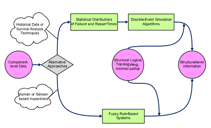
DES also provides estimates for the number of repairs that will be necessary to perform in each scenario → a cost analysis can be easily performed.

7. Conclusions & Future work

- Some authors propose the use of probabilistic methods (as a more realistic alternative to traditional standard codes) to estimate R&A in time-dependent civil engineering structures.
- Among the available methods, DES is one of the most realistic choices. It offers clear advantages over other approaches:
  - a) It allows to create models which accurately reflect the structure's characteristics and behavior, including possible dependences among components' failure and repair times, non-perfect repairs, etc.
  - b) It allows to obtain estimates for almost any structural parameter and to identify structure's critical components.
- The numerical examples provide some insight on how DES can be used to estimate structural R&A functions, how it can contribute to detect critical components and how to make better designing decisions.
- Future work: we are currently adding fuzzy rule-based systems to our model as an alternative to the use of statistical distributions.







Some technical details of our approach can be found at:
- **Juan et al (2007). *European J. of Industrial Engineering***
- **Faulin et al (2008). *Reliability Eng. and System Safety***

8. Some related work

- Marek et al. (1996): recommended the use of probabilistic techniques as a more realistic alternative than standard design codes.
- Lertwongkornkit et al. (2001): stated that techniques other than design codes should be employed to account for uncertainty in structural behavior.
- Laumakis & Harlow (2002): recommended the use of simulation-based methods to incorporate realistic behavior in structural reliability analysis.

Standard design codes do not allow to quantify time-dependent changes in structural R&A levels.

- Fagan & Wilson (1968): presented a MCS procedure to test, compare and verify the results obtained by analytical methods.
- Stewart & Rosowsky (1998): developed a MCS model to calculate probabilities of structural failure for a typical reinforced concrete bridge.
- Kamal & Ayyub (1999): first to use DES for reliability assessment of structural systems that would account for correlation among component failures.
- Marquez et al. (2005): developed simulation-based methods to deal with highly reliable structures.
- Song & Kang (2009): presented a simulation-based numerical method to analyze structural reliability.

MCS has been largely used in structural R&A, but use of DES is much more recent.

Traditionally, use of simulation-based methods in structural R&A has been considered as too expensive in terms of computational time. This is not true anymore!

HAROSA KC WORKSHOP 2009
Castelldefels (Barcelona)
November, 9-11, 2009

IEMAE: Mathematics & Statistics Applied to Civil Engineering & Building

Thank you very much for your attention!!

Carles Serrat
Director of IEMAE
Dept of Applied Mathematics I - EPSEB
UPC – Barcelona Tech