Risk analysis of bridges using a new reliability-based robustness assessment methodology

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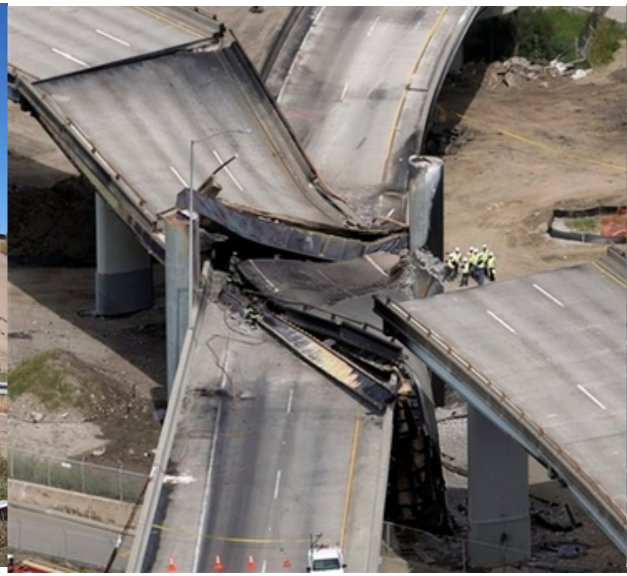
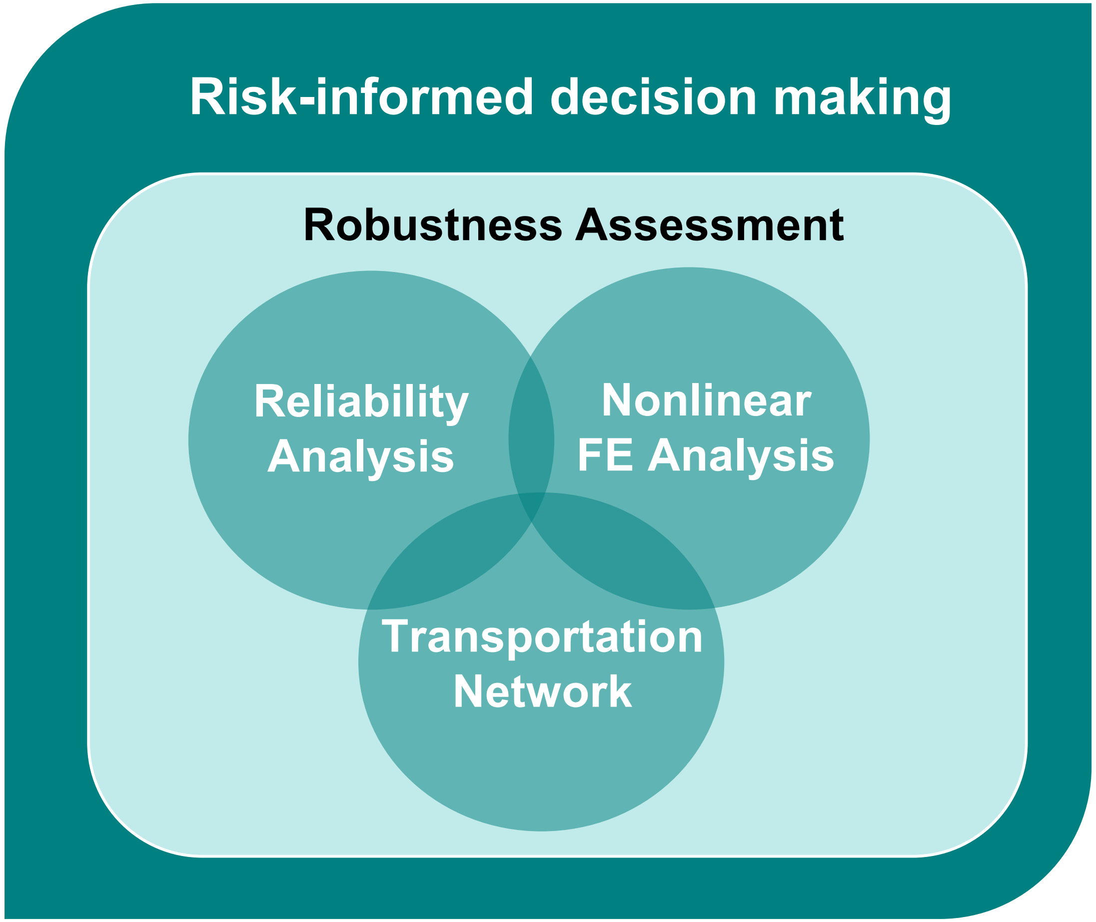



Motivation



The goal is to achieve a performance indicator to be considered in the new generation of risk-based bridge management systems

Framework for Reliability Analysis

Variable screening procedure

Search Domain

Optimized LHS

Initial Experimental Design

$$b_i^{\pm} = \frac{\Delta \mathbf{y}_i / \mathbf{y}_m}{\pm \Delta \mathbf{x}_i / \mathbf{x}_{im}} = \frac{\Delta \mathbf{y}_i / \mathbf{y}_m}{|\pm k \cdot \sigma_{\mathbf{x}_i}| / \mathbf{x}_{im}}$$

$$(b\sigma)_i^{\pm} = |b_i^{\pm}| \cdot (\sigma_{\mathbf{x}_i} / \mathbf{x}_{im})$$

$$\underline{\mathbf{X}_i} = \mathbf{x}_{im} + \underline{K_i} \cdot \sigma_{\mathbf{x}_i}$$

Framework for Reliability Analysis

Double weighted technique

Stepwise regression

Cross-validation

Sparse Response Surface

$$w_g = \alpha_g \cdot \frac{g^g_{\text{best}}}{|g(\mathbf{x}_i)|} \quad \text{and} \quad g^g_{\text{best}} = \min |g(\mathbf{x}_i)|$$

$$w_d = \alpha_d \cdot \frac{g^d_{\text{best}} - ||\mathbf{x}_i - \mathbf{x}_d||}{g^d_{\text{best}}} \quad \text{and} \quad g^d_{\text{best}} = \max ||\mathbf{x}_i - \mathbf{x}_d||$$

$$\widehat{G}(\mathbf{x})$$

Framework for Reliability Analysis

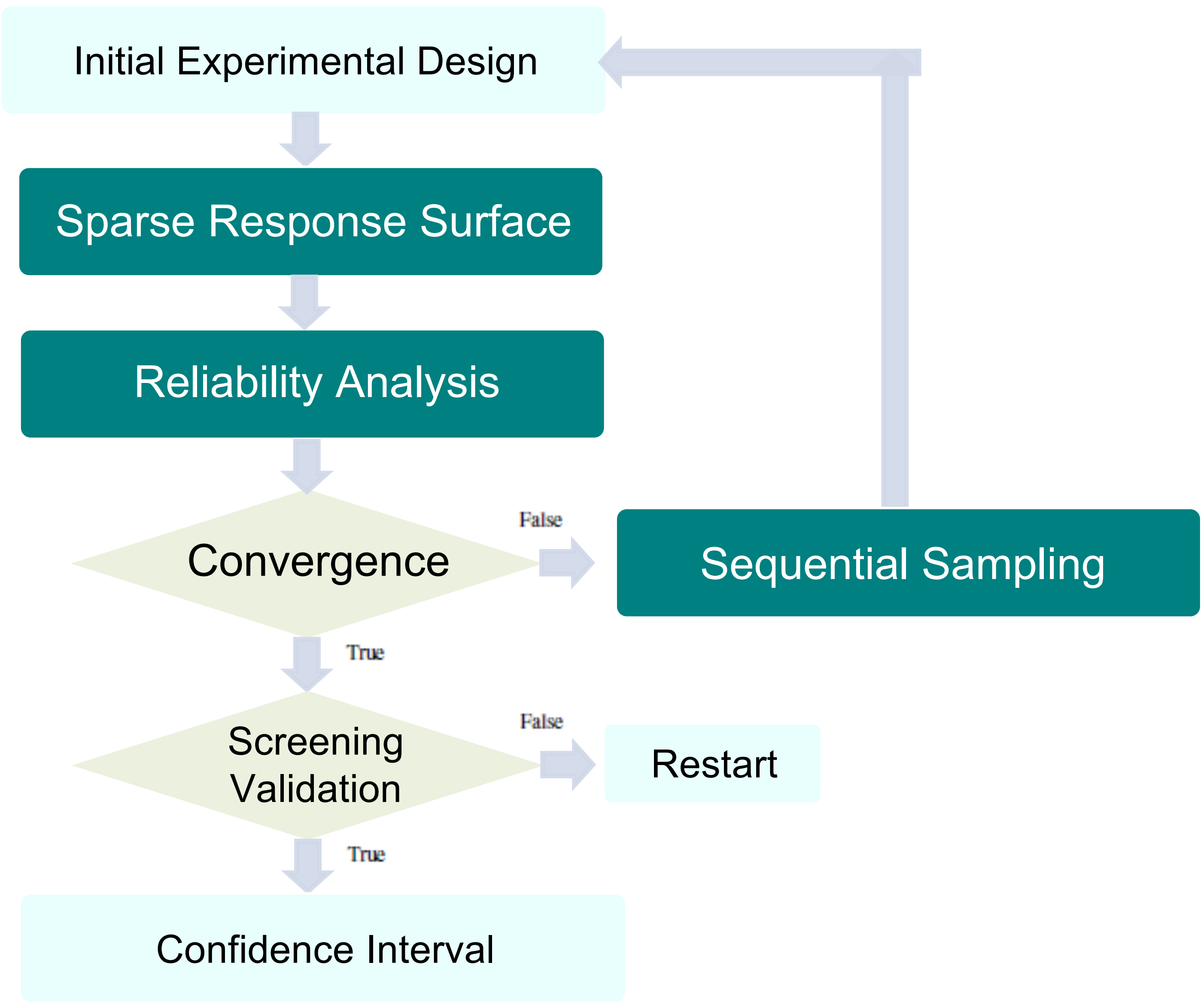
Reliability Analysis

Region of Interest

Sequential Sampling

$$u_i^{\mathrm{lb}} = \arg\min u_i \ \text{ subjected to } \begin{cases} ||\mathbf{u}|| - \beta(1 + \delta_{\varepsilon_{\mathrm{PDF}}}) = 0 \\ G(\mathbf{u}) = 0 \end{cases}$$

Enrich ED

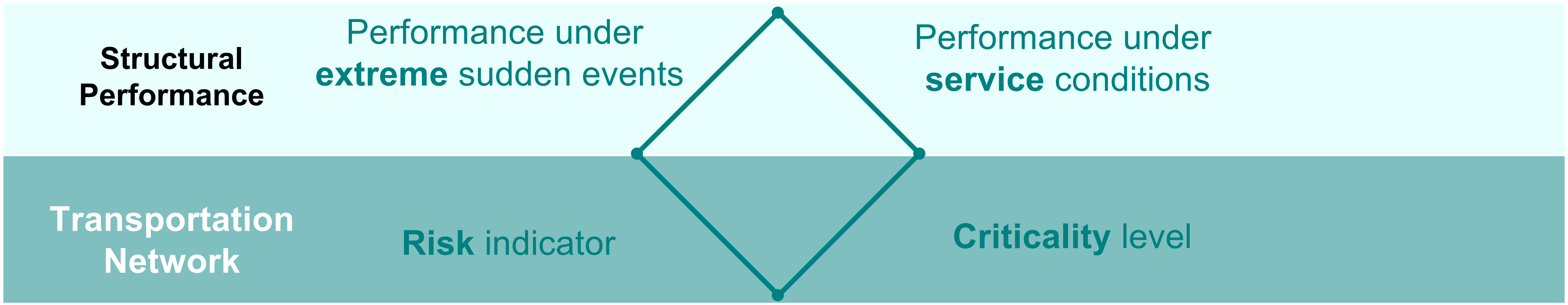


Guimarães, H., Matos, J. C., & Henriques, A. A. (2018). An innovative adaptive sparse response surface method for structural reliability analysis. Structural Safety, 73, 12-28.

Robustness assessment methodology

<u>Reliability analysis</u> of
notional removal of elements

<u>Reliability analysis</u> of
long-term performance considering
effects of corrosion



Normalized risk indicator based
on <u>utility functions</u>

Criticality level based on risk ranking
using <u>utility indifference curves</u>

Performance assessment based on target reliability

Extreme Sudden Event

Effect of local failure

Modeling:

Notional removal of failed elements

- Girder (due to impact)
- Pier (due to hydraulic causes)

Service conditions

Effect of corrosion

Modeling:

- Reduction of cross-section
- Bond strength deterioration
- Ductility reduction

Performance assessment based on target reliability

Resistance capacity
Stress level

Definition Limit State Function

$$G(X) = \cdots$$

Deflection control
Crack control
Stress level

→

Nonlinear FE Analysis

Reliability Analysis

$$P_f = P(G(X) < 0)$$

iRS method

→

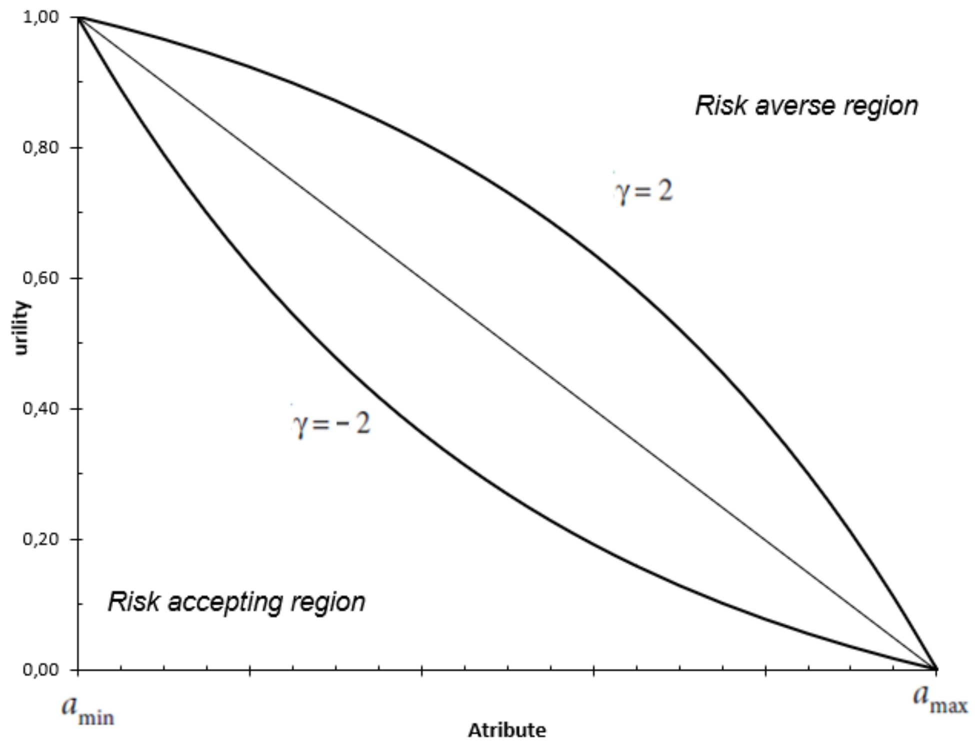
Performance Assessment

$$\beta < \beta_{target}$$

Code-based Recommendation

Risk indicator based on utility functions

Normalized risk indicator which considers <u>consequences</u> of disruption

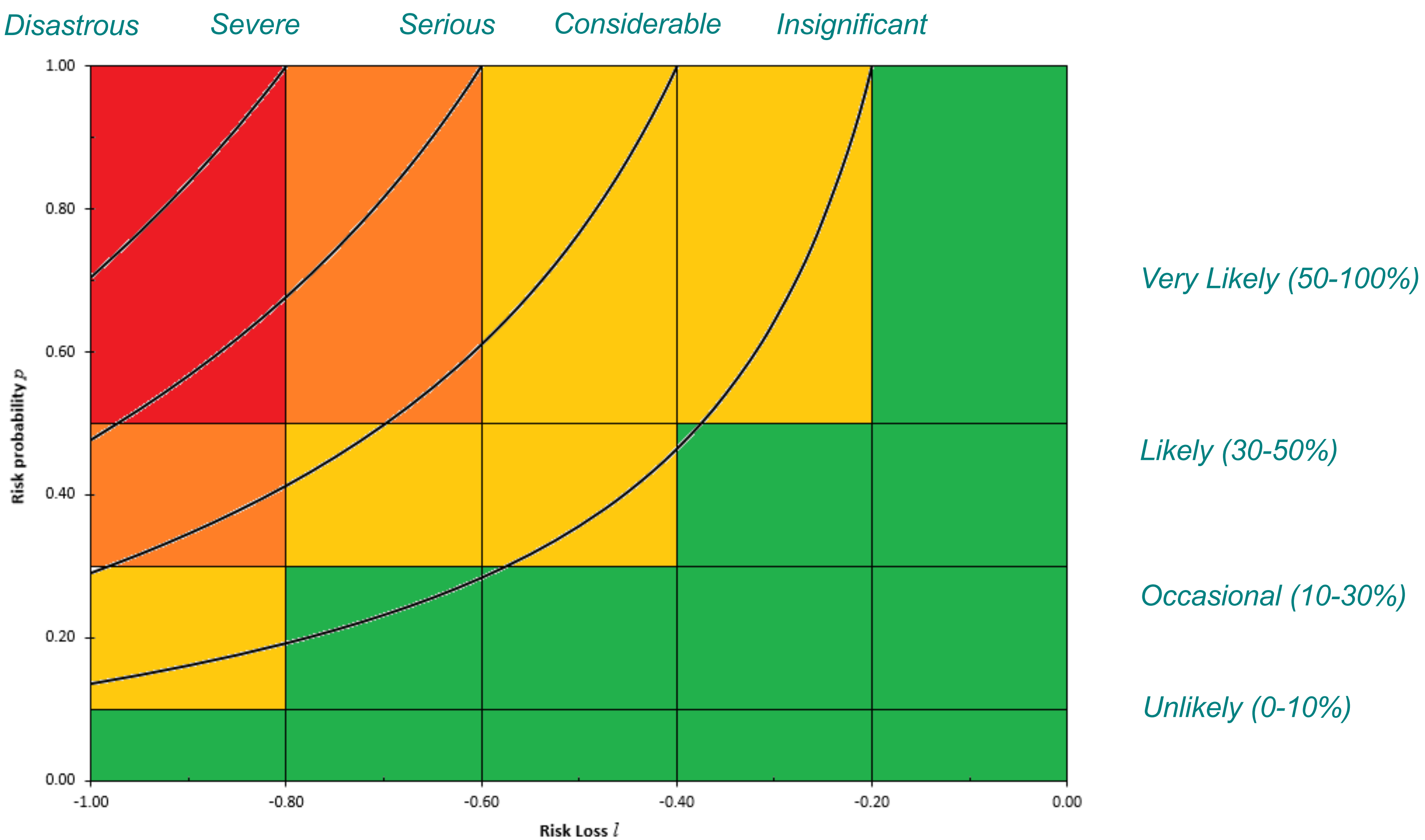


$$u = \frac{1}{1-\exp[-\gamma]}\left(1-\exp\left[-\gamma\frac{a_{max}-a}{a_{max}-a_{min}}\right]\right)$$

Sabatino (2015a, 2015b)

Criticality

Utility indifference curves for risk-averse attitude



Negligible - 1
Acceptable - 0,8
Controllable - 0,6
Critical - 0,2
Unacceptable - 0

Ruan et al. (2015a)

Case Study – Tercenas Bridge

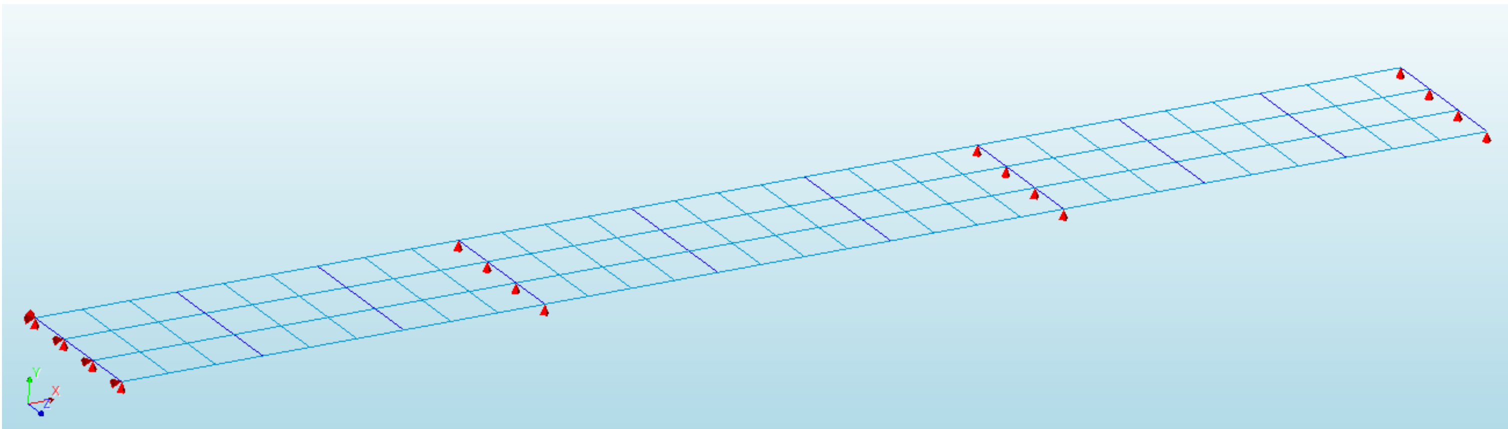
Case Study – Tercenas Bridge

Bridge condition

- Detailed visual inspection pointed out severe deterioration due to reinforcement corrosion
- An average value of 50% of area loss was estimated at girder 1.
- Bridge was demolished and replaced in 2012 due to doubts about its safety.

FE model

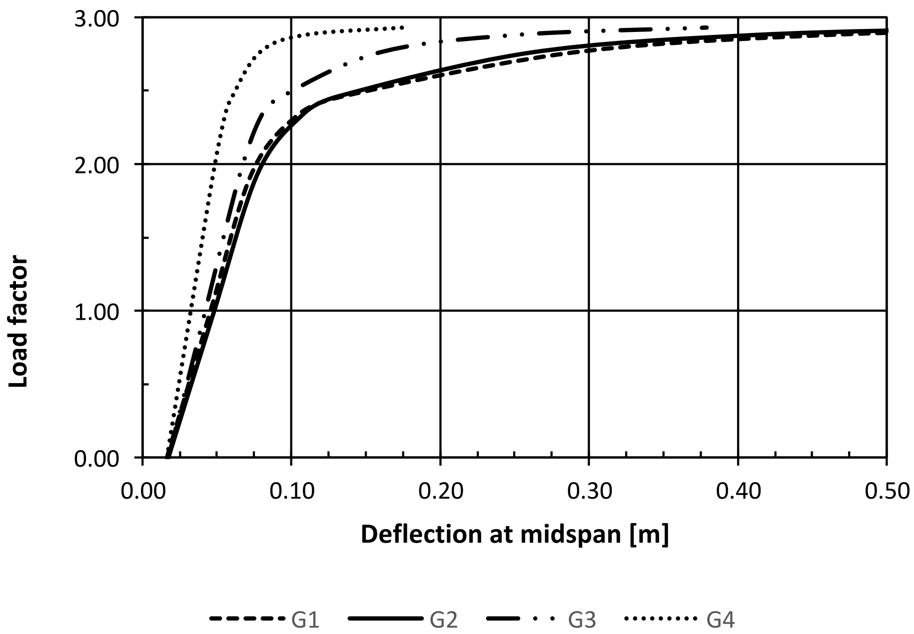
- 3D nonlinear grillage model using TNO DIANA
- Cross-section discretized in several fibers



Deterministic Analysis

Intact structure

Traffic Loads based on LM1 – CEN 2001



Reliability Analysis

$$G(X) = LF(X) - LL$$

Scenario	β
Intact	5.5
Girders equally correded	4.02
Failure of Girder 1	3.65
Failure of Girder 4	3.17

The structure presents a satisfactory reserve capacity.

The slab reinforcement allows to redistribute loads in the transverse direction.

Performance under extreme sudden event meets the target requirements!

Consequences Analysis

Location: Praia da Vieira, Leiria (Portugal)

Road Type: Local road (municipal road)

Direct Costs for Road Administrator

Indirect Costs for Society

	Parameter	Mean value	Unit	Reference
Rebuilding costs	Rebuilding cost parameter, c_{reb}	1545	€ /m^2	Almeida (2013)
	Bridge's width, W	8.9	m	(data)
	Bridge's length, L	60	m	(data)
Detour costs	Running cost for car due to detour, $c_{Run,car}$	0.20	€/km	Santos et al. (2011)
	Running cost for truck due to detour, $c_{Run,truck}$	0.75	€/km	Santos et al. (2011)
	Time loss cost for car due to detour, $c_{TL,car}$	7.46	€/h	Santos et al. (2011)
	Time loss cost for truck due to detour, $c_{TL,truck}$	11.27	€/h	Santos et al. (2011)
Detour	Duration of detour, D_d	540	days	(data)
	Average daily traffic, ADT	100	vehicles	Almeida (2013), IMTT (2016)
	Percentage of truck traffic (% of truck ADT), TT_p	1	%	Almeida (2013)
	Average detour speed for cars, $S_{d,car}$	50	km/h	IMTT (2016)
	Average detour speed for trucks, $S_{d,ctruck}$	40	km/h	IMTT (2016)
	Detour Length, D_l	8.50	km	Google Maps

Consequences Analysis

$$I_{rob} = \frac{R_{dir}}{R_{dir} + R_{ind}}$$

Rebuilding Costs		825,030 €
Running Costs	Car	90,882 €
	Truck	3,443 €
	Total	94,325 €
Time Loss Costs	Car	67,798 €
	Truck	1,293 €
	Total	69,091 €
Time Loss (h)	Car	9088
	Truck	115
	Total	9203
Direct Costs	Total	825,030 €
Indirect Costs	Total	163,416 €
Risk-based Indicator		**0.83**
Direct Costs	Utility	0.26
Indirect Costs	Utility	0.81
Proposed Risk Indicator		**0.49**
Direct Costs	Utility	0.73
Indirect Costs	Utility	0.97
Proposed Risk Indicator		**0.86**
Direct Costs	Utility	0.62
Indirect Costs	Utility	0.94
Proposed Risk Indicator		**0.79**

Risk taking attitude

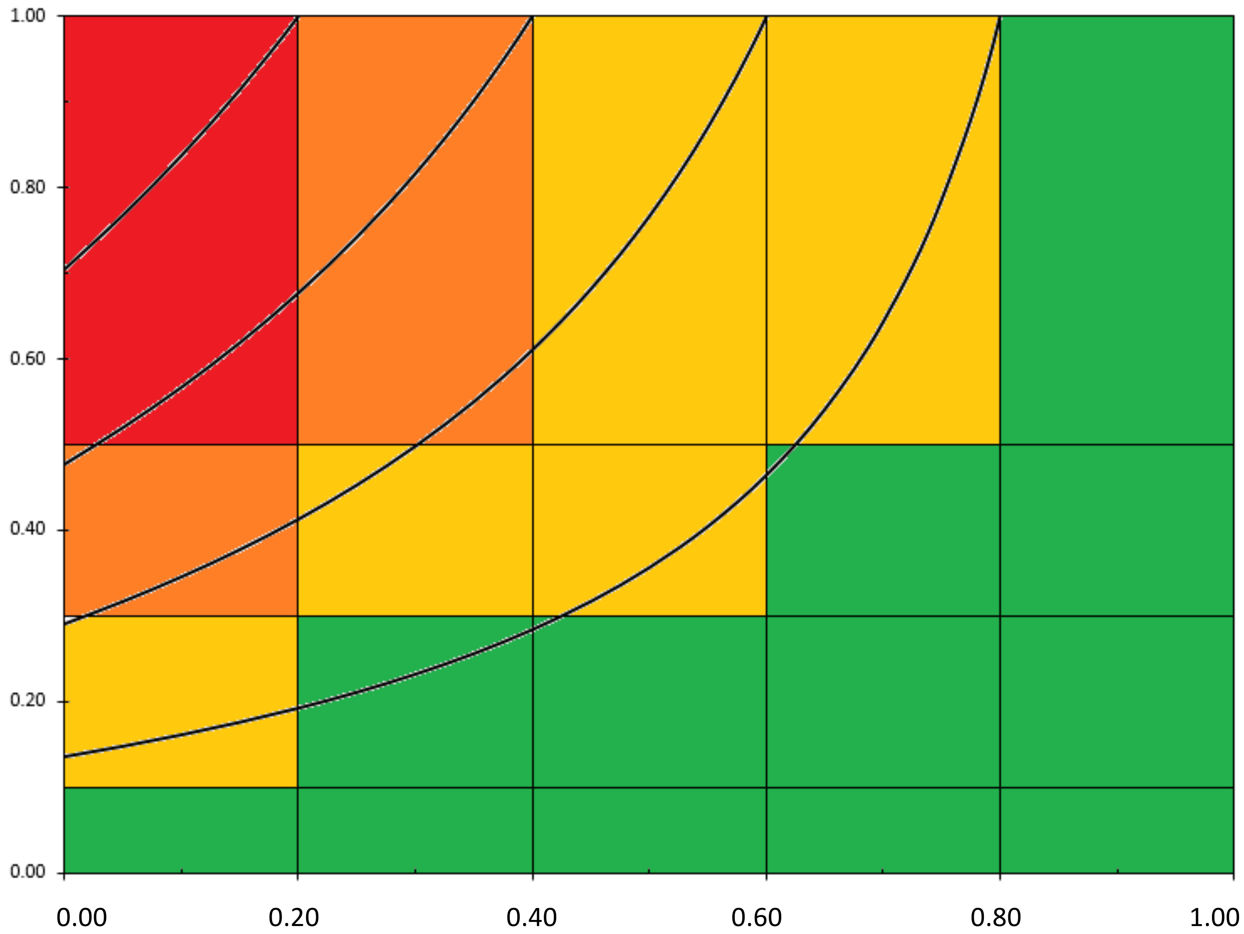
Risk averse attitude

Risk neutral attitude

Maximum admissible direct losses:
% annual budget for maintenance

Maximum admissible indirect losses:
% GDP of affected region

Criticality



Very Likely (50-100%)

Likely (30-50%)

Occasional (10-30%)

Unlikely (0-10%)

Negligible - 1
Acceptable - 0,8
Controllable - 0,6
Critical - 0,2
Unacceptable - 0

$$w_d C_{dir} + w_i C_{ind}$$

Robustness Assessment

		Risk Averse	Risk Neutral	Risk Taking
	Weight	**PI**	**PI**	**PI**
Sudden Event	0.3	1.00	1.00	1.00
Serviciability	0.2	0.00	0.00	0.00
Risk	0.3	0.86	0.79	0.49
Criticality	0.2	0.80	0.80	0.80
Robustness Indicator		**0.72**	**0.70**	**0.61**

Conclusions

- This covered the two main tasks of the research:
  - Response Surface methodology for reliability analysis
  - Robustness assessment methodology

- Case Studies
  - Short span RC bridge (underpass)
  - Tercenas Bridge
  - Highay overpass PS8 (three-span with precast I-girders)