LEONARDO DA VINCI PROJECT CZ/11/LLP-LdV/TOI/134005
SEMINAR ON ASSESSMENT OF EXISTING STRUCTURES
Praha. 26-09-2013

ON THE ASSESSMENT OF SOUND, DETERIORATING AND COLLAPSED STRUCTURES

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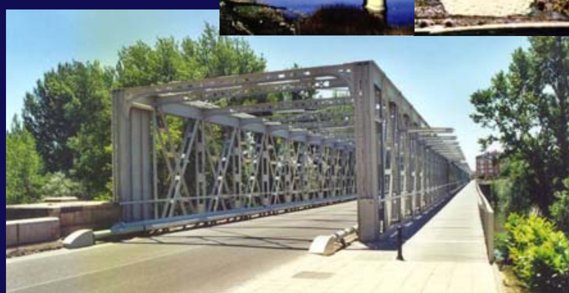
Introduction

MOTIVATION

– The need to assess the reliability of an existing structure may arise from different causes
– All can be traced back to doubts about the structural safety



→ Reliability **ok** for future use ?

MOTIVATION

- Fundamental problem is to find an answer to the question: is the structure safe enough?
- Only two possible answers: yes or no
- Wrong decisions may imply significant consequences

Do nothing

Over-reaction

MORE DOUBTS ABOUT STRUCTURAL SAFETY

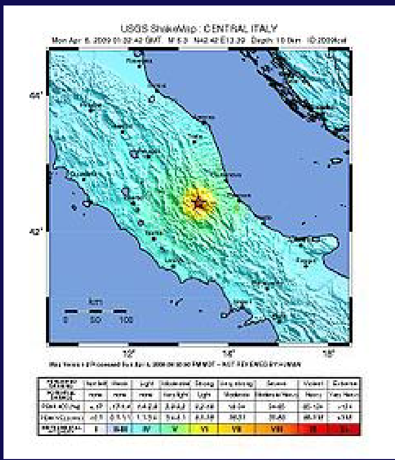
- Derailment of overhead gantry for erection of precast bridge girders

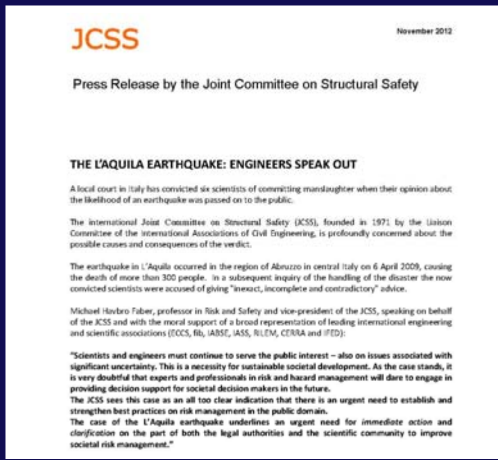
- No problems during previous construction stages under identical conditions

→ How could this happen ?

MORE DOUBTS ABOUT STRUCTURAL SAFETY

- Wrong decisions may imply significant consequences
- Also for experts ...





JCSS

November 2012

Press Release by the Joint Committee on Structural Safety

THE L'AQUILA EARTHQUAKE: ENGINEERS SPEAK OUT

A local court in Italy has convicted six scientists of committing manslaughter when their opinion about the likelihood of an earthquake was passed on to the public.

The international Joint Committee on Structural Safety (JCSS), founded in 1971 by the Liaison Committee of the International Associations of Civil Engineering, is profoundly concerned about the possible causes and consequences of the verdict.

The earthquake in L'Aquila occurred in the region of Abruzzo in central Italy on 6 April 2009, causing the death of more than 300 people. In a subsequent inquiry of the handling of the disaster the now convicted scientists were accused of giving "inexact, incomplete and contradictory" advice.

Michael Havbro Faber, professor in Risk and Safety and vice-president of the JCSS, speaking on behalf of the JCSS and with the moral support of a broad representation of leading international engineering and scientific associations (ECCS, fib, IABSE, IASS, RILEM, CERRA and IFED):

"Scientists and engineers must continue to serve the public interest – also on issues associated with significant uncertainty. This is a necessity for sustainable societal development. As the case stands, it is very doubtful that experts and professionals in risk and hazard management will dare to engage in providing decision support for societal decision makers in the future.
The JCSS sees this case as an all too clear indication that there is an urgent need to establish and strengthen best practices on risk management in the public domain.
The case of the L'Aquila earthquake underlines an urgent need for *immediate action* and *clarification* on the part of both the legal authorities and the scientific community to improve societal risk management."

ASSESSMENT VS. DESIGN

Structures	Existing	New
Available information	"Measurable" characteristics	Assumed characteristics
Reliability depends on	Available data Knowledge	Variables according to codes
Reliability	→ subjective	→ +/- objective

→ Fundamental difference lies in the state of information

→ Staged evaluation procedure, improving accuracy of data

Lifelong Learning Programme

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- Introduction
- **Updated models for the assessment of sound structures**
- Corrosion-damaged reinforced concrete structures
- Analysis of the deteriorating main dome over La Laguna cathedral
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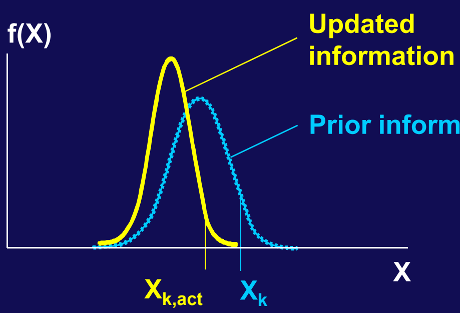
ASSESSMENT WITH PARTIAL FACTOR METHOD

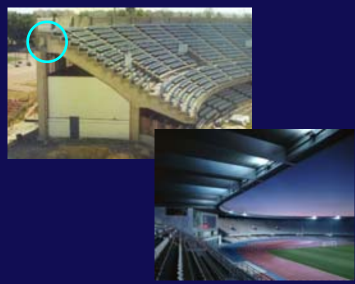
- Probabilistic methods are most accurate to take into account updated information
- But they are not fit for use in daily practice
- Partial factor method should be available for assessment

$$\gamma_{E,act} \cdot E_{k,act} \leq \frac{R_{k,act}}{\gamma_{R,act}}$$

ASSESSMENT WITH PARTIAL FACTOR METHOD

– Updated characteristic value of **X**





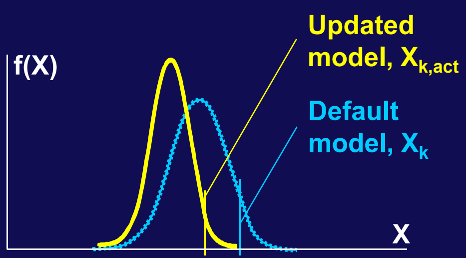
– Updated partial factor $\gamma_{X,act}$ → $\gamma_{E,act} \cdot E_{k,act} \le \dfrac{R_{k,act}}{\gamma_{R,act}}$

→ Can not be derived directly

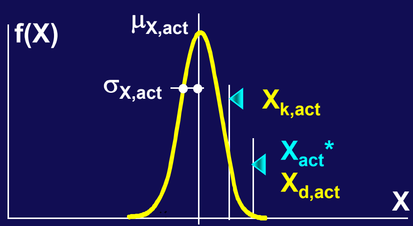
→ Link between probabilistic and partial factor methods: **design point**, the most probable failure point on LS surface

DEVELOPMENT OF PRACTICAL TOOLS FOR THE ASSESSMENT

– Identification of representative failure modes and LSF
– Adoption of partial factor format for assessment
– Definition of reference period
– Deduction of default probabilistic models
– Establishment of required reliability
– **Updating of characteristic values and partial factors**



$X_{d,act}$ (PDF; $\mu_{X,act}$; $\sigma_{X,act}$; $\alpha_{X,act}$; β_{req})



Tools developed

PARTIAL FACTOR FORMAT FOR ASSESSMENT

– Design value for action effects

$$E_{d,act} = \gamma_{Sd,act} \cdot E\left\{\sum_{j\geq 1}\gamma_{g,j,act}\cdot G_{k,j,act}\text{"+"}\gamma_{q,1,act}\cdot Q_{k,1,act}\text{"+"}\ldots\right\}$$

$\gamma_{f,i,act}$	Updated partial factor for actions (statistical variation)
$\gamma_{Sd,act}$	Updated partial factor for the models for action effects and for the simplified representation of actions

– Model uncertainties vary depending on the action effects → distinguish between

$\gamma_{Sd,M,act}$	Bending moments
$\gamma_{Sd,V,act}$	Shear forces
$\gamma_{Sd,N,act}$	Axial forces

– Format differs from EC but is more accurate for evaluation

Tools developed

PARTIAL FACTOR FORMAT FOR ASSESSMENT

– Design value for resistance

$$R_{d,act} = \frac{1}{\gamma_{Rd,act}}\cdot R\left\{\eta_{i,\,act}\cdot\frac{X_{k,i,act}}{\gamma_{m,i,act}};a_{d,act}\right\}$$

$\gamma_{m,i,act}$	Updated partial factor for the material or product property
$\gamma_{Rd,act}$	Updated partial factor for the resistance model

– Model uncertainties vary depending on the resistance mechanism → distinguish between (RC structures)

$\gamma_{Rd,M,act}$	Bending moments
$\gamma_{Rd,V_s,act}$	Tensile forces in the web
$\gamma_{Rd,V_c,act}$	Diagonal compression forces in the web
$\gamma_{Rd,N,act}$	Axial compression forces

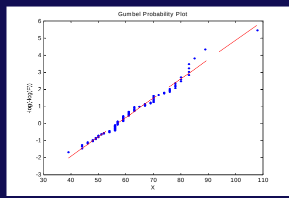
– Format differs from EC-2 but is more accurate for evaluation

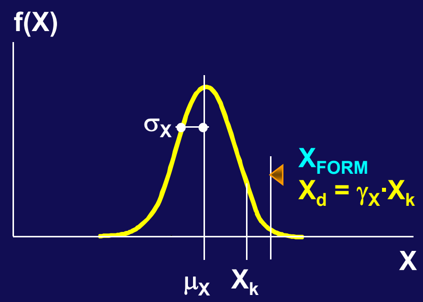
Tools developed

DEFAULT PROBABILISTIC MODELS COMPLYING WITH THE FOLLOWING REQUIREMENTS

- Representation of physical properties of the corresponding variable
- Consistency with *JCSS* models
- Representation of the state of uncertainty associated with code rules
- Representation of uncertainties by means of random variables, suitable for practical applications

$$X_i = Type\left(\mu_{X_i};\sigma_{X_i}\right)$$

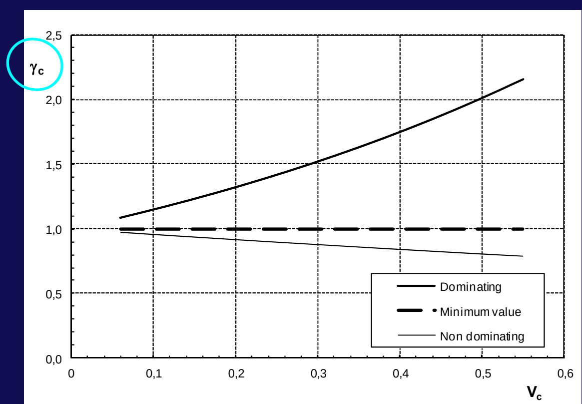




Tools developed

UPDATED PARTIAL FACTORS

- For example partial factor for concrete strength versus CoV



Definition $\gamma_c \neq \gamma_{c,EC\text{-}2}$

Comparable $\gamma_c \cdot \gamma_{Rd} \Leftrightarrow \gamma_{c,EC\text{-}2}$

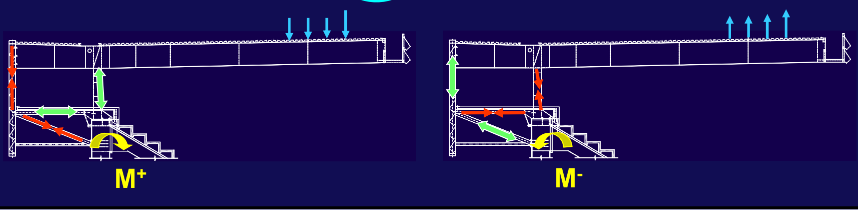
$$R_{d,act} = \frac{1}{\gamma_{Rd,act}} \cdot R\left\{\eta_{i,act} \cdot \frac{X_{k,i,act}}{\gamma_{m,i,act}}; a_{d,act}\right\}$$

EXAMPLE

– Assessment of existing RC structure for new conditions

– Site data collection has been decided, planned and carried out

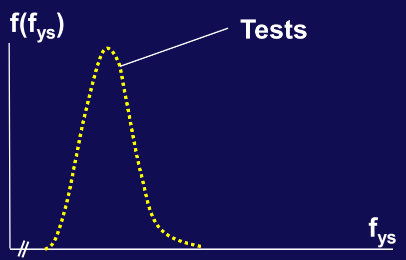
→ Sample of n test results is available for updating of reinforcement yield strength, f_{ys}



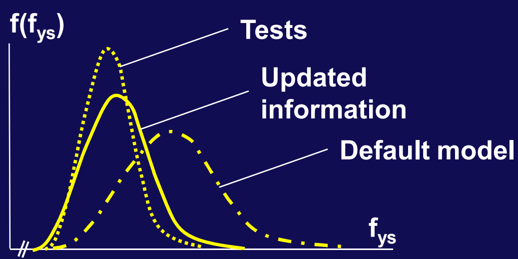
PROCEDURE

1. Statistical evaluation of results of observations

   → PDF: $f_X(x)$

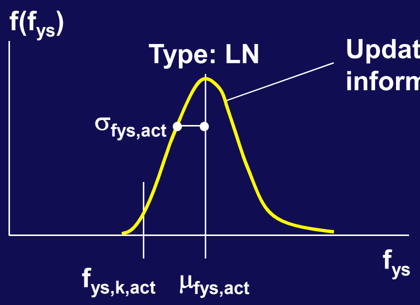


2. Combination of the results of observations with the available prior information (default probabilistic models)



PROCEDURE

3. Description of the updated distribution function by means of relevant parameters: Type; $\mu_{X,act}$; $\sigma_{X,act}$; $x_{k,act}$



4. Coefficient of variation for the relevant function of updated random variables, depending on the partial factor format for assessment

EXAMPLE

– Partial factor for reinforcing steel takes into account
  – Uncertainties related to the yield strength, f_{ys}
  – Uncertainties related to the cross-sectional area, A_s

– f_{ys} and A_s enter the LSF as a product: tensile force →
  $F_{ys} = f_{ys} \cdot A_s$

– Only f_{ys} has been updated

– Updated coefficient of variation for the tensile force

$$V_{Fys,act} \cong \sqrt{V_{fys,act}^2 + V_{As}^2}$$

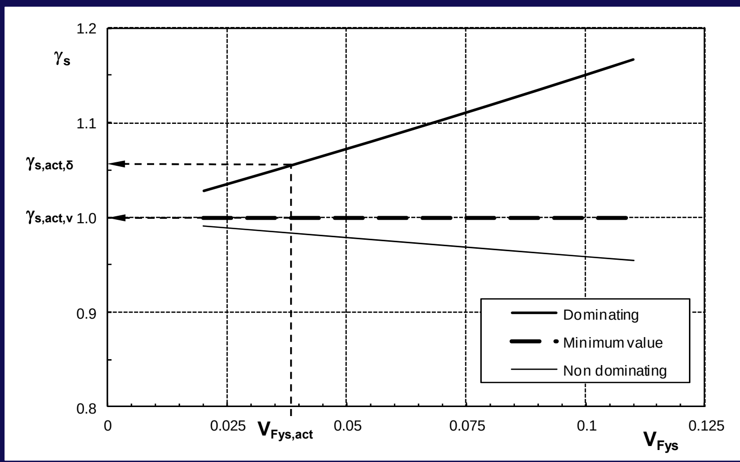
$$V_{fys,act} = \frac{\sigma_{fys,act}}{\mu_{fys,act}}$$

Default value
$V_{As} = 0.02$

Assessment with site-specific models

PROCEDURE

5. Updated partial factor, considering the updated variable dominating or non dominating (unknown in advance)

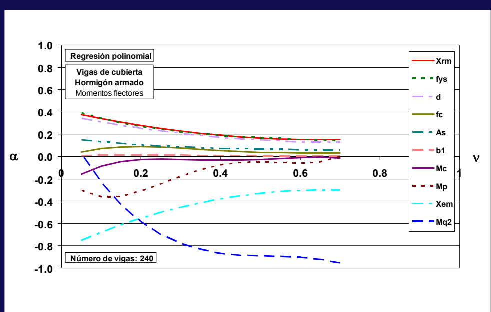


Assessment with site-specific models

PROCEDURE

6. Verification of structural safety with updated characteristic values and partial factors: $x_{ik,act}$; $\gamma_{Xi,act}$

Dominating variable unknown in advance → trial and error or considering α_x



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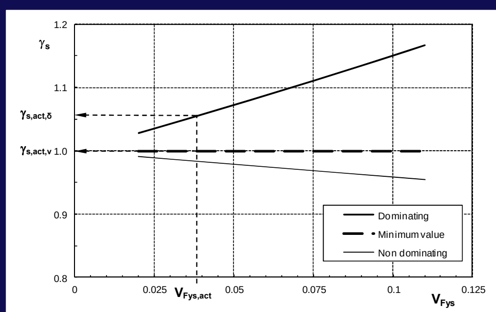

EXAMPLE

- Verification of bending resistance of RC element
- Only f_{ys} has been updated
- Dominating resistance variable: F_{ys}
- Verification of structural safety: $M_{Ed,act} \leq M_{Rd,act}$

$$M_{Rd,act} = \frac{1}{\gamma_{Rd,M}}\left(\frac{A_s \cdot f_{ys,k,act}}{\gamma_{s,act,\delta}} \cdot d - 0.5\left(\frac{A_s \cdot f_{ys,k,act}}{\gamma_{s,act,\delta}}\right)^2 \cdot \frac{\gamma_c}{\eta_c \cdot f_{ck}} \cdot \frac{1}{b}\right)$$



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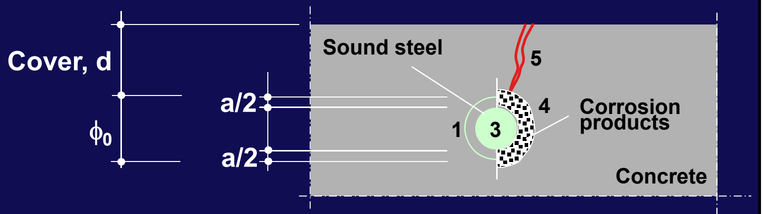
MAIN EFFECTS OF CORROSION OF REINFORCEMENT BARS

1. Decrease of bar cross-section
2. Stress concentrations due to uneven corrosion
3. Decrease of ductility of steel (ε_u: reduction of 30 to 50%)
4. Bond deterioration
5. Cracking and loss of concrete cover (corrosion products)



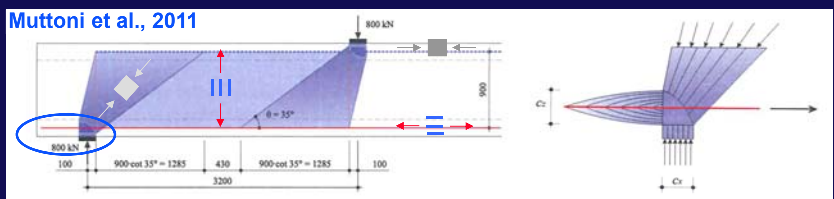
→ Corrosion may affect performance at ULS and SLS

ASSUMPTIONS

– Lower bound theorem of the theory of plasticity is valid

A load system, based on a statically admissible stress field which nowhere violates the yield condition is a lower bound to the collapse load.

– Stress field models can be established



– Required information
  - Geometry, particularly remaining bar cross-sections
  - Material properties
  - Bond strength

SITE DATA COLLECTION

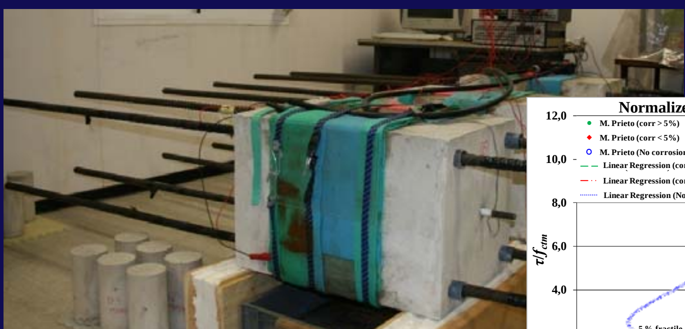
– Geometry and material properties can be updated

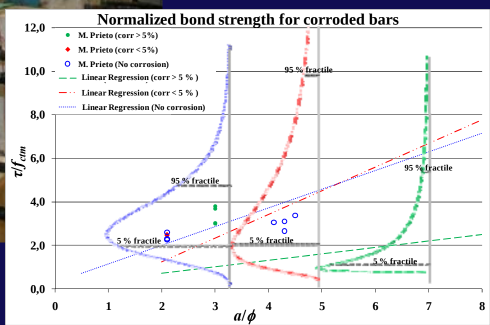
BOND STRENGTH

– Updating is difficult

→ Experimental and numerical study has been conducted

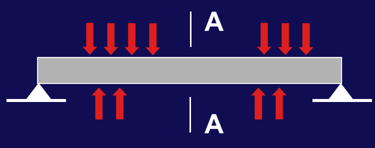
→ Normalized bond strength available

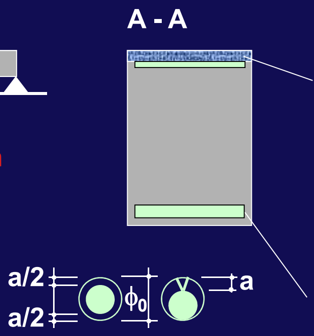




SIMPLE MODELS

– Example: bending resistance





Upper bound: active

Lower bound: disregarded (spalling)

$$A_s(t) = n \frac{\pi (\phi_0 - a(t))^2}{4}$$

→ Similar rules for other failure modes, including shear, and SLS

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Context

SAN CRISTÓBAL DE LA LAGUNA

- Historic city located in Tenerife
- Typical urban structure developed in Latin America during colonisation
- → Declared a UNESCO World Heritage Site in 1999

Context

CATHEDRAL

- Built over former church of *Nuestra Señora de los Remedios*
- Cathedral since 1818
- Declared in ruins in 1897 due to settlements induced damage
- → Except neo-classical facade, it was completely demolished

Context

CATHEDRAL

– Rebuilt between 1905 and 1913 in neo-gothic style according to engineering drawings by José Rodrigo Vallabriga
– Novel technology was used: reinforced concrete
  – Shorter construction time
  – Lower costs

Motivation

RISKS ASSOCIATED WITH SCANTILY PROVEN TECHNOLOGY

– Aggregates with inbuilt sulfates, chlorides, seashells, ...
– Concrete with high porosity and low resistivity
– High relative humidity and filtration of rainwater
→ Ongoing deterioration mechanisms with severe damage to both, concrete and reinforcement
  – Corrosion
  – Spalling
  – ...

RISKS ASSOCIATED WITH SCANTILY PROVEN TECHNOLOGY

– Less than 100 years after reconstruction, the cathedral was to be closed to the public again and was propped ...

→ Detailed assessment showed
  - Impossibility to detain deterioration mechanisms
  - Technical difficulties and uncertainties entailed in repairing roof

→ Recommendation to demolish and rebuild the roof maintaining the rest of the temple

WORLD HERITAGE SITE

– Authorities wish to save existing main dome → Assessment

– For this purpose, durability requirements are reduced
  - Service period for normal building structures, not for monumental buildings
  - → Future techniques might be suitable to fully detain deterioration mechanisms

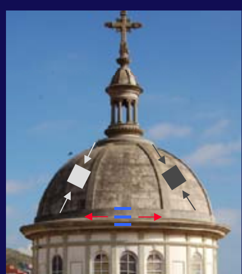
GEOMETRY

– Global system

– Structural members of the spherical dome
  – 8 arches
  – Shells
  – Tension ring

STRUCTURAL BEHAVIOUR

– No significant seismic actions
– Distributed loads produce mainly membrane forces →■←
– Thrust is equilibrated by tension ring forces ←☰→
→ Mainly vertical loads are transmitted to the robust cylindrical "drum"
→ Assessment focuses on the dome



PRIOR INFORMATION

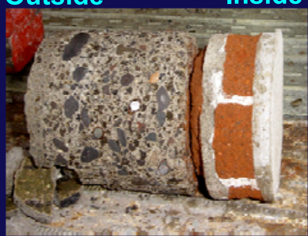
- Previous assessment of the existing building, particularly the lower roof
- Available information about
  - Material properties
  - Cross sections of main elements
  - Deterioration mechanisms

→ Prior information for the main dome

DATA ACQUISITION PROGRAM

- Geometry
  - Overall system dimensions
  - Cross sections of structural and ornamental elements
- Self weight and permanent actions
- Material properties
- Qualitative and quantitative determination of damage
  - Cracks
  - Spalling
  - Carbonation and chloride ingress
  - Corrosion velocity and cross section loss
  - Material deterioration such as crystallization of salts, efflorescence, humidity
  - Previous interventions

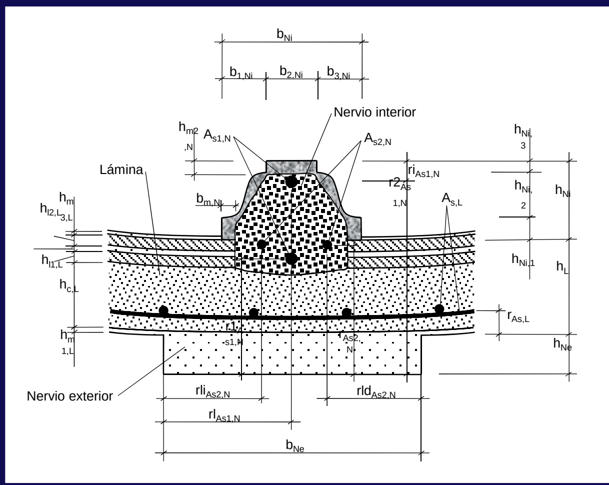
Outside Inside



Updated models

CROSS SECTIONS

– Parameters for different variables derived from a minimum of **4 measurements**

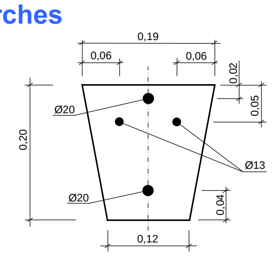


Updated models

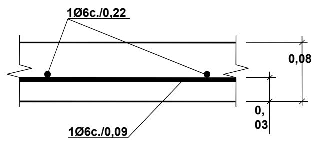
CROSS SECTIONS

– Equivalent cross sections for structural analysis

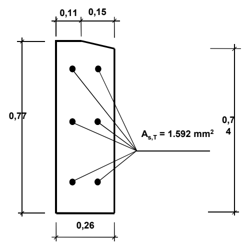
Arches



Shell



Tension ring



SELF WEIGHT AND PERMANENT ACTIONS

– For each layer, j, establishment of
  – Thickness, h_j
  – Density of material, ρ_j

→ Mean values and coefficients of variation for self weight and permanent actions

→ Updated partial factors, for example for self weight

$$\gamma_{g_c,act,v} = 1-\alpha_{g_c}\cdot\beta\cdot\sqrt{V^2_{\rho_c,act}+V^2_{h_c,act}} = 1{,}11$$

$$\gamma_{Sd,N,act,v} = \gamma_{Sd,N,v} = e^{-\alpha_{\xi_{E,N}}\cdot\beta\cdot V_{\xi_{E,N}}} = 1{,}06$$

MATERIAL PROPERTIES FOR REINFORCING STEEL

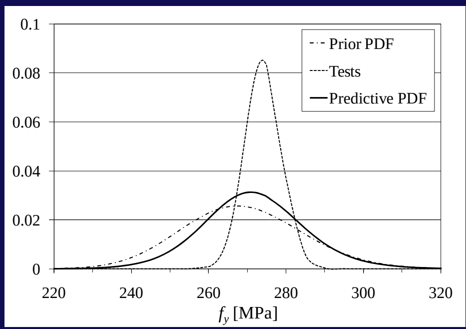
– Manufacturing of specimens

– Execution of tensile tests

Updated models

MATERIAL PROPERTIES FOR REINFORCING STEEL

– Evaluation of test results and combination of information



– Updated parameters: LN; $\mu_{fys,act}$; $\sigma_{fys,act}$

– Updated characteristic values and partial factor

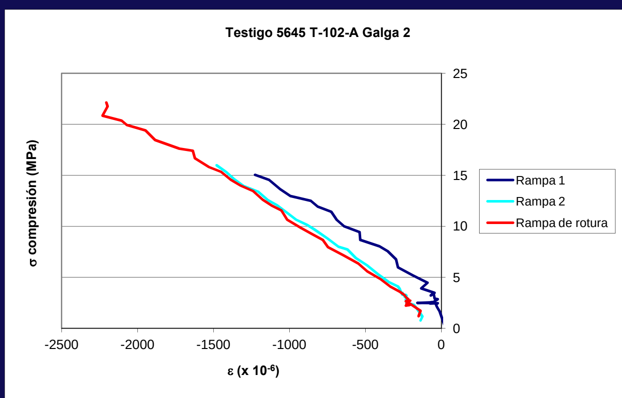
  – ϕ < 10 mm: $f_{ys,k,act}$ = 304 N/mm^2 $\gamma_{s,act,\nu}$ = 1,04
  – ϕ > 10 mm: $f_{ys,k,act}$ = 250 N/mm^2 (Definition $\gamma_s \neq \gamma_{s,EC\text{-}2}$)

Updated models

MATERIAL PROPERTIES FOR CONCRETE

– Manufacturing of specimens

– Execution of compression tests



Updated models

MATERIAL PROPERTIES FOR CONCRETE

- Evaluation of test results
- Updated parameters
  - Compressive strength: LN; $\mu_{fc,act}$; $\sigma_{fc,act}$
  - Modulus of elasticity: $\mu_{Ec,act}$; $\sigma_{Ec,act}$
- Updated characteristic values and partial factor
  - Arches: $f_{ck,act}$ = 6,8 N/mm²
  - Shells: $f_{ck,act}$ = 3,1 N/mm²
  - “Drum”: $f_{ck,act}$ = 4,9 N/mm²

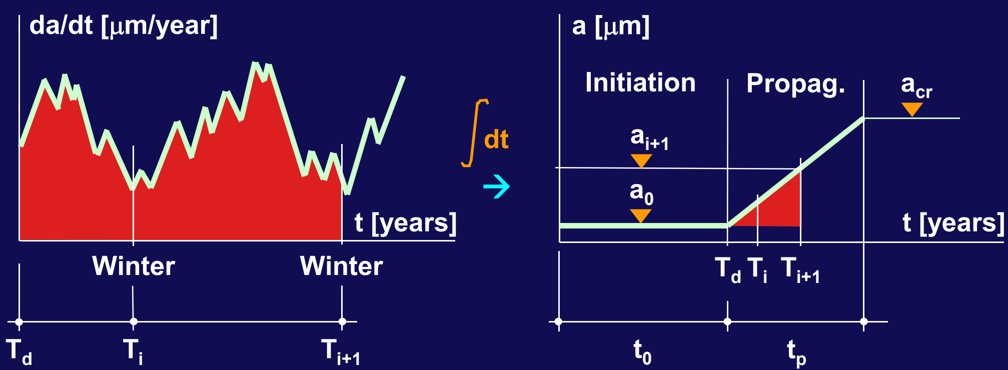
$\gamma_{c,act,\delta}$ = 1,2
(Definition $\gamma_c \neq \gamma_{c,EC\text{-}2}$)

Updated models

REINFORCEMENT CORROSION

- Corrosion rate measurements require careful interpretation
- Mean velocity to be estimated from remaining cross sections

Propagation rate → Mean velocity



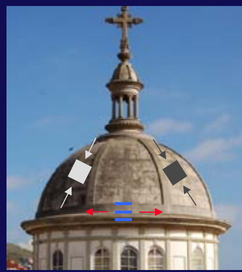
→ Extrapolation for future service period: $A_{s,corr}$

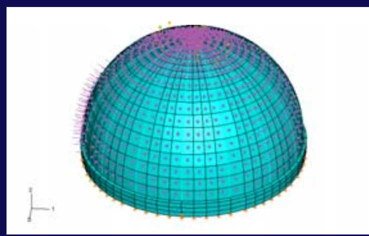
Structural analysis

SHELLS AS AN EXAMPLE

- Relevant design situation for structural safety
  - Permanent actions and influences
    - Self weight structural elements
    - Self weight ornamental elements
    - Corrosion
  - Leading variable action
    - Wind
  - Accompanying variable action
    - Temperature increase

→ Non linear FE analysis





Verification of structural safety

SHELLS AS AN EXAMPLE

- Updated design action effects

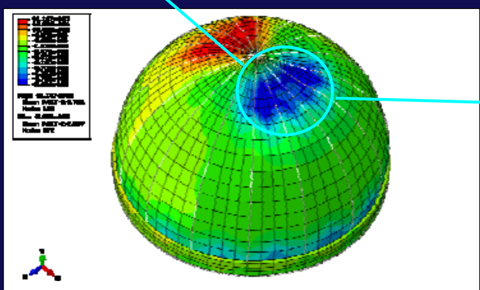
  $N_{Ed,max,act} = 77$ kN/m (+ compression)

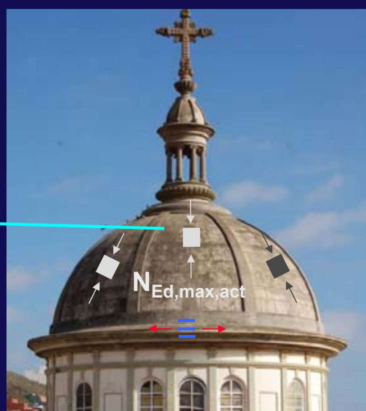
- Updated design resistance at the end of future service period

  $N_{Rd,act} = 219$ kN/m

- Verification

  $N_{Ed,max,act} < N_{Rd,act}$



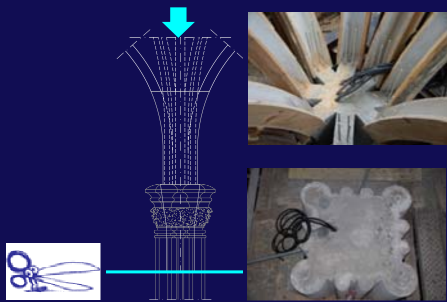


Decision

RECOMMENDATION

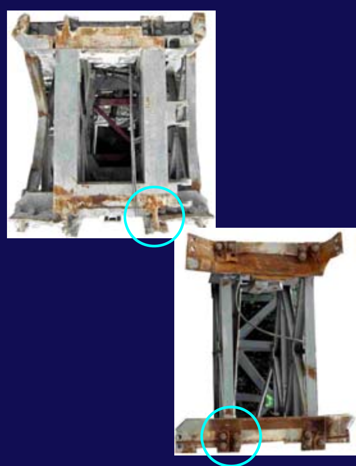
- Structural reliability can be verified, but
  - Severe damage to concrete and reinforcement
  - Impossibility to detain deterioration mechanisms
  - Technical difficulties and uncertainties entailed in repairing dome

→ Demolition and reconstruction of the roof is advisable



ON THE ASSESSMENT OF SOUND, DETERIORATING AND COLLAPSED STRUCTURES

- Introduction
- Updated models for the assessment of sound structures
- Corrosion-damaged reinforced concrete structures
- Analysis of the deteriorating main dome over La Laguna cathedral
- Collapse of the River Verde viaduct scaffolding system
- Final remarks



TREND IN MODERN BRIDGE BUILDING

- Deployment of automated solutions to shorten construction times and lower costs
- Standardised equipment is employed, designed to be reused
- Special equipment is increasingly sophisticated


COMPETITIVE BRIDGE ERECTION TECHNIQUES AND RISKS

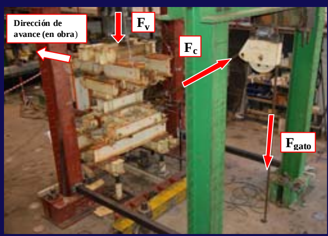
- Derailment of overhead gantry for erection of precast bridge girders

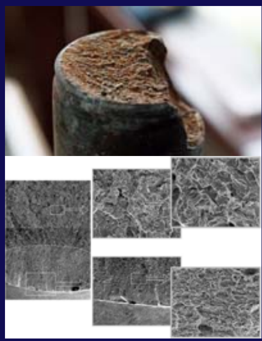

- Consequences
  - No damage to persons
  - Economic loss

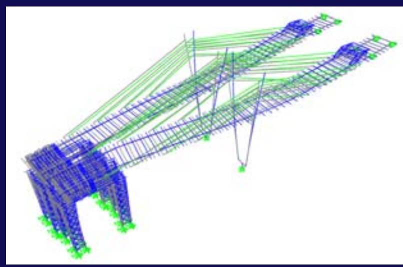
Context

FORENSIC ENGINEERING

– Experimental, analytical and numerical studies





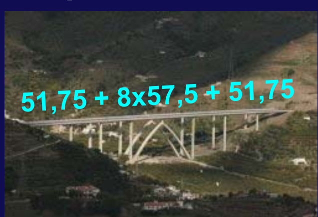


– Interesting results and conclusions
– But: lack of transparency
→ Case with closed trial to illustrate vulnerability of bridge erection techniques

The bridge

LAYOUT

– Construction of Mediterranean Highway A7 at Almuñécar
– Two parallel bridges required, curved in plan view: R 941 m
– Total length: 563,5 m
– Superstructure constituted by prestressed concrete box girders with 11,8 m wide decks, continuous over 10 spans
  – End spans of 51,75 m
  – 8 inner spans of 57,5 m
– Two midspans over the river supported by concrete arch



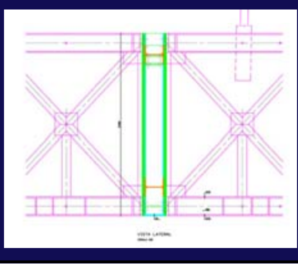
MOVABLE SCAFFOLDING SYSTEM

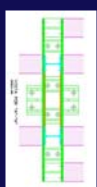
– MSS used to build the bridge superstructure
– Formwork supported by two main parallel truss girders, spaced at 9,5 m

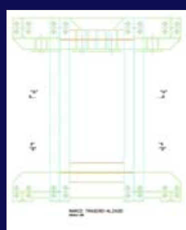
MSS MEMBERS

– Each main girder consists of three parts

– Centre is bolted to front and rear by connection frames

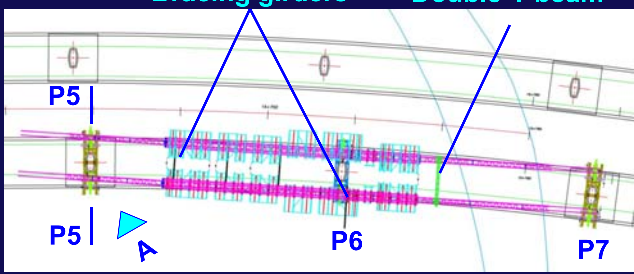






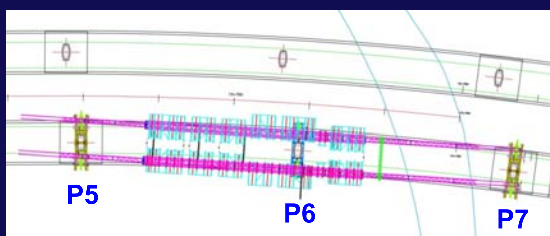
MSS MEMBERS

- Main girders connected by four transverse bracing girders and a double-T beam
- Bracing girders fitted with sliding devices to clear piers
- Supports for main girders fitted with sliding bearings and hydraulic jacks for longitudinal and transverse movements



PROCEDURE

- Casting of concrete for one span, e.g. span 6
- Stages for MSS launching
  - Folding back of formwork
  - Disconnection of rear part of main girders from deck
  - Transverse movement for alignment of MSS with curved bridge
  - Opening of front transverse bracing girder to clear the pier P6
  - Longitudinal launching
  - Upon arrival at the pier P7, lifting of launching nose by truck crane



LAUNCHING OF THE MSS AFTER CASTING OF SPAN 6

- Launching nose lifted by truck crane at pier P7
- After launch of 2 m, power supply outage in right main girder
- → Operation stopped
- Collapse after a few moments
  - Initiation at the left main girder according to eyewitnesses
  - Right girder dragged down due to transverse bracings

Fred Nederlof. http://www.ideal.es


Fred Nederlof. http://www.ideal.es

CONSEQUENCES

- 6 persons killed and several injured
- Delay in construction and economic loss
- Loss of public confidence


Picture: Fred Nederlof. Source: http://www.ideal.es

The accident

HOW COULD THIS HAPPEN?

- Only self-weight during launching
- No problems during previous launching stages over equal spans

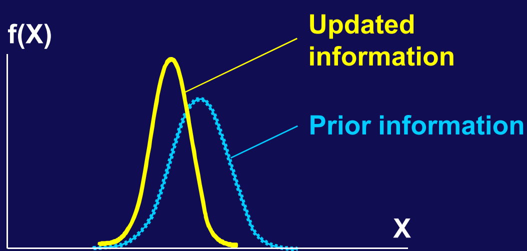
→ Examining magistrate asked for report with dual purpose

- Establishment of mechanism and causes of the failure
- Assessment of structural reliability: in spite of the collapse, auxiliary structure might have reached reliability level

Evaluation procedure

REMINDER

- Major difference between assessment and design: information available
- In the assessment of existing structures, many uncertainties may be reduced, also in the case of collapsed structures
- Probabilistic methods are most accurate to take into account site-specific data



→ Explicit risk analysis is applied to investigate the collapse

RISK ANALYSIS IN TWO STAGES

- Qualitative analysis to identify hazards and scenarios
- Quantitative analysis to establish likelihood of scenarios

Qualitative risk analysis

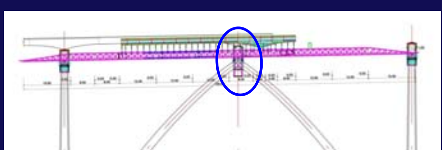
- Identify potential hazards
- Planning data acquisition
- Reduce uncertainties
  Inspections – Tests – Analysis
- Identify relevant hazards
- Establish hazard scenarios
  Logic combination of hazards

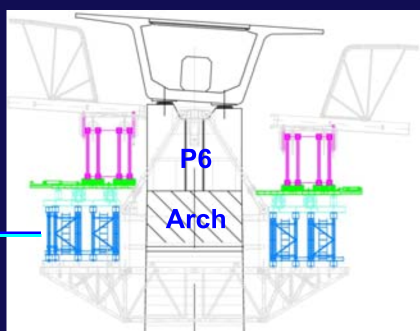
Quantitative risk analysis

- Evaluate scenarios i, j, k, …
  Probability analysis
- Compare probabilities and interpret results
  $P_{f,i} < P_{f,j} < P_{f,k} < \ldots$

DIFFERENT CIRCUMSTANCES COMPARED TO PREVIOUS SPANS

- Nominally identical construction and launching procedure
- But, there are two main differences
  - Bridge geometry at pier P6, resting on the arch, called for ancillary support structure
  - Power supply outage-induced differential travel in left and right main girders





POTENTIAL HAZARDS

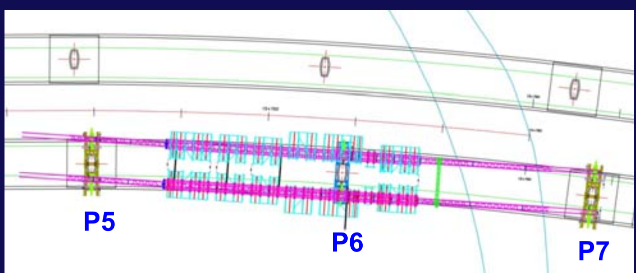
- Potential hazards related to actions, influences, resistance
- Some immediately ruled out as possible origin of accident
  - Settlement
  - Seismic loads
  - Wind
  - Force applied by truck crane: no connection at time of accident

→ Investigative efforts focused on remaining potential hazards

PERMANENT LOADS

- Nominally, formwork partially folded back to clear pier P6
- In reality, formwork completely folded back prior to accident

Drawings



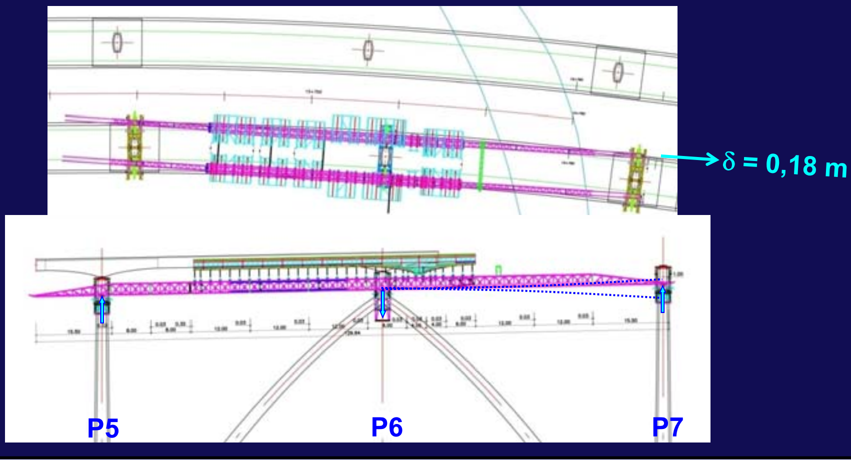
In situ

→ Increase in intensity of action effects

ACTION EFFECTS DUE TO IMPOSED DEFORMATIONS

– Difference between left and right main girder travel: 0,18 m

– Deviations in MSS support elevations or main girder precamber



DEVIATIONS FROM DESIGN RESISTANCE VALUES

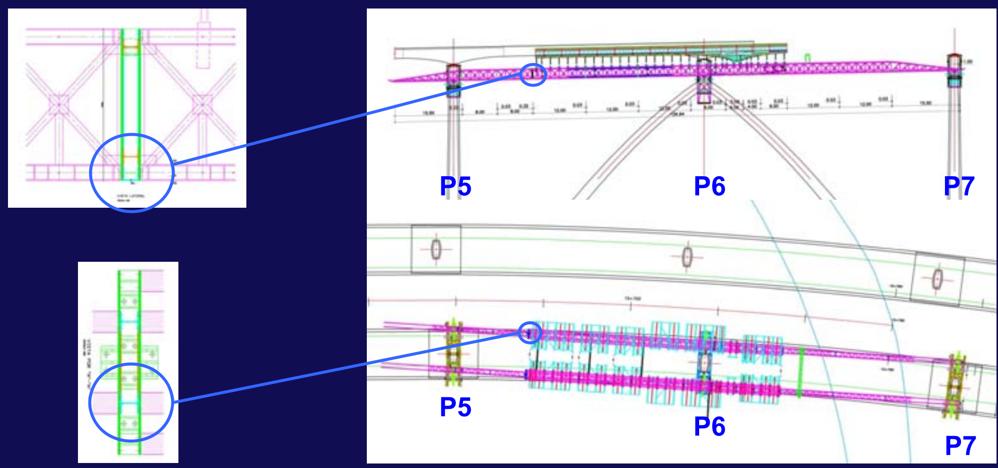
– Deviations from construction tolerances
  - In critical structural members
  - In highly stressed joints, e.g. welds in connection frame

– Effects of load inversion and dynamic actions during launching and casting cycles

TRIGGERING ELEMENT

– Triggering element according to inspections, tests, analysis

→ Joint frame on left girder – right bottom chord of rear module

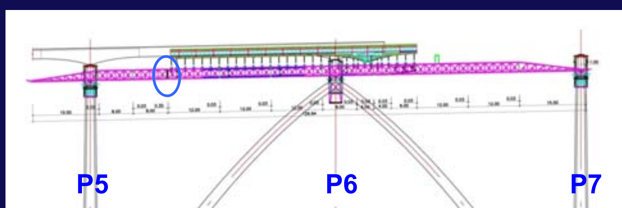


Hazard scenarios

PRIMARY CAUSE

– Primary cause of joint failure could not be unequivocally established
  - More likely: loosening of one or several bolt nuts at the critical joint
  - Less likely: resistance loss in welds due to accumulation of plastic deformations

→ Hazard scenarios for quantitative analysis

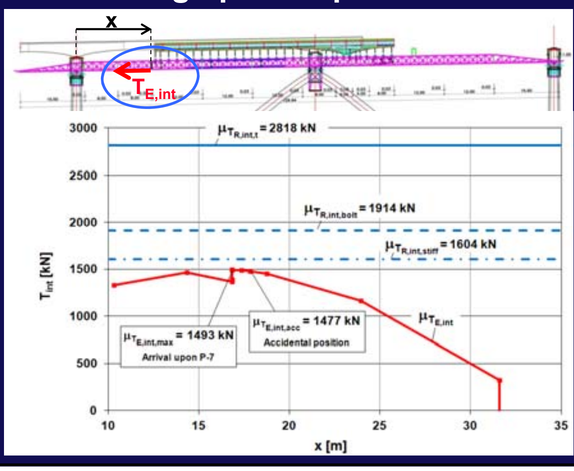


IDENTIFICATION OF RELEVANT HAZARD SECENARIOS

- Leading influence
  - Loosening of at least one bolt nut at the critical joint
    and / or
  - Failure of welds at the critical joint
- Accompanying actions
  - Structure self-weight
  - Permanent loads given the actual position of formwork
  - 0,18 m differential travel between left and right main girders
- Accompanying influences
  - Nominal geometry of the MSS including precamber
  - Actual MSS support elevations
  - Deviations from construction tolerances and design resistance

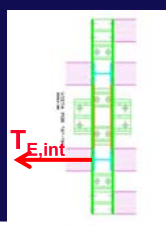
THE PROBLEM R – E

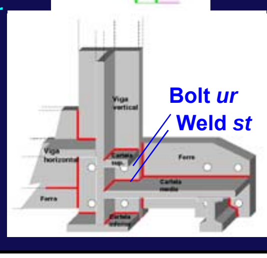
- Failure of critical joint induces system failure: series system
- → Assess $P_{f,joint}$ associated with relevant hazard scenarios by using updated parameters for load and resistance variables



Expected $T_{R,int}$:
As built

Loosening bolt *ur*
Weld failure *st*





FAILURE PROBABILITIES

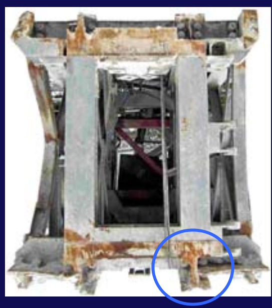
– Assuming a loose upper right bolt at the critical joint

$P_{f,int,bolt} = 0{,}06 >> P_{f,adm}$

– After weld failure at intermediate stiffener

$P_{f,int,stiff} = 0{,}30 >> P_{f,adm}$

→ Unstable equilibrium at the critical joint



FAILURE MECHANISM

– Results from analysis are compatible with inspections, tests and eyewitness accounts

– Most likely failure mechanism
  - Load inversion and dynamic effects during previous construction
  - Loosening of one or several bolt nuts at critical joint
  - Intra-joint stress redistribution
  - Stress concentration in certain welds
  - Failure of highly stressed welds
  - Stress redistribution and failure of other components
  - Joint failure
  - Collapse

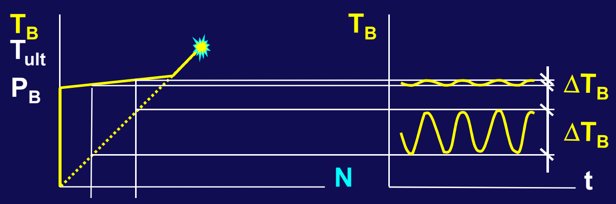
CONCLUSIONS FROM THE FORENSIC ANALYSIS

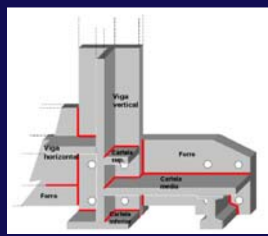
– MSS collapse is associated with unorthodox detailing
  – Complex load transfer mechanisms
  – Lack of stress redistribution capacity
  – Underestimation of consequences of variable load cycles

→ Use of sophisticated construction equipment entails risk

– Systematic qualitative risk analysis at the design stage might have contributed to identify relevant hazards

→ Identified hazards may be mitigated adopting measures





Lifelong Learning Programme

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– Introduction
– Updated models for the assessment of sound structures
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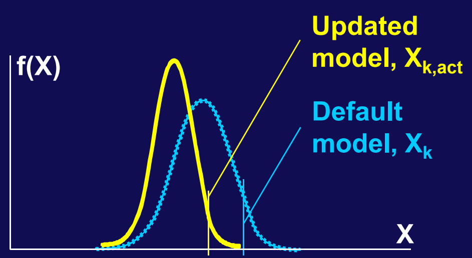
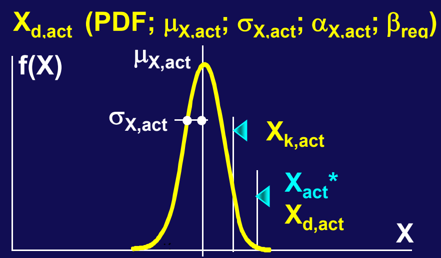
– Final remarks

NAEP CSIC CESMA Ingenieros

FINAL REMARKS

- In the assessment of existing structures, many uncertainties may be reduced, also in the case of collapsed structures
- Probabilistic methods are most accurate to take into account site-specific data
- Such methods are not fit for use in daily practice
- Rational decision making should be possible by using a partial factor format for assessment





FINAL REMARKS

- Tools have been developed to accommodate site-specific data by updating characteristic values and partial factors
- Further efforts are needed to extend these tools to the assessment of deteriorating structures

FINAL REMARKS

– Partial factor method does not always lead to unequivocal conclusions
– In such cases, explicit risk analysis is a powerful decision making tool