LEONARDO DA VINCI PROJECT CZ/11/LLP-LdV/TOI/134005

SEMINAR ON ASSESSMENT OF EXISTING STRUCTURES

České Budějovice. 23-05-2013

ON THE ASSESSMENT OF SOUND, DETERIORATING AND COLLAPSED STRUCTURES

Peter Tanner. Carlos Lara. Ramon Hingorani. Miguel Prieto

Lifelong Learning Programme

NAEP

CSIC

CESMA

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

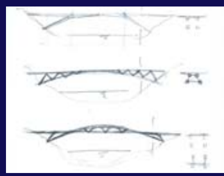
MORE DOUBTS ABOUT STRUCTURAL SAFETY

- Derailment of overhead gantry for erection of precast bridge girders

- No problems during previous construction stages under identical conditions

→ How could this happen ?

ASSESSMENT VS. DESIGN

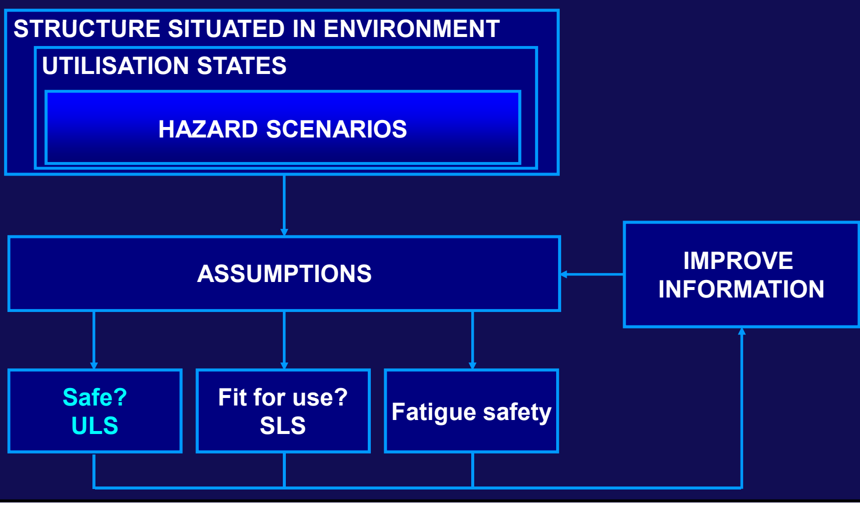
		
Structures	**Existing**	**New**
Available information	"Measurable" characteristics	Assumed characteristics
Reliability depends on	Available data Knowledge	Variables according to codes
Reliability	→ subjective	→ +/- objective

→ Fundamental difference lies in the **state of information**

STAGED EVALUATION PROCEDURE

– Improve accuracy of data from stage to stage

– Decisions on reliability only if no margin to improve accuracy



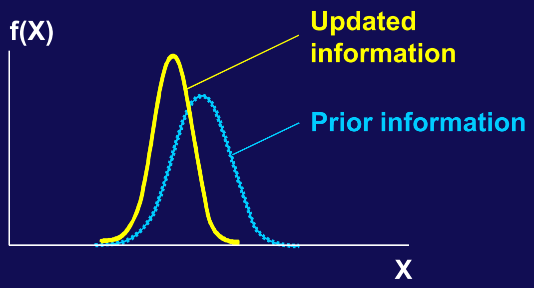
ON THE ASSESSMENT OF SOUND, DETERIORATING AND COLLAPSED STRUCTURES

- 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

Influence of updated information

ASSESSMENT WITH PROBABILISTIC METHODS

- Updated Probability Density Function of variable **X**

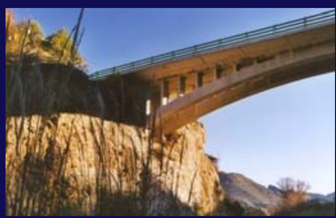
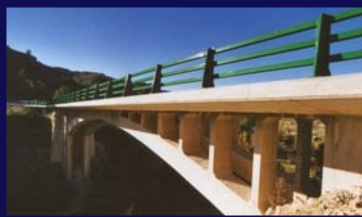


- Updated **PDF** can directly be used for probabilistic analysis → $P_{f,act}$
- Verification $P_{f,act} \leq P_{f,adm}$ → Accepted practice, Risk analysis

ASSESSMENT WITH PARTIAL FACTOR METHOD

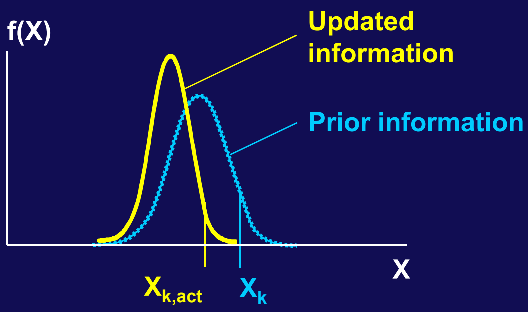
- Probabilistic methods are most accurate to take into account updated information
- But they are not fit for use in daily practice
- Partial factor method should be available for assessment

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

ASSESSMENT WITH PARTIAL FACTOR METHOD

- Updated characteristic value of X



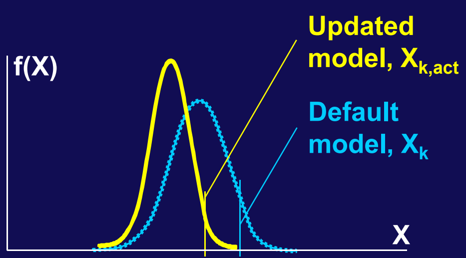
- Updated partial factor $\gamma_{X,act}$ → $\gamma_{E,act} \cdot E_{k,act} \leq \frac{R_{k,act}}{\gamma_{R,act}}$

→ Can not be derived directly

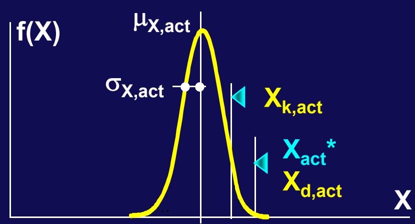
→ Link between probabilistic and partial factor methods: design point, the most probable failure point on LS surface

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})



Lifelong Learning Programme

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

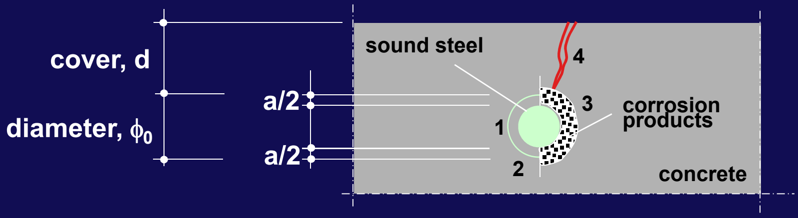
NAEP Národní agentura pro evropské vzdělávací programy

CSIC

CESMA ingenieros

MAIN EFFECTS OF CORROSION OF REINFORCEMENT BARS

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



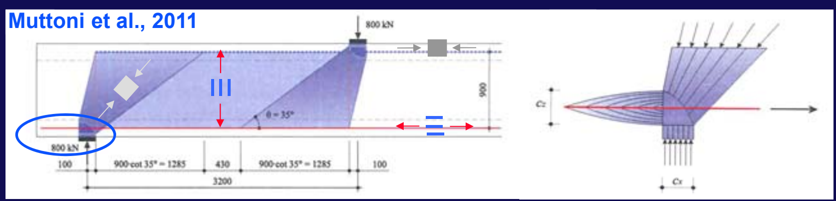
→ Corrosion may affect performance at ULS and SLS

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

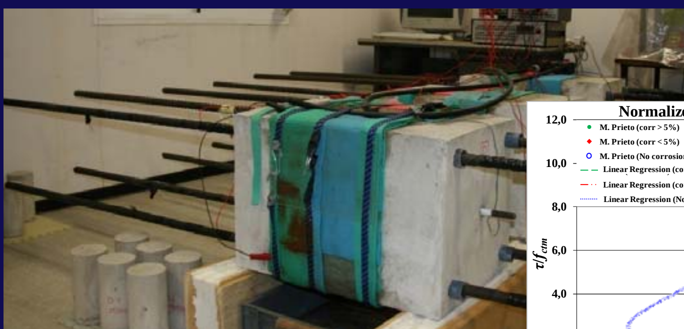
SITE DATA COLLECTION

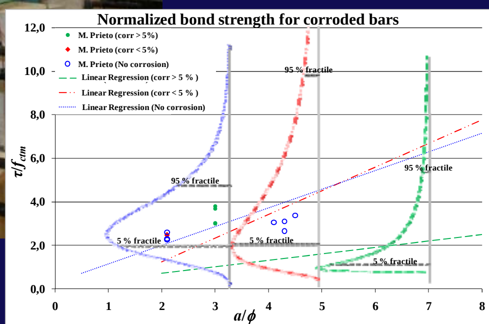
– Geometry and material properties can be updated

BOND STRENGTH

– Pull-out tests on specimens with accelerated and natural corrosion

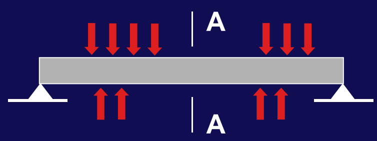
→ Normalized bond strength depending on cross-section loss

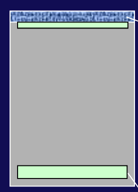




SIMPLE MODELS FOR ESTIMATE OF PERFORMANCE OF CORRODED STRUCTURAL ELEMENTS

– Example: bending resistance

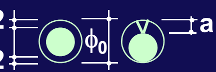




Upper bound: active

Lower bound: disregarded (spalling)

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



→ Similar rules for other failure modes and SLS

Lifelong Learning Programme

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

NAEP Národní agentura pro evropské vzdělávací programy

CSIC

CESMA ingenieros

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 the existing main dome
- 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

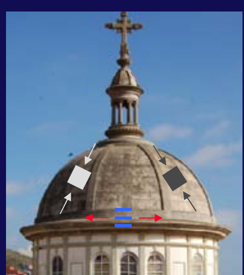
GEOMETRY

– 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



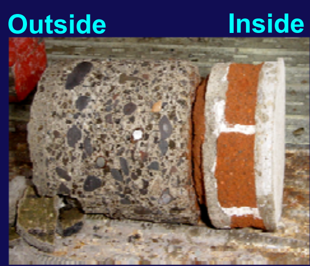
PRIOR INFORMATION

- 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

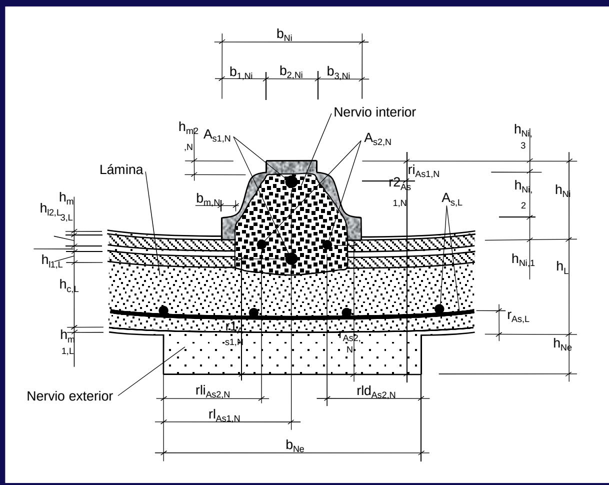
DATA ACQUISITION PROGRAM

- 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



CROSS SECTIONS

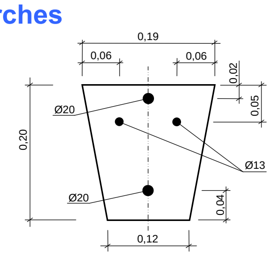
– Parameters for different variables derived from a minimum of 4 measurements



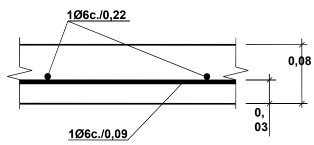
CROSS SECTIONS

– Equivalent cross sections for structural analysis

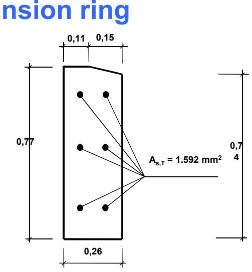
Arches



Shell



Tension ring



Updated models

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

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

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

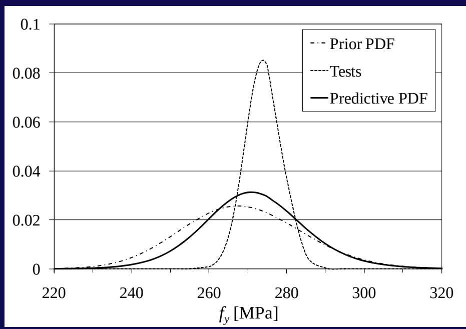
Updated models

MATERIAL PROPERTIES FOR REINFORCING STEEL

- Manufacture of specimens
- Execution of tensile tests

MATERIAL PROPERTIES FOR REINFORCING STEEL

– Evaluation of test results and combination of information



– Updated parameters: LN; $\mu_{fys,act}$; $\sigma_{fys,act}$; $f_{ys,k,act}$; $\gamma_{s,act}$

– Updated characteristic values

  – ϕ < 6 mm: $f_{ys,k,act}$ = 304 N/mm^2

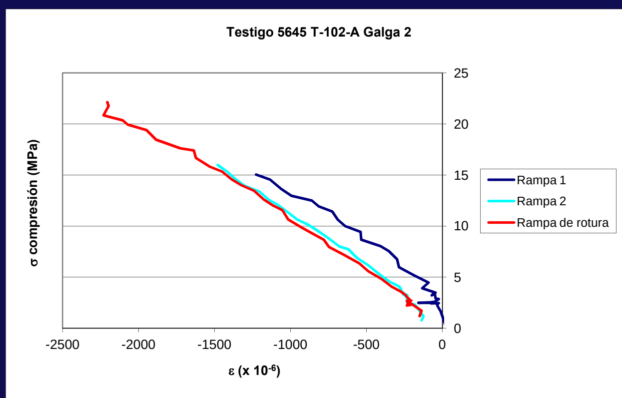
  – ϕ > 6 mm: $f_{ys,k,act}$ = 262 N/mm^2

Updated models

MATERIAL PROPERTIES FOR CONCRETE

– Manufacture of specimens

– Execution of compression tests

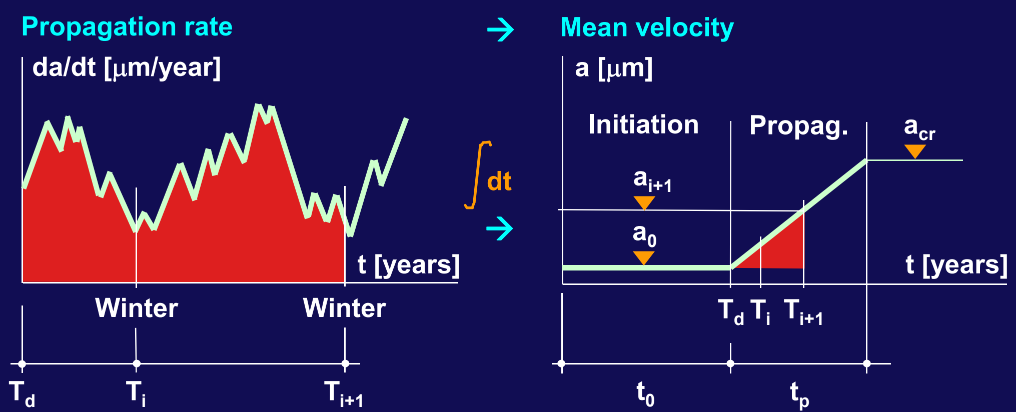


MATERIAL PROPERTIES FOR CONCRETE

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

REINFORCEMENT CORROSION

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

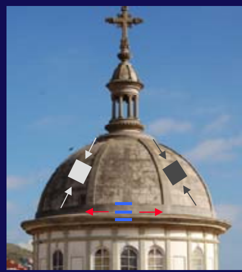


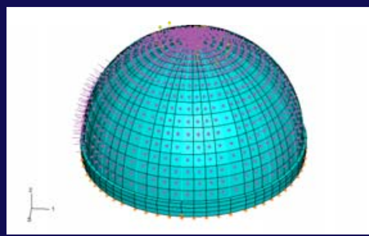
→ Extrapolation for future service period: $A_{s,corr}$

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





SHELLS AS AN EXAMPLE

– Updated design action effects

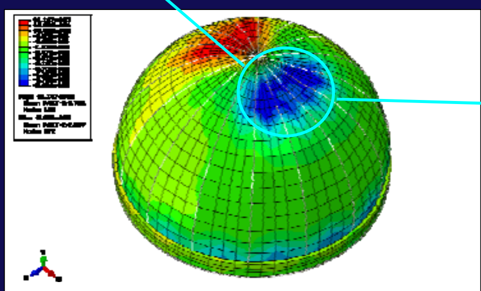
  $N_{Ed,max,act} = 77$ kN/m (+ compression)

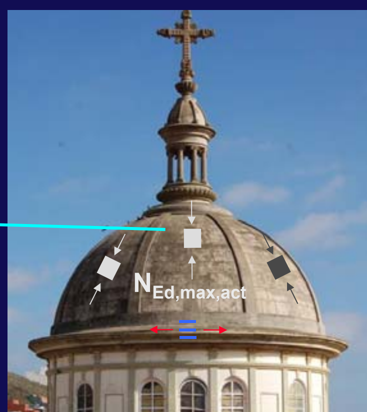
– Updated design resistance at the end of future service period

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

– Verification

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



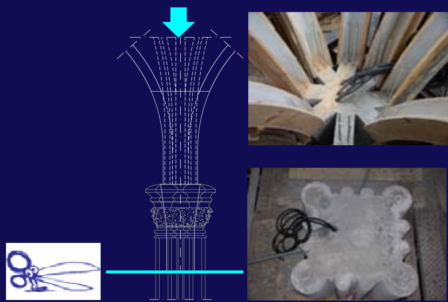


Decision

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

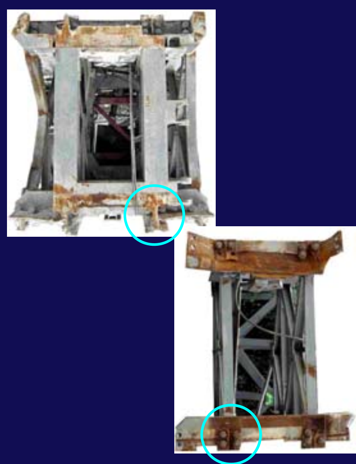
→ Demolition and reconstruction of the roof is advisable



Lifelong Learning Programme

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



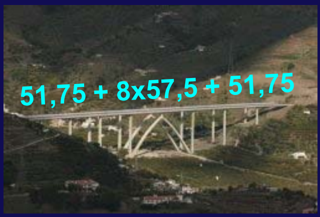
NAEP Národní agentura pro evropské vzdělávací programy

CSIC

CESMA ingenieros

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

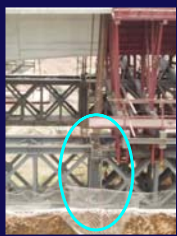

Picture: Fred Nederlof. Source: http://www.ideal.es

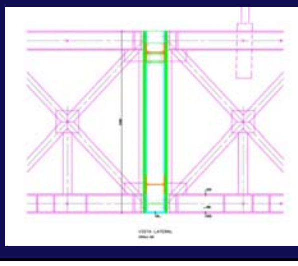
Picture: Fred Nederlof

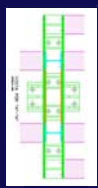
MSS MEMBERS

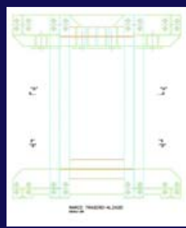
– Each main girder consists of three parts

– Centre is bolted to front and rear by connection frames







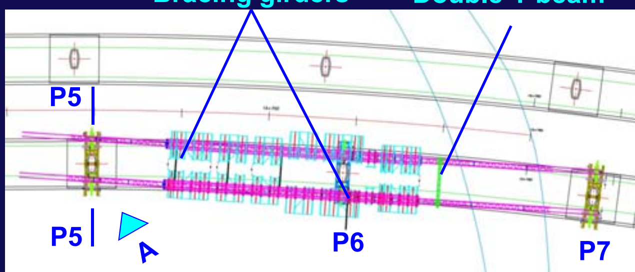


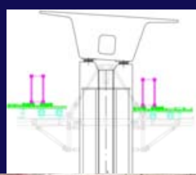
MSS MEMBERS

– 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

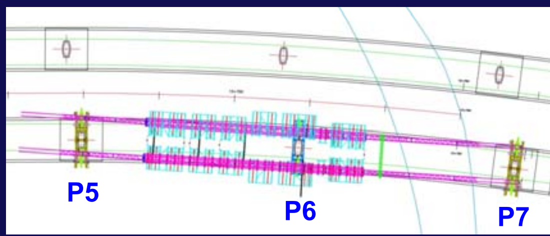




Construction

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



The accident

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

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

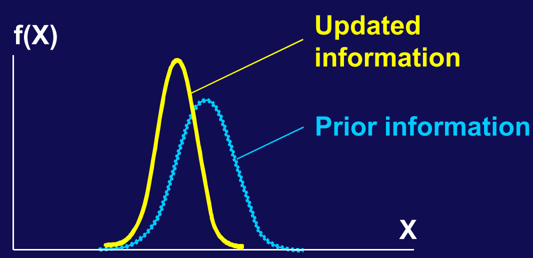
HOW COULD THIS HAPPEN?

– 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

REMINDER

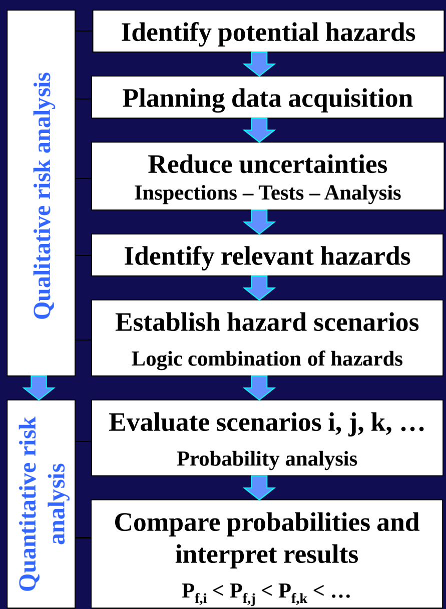
- Major difference between assessment and design: information available
- In the assessment of existing structures, many uncertainties may be reduced, also in the case of collapsed structures
- Probabilistic methods are most accurate to take into account site-specific data



→ Explicit risk analysis is applied to investigate the collapse

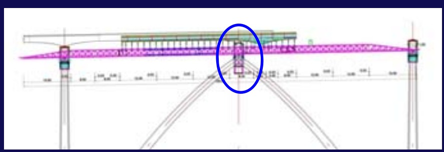
RISK ANALYSIS

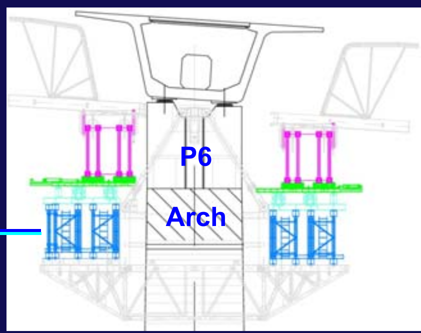
- Two stages
- Qualitative analysis to identify hazards and scenarios
- Quantitative analysis to establish likelihood of scenarios



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

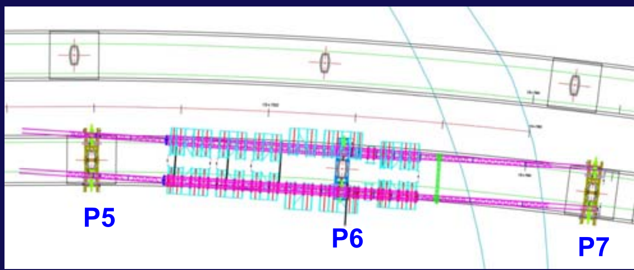
→ Investigative efforts focused on remaining potential hazards

Hazard identification

PERMANENT LOADS

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

Drawings



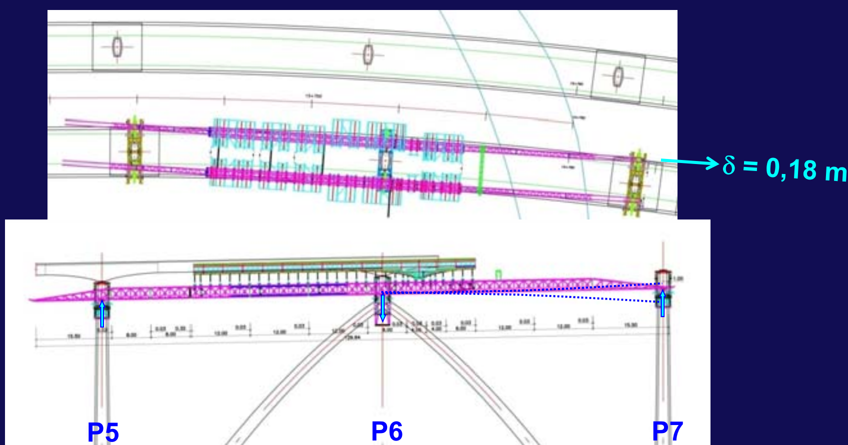
In situ

→ Increase in intensity of action effects

Hazard identification

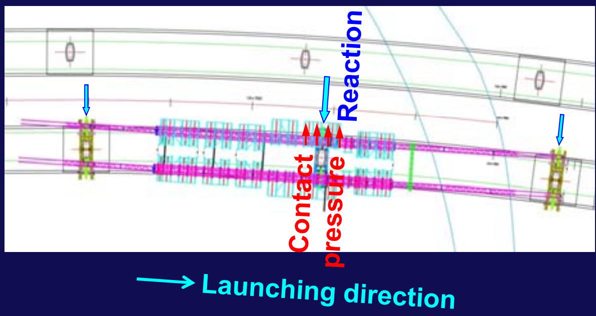
ACTION EFFECTS DUE TO IMPOSED DEFORMATIONS

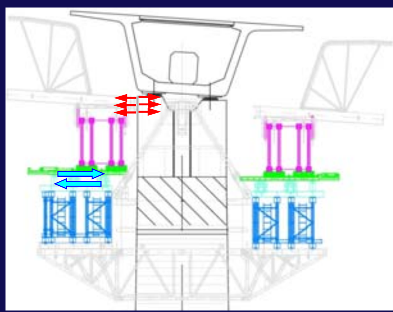
- Difference between left and right main girder travel: 0,18 m
- Deviations in MSS support elevations or main girder precamber



SLOW MOTION IMPACT

– MSS is straight in plan view and bridge is curved
– In case of contact, increasing contact pressure during launching
→ Unforeseen horizontal force on supports





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

MONITORING

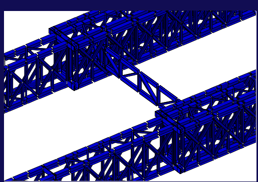
- MSS similar to the one that collapsed
- Monitoring for action effects during a full launch cycle
- Focus on effects due to
  - Differential travel in left and right girders
  - Force applied by truck crane (for informative purposes only)

→ Both hazards irrelevant to the collapse

Reduction of uncertainties

STRUCTURAL ANALYSIS

- Development of different FE models for structural analysis
- Study of action effects on MSS structural members due to
  - Position of the formwork
  - Support elevation
  - Precamber deviations from the nominal geometry



→ Scantly relevant hazards, unlikely to have triggered accident

MATERIAL TESTING

- Experimental investigation of material properties
  - Structural members
  - Bolts
  - Welds
- Influence of poor workmanship on the resistance of welds

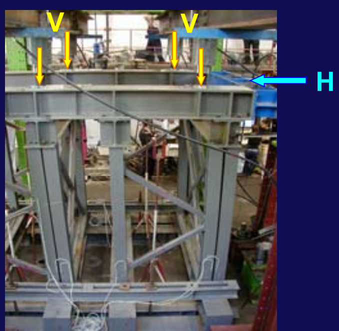
DCM-ETSICCP
UPM 2007

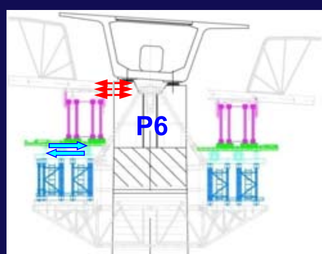
→ Possible deviations from nominal properties irrelevant

→ Deviations from welding tolerances, scantly relevant

FULL SCALE TESTING

- Fabrication of replicas of support devices at piers P5, P6, P7
- Study of structural behaviour under combined loads
  - Application of vertical loads, V, corresponding to support reactions
  - Application of gradually increasing horizontal load, H, until failure



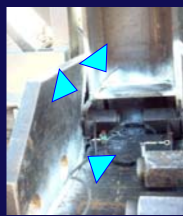


→ Magnitude of H required for destabilisation unlikely to occur

FULL SCALE TESTING

- Fabrication of connection frame replicas
  - 4 nominally identical to the frame from the collapsed structure
  - 2 without intermediate stiffener assuming premature failure due to stress concentration or accumulation of plastic deformations
- Experimental study of connection frame and joint resistance



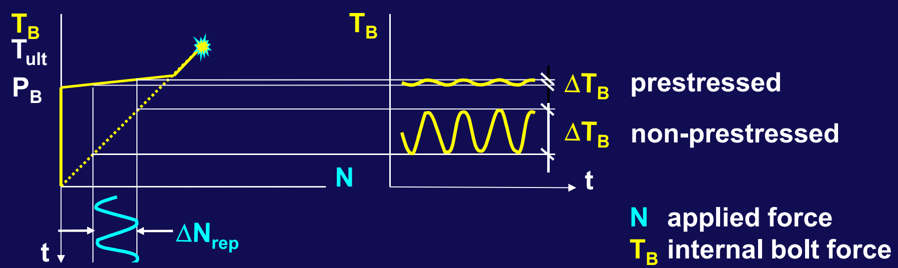


→ Weld failure between vertical profile and intermediate stiffener is a relevant hazard

→ Updated probabilistic resistance models for analysis

ANALYSIS OF THE BEHAVIOUR OF NON-PRESTRESSED BOLTS

- Connection frames and adjacent modules connected by non-prestressed bolts
- Behaviour of bolts exposed to variable load cycles
  - Number of cycles to failure or bolt nuts loosening depends on ΔT_B
  - Mechanisms may be accelerated by sign-changing load cycles and dynamic effects

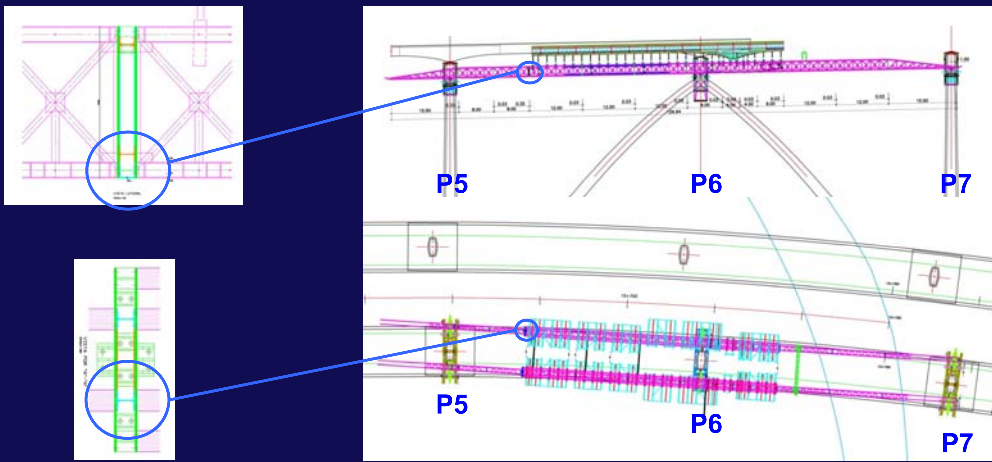


→ Loosening of bolt nuts may be relevant to the collapse

TRIGGERING ELEMENT

– Triggering element according to inspections, tests, analysis

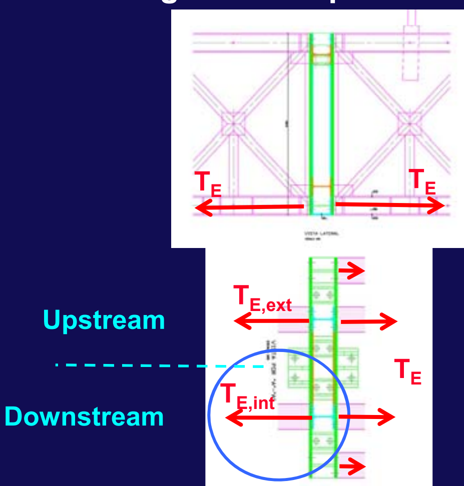
→ Joint frame on left girder – right bottom chord of rear module



TRIGGERING ELEMENT

– Element with highest internal forces on left girder

– Findings are compatible with eyewitness accounts

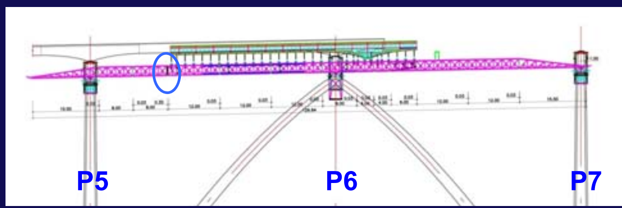


Hazard scenarios

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



Hazard scenarios

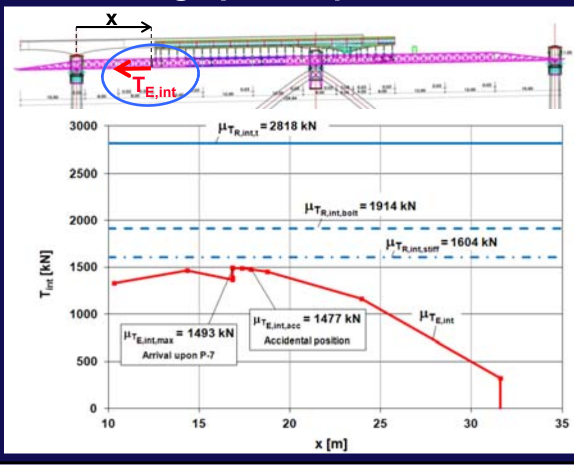
IDENTIFICATION OF RELEVANT HAZARD SECENARIOS

- 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

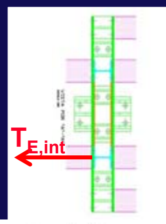
– Failure of critical joint induces system failure: series system

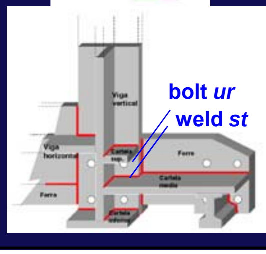
→ Assess $P_{f,joint}$ associated with relevant hazard scenarios by using updated parameters for load and resistance variables



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

loosening bolt *ur*
weld failure *st*





Quantitative assessment

FAILURE PROBABILITIES

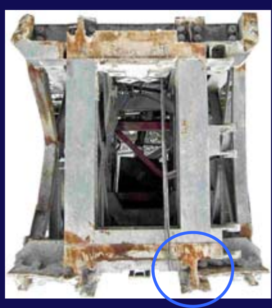
– Assuming a loose upper right bolt at the critical joint

$P_{f,int,bolt}$ = 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

Lifelong Learning Programme

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

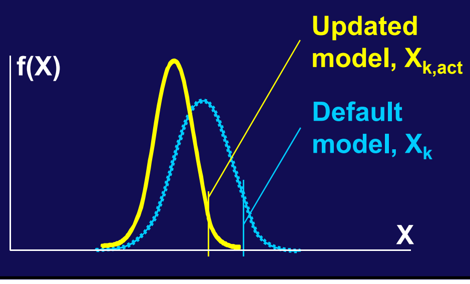
NAEP

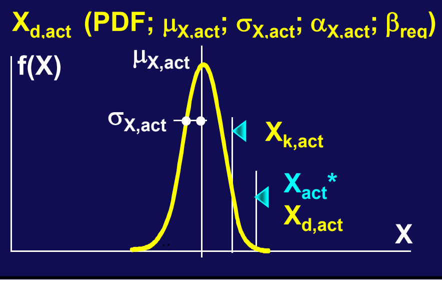
CSIC

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