LEONARDO DA VINCI PROJECT CZ/11/LLP-LdV/TOI/134005
SEMINAR ON ASSESSMENT OF EXISTING STRUCTURES
Pisa. 15-03-2013

ON THE ASSESSMENT OF DETERIORATING STRUCTURES

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MOTIVATION

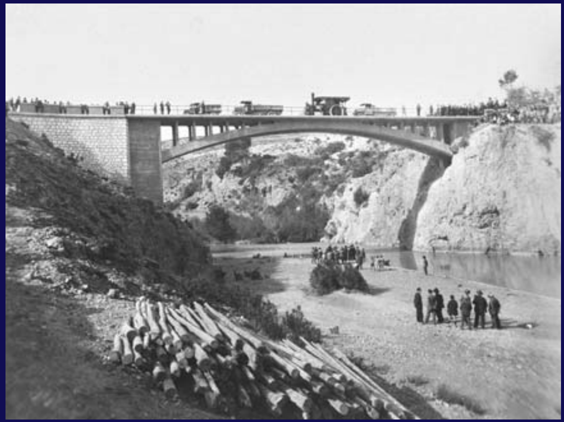
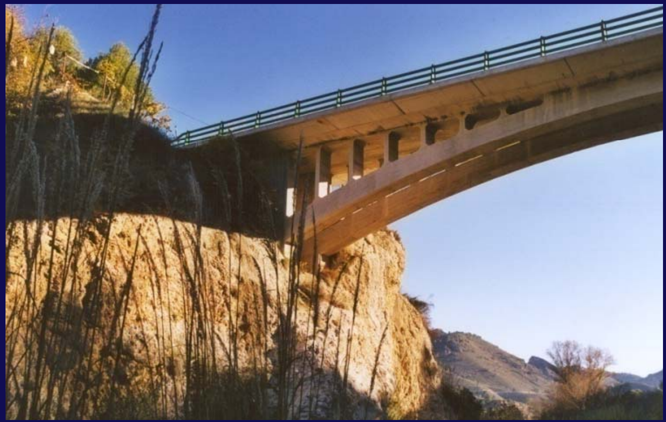
– The need to assess the reliability of an existing structure may arise from different causes
– All can be traced back to doubts about the structural safety

→ Reliability ok for future use ?
→ Staged evaluation procedure, improving accuracy of data

ASSESSMENT WITH PARTIAL FACTOR METHOD

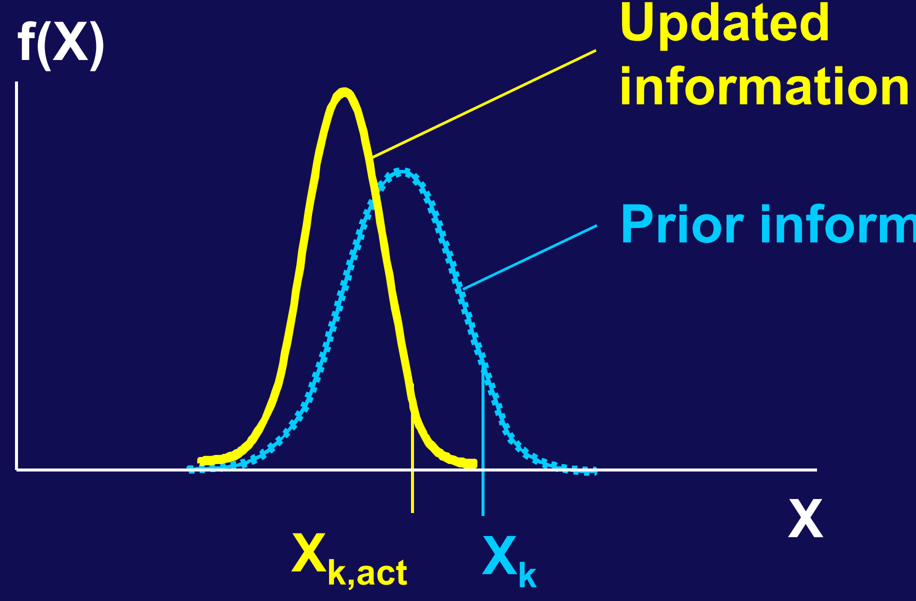
- Probabilistic methods are most accurate to take into account updated information
- But they are not fit for use in daily practice
- Partial factor method should be available for assessment

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


ASSESSMENT WITH PARTIAL FACTOR METHOD

– Updated characteristic value of X



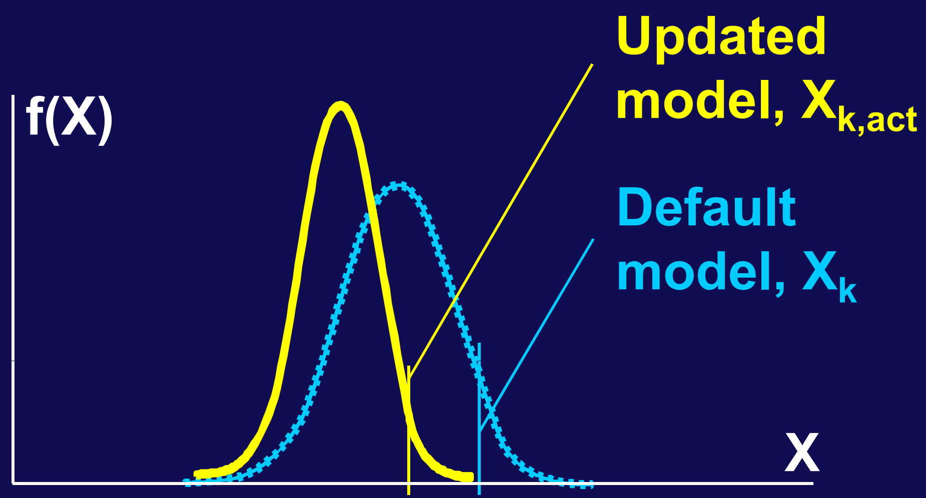
– Updated partial factor $\gamma_{X,act}$ → $\gamma_{E,act} \cdot E_{k,act} \leq \dfrac{R_{k,act}}{\gamma_{R,act}}$

→ Can not be derived directly

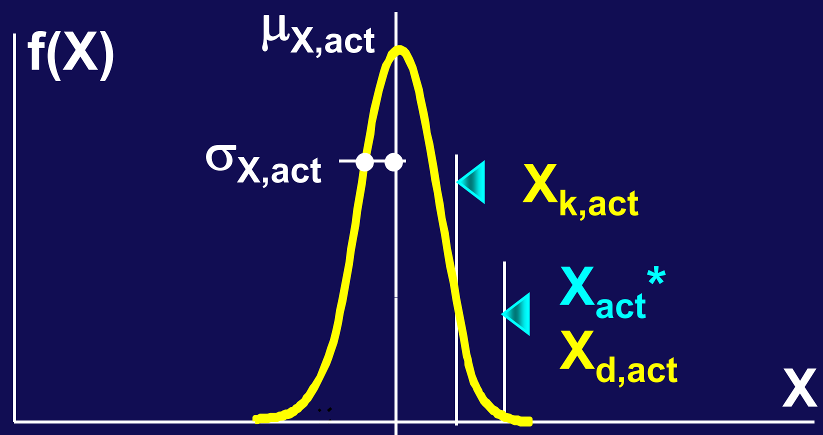
→ Link between probabilistic and partial factor methods: design point, the most probable failure point on LS surface

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})



ON THE ASSESSMENT OF DETERIORATING STRUCTURES

- Introduction
- Updated models for the assessment of sound structures
- Corrosion-damaged reinforced concrete structures
- La Laguna cathedral
- Final remarks

PARTIAL FACTOR FORMAT FOR ASSESSMENT

– Design value for action effects

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

$\gamma_{f,i,act}$ 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

PARTIAL FACTOR FORMAT FOR ASSESSMENT

– Design value for resistance

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

$\gamma_{m,i,act}$	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

DEFAULT PROBABILISTIC MODELS COMPLYING WITH THE FOLLOWING REQUIREMENTS

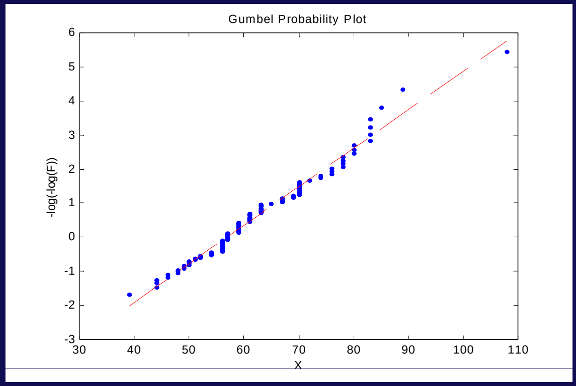
– Representation of physical properties of the corresponding variable

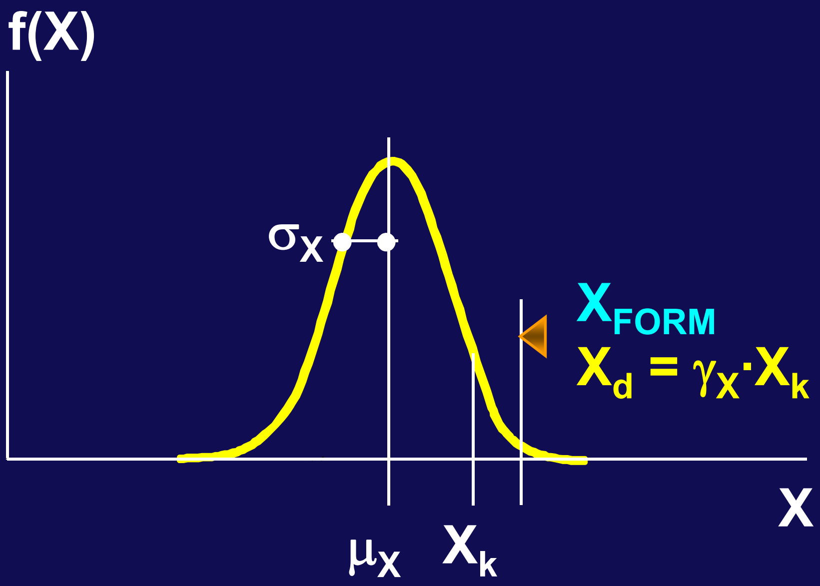
– Consistency with *JCSS* models

– Representation of the state of uncertainty associated with code rules

– Representation of uncertainties by means of random variables, suitable for practical applications

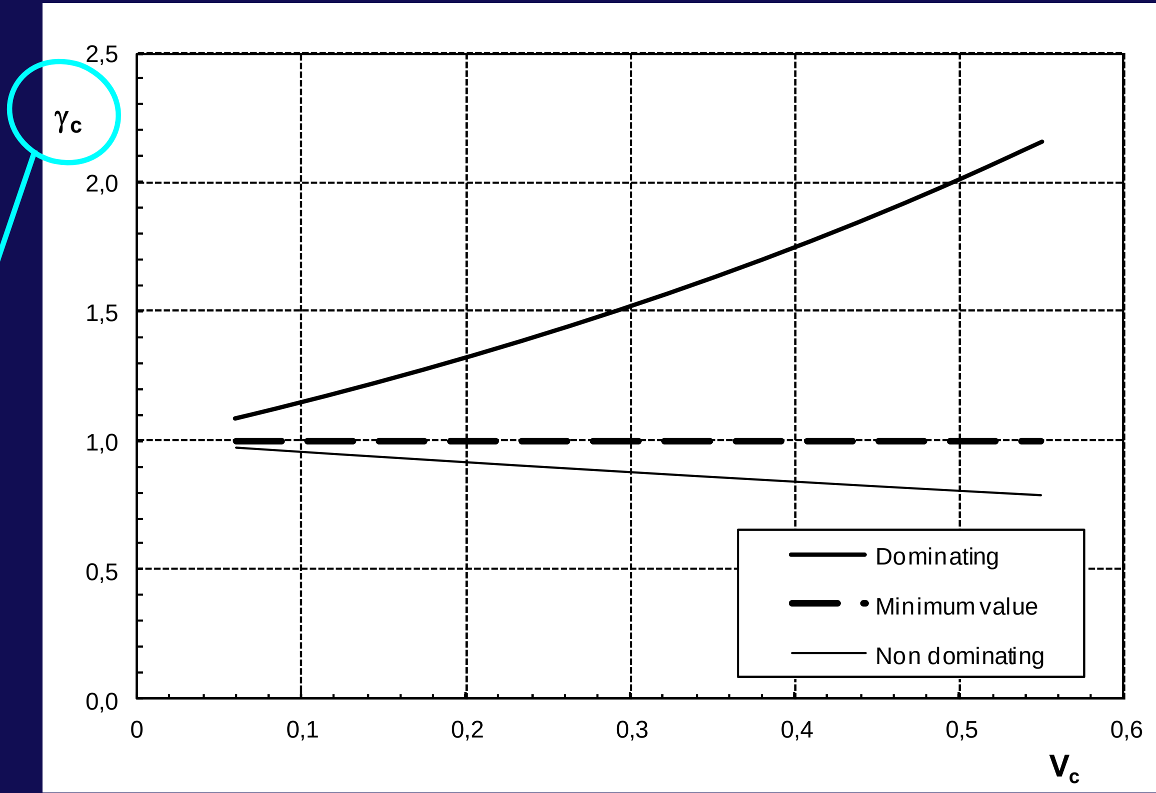
$$X_i = Type\left(\mu_{X_i};\sigma_{X_i}\right)$$





UPDATED PARTIAL FACTORS

– For example partial factor for concrete strength versus CoV



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

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

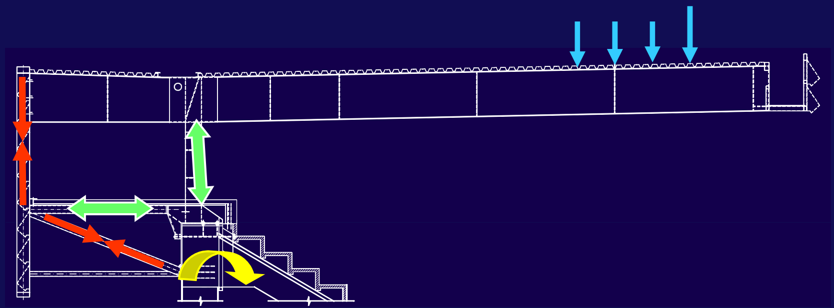
$$R_{d,act} = \frac{1}{\gamma_{Rd,act}} \cdot R\left\{\eta_i \cdot \frac{X_{k,i,act}}{\gamma_{m,i,act}}; a_{d,act}\right\}$$

EXAMPLE

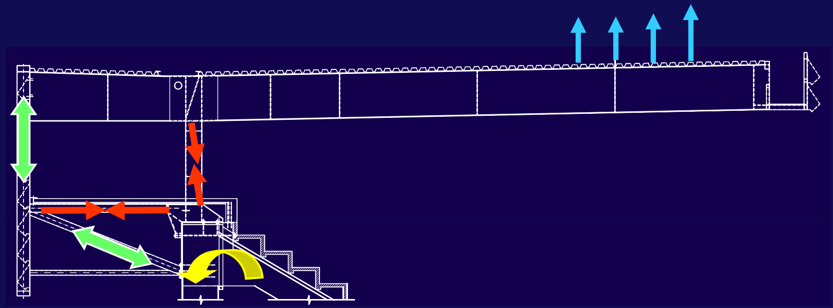
– Assessment of existing RC structure for new conditions

– 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}



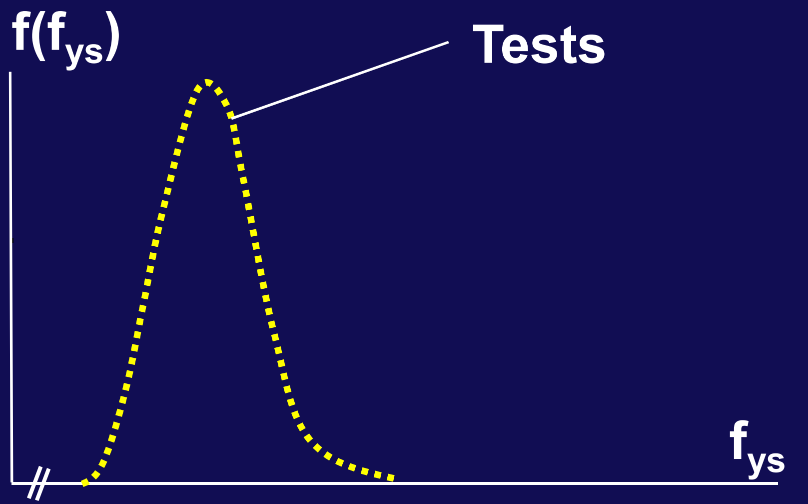
M+



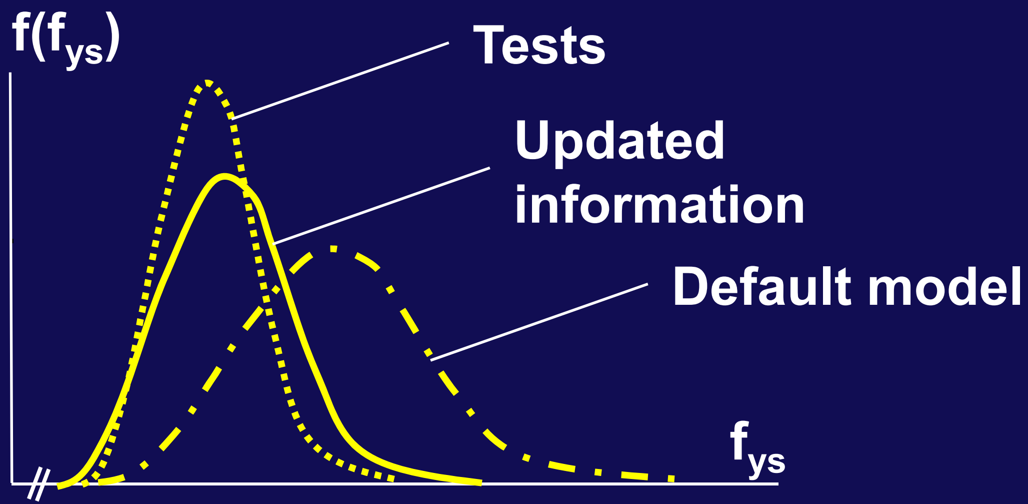
M-

PROCEDURE

1. Statistical evaluation of results of observations
   → PDF: $f_X(x)$

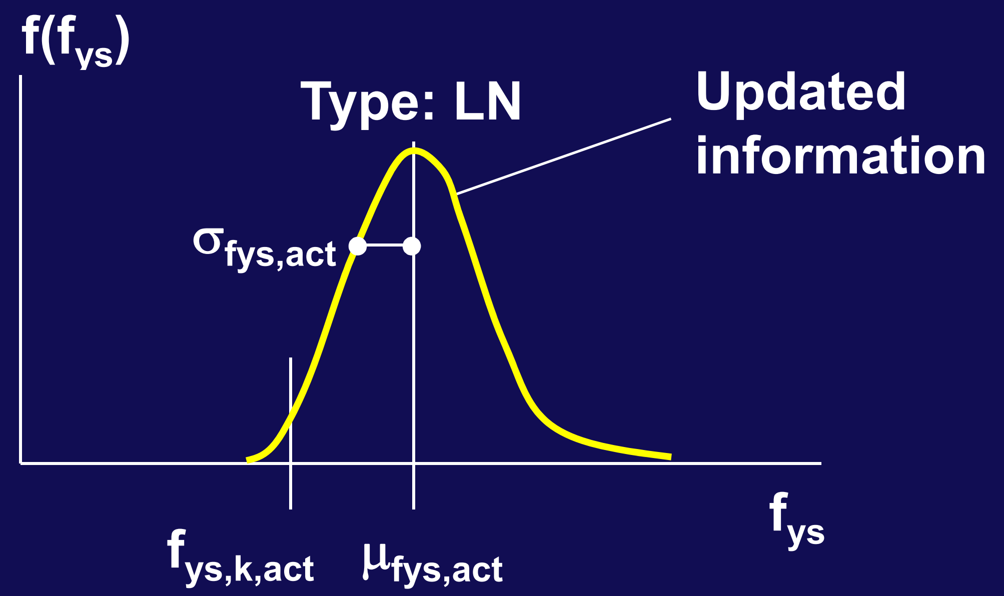


2. Combination of the results of observations with the available prior information (default probabilistic models)



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

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

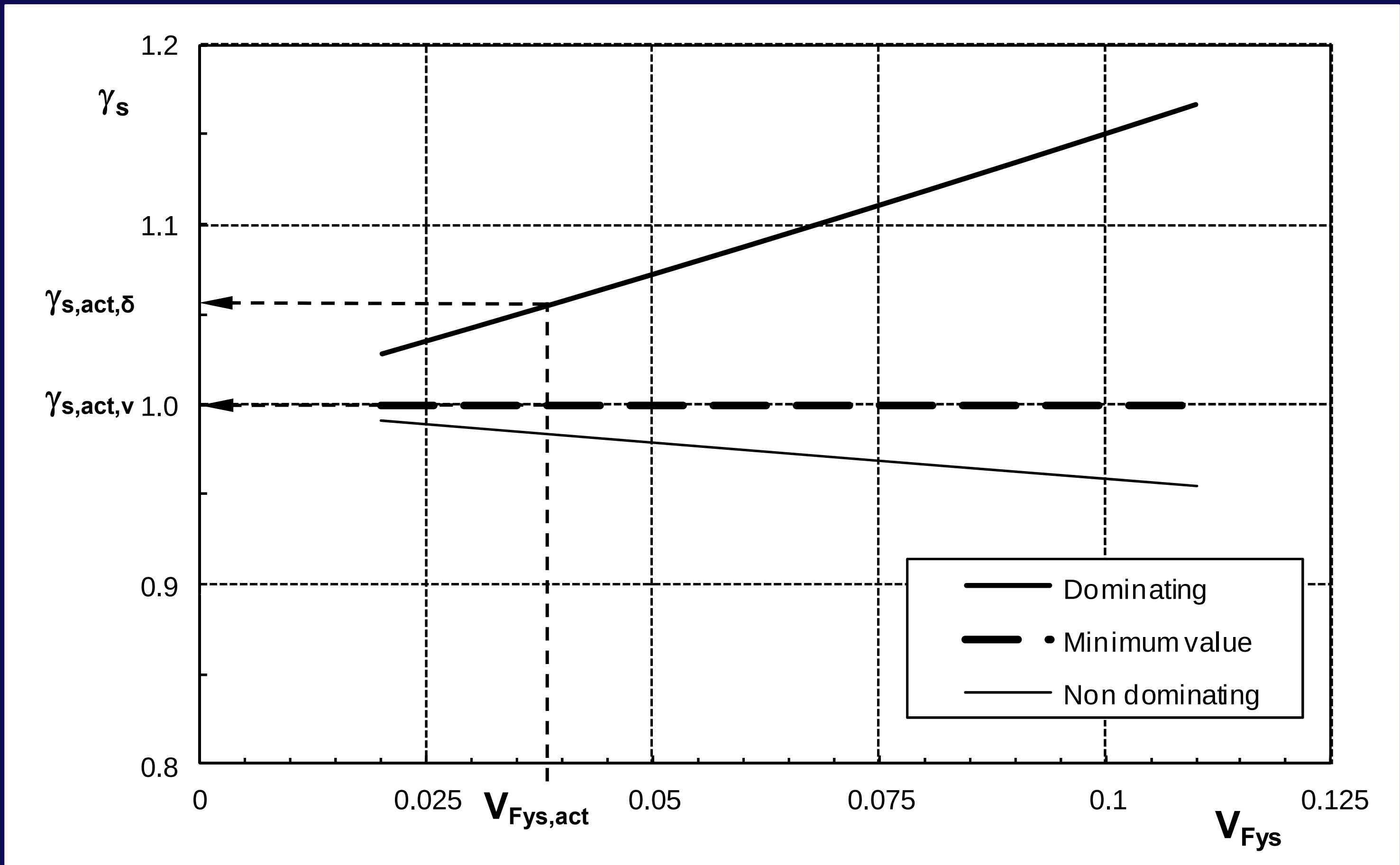
$$V_{fys,act} = \frac{\sigma_{fys,act}}{\mu_{fys,act}}$$

Default value

$$V_{As} = 0.02$$

PROCEDURE

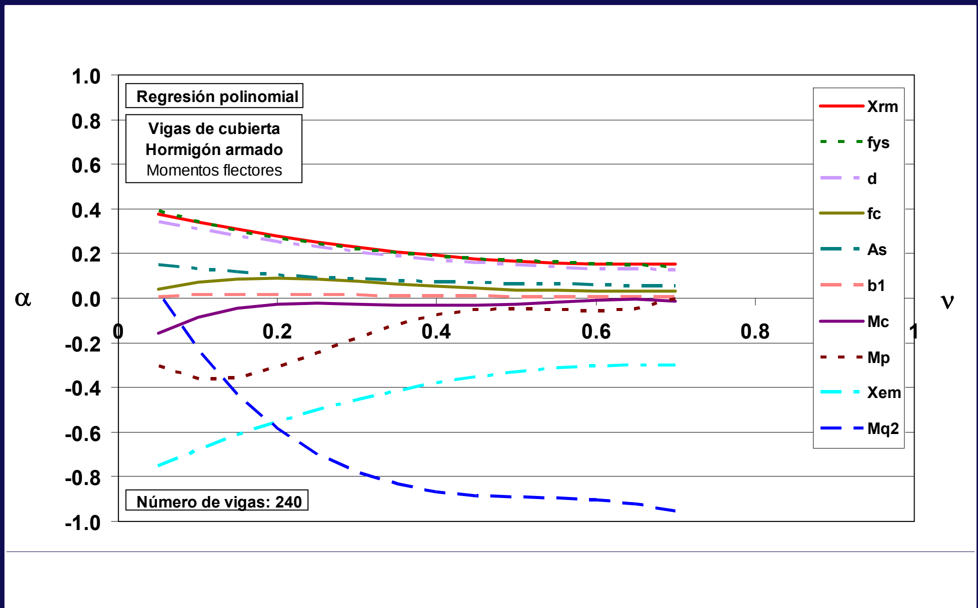
5. Updated partial factor, considering the updated variable dominating or non dominating (unknown in advance)



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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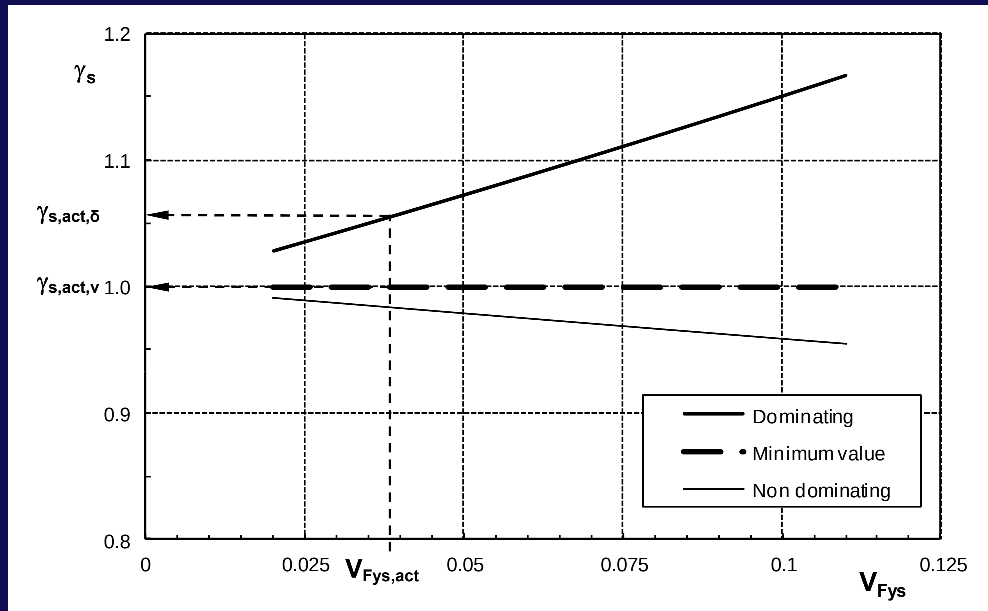

EXAMPLE

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

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

Lifelong Learning Programme

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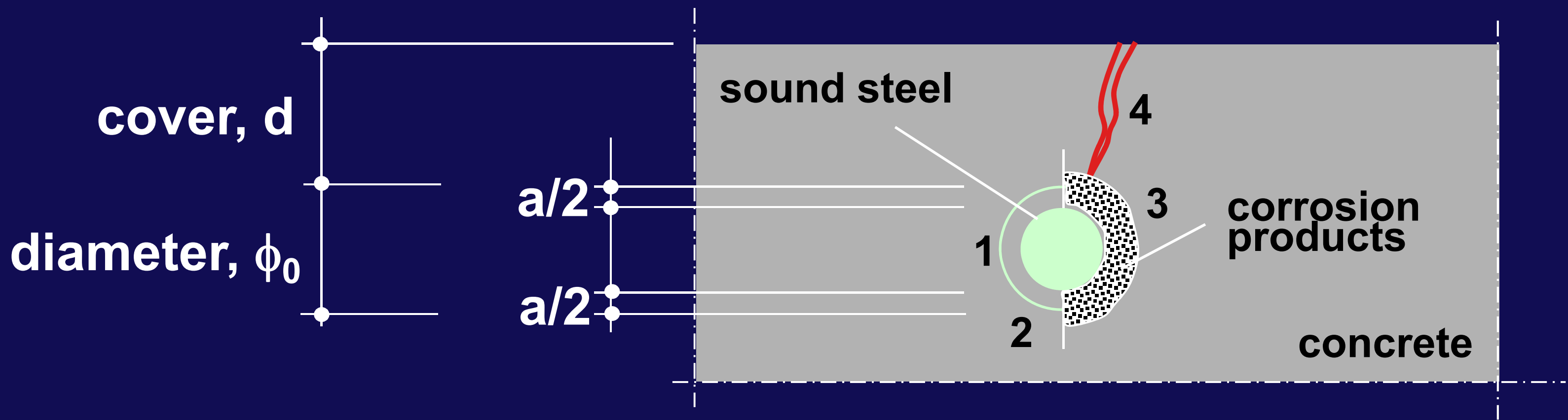
MAIN EFFECTS OF CORROSION OF REINFORCEMENT BARS

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)



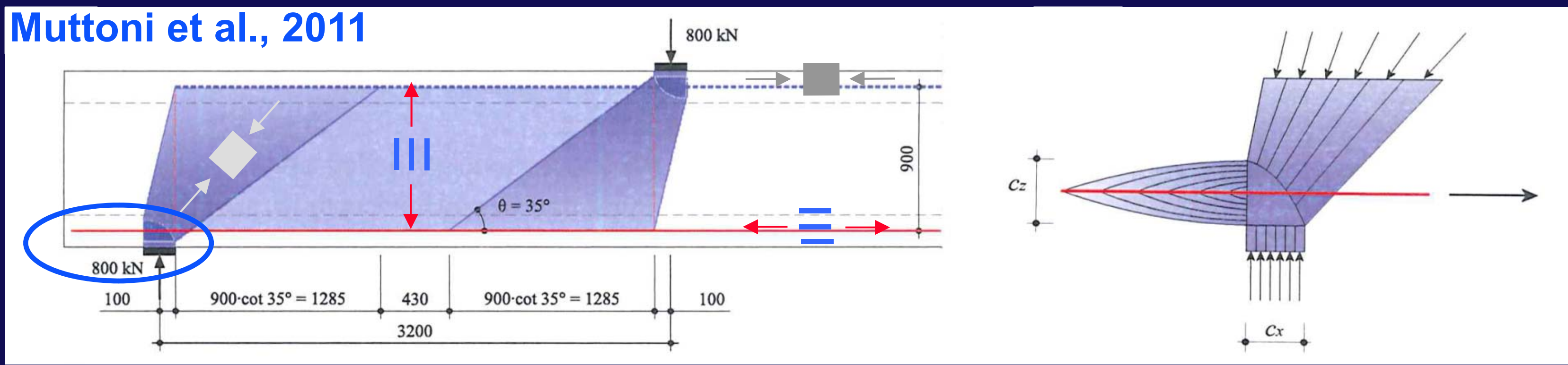
→ Corrosion may affect performance at ULS and SLS

ASSUMPTIONS

- Lower bound theorem of the theory of plasticity is valid

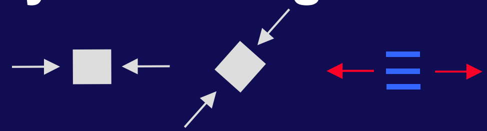
  A load system, based on a statically admissible stress field which nowhere violates the yield condition is a lower bound to the collapse load.

- Stress field models can be established



Muttoni et al., 2011

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



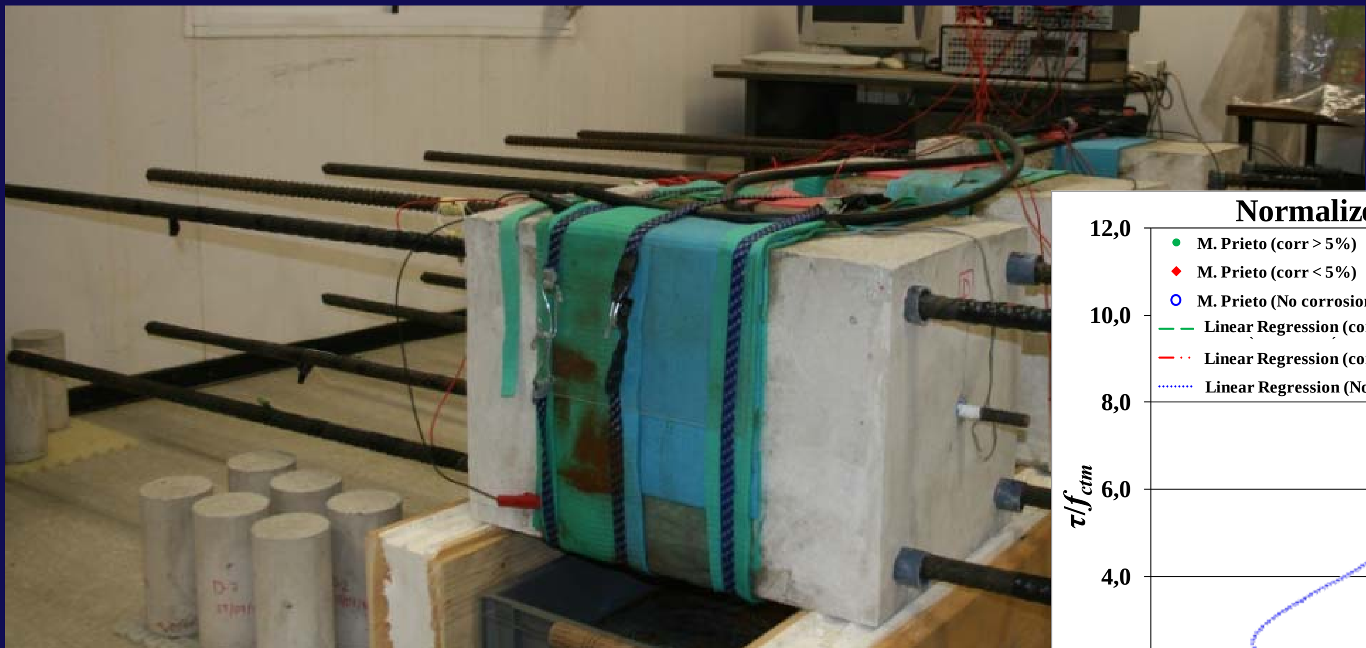
SITE DATA COLLECTION

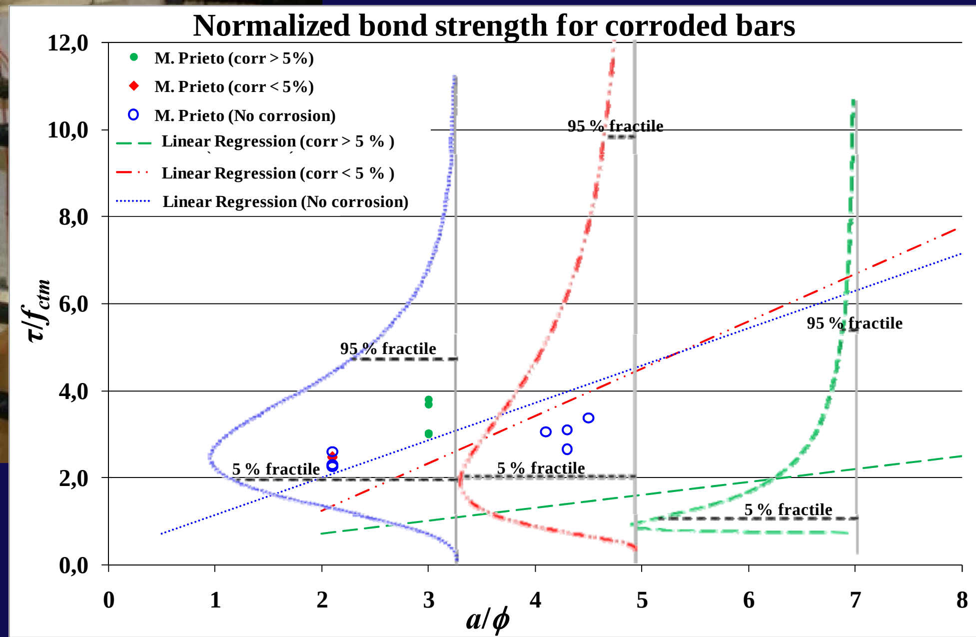
– Geometry and material properties can be updated

BOND STRENGTH

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

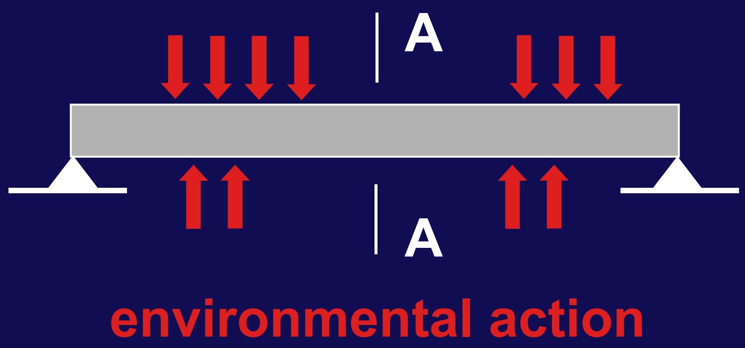
→ Normalized bond strength depending on cross-section loss

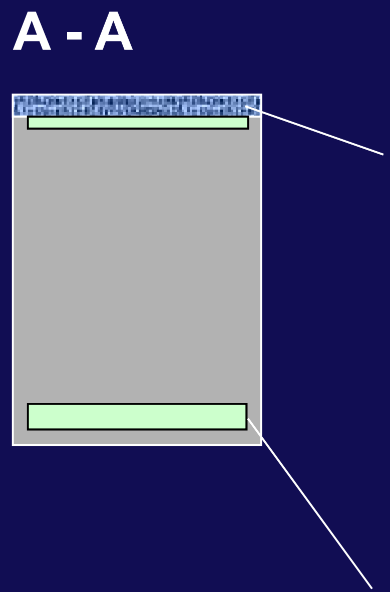




SIMPLE MODELS FOR ESTIMATE OF PERFORMANCE OF CORRODED STRUCTURAL ELEMENTS

– Example: bending resistance

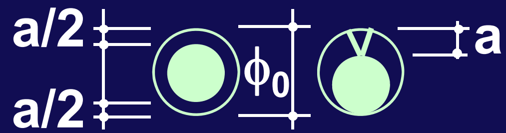




Upper bound: active

Lower bound: disregarded (spalling)

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

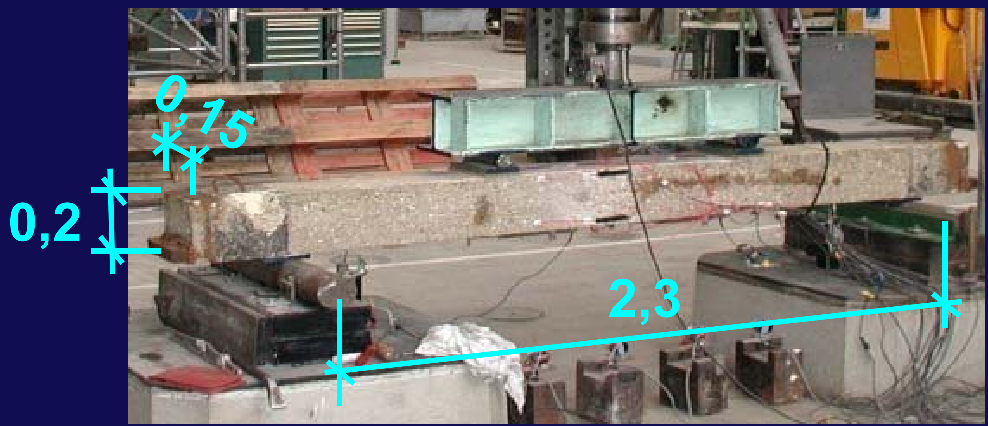


→ Similar rules for other failure modes and SLS

ESTIMATION OF MODEL UNCERTAINTIES

– Available tests from a research project on the residual service life of RC structures [Rodríguez et al.]

– Bending tests on 41 beams, some with accelerated corrosion



Cross-sectional loss:

Top	< 30,3%
Bottom	9,75% to 26,4%

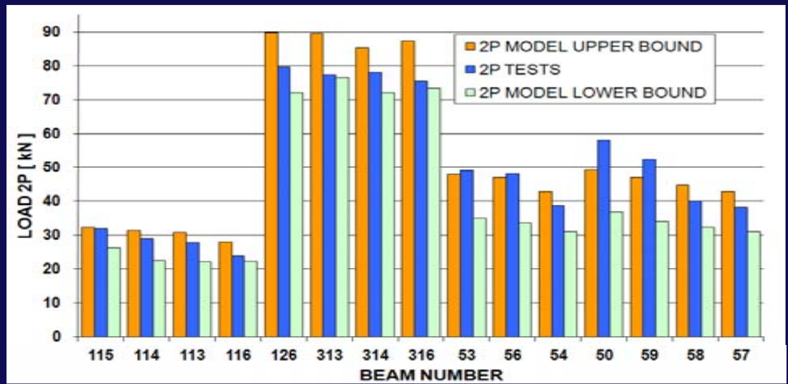
– Bending failure in 25 beams, 15 with corroded reinforcement

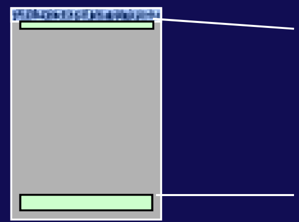
– Material properties and geometry have partly been determined for the tested beams

→ Estimation of model uncertainties

PARAMETERS FOR UNCERTAINTY VARIABLES

– Comparison test – model and statistical evaluation of results





Model	Distribution	μ	CoV
Lower bound	LN	1,34	0,11
Upper bound	LN	0,97	0,11

– Model for lower bound is conservative

– Lower precision than in bending strength models for sound beams → reasonable

CONSEQUENCES

– Higher model uncertainties lead to increase in p_f

– Partial factor should be increased

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

→ Further studies are required, for example for members with

- Larger dimensions
- Natural corrosion

ONGOING TESTS

- Industrial building in the northwest of Spain
  - Construction from the 40's of the last century
  - In disuse for 20 years
  - Exposure to marine environment during 70 years
- Change of use
  - Transformation into cultural centre
  - → Partial demolition required

→

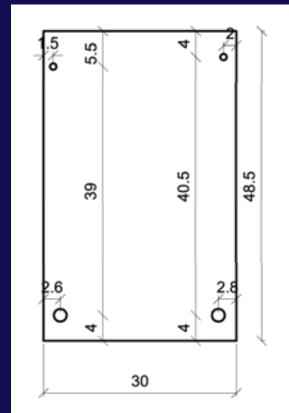
ONGOING TESTS

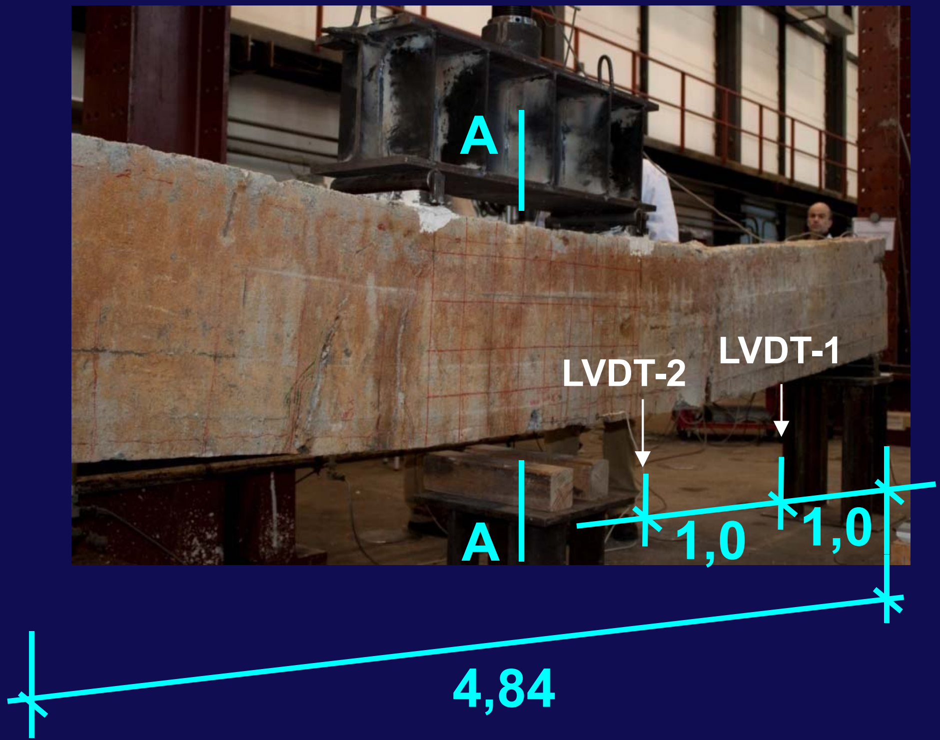
- Selection of representative, corrosion-damaged members for testing
  - 8 beams
  - 5 columns
  - 1 frame

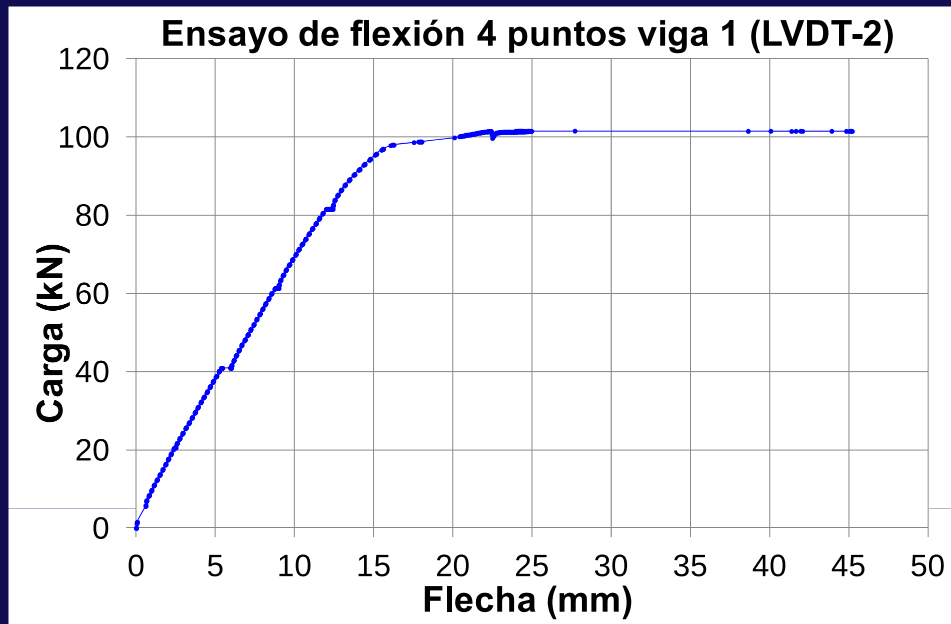
SOME RESULTS

- Bending test on **beam nº 1**
  - Deformation control
  - Ductile behaviour

A - A

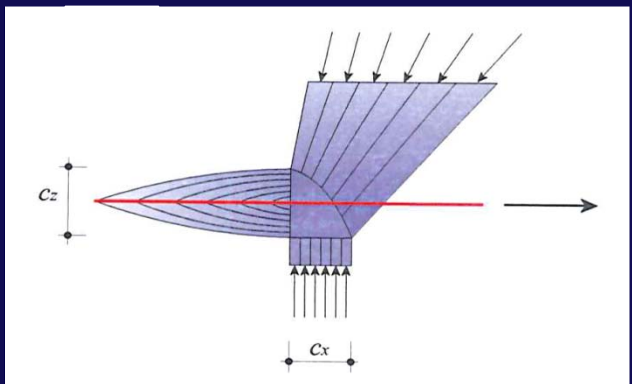


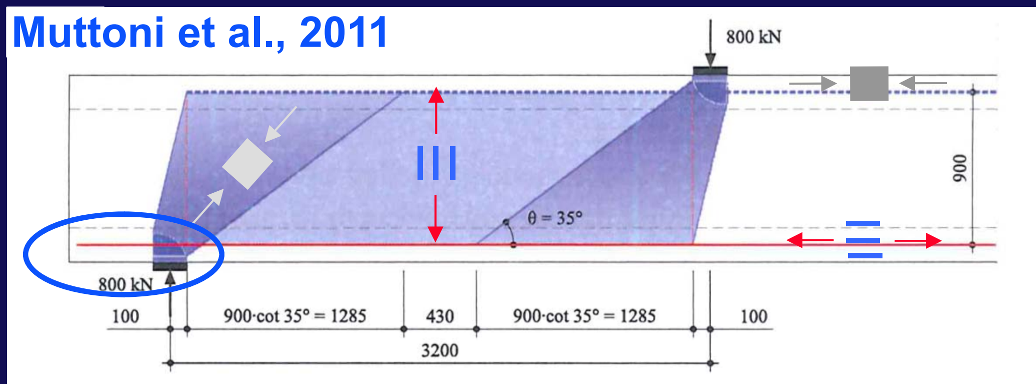




THEORETICAL LOAD BEARING CAPACITY

- *Prior* information
  - Geometry: measured on tested beam prior to the test
  - Material properties: determined for members from the same building
- Analysis based on *prior* information using stress field model and comparison to test
  - $M_{ult,t}$ = 127 kNm
  - $M_{ult,e}$ = 123 kNm





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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

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

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

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
  - ...

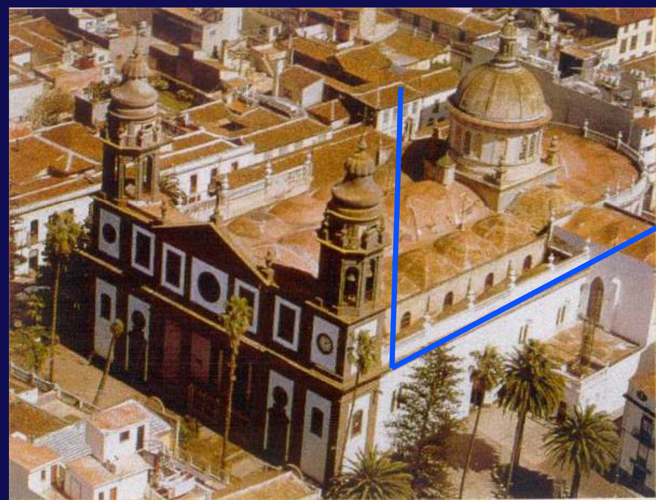
RISKS ASSOCIATED WITH SCANTILY PROVEN TECHNOLOGY

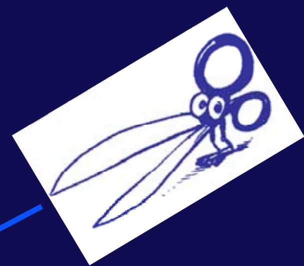
– Less than 100 years after reconstruction, the cathedral was to be closed to the public again and was propped ...

→ 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



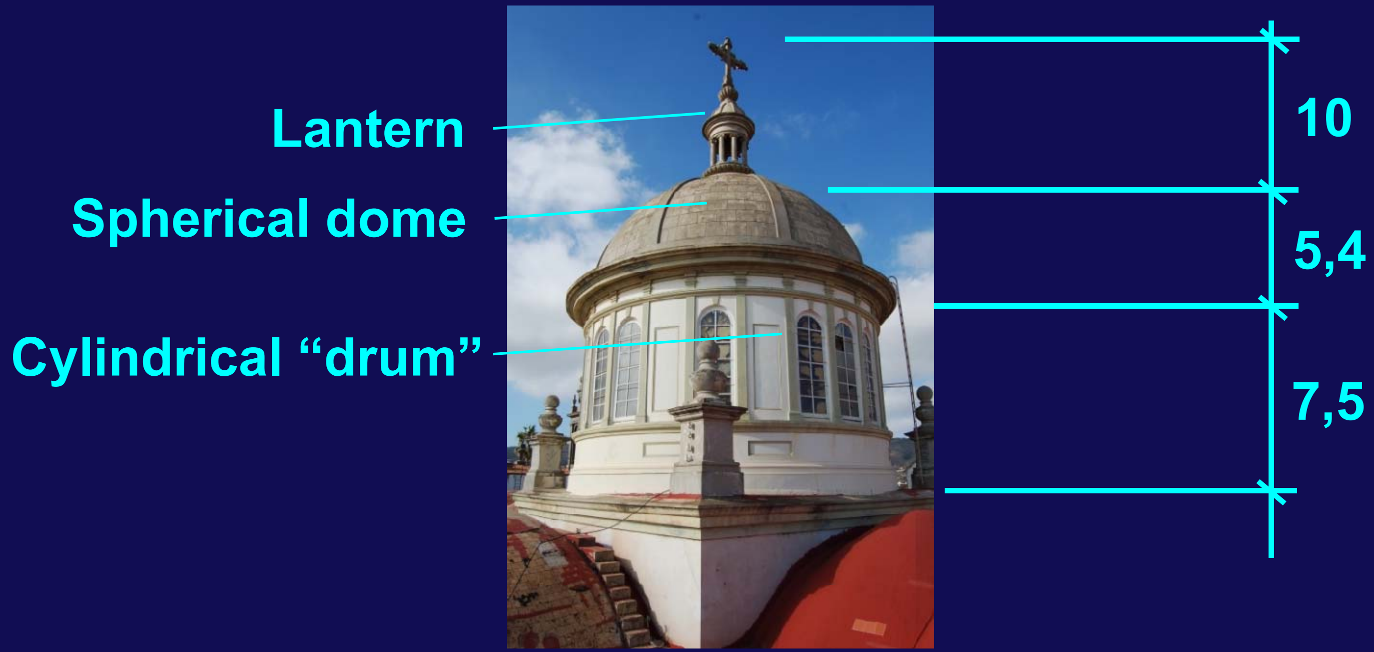


WORLD HERITAGE SITE

- 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

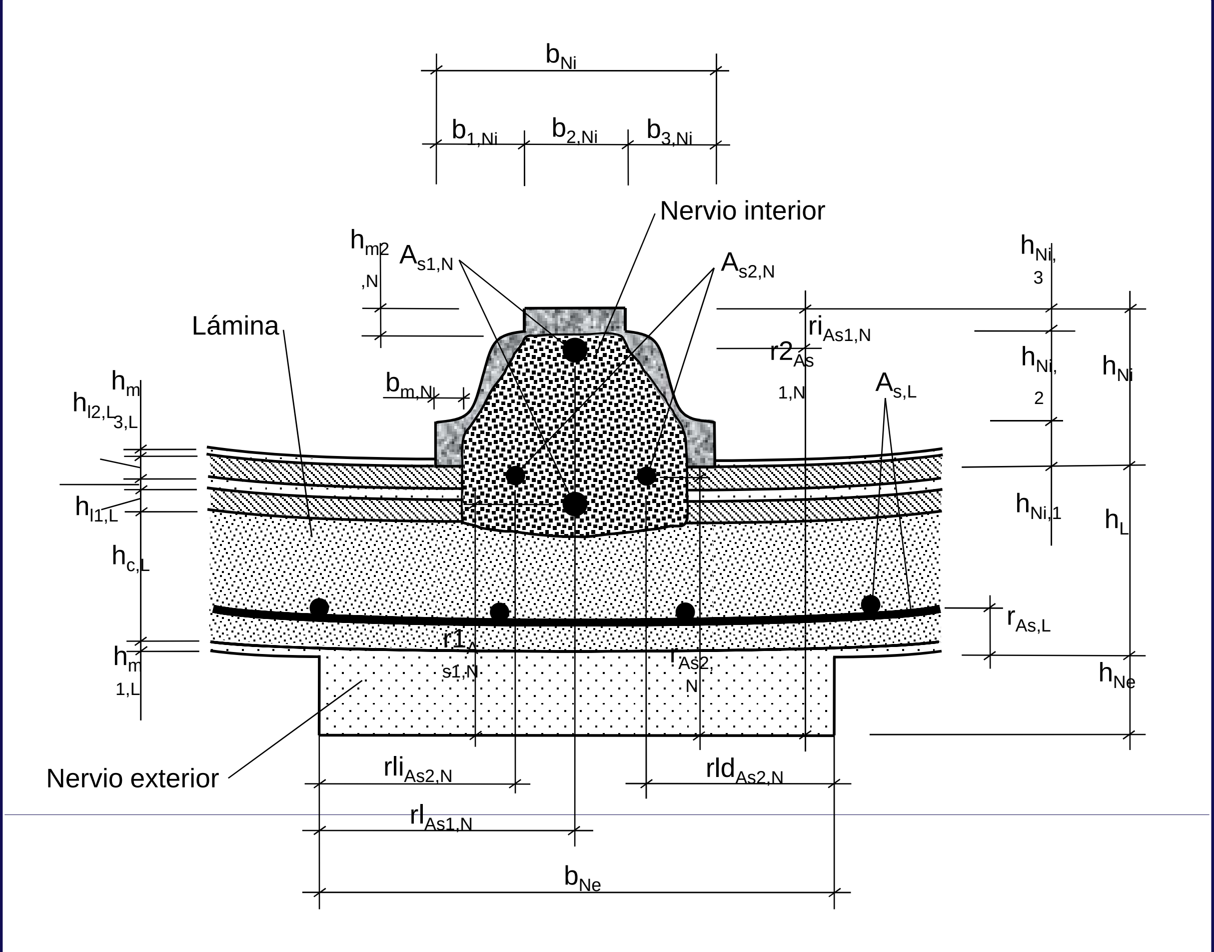
DATA ACQUISITION PROGRAM

- 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

Outside Inside

CROSS SECTIONS

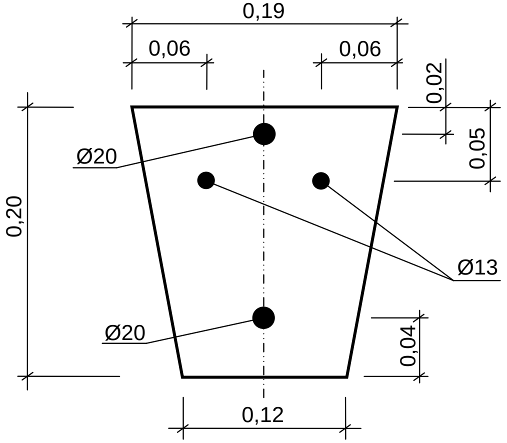
– Parameters for different variables derived from a minimum of **4 measurements**



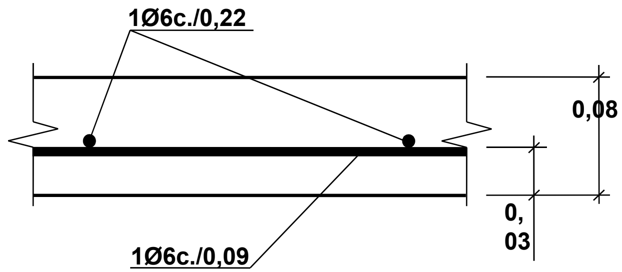
CROSS SECTIONS

– Equivalent cross sections for structural analysis

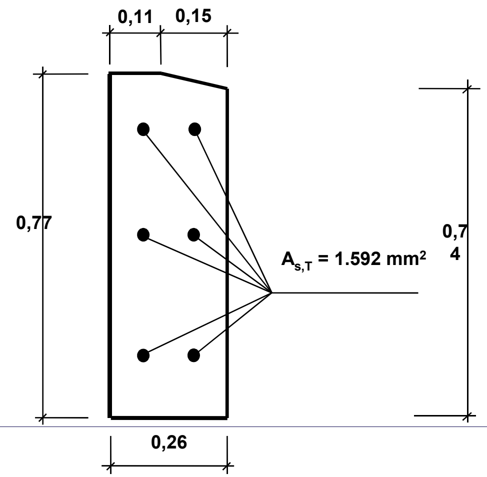
Arches



Shell



Tension ring



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

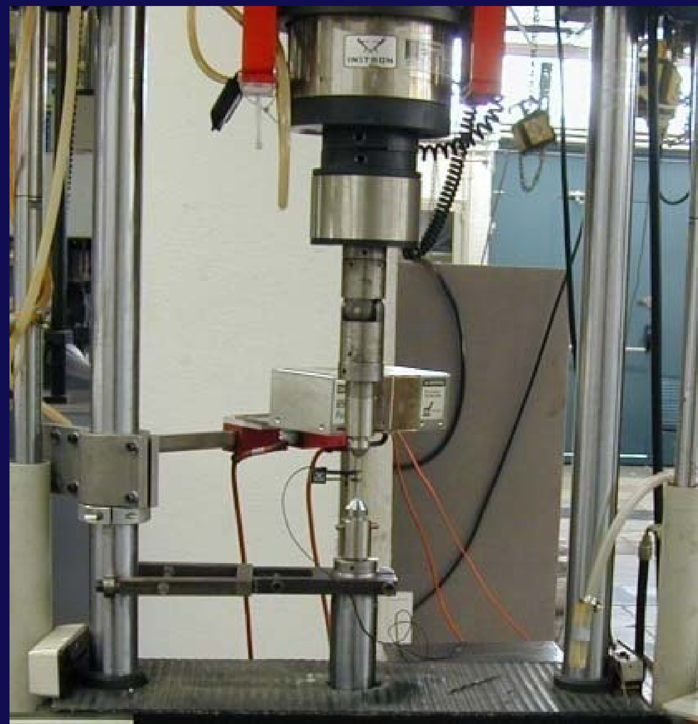
$$\gamma_{g_c,act,v} = 1 - \alpha_{g_c} \cdot \beta \cdot \sqrt{V^2_{\rho_c,act} + V^2_{h_c,act}} = 1{,}11$$

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

MATERIAL PROPERTIES FOR REINFORCING STEEL

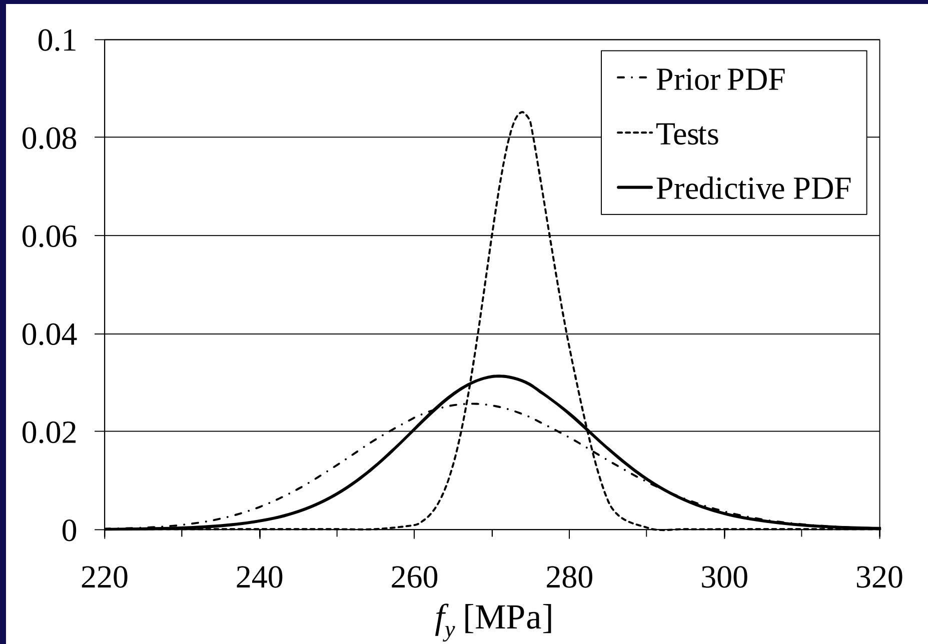
– Manufacture of specimens

– 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

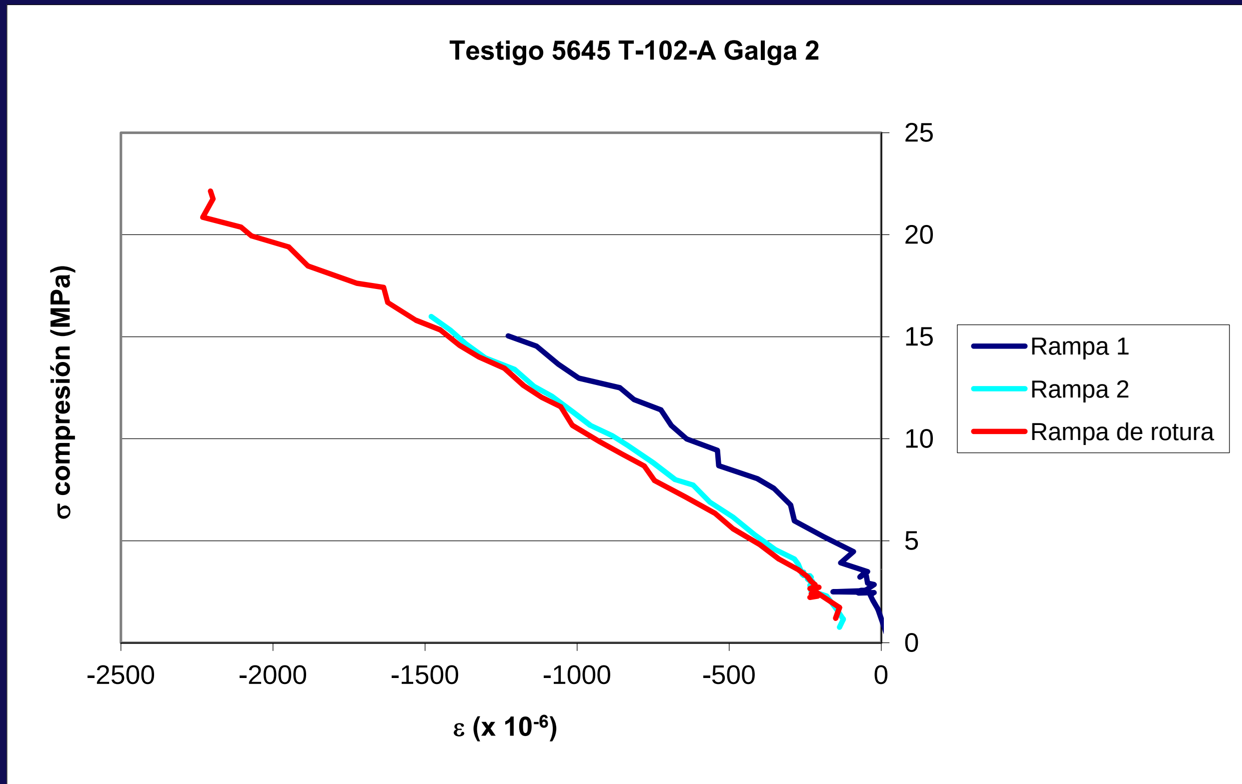
  – ϕ < 6 mm: $f_{ys,k,act}$ = 304 N/mm^2

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

MATERIAL PROPERTIES FOR CONCRETE

– Manufacture of specimens

– Execution of compression tests



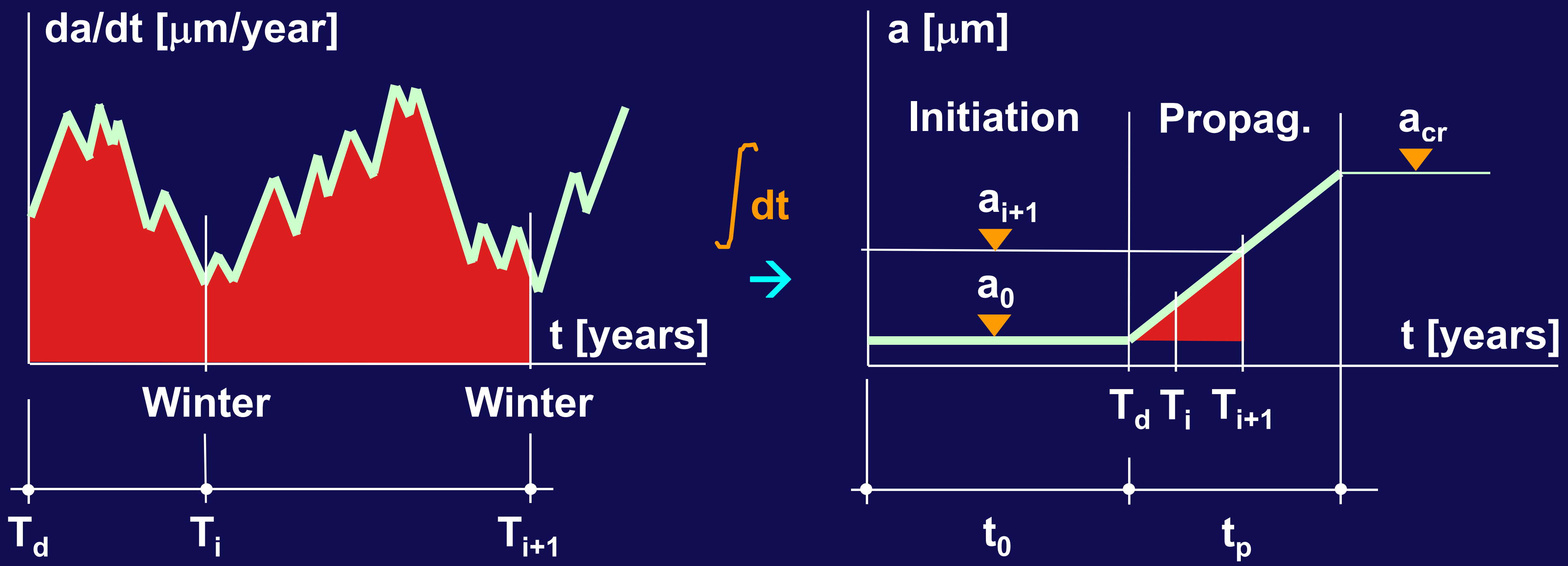
MATERIAL PROPERTIES FOR CONCRETE

- Evaluation of test results and combination of information
- 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: $f_{ck,act} = 6{,}8\ \text{N/mm}^2$
  - Shells: $f_{ck,act} = 3{,}1\ \text{N/mm}^2$
  - "Drum": $f_{ck,act} = 4{,}9\ \text{N/mm}^2$

REINFORCEMENT CORROSION

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

Propagation rate → **Mean velocity**

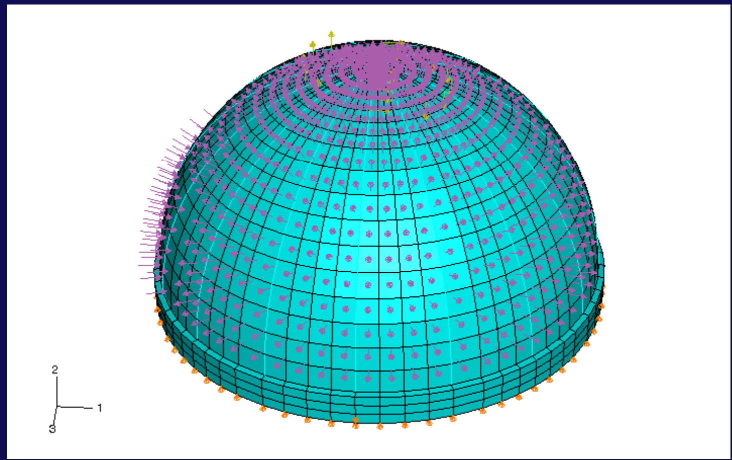


→ Extrapolation for future service period: $A_{s,corr}$

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

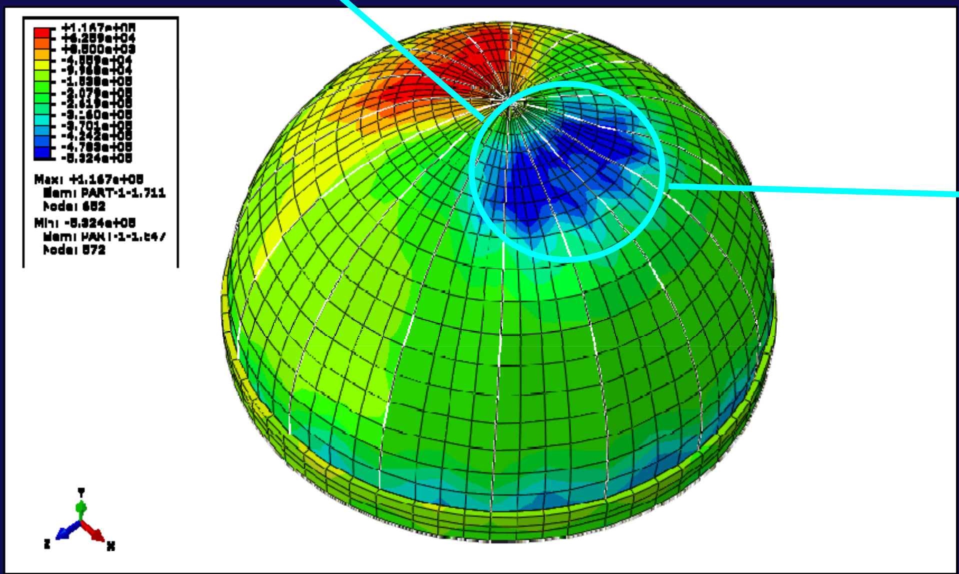
$N_{Ed,max,act}$ = 77 kN/m (+ compression)

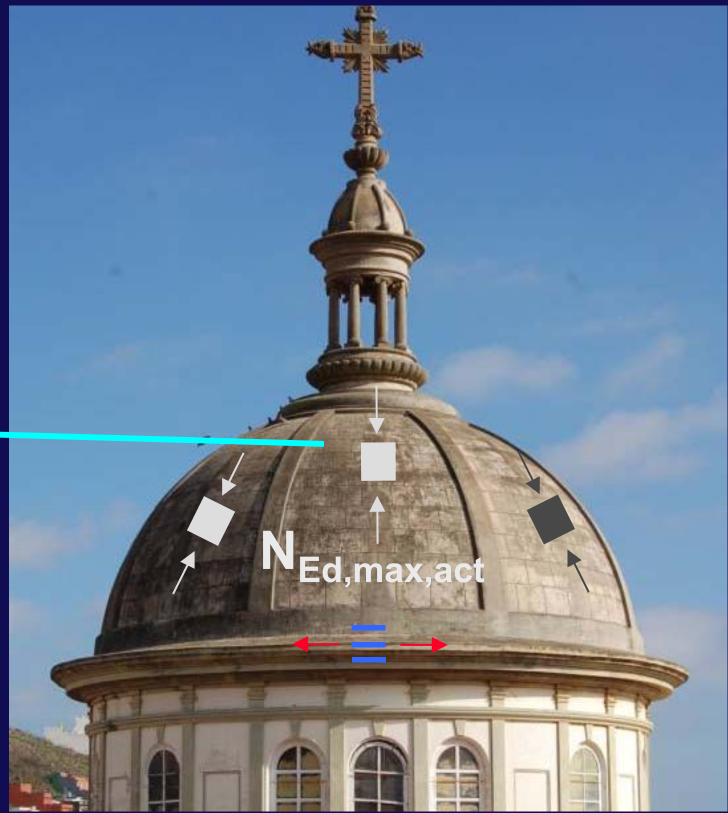
– Updated design resistance at the end of future service period

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

– Verification

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

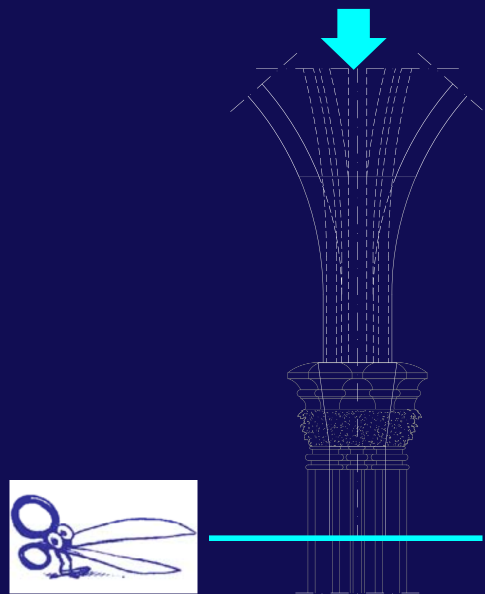




RECOMMENDATION

- 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 DETERIORATING STRUCTURES

- Introduction
- Updated models for the assessment of sound structures
- Corrosion-damaged reinforced concrete structures
- La Laguna cathedral
- Final remarks

Lifelong Learning Programme

Národní agentura pro evropské vzdělávací programy

CSIC Consejo Superior de Investigaciones Científicas

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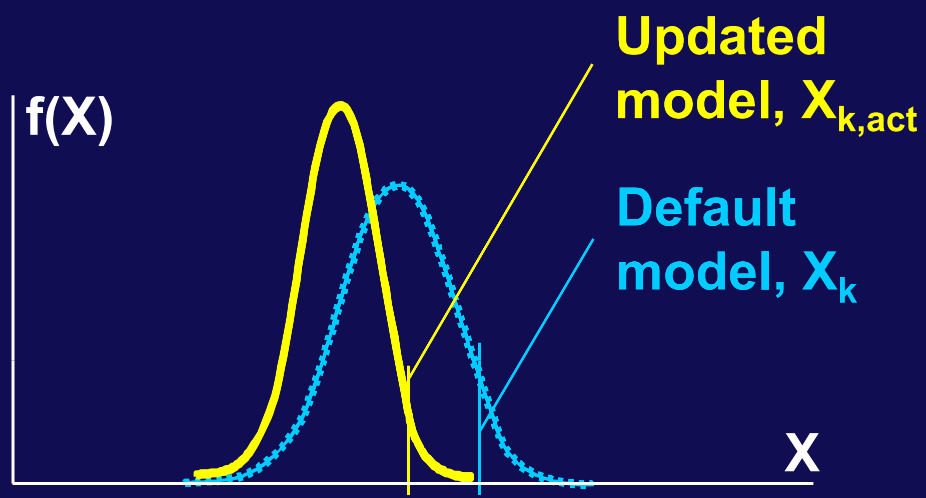
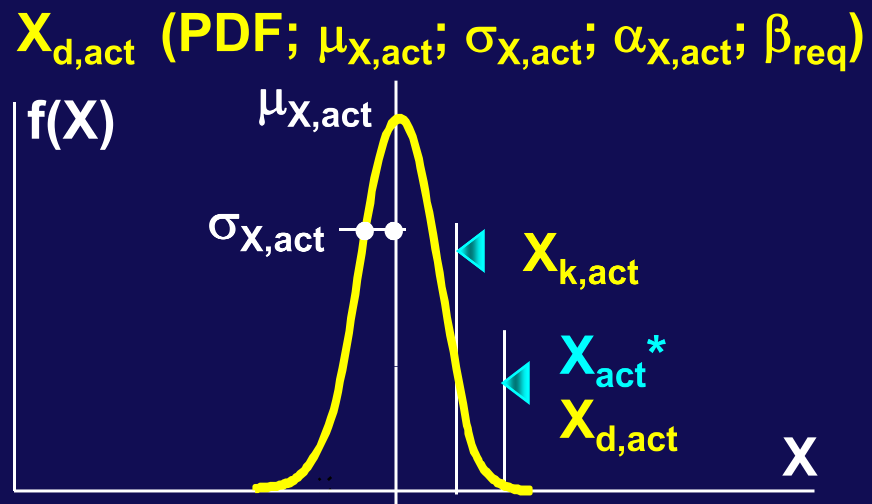
FINAL REMARKS

- In the safety assessment of existing structures, many uncertainties may be reduced
- 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