LEONARDO DA VINCI PROJECT CZ/11/LLP-LdV/TOI/134005
SEMINAR ON ASSESSMENT OF EXISTING STRUCTURES
Barcelona. 14-06-2012

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**
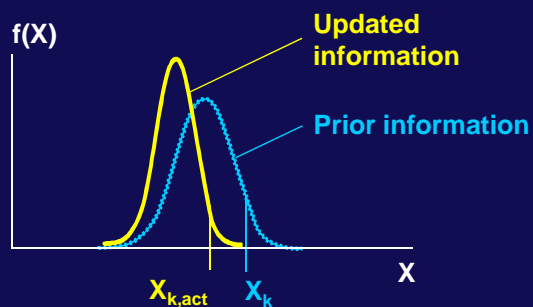
ASSESSMENT WITH PARTIAL FACTOR METHOD

- **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**

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

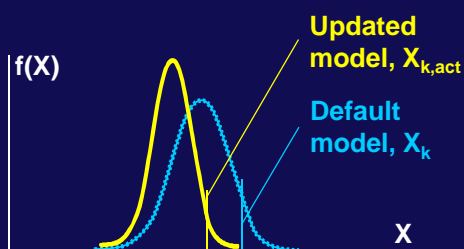

ASSESSMENT WITH PARTIAL FACTOR METHOD

- **Updated characteristic value of X**

f(X)

Updated information
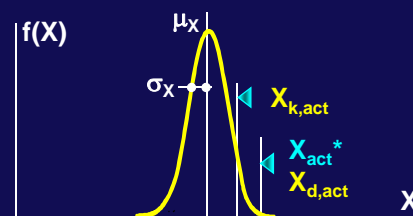
Prior information

$X_{k,act}$ X_k

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**
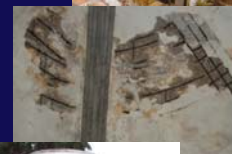–   **Updating of characteristic values and partial factors**

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

f(X)

Updated model, $X_{k,act}$

Default model, X_k

X

f(X)

μ_X

σ_X

$X_{k,act}$

$X_{act}*$
$X_{d,act}$

X

ON THE ASSESSMENT OF DETERIORATING STRUCTURES

Lifelong Learning Programme

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

NAEP
Národní agentura pro evropské vzdělávací programy

CSIC
Consejo Superior de Investigaciones Científicas

INSTITUTO EDUARDO TORROJA

CESMA
ingenieros

PARTIAL FACTOR FORMAT FOR ASSESSMENT

–   **Design value for action effects**

$$E_{d,act} = \gamma_{Sd,act} \cdot E\left\{ \sum_{j\geq1} \gamma_{g,j,act} \cdot G_{k,j,act} \text{ "+" } \gamma_{q,1,act} \cdot Q_{k,1,act} \text{ "+"} ... \right\}$$

$\gamma_{f,i,act}$ **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**

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

$\gamma_{m,i,act}$ **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**

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

$f(X)$

σ_X

X_{FORM}
$X_d = \gamma_X \cdot X_k$

μ_X X_k

X
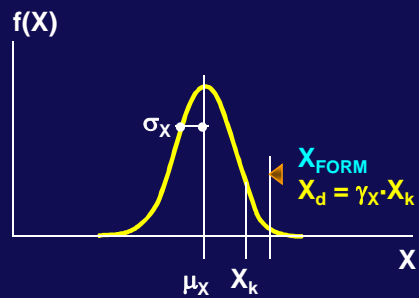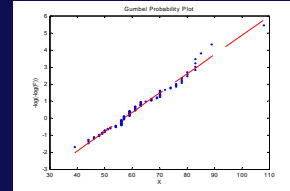
UPDATED PARTIAL FACTORS

– **For example partial factor for concrete strength versus CoV**

γ_c

——— Variable dominante
——— No Dominante

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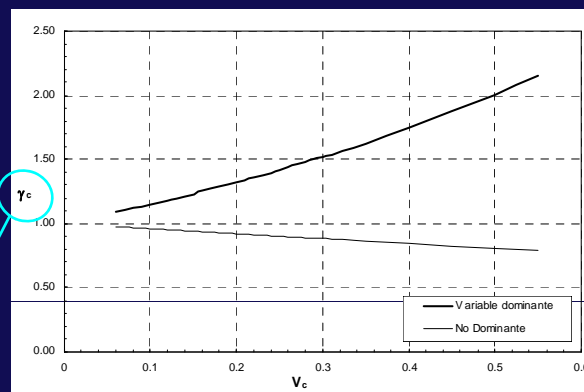
Definition $\gamma_c \neq \gamma_{c,EC\text{-}2}$

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

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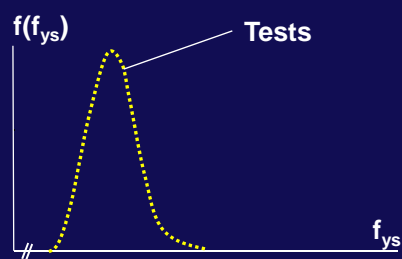
EXAMPLE

- Assessment of existing RC structure for new conditions
- Site data collection has been decided, planned and carried out
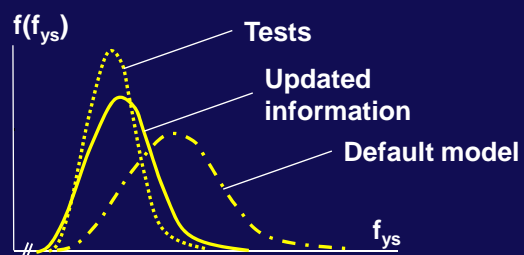→ Sample of **n** test results is available for updating of reinforcement yield strength, **f$_{ys}$**

M⁺ M⁻
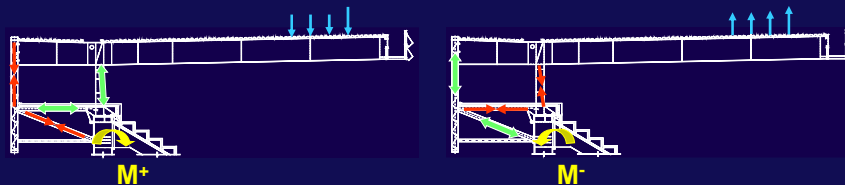
PROCEDURE

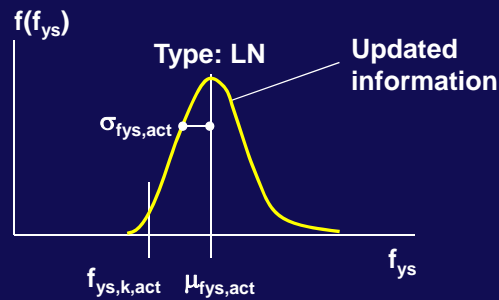1. **Statistical evaluation of results of observations**
   → PDF: **f$_X$(x)**

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; $\mu_{X,act}$; $\sigma_{X,act}$; $x_{k,act}$**

$f(f_{ys})$

Type: LN　　Updated information

$\sigma_{fys,act}$

$f_{ys,k,act}$　$\mu_{fys,act}$

f_{ys}

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**

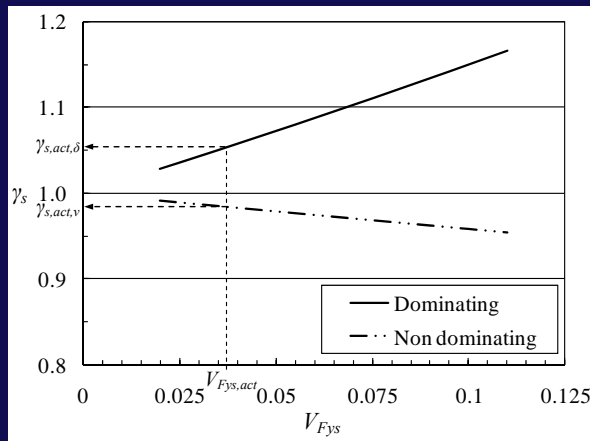– 　**Updated coefficient of variation for the tensile force**

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

Default value
$V_{As} = 0.02$

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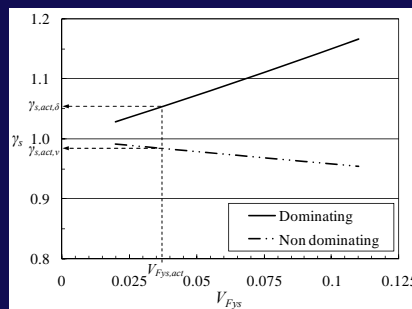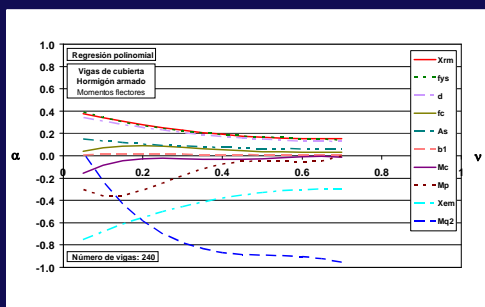
PROCEDURE

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**

EXAMPLE

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

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


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**
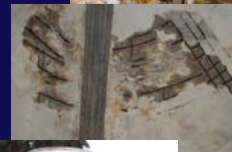
MAIN EFFECTS OF CORROSION OF REINFORCEMENT BARS
1. **Decrease of bar cross-section**
2. **Decrease of ductility of steel (ε_u: reduction of 30 to 50%)**
3. **Bond deterioration**
4. **Cracking of concrete cover (due to corrosion products)**
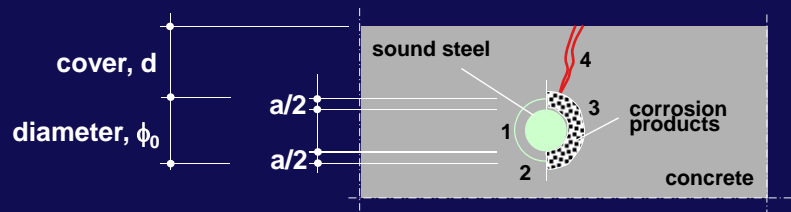
→ **Corrosion may affect performance at ULS and SLS**

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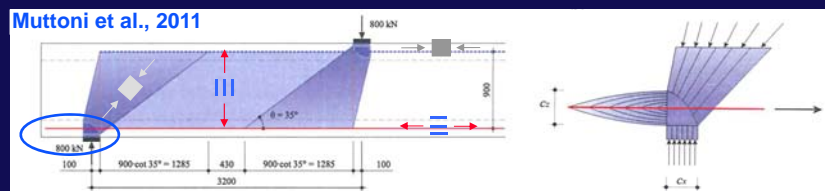
– **Required information**
   – **Geometry, particularly remaining bar cross-sections**
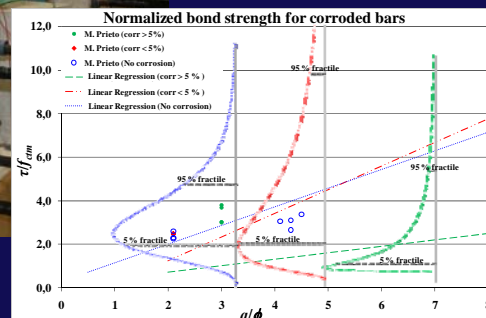   – **Material properties**
   – **Bond strength**

SITE DATA COLLECTION
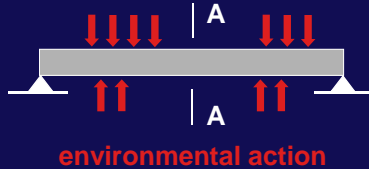
– **Geometry and material properties can be updated**

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**

environmental action

A - A

**Upper bound:
active**

**Lower bound:
disregarded
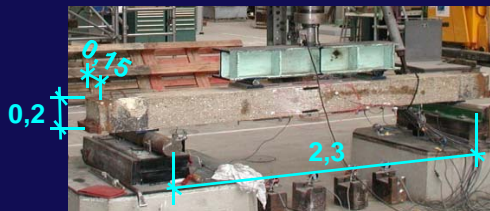(spalling)**

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

→ **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**
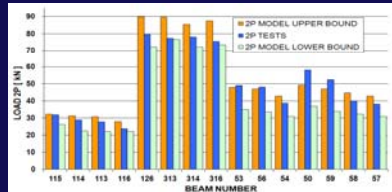
Upper bound: active

Lower bound: disregarded

Remaining cross-sections

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**

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

→ **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**
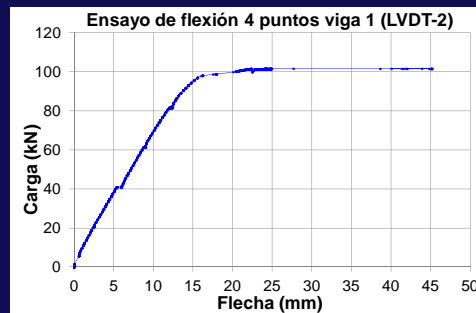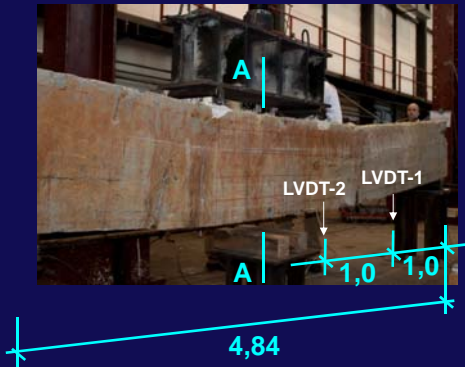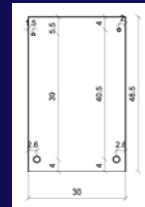 – **Transformation into cultural centre**
  → **Partial demolition required**

 →

ONGOING TESTS

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

FIRST RESULTS

– **Bending test on beam nº 1**

– **Deformation control**

– **Ductile behaviour**

A - A

Ensayo de flexión 4 puntos viga 1 (LVDT-2)


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
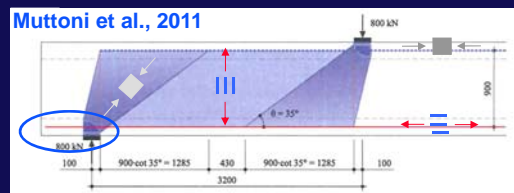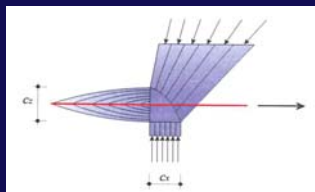
Muttoni et al., 2011

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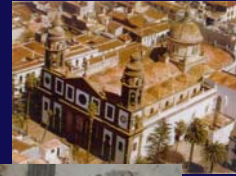
SAN CRISTÓBAL DE LA LAGUNA

- 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**
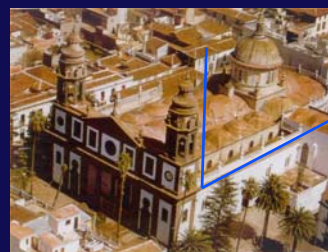
WORLD HERITAGE SITE
– **Authorities wish to save the existing main dome**
– **For this purpose, durability requirements are reduced**
  – **Service period for normal building structures, not for monumental buildings**
 → **Future techniques might be suitable to fully detain deterioration mechanisms**

GEOMETRY
– **Global system**

Lantern
Spherical dome
Cylindrical "drum"

10
5,4
7,5
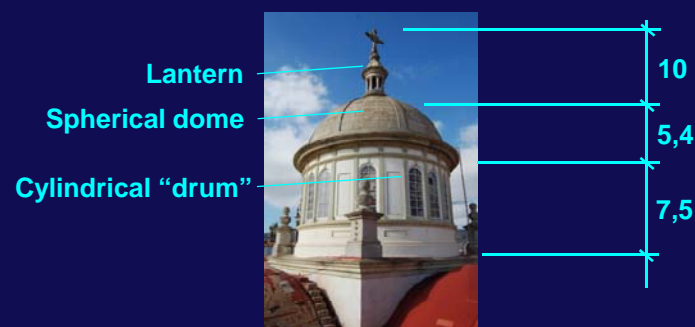
– **Structural members of the spherical dome**
  – **8 arches**
  – **Shells**
  – **Tension ring**

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**
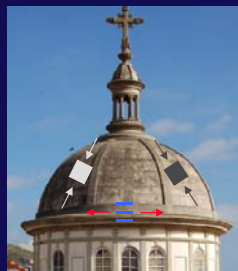
PRIOR INFORMATION

– **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**

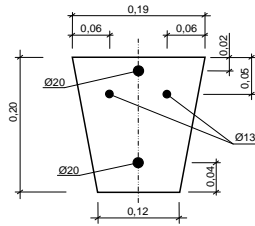**Outside**   **Inside**

CROSS SECTIONS

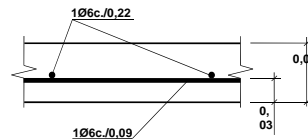– **Parameters for different variables derived from a minimum of 4 measurements**
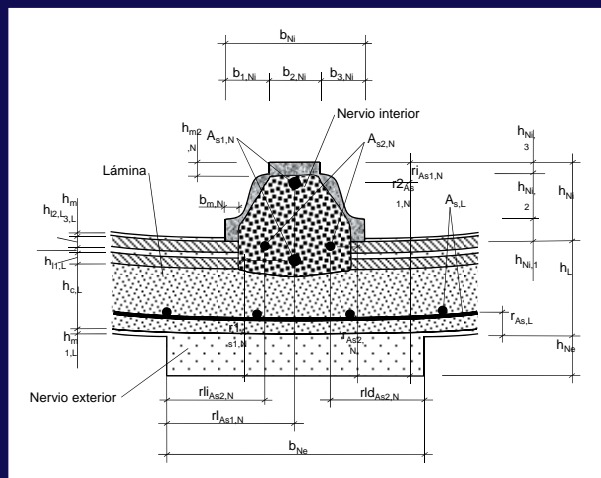
CROSS SECTIONS
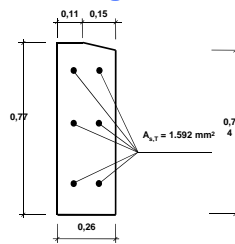– **Equivalent cross sections for structural analysis**

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**
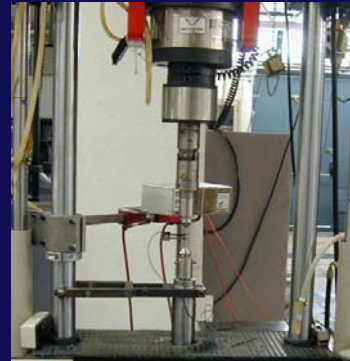
→ **Updated partial factors, for example for self weight**

$$\gamma_{g_c,act,\delta} = 1 - \alpha_{g_c} \cdot \beta \cdot \sqrt{V_{\rho_c,act}^2 + V_{h_c,act}^2} = 1,18$$

$$\gamma_{Sd,N,act,v} = \gamma_{Sd,N,v} = e^{-\alpha_{\xi_{E,N}} \cdot \beta \cdot V_{\xi_{E,N}}} = 1,06$$
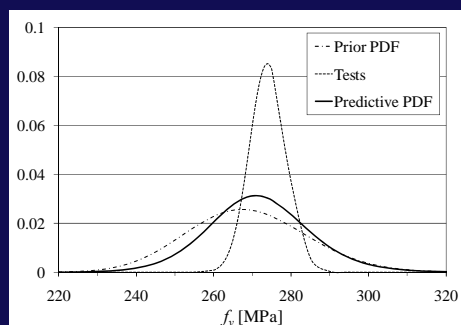
MATERIAL PROPERTIES FOR REINFORCING STEEL
- **Manufacture of specimens**
- **Execution of tensile tests**
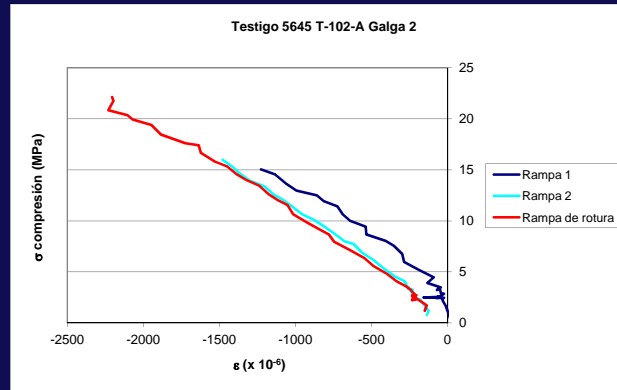
MATERIAL PROPERTIES FOR REINFORCING STEEL
- **Evaluation of test results and combination of information**

- **Updated parameters: LN; $\mu_{fys,act}$; $\sigma_{fys,act}$; $f_{ys,k,act}$; $\gamma_{s,act}$**
- **Updated characteristic values**
    - **$\phi < 6$ mm:** **$f_{ys,k,act} = 304$ N/mm^2**
    - **$\phi > 6$ mm:** **$f_{ys,k,act} = 262$ N/mm^2**

MATERIAL PROPERTIES FOR CONCRETE
- **Manufacture of specimens**
- **Execution of compression tests**

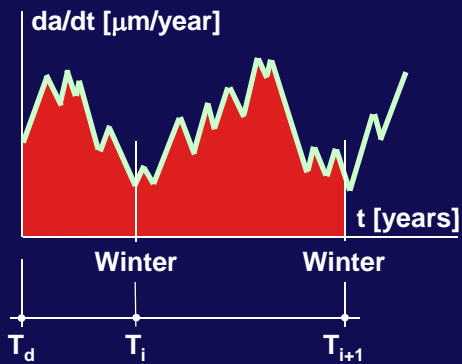## MATERIAL PROPERTIES FOR CONCRETE
- **Evaluation of test results and combination of information**
- **Updated parameters**
  - **Compressive strength: LN; $\mu_{fc,act}$; $\sigma_{fc,act}$; $f_{ck,act}$; $\gamma_{c,act}$**
  - **Modulus of elasticity: $\mu_{Ec,act}$; $\sigma_{Ec,act}$**
- **Updated characteristic values**
  - **Arches:** **$f_{ck,act} = 6{,}8$ N/mm^2**
  - **Shells:** **$f_{ck,act} = 3{,}1$ N/mm^2**
  - **"Drum":** **$f_{ck,act} = 4{,}9$ N/mm^2**
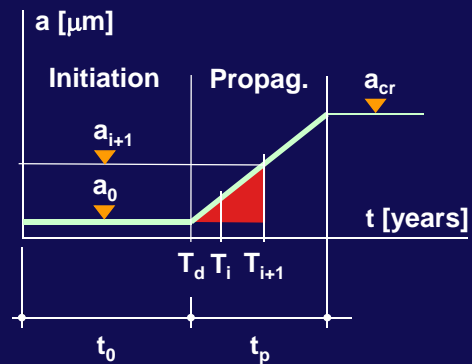
Slide 1:

REINFORCEMENT CORROSION
– Corrosion rate measurements require careful interpretation
– Mean velocity to be estimated from remaining cross sections
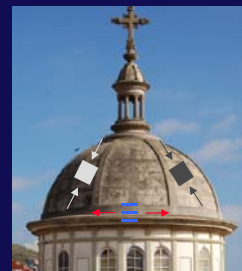
Propagation rate → Mean velocity

da/dt [μm/year]

∫ dt

→

t [years]

Winter   Winter

T_d T_i T_{i+1}

a [μm]

Initiation | Propag. | a_{cr}

a_{i+1}

a_0

t [years]

T_d T_i T_{i+1}

t_0 t_p

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

Slide 2:

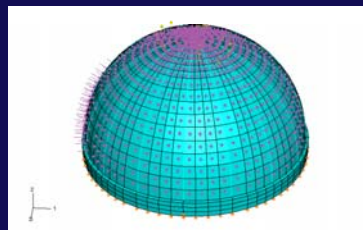**TENSION RING AS AN EXAMPLE**
– Relevant design situation for structural safety
    – Permanent actions and influences
        Self weight structural elements
        Self weight ornamental elements
        Corrosion
    – Leading variable action
        Temperature increase
   – Accompanying variable action
        Wind
→ Non linear FE analysis

TENSION RING AS AN EXAMPLE

– **Updated design action effects**

$N_{Ed,act} = 175$ kN

– **Updated design resistance at the end of future service period**

$N_{Rd,act} = 363$ kN

– **Verification**
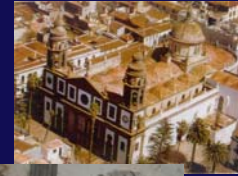
$N_{Ed,act} < N_{Rd,act}$

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**
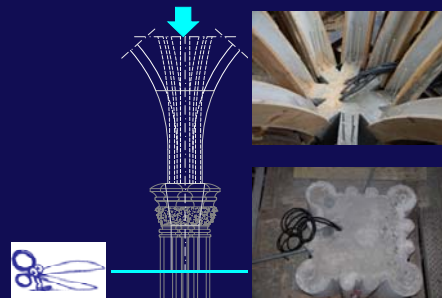
ON THE ASSESSMENT OF DETERIORATING STRUCTURES

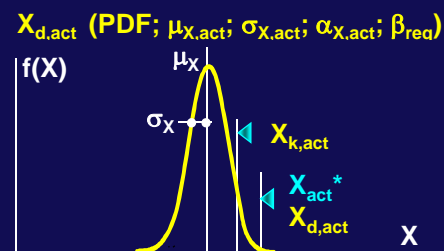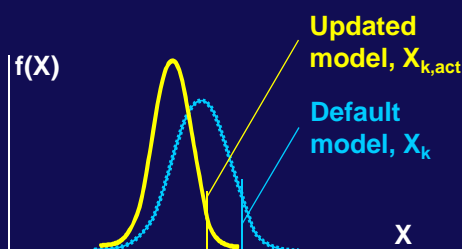- Introduction
- Updated models for the assessment of sound structures
- Corrosion-damaged reinforced concrete structures
- La Laguna cathedral
- Final remarks

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

$f(X)$

Updated model, $X_{k,act}$

Default model, X_k

X

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

$f(X)$

μ_X

σ_X

$X_{k,act}$

X_{act}^*

$X_{d,act}$

X

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**