

ON THE ASSESSMENT OF DETERIORATING STRUCTURES

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Assessment of existing structures

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

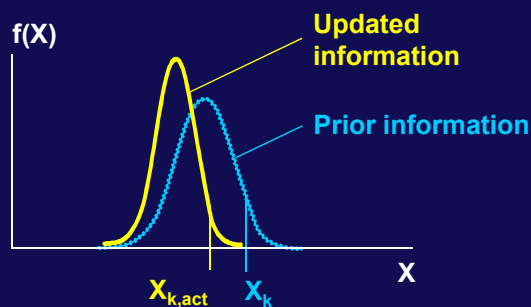
- Probabilistic methods are most accurate to take into account updated information
- But they are not fit for use in daily practice
- Partial factor method should be available for assessment

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



ASSESSMENT WITH PARTIAL FACTOR METHOD

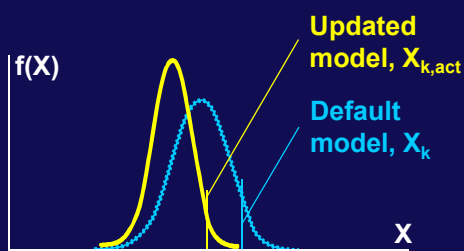
- Updated characteristic value of X



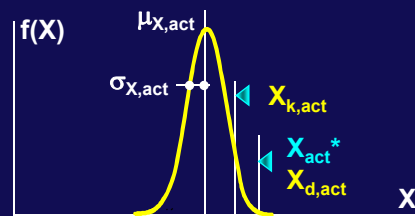
- Updated partial factor $\gamma_{X,act}$ → $\gamma_{E,act} \cdot E_{k,act} \leq \frac{R_{k,act}}{\gamma_{R,act}}$
- Can not be derived directly
- Link between probabilistic and partial factor methods: **design point**, the most probable failure point on LS surface

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

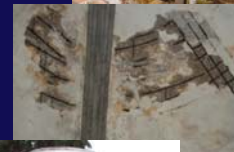


$X_{d,act}$ (PDF; $\mu_{X,act}$; $\sigma_{X,act}$; $\alpha_{X,act}$; β_{req})



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

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

$\gamma_{f,i,act}$ 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

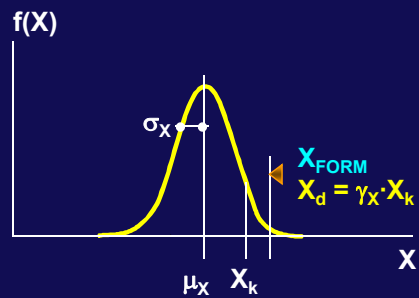
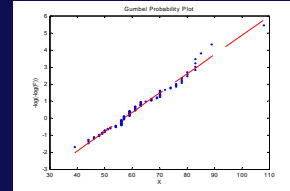
$\gamma_{Rd,V_c,act}$ Diagonal compression forces in the web

$\gamma_{Rd,N,act}$ Axial compression forces

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

DEFAULT PROBABILISTIC MODELS COMPLYING WITH THE FOLLOWING REQUIREMENTS

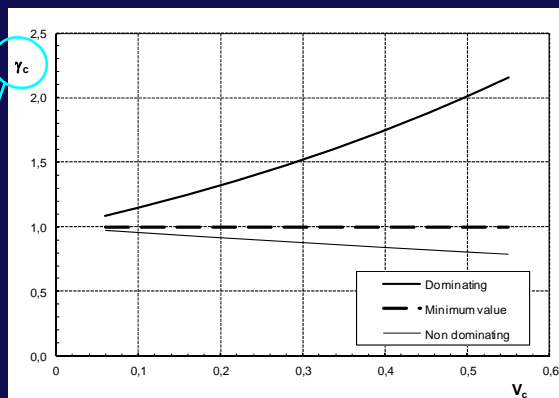
- Representation of physical properties of the corresponding variable
- Consistency with JCSS models
- Representation of the state of uncertainty associated with code rules
- Representation of uncertainties by means of random variables, suitable for practical applications



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

UPDATED PARTIAL FACTORS

- For example partial factor for concrete strength versus CoV



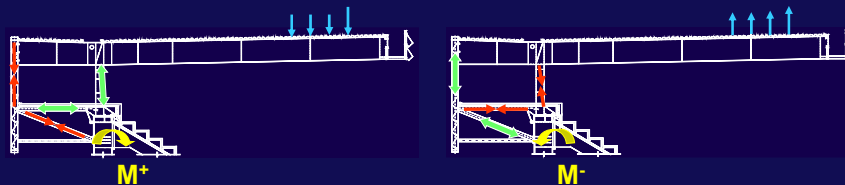
Definition $\gamma_c \neq \gamma_{c,EC-2}$

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

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

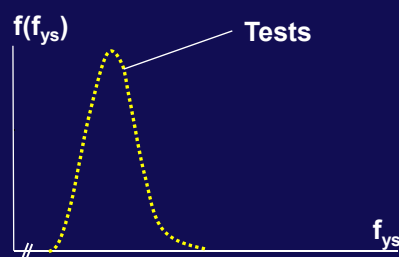
EXAMPLE

- 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}

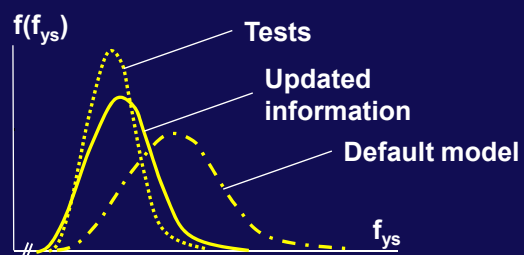


PROCEDURE

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

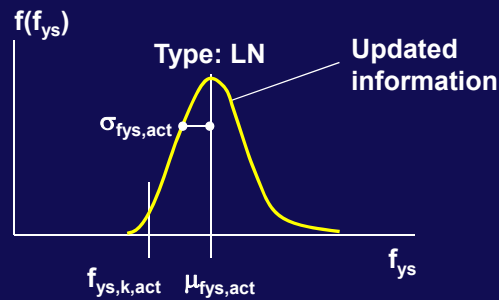


2. Combination of the results of observations with the available prior information (default probabilistic models)



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 \rightarrow
 $F_{ys} = f_{ys} \cdot A_s$

- Only f_{ys} has been updated

- Updated coefficient of variation for the tensile force

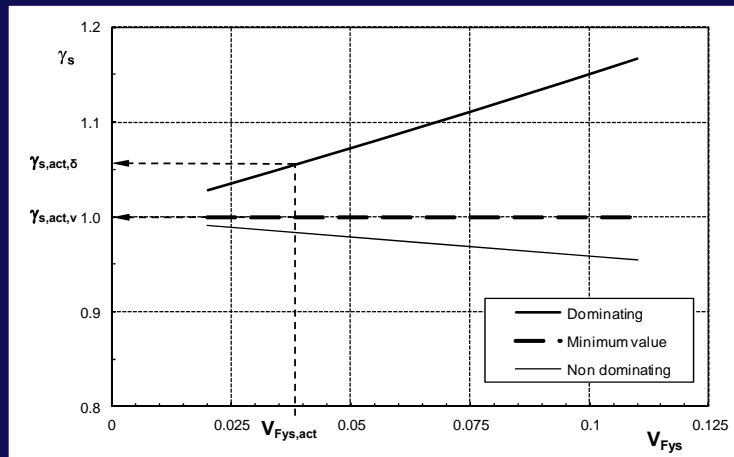
$$V_{F_{ys,act}} \cong \sqrt{V_{f_{ys,act}}^2 + V_{A_s}^2}$$

Default value
 $V_{A_s} = 0.02$

$$V_{f_{ys,act}} = \frac{\sigma_{f_{ys,act}}}{\mu_{f_{ys,act}}}$$

PROCEDURE

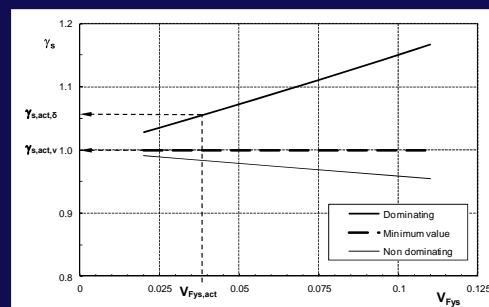
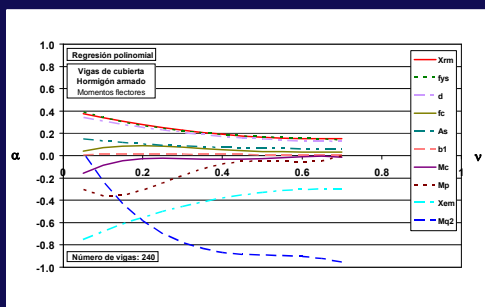
- Updated partial factor, considering the updated variable dominating or non dominating (unknown in advance)



PROCEDURE

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

Dominating variable unknown in advance \rightarrow trial and error or considering α_x



EXAMPLE

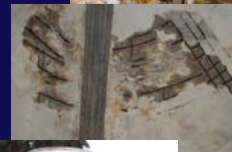
- Verification of bending resistance of RC element
- Only f_{ys} has been updated
- Dominating variable: F_{ys}
- Verification of structural safety: $M_{Ed,act} \leq M_{Rd,act}$

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



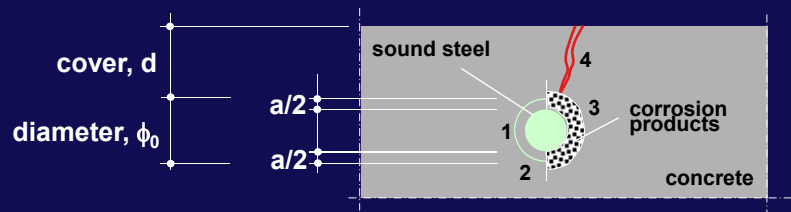
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MAIN EFFECTS OF CORROSION OF REINFORCEMENT BARS

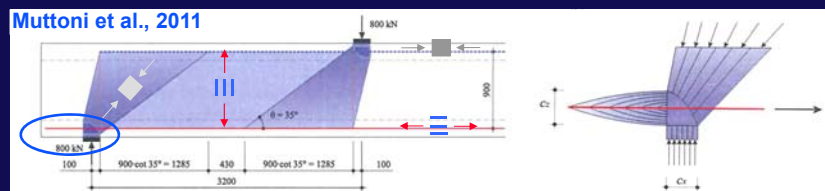
1. Decrease of bar cross-section
2. Decrease of ductility of steel (ϵ_u : reduction of 30 to 50%)
3. Bond deterioration
4. Cracking of concrete cover (due to corrosion products)




→ 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



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

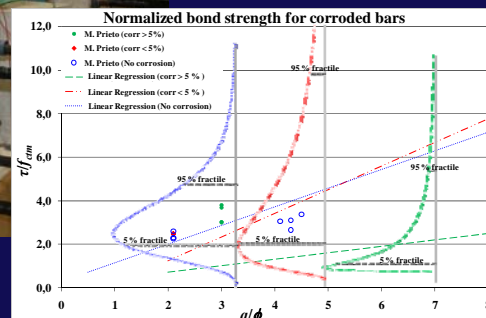
SITE DATA COLLECTION

- Geometry and material properties can be updated



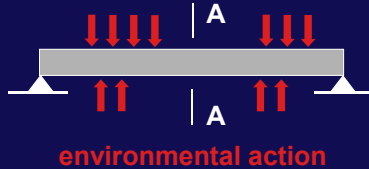
BOND STRENGTH

- Pull-out tests on specimens with accelerated and natural corrosion
- Normalized bond strength depending on cross-section loss

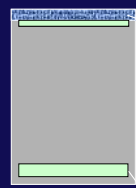


SIMPLE MODELS FOR ESTIMATE OF PERFORMANCE OF CORRODED STRUCTURAL ELEMENTS

- Example: bending resistance



A - A



Upper bound:
active

Lower bound:
disregarded
(spalling)



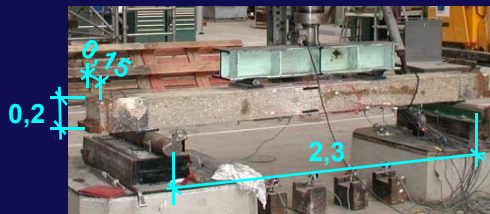
$$A_s(t) = n \frac{\pi (\phi_0 - a(t))^2}{4}$$

- 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

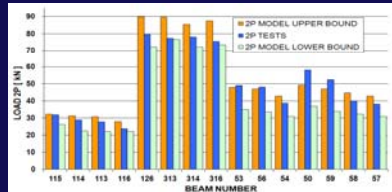


Cross-sectional loss:
Top < 30,3%
Bottom 9,75% to 26,4%

- 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

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

- 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

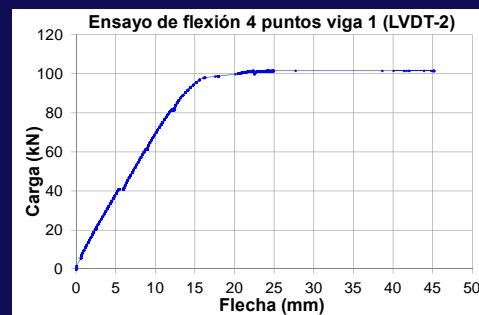
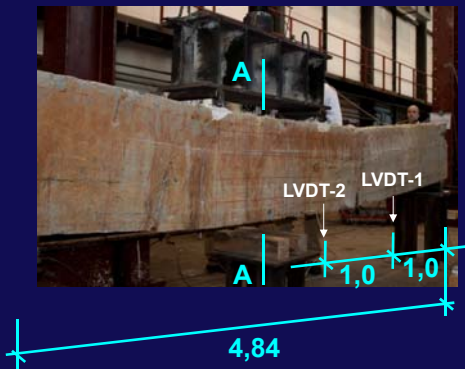
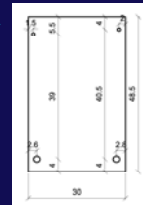
- Selection of representative, corrosion-damaged members for testing
 - 8 beams
 - 5 columns
 - 1 frame



SOME RESULTS

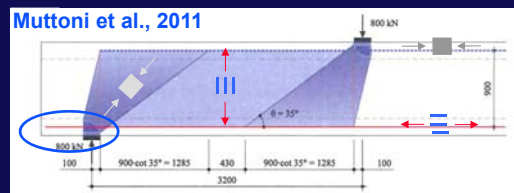
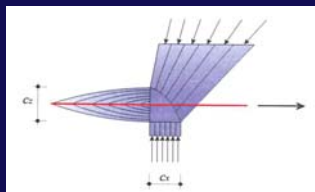
- Bending test on beam n° 1
 - Deformation control
 - Ductile behaviour

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
 - $M_{ult,t} = 127 \text{ kNm}$
 - $M_{ult,e} = 123 \text{ kNm}$



- Introduction
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- **La Laguna cathedral**
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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



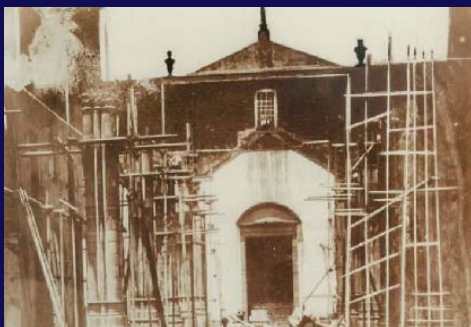
CATHEDRAL

- 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



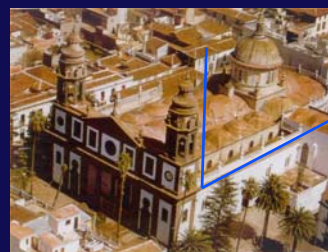
RISKS ASSOCIATED WITH SCANTILY PROVEN TECHNOLOGY

- 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

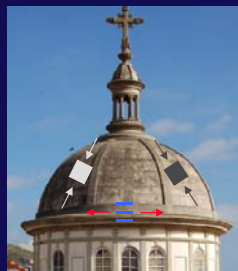
- Global system



- 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

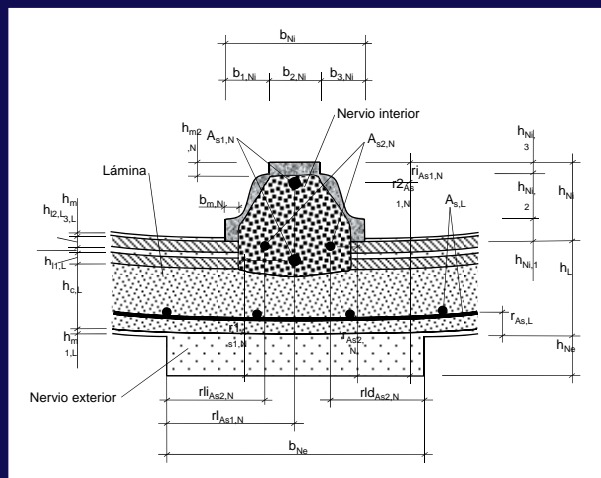
- Geometry
 - Overall system dimensions
 - Cross sections of structural and ornamental elements
- Self weight and permanent actions
- Material properties
- Qualitative and quantitative determination of damage
 - Cracks
 - Spalling
 - Carbonation and chloride ingress
 - Corrosion velocity and cross section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

Outside Inside



CROSS SECTIONS

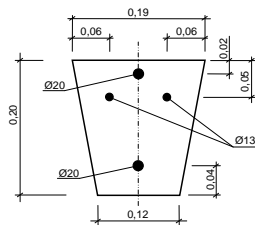
- Parameters for different variables derived from a minimum of 4 measurements



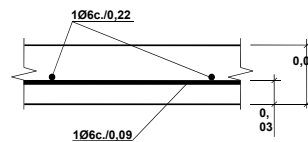
CROSS SECTIONS

– Equivalent cross sections for structural analysis

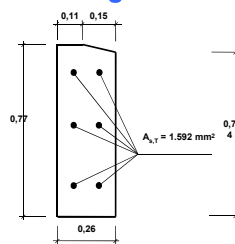
Arches



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

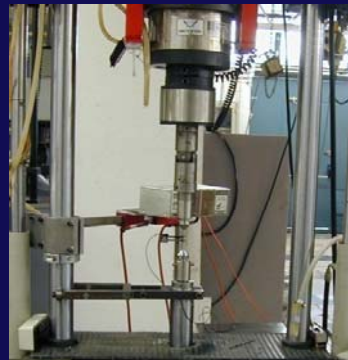
→ Updated partial factors, for example for self weight

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

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

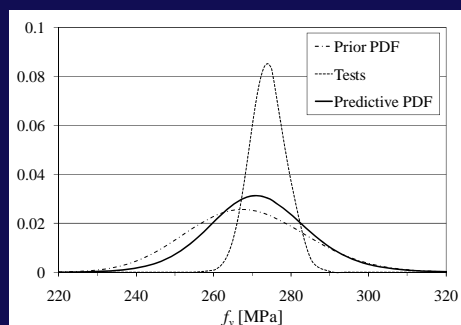
MATERIAL PROPERTIES FOR REINFORCING STEEL

- Manufacture of specimens
- Execution of tensile tests



MATERIAL PROPERTIES FOR REINFORCING STEEL

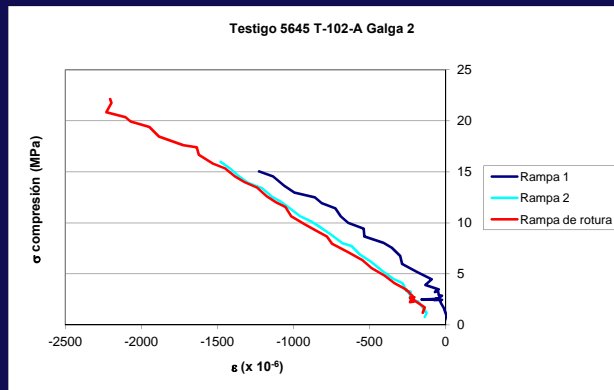
- Evaluation of test results and combination of information



- Updated parameters: LN ; $\mu_{f_{ys,act}}$; $\sigma_{f_{ys,act}}$; $f_{ys,k,act}$; $\gamma_{s,act}$
- Updated characteristic values
 - $\phi < 6$ mm: $f_{ys,k,act} = 304$ N/mm²
 - $\phi > 6$ mm: $f_{ys,k,act} = 262$ N/mm²

MATERIAL PROPERTIES FOR CONCRETE

- Manufacture of specimens
- Execution of compression tests



MATERIAL PROPERTIES FOR CONCRETE

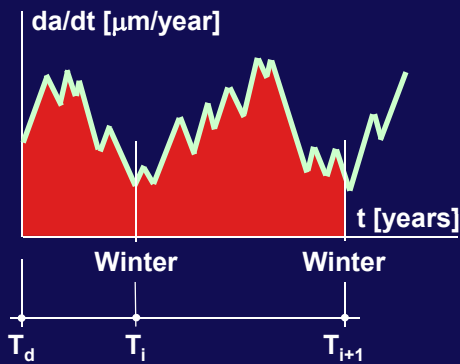
- Evaluation of test results and combination of information
- Updated parameters
 - Compressive strength: $\mu_{f_c,act}$; $\sigma_{f_c,act}$; $f_{ck,act}$; $\gamma_{C,act}$
 - Modulus of elasticity: $\mu_{E_c,act}$; $\sigma_{E_c,act}$
- Updated characteristic values
 - Arches: $f_{ck,act} = 6,8 \text{ N/mm}^2$
 - Shells: $f_{ck,act} = 3,1 \text{ N/mm}^2$
 - “Drum”: $f_{ck,act} = 4,9 \text{ N/mm}^2$



REINFORCEMENT CORROSION

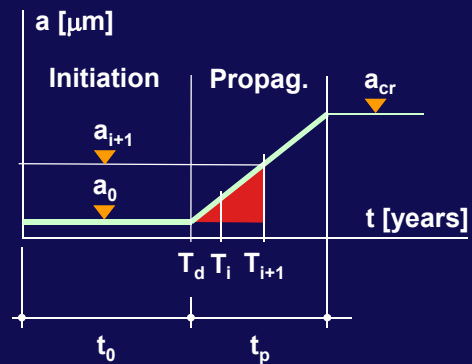
- Corrosion rate measurements require careful interpretation
- Mean velocity to be estimated from remaining cross sections

Propagation rate



→

Mean velocity

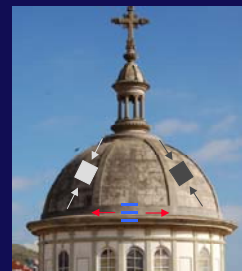


→ Extrapolation for future service period: $A_{s,corr}$

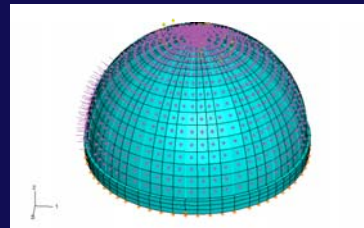


SHELLS AS AN EXAMPLE

- 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



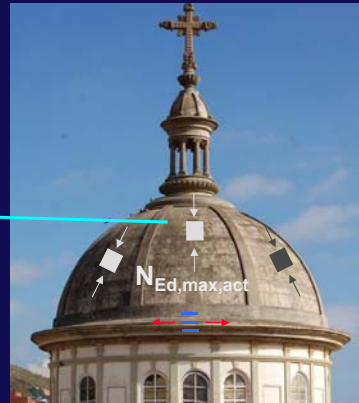
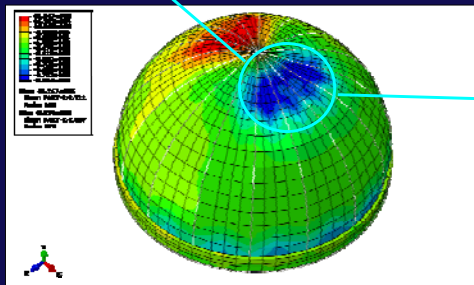
→ Non linear FE analysis



SHELLS AS AN EXAMPLE

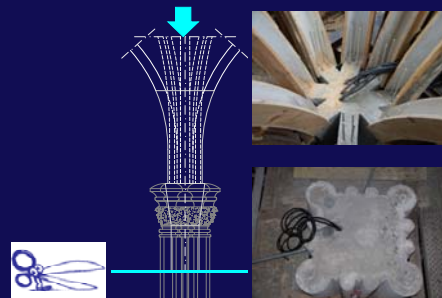
- Updated design action effects
 $N_{Ed,max,act} = 77 \text{ kN/m}$ (+ compression)
- Updated design resistance at the end of future service period
 $N_{Rd,act} = 219 \text{ kN/m}$
- Verification

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



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



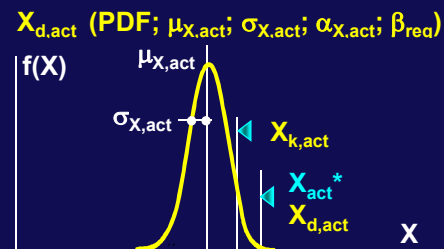
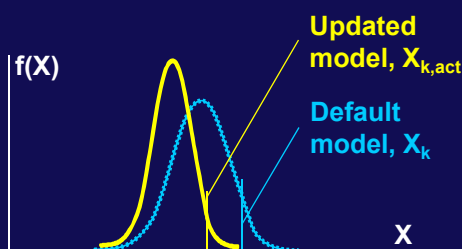
- Introduction
- Updated models for the assessment of sound structures
- Corrosion-damaged reinforced concrete structures
- La Laguna cathedral
- **Final remarks**



On the assessment of deteriorating structures

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

