Giornate **aicap** 2014

Bergamo 22 – 24 Maggio 2014

Durability of reinforced concrete structures – Problems and Progress

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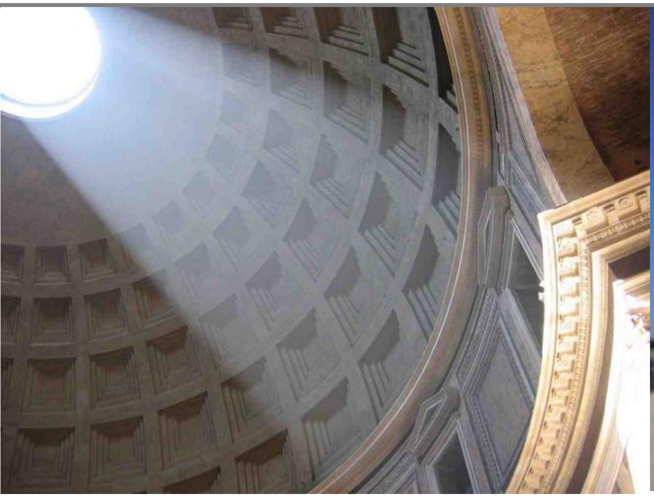
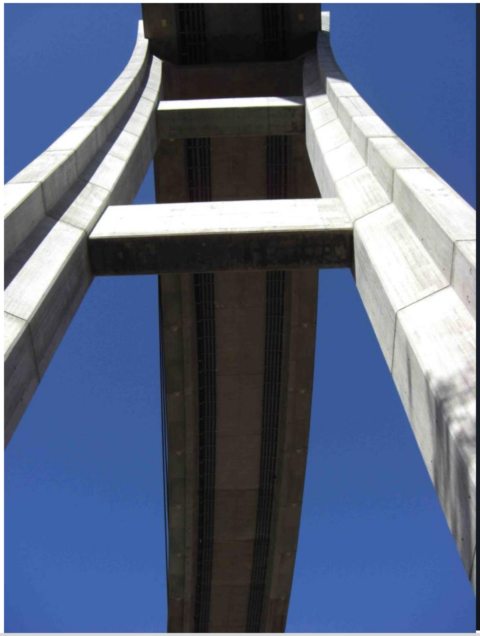


Pantheon, Rome

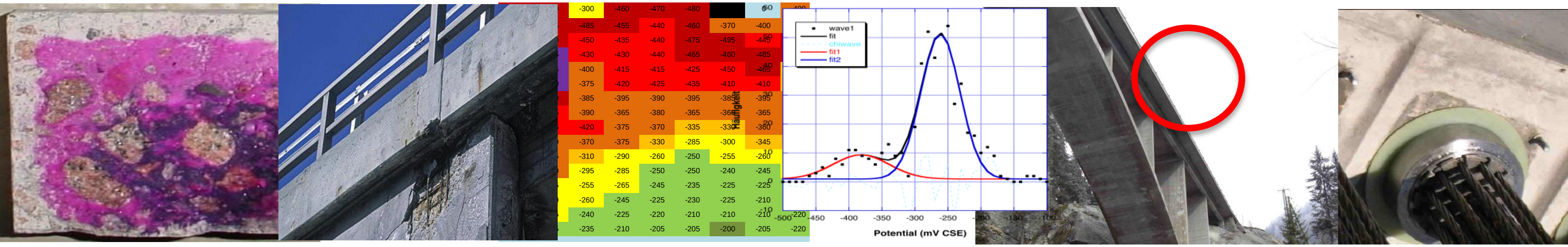
Jubilee Church, R. Meier, Rome

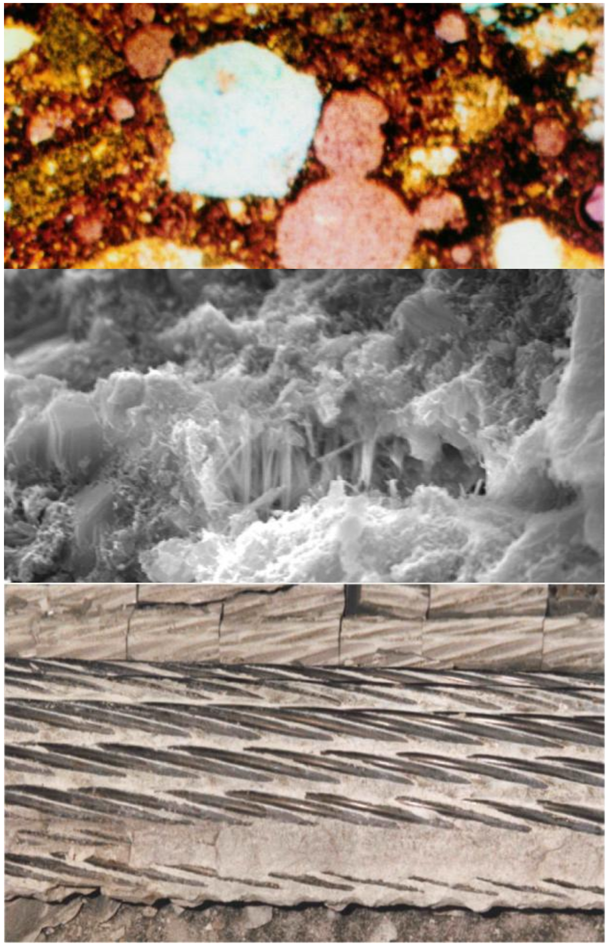
Fiera di Milano



Content of the presentation

- Theoretical basis
- Inspection and Monitoring
- New systems for post-tensioning
- Use of new “green” cements





Concrete = Cement + water + aggregates + …
Cement reacts with water

Hydratation: $C_3S + H_2O = CSH + Ca(OH)_2$
Cement paste (CSH): nano-porous matrix
$Ca(OH)_2$ forms alkali reserve

Passivation:
In the alkaline pore solution (pH 13) a protective oxide film is formed on the steel surface (passive film, similar to CrNi steel in water)

Steel in alkaline environment of concrete is passive

Corrosion of steel in concrete

Loss of passivity of the steel due to a decrease in pH or due to chloride attack

Corrosion due to carbonation

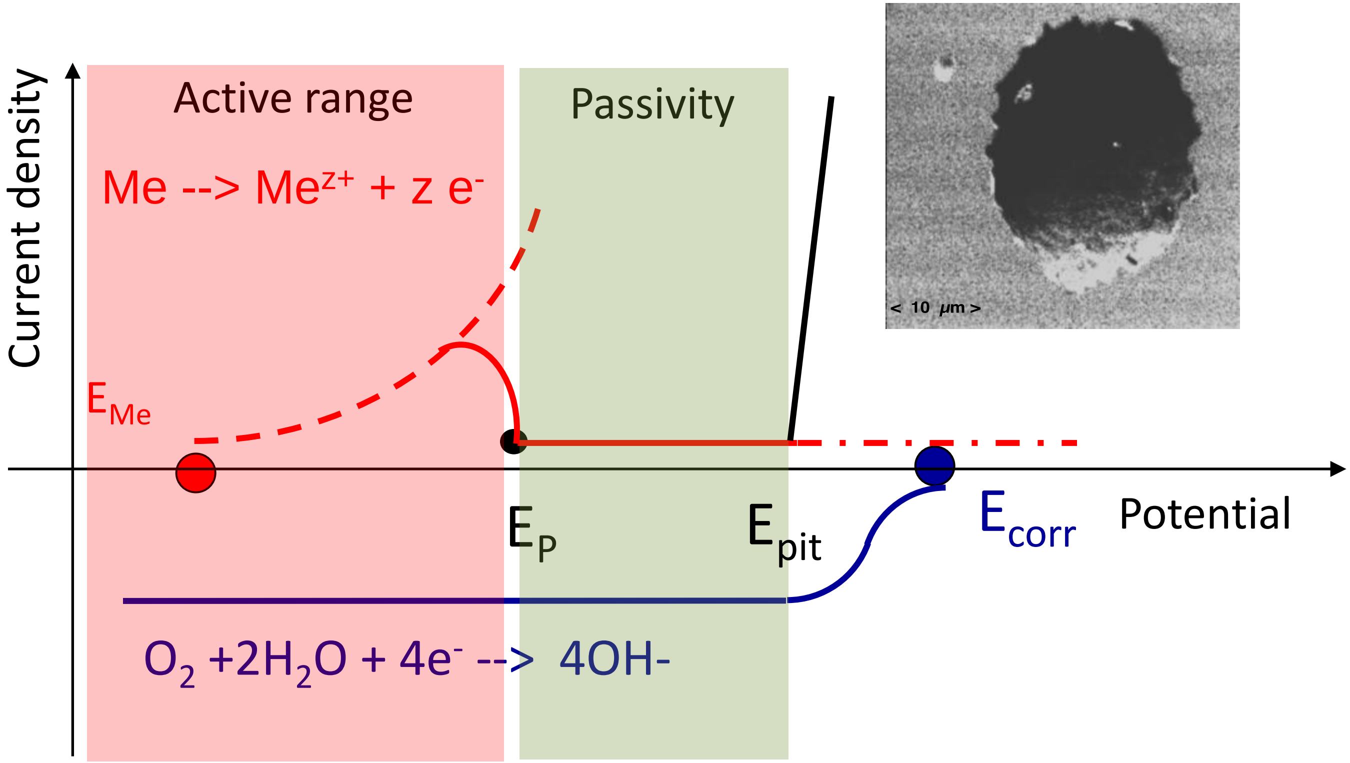
Uniform corrosion with rust formation

Chloride induced localized corrosion

Typical corrosion attack in a bridge deck with high chloride concentration

Note: very often the localized attacks appear blank, without rust. Visual inspection might not reveal corrosion damage (cracks, delamination).

Localized corrosion – pitting

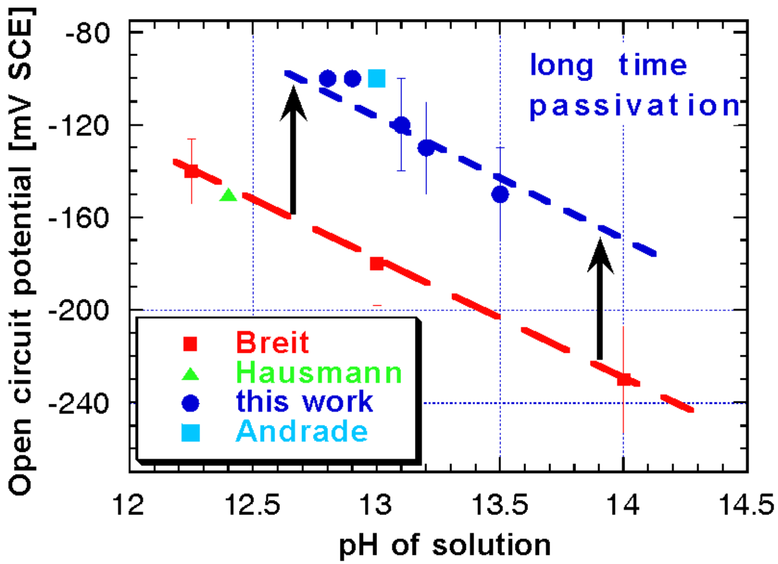


The protective passive film can be destroyed by chloride ions

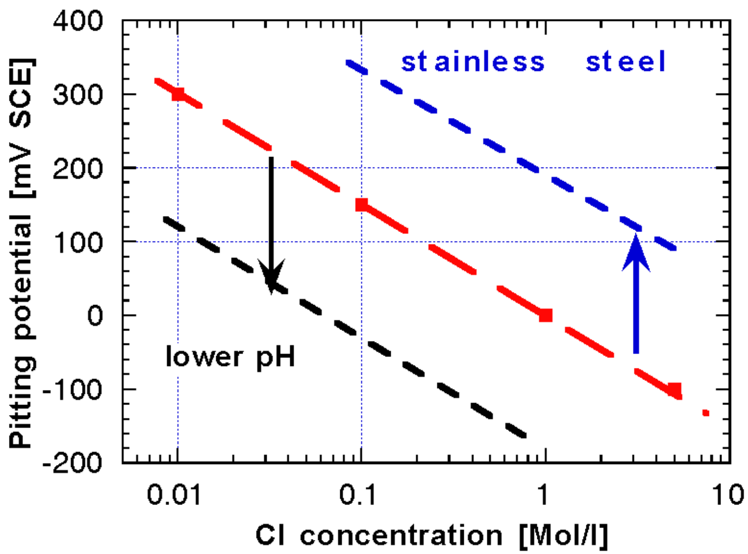
Condition for occurrence of pitting: Epit < Ecorr

Condition for the occurrence of localized corrosion Epit < Ecorr

Corrosion potential Ecorr



Pitting potential Epit



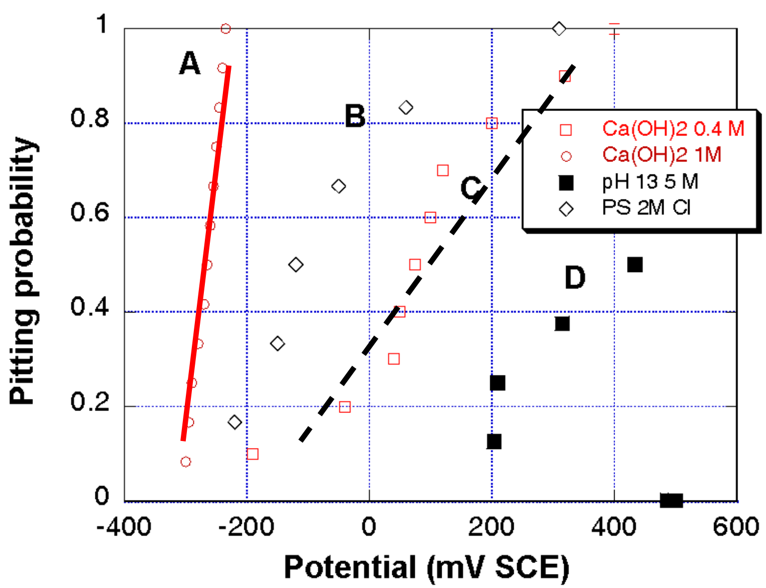
Ecorr depends on pH, oxygen, time
-> higher risk after carbonation
-> higher risk in blended cements

Epit decreases with higher Cl^- concentr.
-> higher risk for pitting corrosion

System behavior: no fixed “critical chloride content” for occurrence of pitting.

Epit and Ecorr are both not constant but distributed values

Pitting potential Epit

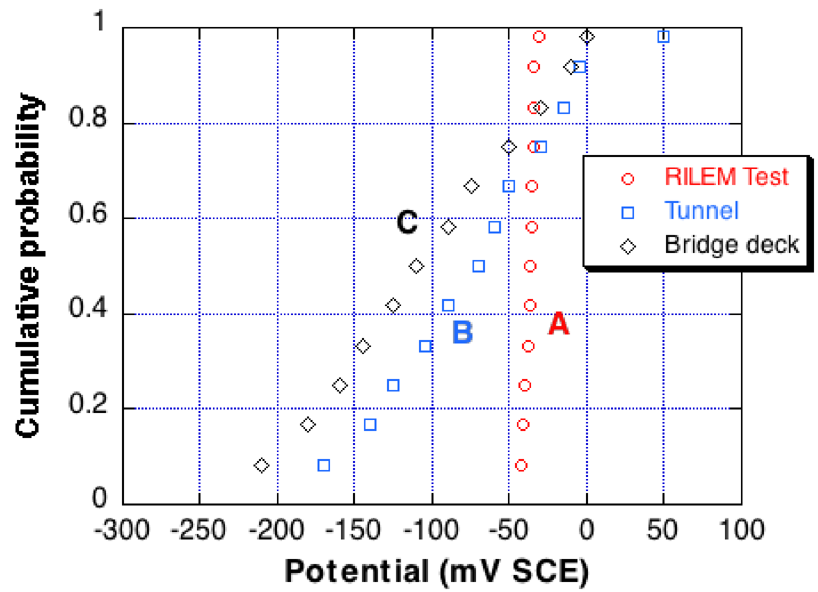


A: aggressive pH 12.5, 1 M Cl^-

C: mild, pH 12.5, 0.4 M Cl^-

More aggressive conditions result in well defined Epit

Corrosion potential Ecorr



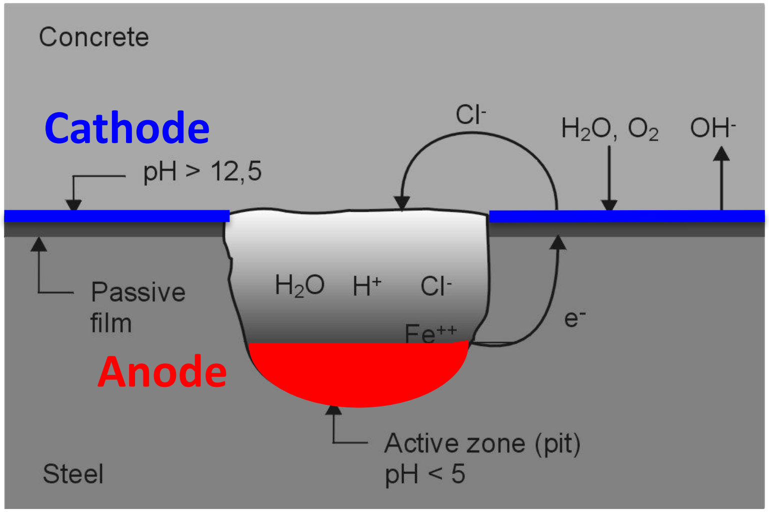
A: laboratory samples (10)

B, C: structures (> 1000 readings)

Probability for pitting increases with a broad distribution of the potentials.

Chloride induced localized corrosion of steel in concrete

Typical corrosion attack in a bridge deck with high chloride concentra-tion. Loss in cross section, no rust formation !



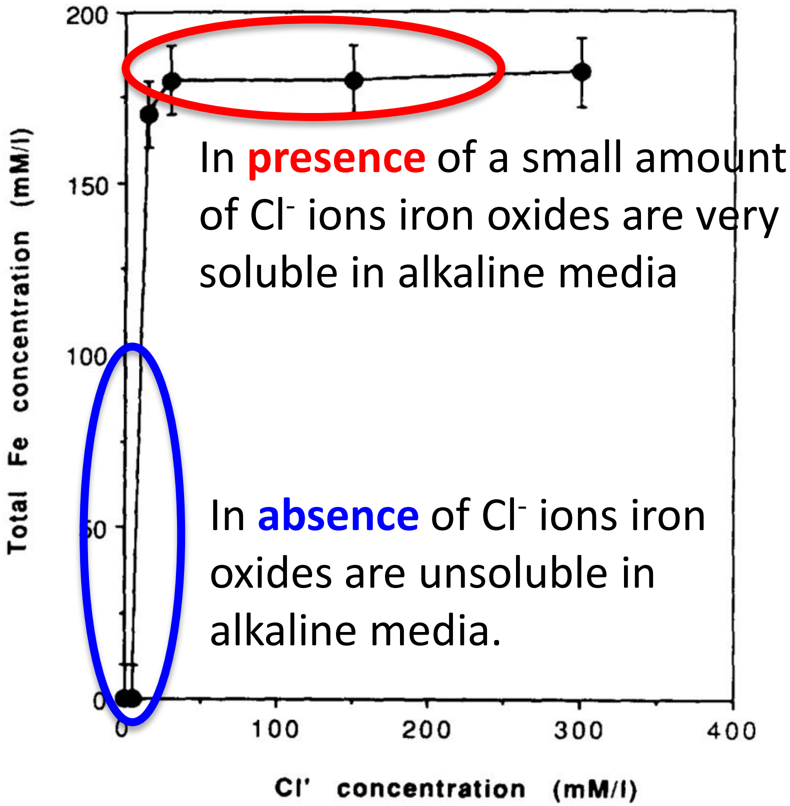
Macrocell corrosion, high local current densities.
Acidification of the pit electrolyte.

Because no rust is formed cracking and spalling does not occur….

Chloride induced localized corrosion of steel in concrete

Typical corrosion attack in a bridge deck with high chloride concentration.
Loss in cross section, no rust formation !

A monitoring technique is needed that detects this “invisible” corrosion….

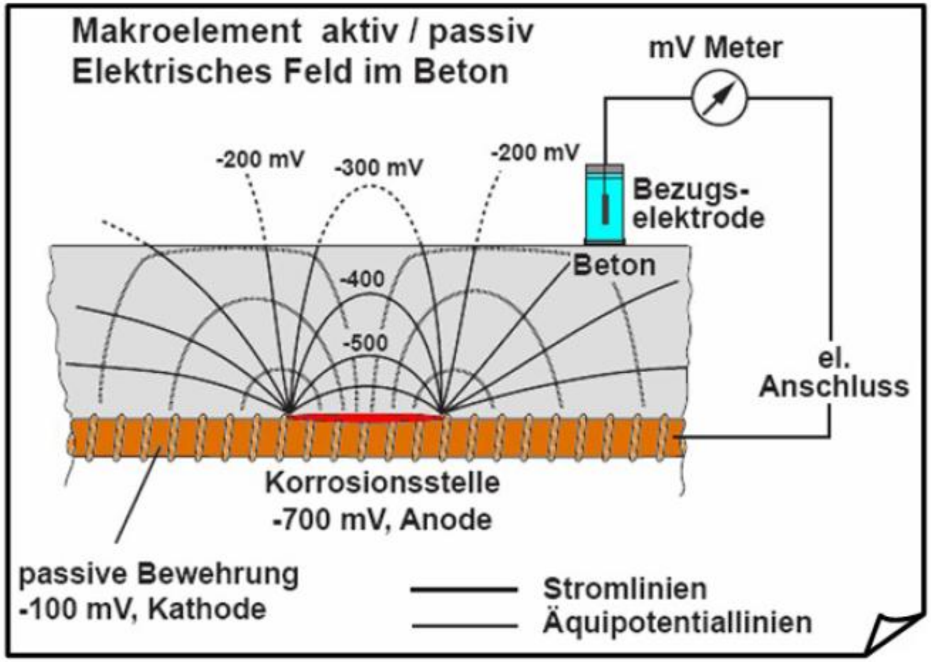


Total soluble iron (Fe^{2+}, Fe^{3+}) in solution of pH 12.5

U. Angst, B. Elsener, A. Jamali, B. Adey, Materials and Corrosion 63 (2012) 1069

Half-cell potential mapping

The potential difference between can be measured by a suitable half-cell (reference) electrode.



-> locate the areas of corroding reinforcement.

Parameters: size of the corroding area, resistivity, chloride content, carbonation, oxygen content.

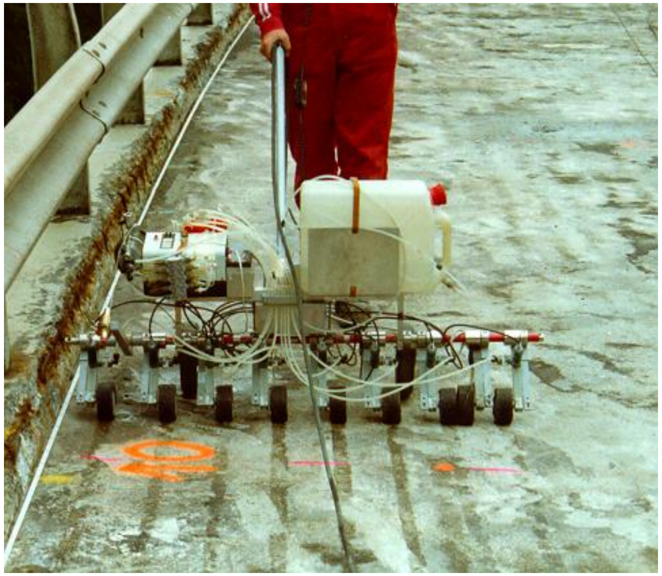
B. Elsener, C. Andrade, R. Polder et al., Materials and Structures 63 (2003) 1069

Half-cell potential mapping

single electrode

single wheel electrode

8 wheel electrode



This technique is today **state of the art** in condition assessment of reinforced concrete structures (national and international guidelines)….

It can – in principle – be used also for **regular inspection** of RC structures

Difficulty to reach and "touch" the concrete surface…..

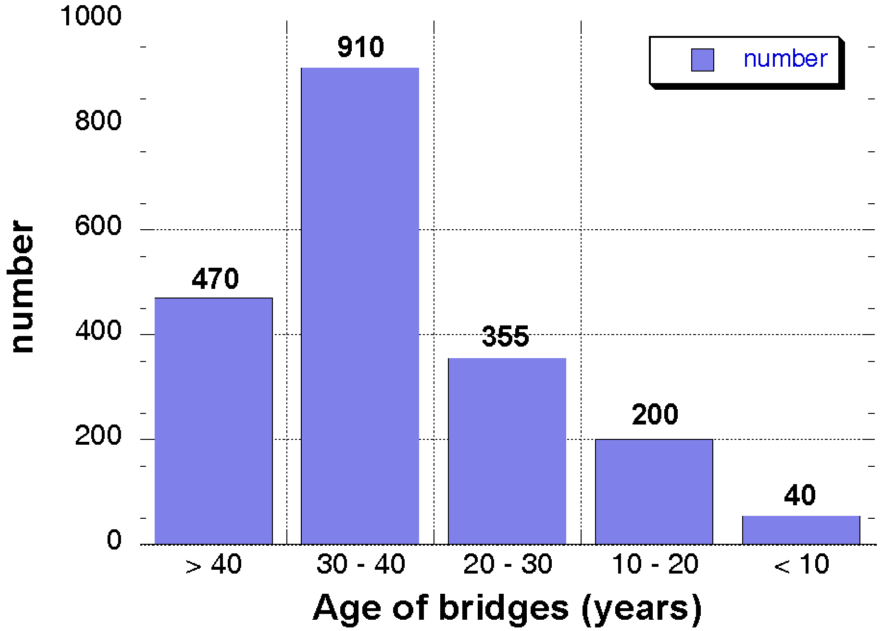
With the result that **we still rely on visual inspections only ….**

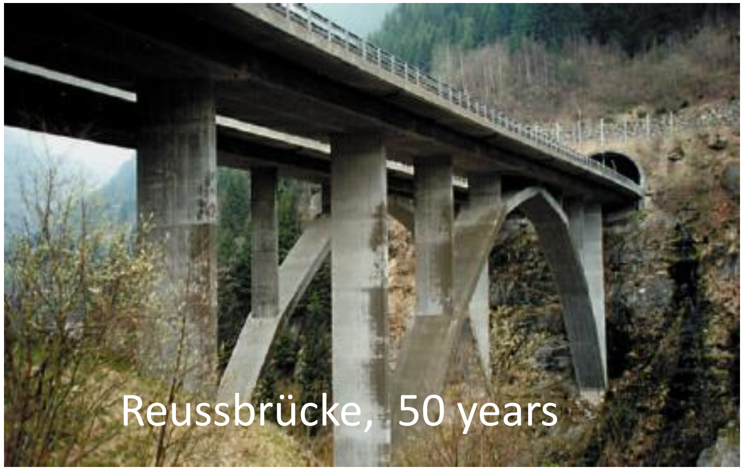
- "weak spots on weak structures" are not detected
- Corrosion of the reinforcement is found only when it manifests at the surface
- Preventive measures cannot be applied in time

….. and economic consequences (very high repair costs).

Bridges – backbone of traffic infrastructure

Age distribution of bridges in Switzerland



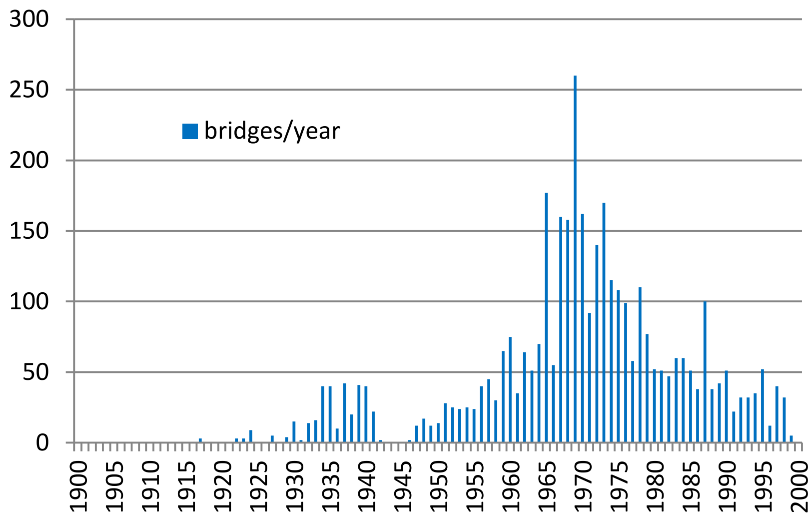


Costs for restoration of 1 m^2 bridge deck amounts to **1200 – 1500 € (CH 2001)**

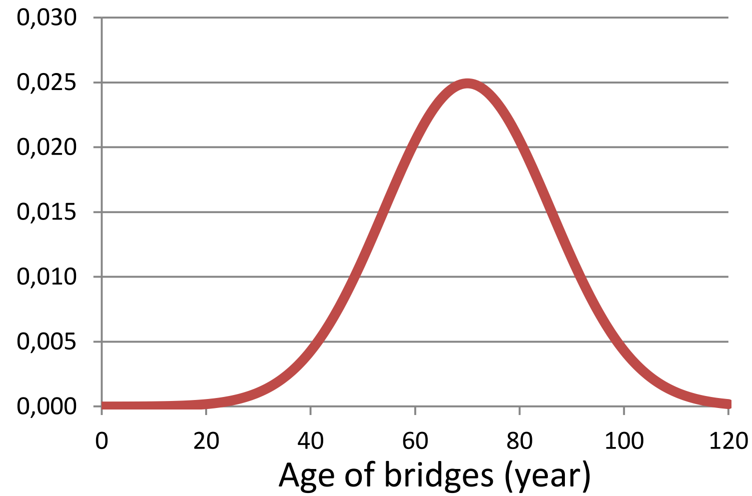
Codes of practice: every 5 year a **general inspection** has to be performed.

Bridge performance

Year of construction (bridges NL)



Age at repair (bridges NL)



Huge stock of bridges older than 40 years

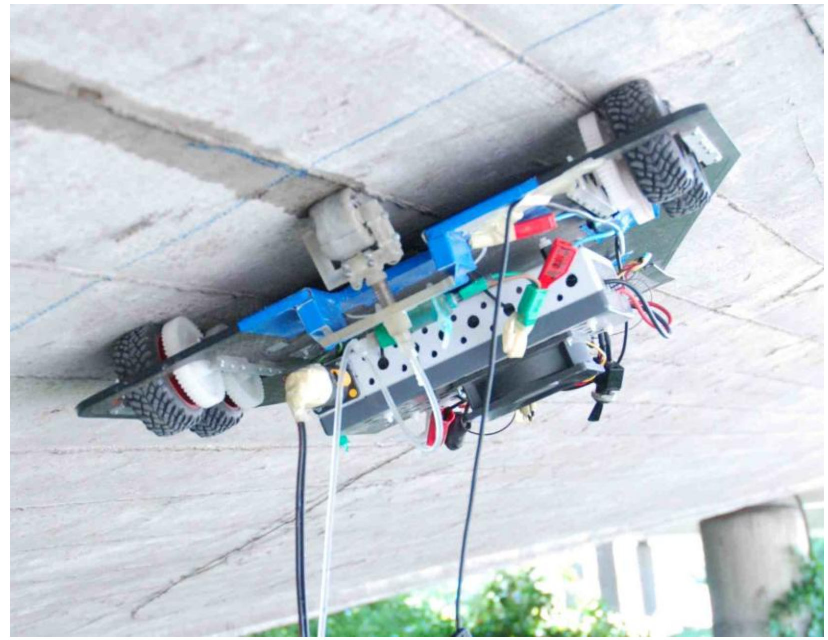
Inspection is needed to come to a pro-active approach for repair.

Age of bridges at first repair

- 10% 50 years old until repair
- 50% 70 years old until repair

R. Polder, Workshop "Challenges for Durability", Zurich 17/18 April 2012

Climbing corrosion detection robot



- Vortex system
- Half cell potential wheel
- Continuous operation (power supply)
- Can be equipped with more sensors

Regular inspections will have much higher quality of information.

See www.ifb.ethz.ch

Post-tensioned structures

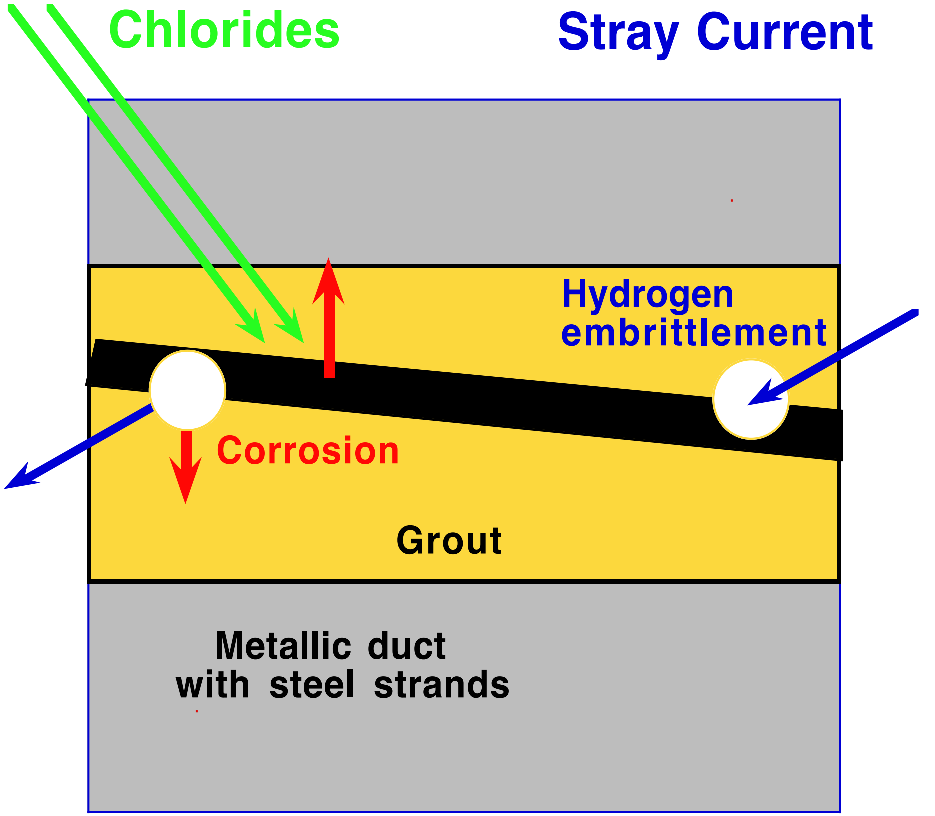
Tendons in post-tensioned structures

Traditional metallic ducts in more than 90% of all structures succesful and durable over whole service life

In several cases severe corrosion of the strands in the grouted tendons was detected

- ➢ Collapses without warning
- ➢ No established NDT technique

Situation with metallic ducts



Corrosion of strands

- Chlorides from environment
- Stray currents (DC railway)
- Metal dissolution -> loss in cross section
- Hydrogen embrittlement

Fretting fatigue

- Fretting between duct and steel

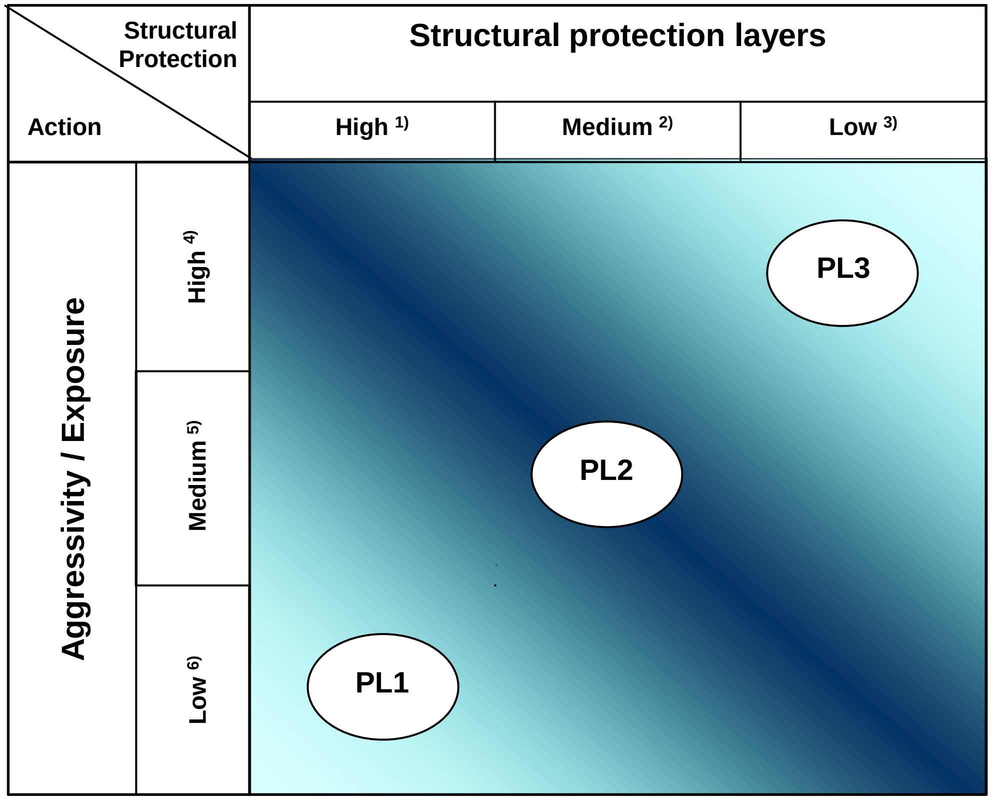
Electrical contact

- Measurements very difficult

No information on corrosion protection of the structurally most important element for safety and durability

ETH zürich

The fib approach – protection levels



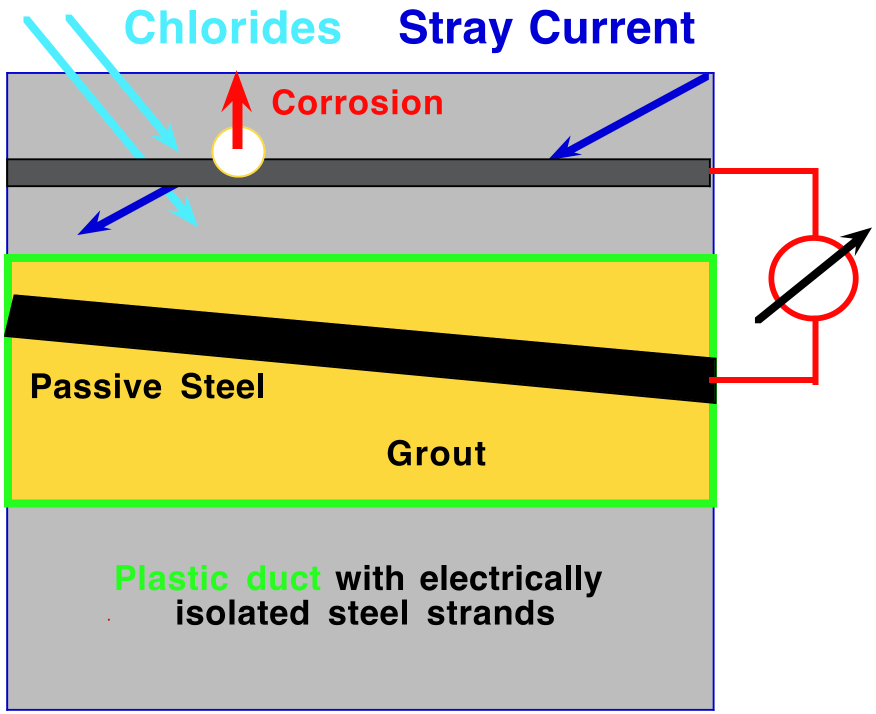
The protection level (type of post-tensioning system) should be Defined in the design stage based on

- Structural protection layers
- Environmental aggressivity

Protection level PL3 = electrically isolated post-tensioning tendons

fib bulletin Nr. 33 (2005) prepared at the fib workshop at ETH Zurich (2004)

New approach: Thick wall corrugated polymer ducts



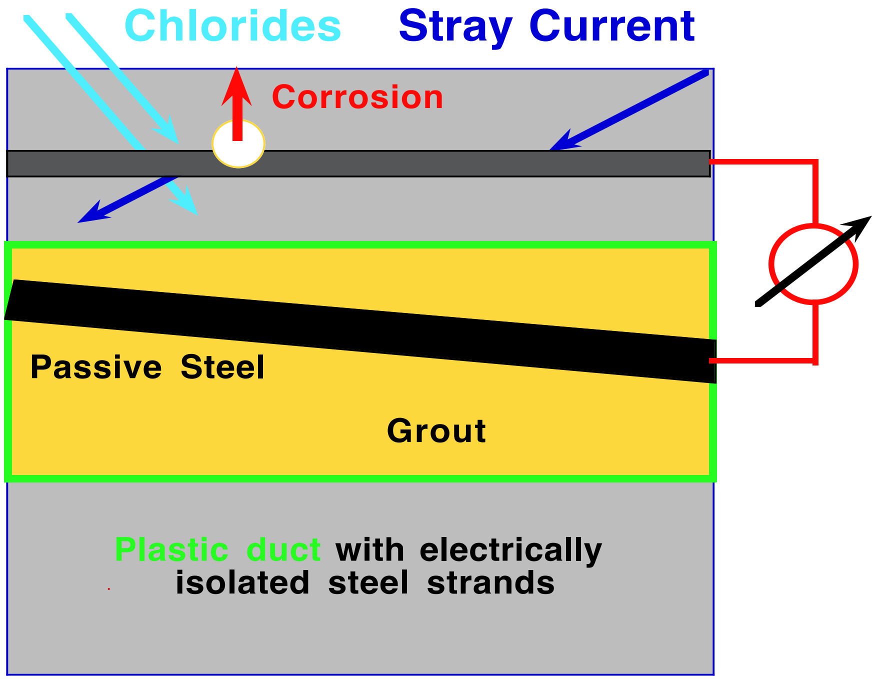
Thick corrugated plastic ducts
Tight envelope, avoids chloride ingress to the high strength steel

Enhanced corrosion protection
Polymers such as PE or PP form a tight barrier against the ingress of water and chloride ions

Fretting fatigue
Lower more reliable fretting coefficient reduces risk of fretting fatigue

Important for long tendons

New approach: electrical isolation of the high-strength steel



Electrical isolation
Insulating anchor plates, plastic trumpet for anchorages
Close grout vents, grout inlets

Avoids stray current on tendon steel

Allows measurements
Possibility to control and monitor with non-destructive techniques
Enhanced safety and durability

Italian high-speed train lines

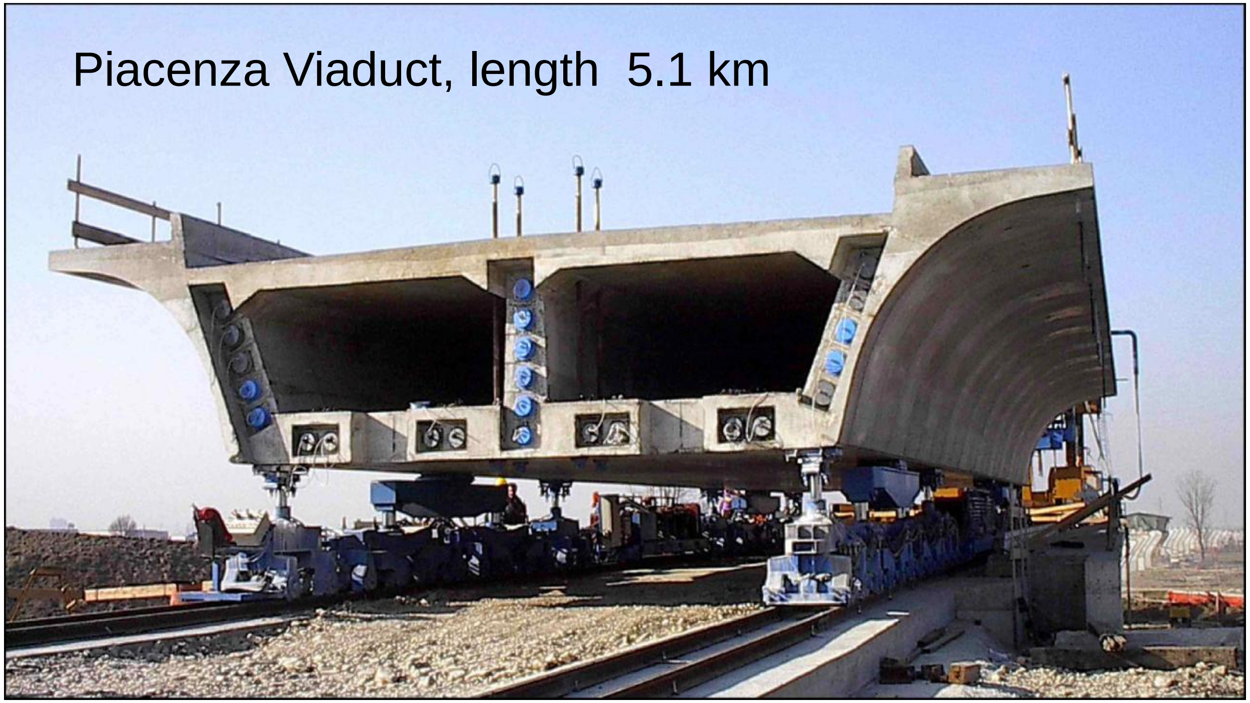
18% of the length are viaducts, simply supported P.C. spans

PADULICELLA VIADUCT, **ROMA-NAPOLI**

MODENA **VIADUCTS, MILANO-BOLOGNA**

In collaborazione con Ing. Maja Della Vedova, Italferr. European project COST 534

Electrically isolated tendons at Piacenza Viaduct



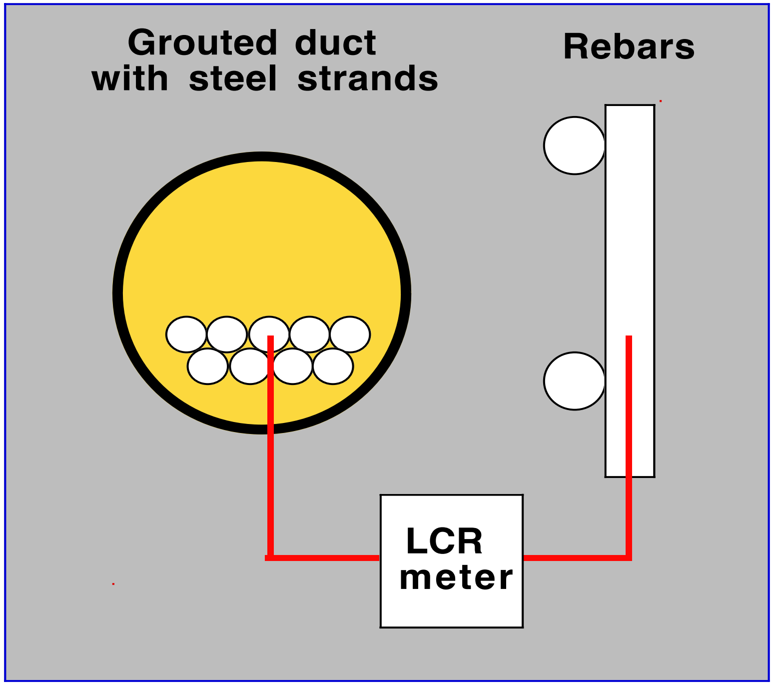
1 Segment 32.1 m
Weight 900 t
Costs 300’000 €

EIT Tendons
15 19 wires ø 100
9 12 wires ø 76

Access for inspection (stairs, inspection ways)
Good drainage (thick waterproofing layer)
PT tendons (vacuum grouting, HDPE ducts)
Electrically isolated tendons (EIT)

M. Della Vedova, B. Elsener, paper 115, 2nd Int. *fib* conference, Naples (2006)

Measurement principle - impedance

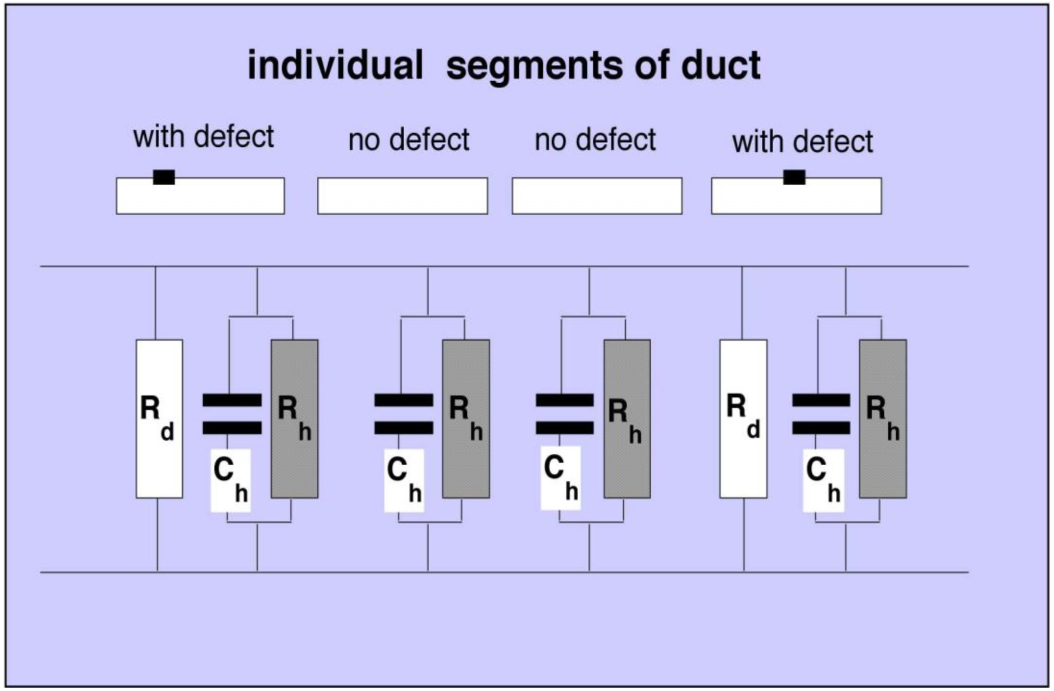


- Measurement of the electrical impedance (AC resistance) of the system steel strand / grout / plastic duct / concrete / rebars
- $Z^{-1} = 1/\omega C + R^{-1}$
- Duct is a pure capacitance
- Concrete and grout resistance

Scope

Control the electrical isolation - tightness of the ducts
corrosion protection of the steel strands in the grouted ducts

Measurements – ducts with defects



- Measurement of the electrical impedance (AC resistance) of the system steel strand / grout / plastic duct / concrete / rebars

- $Z^{-1} = 1/\omega C + R^{-1}$
- Duct is a pure capacitance (R_h of the duct is very high)
- Concrete and grout resistance
- Defect has a very low resistance R_d

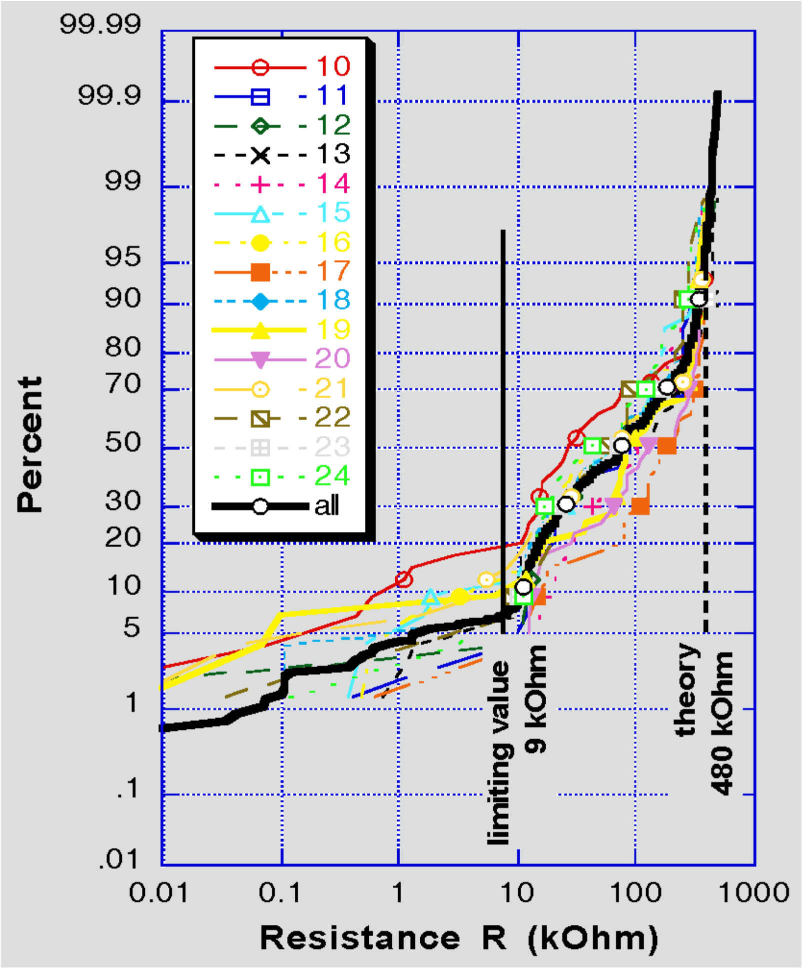
Result

Electrical resistance measurements allow to detect defects in the duct.

Resistance decreases in presence of defects

-> diagnostic method

Results Piacenza Viaduct



Resistance values

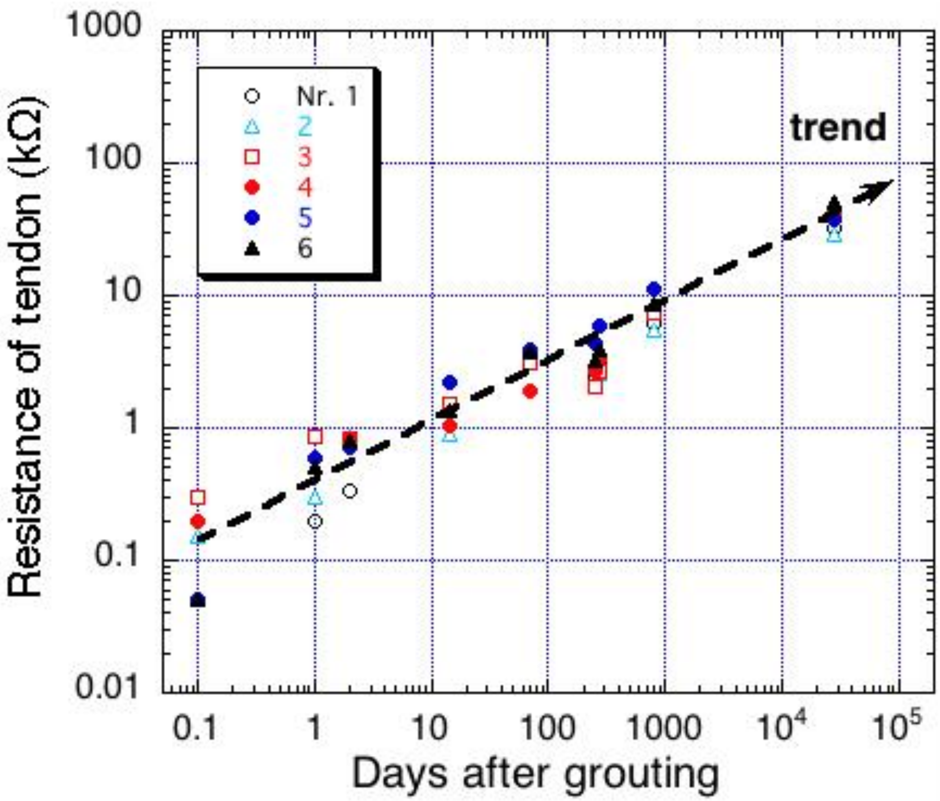
38 segments x 15 cables
(19 wires ø 100 mm) 33 m long

- Some scatter between tendons
- ca. 2% short circuits
- ca. 10% of cables that do not fulfill the criteria for isolation
- For each tendon some cables show the maximum (theoretical) value

-> Very good success of EIT

M. Della Vedova, B. Elsener, paper 115, 2nd Int. *fib* conference, Naples (2006)

Bridge in Switzerland - Prés du Mariage, L = 49 m, ø 76 mm



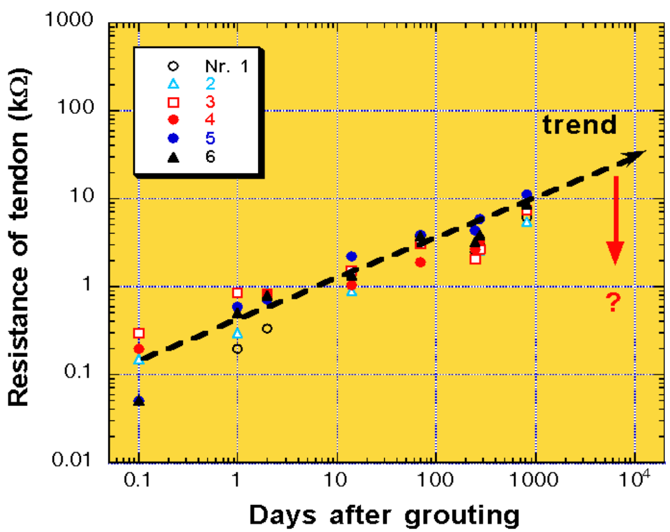
Evolution of resistance with time (8 years)

- Progressive increase due to hydration of grout and concrete, drying
- 28 day initial check

Control and monitoring of the corrosion protection during the whole design life of the structure

Smart post-tensioned structures

- No sensors needed - the tendon under test is the sensor
- Rapid AC resistance measurements at any time during service life
- **Quality control of execution**



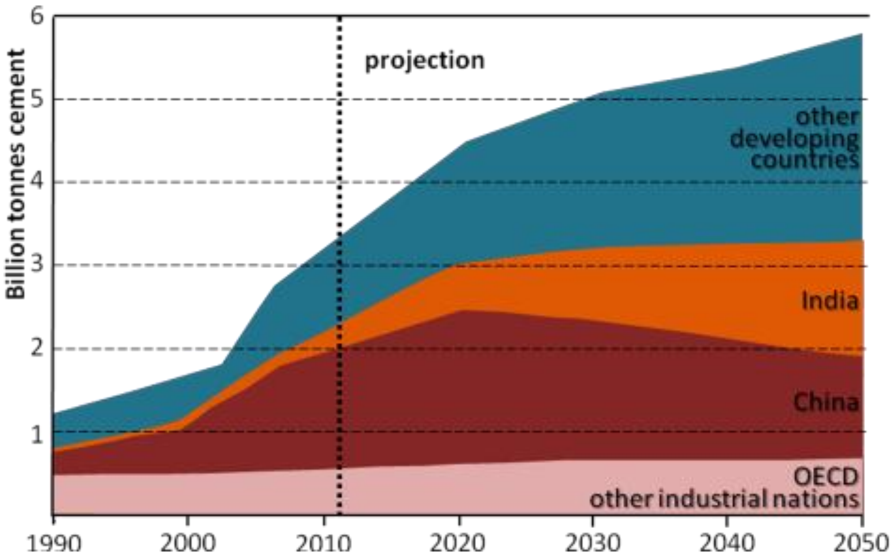
- Continuous increase of resistance
- Decrease = early warning system
- **Long term monitoring of structurally most important elements**

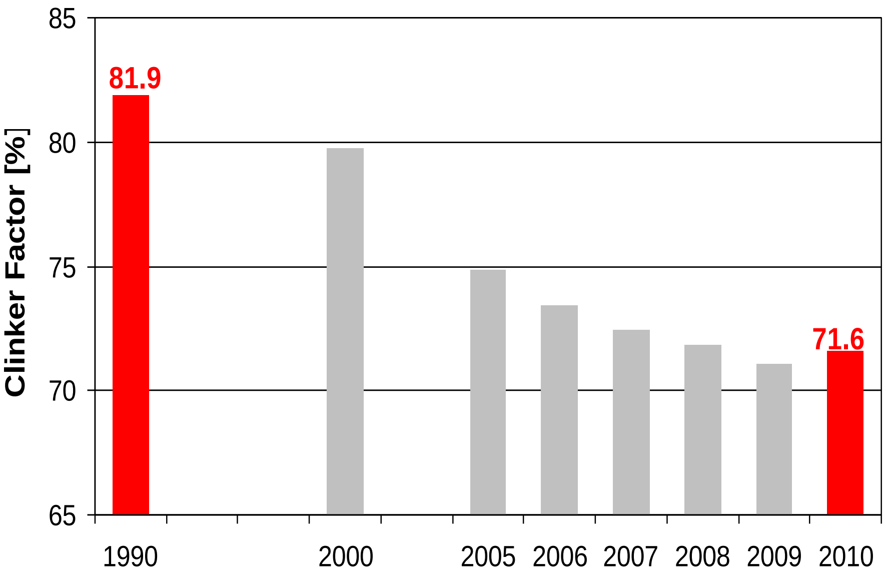
> Early warning system...

For the first time the structurally most important elements can be monitored

New “green” cements

Cement production



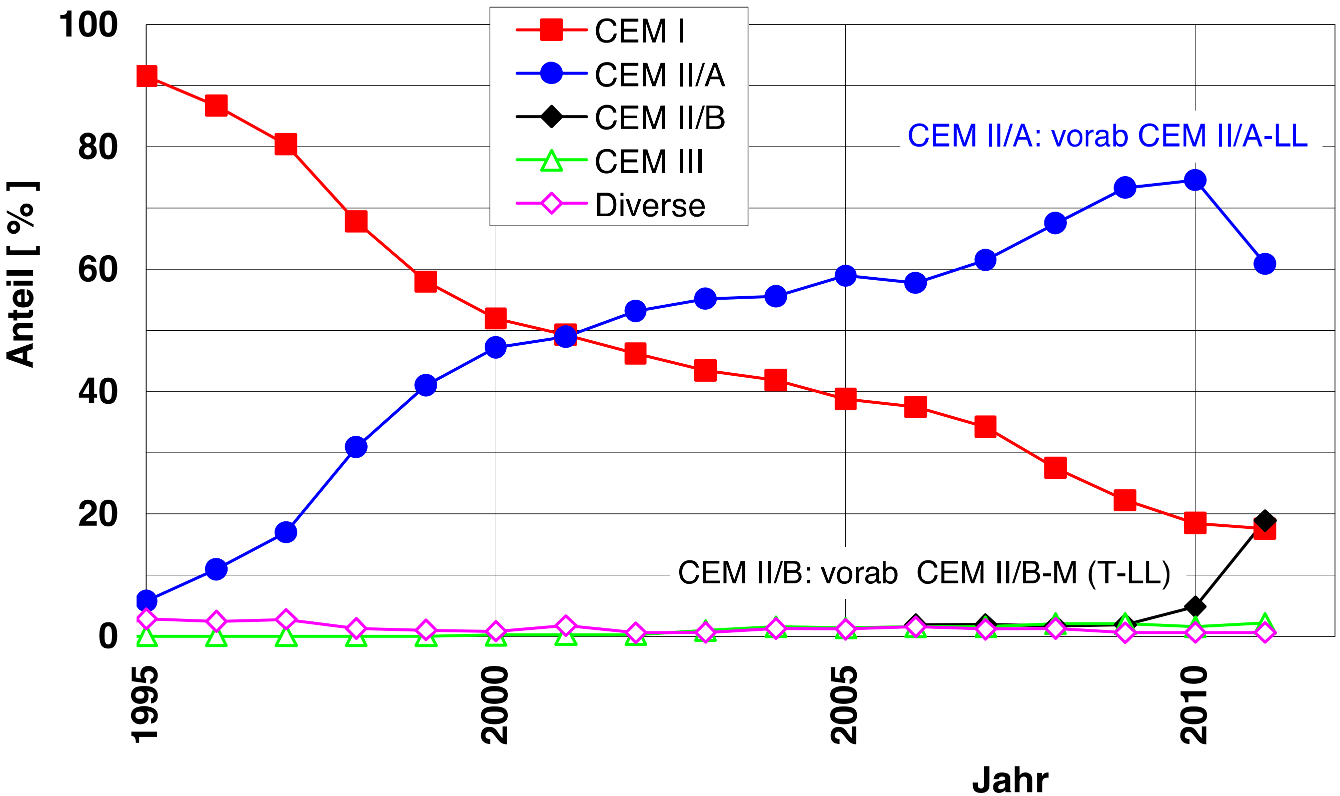


Global cement production will greatly increase, making the problem of CO_2 more critical (5% world CO_2 production)

The clinker content in the cements is continuously decreasing. Today about 85% is CEM II (data Switzerland).

Reducing the clinker content means that less $Ca(OH)_2$ is present in the “green” cements. This can be considered as durability problem but also as a challenge.

New “green” cements – CEM II



Data from Switzerland (cemsuisse)

Other reasons to use new blended cements

Decrease the **concrete permeability** by adding SCM

- Pozzolanic reaction (cement paste is formed in the pores)
- Filler effect (limestone)
- Lower hydration heat evolution

Pozzolanic reaction

Pozzolan + $Ca(OH)_2$ + H_2O → C-S-H (cement paste)

Decrease the **pH of the pore solution**

- Avoid alkali silika reaction (ASR)

Carbonation

Carbonation of concrete

Penetration of CO_2

$CO_2 + Ca(OH)_2$ ---> $CaCO_3$

pH value as indicated by phenolphtalein

In carbonated concrete the pH value drops to < 10: **steel depassivation**

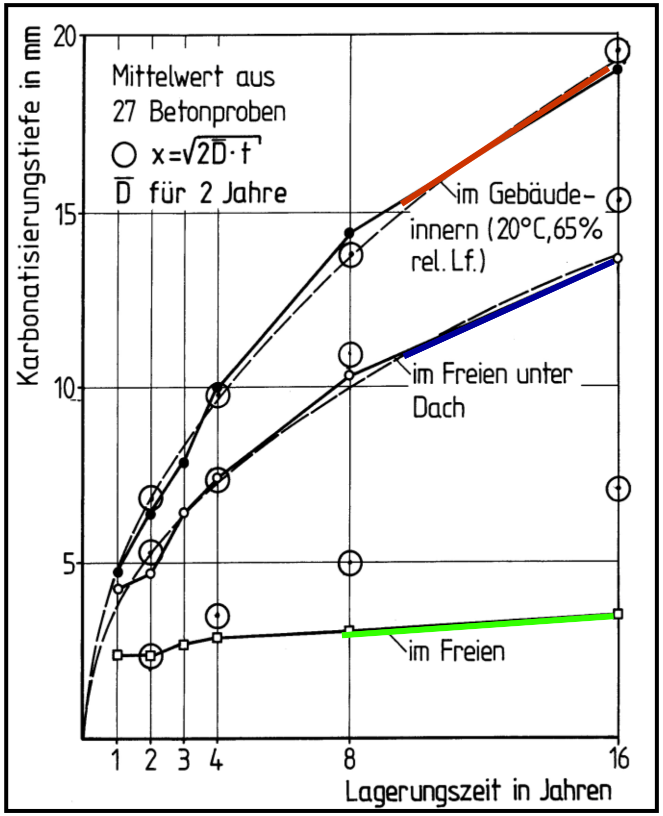
Corrosion of the reinforcing steel

In presence of H_2O and O_2 rust products are formed

Iron oxides (rust) are more voluminous then steel: **cracking or spalling**

Carbonation rate

Penetration of the carbonation zone $d = K * t^b$



Laboratory, constant climate 65% RH $b = 0.5$
(capillary pores open, slightly humid, n = 2)

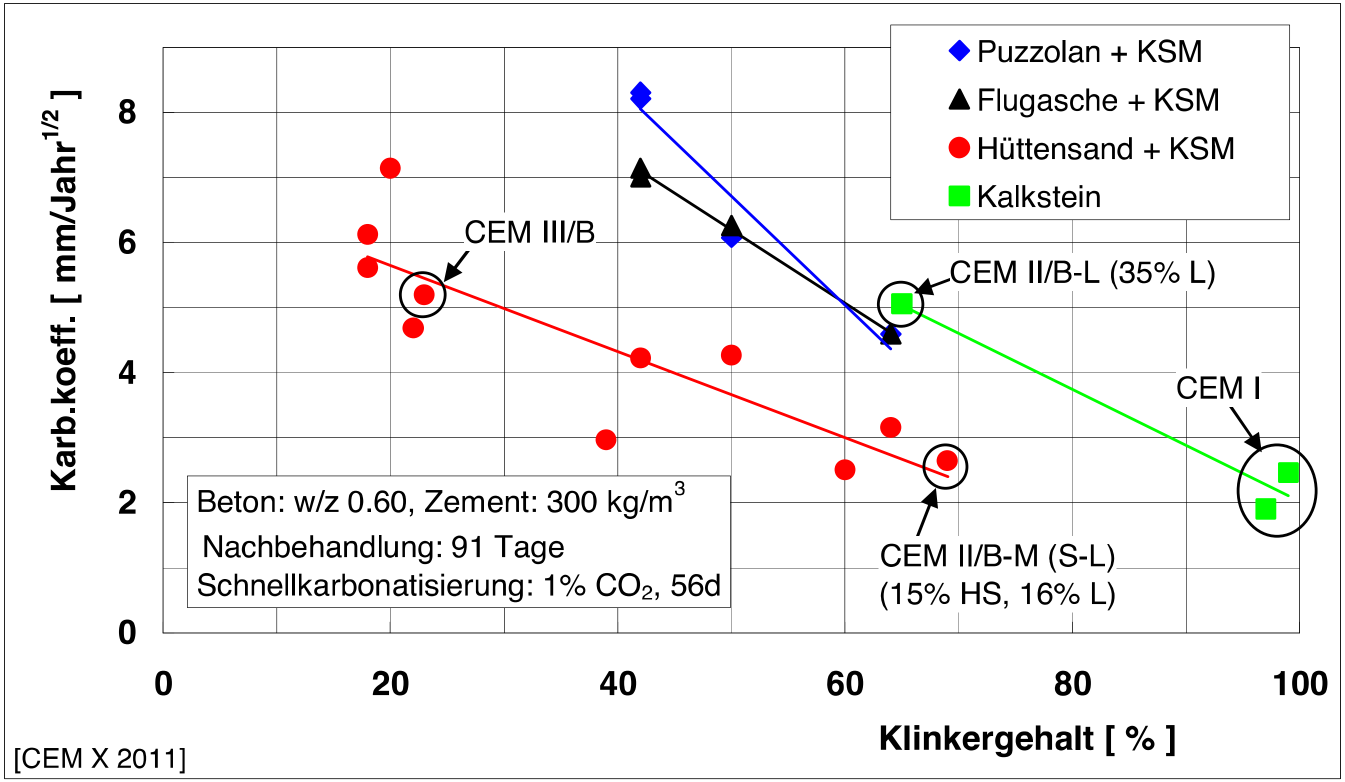
Outdoors, under a roof $b < 0.5$
(humidity condenses in small pores -> ingress of CO_2 is temporarily stopped, n > 2)

Outdoors, exposed to rain $b \to 0$
(After rain concrete becomes rapidly wet, Drying out is a slow process -> ingress of CO_2 is stopped, carbonation depth limited)

For ordinary portland cement (OPC) with w/z 0.5 carbonation is no problem, high alkalinity due to $Ca(OH)_2$ formation.

Carbonation rate

Carbonation depth d = K * t ^{b} → **K carbonation coefficient**



F. Hunkeler, L. Lammar, VSS research report 649 (2012) in German

Carbonation of blended cements

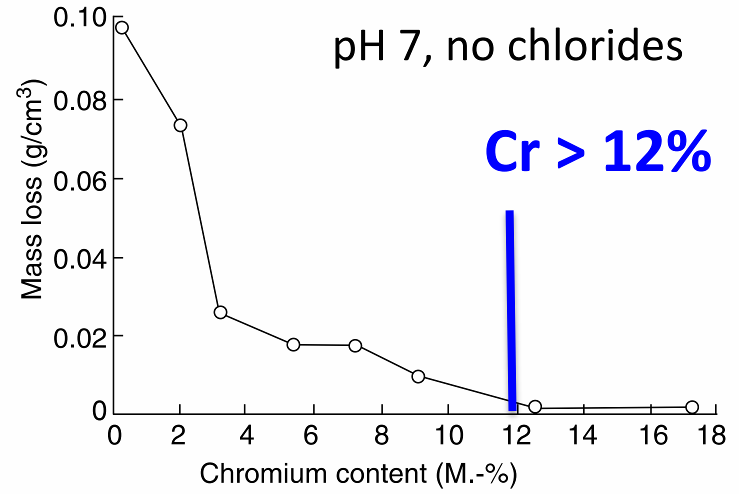
Poses a new (old) problem that had become negligible with CEM I, that is **corrosion of the reinforcement due to carbonation**

Lack of experience
Reliable accelerate test methods needed

F. Hunkeler, L. Lammar, VSS research report 649 (2012) in German

Possible (robust) solution

Problem of carbonation is the loss of alcalinity, drop of the pH or concrete to values pH < 9 and corrosion of the reinforcement

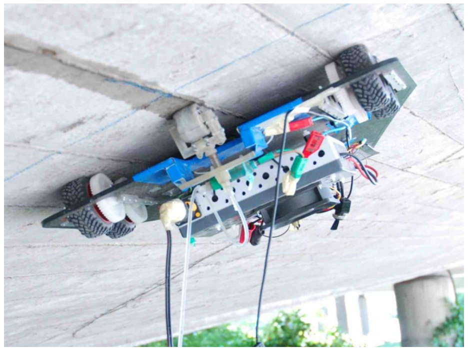


Choose a more corrosion resistant reinforcement

Iron 12% chromium alloy (Fe 12%Cr) is passive at pH 7 (without concrete….)

Corrosion is completely avoided (even at very low cover depths)

Challenges for the future of concrete industry

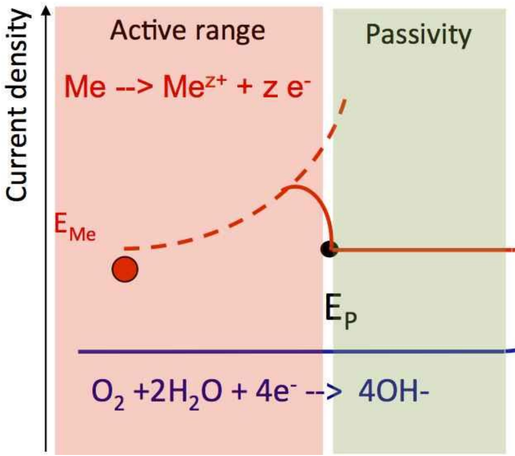


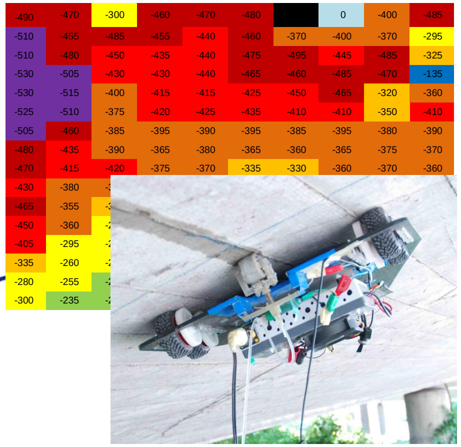
Huge existing stock of structures becoming older – high costs for repair
Develop a new pro-active repair strategy, inspection methods

New post-tensioned structures should be built in such a way that the protection of the high-strength steels can be assessed during the whole service life.

New “green” cements reduce CO_2 emissions but may greatly increase the risk of corrosion due to carbonation
Use of “low cost” stainless steel Fe 12%Cr

How to tackle and resolve "real" problems





Scientific basis
mechanisms and new materials

Engineering approach
go to practice
methods, monitoring

Find solutions for
durable structural concrete

Education
University

Interdisciplinary collaboration
continuous formation

aicap

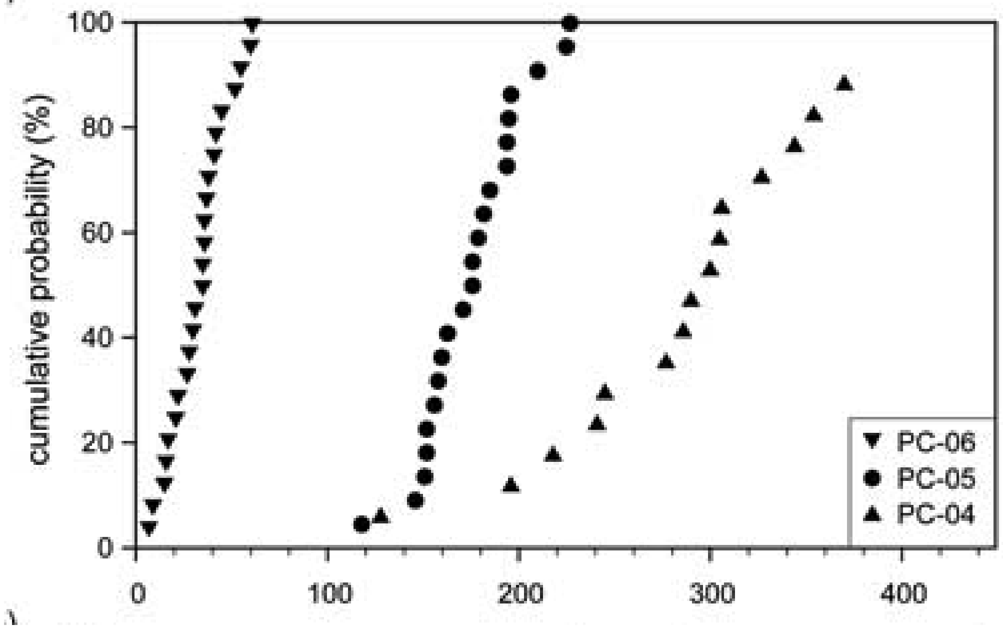
Industry
Associations



Grazie dell‘ attenzione

ETH zürich

Freie Chloridionen können mit **Ionensensitiven Sensoren** im Beton zuverlässig bestimmt werden. Dies erlaubt das Eindringen der "Chloridfront" zu verfolgen.



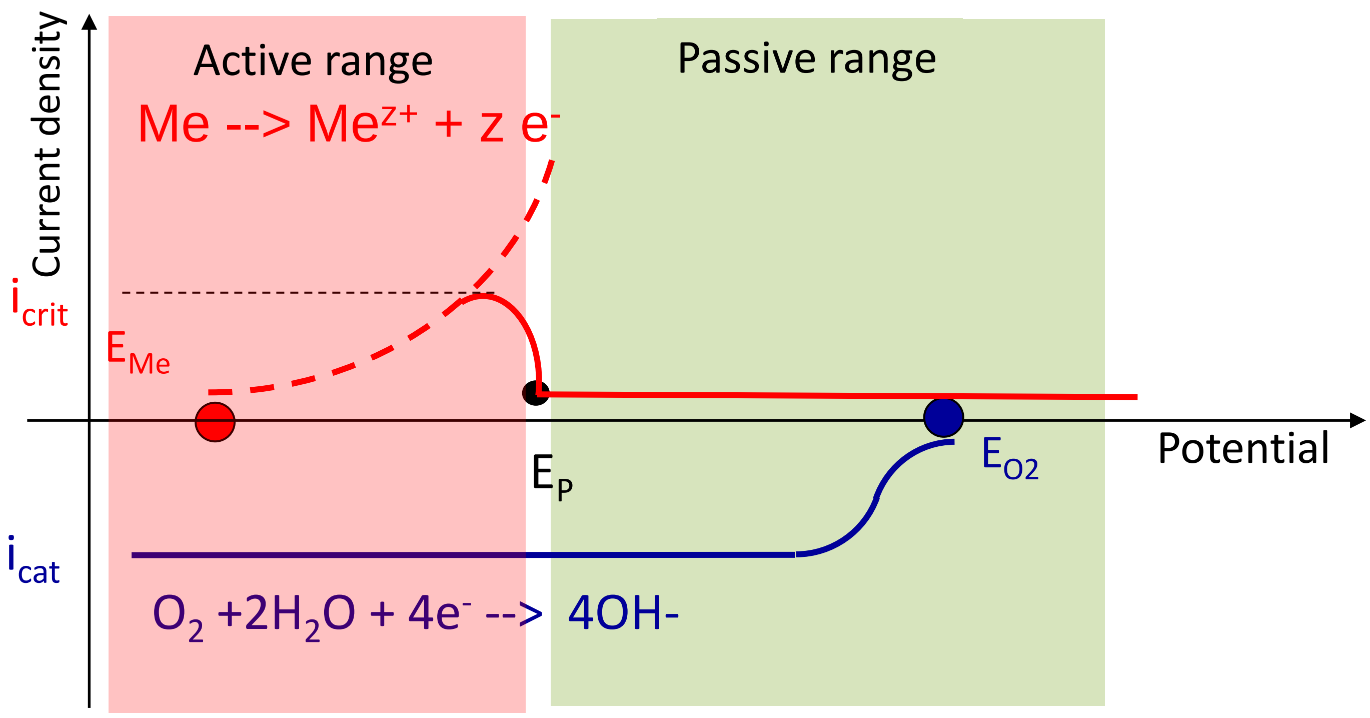
Proben:

- Beton mit CEM I
- 42 Tage Nachbehandlung
- 2 d Ponding / 5 d trocken
- Ueberdeckung 10 mm
- 4 Replika, 24 Cl Sensoren

- ➢ Offensichtlich ist auch die "Chloridfront" statistisch verteilt
- ➢ Standardabweichung wird grösser je tiefer w/z Wert
- ➢ Probabilistische Berechnungen werden komplex...

Diss. U. Angst, NTNU Trondheim (No), U. Angst, B. Elsener, in preparation

Spontaneous passivation in alkaline pore solution (pH > 12)

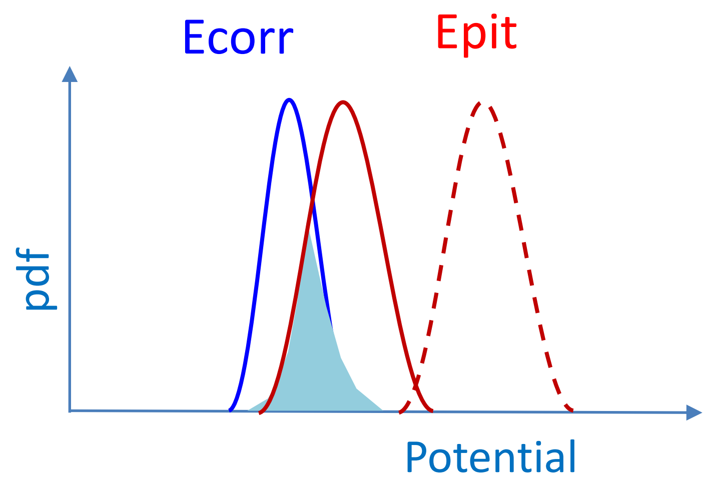


Passivation: Formation of a thin protective oxide film

Condition for spontaneous passivation: $i_{crit} < i_{cat}$

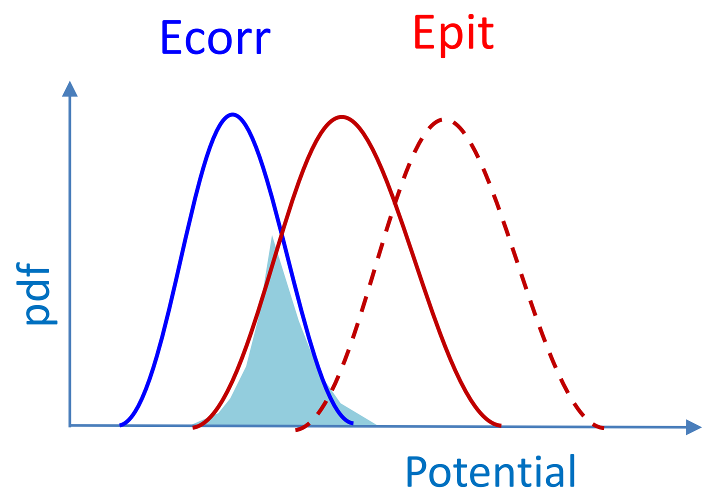
Epit and Ecorr are both not constant but distributed values

Well defined values



For the same pitting probability the mean values have to be very close

distributed values



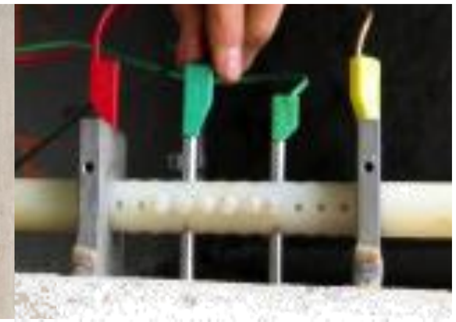
Relative high pitting probability already at high difference of the mean values.

Care has to be taken when transferring results from laboratory to practice.

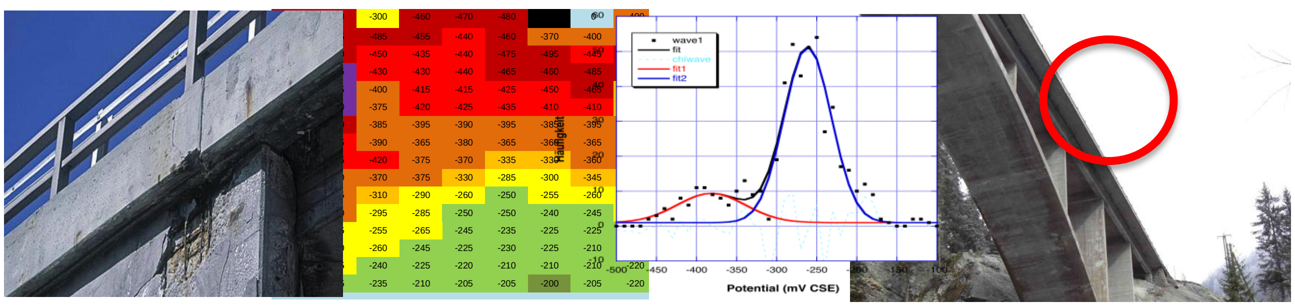
Solution: higher quality of the information on bridge condition

Cover depth

Half-cell potential



Resistivity



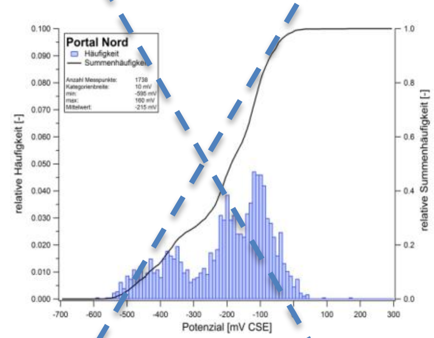
With the result that **regular inspections** allow to …

- Locate areas with problems ("weak spots on weak structures")
- detect problems much earlier
- Preventive measures save huge amount of money

Implemention in bridge management systems (BMS) needed

-490	-470	-300	-460	-470	-480		0	-400	-485
-510	-455	-485	-455	-440	-460	-370	-400	-370	-295
-510	-480	-450	-435	-440	-475	-495	-445	-485	-325
-530	-505	-430	-430	-440	-465	-460	-485	-470	-135
-530	-515	-400	-415	-415	-425	-450	-465	-320	-360
-525	-510	-375	-420	-425	-435	-410	-410	-350	-410
-505	-460	-385	-395	-390	-395	-385	-395	-380	-390
-480	-435	-390	-365	-380	-365	-360	-365	-375	-370
-470	-415	-420	-375	-370	-335	-330	-360	-370	-360
-430	-380	-370	-375	-330	-285	-300	-345	-350	-340
-465	-355	-310	-290	-260	-250	-255	-260	-265	-265
-450	-360	-295	-285	-250	-250	-240	-245	-260	-240
-405	-295	-255	-265	-245	-235	-225	-225	-225	-220
-335	-260	-260	-245	-225	-230	-225	-210	-230	-230
-280	-255	-240	-225	-220	-210	-210	-210	-220	-225
-300	-235	-235	-210	-205	-205	-200	-205	-220	-215

huge amount of data



elaborate and condense

Interpret and rate

Semi-automatic software
specialists

structural behavior, experience
bridge engineers

Interdisciplinary collaboration

Bridge management system

Decision making

Bridge management – challenges for today and the future

Huge stock of bridges of different ages

Condition of the structures
- Bridge inventory
- Based on visual inspections
- Corrosion detected too late
- ....

Optimum time of repair ?

Several constraints
- Limit traffic interruptions
- New constructions / replace
- Budget constraints
- Repair technologies
- .....