ETH zürich

DURABILITY OF REINFORCED AND POST-TENSIONED CONCRETE STRUCTURES

Problems and Solutions

DURABILITY OF REINFORCED AND POST-TENSIONED CONCRETE STRUCTURES – PROBLEMS AND PROGRESS

Corrosion of reinforcement in concrete is an increasingly significant problem around the world. Infrastructure is ageing and environmental actions adversely affect the durability and safety of our infrastructure (bridges, power plants, tunnels or buildings). The main cause of damage and premature failure of reinforced and post-tensioned concrete structures is chloride induced reinforcement corrosion caused by the ingress of chloride ions from sea-water or de-icing salts. Chloride ions destroy the protective oxide films on the reinforcement and in presence of humidity and oxygen localised corrosion attacks develop, leading to a dangerous loss of cross-section (figure 1). These localised attacks do not manifest at the surface by cracking or spalling because no rust is formed [1].

AGE OF INFRASTRUCTURE

Detailed statistical information on the age of infrastructure is rare. Highway bridges in Switzerland were built mainly in the years 1965 to 1975 (figure 2), thus these structures today have reached an age of 40 to 50 years. From the Netherlands it is known that about 10% of all the bridges need substantial repair after 50 years of service life. Thus it can be concluded that the aging infrastructure is one of the most serious problems faced by society today. Great efforts will be needed in future to maintain the infrastructure.

COST OF CORROSION

A detailed study on the cost of corrosion in industry (figure 2) was conducted by NACE in 1998 for the USA [2]. Infrastructure in the NACE study was divided into the following sectors: highway bridges, gas and liquid transmission pipelines, waterways and ports, hazardous materials storage, airports, and railroads. The total annual direct cost in the category “infrastructure” was estimated to be $22.6bn.

From the approximately 583,000 highway bridges in the U.S. about 15% are structurally deficient because of corroded steel and steel reinforcement. Annual direct cost estimates total $8.3bn, including $3.8bn to replace deficient bridges over the next 10 years, $2bn for maintenance and capital costs for concrete bridge decks and $2bn for their concrete substructures, and $0.5bn for maintenance painting of steel bridges. Indirect costs to the user, such as traffic delays and lost productivity, were estimated to be as high as 10 times that of direct corrosion costs. Today, it is estimated that the numbers in the NACE corrosion study in 1998 approximately can be doubled [3].

More detailed information on the age distribution of bridges and the costs for repair and maintenance are reported for Switzerland. The Swiss

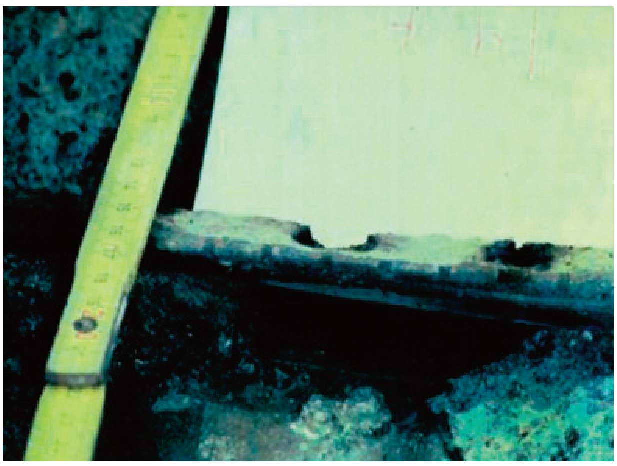

figure 1

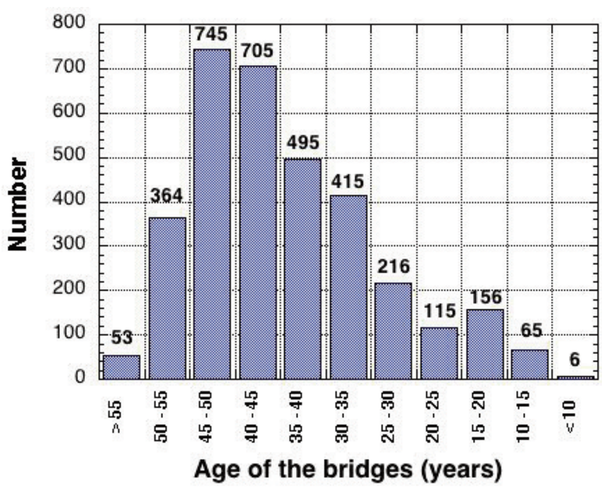

figure 2

National Highway system has a very high network complexity: from the total length about 10% are ramps, 12% tunnels and 15% bridges (about 3350 individual objects). From the detailed distribution of the age of the bridges (Figure 3) it can be seen that a great part of bridges were built between 1965 and 1975, today their age is between 40 and 50 years. This indicates that compared to the past only a few new bridges are constructed and the existing stock becomes older. In Switzerland detailed costs are reported for repair and maintenance of the national highway system (figure 4), [4] showing an increase from 249 Mio (1995) to 768 Mio (2010). While corrosion of the reinforcing steel might not be the sole cause of all repair work, it is a significant contributor [4]. Repair costs per square meter bridge deck are reported to be 1200-1800 sFr. For other European countries the numbers might be similar.

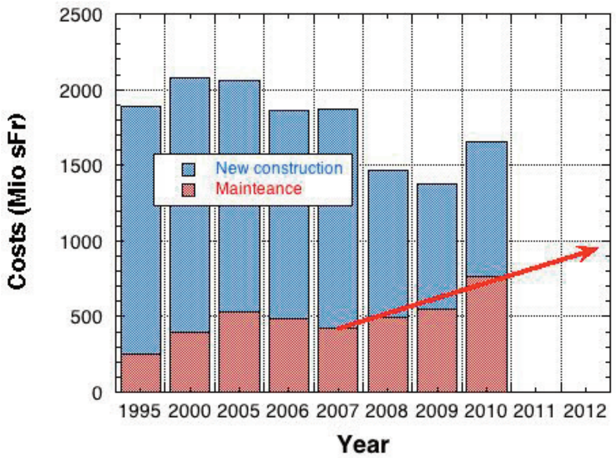

figure 3

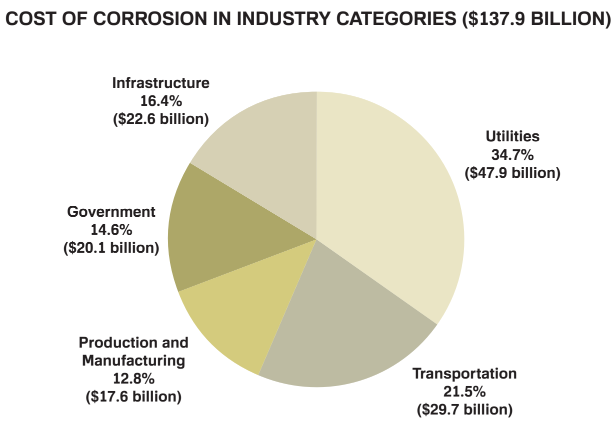

figure 4

THE IMPORTANCE OF INSPECTION

Existing concrete infrastructure is aging, while being exposed to aggressive influences, which increases the occurrence of corrosion and damage over time. Today, as much of the aging infrastructure reaches the end of its designed lifetime, the emphasis is on maintaining and extending the life of these valuable assets, becoming the main tasks of bridge management operation.

Inspections are part of the (bridge) management operation, assuming that signs of deterioration will be detected and proper follow-up can be taken before damage is too large. Regular inspections today are relying solely on visual inspection with the risk that damage, especially chloride induced localised corrosion (figure 1), will be detected only at a very late stage when maintenance already has become very expensive.

As corrosion is an electrochemical process, electrochemical techniques are especially well suited to assess the corrosion state of the reinforcement and to locate corrosion sites. Half-cell potential mapping is a widely recognised and standardised non-destructive method for assessing the corrosion state of reinforcement

figure 5

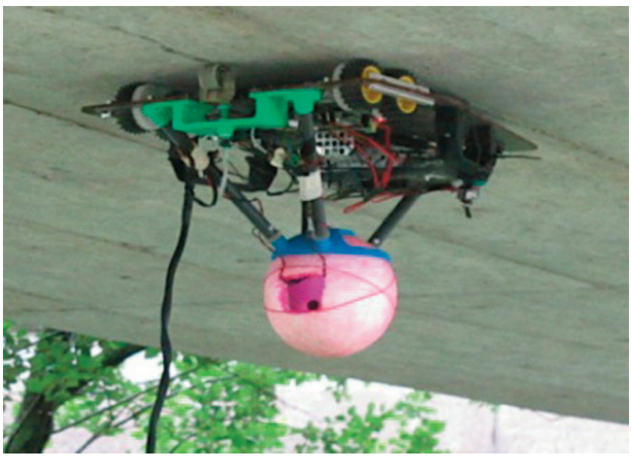

figure 6

in concrete structures [6]. A reference electrode, also in the form of a wheel electrode has to be put on the concrete surface (figure 5). A RILEM recommendation was published [5] where the experience with potential mapping was incorporated. Several national guidelines describe the procedure and interpretation of half-cell potential measurements.

Half-cell potential maps allow locating areas of corroding reinforcement, being the most negative zones in the potential field. As an early warning system, corrosion is detected long before it becomes visible at the concrete surface.

The main problem in practice is that most of the reinforced concrete surfaces are not or only with costly scaffolding accessible for this type of inspection. The climbing corrosion detection robot (figure 6) developed by ETH Zurich [7, 8] can overcome this difficulty. With its Vortex system it can adhere on virtually any concrete surface in any inclination and with the half-cell potential sensor the corrosion state of the reinforcement can be mapped. Corroding areas can be located precisely long before becoming visible at the concrete surface.

BUILT TO BE MONITORED – ELECTRICALLY ISOLATED POST-TENSIONING TENDONS

New reinforced and post-tensioned concrete structures are still built worldwide. In all these structures such as bridges, power plants, towers etc. tendons containing the high-strength steels are structural elements contributing decisively to the serviceability, safety and durability of pre-stressed concrete structures (figure 7a). Chloride containing water penetrating into the ducts is the major cause of corrosion of the pre-stressing steel (figure 7b) ducts. Until now no non-destructive technique exists that can reliably assess the condition of a tendon with metallic duct. Thus bridge engineers and owners do not know the corrosion state of the most important structural elements – with sometimes catastrophic collapses.

To overcome this problem industry has developed new tight plastic ducts for bonded post-tensioning tendons (figure 8) that greatly improve corrosion protection of the steel [9]. Together with electrically isolated anchorages (figure 9), EIT tendons that are protected against corrosion and are easy to monitor can be achieved. Thus for any individual tendon in a structure the degree of corrosion protection of the high-strength steel can be assessed by simple non-destructive measurements at any time (figure 10). This allows a long-term monitoring

figure 7a & 7b

figure 8

of every individual tendon; a decrease of the resistance indicates the ingress of water (and chlorides) at a defect of the duct – long before damage has occurred.

Our group has performed several research projects [10] to develop the NDT technique in the laboratory and on-site since long time. ETH Zurich, the Institute for Building Materials, was actively involved in preparing the guideline of the Swiss Federal Highway Administration "Measures to ensure the durability of post-tensioning tendons" [11]. This guideline has been adapted by fib (federation international du béton) [12] and the technology of EIT is increasingly used worldwide.

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[6] L. Bertolini, B. Elsener, E. Redaelli, P. Pedeferri, R. Polder, Corrosion of Steel in Concrete, WILEY VCH 2013 (second edition) chapter 16

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figure 9

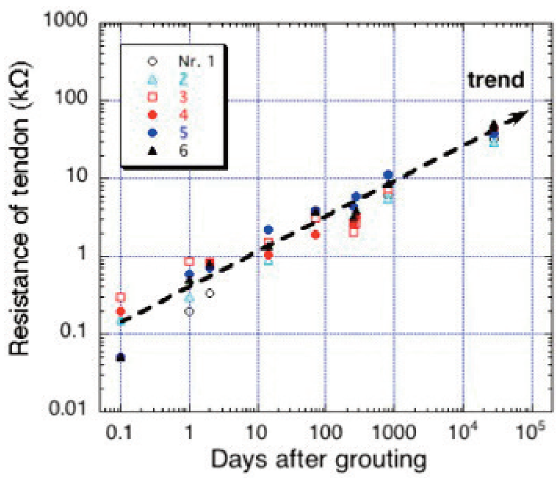
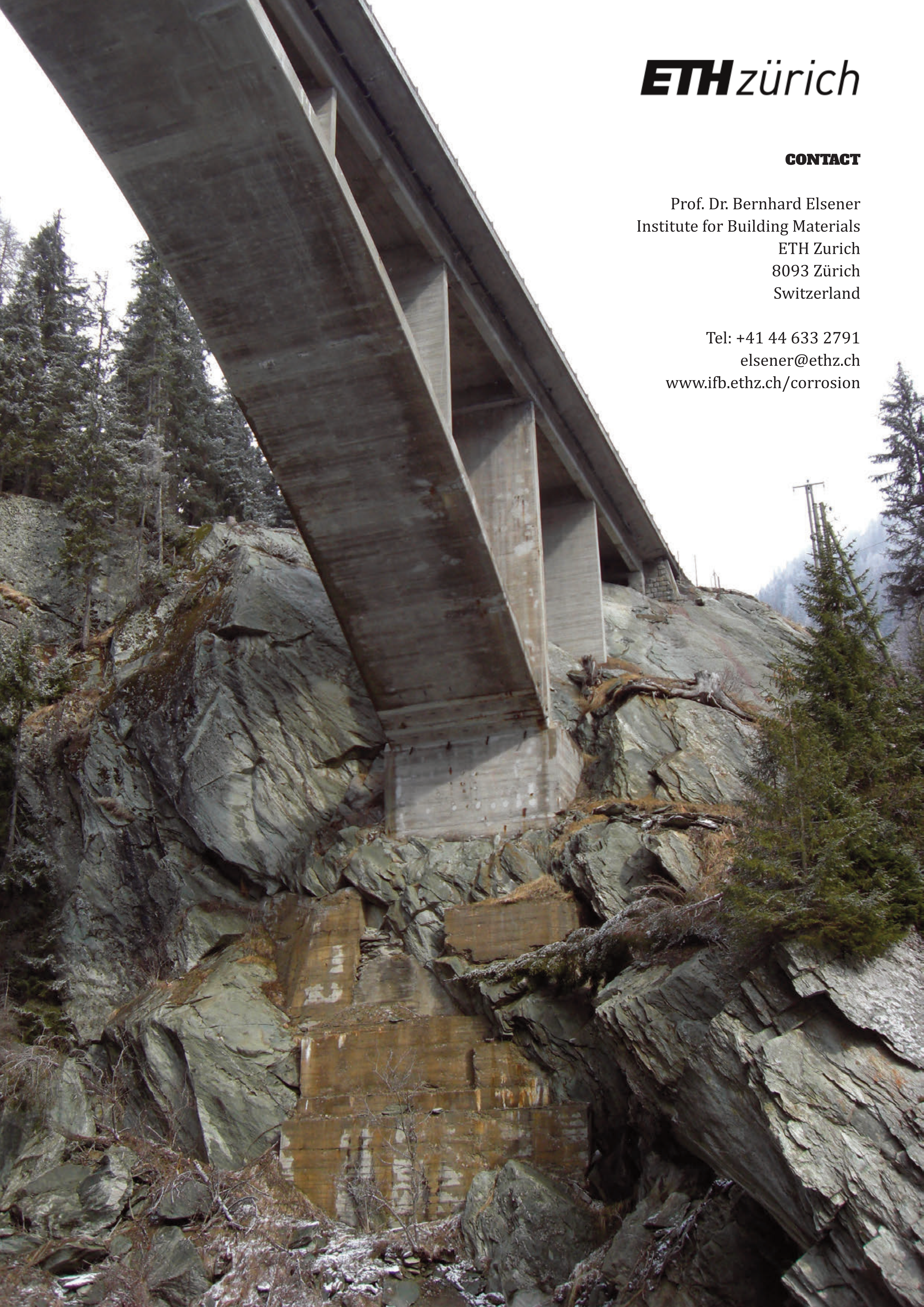


figure 10



ETH zürich

CONTACT

Prof. Dr. Bernhard Elsener
Institute for Building Materials
ETH Zurich
8093 Zürich
Switzerland

Tel: +41 44 633 2791
elsener@ethz.ch
www.ifb.ethz.ch/corrosion