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DAMAGE TO CONCRETE BRIDGES DUE TO REINFORCEMENT CORROSION. PART I. SITE INVESTIGATIONS

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Abstract. Corrosion of reinforcement initiated by concrete carbonation and chloride contamination is the most common type of deterioration of concrete bridges. Based on the author's experience a number of cases is reported in which the corrosion of ordinary and prestressed reinforcement as well as the causes and consequences of deterioration observed are presented. Investigations have shown that the main reasons are: insufficient concrete cover, poor quality of concrete, and ingress of aggressive salts. The carbonation depth must be related to the histogram of rebar cover depths and the probability of their coincidence can be predicted. The monitoring of tendon conditions in prestressed concrete precast post-tensioned segmental bridge decks shows that the voids and the water are often present in the ducts leading to the local rusting of tendons. The wires used in tendons are liable to fail in tension that was observed in some prestressed concrete bridges. Unfortunately, no reliable procedures of determining the condition of prestressing steel in existing structures are available.

Keywords: concrete bridges; concrete carbonation; chlorides; reinforcement corrosion.

1. Introduction

Corrosion of reinforcement is the most common type of deterioration of concrete structures. In many countries there is an enormous stock of existing bridge structures suffering serious damages [1–3]. Our surveys and structural appraisals of concrete bridges which were carried out over the last several years also show that at present many concrete bridges in Lithuania show the signs of damage caused by reinforcement corrosion [4]. The structures show steel corrosion and concrete deterioration only a few years after the construction. The main causes are related to:

- poor design/conception without rational strategy for durability possible deterioration mechanisms involved;
- poor workmanship (especially in positioning of reinforcement, waterproofing system) without quality control and quality assurance;
- lack of maintenance;
- insufficient requirements for durability in the codes.

The assessment of concrete structures suffering reinforcement corrosion is the major problem in maintenance policy of concrete bridges. It is apparent that the problem is influenced by variety of bridges built in different localities, of different materials, and in different years.

The purpose of this article is to describe and illustrate examples of concrete bridge structures deterioration due to reinforcement corrosion and to analyse the causes and the consequences of deterioration observed.

2. Mechanism of Reinforcement Corrosion

Corrosion of steel in concrete is an electrochemical process which can be divided into anodic and cathodic reactions. The electrochemical process requires the presence of an electrolyte, oxygen from the air and different electric potentials between metallic surfaces. The reinforcement surface on which corrosion is taking place is formed of electric cells, i. e. anodes and cathodes. Electron current flows from the anode to the cathode as shown in Fig 1. All corrosion cells can produce pits in steel and loss of cross section in bars.

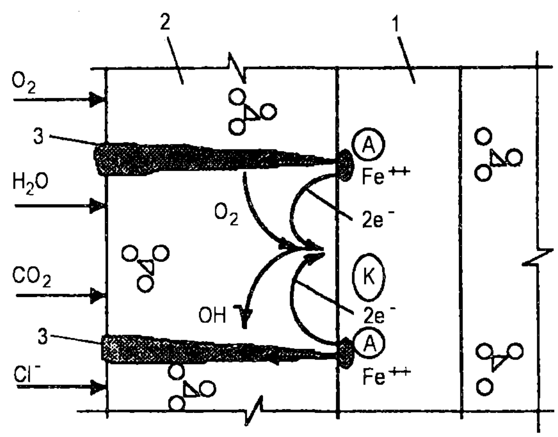

Fig 1. Scheme of reinforcement corrosion in concrete: 1 – reinforcement; 2 – concrete cover; 3 – steel corrosion products (rust); A – anode; K – cathode

The principal chemical reaction at the anode $Fe \rightarrow Fe^{++}+2e-$ and at the cathode $O_2+2H_2O+4e-=4OH-$. The overall reaction is as follows:

$$2Fe+O_2+2H_2O=2Fe^{++}+4OH-=2Fe(OH)_2.$$

The rate of this reaction is affected by concentration of oxygen at the cathode where corrosion occurs, by electrical resistivity of the electrolyte as influenced by concentration of soluble substances therein, as well as by temperature.

Reinforcement in concrete is protected from corrosion by the chemical reactions of Portland cements on the steel surface leading to the formation of protective film on the steel and its passivity as a result of the high alkalinity (high pH) as well as the environmental barrier provided by the concrete cover. There are two common conditions of steel depassivation in concrete bridges: concrete carbonation and chloride ions penetration from outside. The mechanism of corrosion of steel in concrete is complex and depends on a number of factors, including the environment conditions, the nature, size and spacing of reinforcement bars, the depth and quality of concrete cover.

3. Carbonation of Concrete

The steel reinforcement is protected against corrosion by the alkalinity of concrete which has a pH value of approximately 12-13. Carbon dioxide from the air can react with the calcium hydroxide in concrete to form calcium carbonate

$$Ca(OH)_2+CO_2+H_2O \rightarrow CaCO_3+2H_2O.$$

This process is known as concrete carbonation. The carbonation of the concrete by the carbon dioxide of the air (typically 0.03–0.04%) decreases the pH from 12.5–13.5 to 9–8.5 of the concrete and its protective effect. In some areas (in the streets with intensive traffic circulation) of Vilnius the concentration of CO_2 was found from 2 to 10 times higher than that in normal atmosphere. As a result pH falls below a limiting value of 8.5–9 leading to rusting of steel which increases volume by a factor 2–3. When the front of carbonation reaches the reinforcement the products of steel corrosion damage the concrete cover. Serious corrosion of reinforcing steel is usually accompanied by cracking of the concrete in a direction parallel to that of the steel bar. In good quality concrete carbonation does not penetrate deeply.

The speed of carbonation can be determined in laboratory or in site tests. Laboratory tests are normally carried out in constant laboratory conditions (temperature and humidity). A better judgement can be made on the basis of quantitative destructive or non-destructive inspections of existing structures. The tests were carried out in some existing bridge structures ageing from 1 to 25 years old. The carbonated concrete thickness was determined using phenolphthalein and the depth of cover by a cover meter.

The carbonation depth determined in a bridge slab after 1, 17 and 23 years in service is presented in Fig 2. Carbonation increases at a rate of 0.43 mm a year with carbonation depth COV of 0.23, 0.28, and 0.22 respectively. The average carbonation depth does not exceed 10 mm after 23 years. The equation for X_{max} in mm would be:

$$X_{\max} = 2.085(1+COV)\sqrt{t}. \quad (1)$$

We can predict carbonation depth of ~25.4 mm at design life of 100 years. In a properly constructed structure, in well-compacted and dense concrete (f_c≈40MPa), and in the absence of cracks and spalls there should be no problem of reinforcement corrosion during the service life. Unfortunately high cover variation exists.

Fig 3 shows the typical distribution of the depth of concrete cover over the bars. Average cover (22.2 mm) has been found to be less to the design cover (25 mm).

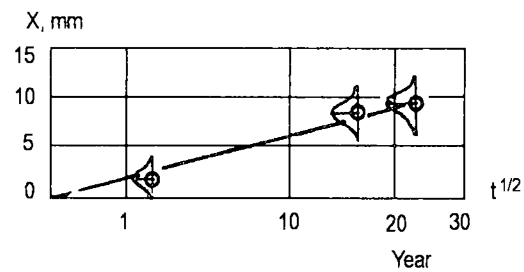

Fig 2. Carbonation depth of concrete in reinforced concrete bridge slabs

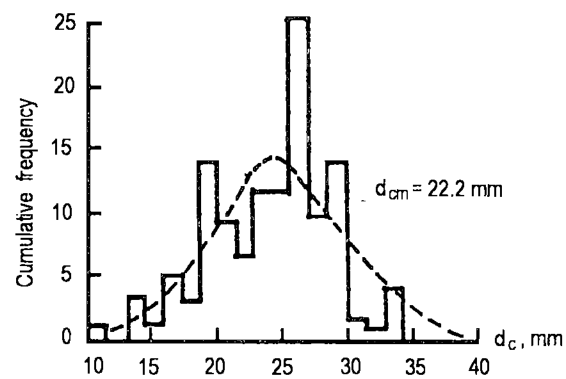

Fig 3. Variation in cover depth of stirrups in the prefabricated reinforced concrete pier caps of Sea Bridge in Palanga

The measurements confirm that the placing of reinforcement often varies widely. In the investigated bridges poor control of cover was the most frequent cause of early corrosion of reinforcement (Figs 4 and 5). As it is mentioned above it is not uncommon to see delaminated and spalled areas even after few years of service.

The carbonation depth date must be related to the histogram of rebar cover depth (Fig 6). The depth of carbonation (x) and the cover over the reinforcement (d_c) are random factors, the probability of their coincidence can be expressed as

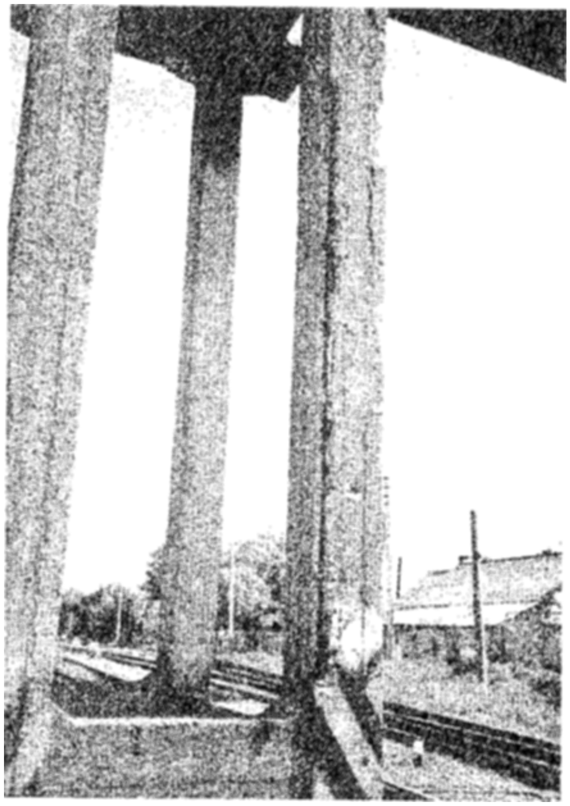

Fig 4. Corrosion of reinforcement of the multiple-column pier accompanied by cracking and deterioration of concrete cover

Fig 5. Debounding and corrosion of longitudinal bars and stirrups of reinforced concrete bridge beam

$$P(x \geq d_c) = P(d_c) \times P(x). \qquad (2)$$

Using this expression it is possible to determine the probability of reinforcement corrosion in successive years.

The measurements of the thickness of a concrete cover in connection with the position of carbonation front were made in the girders of a bridge deck after 25 years of service (Fig 7). According to the calculations the total carbonation of a concrete cover is observed in 31.5% cases (curb 2). After 50 years total carbonation depth, which was determined as $x_{t=50} = x_{t=25}(50/25)^{1/2}$, will be in 47.6% cases (curb 3).

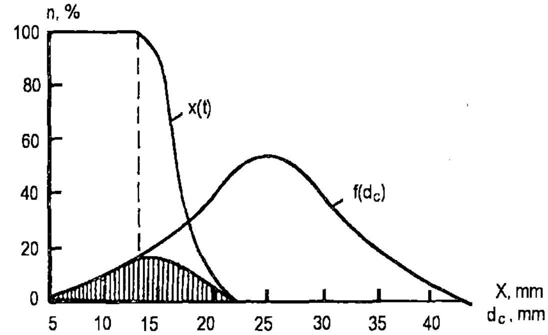

Fig 6. Histograms of carbonation depth $x(t)$ and depth of rebar cover d_c in reinforced concrete bridge pier (f_c'=20 MPa; t=30 years)

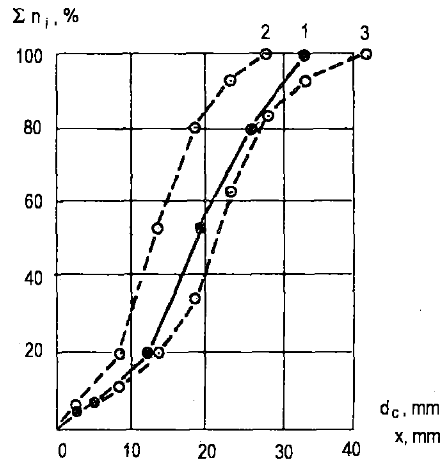

Fig 7. Distribution of concrete cover (1) and carbonation depth of a bridge slab in 25 (2) and 50 (3) years

Concrete for prestressed concrete structures is usually of high quality and strength. The thickness of concrete cover for prestressed steel or ducts is higher than for ordinary reinforcement. Normally the steel tendons in post-tensioned bridge beams are protected by grout, which is injected into the tendon duct. Therefore in the absence of defects in the structures there should be no problem of prestressing steel corrosion due to concrete carbonation.

4. Chloride Induced Corrosion

A much more aggressive material which can destroy the protective film of reinforcement in the concrete is the chloride ion. Chlorides may be present in concrete of bridge structures from the exposure to de-icing road salts. Chloride ions are able to disrupt the passivity of reinforcement in the high alkaline conditions in uncarbonated concrete. In carbonated concrete the corrosion process is controlled mainly by the permeability and thickness of concrete cover.

Spray of chloride solutions from vehicles is observed in parapet beams, footways, and guardrails. Most of these members are subjected to an intensive deterioration process, in many cases exclusively visual due to the salts crystallisation and concentration increased by capillary action and evaporation. The deterioration of ancillary members of a bridge by de-icing salts in winter maintenance is accelerated by concrete disintegration resulting from the chemical reactions between salts and components of Portlandcement (CA_3) as well as physical cause due to a larger temperature drop that occurs when the surface comes into contact with the de-icing salts. Deterioration is most common in areas somewhere in the splash zones (Fig 8).

For bridge super and substructures the process is much more complex. Deficiency of waterproofing system and expansion joints permit the penetration of water and de-icing salts to the caps of piers and abutments, edges of beams, bearings (Fig 9). The deterioration of bridge structures caused by chlorides is due to constantly changing amount of moisture as a result of improper drainage, concentration of chlorides, and the degree of concrete saturation.

The corrosion of prestressed reinforcement is considerably more serious than that of normal unprestressed steel. The monitoring of tendon conditions (for example, by gamma radiography, impulse radar, residual magnetism) is very complex and is not described here (see [5]). The reliable non-destructive techniques to determine the degree of corrosion and the remaining cross-section area of each tendon along its full length in an existing structure do not currently exist. The most useful technique at present is visual inspection of the tendons after removing of concrete. Although the method is not completely successful. The reason is that it is impossible exactly to prelocalise the damages of prestressing tendons.

The detection and evaluation of prestressed tendons condition were performed on existing pre-tensioned and two post-tensioned bridges after 16 and 23 years of service. In post-tensioned structures the inspection 60 and 100 mm diameter holes were drilled (Fig 10) and concrete samples were taken for laboratory analysis (Fig 11). It has been found that in the prestressed concrete precast post-tensioned bridge decks the voids and the water are often present in the ducts. The absence of grout in some parts of the ducts and local tendons rusting was observed in some post-tensioned segmental bridges [4]. Pitting corrosion generally attacked prestressing steel. The water with de-icing salts penetrates through the joints into the ducts creating a permanent risk of corrosion in the tendons. The wires used in tendons or strands are liable to fail in tension due to embrittlement rather than a loss of steel area.

In 1985 a bridge in Wales suddenly collapsed, fortunately without loss of life. In 1992 the Department of Trans-

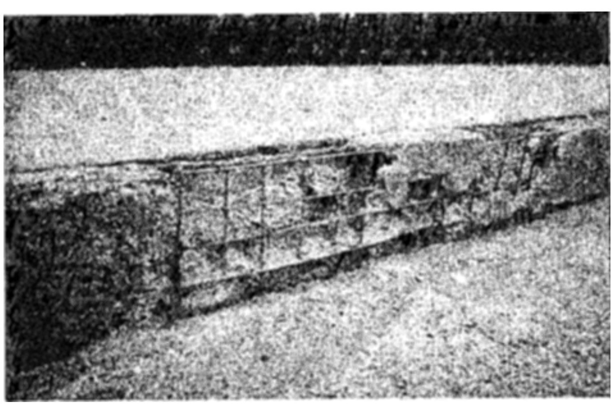

Fig 8. Detail of damaged reinforced concrete parapet in the splash zone

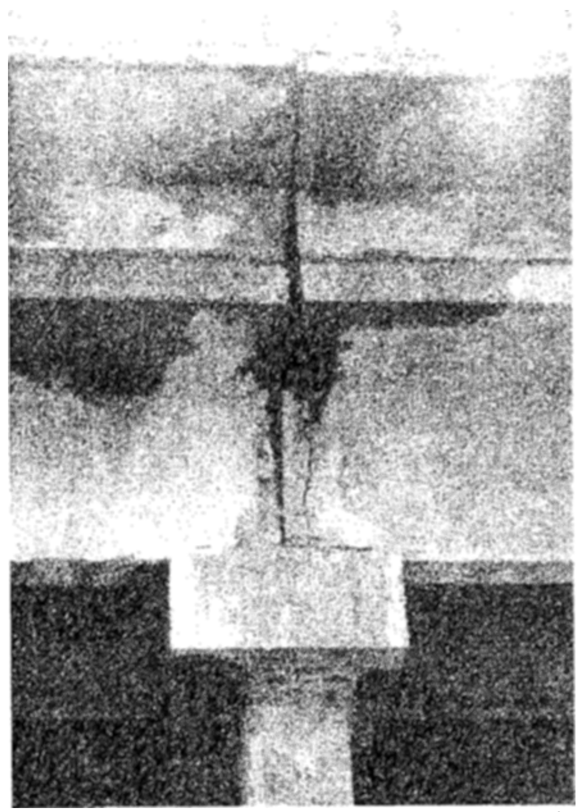

Fig 9. Deterioration of edges of beams and cap of pier due to leakage of expansion joint

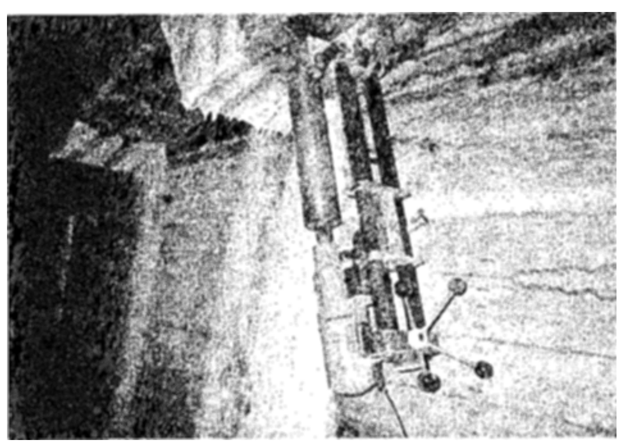

Fig 10. Special coring equipment for inspection of prestressed tendons and their ducts

port of the UK decided no longer to permit any post-tensioned bridge with grouted duct tendons to be built [5]. In Switzerland three bridges were dismantled after 30 years (in 1992) of service due to significant corrosion damages [6]. Sudden collapse without prewarning of bridge staircases in Vilnius due to prestressed tendons corrosion and rupture can be mentioned (Fig 12).

The effect of leaking expansion joints is also the corrosion of anchors of prestressed cables (Fig 13) and areas of beam supports. Chloride contaminated water flows down to the lower flange areas and then penetrates into the concrete. In the pre-tensioned beams corrosion products around the prestressing tendons were observed loosing their bond [7].

When a prestressing wire is held in outdoor storage for a long time, the loss of mechanical properties should occur. It is evident that corrosion is a function of the environment. During the construction of a pre-tensioned bridge in Vilnius some tendons failed when stressed to the design level. The tendons have been stored in industrial atmosphere without special protection for few years. The surface of tendons was covered by rust. The rusted tendons placed in the structure will continue to deteriorate and the drop of tensile strength is to be expected.

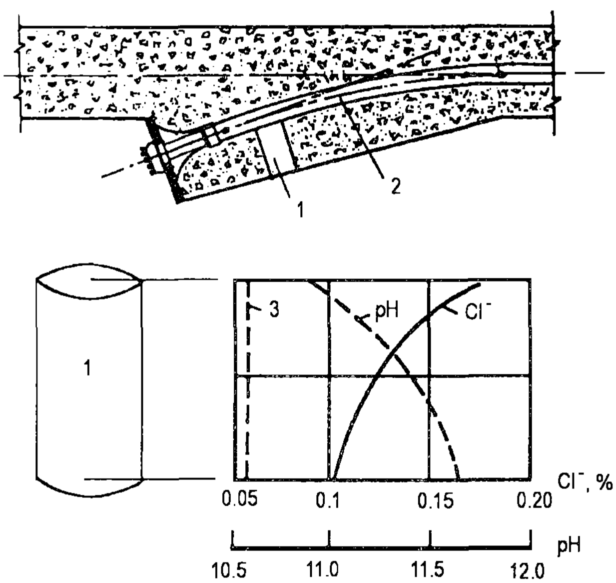

Fig 11. Distribution of chlorides Cl- and pH in concrete cylinder (1) drilled from post-tensioned prestressed bridge beam near the cable duct (2); 3 - admissible level of chlorides

Fig 12. Rupture of bridge staircases due to corrosion of prestressed tendons

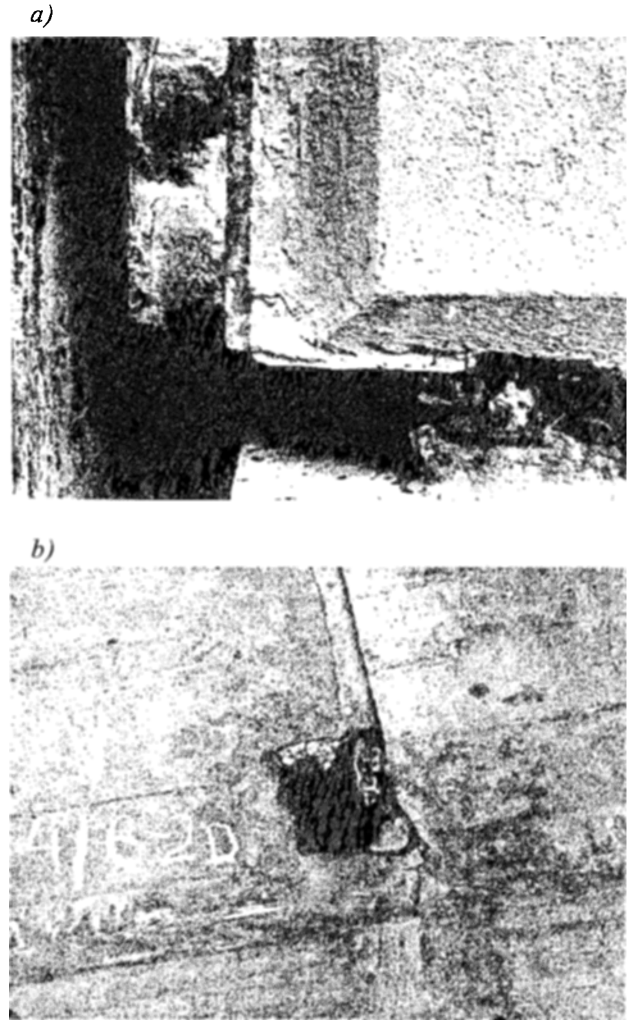

Fig 13. Corrosion of exterior anchors of tendons: *a)* – at the edge of simple beam; *b)* – at the joint of segmental post-tensioned bridge beam

5. Conclusions

1. In this article the examples of the deterioration of concrete bridges due to reinforcement corrosion are described and illustrated. The causes and the consequences of the deterioration observed are analysed. There are two common conditions of steel depassivation in concrete bridges leading to its degradation: concrete carbonation and chloride penetration to the concrete. The results of detailed field investigations have demonstrated that con-

crete carbonation and chlorides can cause severe corrosion of reinforced concrete bridges.

2. A very important factor for reinforced concrete decay is the quality of concrete cover. In a properly constructed structure, in well-compacted and dense concrete, and in the absence of cracks and spalls there should be no problem of reinforcement corrosion during the service life. Unfortunately, high cover variation exists in practice.

3. The rate at which carbonation and chloride ingress develop is of vital importance for predicting the durability of structures. It is shown that the carbonation and the rebar cover depths date obtained from field-testing allow to predict the probability of reinforcement corrosion (see Eq. (2)).

4. The corrosion of prestressed reinforcement is considerably more serious than that of normal unprestressed steel. Our findings show that insufficiently injected ducts, moisture in ducts and corroded tendons exist in post-tensioned structures. There are no reliable procedures of determining the condition of prestressing steel in existing structures.

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