The effect of reinforcement corrosion on the structural behaviour of prestressed bridges in the Norwegian coastal regions

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ABSTRACT

Prestressed concrete (PC) is one of the main structural materials used in Norway for bridge structures. Prestressed and precast concrete beams were even used for building the historical Atlantic Road, which has the status of a National Tourist Route and is of strategic importance for the infrastructure. Bridges located along the Norwegian coast are exposed to an aggressive marine environment, containing chlorides, which can be the cause of reinforcement corrosion. Severe deterioration of prestressed concrete structures may lead to serious consequences, including sudden and brittle failure. Reliable assessment of existing damages, as well as prediction of residual behaviour and service life is crucial for PC.

Key words: Pre-stressed concrete, Deterioration, Corrosion, Stress Corrosion Cracking

1. INTRODUCTION

In the past few decades, prestressed concrete has been widely used in Norway for construction of bridges. According to the Norwegian bridge management system Brutus [1], in total more than 150 bridges have been built using the popular prestressed and precast concrete beams type NIB (normalized I-beams), with 61 of them located in coastal areas and 13 in a harsh coastal environment, see Table 1. Apart from NIB beams other types (NOB, NOT and MOT) were sporadically used in bridges. In these beam types, the reinforcement is pretensioned before the concrete is cast and their steel strands are lying naked in the concrete (without ducts). Moreover, increased use of prestressed elements in new-build structures can be motivated by several advantages of pre-stressing like significantly increased span length, reduced material, costs and time-to-build of the bridge.

However, deterioration of prestressed structures can lead to serious consequences affecting structural safety. In marine environment, PC is exposed to seawater and deicing salts, both containing chlorides. These aggressive ions may penetrate the concrete cover, reaching finally the reinforcement depth. When a certain chloride concentration (the chloride threshold value) is obtained on the steel level, localized corrosion (pitting) may initiate and propagate, causing, in worst case, sudden and brittle failure of the prestressing wires. Although prestressing reduces, or even fully prevents, flexural cracking of the structural elements in comparison with traditional reinforced concrete, in older structures cracks may occur due to increasing service loads, concrete aging and deterioration. These main cracks will facilitate chloride ingress and might increase risk of corrosion initiation. Considering the age of existing bridges with prestressed beams, their current state, any possible deterioration and its effect, as well as the residual service life, need to be carefully assessed.

2 EFFECT OF CORROSION ON PRESTRESSED AND ORDINARY REBARS

Prestressed concrete beams usually consist of both, ordinary reinforcement (stirrups, additional longitudinal rebars) and prestressing high strength steel loaded in tension [2]. Prestressed reinforcement is mostly arranged as strands consisting of several small-diameter wires, twisted around each other. Considering the rather small size of a single wire (typically 4 mm), corrosion will rapidly lead to a relatively great reduction of the cross-sectional area, when comparing to large-diameter, ordinary bars [9], and thereby to a local increase of the already high stresses in the wire. Cross-section loss, particularly localised, will have significant impact on mechanical performance of both, prestressed and ordinary rebars.

Chloride-induced corrosion changes the steel reinforcement behaviour from ductile to more brittle, and this effect was observed for both types of reinforcement, ordinary and prestressed [3, 5, 6, 9]. The main cause of the reduced ultimate strain for ordinary bars is a substantial local loss of the cross section (pits). Risk of brittle failure is even more pronounced for corroded high strength steel, where fracture can occur due to different mechanisms than the usual chloride-induced corrosion. Sudden failure of the prestressing wire can be the result of stress corrosion cracking (SCC), hydrogen-induced cracking or hydrogen-induced stress corrosion cracking (HI-SCC) [3, 7]. That kind of damage in high strength steel takes place only if its surface has some defects: notches or sharp cracks [7]. Initiated pits can be considered as one of the material defects resulting in stress corrosion crack development.

In addition to a significant decrease in ultimate strains, degradation of other mechanical parameters of corroded, stressed wires can be observed [3]. Increased corrosion results in decreased yield and ultimate stresses, which are calculated from the applied load and residual cross-section in a pit location [3]. This phenomenon was not observed for true yield and ultimate stresses in ordinary reinforcement. While the nominal yield and ultimate strength for regular bars reduces with the degree of reinforcement corrosion, the true yield strength of all corroded and control bars had the same value, meaning that corrosion hardly alters the yield behavior of the steel [8]. Another parameter of prestressed steel affected by corrosion is the apparent Young's modulus [3]. A decrease in the elastic modulus and yield limit was explained by material damage due to the evolution of microcracks and microvoids in wire exposed to SCC.

The mechanical behaviour of corroded prestressing reinforcement, as well as its maximum mass loss, is strongly dependent on the stress level. According to [3], for wires loaded up to 80% of the yield strength f_y, the loss of mass was 10-15% higher than for unstressed ones. In addition, a reduction of the elastic modulus and yield strength was observed exclusively for stressed wires, while for unstressed wires only loss of ductility was detected [3]. Moreover, only for high levels of stress, brittle failure of prestressed wires was induced by SCC [3]. Experiments in [3] revealed, that for wires loaded up to 70% of f_y no brittle failure occurs. Similarly in [9], no brittle fracture was observed for stresses equal to 63% of ultimate tensile strength (less than 80% of f_y), although the failure mode changed to less ductile. It seems that the stress level has a high influence on the mechanical performance of corroded prestressed reinforcement, and its increase leads to a decrease of the wire's service life [3]. It needs to be mentioned, that except environmental conditions and stress levels, the behaviour of prestressed reinforcement depends also on its metallurgical properties [7]. That is why mechanical properties need to be carefully assessed for relevant types of steel.

Nevertheless, severe chloride-induced corrosion, under certain loading conditions, may result in sudden, brittle failure of prestressing wire, leading to a reduction of prestressing force and bending stiffness of the element [3, 4]. Moreover, as local pitting does not affect the overall tension in the wire [3], corrosion damage may not be detectable in structural members before a brittle failure occurs [4]. In addition to the loss of cross section and the degradation of mechanical properties of corroded prestressed steel, also a degradation of the bond need to be taken into consideration when assessing structural behavior of PC.

3 HULVÅGBRUA AS PC BEAM BRIDGE IN NORWAY – CASE STUDY

Hulvågbrua is one of the eight road bridges belonging to Atlantic Road, which is part of Norwegian national road 64 (Rv 64) in Møre og Rømsdal. The bridge was built in 1987 [1], and opened for traffic in 1989. Hulvågbrua is placed between small islands in Norwegian Sea, only four meters above the waterfront, and is exposed to extremely aggressive marine environment. The main structure of the bridge consists in total of thirty six prestressed and precast longitudinal NIB beams (4 in cross-section), with maximum span length 26.56 m [1]. A reinforced concrete (RC) plate is placed on top of the NIB beams and designed as a composite. The I-shaped PC beams are made of C55 concrete, high strength prestressed strands, and ordinary reinforcement [2].

When assessing the load-bearing capacity of the PC, both concrete and steel deterioration need to be reliable evaluated, based on inspection and tests data. Degradation of concrete, bond, loss of the steel cross-section and possible reduction of mechanical properties of prestressing and ordinary steel need to be taken into account. Stresses in steel wires depend on loading conditions. Moreover, they are changing in time due to steel relaxation, concrete creep and shrinkage, possible increase in service loads, and concrete deterioration (particularly cracking). The stress level is also one of the major parameters affecting cross-section loss (due to corrosion) and mechanical behaviour of corroded prestresses steel. The relation between time-dependent environmental, material and loading conditions makes modelling of PC long-term performance complex. That is why the prediction of the residual service life and load-bearing capacity will be analysed with nonlinear finite element modelling.

Table 1 –Pre-stressed, NIB beam bridges in Norway, in harsh coastal environment [1].

No.	Bridge	Location	Year of construction	Length [m]
1	Rong II	Hordaland	1972	22.7
2	Skrubbholmsundet	Hordaland	1989	25.4
3	Dampleia	Møre og Romsdal	1986	161.0
4	Hulvågbrua	Møre og Romsdal	1987	208.0
5	Myrbærholmbrua	Møre og Romsdal	1987	87.0
6	Hestøysundet bru	Møre og Romsdal	1987	69.5
7	Geitøybrua	Møre og Romsdal	1988	45.0
8	Storlauvøybrua	Møre og Romsdal	1988	45.5
9	Litllauvøybrua	Møre og Romsdal	1988	116.5
10	Askjesundet	Rogaland	1991	170.0
11	Herdlevær	Hordaland	1979	103.0
12	Søre Vetterhusstraumbrua	Nord-Trøndelag	1986	23.0
13	Mastadsvaet	Sør-Trøndelag	1992	153.5

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