Natural corrosion effects on prestressed beams failure modes

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Abstract

Research carried out on the load-bearing capacity of naturally corroded beams in laboratory tests and existing structures is presented and analysed. Load tests were performed on short span pretensioned beams that experienced corrosion under service loads in two different industrial environments for 25 years. Prestressed beams from a decommissioned bridge after 40 years of service life with chloride attack were tested to failure. Different failure modes are analyzed using non linear finite element (NLFE) modelling and limit state models. Flexural and shear-bond failure are shown and analysed for prestressed beams with shear reinforcement. The results show that flexural failures can be predicted with simple resistance models and an estimate of the maximum cross-section loss. Lab tests show that bond-shear failure must be considered in corroded prestressed beams; these have been analysed by a NLFE model, but models for the bond deterioration and this structural limit state are not yet available.

1 Introduction

The assessment of corroded structures requires knowledge of the structural response and failure modes of deteriorated members, that may differ from those of non deteriorated structures. Focusing on real *in situ* conditions requires the study of natural corrosion effects, because the related electrochemical processes, type of oxides, damage distribution and cracking differ from research carried out in the past decades, typically using artificial accelerated processes. Moreover reinforced concrete members were studied in the majority of cases. Long duration lab tests in natural conditions and on existing structures are very rare, even more so for prestressed structures; examples of these are presented and analysed in this study, in relation to their response and failure.

Analytical models for use in assessment and reliability evaluation are needed, including phenomena that may show only for deteriorating structures. While advanced non linear finite element analyses provide a useful tool to interpret test results (Coronelli et al., 2009), more simple resistance models are needed for reliability calculation and limit state verifications (Coronelli, 2021). The former are here used for beams tested in a laboratory and the latter for full-scale bridge beams tested to failure.

2 Experiments

2.1 Laboratory tests

Tests were carried out at INCERC in Cluj Napoca (Romania) on naturally corroded prestressed beams (Fig. 1) exposed for 10-12 years [1] and 25 and 27 years to two industrial environments, under load with a constant bending moment in the span. Ordinary concrete (OS) or lightweight concrete (US) were used. Each specimen was reinforced by two prestressing strands, top ribbed bars and stirrups (Fig1a).

Reinforcement corrosion was measured with gravimetric loss measurement, removing the strands after the load test; the generalized cross-section loss ranged 2-5% (chloride attack) and 1-12% (nitrogen attack). Four point bending load tests were carried out (Fig1a). The mean capacity deterioration (Fig.1c) in a chloride environment was 12% for OS and 21% for US specimens. For the nitrogen environment, the deterioration for OS was 11% with a protective coating, and 18% without protective coating; the deterioration for US 14% with a protective coating and 19% without protective coating.

The most numerous failure modes were flexural (Fig.2a); shear-bond failure (Fig.2b) occurred in specimens with nitrogen attack and the maximum cross-section loss, with the minimum resistance and deflection. Complete spalling of the corner cover occurred, and the exposed prestressing reinforcement showed corrosion on the whole length. Diagonal shear cracks formed connecting one load point to the support.

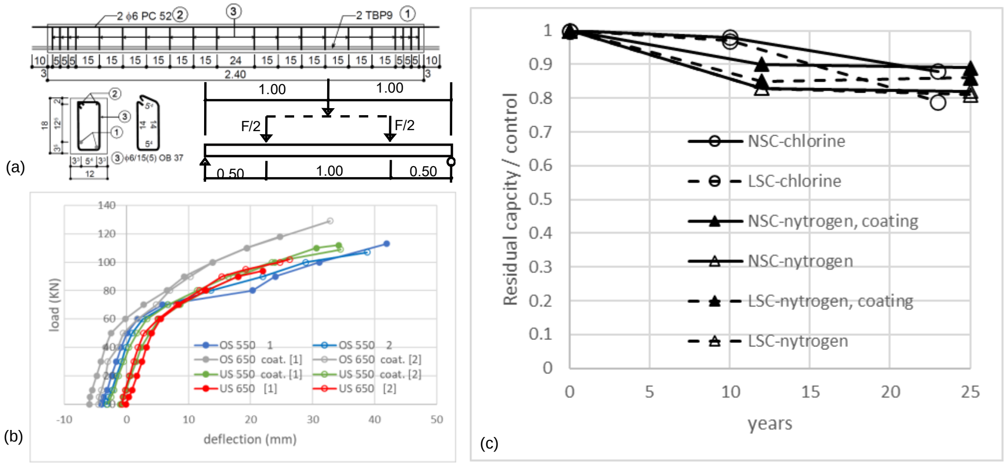


Fig. 1 Laboratory beams (a) geometry and test scheme (m); (b) load-deflection diagrams, beams with 25 years of nitrogen attack (coat. = coating); (c) capacity deterioration, including 10 years tests [1].

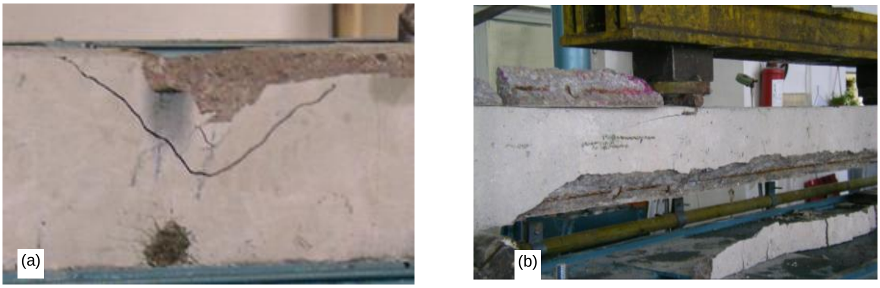
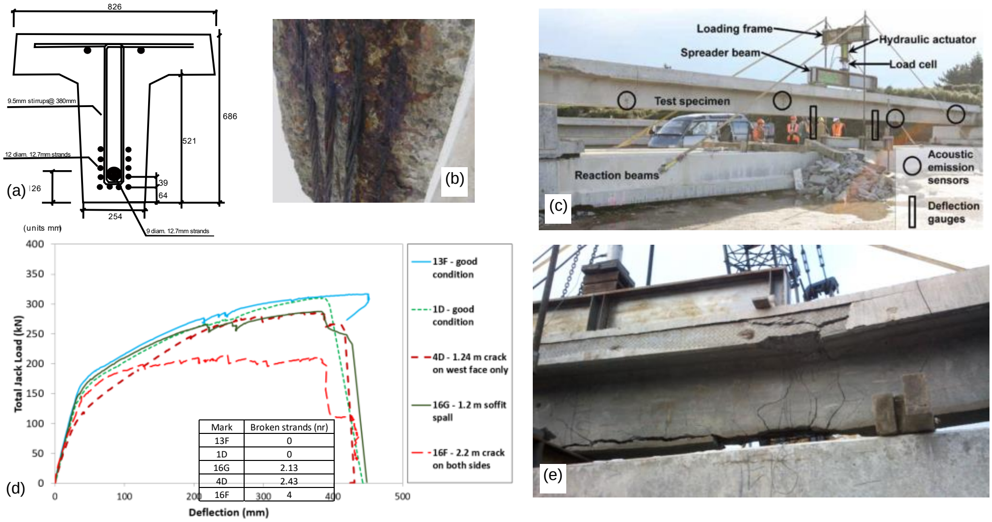


Fig. 2 Failure modes: (a) flexural and (b) bond-shear (US 650 [2] in Fig.1b).

2.2 Bridge beams



Mark	Broken strands (nr)
13F	0
1D	0
16G	2.13
4D	2.43
16F	4

Fig.3 Bridge beams [2]: a) cross-section; b) corrosion of bottom strands c) test setup; d) load-deflection; e) delamination in heavily corroded zones, load test at failure.

Load tests [2] were carried out on 18m span corroded prestressed beams from the 40 year old decommissioned Tiwai bridge (NZ) in a marine environment. Reinforcement included pre- and post-tensioned strands (Fig.3a). A corrosion survey was carried out with both visual observation and NDT techniques. The cover was either cracked or spalled for lengths approximately 1-2m in different specimens. Corrosion affected mainly the four bottom strands; after the test to failure the number of strands and wires that were corroded was reported.

Load tests results for one series of beams are shown in Fig.4. Delamination of the cover in the corroded zone occurred at low displacement. The reduction of resistance was closely related to the observed deterioration. The highest capacity deterioration was for Beam 16F, with 4 of 12 pretensioned strands fully corroded.The failure mode was flexural or combined shear and flexure close to the load. The failures showed cracks extending from the corroded zone to join the load points.

3 Modelling

3.1 Finite element modelling

Finite element analyses were used for the beams of the INCERC tests (§2.1). The model [3] includes separate concrete, reinforcement and bond contact elements. Non linear material models are used, considering corrosion effects on cracked concrete compressive strength and the parameters of the bond stress-slip relation. Generalised corroded strand cross section loss was input. Bond deterioration was determined based on tests on strands [3], and the bond strength was reduced in the bond stress-slip model. No reduction of the steel ultimate deformation was considered, as information on localised corrosion was not available. The failure mode predicted for the maximum corrosion (Fig.4) shows the formation of shear cracks with high values of slip of the reinforcement in the shear span, indicating bond break down (see also Fig.2b).

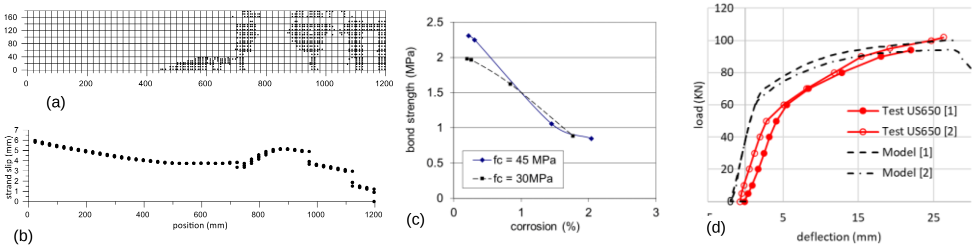


Fig. 4 Model vs. test results, lab test beams: (a) cracking (vs Fig.2b); (b) reinforcement slip after failure; (c) bond deterioration tests on strands [3]; (d) load-deflection diagrams, with model predictions vs tests.

3.2 Flexural Resistance model

A limit state model for flexural strength is used, considering the residual non-corroded reinforcement at the maximum load effect section. The critical section for flexure in the tests is at midspan, while the position of the zones with maximum corrosion was in the shear span and varied in each beam. It is assumed that the propagation of splitting cracks along the corroded strands and delamination during the load test, led to bond break-down, and the ensuing increase in tension led to rupture of the strands before the beam failure took place. Hence only the sound reinforcement cross section is input in the model. Perfect bond, plane sections and plastic unfactored material properties are used. The steel model is elastic perfectly plastic. The no-tension concrete stress-strain in compression is parabolic followed by a plateau. A strategy to predict the cross section loss *in situ* based on the observation of corrosion cracking and electro-potential mapping was proposed by [2]. In the model the number of corroded strands and wires found broken after the test (Fig.5a-b) is subtracted from the total tension steel cross section.

(a)

Mark	Broken strands (nr)
13F	0
1D	0
14G	0
3C	0
16G	2.13
4D	2.43
21F	3
3D	3.3
16F	4
18E	4
2C	4

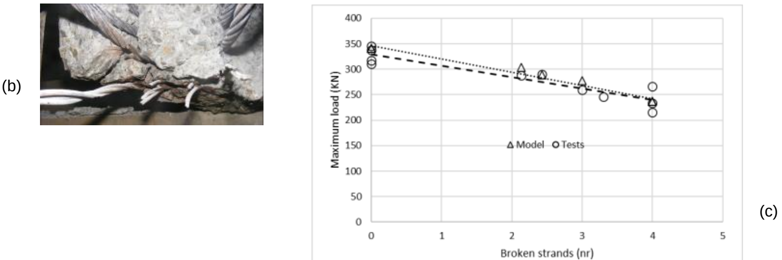


Fig.5 - Bridge beam tests: (a) cross-section loss; (b) example of broken reinforcement for beam 16F; (c) model and test results for maximum load.

Results of the maximum load predicted by flexural resistance model are shown in Figure 5c, compared to the experimental value. The average model to test ratio is 1.03 with a standard deviation 0.07. It can be noted that the standard deviation is lower for the lower corrosion tests (0.03) while it increases for the maximum attack (0.10).

4 Conclusions

Tests to failure for naturally corroded specimens have been presented, both for laboratory tests on beams with 25 years of exposure and corrosion in industrial environments and girders from an existing bridge decommissioned after 40 years in marine exposure.

The capacity deterioration was different in function of the industrial environment, reaching a maximum of approximately 20% in 25 years. For the bridge beams, the most deteriorated specimens in a set deteriorated more than 30% of capacity in 42 years.

Corrosion of strands and the related cracking or spalling and delamination caused different effects according to the members taken into consideration. The predominant type of failure was flexural with concrete crushing and plastic deformations of the reinforcement, both in the lab specimens and the bridge beams. The former type of tests showed sudden shear-bond failures as well, with the cover spalling contemporarily, for a corrosion level of approximately 10%. Although spalling occurred during the bridge beam tests as well, ductile flexural response was observed in all cases, with the loss up to 20% of the main prestressing reinforcement cross-section.

The numerical analyses show that the occurrence of the shear failure can be predicted by varying the bond properties of the corroding strands and considering the reinforcement cross-section loss. This demonstrates the relevance of bond deterioration it the response, and the need to consider this in appropriate resistance models for limit state verifications – that are though not yet available.

The failure of the bridge beams was predicted by a simple flexural strength model for the mid-span cross-section; the input was the reduction of reinforcement equal to the strands affected by corrosion. The estimation of the maximum cross-section loss is crucial for the results of the simple model. Due to the bond break down the verification of the maximum load effect at midspan must consider the reinforcement loss in positions different from the mid-span.

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