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THE DEPARTMENT OF THE ENVIRONMENT
FOR NORTHERN IRELAND

The Assessment of Concrete Structures affected by Steel Corrosion

Summary: This document provides guidance on the strength assessment of concrete structures affected by steel corrosion.

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REGISTRATION OF AMENDMENTS

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VOLUME 3 HIGHWAY STRUCTURES: INSPECTION AND MAINTENANCE

SECTION 4 ASSESSMENT

PART 13

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THE ASSESSMENT OF CONCRETE STRUCTURES AFFECTED BY STEEL CORROSION

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1. INTRODUCTION

General

1.1 Reinforced and prestressed concrete bridges suffer damage due to corrosion of steel reinforcement. This Advice Note considers the effect of steel corrosion on the strength of concrete bridges and provides guidance for the assessment of structures affected by reinforcement corrosion.

1.2 The normal mechanism by which concrete protects embedded reinforcement and prestressing steel is "passivation", which involves the formation of a passive oxide layer on the surface of the steel.

1.3 Passivation can be broken down by at least two effects; the first of these is carbonation which is a chemical reaction between the cement paste and the carbon dioxide in the air and has the effect of reducing the alkalinity of the concrete. The second is the presence of chloride ions.

1.4 Carbonation is a relatively slow process and has not posed significant problems for the Overseeing Organisation's bridge stock. Corrosion resulting from chloride penetration, however, is less predictable and usually proceeds faster. In recent years a considerable number of bridges in the UK have been found to be suffering from corrosion of reinforcement, mainly as a result of the effects of de-icing salts. Post-tensioned bridges with inadequately grouted ducts have been found to be particularly susceptible to tendon corrosion. A programme of Special Inspections for this type of structure has been undertaken. See BA 50, (DMRB 3.1.3) for planning, organisation and methods for carrying out the Special Inspection of post-tensioned bridges.

1.5 Although severe corrosion will eventually call for remedial action, limitations on resources may make it desirable to keep structures with significant corrosion in service for considerable periods of time. It is therefore necessary to assess the strength and safety of affected structures. This document gives advice on such assessments.

Scope

1.6 This Advice Note gives guidance on the quantification of corrosion in steel reinforcement and prestressing tendons in structures being assessed, and provides criteria to determine their strength.

Implementation

1.7 This Advice Note should be used in all future assessments of structures or structural elements where corrosion of reinforcement or prestressing tendons is suspected. It should also be taken into account in assessments currently in hand unless, in the opinion of the Overseeing Organisation, this would result in an unacceptable additional expense or delay.

1.8 This Advice Note is to be read in conjunction with BD 44 (DMRB 3.4), BA 44 (DMRB 3.4), BA 38 (DMRB 3.4.5), BA 50 (DMRB 3.1.3) and BA 35 (DMRB 3.3.3).

2. NATURE AND EXTENT OF CORROSION

Mechanisms of Corrosion

2.1 Steel corrosion takes two main forms; local and general with a variety of gradations between them.

2.2 Local corrosion takes place when there is considerable spatial variation in the distribution, at reinforcement level, of the chloride concentration and where conditions of moisture and oxygen supply are favourable. It is an electrochemical reaction and can lead to localised section loss by pitting corrosion. In some situations the corrosion product can be accommodated in the paste without disrupting the concrete cover. Because of this, the reaction can be difficult to detect visually.

2.3 General corrosion leads to much less local section loss but produces larger quantities of corrosion product, an expansive process which leads to spalling and rust staining. As the structural effects of the two types of corrosion are different, they are treated separately in this document. It should be noted, however, that the distinction is not completely clear cut. In particular, large amounts of local corrosion tend to lead to general corrosion. Consequently the presence of general corrosion should not be taken to indicate the absence of significant local corrosion.

Corrosion of Reinforcement

2.4 General corrosion will normally be apparent from rust staining, spalling and cracking. The major strength loss from general corrosion is due to the loss of bond and the spalling which it causes. The strength loss is not directly related to the reinforcement section loss and consequently it is not necessary to quantify the section loss due to general corrosion. However, if the strength of the structure is very sensitive to loss of steel area, it is desirable to expose some corroded bars to check that the steel is not suffering from significant loss of section.

2.5 Local corrosion is difficult to detect. Indirect methods, such as half-cell potential, resistivity and chloride gradient readings, only give an indiction of a risk of corrosion. Where these methods indicate a high risk and the structure is sensitive to local loss of section, it will be necessary to expose some bars to check if local corrosion is actually happening. The section loss of the steel area should be estimated. Test results show that the loss of strength is not directly proportional to loss of section; it can be substantially less. For assessment purposes however, it will generally be necessary to assume that the loss of strength is proportional to the estimated loss of area; the effective cross-sectional area of corroded bars being determined in accordance with the guidelines in Appendix A of BA 38 (DMRB 3.4.5). Alternatively, corroded bars can be tested for strength. In this case, an uncorroded section of bar should also be tested. A relationship between estimated section loss of area and strength can then be established.

2.6 Although local corrosion may not reduce the static strength of bars as much as the loss of section suggests, it may have a disproportionately large effect on fatigue strength. Where bars subjected to significant live load stress range are suffering from local corrosion, they should be checked for fatigue in accordance with BA 38 (DMRB 3.4.5).

2.7 Local corrosion tends to be very variable throughout the length of the member. A random distribution of even quite severe local corrosion may have little effect on strength. However, a similar amount of corrosion concentrated at particular sections may have a large effect.

2.8 An assessment can reflect the strength of the structure at the time of inspection. It will, however, be necessary to assume that the assessment will be valid for a significant period. It is, therefore, necessary to make some allowance for future deterioration. Such allowance should be for deterioration up to the time when the next Principal, Special or Monitoring Inspection is undertaken. The requirements for such inspections or other bridge management measures, eg replacement, should be clearly recorded in the Structures File. This should always be referred to prior to carrying out any inspection or assessment. Where such records are already available, an indication of the rate at which deterioration is progressing, may be obtained.

Corrosion of Prestressing Tendons

2.9 Significant corrosion of pretensioned tendons, where the concrete is placed directly against them, is relatively rare and can be detected and quantified in the same way as that in reinforcement.

2.10 The corrosion of conventional ducted post-tensioned tendons is difficult to detect by direct methods. For methods of inspecting structures with grouted duct post-tensioning, see BA 50 (DMRB 3.1.3) 'Post-tensioned Concrete Bridges; Planning Organisation and Methods for carrying out Special Inspections'. It should be noted that the deflection of structures which are prestressed with bonded tendons is not sensitive to local corrosion. Because of this, deflection measurements, even in load tests, cannot be used as a means of detecting tendon corrosion except possibly in structures in which the tendons have become entirely unbonded.

2.11 Tendon force, and hence concrete stress, will not be affected by loss of tendon area due to local corrosion until individual wires break. For this reason any measured loss of prestress attributed to loss of tendon area will give an under-estimate of the loss of tendon strength. Allowance for this should be made in the assessment.

3. STRENGTH ASSESSMENT

Local Corrosion of Reinforcement

3.1 Local corrosion causes significant steel section loss. Unless test results indicate otherwise, it will be necessary to assume that the strength loss is proportional to the estimated section area loss. Individual elements can then be assessed for shear and flexural strength in accordance with BD44 (DMRB 3.3), ignoring the steel area in both flexural and shear reinforcement which is assumed to be lost.

3.2 Local corrosion concentrates the area over which reinforcement yields. Because of this it effectively reduces the ductility of reinforcement. For this reason bars which are assumed to be suffering from local corrosion should not be considered effective in plastic analyses, such as yield line analysis, unless tests on corroded bars show them to still have the ductility required by BS 4449 for the equivalent grade of steel.

General Corrosion of Reinforcement

3.3 Where general corrosion is very severe, sectional loss should be estimated as for local corrosion. In most cases, however, the loss of steel area will not be significant. The loss of strength due to general corrosion is mainly due to loss of bond and also spalling. Tests show that the loss of bond strength is not significant until the point where longitudinal cracks form over the bars. The bond strength of bars with longitudinal cracks over them should be reduced by 30%.

3.4 General corrosion is most likely to occur, and most likely to cause cracks over the bars nearest the surface, in regions where cover is low. Tests show that bond strength is reduced in regions of low cover. Where cover is less than one bar diameter and there are no links, the ultimate local and anchorage bond stress given in BD 44 (DMRB 3.4) should be multiplied by a factor of $\sqrt{(c/\phi)}$ where c is the actual cover provided to the bar under consideration and ϕ is the bar diameter. This reduction is in addition to other reductions required by BD 44 (DMRB 3.4) and the aforementioned allowance for corrosion.

3.5 When general corrosion becomes extensive, it leads to spalling and delamination. Where the cover concrete is spalling or delaminating over a significant area, the structure should be assessed ignoring the cover concrete in those regions. The bond with bars which are in the plane of delamination should also be ignored. The bars should also be ignored for the purposes of calculating the concrete shear strength, v_c, unless they are restrained by links which are still effective.

Corrosion of Prestressing Tendons

3.6 In contrast to reinforcement where loss of bond and spalling determines the residual strength, it is the direct effect of tendon corrosion on the loss of steel section which is likely to be important when assessing prestressed structures. The prestressing force will not be reduced by local corrosion and consequently local failures in wires or strand may occur once the corroded tendon strength is reduced to the prestress force. For this reason, wires which are assumed to have lost more than 40% of their area locally should be considered ineffective.

3.7 Fully grouted tendons, strands or wires which are ineffective locally, can re-anchor and become effective elsewhere. In post-tensioned concrete construction, the anchorage length required will depend on the quality of grouting. Figures for likely re-anchorage lengths are given in Reference 2. Where the grouting is good and where the tendons are surrounded by at least the nominal links required by BS 5400: Part 4, (see Clause 6.8.5), the re-anchorage length may be taken as the transmission length given by Clause 6.7.4 of Part 4 multiplied by the square root of the number of strands in the tendon. This gives a conservatively high estimate for the re-anchorage length.

3.8 Where the grouting is poor, or where the links provided are less than minimum required by BS 5400: Part 4, assessments which depend on re-anchorage should not be undertaken without special investigation.

3.9 Once the loss of effective tendon strength at a particular section has been estimated, the strength of the section can be calculated in the normal way.

Slabs

3.10 The assessed carrying capacity of reinforced concrete slabs is not normally sensitive to localised corrosion. This is because their strength is a function of the average strength of reinforcement over significant widths of slab; they are not sensitive to the strength of individual bars. Unless there are reasons for believing that localised corrosion is concentrated at particular sections they do not normally require special consideration except when plastic analysis is used (see 3.2).

3.11 Because of the effects of membrane action, a phenomenon by which restrained reinforced concrete slabs fail at a load which may be several times greater than simply supported slabs, the assessed carrying capacity of deck slabs in beam and slab bridges is particularly insensitive to reinforcement strength. They will therefore not normally require special consideration unless there is evidence of delamination caused by general corrosion.

Segmental Construction

3.12 The tendons in segmental post-tensioned structures are particularly vulnerable to corrosion at the joints. This means that any tendon corrosion is likely to concentrate at these sections and consequently leads to a much greater risk of significant loss of strength than in monolithic structures. If the loss of tendon area at a particular section is known, the effect on the strength of the structure can be estimated from the loss of tendon area in accordance with 3.6.

3.13 In bonded segmental structures, because the loss of effective prestress can be very localised, concentrated at joints, the overall stiffness of the structure is not significantly affected by tendon force loss. Deflection readings are not a good indicator of tendon force loss as there may be little effect on deflection until the structure is close to collapse. See also BA 50 (DMRB 3.1.3).

Future Deterioration

3.14 In assessing the strength of a structure with corroded reinforcement or prestressing tendons, allowance should be made for possible future deterioration. See 2.8. In doing so, the engineer will have to estimate the anticipated corrosion rate. However, the actual corrosion rate may be extremely variable. Where a structure has a significant level of reinforcement or tendon corrosion, it should be monitored by Special Inspections to determine whether deterioration has occurred in addition to that which has been allowed for in assessment. A programme of monitoring should be established to enable the progress of any deterioration to be recorded and checked against that allowed for in the structural assessment.

4. REFERENCES

1 Design Manual for Roads and Bridges. Volume 3 Section 4.

BD 44 The Assessment of Concrete Highway Bridges and Structures (DMRB 3.4.14)

BA 44 The Assessment of Concrete Highway Bridges and Structures (DMRB 3.4).

BA 38 Assessment of the Fatigue Life of Corroded or Damaged Reinforcing Bars. (DMRB 3.4.5)

BA 50 Post-tensioned Concrete Bridges, Planning, Organisation and Methods for Carrying out Special Inspections (DMRB 3.1.3)

BA 35 Inspection and Repair of Concrete Highway Structures (DMRB 3.3.3)

2. Buchner SH and Lindsell P. Structural Assessment: the use of full and large scale testing. London. Butterworths 1987. pp. 46-54, Editors Garas F K, Clarke J L and Armer G S T.

3. Jackson PA. The effect of local corrosion on the life of bridge decks slabs. The life of structures; physical testing. London. Butterworths 1989. pp. 360-367. Editors Garas F K, Clarke J L and Armer G S T.

4. BS4449 Carbon Steel Bars for the Reinforcement of Concrete. BSI, 1988.

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