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RELATIONSHIP BETWEEN CORROSION AND ELEMENT SEVERITY SCORE FOR REINFORCED CONCRETE BEAMS

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Guidance for highway bridge and structure maintenance management in the UK is provided by the code of practice (CoP) 'Management of Highway Structures'. With regards to inspection of reinforced concrete beams in accordance with the code, the professional judgement of the bridge engineer is required to assess the extent and severity of deterioration with help from a library of different defects. The Extent of the defects is rated A – E whilst the Severity is scored 1 – 5, giving an Extent and Severity score for each element, known as the element condition score. However, the Code does not provide information on the corresponding levels of corrosion in the steel reinforcement in the damaged beam. The purpose of this paper is to relate the element severity scores for a range of damaged reinforced concrete beams to approximate levels of corrosion of the main steel, thereby giving the bridge inspector an understanding of the seriousness of corrosion for each of the five Severity scores.

Keywords: Management of Highway Structures, Code of Practice, Deteriorated Reinforced Concrete Beams, Severity Score, Corrosion

1 INTRODUCTION

The increasing age of the highway bridge stock has led to increased deterioration in existing structures. Surveys have indicated that the main reasons for deterioration, besides normal wear and tear, are the increasing weights and volume of traffic using the road network, and adverse environment conditions such as exposure to chlorides and freeze-thaw attack. Effective maintenance is required to ensure that the bridges are kept in safe service at optimum cost. Reliable assessment methods are key to assisting the bridge engineer in evaluating the residual strength of deteriorated elements due to deterioration.

A sound concrete cover provides a direct barrier preventing degradation substances (chloride ions, carbon dioxide) from reaching the surface of the rebar. High alkalinity in concrete pore solution chemically protects the embedded bar against corrosion. However, premature deterioration caused by reinforcement corrosion is increasingly being reported. In general, corrosion is caused by the destructive attack of chloride ions penetrating by diffusion (and/or other penetration mechanisms) from the outside or by incorporation into the concrete mixture during construction. Carbonation, on the other hand, reduces the high protective alkalinity of the concrete.

When steel reinforcement corrodes, tensile stresses are generated in the concrete as a result of the expansive corrosion products. Since concrete can endure much less tensile stress than compressive stress, tensile cracks are readily nucleated and propagated as a result (O'Flaherty et al 2008a). The development of corrosion products along the bar surface may affect the failure mode and ultimate strength of flexural members due to two causes: firstly, due to a reduction in the degree of bar confinement caused by an opening of longitudinal cracks along the reinforcement and, secondly, due to significant changes at the steel-concrete interface caused by changes in the surface conditions of the reinforcing steel (Mangat and O’Flaherty 1999, Mangat and O’Flaherty 2000). In all corrosion cases, repair is necessary to increase the service life of the member and it is estimated to cost approximately €1.5bn in Europe each year (Davies 1996).

2 RESEARCH SIGNIFICANCE

Guidance for highway bridge and structure maintenance management in the UK is provided by the 'Management of Highway Structures' Code of Practice (CoP). With regards to inspection of reinforced concrete beams in accordance with the Code, the professional judgement of the bridge engineer is required to assess the Extent and Severity of deterioration with guidance from a library of different defects. The Extent of the defects is rated A – E whilst the severity is scored 1 – 5, given an extent and severity score for each element, known as the element condition score. However, the code does not provide information on the corresponding levels of corrosion in the steel reinforcement in the damaged beam. The purpose of this paper is to relate the element severity scores for a range of damaged reinforced concrete beams to approximate levels of corrosion of the main steel, thereby giving the bridge inspector a better understanding of the condition of the corroded reinforced concrete within the deteriorated reinforced concrete member.

3 INSPECTION MANUAL FOR HIGHWAY STRUCTURES

The purpose of the CoP is to provide guidance on the inspection process for all staff involved in the management of highway structures. The manual is divided into two separate volumes. Volume 1 is a reference manual and covers all aspects of highway structures inspection, and, in particular, Part D deals with 'Defects, Descriptions and Causes' (Highways Agency 2007a). Section 3 within this part deals with Concrete Defects. Table 1 reproduces the generic severity descriptions and is used as a primary source for defining severity. Volume 2 is an inspector handbook and acts as a quick reference for inspectors on site (Highways Agency 2007b). Part B in Volume 2 provides a library of photographs illustrating some of the different types of defects that are likely to be encountered on highway structures. Although a library of photos is given which illustrates the some of the different types of defects encountered (in this case, deterioration due to corrosion), a relationship between the level of corrosion and cracking/rust staining is not given, hence the inspector will not be able to appreciate the level of corrosion that potentially is present, especially in beams with high Severity scores.

Table 1. Severity Codes.

Code	Description
1	As new condition, defect has no significant effect on the element (visually or functionally)
2	Early signs of deterioration, minor defect/damage, no reduction in functionality of element
3	Moderate defect/damage, some loss of functionality could be expected
4	Severe damage/defect, element no longer able to entirely fulfil its function and/or is close to failure/collapse
5	The element is non-functional/failed

4 METHODOLOGY

A total of thirty-eight reinforced concrete beams were cast in the laboratory and the main steel reinforcement was corroded to differing degrees of steel loss via an accelerated process. Beams were 910 mm long with a cross-section of 100 mm x 150 mm deep. All specimens were detailed for flexural failure; sufficient links were provided to ensure adequate shear capacity at the anticipated maximum load of the corroded beam. Main reinforcement consisted of high yield (ribbed) bars with a nominal characteristic strength of 460 N/mm^2. Shear reinforcement was 6 mm diameter plain round mild steel bars with a yield strength of 250 N/mm^2. Hanger top bars for all beams consisted of two 6 mm diameter plain round mild steel bars with a yield strength of 250 N/mm^2. The steel reinforcement was weighed before casting to enable the actual percentage corrosion to be calculated at a later stage. Test specimens were cast in the laboratory using a concrete with target cube strength of 40 N/mm^2. Mix proportions were 1:1.7:3.8 of Portland cement: fine aggregate: coarse aggregate. Fine and coarse aggregates were oven dried at 100°C for 24 hours. Calcium chloride ($CaCl_2$) was added to the mix (1% by weight of cement) in order to promote corrosion of the reinforcement. The material was placed in steel moulds in three layers, each layer being carefully compacted on a vibrating table. The specimens were then placed in the mist curing room (20°C and 95% ± 5% Relative Humidity) for 24 hours. The samples were demoulded after 1 day and cured in water at 20°C for a further 27 days (28 days in total). Specimens were then transferred to a tank filled with a saline solution for accelerated corrosion at 28 days age. The beam specimens were immersed in artificial seawater in a plastic tank at the end of the curing period. A 3.5% $CaCl_2$ solution was used as the electrolyte. The direction of the current was arranged so that the main reinforcing steel served as the anode and the hanger bars and the stirrups acted as the cathode, care being taken to isolate the cathodic steel from the anodic steel. A constant current density of 1 mA/cm^2 was passed through the reinforcement, the duration was dependent upon the target level of corrosion required (0%-20%+). This current density was adopted on the basis of pilot tests to provide desired levels of corrosion in a reasonable time. The relationship between corrosion current density and the weight of metal lost due to corrosion was determined by applying Faraday's law.

A sample of the thirty-eight reinforced concrete beams were graded in accordance with the codes and descriptions given in Table 1. Professional judgement was required to assign the sample of beams to each of the five codes, as is the case with a bridge inspector during a principal inspection and in conjunction with Volume 2 of the CoP. The beams were subsequently tested to failure in flexure. The steel reinforcement cage was then carefully removed from the concrete beam and the main steel re-weighed. The actual degree of corrosion was obtained by comparing the loss in weight to the original, uncorroded weight and calculated as a percentage loss in section.

5 RESULTS

Table 2 shows an example of a deteriorated beam assigned to each of the five severity descriptors from Table 1. The corresponding degrees of corrosion are given as a range as it is more representative of what would be encountered on site. Table 2 shows that a Code Level 5 beam would exhibit a degree of corrosion of the main steel greater than 20% with the other codes 4, 3, 2 and 1 exhibiting degrees of corrosion in the ranges 10%-20%, 7%-10%, 4%-7% and 0%-4% respectively.

It was reported previously by the authors that beams exhibiting main steel corrosion greater than 10% generally failed in flexure before reaching the service load (O'Flaherty et al, 2008b). Therefore, with safety in mind, beams in practice with main steel corrosion around 10% should be considered as reaching their serviceability limit state and repair and maintenance is required to extend their service life. Referring to Table 2, beams exhibiting 10% corrosion to the main steel would occupy Code Level 3 (Moderate defect/damage, some loss of functionality could be expected) but is not close to failure or collapse. Code Level 3 is the limit for a beam still to be performing in-service, Codes 4 and 5 describe beams which should not be expected to continue to perform in-service, they are either close to collapse or non-functional.

6 RECOMMENDATIONS FOR FURTHER RESEARCH

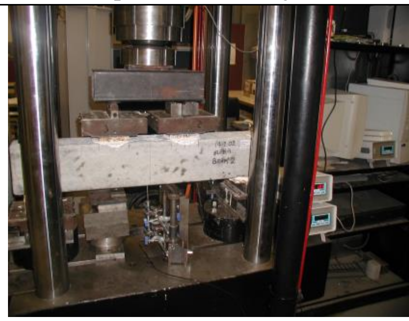
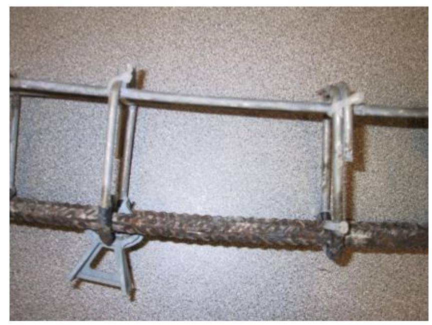
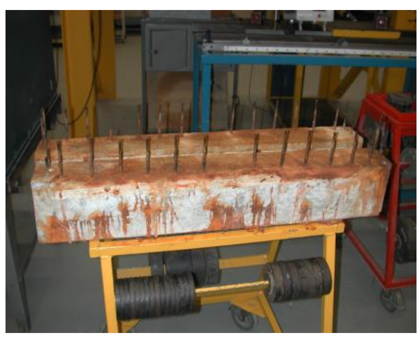
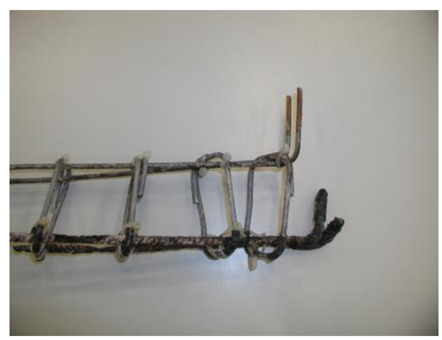
The two main types of bridge inspection in the UK are General Inspections, conducted every two years and Principal Inspection, conducted every six years. The General Inspection is normally conducted from ground level and is not intrusive, whereas the Principal Inspection is conducted at touching distance to the various elements of the bridge. Therefore, there is scope for correlating corrosion crack widths, obtained from in-service beams during the Principal Inspection, to the degree of corrosion in the main steel, obtained when the reinforcement is accessible prior to reinstatement of a new repair material. If sufficient data is gathered, an empirical relationship can be formed between the two.

7 CONCLUSIONS

The following are the conclusions emanating from the results presented in this paper:

- based on the professional judgement of the authors and outputs from previous research, it is proposed that a Code Level 5 beam would exhibit a degree of main steel corrosion greater than 20% with the Codes 4, 3, 2 and 1 exhibiting degrees of corrosion in the ranges 10%-20%, 7%-10%, 4%-7% and 0%-4% respectively.

Table 2. Deteriorated beams with corresponding degrees of corrosion

Code	Description	Examples of laboratory beams	Actual degree of corrosion %	
1	As new condition, defect has no significant effect on the element (visually or functionally)		0%-4%	
2	Early signs of deterioration, minor defect/damage, no reduction in functionality of element		4%-7%	
3	Moderate defect/damage, some loss of functionality could be expected		7%-10%	

4	Severe damage/defect, element no longer able to entirely fulfil its function and/or is close to failure/collapse		10%-20%	
5	The element is non-functional/failed	-	>20%	-

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