Correlation between the inspection manual severity codes and moment coefficient for deteriorated concrete beams

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CORRELATION BETWEEN THE UK INSPECTION MANUAL SEVERITY CODES AND MOMENT COEFFICIENT FOR DETERIORATED CONCRETE BEAMS

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Bridges form a vital part of any countries transport network. Roads users expect that these structures remain safely in-service day after day to enable travelers to complete their intended road journey without disruption. Concrete bridges in particular suffer deterioration due to the harsh environment that they are subjected to such as chloride attack from de-icing salts or carbonation attack due to the atmosphere. Inspection is, therefore, required to ensure that these structures are fit for purpose and safe to use. The UK Bridges Board has developed a comprehensive Inspection Manual to ensure all structures are uniformly inspected and to a high standard. The inspection process involves completing a proforma where defects are graded between 1 (no defect) to 5 (collapse). The inspector is able to use a table (Table G. 10) within the Inspection manual which provides guidance on severity descriptions for different construction materials. However, for reinforced concrete beams exhibiting main steel corrosion, the relationship between severity of defect and loss of strength is not quantitatively obvious. The paper gives the bridge inspector an appreciation of the loss of strength as a result of corrosion to reinforced concrete simply supported beams. The analysis is mainly concerned with the predicted loss at severity code 3 from the manual, which assumes moderate defect/damage, with some loss of functionality.

Keywords: Bridges, Corrosion, Main Steel Reinforcement, Residual Strength, Degree of Under-reinforcement, Eurocode 2

1 INTRODUCTION

Good infrastructure, such as bridges on the transport network, has a very high impact on any country's progress. Sometimes it is referred to as the 'lifeline' of a nation as economic growth depends on it. However, bridges are man-made and, therefore, are subject to deterioration throughout their lifetime. In a world where carbon emissions need to be minimized for everyone's benefit, bridges need to be maintained in a manner which not only supports everyday lifestyle, but is done so in a low environmental impact way. Bridge managers face many challenges in keeping their assets safe and in-service to avoid injury or fatalities in the case of collapse or on a lesser scale, severe disruption in the event of a bridge closure on safety grounds.

Roads users expect that these structures remain safely in-service day after day to enable travelers to complete their intended road journey without disruption. Concrete bridges, in particular, suffer deterioration due to the harsh environment that they are subjected to such as chloride attack from de-icing salts or carbonation attack due to the atmosphere. Inspection is, therefore, required to ensure that these structures are fit for purpose and safe to use.

The UK Bridges Board has developed a comprehensive Inspection Manual to ensure all structures are uniformly inspected and to a high standard. The inspection process involves completing a proforma where defects are graded between 1 (no defect) to 5 (non-functional or failed). The inspector is able to use a table (Table G. 10) within the Inspection manual which provides guidance on severity descriptions for different construction materials. Severity descriptions for concrete are listed under Item 2 which covers reinforced and prestressed concrete. Five different categories of defects are given, namely spalling, cracking, damage to prestressing, delamination and thaumasite/freeze-thaw attack.

To assist the bridge inspector in gaining an understanding of the impact of corrosion to the main steel reinforcement, the paper provides information on the residual strength of deteriorated reinforced simply supported concrete beams suffering defects classed under code 3 e.g. where moderate damage is evident but no risk of collapse in the current state. The paper enables the bridge engineer to be able to relate the degree of corrosion to a reduction in residual strength (moment coefficient). This will support more effective management and planning of the bridge stock.

2 INTRODUCTION TO INSPECTION MANUAL FOR HIGHWAY STRUCTURES

The Inspection Manual provides comprehensive guidance for bridge inspectors to assist them with their inspections (Highways Agency 2007a). Volume 1 is a reference manual and is split into five parts, Parts A-E followed by an Appendix section. Part D covers 'Defects, Descriptions and Causes' and Section 3 within this part gives advice on inspecting concrete defects. Five generic severity descriptions are given (see Table 1) which are used for defining severity of the defect. An inspector handbook (Volume 2, Part B) provides a quick reference for inspectors to aid the severity level for a particular defect (Highways Agency 2007b) as it contains a library of photographs which illustrates typical defects likely to be found on bridges. However, a relationship between the degree of corrosion and an appreciation of the loss in strength is not available. From the inspector’s point of view, an appreciation of the reduction in strength is outside the scope of the inspection but nevertheless, this paper will help bridge personnel to identify beams where the residual strength approaches dangerous levels.

Table 1. Severity codes in Highways Manual

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

3 METHODOLOGY

Forty reinforced concrete beams were designed and cast in the laboratory split across five series of beams, labelled Series 1-5. The number of beams in series 1-5 was 7, 9, 9, 7 and 8 respectively. The main steel reinforcement was subjected to differing degrees of steel corrosion from 0% (control) to 18% via an accelerated method. Beams had a cross-section of 100 mm x 150 mm deep and were 910 mm long. A sufficient number of links were provided to avoid shear failure (6 mm diameter plain round mild steel bars with a yield strength of 250 N/mm^2). The two hanger top bars consisted of the same steel. High yield (ribbed) bars with a nominal design yield strength of 460 N/mm^2 were specified. Further information on the mix proportions, casting, curing and accelerated corrosion process is given elsewhere (O’Flaherty & Browne, 2019).

A sample of the deteriorated main steel reinforcement were graded based on the severity descriptions presented in Table 1. In all cases, professional judgement was applied to assign the deteriorated beams to each of the five codes. The deteriorated concrete beams were then tested to failure in flexure. Following failure, the reinforcement cage was removed from the concrete beam, dismantled and the main reinforcement was re-weighed. The precise level of corrosion was obtained by comparing the weights both before and after and calculating the average loss in section as a percentage.

4 ANALYSIS OF DATA

4.1 Beam analysis in flexure

The current standard for design of reinforced concrete beams is EC 2 (British Standards Institution, 1992) which, like its predecessor (British Standards Institution, 1997), designs reinforced concrete beams as under-reinforced. The control beams in this research were rigorously analysed in accordance with EC 2 which included analytically determining the compression resisting moment ($M_c = 0.204f_{ck}bd^2$, unfactored) and experimentally determining the tension resisting moment from the deteriorated beams ($M_t = (0.25\ P_{ult}/2)$). The resisting moment in compression remains unaffected by the degree of corrosion but clearly the resisting moment in tension decreases as corrosion levels increase. The level of under-reinforcement was determined for a particular beam section using the ratio M_t/M_c, where M_t is the tensile resisting moment for the control (uncorroded) beam. The moment coefficient of the deteriorated beam, K_{corr} (= $M_{corr}/f_{ck}bd^2$) was also determined for all beams using the applied moment at failure (M_{corr}), the concrete cylinder strength, f_{ck} and the width and effective depth of the beam, b and d respectively. Detailed information on this analysis is given elsewhere (O'Flaherty & Browne, 2019).

4.2 Severity analysis

The severity codes given in Table 1 are aligned with typical examples of deteriorated reinforced concrete beams in the laboratory in Table 2. Using professional judgement, severity code 1 is assumed for beams with reinforcement corrosion levels between 0-4%, code level 2 is assumed to have corrosion levels in the range 4-7%, code level 3 is 7-10% and code level 4 is assumed when corroion levels are beyond 10%. Code 5 assumes failure has already taken place so this is omitted from Table 2.

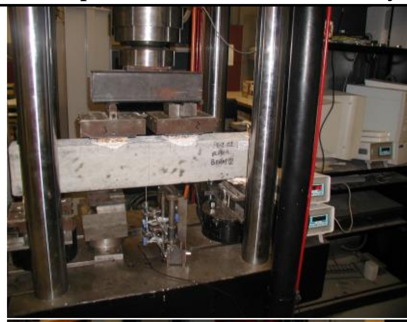
4.3 Influence of corrosion on moment coefficient, K_{corr}

Figures 1-5 show the relationship between degree of corrosion and reduction in the moment coefficient, K_{corr}, for five series of under-reinforced beams. The degree of under-reinforcement, β (= M_t/M_c) is varied for each beam series, ranging from 0.53 to 0.96. The four severity codes under consideration (Codes 1-4) are also shown on Figures 1-5 and are based on engineering judgement as described in Section 4.2. What is immediately obvious in Figures 1-5 is that the slope of the line of best fit changes from graph to graph meaning the degree of corrosion influences the performance of the under-reinforced beams in different ways. A line of best fit is also included in Figures 1-5 and shows satisfactory correlation. Figure 6 summarizes this effect using data from Table 3 as will be discussed shortly.

In terms of performance, previous research by the author (O'Flaherty et al 2008) suggested that when the degree of corrosion reaches 10% an intervention should be applied to ensure that the reinforced concrete beam does not pose a risk to road users. This correlates to the upper end of severity code 3. Therefore, to get an appreciation of the loss in moment coefficient as a result of an under-reinforced concrete beam suffering deterioration to severity code 3, the regression analysis from Figures 1-5 has been used to calculate K_{corr} at 0% corrosion (e.g. control beams) and at 10%, the assumed maximum limit of corrosion for severity 3. The analysis is summarised in Table 3. Referring to Table 3, the beam series is given in col. 1, the degree of under reinforcement is given in col. 2. The slope of the lines of best fit and intercepts are given in cols.

3 and 4 respectively. Cols. 5 and 6 show the values of K_0 at 0% and $K_{corr(10)}$ at 10% corrosion. The difference between them (ΔK) is shown in col. 7, which is also the loss in the moment

Table 2. Deteriorated beams with corresponding degrees of corrosion

Description	**Code**	**Examples of beams in the laboratory**	**Degree of corrosion %**	
As new condition, defect has no significant effect on the element (visually or functionally)	1		0-4%	
Early signs of deterioration, minor defect/damage, no reduction in functionality of element	2		4-7%	
Moderate defect/damage, some loss of functionality could be expected	3		7-10%	
Severe damage/defect, element no longer able to entirely fulfil its function and/or is close to failure/collapse	4		10%+	
The element is non-functional/failed	5	-		-

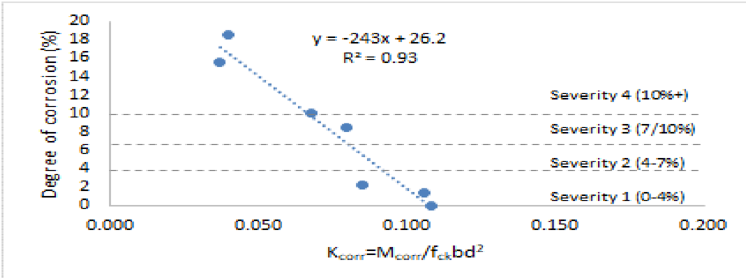


Figure 1. Beam Series 1, $\beta = 0.53$.

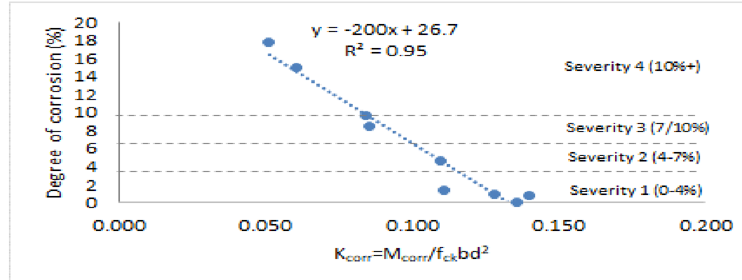


Figure 2. Beam Series 2, $\beta = 0.67$.

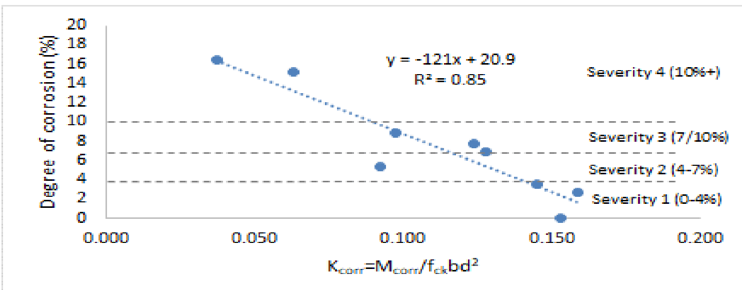


Figure 3. Beam Series 3, $\beta = 0.75$.

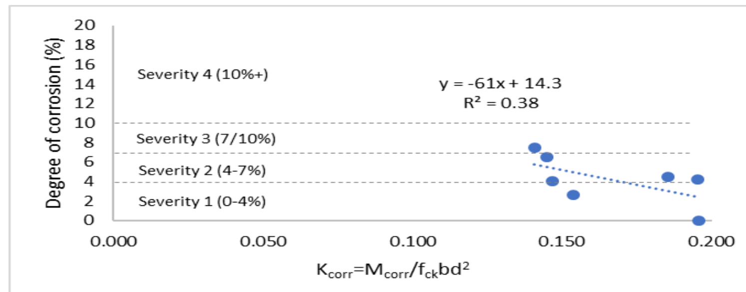


Figure 4. Beam Series 4, $\beta = 0.96$.

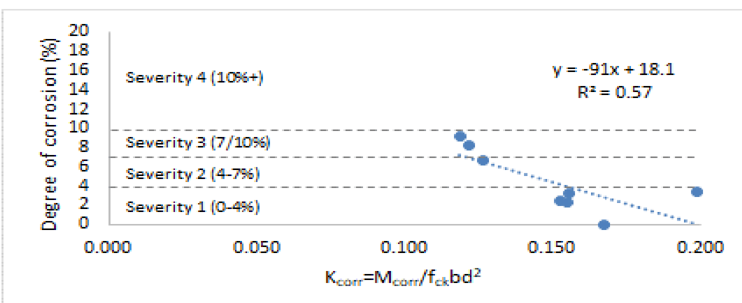


Figure 5. Beam Series 5, $\beta = 0.82$.

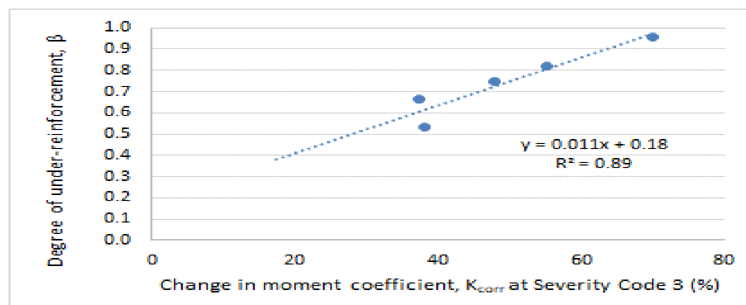


Figure 6. Relationship between β and loss in K_{corr} at severity code 3.

Table 3. Reduction of moment coefficient, K_{corr} at Severity Code 3

1	2	3	4	5	6	7	8
Series ID	**Degree of UR ($\beta=M_t/M_c$)**	**Slope (m)**	**Intercept (c)**	**K_0 (uncorroded)**	**$K_{corr(10)}$ (10% corrosion)**	**ΔK (K_0-$K_{corr(10)}$)**	**ΔK (%)**
1	0.53	-243	26.2	0.108	0.067	0.041	38
2	0.67	-200	26.7	0.134	0.084	0.050	37
3	0.75	-121	20.9	0.173	0.090	0.083	48
4	0.96	-61	14.3	0.234	0.070	0.164	70
5	0.82	-91	18.1	0.199	0.089	0.110	55

coefficient as a result of severity code 3 damage to the under-reinforced beams. The loss of moment coefficient is also shown as a percentage in col. 8. The relationship between degree of under-reinforcement, β and loss in moment coefficient, K_{corr} as a percentage for severity code 3 is given in Figure 6. Referring to Figure 6, it is clear that there is a higher loss in moment coefficient for reinforced concrete beams exhibiting higher β ratios (higher M_t/M_c ratios) but this reduces as β reduces.

5 DISCUSSIONS AND CONCLUSIONS

Although it is well known that corrosion to the reinforcement of concrete beams leads to a loss in ultimate strength, the bridge inspector will not be able to appreciate the precise loss in strength during an inspection. That task is for the bridge engineer to reassess the strength of the reinforced concrete beams using research findings such as those given in O'Flaherty & Browne, 2019. However, the information presented in this paper is unique in that it provides an appreciation of the possible loss in moment coefficient for beams adjudged to be at severity code 3 e.g. corrosion to the main steel reinforcement of about 10% (limit of moderate damage). In addition, it also relates the degree of under-reinforcement of the beam section to the loss in moment coefficient and it is shown that beams with a higher M_t/M_c ratios (β) exhibits a higher percentage loss in moment coefficient. For example, using the equation of the line of best fit from Figure 6 ($y = 0.011x + 0.18$), the loss in K_{corr} at $\beta = 0.9$ is 65 % but when $\beta = 0.5$, the loss reduces to 29 %. This is useful information for the bridge inspector in that they can appreciate the effect corrosion can have on the ultimate strength of a reinforced concrete beam and, therefore, be in a position to highlight potential risks to the public as a result of their inspection.

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