Statistical analysis of concrete cover in new highway bridges

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Abstract.
Quality control is one of the important aspects of any major construction works, that is to be undertaken to ensure work execution according to design requirements. The work presented in this paper involved measurement of cover thickness in three newly constructed highway bridges. Testing was conducted to ensure that specified requirements were attained prior to commissioning of the structures; otherwise, the quality control survey would identify problem areas for consideration of corrective measures.

A total of 328 data sets were obtained during cover measurements. In this paper, the results obtained are discussed and evaluated. Data are characterised on the basis of statistical quantities.

1. Introduction

Concrete cover to steel reinforcement in reinforced concrete structures plays a significant role related to the service life of structures. This thin layer of concrete, typically 20 to 40 mm [1,2], depending on the severity of the exposure environment, is largely responsible for providing protection against corrosion of reinforcement. Worldwide, steel corrosion is the most predominant deterioration problem in reinforced concrete structures. The primary causes of the corrosion are carbonation and chloride attack resulting from ingress of aggressive agents, CO_2 and chloride ions respectively. Concrete being non-metallic is, firstly, not subject to corrosion and secondly, the concrete matrix is highly alkaline with pH ranging from 12.6 to 13pH. At such a high pH, the steel embedded in concrete is protected and will not corrode. However, the ingress of CO_2/Cl^- ions causes loss of alkalinity, de-passivating steel and allowing corrosion to ensue. Clearly, the time taken for the aggressive agents to reach the level of steel is a defining point for service life of the structure.

It should also be considered that the concrete cover quality is usually a vulnerable layer of concrete during construction. This emanates from the fact that during construction, the cover is exposed to environmental factors that lead to rapid loss of moisture to the atmosphere, while the interior concrete typically retains higher moisture levels. Accordingly, the permeability of cover concrete can be higher than that of interior concrete. If the site curing applied is poor or inadequate, this effect can be exacerbated. Similarly, adequate compaction is required to ensure attainment of pore tortuosity towards lower permeability. Therefore the most important quality control considerations in cover placement are attainment of specified cover thickness, adequate curing and compaction [3]. Achieving the specified concrete cover during construction is usually quite difficult and leads to many failures [4]. Even when detailing is done correctly and spacers are properly placed, the loads applied during placement of fresh concretes and associated pressures may cause movement of the placed steel reinforcement. These effects from the construction process can cause lower cover and high variability of results in certain sections of elements.

Not only is concrete cover a major factor in the durability and service life of structures, its thickness has significant structural effect on the capacity of elements to resist applied loads. The structural effects of concrete cover on members is two-fold: Firstly, a lower cover could reduce the moment capacity of a flexural member such as a slab or beam. Secondly, it would also rapidly lead to corrosion of reinforcement, which when combined with reduced compression area, can have the dual effect of causing a greater reduction on structural capacity. Figure 1 shows a suspended floor slab and a beam, experiencing severe delamination and corrosion of steel in the tension side. At this point, the slab has undergone all initial stages of deterioration from cracking, spalling to delamination; superimposed on these effects is the loss of steel area due to corrosion.

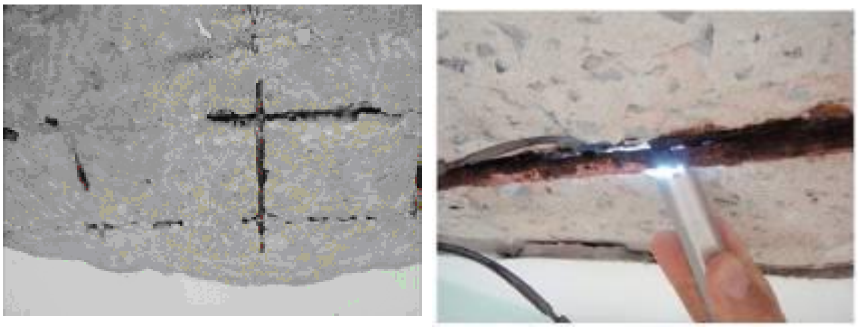

Figure 1. Effects of thin concrete cover on corrosion of steel reinforcement; (a) slab soffits (b) beam [5]

Tapan and Aboutaha [6] reported that the ratio of cover thickness to reinforcement bar size (C/D) has major influence on corrosion-induced cracking. The higher the C/D ratio, the greater the amount of steel corrosion required to cause cracking. For example, it was reported that 2.25% steel corrosion was required for cracking to occur under C/D =1 while 5.25% corrosion was required for cracking under C/D = 2.5. Yagaanbuyant and Bayar [7] found that a small change in cover thickness can lead to significant decrease in the moment capacity in floor slab. A reduction in cover thickness by 10 mm and 20 mm led to a moment capacity decrease of 12.5% and 21.6% respectively. Investigations by Al-Kubaisy and Jumaat [8] found that by adding a layer of ferrocement cover on the tension side of floor slabs, not only was the capacity of the slab increased but the load or moment to first crack also increased.

Keeping these effects of concrete cover thickness in mind, it is therefore important to ensure that not only do the construction processes not only achieve the specified cover thickness and quality during construction but that quality control testing is conducted before commissioning of the new structure. Often, the project stakeholders, such as the contractor, consultant or owner of the structure would require quality control testing for cover thickness. This is done to determine the cover thickness in the structure as-built, against the specified requirements. Typically, testing for cover thickness may reveal areas or sections of the structure where the cover thickness may have fallen below the specified minimum thickness. Such findings provide an opportunity for corrective measures to be applied before commissioning of the structure. Taking remedial actions at this early stage would save future high costs of premature repairs that would result from early deterioration.

A standard covermeter is the most commonly used technique for conducting cover survey in massive structures such as bridges and buildings, Basically, it involves dividing the structure into a grid pattern, detecting the position of steel bars running in both directions and measuring the cover thickness over the bar location. Modern covermeters are quite sophiscated and measure a number of parameters including location of bar and the bar size of steel reinforcement in addition to the cover thickness [9]. Most covermeters operate on the basis of electromagnetic fields; so care has to be exercised against factors that may influence measurements. Another modern but quite complete technique that has been investigated for cover measurement is the Ground Penetrating Radar (GPR).

GPR is often used for sub-surface imaging in investigation of pavements, concrete, or detection of subsurface objects such as metals in soils. Although not commonly used in cover measurement in the superstructure, some case study measurements have been conducted with satisfactory results [10].

2. Case studies

The purpose of this work was to determine and characterise the variability of cover in three newly constructed highway bridges, arbitrarily referred to as *1G*, *2R* and *3C*. The variability examined was expected to be a result of various natural site factors including materials used, site conditions and more importantly, the construction process. The new bridges were among several highway structures that were newly constructed for the N17 highway extension. The highway is a main artery carrying east bound traffic to and from Gauteng through Mpumalanga to neighbouring provinces and coastal cities. The three-span new bridges were approximately 40 to 50 m long and 10 to 12 m wide. Each bridge consisted of two piers and two abutments with the main (centre deck) spanning between the two piers, and the two end jack spans running between the piers and abutments.

Cover survey on the bridges was conducted upon completion of the whole bridge superstructure construction. The survey was conducted based on the different elements, consisting of the deck, piers and abutments. This was done in such a way as to survey the whole bridge structure. Each element was divided into a grid pattern that was used to select points of measurements. A view of one of the bridges can be seen Figure 2.

Figure 2. A newly completed highway bridge structure

3. Results and discussions

The three bridges *1G, 2R* and *3C*, were constructed consecutively and the survey was done once the superstructure of each bridge had been completed. A total of 111, 107 and 110 data points were measured for *1G, 2R* and *3C* bridges respectively. These measurements are distributed among the structural elements as shown in Table 1. Measurements done on piers included pier heads. Since grid patterns were used, the distribution of the data points across the elements depended on the surface area of the element. Hence the deck had more measurements than the piers and abutments. All deck cover measurements were made at the deck soffit i.e the tension side.

A cover depth of 40 mm was specified for the superstructure elements. As seen in Table 1, the cover placed in the structure was in the range of 50 mm which exceeded the minimum specified cover. It should be underscored, however, that the achievement of the minimum cover does not necessarily imply that all sections of the structural elements achieved the required criteria. Typically, certain sections may have very low cover while others may show excessively high cover. The scatter in data gives an indication of the uniformity of cover thickness as built. For this purpose, scatter diagrams of results have been plotted in Figures 2, 3, and 4 for the bridges *1G, 2R* and *3C* respectively. It is evident, for example, in Figures 3 and 4 that the deck soffit exhibit cover thickness values as low as 30 mm while others were as high as 67 mm. Similar scatter can be seen in Figure 2 data for the abutments.

Histograms shown in Figures 2, 3 and 4 show data which is characterised by a normal distribution curve, indicating normalcy of the data generation process. The histograms for bridge *1G* gave a much broader peak than the other two bridges 2R and 3C while the range of cover thickness remained similar for all the bridges. Table 1 also gives the standard deviation for the various elements and the overall coefficient of variation (CV) of the measurements. Of all the structural elements, only the bridge decks showed a consistent standard deviation of about 7.0. The piers had a relatively low standard deviation of 5.0 for bridges 1G and 3C but for some reason, the corresponding standard deviation was very high for bridge 2R. Of all the elements, abutments gave the highest standard deviation, ranging from 10 to 11 compared to 5 to 7 for the deck and pier. This observation may be related to higher quality control measures being applied to the deck and piers, compared to abutments, as the former elements are more crucial for load bearing than the latter. In all the three bridges, however, the CV is consistent, falling in the range of 18 to 21%.

In order to investigate whether there may be some bias in data in relation to the type of structural element, statistical data were analysed according to the type of element. Data from all three bridges were combined according to the type of element i.e. decks, piers and abutments. Figure 5 gives a plot of histograms for the bridge decks, piers and abutments. It can be seen that a relatively large number of measurements were done on the bridge deck soffits compared to the piers and abutments. This was directly related to the relative surface areas of the elements, of which the bridge decks had larger areas. It was mentioned earlier that the selection of the measurement points was based on a grid spacing, which amounted to more data points being measured for elements of larger surface areas. None-the-less, it is clear that all the elements gave normal distribution curves. Note that all the histograms in Figure 5 are plotted on the same scale.

Table 1. Cover survey results for new highway bridges

Bridge	Element	No. of data points	Average cover (mm)	Standard deviation	Coefficient of variation
1G	Deck	74	49	7.6	0.194
	Piers	11	50	5.2	
	Abutments	26	50	15.0	
	All elements	111	50	8.8	
2R	Deck	78	46	6.8	0.212
	Piers	11	62	18.3	
	Abutments	18	55	9.8	
	All elements	107	54	11.0	
3C	Deck	54	47	7.1	0.184
	Piers	20	49	4.8	
	Abutments	36	55	11.4	
	All elements	110	50	7.1	

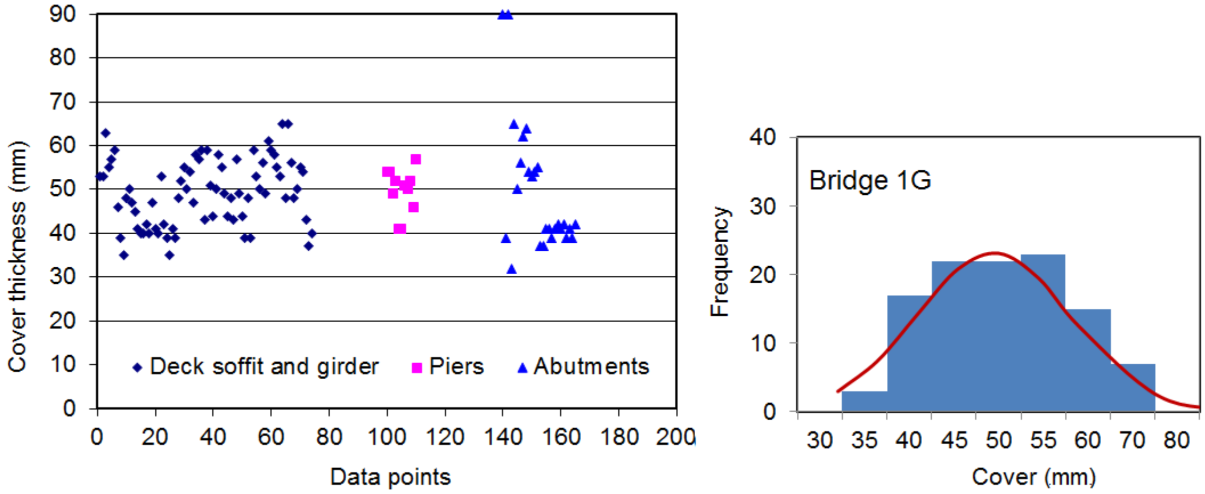

Figure 2. Scatter plot and histogram of cover for bridge *1G*

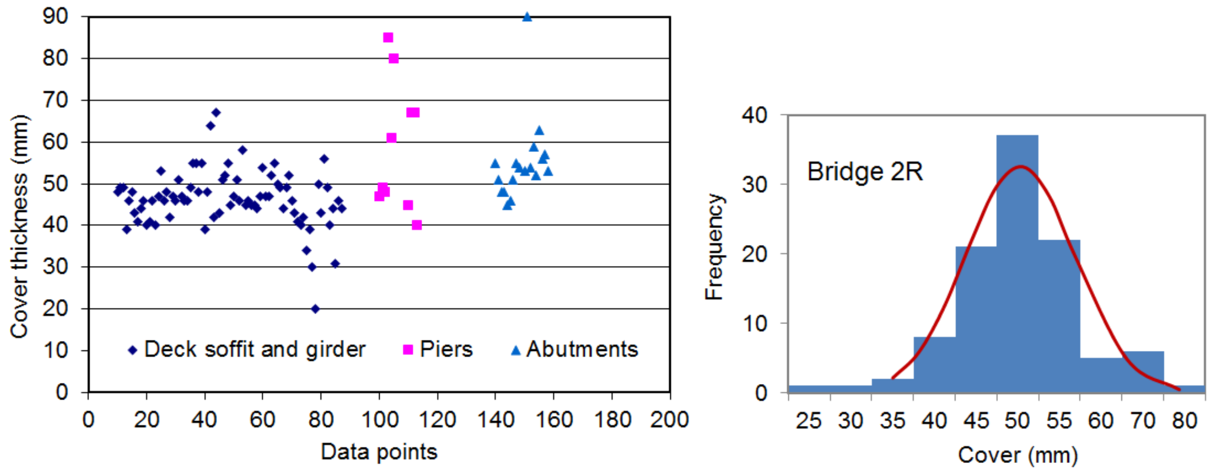

Figure 3. Scatter plot and histogram of cover for bridge *2R*

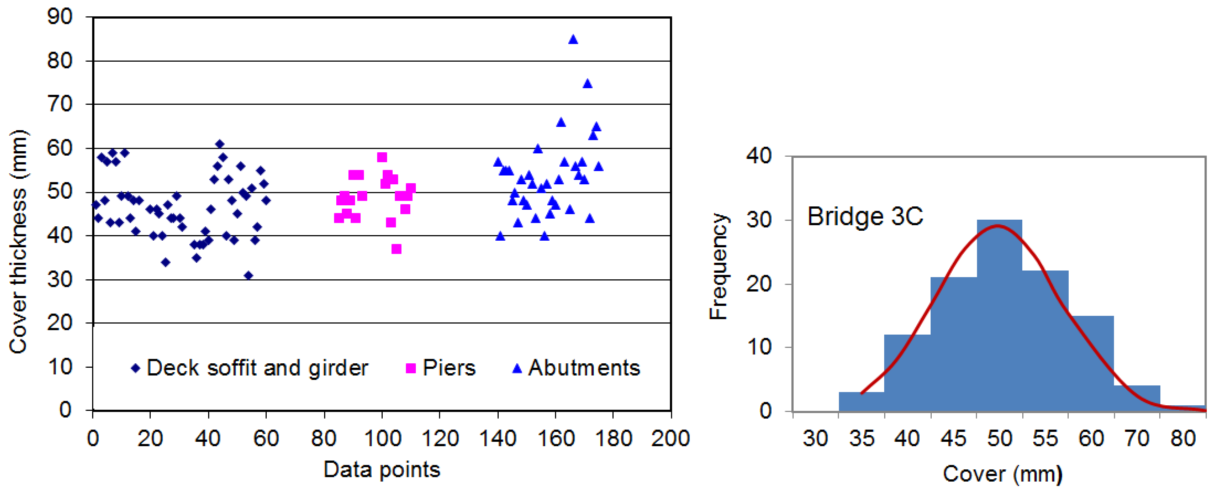

Figure 4. Scatter plot and histogram of cover for bridge *3C*

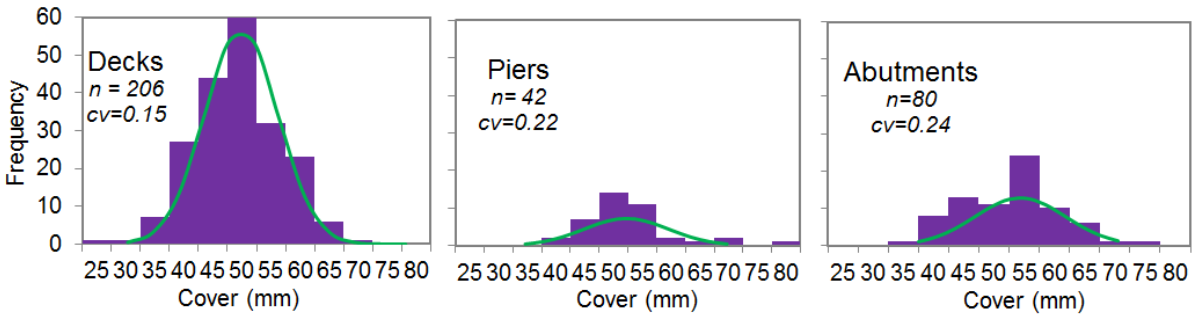

Figure 5. Histograms of cover for the different structural elements (n – number of data points, cv – coefficient of variation)

In Table 1, it can be seen that in all the bridges, decks had a cover thickness that was lower by about 2 to 3 mm, compared to the cover in piers and abutments. This may be attributed to the flexural behaviour of decks, in which case, steel reinforcement is vulnerable to deflection movement during concrete placement and compaction, unlike in compression members (piers and abutments) where no such problems may exist. Figure 5, however, shows that decks had the lowest CV of 0.15, much lower than the CV = 0.22 for piers and CV = 0.24 for abutments. This pattern appears to indicate that much tighter quality control may have been placed on deck construction relative to the construction of other bridge elements.

4. Conclusions

In the foregone work, statistical analysis was conducted on the cover thickness data acquired from three new highway bridges. The inspection was done for the purpose of quality control. It was found that the specified cover depth of 40 mm was met with a margin of safety of 10 mm. The standard deviation of the deck and piers were generally in the range of 5 to 7, which indicates good quality control with respect to the material and the construction execution. However, bridge 2R gave a particularly high standard deviation but this was due to the presence of higher cover while all values exceeded the minimum requirement. Similarly, abutments gave higher standard deviations but it was due to the presence of much higher values of cover rather than the opposite. The overall coefficient of variation was consistent in all bridges, giving values of coefficient of variation of 18 to 21%.

Bridge decks, which are flexural members consistently gave a lower cover than compression members, consisting of piers and abutments.

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