Pergamon

Cement and Concrete Research, Vol. 26, No. 3, pp. 345-353, 1996

0008-8846/96 $15.00 + .00

PII S0008-8846(96)00009-9

COMMUNICATED PAPERS

INFLUENCE OF CRACK FREQUENCY ON REINFORCEMENT CORROSION IN CONCRETE

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(Communicated by C.D. Pomeroy)
(Received November 17, 1995; in final form December 14, 1995)

ABSTRACT

The relationship between crack frequency and reinforcement corrosion was investigated using two models: (a) reinforced concrete beams, 1.36 m long, containing 0, 1, 4, 8, 12, 16 or 20 parallel sided cracks of equal width giving in each case a sum total width of 2.4 mm and (b) a 4 m long beam containing a 20 mm diameter bar in nineteen segments, ten 352 mm long stainless steel segments and nine 10 mm long mild steel segments which simulated the position of cracks. Corrosion was initiated in (a) by spraying the beams with a 3% chloride solution and in (b) by using concrete dosed with 5% Cl (by weight of cement). The weight loss due to corrosion of the reinforcement was estimated via linear polarisation resistance and/or galvanic current measurements using a zero resistance ammeter. The results obtained from both models suggest that decreasing the frequency of cracking leads to a decrease in corrosion. Possible implications of this finding on the design of concrete structures are discussed.

Introduction

The relationship between cracking in concrete and the corrosion of embedded reinforcement has been investigated worldwide but still remains an unresolved technical problem with seemingly no proper solution [1]. It is widely recognised that if depassivating substances (i.e. chlorides/carbon dioxide), moisture and oxygen are present in sufficient concentrations in the service environment, corrosion can occur. Cracks which follow the line of the reinforcement (coincident cracks) are liable to give rise to significant corrosion and steps should be taken to avoid their occurrence. The risk of corrosion with cracks which cross the reinforcement (intersecting cracks) remains less certain.

Studies on intersecting cracks have tended to focus on the role of the surface crack width as the primary indicator of corrosion risk. Several investigators have found that there is a relationship between crack width and corrosion [2–5]. This result has influenced the recommendations contained in many contemporary structural design codes which suggest that limiting the maximum surface crack width can prevent reinforcement corrosion [6–8].

Other studies conclude, however, that there is no relationship between crack width and corrosion [9–13]. Based on the results in reference [10], Beeby has further suggested that a critical

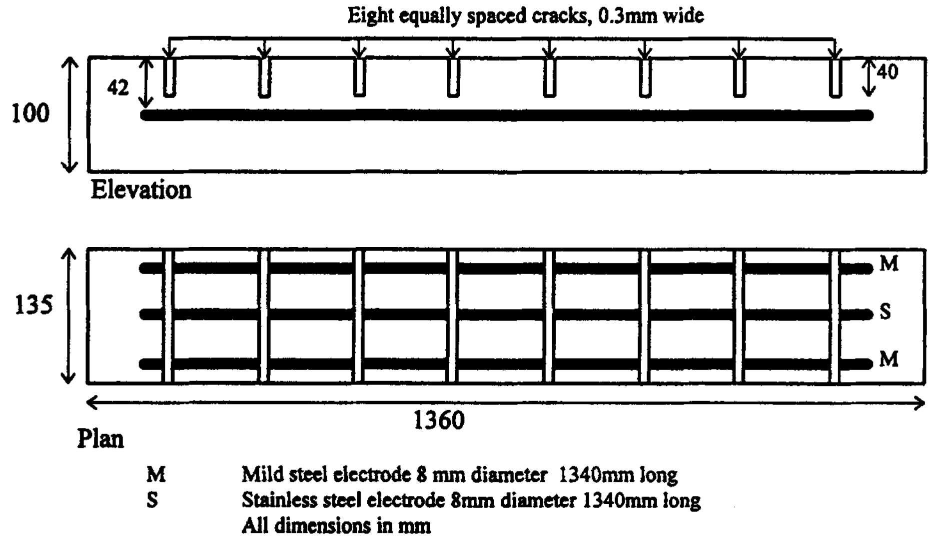

FIG. 1.
Model A beam containing eight cracks.

factor determining the amount of corrosion may be the frequency of cracking [13]. This finding can be explained in terms of the electrochemical processes involved in the corrosion of steel in concrete [14] and agrees with the current theory of crack formation in reinforced concrete which assumes that crack spacing is a more fundamental parameter than surface crack width. For example, BS8110 [15] and Eurocode 2 [7] assume the crack width to be a function of the crack frequency. However, there is still no experimental work which has been carried out to establish if a significant relationship between crack frequency and corrosion exists.

The purpose of this study is to investigate the influence of crack frequency on reinforcement corrosion experimentally. This was done by using two design of specimens the construction details of which are given below.

Experimental Procedure

Model A. Model A beams were 135 mm × 100 mm × 1360 mm long, containing 0, 1, 4, 8, 12, 16 or 20 parallel sided cracks, 40 mm deep, and of equal width giving in each case a sum total width of 2.4 mm (Fig. 1). The cracks were formed by casting plastic shims of appropriate thicknesses into the concrete. Each beam was reinforced with a central stainless steel and two mild steel rods, 8 mm diameter × 1.34 m long, at a cover depth of 42 mm. The stainless steel rod was provided in order to estimate the amount of corrosion occurring on the mild steel rods.

Four replicates of each beam i.e. twenty eight beams in all, were cast in timber moulds and compacted by vibration. The mix proportions of the concrete used in the beams is shown in Table 1. Tests on 100 mm cubes showed that the average 28 day compressive strength of the mix was 30 N/mm^2. The beams were demoulded 24 hours after casting and stored in a sealed room at a relative humidity of 90% and temperature of 20°C for the duration of the experiment.

TABLE 1

Mix Proportions (By Weight)

OPC	1.00
Sand (Zone 3)	2.38
10 mm aggregates (flint gravels)	2.89
Water	0.65

The beams were sprayed with a 3% NaCl solution 28 days after casting in order to initiate corrosion. For the first seven months of testing the beams were sprayed three times a week. For the next five months the beams were sprayed three times a month.

The corrosion current densities were measured monthly for the first 14 months and two-monthly thereafter. The current densities in two replicates was assessed using linear polarisation resistance (LPR) and in the remaining two replicates by measuring the galvanic currents using a zero resistance ammeter (ZRA). The resulting current densities were converted to metal loss using Faraday's law [16].

The LPR current density was determined using an automatic potentiostat linked to a ramped generator. The ramp applied was from -10 mV to +10 mV from the rest potential at a sweep rate of 0.1 mV/sec using the stainless steel rod as a counter electrode and a silver/silver chloride half-cell as an external reference electrode. The current densities were measured at several points on the mild steel rods in order to estimate the metal loss.

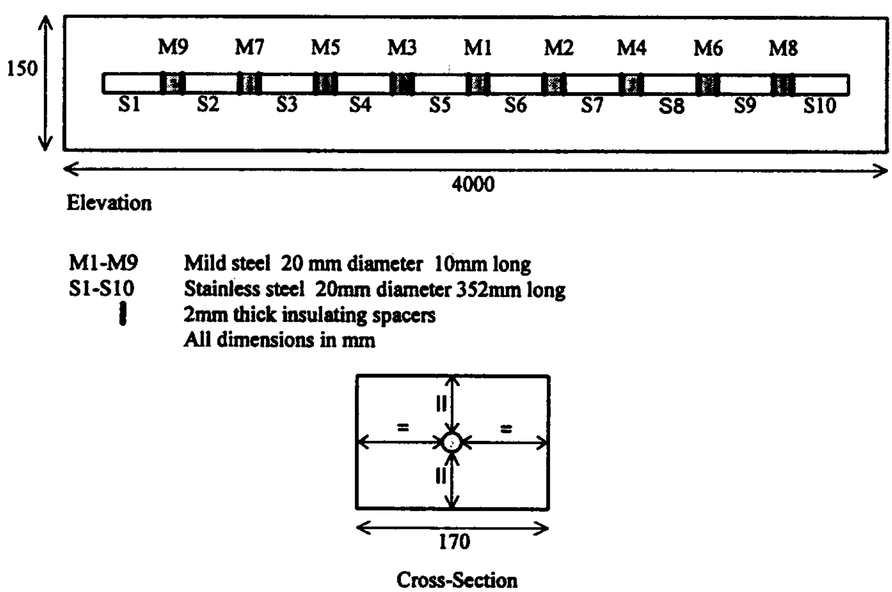

FIG. 2.
Model B beam.

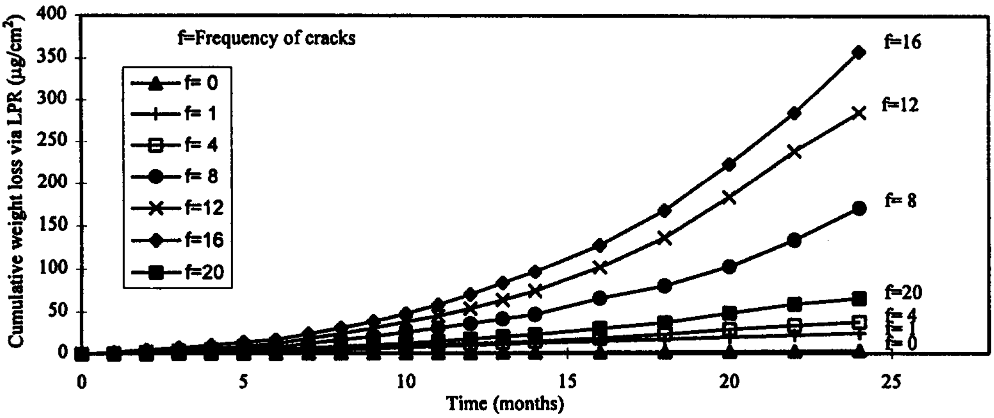

FIG. 3.
Effect of crack frequency on cumulative weight loss due to corrosion.

The (average) corrosion current flowing in the mild steel rods was measured with a ZRA, by connecting between the stainless steel rod and each mild steel rod in turn.

Model B. Model B was 170 mm × 150 mm × 4 m long beam, containing a central 20 mm diameter bar in nineteen segments, ten 352mm long stainless steel and nine 10 mm long mild steel segments which simulated the position of cracks (Fig. 2). The mild steel segments were made of solid sections of reinforcement while the stainless steel segments were made of hollow lengths of AISI type 316 steel. Adjacent lengths of mild steel/stainless steel were electrically isolated by using nylon washers in the assembly.

Each segment was electrically connected at one point using stainless steel type 316 wire, sleeved with PTFE. This was to allow any combination of mild steel and stainless steel segments to be electrically connected via an external connection.

The beam was cast in a timber mould. The mix proportions were the same as in Table 1 except that the concrete was dosed with 5% Cl (by weight of cement) from NaCl. The beam was demoulded 48 hours after casting. It was initially wrapped in damp hessian and left to cure for 28 days. Thereafter, it was left for a further 56 days in the laboratory at a temperature of 20°C and relative humidity of around 40%. This lengthy conditioning period was to ensure that steady state conditions were attained prior to testing.

At the start of the experiment, the stainless steel segments were all electrically connected. The galvanic current flowing in the beam was then measured using a ZRA as successive mild steel segments were connected.

Results and Discussion

Model A. Figs. 3 and 4 show the cumulative weight losses due to corrosion for model A beams based on, respectively, the LPR and galvanic current density measurements. The cumulative weight loss will probably determine the time to cracking and spalling of concrete. It can be seen that, except for the specimens containing 20 cracks, the higher the frequency of cracking the

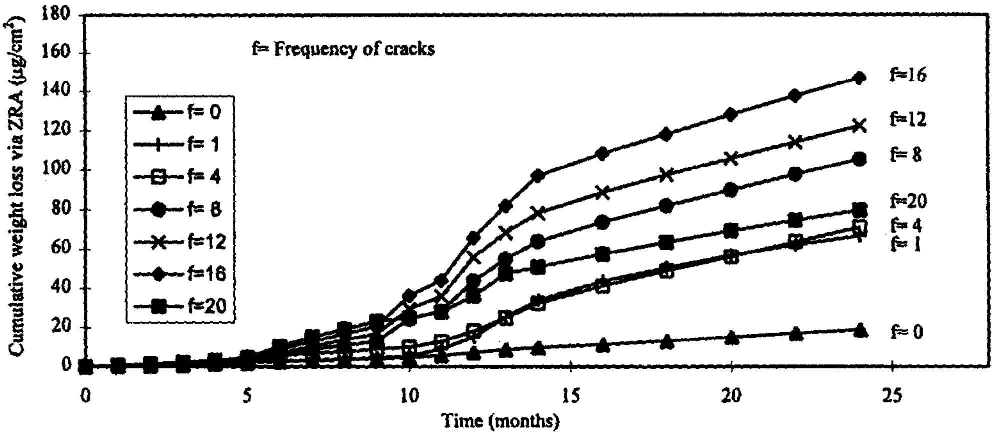

FIG. 4.
Effect of crack frequency on cumulative weight loss due to corrosion.

greater the weight loss. The reason why the specimens with 20 cracks did not conform to this trend was probably attributable to some of the cracks undergoing self-healing. Self-healing may not occur in practice however, since the most common cause of intersecting cracks is bending which normally results in cracks whose width varies with time [1], thus deposits in the cracks will soon be dislodged.

The weight losses determined using LPR are significantly higher than those determined on parallel specimens using galvanic current measurements. This is probably due to the fact that the galvanic technique measures the current flowing between the electrodes whereas LPR measures the total corrosion activity [17].

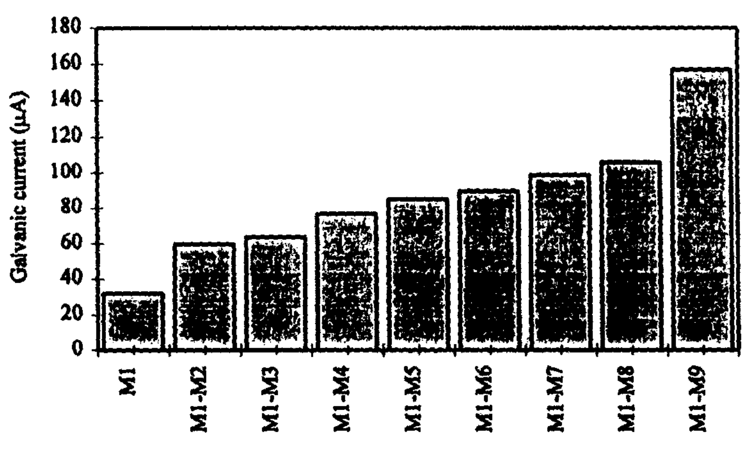

FIG. 5.
Effect of the number of electrically connected mild steel segments on galvanic currents.

TABLE 2

Influence of Cover on Corrosion [18]

Investigators	Cement content (kg/m^3)	w/c ratio	Cover (mm)	Measure of corrosion
E.A. Baker, K.I. Money &	296	0.66	12	25
C.B. Sanborn			37	5
(STP 629, ASTM, Philadelphia, 30–50, 1977)		0.71	12	64
			37	12
F.M. Lea & C.M. Watkins	593	0.37	50	0
(Research Paper No. 30 BRE, HMSO, London, 1960)			25	25
	356	0.55	50	10
			25	82
	214	0.96	50	75
			25	100
Huston et al. [19]	335	0.62	25	75
			38	98
			25	100
			20	100
	446	0.55	25	60
			20	88
	558	0.49	50	0
			38	22
			25	44
			20	490

For specimens containing 1, 4, 8, 12, 16 and 20 cracks, it was further found that the maximum cumulative weight losses at individual cracks determined using LPR at 24 months were, respectively, 24.9, 9.8, 26.1, 34.6, 54.0, 7.1 $\mu g/cm^2$. Excluding the anomalous results for the specimen with twenty cracks it can be seen that for the range of crack widths normally found in concrete structures, increasing the frequency of cracking generally increases the maximum corrosion level [13], important with respect to structural safety.

Model B. Fig. 5 shows the steady state galvanic currents in model B beam as a function of the number of connected mild steel segments. The mild steel segments were electrically connected to the stainless steel segments in the order: M1 to M9.

From Fig. 5 it can be seen that the galvanic current increases with increasing number of connected mild steel segments. Since the mild steel segments simulate the behaviour of corroding reinforcement at cracks, this result also implies that for a given structure, increasing the number of cracks will increase the amount of corrosion.

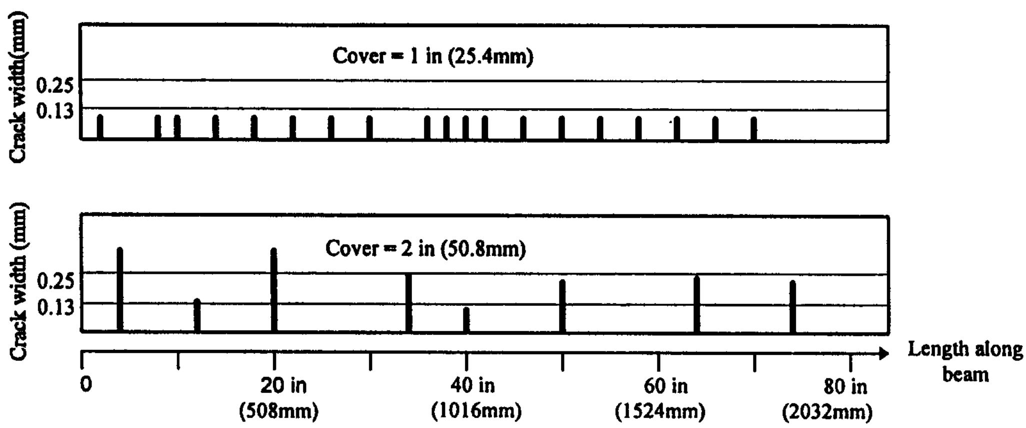

FIG. 6.
Influence of cover on crack frequency [19].

Implication. Both experiments show that for a particular design of specimen the weight loss due to corrosion decreases with decreasing number of cracks. This finding is consistent with the studies on the influence of concrete cover on corrosion which provide strong evidence for believing that increasing the depth of cover leads to a decrease in corrosion.

Beeby, for instance, who reviewed the results from several major investigations concluded that increasing the cover leads to a decrease in corrosion (Table 2). Ohta, who exposed reinforced concrete beams with covers of 20, 30, 40, 50 and 68 mm to sea air for 10 and 20 year periods found that the beams with 20 mm cover suffered heavy corrosion damage, the beams with 30 mm and 40 mm covers suffered average losses of sectional areas of 3.25 and 2.68% respectively and the beams with 50 mm and 68 mm cover experienced only slight corrosion [12].

In the same work cited by Beeby, Huston et al [19] also showed that crack frequency and concrete cover are related such that the smaller the thickness of concrete cover the larger number of flexural cracks (Fig. 6). This trend has been also noted by Swamy [20] and can be shown to be generally true. For example, Fig. 7 illustrates the variation in frequency of cracking with depth of cover obtained for a particular beam using the formulas given in BS8110.

Since deeper covers imply fewer (flexural) cracks, it is suggested that frequency of cracking is a more fundamental factor influencing the amount of corrosion. On this basis it would seem that an effective measure against corrosion may be to limit the frequency of cracking (i.e. by increasing the thickness of concrete cover), rather than the maximum surface crack width as is currently suggested in various design codes. Increasing the concrete cover to the reinforcement will increase surface crack widths which may be undesirable for aesthetic reasons. In this circumstance, consideration should be given to introducing reinforcing bars made of non-metallic materials in the cover zone [21].

Conclusions

This paper has presented the results of a two year study on the influence of frequency of intersecting cracks on reinforcement corrosion. The results obtained show that the smaller the

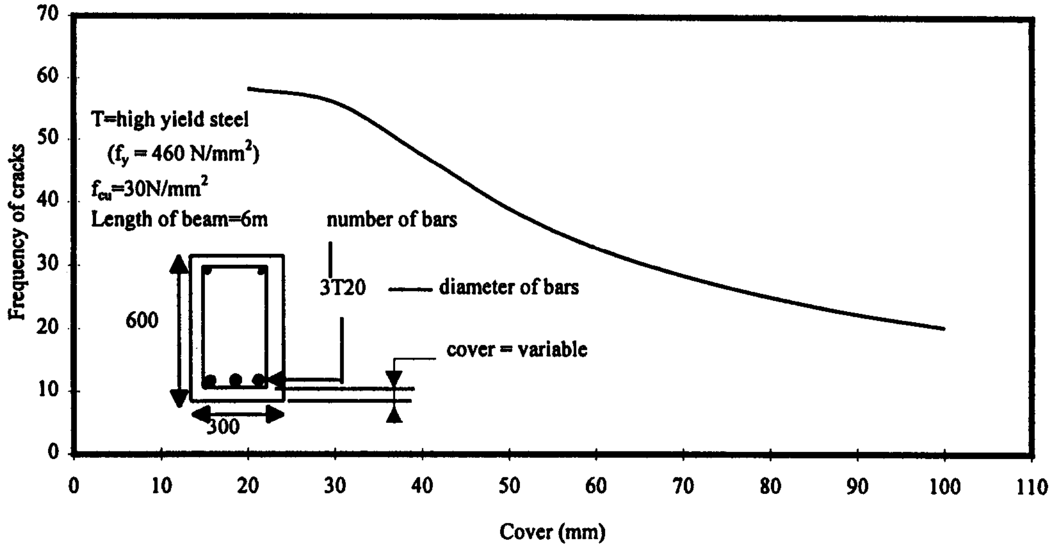

FIG. 7.
Relationship between cover and crack frequency calculated using BS8110 for the beam shown.

frequency of cracks the smaller the amount of corrosion. This suggests that an effective measure against corrosion may be to limit the frequency of intersecting cracking, by increasing the depth of cover to the reinforcement, rather than by controlling surface crack widths.

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