# CONDITION ASSESSMENT AND PROTECTION OF CONCRETE STRUCTURES AGAINST CORROSION: DO CRACKS MATTER?

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**ABSTRACT.** This paper describes the findings of a recent investigation on the relevance of cracking in concrete to reinforcement corrosion, a subject of international debate over many years. Many of the early studies on this topic focused on the effect on crack width and exposure environment and largely showed that the larger the crack width and the more severe the exposure environment the greater the amount of corrosion. However, latter studies contradicted this type of finding suggesting that corrosion rate was independent of crack width and that the corrosion resulting from cracks was unlikely to affect the overall safety of structures. More recent studies suggest that whilst crack widths may be less important than was originally envisaged, there are other characteristics of cracks and the adjacent concrete that have a more profound influence on this process. They include crack orientation, number of cracks, thickness of concrete cover, propagation status and the quality/moisture content of concrete. The paper discusses the effect of each of these variables on reinforcement corrosion, a better appreciation of which would lead to an improvement in the durability of concrete construction as well as more effective scheduling of maintenance.

**Keywords:** Crack widths, crack orientation, cover, reinforcement corrosion, condition assessment, concrete durability

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# INTRODUCTION

The subject of cracking in concrete is important both to engineers engaged in the design of new structures as well as condition assessment of existing structures. This stems from the belief that cracks allow the penetration of aggressive substances present in some external environments to the level of the reinforcing bars more rapidly than sound concrete and hence will give rise to premature deterioration. Premature deterioration of concrete infrastructure such as bridges impedes economic growth, depletes natural and non-renewable resources, and threatens human safety. Considering purely the economic losses due to premature concrete deterioration, these are substantial with the annual cost of corrosion worldwide estimated at US$ 2.2 trillion (2010), which is about 3% of the world's GDP of US$ 73.33 trillion [1], and concrete corrosion contributes in some measure to this [2].

Investigations on the effect of cracks on concrete durability, specifically corrosion of embedded steel reinforcement, have been ongoing for decades. Early work on the subject confirmed that cracks will facilitate the ingress of the agents of corrosion, namely carbon dioxide/chlorides, oxygen and moisture, to embedded reinforcing bars and hence increase the risk of corrosion. Furthermore, in order to reduce this risk it is necessary to limit crack widths; the more aggressive the exposure environment the narrower the permissible crack width. However, tests begun in the late fifties and concluded in the early seventies by a team in Germany, most notably Schiessl [3], acknowledged that whilst cracks permit more rapid penetration than sound concrete of substances necessary for corrosion the subsequent rate of corrosion is independent of crack width. Beeby [4] also reached the same conclusion by considering the processes involved in corrosion. He argued that for significant corrosion to occur oxygen and moisture would need to penetrate to cathodic regions which usually occur in areas of sound concrete and also for ionic flow to occur between anodic and cathodic regions. Since both processes are independent of crack width so too must be the rate of corrosion. He also demonstrated that the width of a crack at the concrete surface may bear no relationship to the width of the crack near the steel bar where anodic activity occurs and therefore a relationship between surface crack width and corrosion was unlikely. More significantly, by analysing the results presented by Schiessl (and others) he concluded that rates of corrosion were generally small and unlikely to present a safety risk. Besides, Beeby suggested, cracks can become blocked over time due to pollution, leaching, cement hydration and even the products of corrosion, thereby further reducing the risk of significant corrosion.

The above two views on the significance of cracks have shaped the recommendations on crack control in codes of practice on structural concrete design the world over. Thus, some codes such as Indian Standard 456 [5] suggest that there is a strong link between crack width, exposure condition and reinforcement corrosion. Eurocode 2 [6], on the other hand, recommends a single value of crack width of 0.3mm irrespective of exposure class. The American Concrete Institute 318 [7] has removed all references to crack width and corrosion in its latest advice. Nonetheless, the results of a recently completed literature review on crack-induced reinforcement corrosion suggests that whilst crack width may be less important than was originally envisaged this does not mean that cracks are unimportant. In fact there are several other aspects of cracks as well as the properties of the surrounding concrete that have a more profound influence on corrosion and which should also be considered [8]. These include the following and their influence on crack-induced corrosion are discussed below.

- Orientation
- Frequency

- Cover
- Propagation status
- Concrete properties

## CRACK ORIENTATION

Most investigators working in the field of cracking and corrosion have distinguished between two types of cracking in concrete, namely longitudinal and transverse. Longitudinal cracks run parallel to the main steel and transverse cracks are generally assumed to occur at right-angles to the main steel. However, this classification system is ambiguous since in actual structures reinforcement is usually placed in two directions at right-angles; in two-way spanning slabs, for instance, both sets of bars are main steel. It would be clearer if cracks were categorised under the headings:

- Intersecting cracks (Figure 1)
- Coincident cracks

Intersecting cracks are cracks which cross the reinforcement and include diagonal cracks. Coincident cracks are cracks which follow the reinforcement. The term reinforcement in these definitions includes the main steel, secondary steel and links.

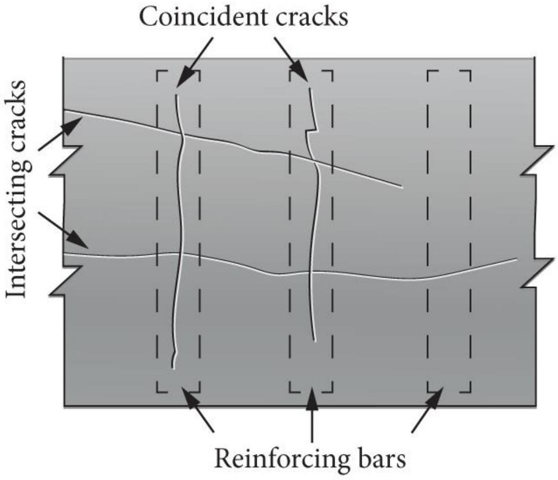


Figure 1 Coincident and intersecting cracks

Intersecting cracks will increase the rate of penetration of aggressive substances to the reinforcing steel and hence accelerate corrosion initiation. However, since the cathodic sites are mainly confined to the crack-free regions of concrete, any oxygen and moisture which penetrates the crack may not significantly affect the rate of corrosion propagation. But this situation may change depending on the proximity of adjacent cracks and the quality/condition of the intervening concrete as discussed later in the paper.

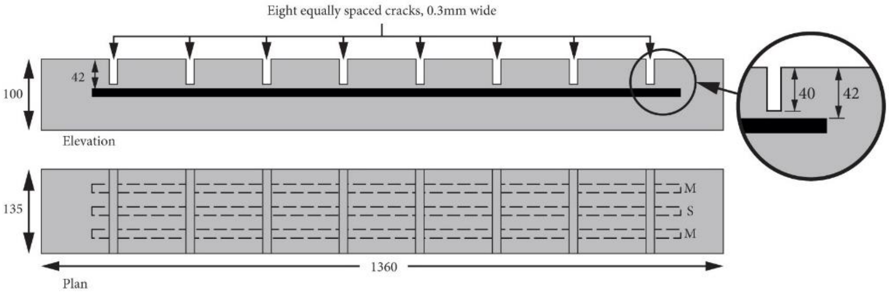
With coincident cracks, the passivity of the reinforcement steel may be lost at several locations. The same crack will also readily transmit oxygen and moisture to the cathodic areas of the reinforcing steel. Since there is no way of inhibiting or confining the corrosion process, corrosion may then proceed unchecked and possibly even accelerate. Coincident cracks would, therefore, seem to present a serious risk of corrosion no matter what their width.

Coincident cracks are caused by various mechanisms including plastic settlement, plastic shrinkage, early thermal contraction as well as direct loading of structures. For example, bending induced by vertical loading on beams will give rise to cracks which intersect longitudinal bars but can coincide with stirrups [9]. Good workmanship, good detailing and following the design recommendations in appropriate codes of practice may reduce the occurrence of coincident cracking due to the first three mechanisms. Coincident cracks caused by loading are unavoidable, however, and the best advice that can be offered at this stage is that coincident cracks should be as narrow as possible.

## FREQUENCY OF CRACKING

A number of workers have shown that the frequency of cracks is an important factor influencing the degree of corrosion in reinforced concrete elements.

For example, a study by Arya and Ofori-Darko [10] found using a number of similar concrete beam specimens, 1.36m 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 2.4mm (Figure 2) that the total amount of corrosion increased with increasing number of cracks (Figure 3). The anomalous result for specimens with twenty cracks was attributed to the fact that a number of the cracks had undergone self-healing, a situation which the authors felt might not always occur in practice.



M Mild steel electrode, 8mm diameter, 1340mm long.
S Stainless steel electrode, 8mm diameter 1340mm long.
All dimensions in mm

Figure 2 Schematic of beam containing eight cracks [10]

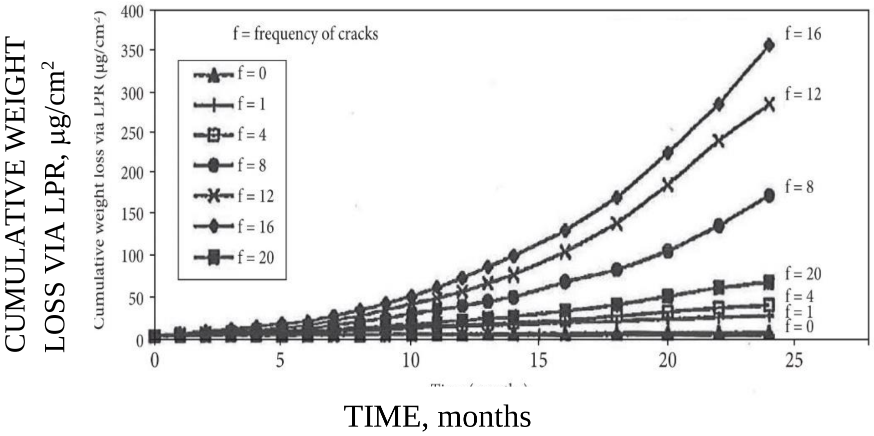


Figure 3 Effect of crack frequency on cumulative weight loss due to corrosion – By linear polarization resistance (LPR) measurements [10]

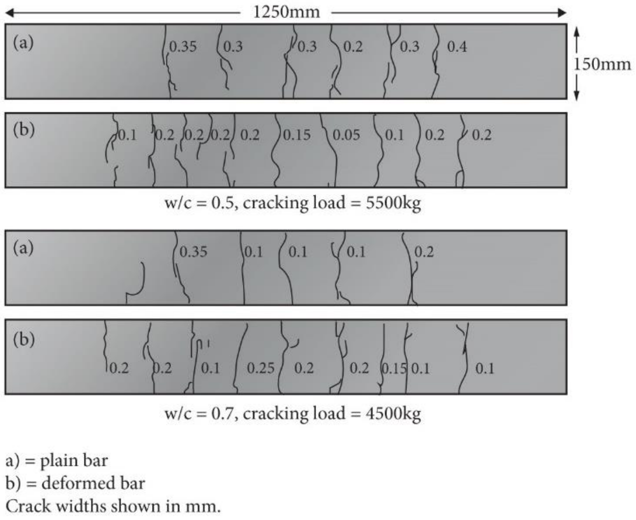


Figure 4 Cracks patterns in beams reinforced with plain and deformed bars [11]

Further evidence in support of a relationship between crack frequency and corrosion is provided by work presented by Mohammed et al [11]. These workers tested beams which were loaded back to back. The number of cracks was varied by reinforcing with either plain or deformed bars. The beams were made with two w/c ratios: 0.5 and 0.7 and subjected to maximum loads of 5500 and 4500 kg respectively. The resulting crack patterns are shown in Figure 4. Here it can be seen that the specimens reinforced with deformed bars experienced a greater number of cracks than the specimens reinforced with plain bars, which is consistent with cracking theory. The specimens were stored outdoors and sprayed with a 3.5% sodium chloride solution once a week for 16 months. As predicted, the results presented in Table 1 show that specimens reinforced with deformed bars experienced more corrosion damage than similar specimens reinforced with plain bars.

This finding can be explained using the models shown in Figure 5. When a concrete member with a single crack is exposed to a chloride-rich environment, any steel reinforcement at the crack will be rapidly depassivated. However, because the cathodic regions which occur mainly in the crack-free regions of concrete extend over relatively large distances and possibly because the oxygen supply to these regions may be limited due to the concrete cover, the subsequent rate of corrosion will be small. If, on the other hand, the same member contains a larger number of cracks, albeit of narrower widths, the cracks will not only increase the oxygen supply to the steel surface but also reduce the distance between anodes and cathodes, thereby resulting in a higher combined amount of corrosion.

Table 1 Total crack width, total corroded area and corroded area per unit crack width [11]

| | w/c = 0.5 | | w/c = 0.7 | |
|---|---|---|---|---|
| | PLAIN BAR | DEFORMED BAR | PLAIN BAR | DEFORMED BAR |
| Total crack width (mm) | 1.85 | 1.6 | 0.85 | 1.5 |
| Total corroded area ($cm^2$) | 30 | 90 | 46 | 107 |
| Corroded area per unit crack width ($cm^2$/mm) | 16.2 | 56.3 | 54.1 | 71 |

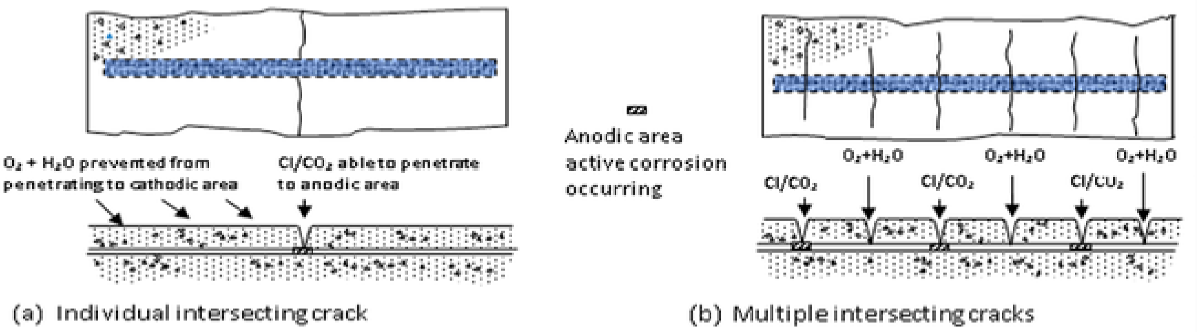


Figure 5 Cracks and corrosion (a) individual intersecting cracks (b) multiple intersecting cracks [12]

## COVER

Several workers including Lea and Watkins [13] and Houston et al [14] noted a reduction in the amount of corrosion damage to specimens when the thickness of concrete cover to embedded bars was increased (Table 2).

Interestingly, this finding is consistent with the results of the experiments on crack frequency described above. Here it was found that increasing the frequency (number) of cracks increased the total amount of corrosion damage. Increasing the frequency is the same as decreasing crack spacing. Studies on reinforced concrete beams show that crack spacing is a function of both the cover to the reinforcement and the bar diameter to steel percentage ratio ($\varphi/\rho$). However, the cover is the most important variable controlling crack spacing and the influence of $\varphi/\rho$ in flexural situations is usually secondary. Increasing the cover therefore increases crack spacing which results in fewer (albeit wider) cracks. Based on the finding of the crack frequency experiments this should reduce the amount of corrosion damage as indeed was found to be the case by the authors cited in Table 2.

It is worth noting that restricting crack widths to permissible values effectively prevents engineers specifying deeper covers to steel bars despite the fact that the benefits of deeper covers are not disputed whereas the merits of controlling crack widths is still controversial.

## PROPAGATION STATUS

Cracks can become blocked overtime due to various mechanisms including the deposition of dust and other airborne particles or because of self-healing. This may stop or reduce the amount of corrosion occurring during the life of the structure. However, self-healing or blocking is unlikely or at least will occur over a much longer period of time where the two sides of the crack move relative to each other. As discussed in section 2, the type of cracking which is most problematic from the view point of corrosion is cracks due to loading, which can give rise to live cracks and suggests that it would be conservative to assume cracks remain open during the design life of concrete structures and therefore crack-induced corrosion remains a possibility.

Table 2 Influence of cover, water/cement ratio and cement content on corrosion [15]

| INVESTIGATORS | CEMENT CONTENT (Kg/m$^3$) | WATER/CEMENT RATIO | COVER (mm) | MEASURE OF CORROSION |
|---|---|---|---|---|
| Lea and Watkins [13] | 593 | 0.37 | 50 | 0 |
| | | | 25 | 25 |
| | 356 | 0.55 | 50 | 10 |
| | | | 25 | 82 |
| | 214 | 0.96 | 50 | 75 |
| | | | 25 | 100 |
| Houston, Atimtay and Ferguson [14] | 558 | 0.49 | 50 | 0 |
| | | | 38 | 22 |
| | | | 25 | 44 |
| | | | 20 | 49 |
| | 446 | 0.55 | 25 | 60 |
| | | | 20 | 88 |
| | 335 | 0.62 | 50 | 75 |
| | | | 38 | 98 |
| | | | 25 | 100 |
| | | | 20 | 100 |

## CONCRETE PROPERTIES

As previously noted, the cathodic areas of reinforcement are generally located in the crack-free regions of concrete. Corrosion propagation requires that oxygen should be available at cathodes and that the concrete is sufficiently moist to allow movement of ions between anodic and cathodic regions. The permeability and moisture content of the uncracked concrete cover therefore have an important influence on corrosion.

### Permeability

The permeability of concrete is a function of curing, compaction, water/cement ratio, cement content, cement type, among other factors. A quality concrete is one which has a low permeability. Such a mix will reduce the rate of corrosion by

- restricting ionic movement within the concrete
- possibly reducing oxygen access.

Several workers have considered the effect of water/cement ratio on the rate of reinforcement corrosion in cracked concrete specimens, often in combination with other factors such as cement content and cement type. The results generally show that there is a significant reduction in the extent of surface corrosion of embedded steel with decreasing water/cement ratio and increasing cement content (Tables 1 and 2).

Concrete made with blended cements have much lower diffusion coefficients than pure CEM I cement and tests by Scott and Alexander [16] who compared corrosion rates in cracked concrete beams made of pure CEM I and blended cements containing various levels of GGBS, FA and SF found that all the blended cement concretes experienced at least 50% reduction in the rate of corrosion compared with the pure CEM I mix.

### Moisture Content

The moisture content of concrete largely depends on the service environment. Thus, exposure to the marine environment may mean that the concrete is always permanently saturated. This will reduce the rate of oxygen diffusion into concrete. On the other hand, exposure to hot climates or a sheltered indoor environment may result in a fairly dry concrete cover. Under these conditions, ionic mobility between anodic and cathodic sites will become restricted.

## CONDITION ASSESSMENT

From the foregoing it would appear that the factors influencing the risk of crack induced corrosion and which should therefore be considered by engineers responsible for evaluating the condition of existing structures and subsequently recommending remedial work are:

- service environment
- crack orientation, width and depth of concrete cover
- self-healing potential
- internal conditions and quality of concrete

### Service environment

For corrosion to occur, carbon dioxide and/or chlorides must be present at the anode, oxygen must be available at the cathode and the concrete must be sufficiently moist. Many of these substances either originate from the service environment or are influenced by it and it is the particular combination of environmental conditions and concentrations of substances within the environment that will determine the risk of corrosion.

Thus, corrosion is usually absent from members exposed to indoor conditions, even though the cover may sometimes be cracked and fully carbonated. This is almost certainly due to the dry atmosphere which reduces the volume of electrolyte and so impedes ionic diffusion.

A cracked reinforced concrete member immersed in a chloride solution is unlikely to corrode because oxygen is not very soluble in water which results in the cathodic reaction being suppressed [17]. This situation is typical for the lower part of coastal and off-shore structures which always remain below sea water.

### Crack Orientation, Width and Cover

Not all cracks will present a risk to embedded reinforcing bars of corrosion since they may form between bars. This can be established by carrying out a cover meter survey. This type of survey can also be used to determine the orientation of the crack with respect to the underlying reinforcement as well as the thickness of concrete cover.

Coincident cracks will accelerate the onset of corrosion and also the subsequent rate of corrosion propagation where the service conditions are favourable i.e. oxygen and moisture are present. On the other hand, although intersecting cracks will also accelerate corrosion initiation, they may not necessarily influence the rate of propagation. The more intersecting cracks there are the more corroded reinforcement there will be and so the risk that an intersecting crack will have a large amount of corrosion will increase.

For a given crack width the smaller the associated thickness of concrete cover the greater the disruption at the concrete/steel interface where anodic activity can occur and hence the higher the risk of significant corrosion of the underlying reinforcement.

## Self-healing Potential

Cracks can become blocked overtime. This is a function of a number of factors including cause of cracking, service environment and type of structure.

Cracks that are dormant are more likely to self-heal than those that are live. This property can be assessed by determining the likely cause of cracking. Thus cracks due to loading and thermal movements are likely to be live whereas cracks due to plastic shrinkage and differential hydration temperatures are likely to be dormant.

Dust or other extraneous material from the service environment could result in blocking of cracks with time.

In moist conditions, cracks in concrete structures may experience self-healing through on-going cement hydration resulting in the formation of calcium hydroxide and calcium silicate hydrates. Cracks in retaining walls and water retaining structures may self-heal due to the passage of water. If the water is slow moving, the crack may self-heal through the calcium hydroxide precipitate carbonising and blocking the crack. However, it is also possible that water flow through cracks in fluid-retaining structures may cause severe leaching of calcium hydroxide, resulting in local reduction in pH and ultimately corrosion of embedded steel. Moreover, if chlorides are present in the retained liquid e.g. swimming pool, seepage through cracks may cause severe pitting of the reinforcement [18].

## Internal Conditions and Quality of Concrete

Where uncertainties exist regarding the risk of crack-induced corrosion of the steel reinforcement the above checks can be supplemented with tests on the concrete cover. These could include test to determine the depth of carbonation, depth/concentration of chloride and the moisture content and permeability of concrete.

Clearly if the concrete is not carbonated or the chloride concentration at the depth of the reinforcing bar has not exceeded the threshold value, corrosion will not occur no matter what the crack width.

The moisture content and permeability of concrete can be assessed by measuring its resistivity and used to assess the likely rate of corrosion in the event that the steel reinforcement has become depassivated.

# PROTECTION OF NEW STRUCTURES

The work on crack-induced corrosion suggests that the depth of concrete cover is more important to reducing the risk of corrosion than crack width. The reason for this is not entirely clear. Increasing the thickness of concrete cover increases surface crack widths but crucially this means that crack spacing also increases. The effect of this is to reduce the number of sites where corrosion activity can occur thereby reducing the number of sites which may experience a large amount of corrosion. A larger spacing of cracks also increases the distance between anodic and cathodic areas which has been shown to reduce the rate of corrosion [19]. It is also possible that large concrete covers reduce the rate of oxygen supply to cathodic areas thereby reducing the overall rate of corrosion.

The tests on crack-induced corrosion have mostly been carried on members containing only longitudinal bars. In practice, steel reinforcing bars are present in two directions at right angles in virtually all concrete members. In the case of beams this will be the stirrups whereas in the case of slabs and walls this will be either the main or distribution steel. Thus, any cracks which form transverse to the main steel can potentially coincide with steel bars present at right angles. To protect these bars from corrosion it would be better if the cracks were as narrow as possible and ideally zero. Whilst increasing the thickness of concrete cover would appear to be beneficial at preventing corrosion of bars which occur at right angles to steel reinforcing bars this measure may increase the risk of corrosion of the bars in the orthogonal direction [20]. Thus simply increasing the thickness of concrete cover may be insufficient.

One method of protecting both sets of bars would be to increase the thickness of concrete cover and introduce bars made of non-corrodible materials in the concrete cover. The purpose of the bars in the cover is simply to reduce surface crack widths and because they are made of non-corrodible materials should reduce the overall risk of corrosion of concrete members. Laboratory tests show that it is possible to provide deep covers of the order of 100mm to the main steel and achieve crack widths which comply with the requirements of Eurocode 2 by introducing bars made of glass fibre reinforced plastic in the cover at a depth of around 30mm [21].

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