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Propagation of reinforcement corrosion in concrete and its effects on structural deterioration

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With a strong interest in the development of limit-state service life design, it is most encouraging to see such research by the authors. The useful service life during the propagation period will largely depend on how corrosion, such as chloride-induced corrosion, affects the structural behaviour. One approach has been in quantifying when an unacceptable wide crack occurred. The second approach could be when and how cracking adversely affects structural performance either in terms of serviceability or load-carrying capacity. Li and Zheng contribute to the second approach. They conclude that the water/cement (w/c) ratio has some influence on structural deterioration in terms of strength deterioration of reinforced concrete (RC) flexural members whereas there was no clear evidence on the influence of the cement type. They also found different deterioration rates in terms of strength and stiffness (serviceability) with the latter deteriorating faster, and that the corrosion current method underestimates the strength deterioration by an order of 20%.

Limit-state service life design for flexural members

Under limit-state design considerations and for most

structures under normal service loads, the results would suggest that the deterioration owing to corrosion will lead to excessive loss of stiffness and hence deflection. The service life is therefore likely to be determined by the serviceability limit. Should engineers focus on identifying such a limit? In the case of increased allowable load limit such as the use of heavier trucks, assessment of the remaining service life of a structure should then be focused on both serviceability and the ultimate strength limit.

Work at the Laboratoire Matériaux et Durabilité des Constructions in Toulouse, France by Castel *et al.*^{26–29} on the deterioration of under-reinforced RC beams under sustained load and exposed to saltwater fog for various periods up to 17 years, also showed the main deterioration to be the loss of stiffness at service load, and also a reduction of ultimate strength. They attributed the loss of stiffness to the deterioration of the steel/concrete bond strength of the main tensile steel.

In the assessment of structural serviceability, Li and Zheng have chosen to use the ultimate deflection to represent the beam residual stiffness as it has the advantage of measuring the combined effects of flexural cracking, corrosion-induced spalling, debonding and also steel yielding. This may be the scenario when the

structure is subjected to greatly increased loading. Under normal working conditions, the structural serviceability depends more on the beam stiffness in the stabilised flexural cracking phase and before steel yielding.^{26,27} Such behaviour can be observed as deflections at 4.8 kN, 60% of the ultimate load, in Fig. 6 of the paper. They showed the effect of exposure for 7 months with significant increase in the deflection—that is, a reduction in the stiffness owing to corrosion.

The deflection at ultimate load seems more representative of the beam failure and especially of their residual ductility. Results presented by Li and Zheng are surprising and show that corrosion leads to an increase in ultimate deflection. Other researchers such as Castel *et al.*^{26,27} or Cairns *et al.*³⁰ have shown that, on the contrary, corrosion leads to very significant reduction (up to 70%) in steel reinforcement ductility with consequent reduction in ultimate deflection. This contradiction may be explained by the experimental context in which tests by Castel *et al.* and Cairns *et al.* were performed—that is, directly on corroded steel bars or on simply supported beams with corroding steel reinforcement. The cantilever beam configuration, with a reinforcement lapping in the central part of the beam where the bending moment is constant and maximum, is very interesting. It would be useful to know the distribution of the corrosion damage (corrosion concrete cracking, steel cross-section reductions) along the beams and especially around the reinforcement lapping area. Indeed, the slippage between steel and concrete in this area owing to the loss of anchorage capacity could explain the increase of the deflection resulting from corrosion. It would then be interesting to know how the beams failed (tensile steel yielding and failure, steel total debonding in the lapping area).

Initiation based on cover to main reinforcements

As previously mentioned, it would be interesting for Li and Zheng to observe the real extent of the corrosion and its distribution in the tested cantilever beams. This

would confirm the validity of the use of non-destructive corrosion measurement, and the extent of corrosion of the nearest steel (stirrups) and main reinforcement.

It has always been extremely difficult to translate the polarisation resistance into corrosion current or weight loss of steel. This is due to the problem in estimating the area of steel affected and the nature of the corrosion.

Castel *et al.*²⁸ found that the flexural cracks that coincide with the stirrups contribute to the corrosion of these stirrups, whereas chloride ingress leads to the corrosion and subsequent cracking of the main reinforcements. The top steel bars, with respect to casting, are more susceptible to earlier corrosion and cracking because of the voids trapped underneath these bars, and hence the ready availability of oxygen. If such characteristics are confirmed by Li and Zheng, it may be possible for a realistic time to corrosion initiation to be estimated from the concrete cover to the main reinforcement rather than from the cover to the nearest reinforcement used in current codes and standards.

Performance of cement types

The influence of cement types on the strength deterioration would depend on the protection each concrete offers against corrosion initiation and corrosion propagation. The degrees of protection depend on both the cement type and concrete constituents. Extracts of work by Sirivivatnanon *et al.*³¹ on a series of stress-free RC slabs exposed to laboratory simulated tidal exposure are given in Tables 5 and 6. It shows that the initiation period and corrosion rate, evaluated by the time taken for linear polarisation resistance to reach a stable low level and the inverse of the average polarisation resistance level respectively, increase with improved concrete cover and are cement dependent for concretes at the same w/c ratio. Normal cement concrete provides better protection to steel reinforcement compared with a 30% fly ash concrete mix of similar w/c ratio. However, the differences seem to diminish with increases in cover

Table 5. Composition of concrete mixtures (kg/m³)³¹

Constituents	Nominal w/c	Cement	Fly ash	Water	WRA	SP	Sand	Crushed rock	Slump: mm
Normal cement concrete (G)	0.40	420	—	170	1.97	0.86	555	1230	95
	0.60	285	—	170	1.33	1.80	626	1280	90
Fly ash-blended concrete (A)	0.40	290	125	165	1.94	0.65	545	1210	95
	0.60	290	85	170	1.33	0.00	715	1165	130

WRA = water reducing admixture; SP = superplasticiser.

Table 6. Compressive strength and time to reach stable polarisation resistance (days)³¹

Concrete	w/c	28-day compressive strength: MPa	Time to reach stable R_p (days) and average stable R_p (k ohms)	
			10 mm cover	20 mm cover
Normal cement concrete (G)	0.40	63.0	NA	NA
	0.60	38.0	250, 0.65	700, 0.90
Fly ash-blended concrete (A)	0.40	62.5	NA	NA
	0.60	25.5	100, 0.38	500, 0.50

NA: results not available.

thickness from 10 to 20 mm. At 20 mm cover, the corrosion rate in the fly ash concrete appears to be greater than that of normal cement concrete.

Li and Zheng used 25 mm cover to the nearest steel and found little differences in their performance. It is possible that with larger cover, the difference in the initiation period for the two concretes diminishes. The more important factor influencing the corrosion rate in the cantilever RC beams could be the top bar effect as found and reported by Castel *et al.*²⁸

Conclusion

It is argued that work by Li and Zheng and others on the deterioration of performance of RC structures with corroding steel reinforcement will provide engineers with the tool to design realistically for the service life of RC structures. The differences in the load–deflection behaviour of concretes with different degrees of corrosion, such as those shown in Fig. 6 in the paper and Fig. 10 in Ref. 26, are possibly owing to the difference in the reinforcement detailing. This nevertheless highlights the importance of understanding the impact of steel corrosion on the deterioration of different RC designs and primary stresses. For flexural members, there may be a case for considering the cover to the main reinforcement as the critical cover for service life design. A reply by Li and Zheng would be invaluable to this unconventional philosophy. Consideration will also be needed to see if such behaviour applies to other types of structural members subjected to different primary loads such as compression in columns and shear in short beams and slab column joints. Such studies will enable a comprehensive approach to service life design for all structural elements.

Authors' response to contribution by V. Sirivivatnanon, A. Castel and R. François

We are delighted that our paper has generated such interest to the discussers. We thank the discussers for

their compliments and are grateful that the discussers have made very thoughtful and stimulating comments. We totally agree with their comments and would like to reply with following general points.

- (a) We believe that limit-state-based service life prediction is the method to follow for practical application of our methodologies. We believe that research should focus on the development of probabilistic models for structural performance at different stages of service life. This is essential to service life prediction.
- (b) Based on our test results and observations we found that corrosion-induced problems are more severe for serviceability limit states than ultimate limits. As the discussers rightly pointed out, corrosion-induced bond loss between the concrete and reinforcement is a realistic problem. Bond loss causes the increase of deflection. This is not a surprise.
- (c) We have not examined the ductility of corroded reinforcement in our published tests but are doing so currently for our ongoing tests. The information provided by the discussers is very useful.
- (d) We have observed from a number of tests on corrosion effects on structures that the specimens failed by tensile steel snapping.
- (e) We think the notion of cover to main reinforcement is more logical than that of cover to nearest reinforcement. We believe that, for flexible members, the role of cover should at least be re-examined.
- (f) We only conducted tests on the effect of pulverised fuel ash (pfa) blended cement on structural behaviour. Based on our tests and also published results from other researchers, we need to be convinced that pfa blended cement would hugely reduce the corrosion effects on structural behaviour of flexible members.

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