Durability of Reinforced Masonry

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SUMMARY

The potential durability problems arising from corrosion of steel reinforcement are reviewed and discussed in respect to the design of reinforced and prestressed brick and block masonry. The three alternative protection techniques: burial in alkaline concrete; surface coatings and the use of stainless steel are examined and conclusions are drawn as to the design requirements to ensure that each technique will give an acceptable performance in masonry.

INTRODUCTION

This is a short discussion of the durability hazards that threaten the integrity of reinforced brick and block structures in the UK environment. Although such structures are potentially at risk from a number of other environmental hazards such as sulphate attack of the mortar, moisture expansion of clay bricks, and excessive shrinkage of blocks or calcium sulicate bricks, this note concentrates on the problem of corrosion of steel reinforcement which the author regards as potentially the most serious. This is already a widely occurring problem in reinforced concrete structures and for a number of reasons it could be an even more serious hazard for reinforced brickwork if it is not 'designed out'.

THE PROBLEM

Normal carbon steels corrode by oxidation in the presence of free water or water vapour and oxygen ie the normal environment of a building anywhere in the world. During the corrosion process hydrated oxides are produced having a volume seven times that of the metal from which they are formed. Thus if the steel does start corroding the increase in volume inevitably causes damage to the material which it is reinforcing in cases where it is embedded in a matrix. Additionally the effective cross-section of the steel is being reduced and thus the safety of even prestressed structures with air cavities may be affected.

Examples of such damage to concrete are legion and are salutary reminders of what not to allow in a Code of Practice for reinforced masonry. Figure 1 shows two views of some reinforced masonry suffering from damage due to expansive corrosion of steel. These examples are admittedly much rarer than those for concrete but possibly only in proportion to the number of such structures compared to those in concrete!

THE SOLUTIONS

The key to the satisfactory functioning of any reinforced structure is the protection of the reinforcement in some way. There are three accepted ways to protect the reinforcement:

Solution 1: Burial in an alkaline matrix

Normal carbon steels when buried in sufficient depth of alkaline concrete or mortar, free of harmful additives, do not corrode. While such cementitious

Fig.1 Corrosion failure of reinforced brickwork

'tombs' remain in an alkaline state the steel protects itself by forming an insoluble oxide film over its surface which inhibits further reaction.

The enemy of this system is carbonation which acidifies the concrete and nullifies the protection. Carbonation is the reaction of atmospheric carbon dioxide, in the presence of moisture, with the alkalis in the set concrete to form carbonates and is typically of the form:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

During this process the pH of the concrete falls from about 12-13 (alkaline) to 7-8 (neutral). Since the carbonation tends to proceed from any surface exposed to the atmosphere the carbonated zone forms as a surface layer with a 'front' at the boundary between the unaffected and the carbonated concrete. The carbonation 'front' will sooner or later get to the steel, the time being dependent on the depth of cover, cement content, porosity, and ambient conditions. Paradoxically the worst carbonation condition is the interior of a building in an average humidity range. Exterior conditions especially where the masonry gets damp or wet lower the rate of carbonation. However once the carbonation front arrives at the steel surface the process of corrosion will commence and then the more exposed or damp the wall is, the faster will be the rate. Industrial pollutants such as SO_2 will normally increase the rate of acidification.

Research on carbonation rates is still in progress but some idea of the life of such protection systems can be gauged from existing work. Starting with the worst extreme eg very porous and minimal cement content, it has been shown by Grimer and Brewer [1] that autoclaved aerated concrete carbonates at a rate in excess of 50 mm/year in dry conditions. Normal brickwork mortars probably carbonate at a lower rate than this but Moore [2] concludes that most of these are fully carbonated within a period of 10 years except the centre of the 'blobs' in the frog. On the assumption that carbonation proceeds both from the surface and from the interface between brick and mortar (an important assumption) this implies average rates in the region of 1 mm/year or faster. Aerated mortars may carbonate more rapidly because of the intentionally higher porosity and lower alkalinity and such factors may need some study.

The assumption made above implies that the effective cover given by a bed joint to reinforcement buried within it is only $0.5\ (t_m - d_r)$ where t_m and d_r are respectively the thickness of the mortar bed and the diameter of the reinforcement respectively (the cover may be nil if spacers are not used). The other implication is that the effective cover given by the layer of brickwork to reinforcement buried in pockets within it is nowhere near its actual thickness because the interface between brick and mortar is not an efficient barrier.

Mosts tests carried out on old mortar support this conclusion, ie that carbonation of a mortar proceeds from the bed face at almost the same rate as from the external face. Limited durability studies of reinforced grouted cavity brickwork in exposed conditions have supported this contention in that there is frequently more serious pitting of the steel opposite each mortar joint in such tests.

In a review of the performance of their own and some other externally exposed experimental reinforced brick structures Foster and Thomas [3] observed behavior very much in line with the conclusions made so far about structures reinforced with plain steel ie:

i) Mortar in beds or pockets gave very little or unreliable protection against rusting or potting of the reinforcement. Even the strong mortars used (grades (i) and (ii)) appeared to be carbonated within 5 years and generalised corrosion had set in.

ii) There was some evidence of localised pitting in some of the grouted cavity walls probably adjacent to mortar beds.

iii) Generalised corrosion had set in in some of the grouted cavity walls with a nominal cover of 19 mm after only 2 years.

We are now left with the mortar or concrete in the pockets or cavities as the only effective barrier to the corrosion of the steel. It should be stressed here that any factor which increases the porosity is liable to facilitate the diffusion of the CO_2 and the consequent carbonation, thus the designer and the builder must avoid high water:cement ratios, aeration, poor compaction and the use of porous or poorly graded aggregates in concretes intended to protect steel.

This leads to a dilemma in respect of infillgrouts since the other requirements such as high plasticity and low cost would tend to lead to the specification and use of weak high water/cement ratio concretes.

Estimating the life of such protective layers is very difficult since it varies markedly with concrete type and environment but some idea of the range can be got from literature reports.

Bandyopadhyay and Swamy [4] report rates between 1 and 14 mm per year from their own and others studies on lightweight aggregate concretes. Grimer [5] reports rates between 0.5 mm/year for dense 1:5 gravel concrete to 2.5 mm per year for 1:9 gravel concrete with higher rates for lightweight aggregate concretes. Of course these values are somewhat simplistic since the rate is liable to tail off as the carbonation front moves into the concrete just because of the limitations on the rate at which the carbon dioxide and water vapour can diffuse through the concrete. This limitation probably is only important, however, for dense, relatively non porous material and brings out the importance of the use of good quality material and workmanship in the attainment of effective cover.

More complex expressions for rate of carbonation are given by Venuat and Alexandre [6] either proposed by other authors or on the basis of their own work. Their rate was a root of time expression with an initial constant of the form:

$$e = b + a\sqrt{t}$$

where e is the depth of carbonation, t is the time in years and a and b constants dependent on the cement content, porosity etc.

At the minimum grade of concrete currently proposed as cover in the draft Code (Grade 25) the rate quoted is:

$$e = 2 + 12 \text{ to } 15\sqrt{t}$$

eg in 16 years the carbonation front would have penetrated 50 mms!

At higher cement contents or low w/c these rates are lower eg for grade 40 they quote:

$$e = 0 + 5\sqrt{t}$$

This still implies a penetration of 15.8 mm in 10 years, but a reasonable life of 100 years for a 50 mm depth.

Although these rates may be pessimistic to some extent, the implications are that for steel embedded in narrow, pockets or cavities in brickwork the grade necessary to give reasonable durability is a lot higher than the minimum stated in the current draft.

In partial recognition of the carbonation problem the grades of concrete and minimum cover have been uprated in the current draft Code of Practice CP 110 in Table 48, p16 of Section 6 'Specification and workmanship', and they are varied in inverse proportion to the nominal cover.

Another area of uncertainty which can effect profoundly the durability is the positional accuracy to which the steel is placed in cavities and cores. It is of little point designing on the basis of a nominal concrete cover if the bar can vary in position by ±20% of this figure. Also secondary reinforcement should be taken into account if it is any more substantial than 3 mm wire since it can have just the same disruptive effect.

It is well to remember that most examples of structural reinforced concrete are less than 50 years old and there may be more failures than are now known about waiting to be discovered. Buildings should not be designed for a 50 year life, if in reality, people typically expect a 100 or more years life.

Solution 2: Protective coatings applied to the carbon steel

There are a range of protective coatings available which will prevent moisture and oxygen from reaching the steel surface for a limited period. The commonest type is of course a coating of zinc (galvanising) but other coatings that have been used or proposed include cadmium, nickel, bitumen, epoxy resin, thermoplastics, etc or combinations of these. Straight organic coatings such as epoxy resin appear all right in theory but are generally found wanting because they are flawed or are damaged during transport or handling, leading to preferential attack at the 'hole'. Single or duplex organic coatings are probably sufficient for some situations such as air cavities. Metal coatings are satisfactory generally but have a finite life. Treadaway, Brown and Cox [7] have demonstrated that their life can be extremely short in agressive conditions (severe exposure). Recently it has been demonstrated [2] that galvanising layers have a much shorter life in externally exposed mortar beds than was previously assumed and that to achieve even a minimum reasonable life of 60 years in mortar required a thickness of 940 gms/m^2 - four times the previously allowed minimum! BS 1243 for wall ties has now been amended in this light and the Code should recognise this by only accepting such coating levels as minimal for reinforcement protected in this way and subject to external exposure conditions. Other straight metal coatings are generally accepted as being inferior to zinc and are not widely available.

Duplex coatings such as bitumen or epoxy over zinc may have a better durability but are relatively new and untried as yet.

Foster and Thomas [3] showed that although the galvanising gave limited protection there was evidence of zinc loss in experimental grouted cavity brickwork, in the more exposed site ie the writing was on the wall.

Solution 3: Internal protection of steel by alloying to form stainless steels

For all normal applications ie plain reinforcement and low moderately prestressed reinforcement in a range of conditions up the the more severe, austenitic stainless steels (ie those containing 18% chromium and 8%+ nickel) should be very durable.

Evidence so far available indicates that the protective oxide film is effective when such steels are buried in concretes and mortars even after full carbonation.

It should be stressed here that these remarks do not apply to ferritic stainless steels which are no better than carbon steels in this application.

PRESTRESSING IMPLICATIONS

Many brick structures would benefit from the application of a prestress to improve reinforcing efficiency and prevent cracking. Provided the levels of prestress are relatively low, say less than 15% of UTS of the steel, the remarks made above probably apply without qualification. In designs with a signficant level of prestress other failure mechanisms such as stress corrosion cracking have to be taken into account and levels of protection may need to be increased. Even austenitic stainless steels may suffer stress corrosion cracking at high levels of prestress and in the presence of chlorides and thus a great deal of care needs to be exercised in such designs.

CONCLUSIONS

1 The mortar in bed joints offers only a very short term protection to reinforcement embedded in it and thus should be discounted. All bed joint reinforcement should be protected in some other way.

2 The brick or blockwork skin does not offer a significant barrier to carbonation since the carbon dioxide can penetrate the minute cracks at the mortar/unit interface and work in from the inner face. Concrete blocks will have less joints but this may only serve to widen the cracks. They also will allow carbonation to proceed through their own concrete walls at rates higher than that suffered by good structural concrete. At best, the protection offered by a 100 mm masonry skin can only be considered to be equivalent to a few mm of good quality concrete.

3 Hand placed mortars and low strength high w/c grouts, although structurally adequate, are not a satisfactory means of protecting carbon steel reinforcement in small pockets and cores and therefore other means must be used.

4 Carbon steels in properly designed cores, cavities or pockets, spaced accurately to ensure the expected cover and sourrounded by high

quality, well compacted, non-porous concrete will have a reasonable life in moderate conditions.

5 In cases where maximum durability is required or where harsh environments are to be encountered stainless steel reinforcement should be used. For intermediate durability or environment, coated steels should be employed. Coatings should be required to be of similar quality to those given in BS 1243 for externally exposed masonry.

6 The code should make explicit recommendations about the quality of concrete for protection of reinforcement, the workmanship levels required during placing and the accuracy to which the reinforcement is positioned.

7 Secondary reinforcement should be treated the same as primary reinforcement if it is anything more substantial than wire used to fix the position of the primary reinforcement. It should thus have the same degree of cover or other protection.

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