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CORROSION PROTECTION OF PRESTRESSING TENDONS FOR MASONRY

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ABSTRACT

The consequences of two or three tendons becoming severely corroded in a prestressed masonry structure are likely to be more serious than if a few bars of a comparable reinforced masonry structure were to corrode. A cautious approach to protecting prestressing tendons from corrosion therefore appears to be warranted particularly as there is, as yet, little long-term experience of the in-service performance of prestressed masonry. Accepting that a cautious approach is required, proposals for the corrosion protection of tendons in new prestressed masonry construction are presented.

INTRODUCTION

Although not yet widely specified by engineers, prestressed masonry is attracting increasing interest as an alternative to more conventional forms of construction for building and civil engineering structures. In the last thirty years a variety of tall, relatively slender masonry walls have been prestressed to improve their resistance to the lateral forces produced by wind, retained earth, stored materials, surge effects from cranes, thrusts from sloping roofs or the effects of mining subsidence (Phipps 1991). More recently existing masonry buildings damaged by seismic activity have been retro-fitted by prestressing (Ganz 1993) and prestressed masonry has been used for the abutments of new highway bridges (Garrity et al. 1993).

When designing prestressed masonry structures, engineers generally rely on a small number of highly stressed, large diameter tendons to maintain a state of compression in the masonry, one of the principal aims being to counteract any tensile stresses that would be produced under design service loading. In contrast, when designing reinforced masonry elements to resist similar magnitude loading, it is common practice to detail a larger number of comparatively small diameter steel bars which are usually required to

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sustain much smaller tensile stresses than those applied to the prestressing tendons. It follows that the consequences of two or three tendons becoming severely corroded in a prestressed masonry structure are likely to be far more serious than if a few bars of a comparable reinforced masonry structure were to corrode. A cautious approach to protecting prestressing tendons from corrosion therefore appears to be warranted, particularly if past experience with the corrosion of metal ties or steel studs in masonry walls is taken into account.

The most common use of prestressed masonry is likely to be where the tendons are post-tensioned to strengthen vertical structural elements such as walls or columns; pre-tensioned tendons and non-vertical forms of construction such as floors are not considered in this paper. There are many different factors that influence the choice of corrosion protection measures for post-tensioned tendons in masonry construction; the following points are considered:-

a) Corrosion of prestressing tendons - a brief review.

b) Long-term performance of post-tensioned tendons.

c) Design considerations.

d) Recent practice.

e) Review of alternative forms of corrosion protection.

f) Discussion - the need for a cautious approach.

g) Recommendations for new construction.

CORROSION OF PRESTRESSING TENDONS - A BRIEF REVIEW

Corrosion of steel reinforcement

Many engineers will be familiar with the corrosion problems that have afflicted mild and high yield carbon steel reinforcing bars and ties in concrete and masonry construction. Normally, steel components cast in concrete or embedded in mortar are passivated against electrolytic corrosion by the highly alkaline environment provided by the hardened cement paste. Corrosion occurs when the steel becomes de-passivated, often as a result of carbonation of the cement paste or the action of chloride ions. In reinforced concrete construction the risk of corrosion will be reduced if the steel reinforcement is protected by an adequate thickness of low permeability, low porosity cover concrete. Measures adopted to reduce the permeability and porosity include the use of concrete with a low water:cement ratio and a comparatively high cement content. Recently, partial cement replacement materials such as ground granulated blastfurnace slag (ggbs) or pulverised fuel ash (pfa) have been used to reduce shrinkage cracking and the capillary porosity of the cement paste, particularly where exposure to chloride attack is likely. Other measures include ensuring adequate compaction and curing of the concrete on site, the use of surface treatments such as silanes or bituminous membranes and avoiding the use of mix constituents and additives containing chlorides.

It is generally accepted that conventional cementitious mortar used in masonry construction does not provide the same long term corrosion protection to embedded steel as high quality cover concrete. This is because mortars usually have a lower cement content and a higher water:cement ratio than structural grades of concrete, thereby producing a more permeable cement paste which is less resistant to the ingress of deleterious substances. As a result it has become common practice to use galvanised, epoxy coated or stainless steel components such as wall ties and bed joint reinforcement in masonry construction.

Corrosion of prestressing steel - hydrogen embrittlement
Like reinforcing steel, prestressing steel used in masonry or concrete construction is also susceptible to electrolytic corrosion caused by carbonation and chloride attack. Although not a very common problem, prestressing steels may also fail in service due to hydrogen embrittlement (Burdekin and Rothwell 1980). Unlike electrolytic corrosion which usually causes a progressive degradation of the steel and tell-tale signs of impending failure, hydrogen embrittlement leads to a sudden loss of function; it can occur in many types of prestressing steel including stainless steel.

Failure can occur when atomic hydrogen diffuses into the steel. Depending on the amount of atomic hydrogen present and the microstructure of the steel, in particular the number of dislocations, an internal pressure can be generated which causes plastic deformation of the microstructure or microcracking. When the steel is subjected to an externally applied stress, as is the case with prestressed tendons, the combined effect of the diffusing hydrogen and the external stress causes crack initiation and growth leading to brittle failure. The time elapsing between the stressing and eventual failure of the tendons, known as the incubation period, varies between a few days and several years. It is known that susceptibility of metals to hydrogen embrittlement failure is dependent on the intensity of the hydrogen development, the combined magnitude of the residual and external applied stresses and the type of steel (Hampejs et al. 1991).

Sources of hydrogen. There are various sources of hydrogen that could lead to hydrogen embrittlement failure (FIP 1986, Hampejs et al. 1991); these include:-

i) molecular hydrogen present in the steel as a result of the melting process. It should be noted, however, that the hydrogen content in modern steels is usually insignificant.

ii) electrolytic corrosion - hydrogen is produced at cathodic sites. Where pitting corrosion occurs, for example with chloride-induced corrosion, crack growth could initiate at the bases of the pits formed in the steel surface. Failure of steel caused by hydrogen embrittlement in severe corrosion environments is usually known as stress corrosion cracking.

iii) hydrogen may be produced by stray currents or where the steel is electrically coupled to a more anodic metal that corrodes (as is the case with cathodic protection). This is unlikely to be a major cause for concern, however it does cast doubt on the use of cathodic protection as a form of corrosion protection for prestressing tendons, particularly where high currents are used (Berkeley and Pathmanaban 1990).

iv) galvanising. Electro-galvanising, which is rarely used for prestressing steel, can produce hydrogen. Although hot-dip galvanising, which is more commonly used for prestressing tendons does not create hydrogen, acid pickling used as a surface preparation prior to galvanising does. This was thought to be the cause of failure of a small number of galvanised high tensile alloy-steel bars used to prestress the masonry abutments of two bridges in the UK - see later.

v) hydrogen produced from the reaction between cement paste and aluminium. Most likely to be a problem if aluminium ducting is used with a cement grout.

vi) hydrogen evolved from the reaction between cement paste and zinc. This is only likely to be a problem where the zinc coatings on galvanised steel surfaces have become damaged and the hydrogen can diffuse into the steel.

Magnitude of stresses and type of steel. Research by metallurgists has shown that the critical stress intensity factor, K_{ISCC}, can give a qualitative ranking of the susceptibility of steel to hydrogen embrittlement and stress corrosion cracking (Burdekin and Rothwell 1980, Hampejs et al. 1991). For a given material in a known environment, using the critical stress intensity factor, it possible to determine safe values of working stress and the acceptable size of any crack-initiating defects that exist in the steel. It is now generally accepted that quenched and tempered steel is the most sensitive to hydrogen embrittlement. This is because the quenching process produces high residual stresses in the steel and the martensitic microstructure contains relatively few dislocations which reduces the mobility of the molecular hydrogen leading to a greater build up internal pressure and a consequent increased risk of failure. Such steels are also less tolerant of any defects in the microstructure. Conversely, although no steel is immune, cold drawn steel wire is the least susceptible to hydrogen embrittlement. The drawing process produces a pearlitic microstructure containing a higher number of dislocations which allow hydrogen to diffuse more easily thereby reducing the formation of high internal pressures. Furthermore, cold drawn steel wire is relatively free of internal stresses provided that there is no significant mechanical damage during the drawing process. Similarly hot rolled steel is also less sensitive to hydrogen embrittlement than quenched and tempered steels.

Steel prestressing tendons are usually initially stressed to 70% or 75% of their characteristic tensile strength. Allowing for losses of prestress of between 10 to 15% in clay brick masonry means that the working stress in hot rolled alloy-steel bar tendons such as the Macalloy and Dywidag types is likely to be in the order of 550 to 600 N/mm² (79750 to 87000 psi). Where as-drawn 7-wire tendons are used, as with the VSL and similar systems, stresses in the tendons of between 950 and 1100 N/mm² (137750 to 159500 psi) are likely. The stresses in the tendons used to prestress concrete masonry are likely to be lower than those quoted above due to higher expected losses of prestress.

In contrast, the in-service stresses in steel reinforcing bars used in reinforced masonry are likely to be considerably lower. In many cases, the tensile stress due to permanent loads in high yield carbon steel reinforcement is unlikely to be higher than about 250 N/mm² (36250 psi) and may be considerably less. Hence, because of the much lower levels of tensile stress, steel reinforcement is far less susceptible to hydrogen embrittlement failure than prestressing steel.

To summarise, all prestressing steels are susceptible, to some degree, to hydrogen embrittlement failure with quenched and tempered steels being most at risk.

Other forms of corrosion such as fretting corrosion, corrosion fatigue and bacterial attack have also been identified and may need to be accounted for in design (FIP 1986).

LONG-TERM PERFORMANCE OF POST-TENSIONED TENDONS

As prestressed masonry is a recent and, as yet, comparatively rare form of construction, there is insufficient evidence available to judge the long-term corrosion resistance of post-tensioned tendons used in masonry. In contrast, post-tensioning has been used extensively in concrete bridge construction and for ground anchors and the corrosion problems encountered with both these forms of construction are briefly reviewed below. Although concrete bridges and ground anchors are generally subjected to more severe exposure conditions than most likely examples of prestressed masonry, it is, nevertheless, worthwhile carrying out such a review to identify any potential problems needing attention in design.

Long-term performance of post-tensioning systems in concrete bridge construction
The first post-tensioned concrete bridge in the UK was built in 1947; since then post-tensioning has been used for about 3000 bridges in the UK most of which have been of bonded construction, that is where the tendons are located in ducts within the concrete, the annular space between the duct and the tendons being filled with cementitious grout after the tendons have been tensioned and anchored. Concerns about the effectiveness of the grouting operation in post-tensioned construction have been raised for several years; such fears have been fuelled by the results of some surveys of concrete bridges which indicated that a high proportion of the ducts contained voids (Woodward 1981).

One such highway bridge, the single 18m span Ynys-y-Gwas bridge near Port Talbot in South Wales which was built in 1953, collapsed on 4 December 1985. The bridge was of post-tensioned segmental construction, the joints between each precast segment consisting of trowel-applied cementitious mortar. Failure was attributed to severe localised corrosion of the longitudinal prestressing tendons caused by leakage of chloride rich de-icing salts through the mortar joints (Woodward and Williams 1988). A number of other concrete bridges of bonded post-tensioned construction with poorly grouted tendons have been affected by chloride-induced corrosion to such an extent that they have either been demolished or extensively repaired (Mallett 1994).

Long-term performance of post-tensioned ground anchors
In a comprehensive review of the corrosion performance of post-tensioned ground anchors dating back to 1934, 35 cases of tendon corrosion were reported (Littlejohn 1987). Several failures were attributed to hydrogen embrittlement or stress corrosion cracking and the author of the review stated that quenched and tempered plain carbon and high strength alloy steels were more susceptible to hydrogen embrittlement than other types and should be used with extreme caution where the environmental conditions are aggressive. In addition, corrosion of poorly grouted tendons was noted and a number of examples of corrosion were found either at the anchor head or just below it. In addition, one failure was noted due to over stressing of the steel caused by poor alignment of the tendon at the anchor head. Regarding the reported corrosion of some anchor heads, it is interesting to note the warning of the high susceptibility of hydrogen

embrittlement in the harder and more highly alloyed steels generally used in the manufacture of anchorage plates (Burdekin and Rothwell 1980).

DESIGN CONSIDERATIONS

When designing and specifying corrosion protection measures for the tendons used in prestressed masonry construction, the following should be taken into account:-

a) The design life of the prestressed masonry structure.

b) The degree of exposure. Conditions where stress corrosion cracking of the tendons is a risk, such as exposure to chlorides combined with high temperatures and humidity levels, are a particular concern.

c) The consequences of corrosion. How will the safety and stability of the structure be affected in the event of a significant loss of prestress caused by tendon corrosion?.

d) Costs. In particular the need to balance the cost of providing adequate corrosion protection against the likely cost of tendon replacement and the resulting disruption to the users or owners of the prestressed masonry structure.

e) The comparative lack of corrosion protection provided by high water:cement ratio, low cement content materials such as mortar and grout.

f) The risk of tendon failure due to hydrogen embrittlement.

g) The need to inspect the tendons for signs of corrosion in the future.

h) The need to provide protection to all parts of the prestressing system including any exposed anchorages and coupled sections of the tendons. Design details should be adopted which prevent the build-up of moisture and the ingress of corrosion inducing compounds such as chlorides.

i) Care must be taken to ensure that the anchorages are carefully set out on site to avoid any serious misalignment of the tendons. When such tendons are post-tensioned significant flexural stresses may occur that could cause overstressing. The use of details capable of accommodating small misalignments, such as articulating anchor plates, is recommended.

j) Corrosion protection systems should be sufficiently simple enough to install on site using the skills available to increase the likelihood of achieving an adequate standard of workmanship. Linked with this is the need to provide adequate supervision and checking of work on site. If complex, multi-layer protection systems are deemed necessary, a high element of factory-based prefabrication with adequate quality control measures may be necessary.

k) Care must be taken to correctly store prestressing tendons on site to minimise the risk of damage to the corrosion protection systems.

l) Some post-tensioning systems require the use of large amounts of reinforcing steel adjacent to the end anchorages to resist lateral bursting stresses produced during stressing. This must also be considered in the design of the corrosion protection system.

m) The reliability of the proposed method of corrosion protection. Can the system be checked once applied?. Can the prestressing system continue to operate as originally envisaged without major maintenance?.

n) The need to de-stress, remove and replace tendons in structures subjected to potentially severe exposure conditions where the risk of corrosion is high.

o) In some circumstances it may be necessary to restress the tendons. Where this is the case, the upper anchorage must be accessible (and enough space must be available for the connection of the stressing equipment) and unbonded tendons must be specified.

p) The corrosion protection systems must be robust enough to avoid the inevitable damage that will occur during transportation and installation.

q) The tendons and the protection measures should be capable of accommodating the strains in the tendons during tensioning without reducing the degree of protection.

RECENT PRACTICE

Recent UK practice
Although by no means exhaustive, a summary of the corrosion protection measures used in some examples of prestressed masonry built in the UK is given in Table 1. Apart from some early examples of bonded construction in which the tendons were installed in plastic ducts with the annular space grouted after stressing, the more recent examples of prestressed masonry in the UK seem to have been of unbonded construction. Even though unbonded construction is not as structurally efficient as the bonded alternative it is likely to be the preferred form for most applications given the design requirements listed previously.

For ease of construction, designers in the UK have tended to specify tendons consisting of either coupled lengths of high tensile strength steel-alloy Macalloy prestressing bar or high yield hot rolled steel reinforcing bar. In both cases corrosion protection is usually provided by wrapping the tendons on site in two layers of “Denso tape”, a non woven, synthetic fabric impregnated and coated with petroleum hydrocarbons and inert siliceous fillers. End anchorages usually consist of steel plates protected against corrosion by bituminous paint, concrete or cementitious grout. Macalloy bar tendons are usually tensioned using hydraulic rams, whereas reinforcing bars are tensioned using torque wrenches.

Table 1. Corrosion protection of tendons in prestressed masonry - some examples of UK practice

Structure (Reference)	Structural Element	Prestressing Tendons	Corrosion Protection		
			Tendons	Lower Anchorage	Upper Anchorage
Circular water tank. (Maurenbrecher and Foster 1975)	Tank walls - clay brickwork.	Bonded. Vertical and external hoop tendons - 7mm dia. hard-drawn high tensile steel wire.	Vertical wires - in 16mm dia. sheaths - annular space grouted after stressing. Hoop wires - protected by external grouted cavity brickwork	Cast in R.C. ring beam	Cast in R.C. ring beam
Oak Tree Lane Community Centre. (Shaw 1982)	External walls - main hall - clay and calcium silicate brickwork	Unbonded. Threaded and coupled 25mm dia. high yield steel reinforcing bars	Denso paste and Denso tape.	Cast in R.C. foundation	not known
George Armitage office block. (Bradshaw et al. 1983)	External wall and double-fin piers - clay brickwork	Bonded. 20mm (external wall) and 25mm (piers) dia. Macalloy bars	Tendons in plastic duct - annular space grouted after stressing.	Cast in R.C. slab	Bituminous paint
Rushden Fire Station. (Allen 1986)	External walls to fire appliance room - clay brickwork	Unbonded. Threaded and coupled 20mm dia. Macalloy prestressing bars	Denso paste and Denso tape.	Cast in R.C. foundation	Bituminous paint
Earth Retaining Wall (Beck et al. 1987)	Wall Stem - concrete blockwork	Unbonded. Threaded and coupled 25mm dia. high yield steel reinforcing bars	Galvanised then covered with Denso paste and Denso tape.	Cast in R.C. foundation	Located in preformed pocket in capping beam. Covered with cement grout + expanding agent after stressing.
Orsborne Memorial Hall (Shaw et al. 1988)	External walls - clay brickwork	Unbonded. Threaded and coupled 20mm dia. high yield steel reinforcing bars	Denso paste and Denso tape.	Cast in R.C. foundation	Located in preformed pocket in capping beam. Covered with cement grout after stressing.
Foxcovert Road and Rail bridges. (Garrity et al. 1993)	Bridge abutments - clay brickwork	Unbonded. 25, 40 and 50mm dia. threaded and coupled Macalloy bars.	Galvanised then covered with Denso paste and Denso tape.	Cast in R.C. foundation & grouted after stressing	Cast in R.C. capping beam (bearing shelf) & grouted after stressing.

Other examples
Researchers in Australia, Canada and the USA have also used rods or bars to provide the required prestress in large scale experimental work. However, the unbonded VSL system has been used for new prestressed masonry construction and strengthening work in Australia, Switzerland and the United States (Ganz 1990, 1993, 1993a). The tendons used in the VSL system consist of 7-wire strand tendons which are individually greased and sheathed in high density polyethylene under factory conditions. On site, a self-activating dead-end anchorage is initially cast into a concrete foundation. The masonry wall is then built around the required length of galvanised steel or plastic ducting. When the masonry has achieved a suitable compressive strength, each tendon is threaded through its own preplaced duct into the anchorage and stressed using portable stressing jacks.

REVIEW OF ALTERNATIVE FORMS OF CORROSION PROTECTION

As a result of the problems with grouted tendons described earlier, in 1992 the UK Department of Transport decided not to commission any new bridges of bonded post-tensioned construction and intensified the monitoring of its existing stock of post-tensioned bridges. Since the ban was introduced, the UK Concrete Society formed a number of task groups to develop reliable test methods, new specifications, new design guides, recommended details, etc. for grouted post-tensioned construction. As part of this exercise, the performance of different corrosion protection systems for external prestressing tendons was reviewed (Tilly 1994). The results of the review, which relate mainly to horizontal or near-horizontal strands in severe exposure conditions, are summarised in Table 2. Additional comments relating to the performance of different forms of corrosion protection are given below.

Cementitious grout protection
The previous reviews of post-tensioned concrete bridges and ground anchors have highlighted the difficulties encountered in ensuring that the tendons in bonded construction are fully covered with cementitious grout. Evidence of lack of grout or poor quality grouting was also found in some reinforced masonry structures damaged by the Northridge earthquake in Los Angeles, California (TMS 1994). Although the tendons in prestressed masonry will usually be vertical and therefore, in theory, easier to grout than the horizontal and inclined tendons referred to earlier, the grouting of tendons as an anti-corrosion measure still gives cause for concern. To allay such fears, the use of grouting trials prior to construction and insitu test methods to assess the effectiveness of the grouting operation may be necessary. Such an approach is time consuming and will, inevitably, lead to increased costs.

Galvanised steel prestressing tendons
Galvanised high tensile hot rolled steel Macalloy bars wrapped in Denso tape were used to prestress the brickwork bridge abutments for Foxcovert road and rail bridges on the Glinton-Northborough by-pass near Peterborough, England (Garrity et al. 1993). Unfortunately, 9 of the 184 bars used failed between 2 to 3 days after tensioning. Research by the suppliers McCalls Special Products of Sheffield, England showed that failure was probably due to hydrogen embrittlement caused by the atomic hydrogen produced by acid pickling prior to hot dip galvanising. Although not all galvanised products are at risk from hydrogen embrittlement, few engineers aware of the recent

Table 2. Properties of corrosion protection systems (Tilly 1994)

Protective System	Advantages	Disadvantages	Comments
Polymer Coatings: **PVC, PE, Epoxy**	Good barriers if free from defects. Fractures of individual wires can usually be detected by rippled deformations on the coating surface. Epoxy coated strand can be obtained with internal interstices filled.	Susceptible to damage from handling. Corrosion can develop at defects and spread beneath the coating. Early versions of PVC unstable. Available PVC and PE systems do not have internal interstices filled.	About 25 years experience. Performances variable. PE currently used in conjunction with grease.
Cementitious Grout	Possible to detect and fill voids relatively easily.	Inspection of tendons requires invasive techniques but much easier than internal ducts.	Used in conjunction with HDPE ducts.
Greases and Waxes	Fills external interstices between wires and provides additional protection beneath polymer sheath. Eliminates friction losses and fretting.	Does not fill internal interstices in strands. Greases can "fall off". Waxes can exhibit voids and cracking.	Used in conjunction with sheaths and ducts. Variable experience.
Galvanising	Good protection, easily inspected can be painted to give extra performance.	Not totally immune to corrosion. Care must be taken to ensure that the process is correctly specified.	60 years experience in various applications. Fears of embrittlement largely unfounded.
Wrapping tape	Good barrier applied on site. Inspectable and replaceable.	Little independent research. Difficult to apply in constrained locations.	50 years experience in various environments, some hostile. Low technology. Good performance.
Paint	Easily inspectable.	Requires periodic maintenance.	Variable experience due to poor maintenance. Scope for using improved paint systems.
In Situ Concrete	Easy to install. Provides alkaline environment.	Provides inadequate protection under direct leakage. Removal of concrete required for inspection.	Variable experience.
Stainless Steel	Improved corrosion resistance, should not require other forms of protection. Easy to inspect.	Can corrode at positions where it emerges from the concrete. About five times the cost of conventional steel.	No available experience for post-tensioning systems. Reported failures in warm corrosive environments.

aforementioned failures are now likely to use galvanised prestressing steel for masonry construction.

Where carbon steel reinforcement is used for prestressing, as discussed earlier, there is little risk of failure due to hydrogen embrittlement. Galvanising offers increased protection against carbonation-induced corrosion. However, where a high level of chloride contamination is possible, particularly from sodium chlorides, research at the Building Research Establishment in the UK has shown that galvanising provides limited protection against corrosion (Treadaway et al. 1988). In addition, as with all galvanised products, extra care is required on site to minimise the risk of damaging the zinc coating.

Stainless steel prestressing tendons
A recent cost study showed that an earth retaining wall prestressed using stainless steel Macalloy bars was a cost-effective form of construction when compared with other masonry and reinforced concrete alternatives (Garrity and Nicholl 1994). As far as the author is aware, the only type of high strength stainless steel prestressing bar currently available is a precipitation hardened martensitic nickel-chromium alloy; the bar has cold-rolled threads and is readily available in the UK in diameters up to 40mm (1.57"). After hot rolling, the bars are subjected to a heat treatment to provide mechanical properties that are similar to the standard range of carbon steel-alloy Macalloy bars. Testing of Macalloy grade stainless steel samples under sustained high levels of tensile stress in a sodium chloride rich environment indicated excellent corrosion resistance, however, some samples did fail in a simulated industrial environment due to stress corrosion cracking. Hence, although stainless steel Macalloy bars are likely to exhibit very good corrosion resistance, they are still susceptible to the effects of hydrogen embrittlement in the most severe environments because of their martensitic microstructure.

Where lower strength reinforcing bars rather than prestressing bars are used as tendons, austenitic grades of stainless steel, in particular grade 316, should be used as they offer the best corrosion resistance. When stainless and carbon steel types are used care must be taken to avoid bi-metallic corrosion.

Non-metallic prestressing tendons
Various types of non-metallic prestressing tendon have been developed including Parafil (Kevlar) (Burgoyne 1993), Polystal (polyester resin bonded glass fibres) (Wolff and Miesseler 1993) and Arapree (epoxy resin bonded aramid fibres) (Gerritse 1993). Although these different systems offer considerable potential for the future they have only been used in a limited number of applications. Hence, as yet, there is insufficient information concerning their medium-term and long-term performance to recommend their widespread use in prestressed masonry construction.

DISCUSSION - THE NEED FOR A CAUTIOUS APPROACH

Following research and development work in Australia, Canada, the UK, the United States and elsewhere, it is now widely accepted that the structural efficiency of masonry can be significantly improved by prestressing. The speed and relative simplicity of the post-tensioning operation and the improvement in structural performance means that prestressed masonry is set to emerge as an economically viable alternative to some of the more commonly used forms of construction, particularly where walls and columns are concerned. However, engineers will only specify prestressed masonry if they have sufficient confidence in its long-term integrity. It is therefore essential that, when developing design guides or codes of practice, careful attention is paid to providing adequate guidance on corrosion protection.

Construction professionals in many countries are frequently very cautious in adopting new materials or forms of construction. Such caution is fully warranted and indeed expected from an industry with the considerable responsibility it has to Society. Unfortunately, such an approach can lead to the condemnation and widespread rejection of new ideas and innovations. Take the case of the prestressed brickwork abutments referred to earlier. Unfortunately, the project is remembered by most bridge engineers in the UK because of the failure of a few of the prestressing bars, rather than as what is thought to be the first ever use of prestressed brickwork in bridge construction.

In order to promote the wider use of prestressed masonry, it is suggested that representatives of the prestressing and masonry industries, together with researchers and practising engineers with appropriate experience, should take the lead by producing detailed design guidelines that can be used, with confidence, by practising engineers. The guidelines for corrosion protection should be based on a very cautious approach which could be relaxed, if appropriate, in the future. This, hopefully, should minimise the risk of prestressed masonry becoming condemned and ignored by practising engineers because of one or two well publicised problems.

RECOMMENDATIONS FOR NEW CONSTRUCTION

The following recommendations are based on the cautious approach advocated above:-

i) It is suggested that, where engineers are using prestressed masonry for the first time, provision should be made to inspect the tendons for signs of corrosion in order to build up confidence in the form of construction. In the case of the prestressed brickwork bridge abutments referred to earlier, unbonded construction was used and small plastic tubes were built into the external brickwork faces to permit inspection of the tendons using a borescope (Garrity et al. 1993).

ii) It may also be worthwhile designing in provision to de-stress and remove individual tendons for full inspection and testing, at a later date. This approach was used by Cambridgeshire County Council engineers when designing the Macalloy bar tendons used to vertically prestress the brickwork wingwalls to Kimbolton Butts Bridge in England (Garrity and Gregory 1995).

iii) In the majority of cases, where the degree of exposure is not particularly severe, as is the case with the walls in most buildings, the use of unbonded high tensile steel bar or mono-strand tendons encapsulated in waterproof tape (such as Denso tape) or in grease-filled HDPE ducting is likely to be adequate. Such measures are comparatively inexpensive, can be applied under factory conditions and are flexible enough to accommodate any tensile strains during the stressing of the tendons. Until more information and experience is available, it is suggested that the aforementioned protection measures are recommended as the minimum for prestressed masonry construction.

iv) Where prestressed masonry is subjected to very severe exposure conditions, for example high concentrations of chloride ions combined with high levels of humidity, the use of unbonded tendons that can be inspected and subsequently de-stressed and replaced, if necessary, is recommended. In the most extreme cases, the use of uncoated, lowly stressed stainless steel tendons may be necessary.

v) It is suggested that the use of grout injected into a duct after stressing of the tendon as a corrosion protection measure in prestressed masonry construction should only be used with extreme caution and where measures are taken on site to check the effectiveness of the grouting operation.

vi) Although a number of non-metallic prestressing tendons are currently available, as yet there is insufficient knowledge of the long-term behaviour of such materials to recommend their widespread use.

vii) More stringent quality control checks may be necessary when using prestressed masonry construction, for example checks to minimise the risk of chloride contamination of mortar sands and testing of prestressing tendons to reduce the risk of hydrogen embrittlement, particularly where the degree of exposure is severe. In addition, as the magnitude of the stress in the tendons has an influence on the likelihood of hydrogen embrittlement, the use of hydraulic jacks to tension the tendons is recommended rather than less accurate methods such as the use of torque wrenches.

viii) The masonry and prestressing sectors of the construction industry should jointly provide conservative detailed design and specification guidelines for the corrosion protection of tendons for prestressed masonry.

SUMMARY

The consequences of two or three tendons becoming severely corroded in a prestressed masonry structure are likely to be far more serious than if a few bars of a comparable reinforced masonry structure were to corrode. A cautious approach to protecting prestressing tendons from corrosion therefore appears to be warranted, particularly if practising engineers are to gain confidence in the use of prestressed masonry as an alternative to the more conventional forms of construction. Recommendations and design considerations for the corrosion protection of the tendons used in prestressed masonry construction, based on a cautious approach, are presented.

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