Post-Tensioned Structures – Improved Standards Based On Lessons Learnt

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Introduction
Between 1979 and 1992 the UK Standing Committee on Structural Safety (SCOSS) published annual reports (SCOSS, 1979-1992) which included reports on suspected deficiencies of grouting of post-tensioning tendons and in 1992 the UK Department of Transport banned ducted grouted post-tensioning in bridges. This marked the beginning of a process of investigation and review of standards and procedures which have lead over 20 years to national and international bodies introducing improvements to help ensure the safety and reliability of post-tensioned structures. This is a prime example of where industry had to learn from the past, and has used that knowledge to introduce improvements, culminating in the publication (expected in 2012) of new ISO standards.

There are significant lessons to learn from this for structural designers, material scientists, and owners of structures both for new designs and for asset maintenance.

Historical Background of Post-Tensioning
Post-tensioning is a relatively young technology compared with reinforced concrete, and dates from the mid 20th century when due to shortages of steel during and after the Second World War, it rapidly penetrated the market based on being a competitive and economic form of construction and many different systems were developed and introduced around the world. Significant savings in materials were achieved. The theory and history of post-tensioning is well documented (Allen 1986) and, putting aside pre-tensioning, which is outside the scope of this paper, it mainly falls into two types – external and internal post-tensioning, with both being pioneered and leading to distinct structural forms.

Initial developments tended to use individual stretched wires to impart pre-compression force into concrete, as pioneered by Freyssinet, but the search for greater force rapidly led to development of spirally wound wires to make strands. These emerged as 19 wires in the 1950’s and 1960’s but have evolved into a mature product of 7-wire strands, due to more reliable technology to grip them and hold the tensioning force. CIRIA Report 106 (CIRIA 1985) contains a review of prestressing systems in the UK.

High carbon high strength steels are used to provide this tensile strength to concrete structures in the parts subjected to tension, with the concrete itself providing the compressive resistance in compression zones. However these high strength steels are more sensitive to corrosion in the presence of chlorides than normal reinforcement, and the common use of de-icing salts on roads has caused problems.

Common to most systems was the need to inject cement grout into the ducts to protect the steel from corrosion and, for internal tendons, to provide bond to the structure. Ducts for internal tendons were seen as a means to provide a conduit to place the steel where it was needed, and were sometimes initially simply cardboard tubes, or formed by inflated rubber tubes, but later became more commonly of steel. Some early systems of external post-tensioning, often originally used without ducts, relied on surrounding the tendons in cement mortar or fine concrete after tensioning, with or without bonding to the structure.
Other systems rely on grease and plastic sheathing to provide corrosion protection. Early use included polyvinylchloride (PVC) sheathing which was subsequently found to be susceptible to release of hydrogen ions and damaging to high carbon steels. Modern plastic sheathing is normally polyethylene (PE) or polypropylene (PP). External post-tensioning systems usually had purpose cast or forged steel deflectors connected or cast into the concrete structure to deviate the tendons.

One could describe such post-tensioned structures as “highly strung” in that they are finely tuned by the Designer to provide the tensile strength exactly where it is required, by designing the profile or alignment of the tendons to match and counterbalance the expected stresses in service. As such there does tend to be less scope for error in such structures, or less redundancy or reserve of strength, although this depends on the disposition of steel reinforcing bars and the structural form. For example precast concrete segments held together simply by post-tensioning are totally reliant on the prestressing, whereas an in-situ concrete structure with continuous reinforcement has some degree of additional capacity.

The development of prestressed concrete bridges in the UK is described by Smith (1996) and there is a useful summary of the Motorway applications by Sims (2000) in the Motorway archive.

The classical illustration used by Magnel [Fig 1] explains well the principle of post-tensioning showing a pile of books held each in vertical position as a horizontal beam by arm pressure; if the force is released the books would collapse unless there was any other tensile element.

In those early developmental days there would have been no anticipation of the potential impact of de-icing salts on our roads and how consequential chloride penetration could cause serious damage. There could also have been little thought that cement grout may not provide long-lasting protection to the vitally important tendons for the life of the structure, nor to how they might be inspected during future years. Many of the failures can be attributed to chlorides being channelled to the prestressing steel or due to poor grouting leaving voids in the ducts.

Review of Problems

From quite early on there were problems discovered in some UK post-tensioned structures, primarily bridges, for various reasons. Where inspection was possible, often this was attributable to leaking of water reaching the tendons of external post-tensioned bridges [Figures 2, 3]. Other problems related to materials or were unaccounted for. Two significant externally post-tensioned bridges, Braidley Road Bridge in Bournemouth and the A3/A31 Bridge over the A3 in Guildford, both had their external tendons completely replaced in the 1980’s. The fact that such replacement could be achieved is a pointer to one of the major advantages of external post-tensioning. In the case of Braidley Road Bridge, importantly, traffic continued to be able to use the bridge during the replacement works.
Early recorded failures of post-tensioned structures are documented by Clark (1992) in work carried out for the British Cement Association. However this report concluded that performance was generally good.

The UK road building boom of the 1970's and 1980's had resulted in many post-tensioned bridges being constructed although it is believed that the railways of Britain actually have an older average age of such bridges, many of which are being investigated.

As most of the early evidence of problems had been concentrated on externally post-tensioned structures, simply because their cables were visible for inspection, there was a ban introduced by the UK Department of Transport in 1977 on use of external post-tensioning in bridges. With the benefit of hindsight, one can challenge whether this was a sensible decision. There is little doubt that external post-tensioning has a significant advantage in that it is relatively easily inspectable, whereas internal post-tensioning is buried inside the body of the concrete and despite significant investment in recent years has proved extremely difficult to inspect.

Nevertheless fortunately development of external post-tensioning technology continued outside of the UK and now forms an important part of many significant concrete bridges. In the UK the Camel Viaduct in Cornwall [Fig 4], completed in 1993 was the first to utilise new design rules developed by the Highways Agency (1994) and included innovative features to allow replacement of the post-tensioning cables in the future (Hollinghurst 1995).
In 1985 the sudden collapse of the Ynys-y-Gwas Bridge in Wales (Woodward et al, 1988) had sparked investigations which raised serious concerns over the underlying durability of internal post-tensioning. In that instance it was a single span precast segmental bridge with internal tendons which passed through thin concrete joints between the units in ducts formed with cardboard. Over the years de-icing salts had penetrated and corroded the prestressing steel at the joints resulting in collapse.

In 1986 the bridge over the Mandovi River in Goa, India collapsed after less than 20 years in service due to corrosion of the post-tensioning cables. Cracks were unattended for six years and corrosion of prestressed wires, which was noticed in 1983, was neglected until the bridge collapsed. It is reported by Arullappan (2010) that the available workforce were probably not able to provide the required standard of workmanship to construct the bridge.

In 1992 a further bridge collapse occurred in Belgium. The Malle Bridge over the river Schelde relied entirely on buried tie-down prestressing tendons for its stability which failed due to corrosion (ASBI 1998). The tie down cables were completely uninspectable and this is a prime example of a high-risk form of structure. Such details should be avoided.

It was not only bridges which experienced durability problems with prestressing. In Berlin the roof of the West Berlin Congress Hall collapsed in 1980. The thin shell roof had post-tensioning bars in ducts which had corroded partly due to poor quality of grouting (Buchhardt et al, 1984).

Doubts were shed on the adequacy of grouting materials and techniques and some of the construction details, and following the SCOSS concerns a ban on grouted duct post-tensioning was introduced in 1992 by the Department of Transport. There already existed the ban on externally post-tensioned bridges due to previous failures. It was generally accepted that this did not mean that all post-tensioned structures were unsafe, but the immediate response was to carry out a study of different types of post-tensioned structures and systems and broadly categorise them by risk assessment of the potential impact of deficient grouting and possible corrosion of the tendons. At the same time a programme of physical intrusive investigations was embarked upon to assist in understanding the degree of deficiencies and current extent of damage with a view to establishing a programme of repair options. Early studies published by Woodward (1981) had shown a mixed picture of different conditions in existing structures. This manifested itself in some cases as fully grouted but in others as complete lack of grouting, or just a thin coating of the steel. However generally little corrosion was found. Clark (1992) had also presented a generally satisfactory picture.

The Highways Agency in 1994 started a significant structured series of inspections of their bridges and this gradually provided evidence that there was a growing problem with some post-tensioned structures. Problems included corroded anchorages [Fig 5] and broken wires [Fig 6].

![Fig 5 Corroded top slab anchors – some barrel grips completely corroded away](image1)

![Fig 6 Significant wire and strand failures (Encasement concrete removed)](image2)
Lessons to Learn and Areas for Improvement

A joint industry working party was established in 1992 by the Concrete Society and the Concrete Bridge Development Group to plan and instigate a programme of studies with a view to making recommendations for improvements for future structures, with the intent to allow the ban to be lifted. This involved reviewing existing standards, carrying out development and testing of new materials, consultations with consultants, suppliers and contractors.

Publication of an interim Concrete Society report in 1995 presented a preview of proposals and was followed by the first edition of Technical Report No 47 (Concrete Society 1996) which resulted in the ban being lifted. It has been revised over the years and is now Technical Report No 72 (Concrete Society 2010). This has a comprehensive record of the work carried out and contains many recommendations. Most of the materials and grouting related issues have found their way into standards but the document contains important guidance for detailing of both bridges and building structures.

In the rest of the world there was a growing awareness of the problems in the UK disseminated through bodies such as the federation internationale du beton (fib) and gradually it became apparent that the problem was not just limited to the UK. In the USA important bridges in Florida revealed problems at Sunshine Skyway, Niles Channel and some other major bridges and other states. Swiss, German, Japanese and French experience was shared. Fib established a working group to prepare guidance on grouting published as Bulletin 20 (fib 2002) and another to give guidance on use of plastic ducts.

Grout

For many post-tensioned structures grout is used to protect the steel from corrosion. This has proved to be a fundamental weakness in many cases and something to which major attention has been paid over recent years to improve. Long used test methods were found to be inadequate to distinguish between good and bad grout formulations, which resulted in some tendons having voids in their protection or poor quality of grout leaving the steel susceptible to attack by penetrating chlorides. An understanding has been gained through research of the key qualities of grout needed to assist ability to fully grout the ducts and to provide long-lasting protection, with a particular focus on control of bleeding. Use of factory formulated pre-bagged grouts has now become almost the norm in the UK and a certification scheme is in operation by CARES (2010).

Ducts

The lack of any form of long term protection provided by the ducts was identified at an early stage as an area for possible improvement. In aggressive environments such as bridges steel ducts are not considered adequate where de-icing salts may penetrate to corrode them, especially at joints in concrete members. However proposing an entirely new product for what is essentially a public sector market was not easy, especially as there were no purpose made products on the market at the time. It started with a development of rather flimsy corrugated plastic conduits and drainage pipes, and various suppliers designed their own more robust systems. Test methods had to be trialled and evolved, but the requirements were essentially simple – what was needed was a sufficiently robust non-corrodible watertight duct to be able to be set to the required profile, withstand the duress of concreting and strand installation and stressing operations and be fully fillable with grout. It also had to be able to transmit cable force by bond to the concrete body.

The challenge of coordinating introduction of requirements for new non-corrodible plastic ducts was taken up by fib who published an authoritative guideline Bulletin 7 (fib 2000) which has become referenced internationally. Plastic ducts had been previously used in Switzerland with good experience but a new generation of ducts needed to be brought to market. This has now happened internationally [Fig 7, 8] and the guidance is currently being updated by fib with a view to standardisation in the future.
Quality and Skills

The UK also proposed an industry certification scheme which ensued from the process in direct response to requirements of the new recommendations, covering requirements for post-tensioning companies to satisfy certain levels of training and experience of personnel, as well as having documented QA procedures for carrying out post-tensioning work. This also raised a classic dilemma; how to require companies to demonstrate skills and experience with a new set of standards before the standards were in operation.

The solution was to introduce, with the support of the UK Highways Agency, an interim pre-certification scheme to allow close scrutiny, monitoring and recording, which would lead to full certification. This was supported by the UK Post-Tensioning Association and has become an almost universal requirement in the UK. The scheme is administered by CARES. Similar schemes are not universally used around the world although the Post Tensioning Institute in USA has a comprehensive skills and training qualification for firms and their operatives, and many global post-tensioning companies now have their own documented requirements in this area. In Europe similar requirements are now covered by EN13670 (BSI 2009) and the need for companies to hold a European Technical Approval for their system (EOTA 2002) and to comply with a CEN Workshop Agreement for installation (CEN 2003).

Detailing

In addition to the practical aspects of improving the materials it was considered vitally important to learn from design details which had failed or proved to be troublesome and provide guidance for structural designers.

Experience of corrosion of tendons in or near their anchorages, informed the need for added protection to anchors placed in vulnerable locations under expansion joints or construction joints. This was developed to provide the concept of multi-layer protection whereby a second or third line of defence was provided to the tendons rather than simply relying on one single protection method. It was recommended to avoid anchorages in pockets in the top slab of bridges as these appeared particularly vulnerable to leakage. Additional double layers of deck waterproofing was recommended in certain locations and guidance given on placement and sealing of duct vents which had been shown from trials to help complete grouting at vulnerable high-points in duct profiles.

Full scale prototype trials were advocated on projects to verify the suitability of proposed grouting materials and techniques prior to full scale use [Fig 9].
Experience on these was invaluable to reassure clients and designers that the ducts could be fully grouted [Fig 10] and also inform simple but crucial detailed changes to, for example, grout vent locations and grouting procedures.

The concept of multi-layer protection and suggested design details to avoid such problems are described in Concrete Society Report TR72 (2010) and in fib bulletin 33 (fib 2005).

**Inspection**

Owners of post-tensioned structures, especially bridges, have had a wake-up call and special inspection procedures and risk assessments for these structures were introduced by many authorities. Even so it is still the case that defects are in some cases a surprise when discovered such as recently on the Hammersmith Flyover in London which is currently the subject of a major emergency strengthening programme (New Civil Engineer 2012). This precast segmental bridge, post-tensioned both internally and externally was built in 1962 and has classic features of high risk with insitu concrete joints. It does not seem surprising to the author that the post-tensioning cables in ducts at the top slab over the piers could be suffering from chloride induced corrosion, the extent of which has only now been discovered 50 years on. It is fortunate that this was discovered before the structure suffered more serious damage, or even possible collapse, and that remedial measures are, at the time of writing, underway on site.

Methods of inspection are well documented (Concrete Society 1996) and intrusive investigation is generally recognised as the only reliable way to check condition of internal post-tensioning. In many cases this is difficult but initial examination of design details can and must be used to inform targeted investigations.

It is clear that in most cases a post-tensioned structure will be unlikely to show visual signs of distress when close to failure. This makes it all the more important to carry out full investigations where there may be vulnerable high risk details.

Owners of post-tensioned structures must be helped to understand that these structures are unique and very careful consideration needs to be given to their inspection.

**Maintenance**

Experience of repairs of post-tensioned structures is relatively limited. Several bridges have been so complex to evaluate the overall state with confidence that they have been demolished and replaced. However where there has been significant confidence to design strengthening or replacement, various techniques have been used, including supplementary tendons, as in the case of Hammersmith Flyover, passive FRP strengthening, or tendon replacement. The latter has to the author's knowledge only been carried out on externally post-tensioned structures to date.

The bridge at Palau in Indonesia collapsed suddenly in 1992 only a matter of weeks after completion of a strengthening programme and a protracted legal case resulted in details not being revealed until several years later. This was an extremely long span internally post-tensioned box girder cantilever bridge with a pin at midspan. It was initially hypothesised by some that the additional prestressing which was applied to
strengthen the structure and help correct significant sag of the main span may have contributed to the failure. However a later published paper (Burgoyne et al, 2008) postulates (with a cautionary note) that there were weaknesses in the original design and workmanship which could have been the main reason. Tendon corrosion was not apparently a contributor.

It is clear that many poor details on existing post-tensioned bridges should be corrected to ensure longevity and arrest possible deterioration. For many, however, without any obvious poor details, experience is that they should remain trouble-free. Post-tensioned structures when designed and detail properly certainly have the potential to be one of the most durable and long-lasting forms of construction.

**New Standards**

**UK, European and International Developments**

Publication of substantial new recommendations in the first edition of Concrete Society Report TR47 (1996) had led to the Highways Agency announcing a lifting of the ban on internal post-tensioned bridges. This was welcomed by industry but it was recognised that further development was necessary, assisted and informed by the International community.

In parallel CEN had instigated a review of existing standards for grouting, ENs 445, 446 and 447 (BSI 2007a, 2007b, 2007c) and publication of these was the product of a consensus view across Europe for improved grouting materials and injection techniques.

A second edition of TR47 followed in the UK in 2002 to reflect the European experiences. In the meantime international developments were being followed and fib had published bulletin 33 (fib 2005) which further disseminated state-of-the-art knowledge.

By the mid 2000’s Engineers were gradually coming to a consensus view of the ways to improve the durability of grouting for post-tensioning, so an ISO Committee was convened in 2008 to develop International Standards for grouting informed by the ENs, new National standards in USA, Japan and many European countries. It is expected that ISO14824 Parts 1, 2 and 3 will be published in 2012 which will cover basic requirements, test methods and grouting procedures. This would mark a real milestone after more than 20 years since the work to improve grouting started in the UK. However there is still remaining much to learn. Not the least of this is to not necessarily leave unchallenged anything contained in a standard.

Experience from developing these standards has revealed that the current European requirement for grout to contain less than 0.01% of sulfide ion is apparently impossible to ascertain from any current ISO test (it is below measurable tolerances). It has emerged that there has been very little research into threshold limits for sulfide ions in contact with prestressing steel and even more concerning, that it appears that although this has been a required limit in the current EN for some 10 years suppliers appear not to have tested their compliance. This is a note of caution for standard developers to always seek firm evidence as back-up before including requirements proposed by one country.

**Recent Experience and Future developments**

**Recent problems**

In the USA it was revealed in 2011 that SIKA, a pre-bagged grout supplier, had been supplying grout which had chloride levels significantly higher than the USA specification limit of 0.08%. This apparently had been supplied undiscovered and untested for several years, with the supplier relying on the supplier of the bought cement to comply with its certification regarding chloride levels and no further testing being carried out.
It is reported (US FHWA 2012) that this grout has been used on over 30 bridge projects in the USA and may have serious implications which are currently under investigation.

This is potentially seriously damaging for the credibility of self-certification as well as for post-tensioning in general. We must learn from this that Audit testing MUST be a routine part of every supplier’s procedure.

The 2011 findings of major corrosion to tendons in the 50 year old Hammersmith Flyover in London have luckily come in time to potentially save that vitally important structure. We must learn from this to be more questioning and reinforce to owners of structures the need to make deeper and more searching investigations where it appears fairly likely that our older structures have vulnerable details, even though it may be more costly.

**Successes**

We should also champion successes. Relatively few post-tensioned bridges have been constructed in the UK in the last 20 years but those which have will have benefited from much improved technology. Better still is the fact that many post-tensioned elements of our buildings are also now using much improved standards having learned from the experience gained in bridges. This is an important example. The latest edition of the National Structural Concrete Specification (Concrete Centre 2010) embodies many of the key features of good practice for grouting learnt by industry as well as embracing Eurocodes.

Techniques have developed considerably in recent years for investigation and monitoring of post-tensioned structures, and in particular the health of their prestressing cables. However there is certainly further to go and scope for further development. These include acoustic and ultrasound technology as well as use of sensors embodied within the cables at the time of construction. Time has yet to tell whether the latter will prove valuable for long term health monitoring.

New materials are always being developed. Currently there are higher strength steels, carbon based composites and new epoxy fillings for coated strands. Each of these will need to be proven but what we have learnt from the past should enable us to take care about their use.

**Conclusions**

- There is little doubt that much has been learned over the past 20 years and more will be learned in the future to enhance the durability and longevity of post-tensioned structures.
- SCOSS were absolutely correct to start raising concerns as early as 1979 about the sufficiency of grouting, which has been a key influencing factor in starting the drive for improvements.
- Poor detailing has been as much to blame as poor grouting.
- Although properly designed, well detailed and constructed post-tensioned structures have potentially long life if well maintained, we should and must not be complacent about post-tensioned structures – especially the older ones. Owners and Engineers should be pro-active to ensure these have full and proper investigations, especially where tendering requirements may act against thoroughness of approach.
- The importance of suitably frequent audit testing for materials must be emphasised, however comprehensive other requirements for compliance with standards may appear to be.

**References**


