Prestressed structural concrete: New developments and applications

Hans-Rudolf Ganz [1]

ABSTRACT

The paper presents first some recent developments and trends in materials used for prestressed concrete. In particular, ultra-high performance concrete is introduced. After a review of developments in post-tensioning systems some new damping devices are presented which are used for bridge and building structures. Finally, a few specific applications with significant potential for the next years are given. These include post-tensioned buildings, slabs-on-ground, precast segmental bridges, extradosed bridges, and concrete containment and storage structures.

KEYWORDS

prestressed concrete, concrete, damping devices, applications, construction, durability, post-tensioning, post-tensioning systems.

[1] VSL International Ltd., Scheibenstrasse 70, CH-3014 Berne / SWITZERLAND, Phone: +41 (0)58 456 30 80, Fax +41 (0)58 456 30 75, Email: hansrudolf.ganz@vsl.com

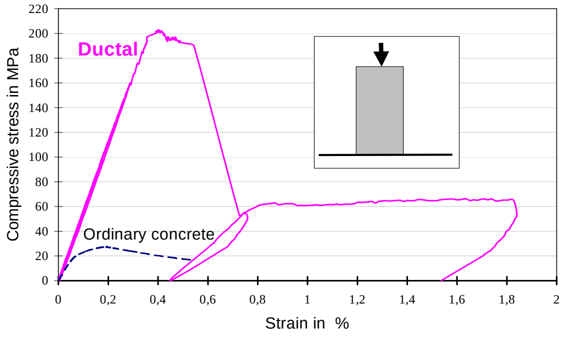
1. INTRODUCTION

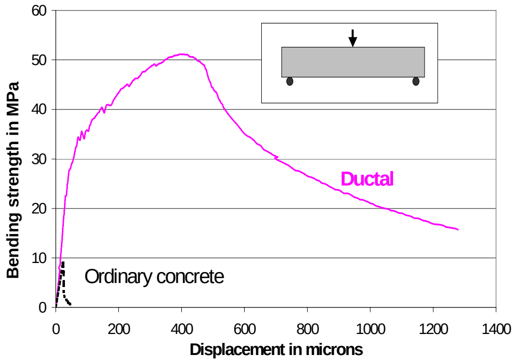
Prestressing, introduced in the first half of the 20th century by visionary engineers and entrepreneurs, has indeed permitted a progress in concrete construction which would have been simply impossible without it. Prestressing is undoubtedly one of the greatest innovations in concrete construction. Many outstanding structures are testimony for this, only a few will be mentioned here for reference. Prestressing covers both pretensioning and post-tensioning. While the use of pretensioning on a world wide basis is much larger than that of post-tensioning, most of the spectacular structures are made with post-tensioning. Therefore, this article will focus on prestressed/post-tensioned concrete.
Post-tensioned concrete bridges have seen an extraordinary development over the last 50 years. They established themselves firmly in a leading position in bridge construction up to spans of the order of 250-300m. This development has transformed a range of bridge spans to concrete which was formerly exclusively in the hands of structural steel. Indeed, in terms of bridge surface they have taken the lead over other construction materials in many countries. Much of this success has been due to (a) local availability of concrete materials, (b) development of specific construction methods and specialized erection equipment like for precast segmental construction, (c) improved knowledge in design of structural concrete as reflected in modern codes, and (d) availability of modern post-tensioning technology.
Norway has been a pioneer in introducing post-tensioned concrete into offshore platform construction. These structures include giant gravity based platforms, floating platforms, and more recently floating movable platforms in the form of concrete vessels. Again, post-tensioned concrete permitted to break successfully into a domain previously held exclusively by steel construction.
Another domain in which post-tensioned concrete has acquired a proven track record are structures such as reservoirs, tanks and containments, in general for storage of dry and liquid materials and for protection against safety hazards. These containment structures will receive significant attention over the next years or decades in view of the increasing energy demands.
Although perhaps less spectacular, application of post-tensioning in building construction - mainly in floors - has become a leading type of use of post-tensioning in many countries in South East Asia and North America. In many of these countries, the use of post-tensioning in buildings exceeds the one in bridge construction. This article presents selected new developments and trends in materials and technologies used in prestressed concrete structures. It then illustrates a number of trends in applications for prestressed concrete.

2. MATERIALS

2.1 Concrete

Concrete quality has gradually evolved in terms of performance and strength over the years 1980 – 2000 through concious selection of concrete constituent materials, reduction of water content, use of otpimised admixtures and additions like silica fume, etc. These types of concretes are called high-performance / high strength concretes. At the beginning of the 1990’s a new generation of concrete was developed, the Ultra-High-Performance-Fibre-Reinforced Concrete (UHPC or UHPFRC). These UHPC use selected fine aggregates to form an extremely dense concrete matrix. Maximum aggregate size is in the order of a few millimeters only. This together with highly efficient admixtures and the use of very low water contents (water-cement ratio of 0.25 and below), and the use of short high strength steel fibres produces mechanical properties previously unachievable with concrete. Compressive strengths of about 200MPa and flexural tensile strengths of 50 MPa have been achieved on projects, [1]. The large amount of fibres, typically 2-4% of volume of concrete, also provides significant ductility to the material. Figure 1 presents stress-strain curves for axial compression and flexural bending of Ductal®, [1].
UHPC also has an extremely low porosity and therefore, is practically impermeable to liquids, [1]. This makes it an ideal material for aggressive environments like exposure to chlorides, sea water, or a wide range of chemicals. Figure 2 compares the porosity of Ductal® with that of normal concrete and high performance concrete.





a) Axial compression test b) Flexural bending test

Figure 1. Stress-strain curves of UHPC (DUCTAL®)

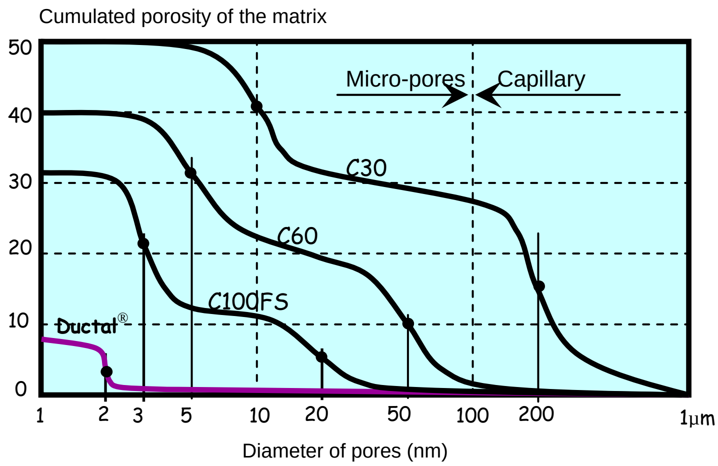


Figure 2. Porosity of UHPC (DUCTAL®)

The high amount of steel fibres provides a significant tensile strength to the material. This is sufficient to carry secondary transverse tensile stresses in concrete structures including shear. The principal (longitudinal) tensile stresses however, are taken by prestressing tendons, in general, to avoid placement of any ordinary non-prestressed reinforcement. This concept of design has been applied to a significant number of structures including beams in buildings, footbridges, and more recent also highway bridges. Presently, parts of the new runway of Haneda International Airport in Tokyo are built with pretensioned Ductal® panels. More than 20’000 m^3 of Ductal® will be eventually cast for the project. Due to the high durability and wear resistance of UHPC the material has also been used for protection of exposed parts of structures. Examples are the splash zone of marine structures and pile caps or the lining of tunnels during repair. Figure 3 illustrates a number of these applications.
Because of its high strength, the volume of UHPC is about 1/3 to 1/2 of that of conventional concrete for comparable structural elements. This makes UHPC also of interest in terms of sustainability and CO_2 footprint. The author sees significant potential for UHPC mainly when used compositely with conventional concrete and/or structural steel to build innovative and very durable structures.

2.2 Reinforcing steel

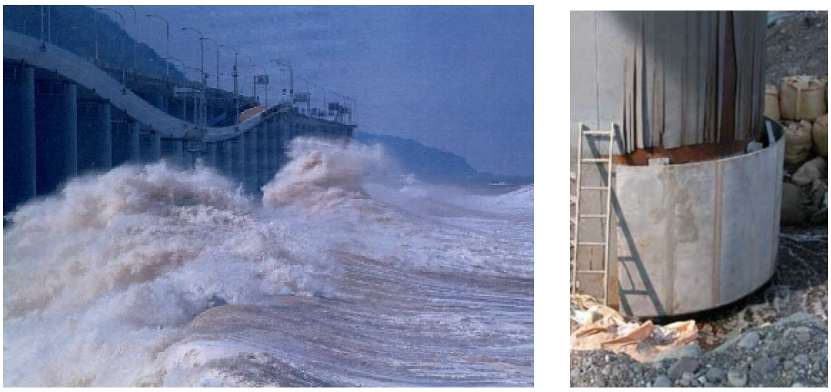
The yield strength of reinforcing steels has evolved over the last 20-30 years from around 420 MPa to more than 600 MPa. This increase in strength and the introduction of some particular fabrication methods have however, led to a reduced ductility of some types of reinforcing steels. This has made these types of steel unsuitable for seismic applications. The ductility of some steels was so low that

even redistribution of forces in plastic regions of structural members has been compromised, i.e. plastic design was no longer applicable to such members. This has been recognized and recent standards have defined ductility classes A to D of which class D offers the highest, class A the lowest durability, see [2]. It is the author’s opinion that the use of Class A steels should be avoided in general.

a) Seonyu footbridge, Seoul/South Korea

b) Roof of railway station, Calgary/Canada

c) Shepherds Bridge, Sydney/Australia



d) Lining of piers in splash zone, Japan

Figure 3. Applications of UHPC (DUCTAL®)

2.3 Prestressing steel

The main issue of the past has been the brittle failure of some special types of prestressing steels. This problem mainly applied to quenched and tempered prestressing wire which was produced and used in some few countries. This type of prestressing steel simply was too sensitive to minor defects and/or environmental exposure conditions as they may occur during installation on construction sites [3]. This type of prestressing steel is not recommended for use in post-tensioned concrete construction [4]

and in fact is not specified in internationally recognized standards for prestressing steel such as ASTM A416, BS 5896 and EN10380. Prestressing steels made of cold-drawn wire in accordance with such internationally recognized standards are of excellent quality and have proven to be insensitive to small defects and environmental exposure conditions which could potentially cause delayed brittle failure. This is also true for the higher grades of prestressing steels of 1860 up to about 2000 MPa. Specifying prestressing steels in accordance with the above internationally recognized standards will ensure the use of high quality prestressing steels without risk for delayed brittle failure, and offering a significant ductility of the prestressing steel, and if adequately designed, of the prestressed concrete members. Hence, requirements in structural concrete standards to provide non-prestressed reinforcement in combination with prestressing steel to avoid brittle failure of prestressed concrete members are not necessary and unjustified.
Prestressing steel in the form of 7-wire strand has been available for about 15 years with a tensile strength of 1860 MPa. A next generation of 7-wire strand is gradually appearing on the market with 2160 MPa and 2060 MPa strength for 12.9 mm and 15.7 mm strands, respectively.

2.4 FRP Materials

Fiber-reinforced plastics (FRP) have been proposed for use as prestressing materials mainly as an answer to some durability problems with prestressing steels. In the author's opinion, today's FRP materials are not suitable for general use in post-tensioned concrete construction. These FRP materials are still much too sensitive to handling and installation procedures on typical construction sites. They are also very sensitive to deviation/ radii of curvature and the effects of mechanical anchorage at the tendon ends. FRP materials may be suitable for certain niche applications mainly in repair/strengthening where certain advantages such as light weight in difficult access outweigh the above disadvantages. However, for general use in post-tensioning there is, in the author's opinion, still no better material than a high quality prestressing steel.

3. POST-TENSIONING SYSTEMS

3.1 Post-tensioning system approval

An acceptable post-tensioning system is made of more than just a combination of acceptable materials and components. There are many interfaces and interactions between materials and components which need to be considered and suitable details be provided to finally obtain an acceptable system. Many countries around the world have concluded that acceptance of post-tensioning systems is therefore, best assessed in an approval procedure by a qualified independent body, and in fact, have made good experience with this approach.
However, some countries and owners still rely on an assessment and approval of the post-tensioning system on a project specific basis by the designer of the structure. In the author's opinion many of these designers simply do not have the experience to fully assess a post-tensioning system. The author therefore, strongly suggests a formal approval process on national or international level by a qualified independent body for all use of post-tensioning systems.
Europe has recently introduced a comprehensive Guideline for Technical Approval of Post-Tensioning Systems, ETAG 013, [5]. This guideline is recommended as basis for other national or international approval procedures to hopefully evolve into a harmonized approval in a more and more globalized market.
No such guideline can ever cover all present and future questions for assessment of post-tensioning systems. Hence interpretation and reasonable adaptation will always be required by the qualified body. Guidelines and their application should also leave some flexibility such that they do not block or even prevent future developments.
Once a post-tensioning system is approved, an independent notified body verifies in Europe that the details and procedures specified in the approval are fully implemented. Systems which comply obtain in Europe the CE-mark, [6].

3.2 Qualification of specialist companies and personnel

Recent investigations showed that early structures of the 1950’s-1970’s were in fact built with good quality, and post-tensioning tendons well grouted, in general [7,8].
Investigations on more recent structures such as in the UK [9] however, showed a very different picture. A significant percentage of post-tensioning tendons were only partly grouted, and 12% of all tendons were not grouted at all. Partially grouted tendons were subsequently found in several other countries [10, 11].
Parts of the partially grouted tendons can be attributed to the use of non-suitable grouting materials which show excessive sedimentation and bleed. This concern has been addressed with improvements introduced in material specifications and test procedures of recent recommendations and standards, [12,13]. However, it is the author’s opinion that even with a non-perfect grout, adequate grouting can be achieved with proper procedures and care of the personnel on site. Experienced and well qualified site supervisors will apply procedures which permit to detect excess bleeding during or shortly after injection, and will then take adequate actions. In fact, if vents are installed at the critical locations at anchorages and at relative high-points of tendon profiles, the areas which are most susceptible to accumulation of bleed water can be checked, and filled if voids are detected.
The author is convinced that many of the problems found with grouting were due to poor workmanship. At the early stages of post-tensioning, only specialist companies, often those who invented the post-tensioning system, carried out post-tensioning works with specialist supervisors with long experience. However, at some stage post-tensioning started to be considered a commodity, and a do-it-yourself mentality was introduced in certain parts of the world. The consequences of this trend are well documented in the above mentioned investigations and have led to a dramatic loss of reputation of post-tensioning.
It is time that we all, including owners and consultants who specify works, recognize the importance of the qualification and experience of the companies who install post-tensioning systems on site and that we take the corresponding actions when preparing tender documents for projects.
Good guidance and recommendations on the subject of qualification of specialist post-tensioning companies and personnel are provided in a CEN Workshop Agreement, CWA 14646, [14]. The document can be used by countries, public and private owners on a voluntary basis, and referenced or included in their project specifications. The author hopes that this document will be integrated into European and International standards after some transition period.

3.3 Corrosion protection of post-tensioning tendons

Already in the conceptual design stage, questions such as aggressivity of the environment, exposure conditions of structures and parts of them, and required level of protection of the post-tensioning tendons to achieve the desired design life have to be addressed. These questions have been discussed in a fib/IABSE workshop in Zurich in 2004. fib has published recommendations for the corrosion protection of post-tensioning tendons as a function of environment, exposure and protection provided by the structure itself [15].
Once suitable materials have been chosen for the tendon, the main concern for durability remains the protection of the tendon from aggressive media penetrating the tendon from the outside. In accordance with [15], the designer should choose a level of protection which ensures that: “Protection provided by the structure surrounding the tendon plus protection applied to the tendon itself is sufficient to resist the expected aggressivity of the environment with the actual exposure conditions”. It is believed that the aggressivity and protection cannot be quantified accurately yet. Therefore, the fib recommendations propose three Protection Levels (PL1, PL2, PL3) for the tendons which seem well adapted to ensure durability for certain groups of environments. These are defined as follows:

- PL1: A duct with a filling material providing durable corrosion protection
- PL2: PL1 plus an envelope, enclosing the tensile element bundle over its full length, and providing a permanent leak tight barrier
- PL3: PL2 plus integrity of tendon or encapsulation to be monitorable or inspectable at any time.

A matrix of environment/ exposure versus protection by the structure itself assists the designer to choose the appropriate Protection Level for the tendon, see Fig. 4.
Examples of generic performance specifications with test procedures and acceptance criteria are given in [15] for each Protection Level. Also examples of existing components which would qualify for each PL are provided in [15] together with the test procedures and acceptance criteria. Aggressivity and exposure conditions are classified in accordance with existing standards, e.g. EN 206.

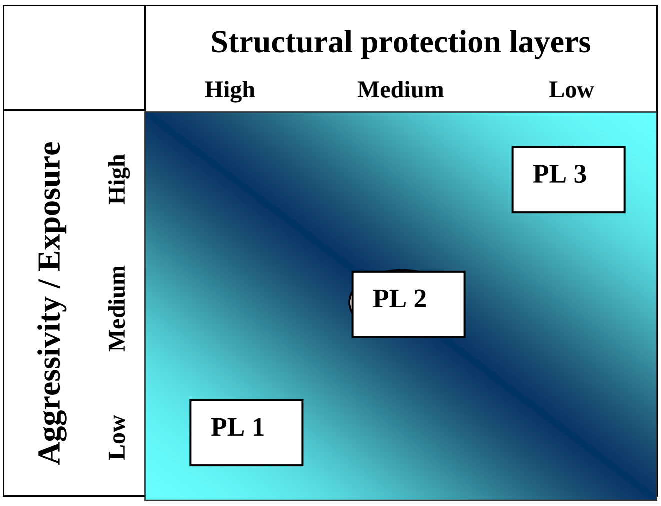
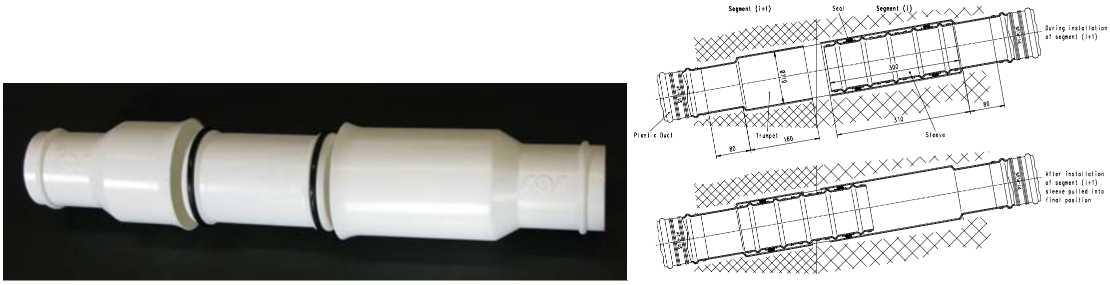


Figure 4. Protection Levels for post-tensioning tendons based on aggressivity /exposure versus structural protection layers

The corrosion protection in accordance with PL1 corresponds to the typical protection provided in the past to essentially all tendons, i.e. metallic duct filled with cementitious grout. This protection has performed well under certain conditions. However, for aggressive environment and/ or relatively low protection by the structure, e.g. thin webs of precast beams, complete encapsulation of the prestressing steel over the entire tendon length in a durable envelope is recommended, PL2. This envelope needs to include in particular the anchorage zones which are often the most severely exposed area. Figure 5 illustrates a tendon fully encapsulated in a plastic envelope in accordance with the specification for PL2. The intent of the envelope obviously is to keep the aggressive media such as chlorides away from the prestressing steel. Full encapsulation of tendons was difficult in precast segmental construction across the segment joints. However, recently several special duct couplers for segmental construction have been placed on market, and have been confirmed by testing, see Fig. 6.

Figure 5.
Fully encapsulated tendon in accordance with PL2 [15]



a) VSL Segmental duct coupler b) Installation schematics

Figure 6. Duct coupler for segmental construction

The highest level of protection, PL3, combines the details of PL2 with a system which permits to monitor the integrity of the protection and/ or of the prestressing steel. One solution for PL3 is the electrical isolation and monitoring of tendons (EIT). In this solution, the prestressing steel is electrically isolated from the surrounding structure through the plastic envelope. The quality of the encapsulation can be verified by a simple electrical resistance measurement between the prestressing steel, inside, and the reinforcing steel cage of the structure, outside the envelope. A high electrical resistance confirms the leak tightness of the envelope. A low or negligible resistance indicates a leak in the envelope. Such leaks can be located by measurements of the magnetic field caused by an applied current. Once located, the defect can be either repaired, if considered necessary, or the particular area can be subjected to more intense inspection to detect any deterioration early enough.

Typically, the electrical resistance of a tendon increases gradually with time due to the hydration/drying of grout and concrete around the prestressing steel. If at any time a defect in the envelope occurs and humidity penetrates the envelope, the electrical resistance will drop significantly. Such a scenario is illustrated in Fig. 7 with a red arrow. Hence, simple electrical resistance monitoring permits reliable detection of the occurrence of a breach in the tendon protection throughout the design life of the structure. As mentioned above, the defect can be located and repaired as may be required. It is interesting to note that the detection mechanism with the drop of resistance works independently of whether the tendon had a complete electrical isolation initially (acceptable level of electrical resistance) or whether the tendon had a reduced electrical resistance already initially (sub-standard level of electrical resistance).

It may be worthwhile noting that such electrical resistance measurements permit an efficient and comprehensive control of the quality of installation of the envelope. Such measurements may form part of the “birth certificate” of a structure which will serve as reference for any future inspections and investigations.

It has been argued that tendon encapsulation and EIT significantly increase the cost of post-tensioned structures. This is not true for most applications. In fact, the cost increase for the structure is below 0.5% in general, and may fall below 0.1% in many cases [16].

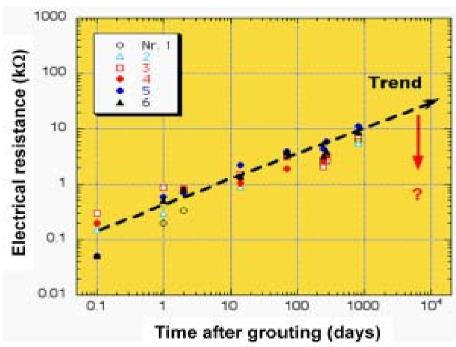
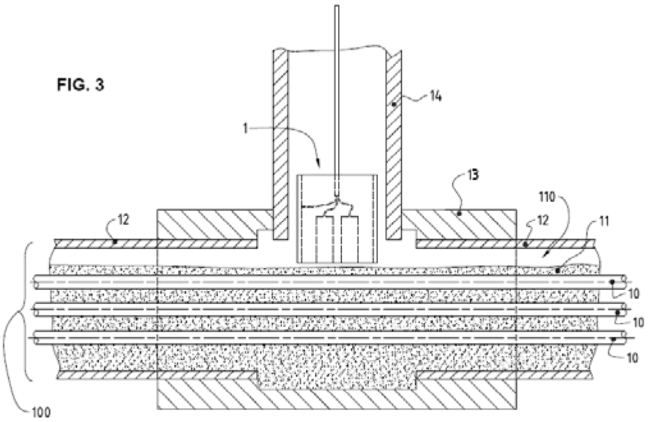


Figure 7.

EIT monitoring permits to detect a defect in the tendon encapsulation.

Specific sensors have been developed in Japan which permit detection of voids in tendons during grouting, [17]. In Europe, another type of sensor has been developed which permits detection of voids during grouting, and confirmation of the passivation (no ongoing corrosion) of the prestressing steel inside the grout during the entire life of the structure. Figure 8 shows the sensor and the positioning of the sensor in the tendon duct vent.

a) Sensor



b) Sensor installed in tendon duct vent

Figure 8. Void and corrosion detection sensor

4. DAMPING DEVICES

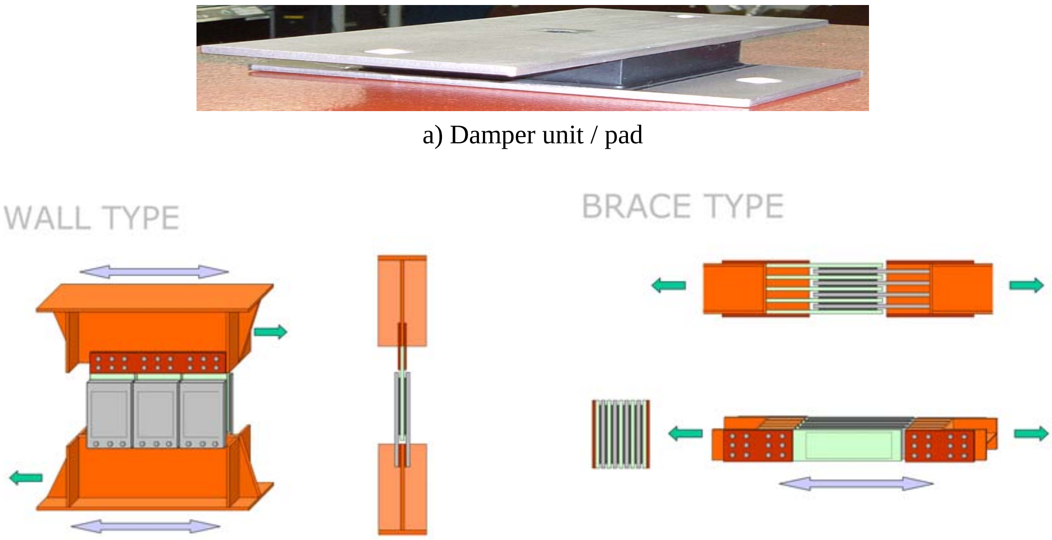
Our knowledge about seismic actions and the behavior of structures under such actions has increased significantly over the past 20 years. With this increase of knowledge, the actions specified in standards have been adapted/raised also and new concepts for seismic design have been proposed. Some of these concepts have already been introduced into recent recommendations, [18]. Unfortunately, prestressed concrete is still poorly treated in most structural concrete standards for seismic design, or not at all. This is very surprising since research has repeatedly demonstrated an excellent behaviour of prestressed members and structures using bonded and/or unbonded prestressing, [19]. In the author’s opinion, prestressed concrete will have to be adequately addressed and covered in future design standards.
The growing demand for strength and ductility of structures to cope with increased seismic actions has led engineers looking for other options than simply adding materials for strength and stiffness. Base isolation of buildings has been one approach introduced mainly in Japan and the USA both for new construction and for rehabilitation of existing structures. However, the cost for such measures is high, and the method has not or only rarely been applied to bridges. Another approach introduced by engineers was to add additional damping into structures to modify the seismic response and reduce the actions in the members of structures. Initially, this damping was provided with hydraulic dampers installed into the bracing between floors of buildings, as necessary, or between superstructure and substructure of bridges. Figure 9 shows an example of a damper installed in a bridge in the French Alps. Introduction of dampers in this structure significantly reduced seismic effects in the substructure, particularly where columns are short. These dampers use a special viscous material which reduces the risk of leakage. These dampers can be “prestressed” to a certain load level. Damper action only starts when the effects exceed that load level.
A similar effect as described above can also be implemented into bridge bearings. Such special bearings will act as “fixed bearings” up to a desired load level. Then a “fusion element” will yield allowing for some relative displacement between superstructure and substructure, and thus providing added damping.
More recently, special high damping rubber has been proposed for damping devices for buildings. Gensui rubber has been used to fabricate special damping pads which are then assembled in the

required number and geometrical configuration to form a damping device. The rubber pads are subject to shear deformations under seismic or general dynamic action. Due to their specific properties such shear deformation dissipates a significant amount of energy, and therefore provides additional damping. Figure 10 shows such damping pads assembled inside steel elements to form a damping advice for buildings. These damping devices are installed in buildings, as required, between the floors of adjacent storeys, typically at least two in each principal direction.

Because of the specific behaviour of the high damping rubber pads, such Gensui dampers are both effective for seismic action with a few relatively large displacements and for wind action with many relatively small displacements. Therefore, they are suitable for damping of wind movements of tall and / or flexible buildings, [20]. Gensui rubber pads have also successfully been used to form damping devices for the control of vibrations of stay cables, [21].

It is the author's believe that the use of damping devices in structures will increase over the next years. This is so because the reliability of such damping devices has significantly improved over the past few years, and their efficiency (cost versus performance) has become very attractive. Use of such damping devices also seems interesting in terms of sustainable development since they permit savings in construction materials. Finally, they can significantly improve user comfort in structures subject to vibrations.

Figure 9. Seismic damper – St. Andre Viaduct, France



a) Damper unit / pad

b) Wall-type damper assembly

c) Brace-type damper assembly

Figure 10. Gensui building damper

5. APPLICATIONS

5.1 Buildings

The USA, Australia and some countries in South East Asia and South America use more than half of the prestressing steel for the post-tensioning of building floors. Typical applications are office buildings, shopping centres, hotels and even some residential construction, see Fig. 11. However, in Europe the use of prestressed concrete in building floors is still marginal in most countries and at best low for special precast pretensioned members in a few Northern European countries.

a) Office building

b) Car parking

c) Hotel

Figure 11. Post-tensioning brings advantages for many types of buildings

Some of the well recognized advantages of the post-tensioning in buildings are:

(1) Longer spans of floors creating large open space in buildings and offering significant flexibility and comfort to the users;
(2) reduced material consumption for concrete (-20%) and reinforcing steels (-65%), and hence, reduced labour (-60%) and cranage needs;
(3) fast cycle times for formwork and reduced need for back-propping because of the load balancing produced by the post-tensioning tendons when stressed;
(4) post-tensioned flat slabs can be used even for quite large spans permitting easier installation of electrical and mechanical installations with reduced overall floor-to-floor height, see Fig. 12;
(5) post-tensioning tendons installed across supporting columns and walls offer significant redundancy under accidental loading and can prevent progressive collapse.

a) Installations with conventional reinforced concrete or composite floor

b) Installations with post-tensioned concrete floor

Figure 12. Mechanical/electrical installations are much simpler with post-tensioned floors

It is the author's opinion that architects, engineers and contractors should seriously look into the use of post-tensioned concrete in buildings, mainly for floors but also for transfer plates / girders, foundation rafts and even for vertical prestressing of building cores and walls. Looking at the above referenced material savings, the use of post-tensioned concrete would, apart from economy, contribute also to a significant reduction of the carbon-dioxide footprint of concrete buildings.

5.2 Slab-on-Ground (SOG)

Slabs-on-ground and industrial floors are relatively thin plates which sit directly on the ground. They are typically used for container terminals, warehouses, storage facilities and distribution centers. These slabs/ floors are subject to wheel loads (trucks, forklifts) and point loads from storage racks. They are used both inside buildings and externally, Fig. 13.

a) Warehouse with indoor SOG b) Outside application of SOG c) Good detailing for SOG

Figure 13. Post-tensioned slab-on-ground ensures durability and low maintenance cost

Many of today's slabs/ floors are built in unreinforced concrete with expansion joints every few meters to limit restraints due to shrinkage and temperature movements of concrete. However, these joints usually have a poor behaviour over time and cause significant maintenance/ repair costs.
Post-tensioned slabs-on-ground / industrial floors receive an orthogonal post-tensioning applied concentrically to the slab. Except along the slab edges there is no non-prestressed reinforcement at all. The post-tensioned floors are typically placed on plastic sheets to reduce friction between slab and ground, Fig. 13. The post-tensioned floors have only few but well designed expansion joints. Detailing and the quality of concreting works are important to avoid cracking of the floors during the first few hours and days after concreting. An early application of the post-tensioning through partial stressing of the tendons before twelve hours after concreting is recommended.
Well designed and constructed post-tensioned slabs-on-ground and industrial floors perform exceptionally well in practice. They are competitive with other construction methods when life-cycle costing is considered due to their low maintenance costs.
Similar comments as to slabs-on-ground apply also to post-tensioned concrete pavements for highways and airports.

5.3 Precast segmental bridges

Precast segmental construction has taken a dominating role in concrete bridge construction in particular for large scale and fast-track projects. Although introduced in France already begin of the 1960's, the construction method made its real break-through only after the successful introduction into the USA with the large scale projects in Florida in the early 1980's. Precast segmental bridge decks, mostly box girders with internal and / or external post-tensioning tendons, have since become a preferred construction method up to spans of about 100-120m. Short-line match casting of segments permits to follow almost any bridge deck alignment even in very constrained space in urban areas. Precast box girders are competitive and are now preferred over precast beam solutions in many parts of the world. Without the availability of precast segmental construction technology, many of today's fast-track urban projects would likely be built in steel.
Figure 14 presents some selected precast segmental road bridges built over the last few years. While in the past, precast segmental construction was almost exclusively used for highway bridges, more

recently some notable examples of railway bridges were constructed. These examples include many light rail structures built in urban areas. However, precast segmental construction was also used for high speed railway structures. Figure 15 presents some examples of railway bridges.

a) Telok Blangah Project, Singapore b) Oakland Bay Bridge, San Francisco / USA

Figure 14. Precast segmental highway bridges

a) Metro Project, Santiago/Chile b) Avignon TGV Viaducts, France

Figure 15. Precast segmental rail bridges

Despite the successful use of precast segmental construction in many countries, some owners and engineers remained reluctant to use this construction method. This was mainly due to some reservations on the use of external tendons, in general.
However, a particular point of concerns was the encapsulation of internal tendons across the joints between precast segments. Dry joints (without epoxy resin) and internal tendons with discontinuous plastic ducts are not considered acceptable for any tendon Protection Level (PL), see Clause 3.3 above. Joints adequately filled with a suitable epoxy resin are acceptable for PL1. However, for PL2 and PL3 either sealing of the exposed segment joints with a suitable membrane and/ or full encapsulation of the tendon with plastic couplers across the joints is considered necessary in addition to the epoxy resin. This can be achieved e.g. by special duct couplers across the segment joints. Figure 6 shows such a type of duct coupler for continuity of the tendon encapsulation across joints in precast segmental construction.
It is the author's opinion that today's external tendon technology and encapsulation technology for internal tendons permit construction of very durable precast segmental concrete bridges even for use in harsh environments. It is expected that the use of precast segmental construction will further increase.

5. 4 Extradosed segmental bridges

As mentioned in the introduction to the above section on segmental bridge construction, the maximum span range of precast segmental bridges is limited to about 100-120m. This span range can be

extended for specific spans of a project without necessarily changing the depth of the deck by the use of extradosed tendons. Extradosed tendons are external tendons placed outside of the envelope of the box girder somewhat similar to stay cables but typically at a shallower inclination to the deck. Extradosed segmental bridges therefore, have a relatively stiff deck when compared with typical cable-stayed bridges.

According to [22], the typical span range for extradosed bridges is 100 – 200 m, with recent examples approaching 300 m. Typical girder depths at pier and mid-span are *Span/35* and *Span/55*, respectively. The height of the pylon above deck is of the order of *Span/12*. The extradosed deck is typically erected by balanced cantilever construction with progressive installation of the extradosed tendons.

The main advantages of the extradosed bridge system are said to include a relatively light deck, appealing aesthetics for its increased deck slenderness, improved geometry control during construction, improved in-service stiffness of the deck, and reduced stress amplitudes in the tendons which allow a more efficient utilization of the tendon at higher loads than stay cables. In practice, the stress range from live load is of the order of 20 – 50 MPa, and therefore, the permissible upper load has been set at 60% GUTS i.e. between the corresponding levels of stay cables and external tendons of 45% and 80%, respectively. However, system acceptance tests are required at the order of 100 – 140 MPa fatigue stress range. With these parameters, extradosed tendons are less sensitive to vibrations than stay cables. This type of bridge seems also suitable for railway structures. Extradosed tendons typically consist of a bundle of 7-wire strands inside a HDPE pipe, injected with cement grout after stressing, i.e. similar to external tendons. More recently, also non-grouted extradosed tendons have been used, initially in Japan and now also elsewhere.

An example of the transition of traditional precast segmental construction into the extradosed system is the Pakse Bridge in Laos, Fig. 16. The new bridge was at the time of construction only the second crossing of the Mekong river in the country. The bridge has a precast segmental deck with 102 m typical spans, and an extradosed main span of 143 m, all erected by balanced cantilever construction with an overhead gantry, Fig. 16. It has a total length of 1,380 m with intermediate expansion joints to form four sections of 306 to 443 m. A total of 384 segments were cast in a long line yard set-up on site, with a typical width of 11.5 m, and 14.5 m at the extradosed span to provide additional space for the tendons anchorages. The depth of the segments varies between 3.0 and 6.5 m. Segment lengths are between 2.5 and 3.5 m to limit the weight to a maximum of 105 tonnes. The 50 tonnes of extradosed tendons consist of 7-wire strands, inside an HDPE pipe, and injected with cement grout. The tendons are continuous across the pylon through special saddles with double steel pipe to permit replacement of the tendons, if ever required. The pylon reaches a height of 15 m above deck level.

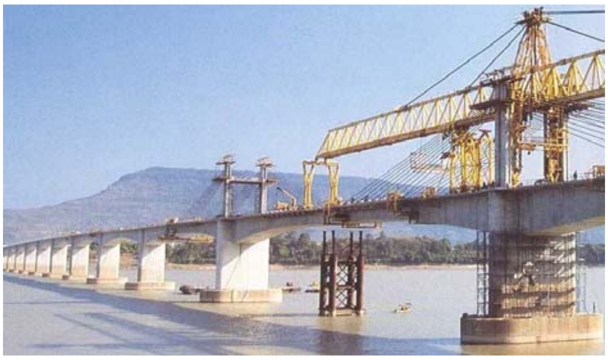


Figure 16. Pakse extradosed bridge, Laos

It is the author's expectation that we will see more extradosed bridge construction in the future. Recommendations for the design of extradosed structures and for extradosed tendons are being prepared by several organisations, including fib.

5.5 Concrete containment and storage structures

Prestressed concrete has been used since long successfully for the construction of storage structures such as silos, water reservoirs and LNG/LPG tanks. There has also been a large number of prestressed concrete containment structures built in the 1970's and 80's for nuclear power plants.
Norway has been leading in the design and construction of offshore structures for the oil and gas production and storage. Both gravity based and floating concrete structures were built. Investigations have shown that these prestressed concrete structures have performed extremely well in the harsh North Sea environment, [23]. These structures have also demonstrated that dense concrete is extremely well suited for storage of oil without particular linings.
Today's demand for energy will also bring needs for more storage structures. Prestressed concrete is extremely suitable and economical to satisfy the needs either on-shore or off-shore. With the increase of steel prices, floating concrete storage structures, such as the N'Kossa Barge, Fig. 17, or similar structures may become again economically interesting.

Figure 17. N'Kossa Barge, France

The construction of a large number of nuclear power plants has been announced all around the world. Prestressed concrete will be the preferred construction technology for many of these structures. The trend in the prestressed containments is to larger post-tensioning tendons up to 55 strands 0.6". To simplify detailing of the containments and reduce the number of buttresses, hoop tendons go around 360 degrees. The size and lay-out impose new challenges in terms of tendon installation, stressing and grouting. These challenges will bring forward new developments in the post-tensioning technology which will be beneficial to other types of structures also. The author also expects that there will be further progress in the monitoring of tendons brought through experience with these structures.
Wind turbines installed on towers either onshore or offshore have become widely accepted for production of electricity. Increasing oil prices have made this form of energy production economically feasible. Early applications with relatively small turbines have favoured the use of structural steel towers. However, increase of turbine size and tower height as well as demands for stiffness and fatigue resistance make now prestressed concrete attractive and economically feasible. Precast segmental concrete towers are expected to become the preferred construction method for these towers for wind turbines.

6. SUMMARY AND CONCLUSION

After a brief review of new developments in materials and specific technologies for structured concrete, trends in selected applications have been discussed. In view of the present trends in material cost, energy demand and needs for sustainable construction, the author sees a very promising future for prestressed concrete construction.

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