Post-Tensioned Masonry Around the World

Post-tensioned masonry is useful in several applications

BY HANS RUDOLF GANZ

Post-tensioned masonry combines an advanced construction technique with an old building material almost forgotten in the education of civil engineers. The major advantages of masonry have always been the overall availability of its raw materials, its easy and economical construction, and its natural beauty and durability. So, why should we post-tension masonry?

Masonry has a relatively large compressive strength but a low tensile strength. Therefore, apart from nonstructural applications, masonry is used primarily as a construction material for vertical members subjected to gravity loads. Minor lateral loads and deformations may be resisted by the weight of the masonry walls.

However, for larger lateral loads and deformations, out of plane or in-plane, unreinforced masonry walls with low axial loads, as typically found in modern construction, exhibit a poor cracking behavior and a low strength. Such walls perform even worse in seismic regions, having a low ductility and developing brittle failure modes.

Originally presented at the Post-Tensioning Institute Engineering Conference, May 5-7, 2002, San Antonio, TX.

These disadvantages of unreinforced masonry may be overcome by applying a moderate amount of axial load using post-tensioning. Post-tensioning offers architects and engineers the possibility of actively introducing any desired axial load into the masonry walls to enhance their strength, cracking behavior, and ductility. Post-tensioning also provides effective connections between walls and diaphragms to avoid failure of the joints, which is often seen in unreinforced masonry structures in earthquake zones. Post-tensioning has a restoring effect on masonry walls that reduces residual deformations after excessive loading. Post-tensioning is effective for strengthening existing masonry structures and is economical for construction of new masonry structures.

Post-tensioned masonry economically competes with nominally reinforced concrete walls, particularly if the wall heights exceed about 12 ft (3.6 m), because of formwork savings. It is competitive with reinforced masonry because one 0.6-in.-diameter (16 mm) seven-wire prestressing strand provides greater strength than five No. 4 (12 mm) reinforcing bars, which means less reinforcement to place and fewer wall cavities to grout.

Post-tensioning is most frequently applied vertically to masonry walls. Anchorage at either end of the tendons is preferably placed in concrete elements, either cast-in-place slabs or beams, or precast blocks. Due to the cost of anchorage, post-tensioned masonry walls are particularly useful for walls exceeding 10 to 12 ft (3.0 to 3.6 m) in height.

Prestressed masonry has been introduced into the design codes of some countries. The UK has had a British Standard for prestressed masonry since 1985. More recently, Switzerland, Australia, and, since 1999, the U.S. have introduced code requirements for the design and construction of prestressed masonry.

Early research and applications of post-tensioned masonry have been reported primarily in England by innovative engineers. Applications included a prestressed water tank, retaining walls, large walls in buildings, pedestrian bridges, and even road and railway bridge abutments. Later, specialty contractors have introduced post-tensioning systems for masonry, and have further promoted the construction method. The following case studies provide a selected number of examples for the possible uses of post-tensioning in masonry construction.

Salvation Army Citadel

Post-tensioning was used in the main hall of the Salvation Army Citadel, which was approximately 25 m (80 ft) long x 15 m (50 ft) wide, and 8.5 m (30 ft) high (Fig. 1). The top of the wall could not be propped laterally due to the inclusion of a clerestory running around the top of the wall. Therefore, it was decided that an economical solution was to design the post-tensioned diaphragm wall as a free cantilever. A section through the diaphragm wall is shown in the inset of Fig 1. The post-tensioning force cancelled out the tensile stresses at the base of the wall when the wall was subjected to full design wind loading.

The diaphragm wall was built as an external brick wall and, for aesthetics, a light-colored internal block wall. The two walls were joined by extensive use of cavity ties, forming a composite box section. Each diaphragm wall segment, located between windows, had two cavities, and each cavity had one stressbar (equivalent to grade 150 ksi [1035 MPa]) 32 mm (1.25 in.) in diameter. A coating of Denso paste and wrapping of Denso tape protected the stressbars from corrosion, and, therefore, they were not bonded to the wall. The stressbars were installed in practical lengths for erection and joined with threaded couplers. A basic bearing plate and nut was used to anchor the stressbars into a precast concrete capping beam on top of the wall. Anchors at the bottom of the wall were within a cast-in-place foundation. Jacking was applied to the stressbars from the top of the wall using a conventional torque wrench. It is believed that this project was completed at the beginning of the 1980s. Significant savings were achieved with the post-tensioned masonry when compared with a solution of steel.

Fig. 1: Salvation Army Citadel, Warrington, UK

Technical Museum

In 1998, a four-story addition to the existing technical museum in Berlin was constructed consisting of a structural steel frame, concrete floors, and double wythe post-tensioned masonry curtain walls (Fig. 2). The curtain walls have low axial loads (due to their self-weight only) but are exposed to full design wind loads and span up to 8.8 m (30 ft) between lateral supports. The walls have a total height of 25.5 m (80 ft).

To accommodate masonry curtain walls under the previously mentioned loading conditions, post-tensioning tendons were introduced in the inner wythe of 240-mm-thick (9.5 in) concrete blocks. A total of 34 individually greased and sheathed monostrand tendons (0.6 in. [16 mm] diameter strands) at 1.75 m (6 ft) on center were installed in steel ducts placed in block cavities at the center of the wall. The tendons were each 26.5 m (90 ft) long and anchored at the bottom in a reinforced concrete basement wall. Anchors were cast-in-place into capping beams—at the top of the curtain walls—on both wythes. A hydraulic jack stressed the tendons from the bottom anchors. Access for stressing was provided with permanent recesses in the wall that permit future inspection and eventual restressing of the tendons, if ever required. For architectural reasons, the outer wythe was built in brick masonry and supported from the inner post-tensioned wythe with ties.

Fig. 2: Technical Museum, Berlin, Germany

Tring Bridges

Fig. 3: Tring Bridges, Tring, UK

In 1994, two 7-m-long (20 ft) pedestrian bridge decks were constructed of post-tensioned masonry in Tring, UK (Fig. 3). These bridges are believed to be the first post-tensioned brick box girder decks ever built.

The design of each 1.5 m (5 ft) wide bridge deck used a 440-mm-deep (17 in.) box section, which was formed by a top and bottom flange connected with five webs. This configuration provided four longitudinal voids inside the section to minimize weight and to accommodate the longitudinal post-tensioning tendons. Transverse and longitudinal camber was provided to the bridge deck to drain water and to improve the durability of the masonry deck.

The tendons inside the box were straight and used the deck camber to provide the required eccentricity at midspan. Tendon anchors at either end of the deck were placed in concrete capping beams (Fig. 3). These capping beams incorporate wing walls to retain the top of the earth embankment (when in the final position) and to provide access to the tendon anchorages for installation and stressing during construction. Apart from the four tendons, the only reinforcement in the deck was steel spirals around the tendon anchorages in the capping beams. One of the two bridge decks used stressbars for the post-tensioning tendons; the other used aramid fiber-reinforced polymer (FRP) tendons.

The masonry decks were built standing vertically; prestressing was then applied just prior to moving the decks into their final horizontal position (Fig. 3). Stressing of the tendons was by a hydraulic jack to 200 kN (45 kips) per tendon.

Industrial Center

Adjacent to an existing industrial center building, a new warehouse was added in 1993 (see the tall building in Fig. 4). Two walls of the warehouse, one of them facing the existing building and one facing an end wall, were designed as post-tensioned masonry. The lower parts of these walls were in contact with the adjacent building while the tops were completely exposed. The lateral wind load for design was assumed to be 0.3 kPa (6 lb/ft^2) and 1.0 kPa (20 lb/ft^2) for the lower and upper parts of the wall, respectively. Post-tensioned masonry was chosen for this project because it proved to be considerably less expensive than reinforced concrete, which requires formwork, over the total wall height of 13.8 m (45 ft).

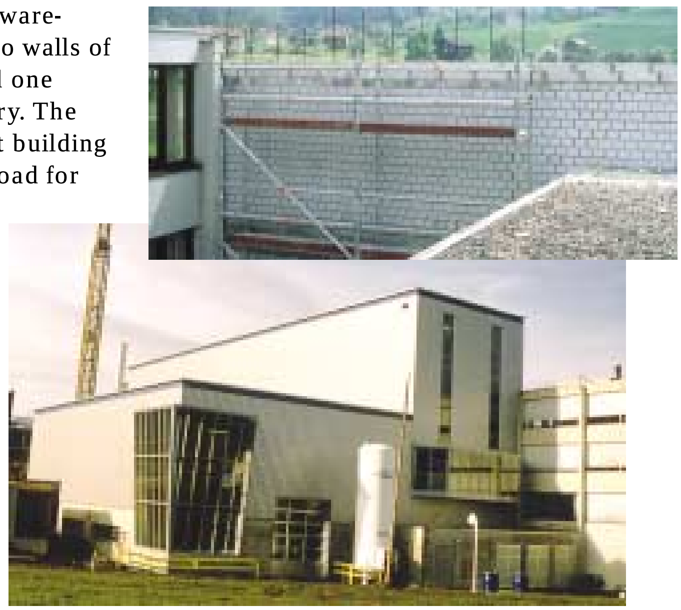


Fig. 4: Industrial Center, Altendorf, Switzerland

The L-shaped, 13.8-m-tall (45 ft), post-tensioned walls are 43.35 m (140 ft) and 9.5 m (30 ft) long. The lower 5.6 m (20 ft) of the 13.8-m-tall (45 ft) walls were cast in concrete. The masonry walls were constructed of 250-mm-thick (10 in.) calcium silicate units. Post-tensioning tendons were individually greased and sheathed 0.6-in.-diameter (16 mm) monostrands, placed vertically inside a steel duct located in block cavities at the center of the wall. Dead-end anchors at the bottom of the masonry were cast 0.5 m (20 in.) into the concrete wall and properly lapped with the reinforcement in this area. A total of 71 tendons were installed at spacings of 0.57 and 0.95 m (20 and 40 in.), depending on actual wind exposure conditions. Stressing anchors were placed in precast elements on top of the wall with layers of bed joint reinforcement in the three joints below the elements.

Tendon ducts were placed concurrently with the wall construction. Once the stressing anchors inside the precast concrete elements were placed on top of the walls, the monostrands were threaded from the top through the stressing anchorage and duct and locked in the self-activating dead-end anchorage at the bottom. Each monostrand was subsequently stressed with a hydraulic jack to 200 kN (45 kips) and locked off. Anchors were filled with corrosion protective grease and closed with a steel cap. Tendons were left unbonded to the masonry.

General Post Office Tower

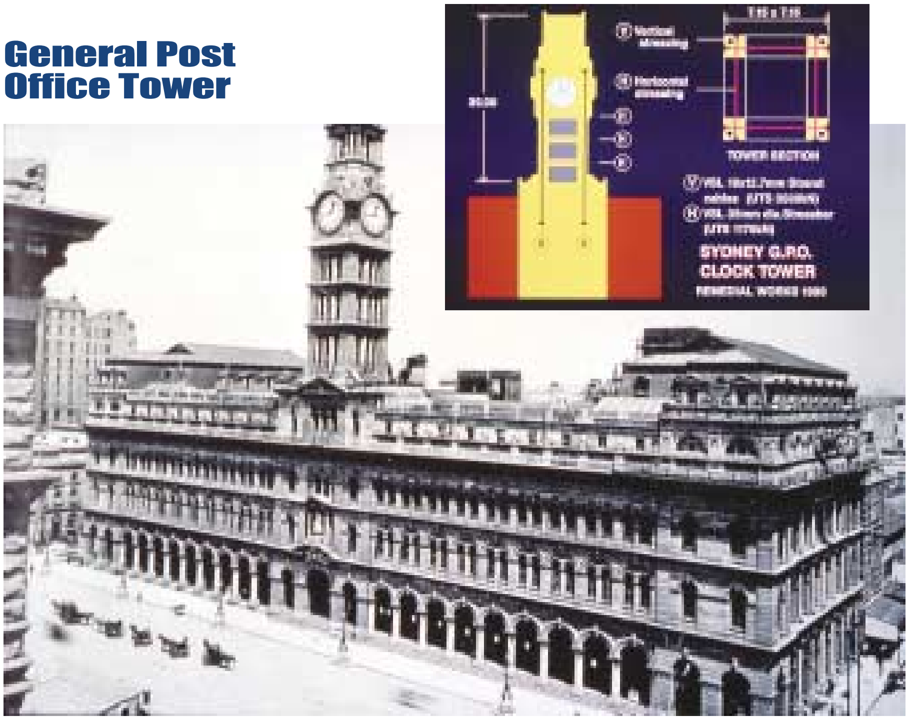


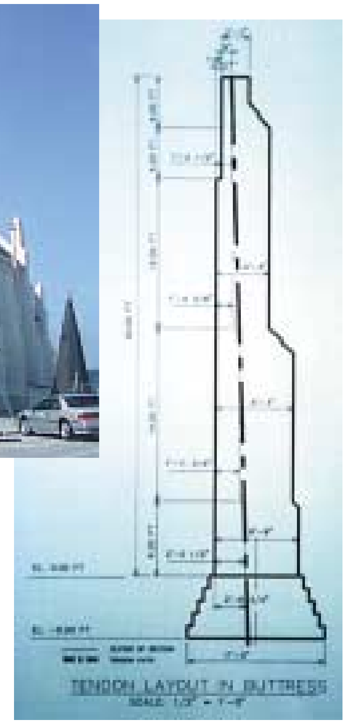
Fig. 5: General Post Office Tower, Sydney, Australia

Towards the end of the 1980s, the General Post Office (GPO) in Sydney, Australia, which is more than 100 years old and a sandstone masonry building, was undergoing a massive restoration both inside and out. As part of the restoration, the GPO Tower needed strengthening for seismic loading. The required strength and ductility for the tower was provided with four vertical post-tensioning tendons, nineteen 0.5-in.-diameter (13 mm) strands each, and a number of horizontal stressbars, 35 mm (1.4 in.) in diameter, at the floor level (Fig. 5). The vertical post-tensioning tendons were placed in 100-mm-diameter (4 in.) holes core drilled from the top of the tower through the sandstone columns at the tower corners. Special steel chairs were used to anchor the tendons and spread the anchorage force of 1771 kN (400 kips). The anchorages of the unbonded tendons allowed for monitoring and adjustment of the tendon forces to compensate volume changes of the sandstone, if ever necessary. The entire restoration took 5 years to complete and installation and stressing of the tendons was done in 1990.

Holy Cross Church

This more than 100-year-old structure was severely damaged during the Loma Prieta Earthquake and, consequently, the bell tower was removed and the church was closed (Fig. 6). The church and tower were built with unreinforced brick masonry walls on a stone rubble foundation. Timber trusses spanned across the church, between buttresses, and provided support for the roof. The tower and walls of the church were severely cracked from both shear and flexural forces. However, the masonry and the foundations were generally found to be in good condition. In-place testing indicated the masonry strength was between 4 MPa (600 psi) and roughly 8 MPa (1200 psi) based on the wall's gross area.

Fig. 6: Holy Cross Church, Santa Cruz, CA



Post-tensioning was considered the most efficient retrofit for the church, providing strength and ductility to the overall structure with minimum of intrusion or alteration of the historical building.

Retrofit of the church also included grouting of cracks in the masonry; reconstructing parts of the bell tower in steel, timber, and cladding to reduce weight and seismic effects; and adding reinforced concrete tie beams on top of the buttresses and a new roof with in-plane steel trusses.

A total of 26 vertical tendons were introduced into the structure to enhance its shear and flexural resistance. Figure 6 illustrates the layout of the tendons in the buttresses. Tendons in the walls and tower consisted of seven and twelve 0.5-in.-diameter (13 mm) strands, respectively, detailed similar to ground anchors, which means greased and sheathed strands were used in the free unbonded length in the masonry and bare strands were bonded to the ground and rubble foundation by cement grout. The tendons were stressed to 910 and 1560 kN (200 and 350 kips), respectively, from the top and anchored with basic bearing plates cast into reinforced concrete beams. The holes for the tendons were core drilled through the walls from the top.

Development of the first retrofit concepts started in 1990. Refined investigations including nonlinear analyses and review of concepts went well into 1991. The retrofit work was finished in 1992 and on October 17, 1992, after successful completion of all tendon stressing, the new steeple was installed on the bell tower.

Selected for reader interest by the editors.

ACI member **Hans Rudolf Ganz** is Chief Technical Officer and Executive Vice President of VSL International Ltd., Berne, Switzerland. Ganz has been with VSL Group for 17 years and has been involved in all aspects of post-tensioning systems and applications of the systems to concrete, composite steel and concrete, and masonry structures. Before joining VSL, he worked as a research associate with ETH Zurich where he investigated the behavior of masonry shearwalls. Ganz serves on several committees of professional organizations such as *fib*, PTI, and ACI, and he has been Co-Chair of the Prestressed Masonry Subcommittee of Joint ACI-ASCE-TMS Committee 530, Masonry Standards.