Critical Milestones in Development of Post-Tensioned Buildings

A look back at the last 50 years of progress

BY BIJAN O. AALAMI

Fig. 1: Rendering of the Khaili Tower, a 38-story residential high-rise structure being post-tensioned in Dubai, U.A.E., by Freyssinet Gulf, LLC

Since they were first used in the U.S. nearly half a century ago, post-tensioned concrete slabs have become a major system for most types of commercial and residential buildings. In addition to economical advantages, the elimination of floor beams and reduction in building weight and height make post-tensioning particularly suitable for regions of high seismic risk. In regions that have a competitive market with stringent seismic design requirements, post-tensioning has been the choice for many notable high-rise buildings, such as the 60-story Millennium Tower at Mission Street and the 41-story Infinity Towers, both currently under construction in San Francisco, CA—one of the highest seismic risk regions in the U.S.

The concept and advantages of post-tensioning were understood as early as 1860, but it was about 100 years before the first successful projects were built in the U.S.[1] The subsequent 50 years saw rapid growth in the number of post-tensioned buildings and maturity in their construction and design technology. Having witnessed the performance and economical advantages of post-tensioned buildings, many other regions of the world, such as Australia, Brazil, the Middle East, South America, South East Asia, and the UK, are now embracing this U.S.-spearheaded technology in their building construction (Fig. 1). This article reviews some of the critical milestones that have led to the successful development of post-tensioning, making it the choice for many residential and commercial buildings.

CONCEPT OF PRESTRESSING AND EARLY ATTEMPTS

In 1872, P. Jackson, a California engineer, obtained a patent for post-tensioning and used tie rods to construct beams or arches from individual blocks. His effort was followed in 1888 by C.W. Doehring who obtained a patent in Germany for prestressing slabs with metal wires. Because early steel had a relatively low yield stress (Fig. 2), none of these early attempts were successful. Low initial jacking stress, combined with high creep and shrinkage of the concrete, eroded the bulk of the prestressing force applied to the structure, leaving the steel practically ineffective. A dramatic increase in the effective stress in the prestressing strands after all stress losses was the first critical milestone in making prestressing a practical proposition. Figure 2 illustrates the significant gain in the effective stress of today's most commonly used strands in comparison to early steel. The same figure includes higher strength stands that are gradually replacing the currently popular prestressing steel in building construction.

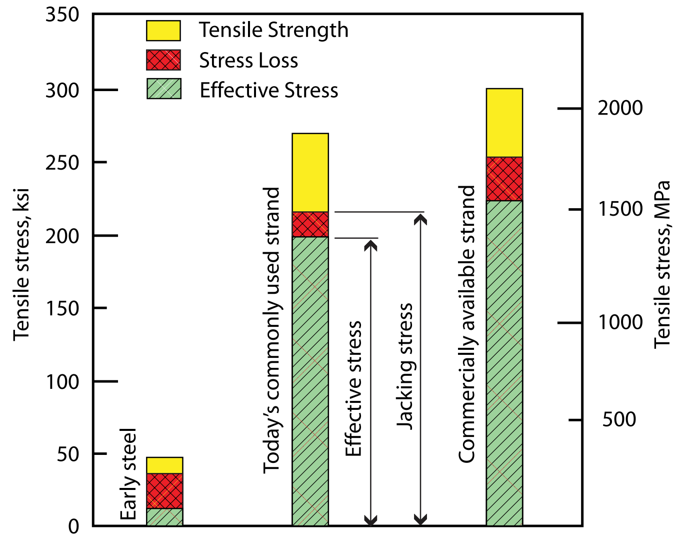

Fig. 2: Comparison of steel strengths and prestress losses for steel used in early attempts at prestressing and those currently available

PRACTICAL HARDWARE

In 1926 to 1928, Eugene Freyssinet recognized the effects of long-term stress losses in prestressing and used a new high-strength steel to successfully construct prestressed members in France. In 1940, he introduced the well-known and well-accepted Freyssinet system comprising conical wedge anchors for 12 wire tendons (Fig. 3). Developments in high-strength steel, coupled with the invention of prestressing hardware, proved to be another critical breakthrough in the effective application of prestressing. Although many prominent engineers including Magnel in Belgium, Guyon in France, Leonhardt in Germany, and Mikhailov in Russia continued to develop prestressing, the focus of prestressing remained in bridge construction and special structures. Little attention was paid to taking advantage of post-tensioning in building construction.

FIRST POST-TENSIONED BUILDINGS

It wasn't until the early 1950s and the introduction of lift slab construction in the U.S. that the pioneering engineers revisited the application of prestressing to eliminate cracks and reduce deflections in thin flat slabs in buildings. While credit is due to innovative engineers and early contractors for the introduction of prestressing, the principal design instrument for its application was put forward by T.Y. Lin[2] through the concept of load balancing. In its basic form, load balancing allows the engineer to view the effects of post-tensioning as a reduction in the design dead load applied to a slab—a design load condition that engineers understand and handle well (Fig. 4). Coupled with the economies made possible by post-tensioning, the simplicity of load balancing allowed pioneering engineers and contractors to drive growth of post-tensioned construction in the U.S.

EARLY DESIGN TOOLS, DETAILING, AND FIELD PROCEDURES

Four elements that helped fuel the concept introduced by T.Y. Lin toward the acceptance and wide application of post-tensioning were:

- Development of effective hardware for stressing and anchoring of single strand tendons;
- Development of easy-to-use design software;
- Development of good engineering practices and details necessary to avert construction failures caused by high prestressing forces that are more common in thin post-tensioned members; and
- Spreading the practice through teaching, seminars, and an effective trade organization.

Edward K. Rice, founder of Atlas Prestressing Corp., is credited with having advanced practical monostrand hardware for stressing and anchoring single strand tendons—a necessity for thin slab construction. Easy-to-use and widely available software such as PTData, spearheaded by Merrill Walstad, enabled many engineers to engage in the design of post-tensioned structures. With an in-depth understanding of construction technology, Nicholas Watry developed a host of practical construction details that provided a basis for a sound construction practice for post-tensioned building structures. Through formal teaching, seminars, and professional committees, Kenneth Bondy helped spread the word on the advantages of post-tensioning and its design. The creation of the Post-Tensioning Institute (PTI) by Clifford Freyermuth was another significant milestone, as it led to PTI's many publications regarding the treatment of post-tensioning in building codes.

COMPLEX FLOOR SYSTEMS

Not all floor slabs have a simple geometry and uniform thickness. In particular, podium slabs that support several levels of a building along with plaza and landscaping regions invariably have irregular geometry; stepped, nonuniform thickness; and slab bands (shallow beams)

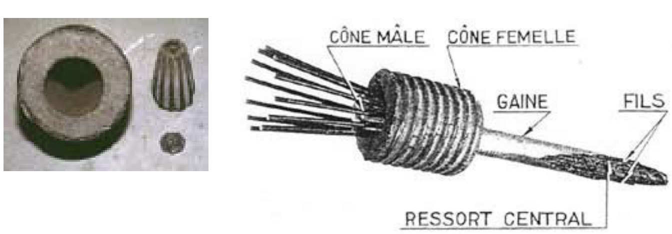

Fig. 3: Freyssinet's early anchorage device: (a) photo of anchorage device; and (b) diagram of anchorage assembly

Simple load balancing is based on suppositions that the axial force and bending effects induced on a member by a prestressing tendon can be decoupled, the prestressing force is constant over the full length of the tendon, and the elevation of the member centroid is constant over the member length: (a) a structure of uniform thickness and subjected to an applied dead load (1) is post-tensioned with a continuous tendon; (b) the tendon is assumed to be removed and replaced with an equivalent load (2); and (c) the net effect, load (1) – load (2), is a reduced load used in combination with traditional methods for design of the member. Note that the concentrated forces resulting from discontinuities in the tendon [see load (2)] are transferred directly to the supports and don't affect the member.

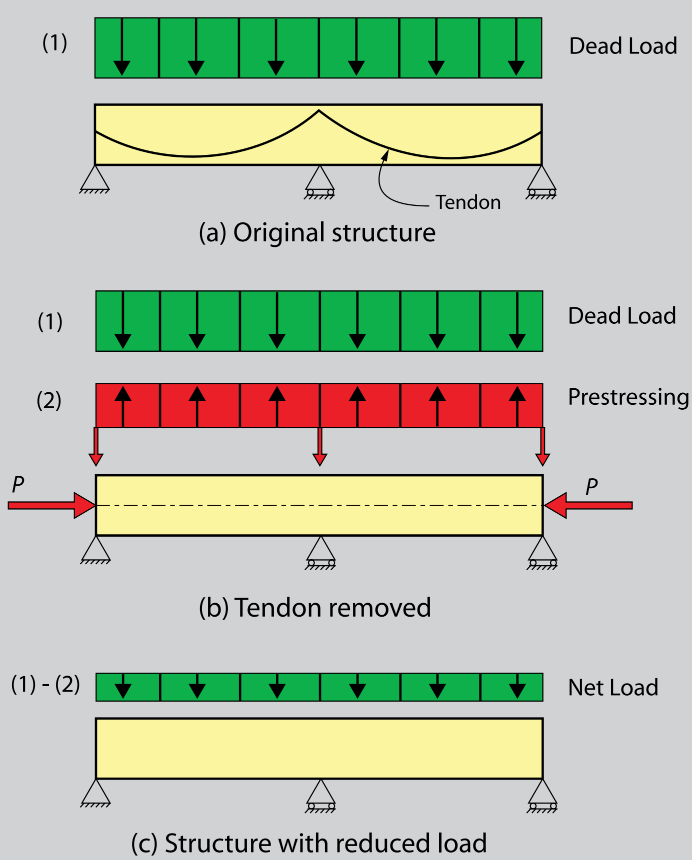

Fig. 4: Simple load balancing

(Fig. 5). The complex geometry of these floor slabs called for an extension of simple load balancing[3] by the introduction of moments at locations of change in slab thickness. This is explained in greater detail in Fig. 6.

Unlike the U.S., many other parts of the world use grouted (bonded) post-tensioning systems—these undermine the premise of "constant force" that is a cornerstone of load balancing. In grouted post-tensioning, unlike the greased and plastic-coated unbonded alternative, high friction losses significantly decrease the post-tensioning force along the length of a tendon. This accelerated the move to the next milestone in design technology, the use of finite element analyses. Through extensive educational seminars, technical publications, consulting in post-tensioning, and software development in particular, ADAPT Corp. has been instrumental in advancing the effective application of post-tensioning to a wider range of building structures.

SEAMLESS INTEGRATION OF THE DESIGN PROCESS

The current era in architecture is driven by elaborate structural engineering, advanced materials, and innovative and creative geometry. The open spaces, large spans, and oftentimes architecturally-driven nonorthogonal support layouts of modern multistory buildings have further fueled the growth of post-tensioning and led to new demands on its design technology.[4] These designs, coupled with advances in computers and software and the desire for universal, seamless integration of the work of different design professionals (architectural, structural, and mechanical) into a single environment, have created a new challenge for structural engineers.

Representation of a building in three dimensions with the ability to interchange information among the various construction disciplines, by such software as Revit® Structure of Autodesk, has become a central theme in the development of new design tools. Finite element technology, such as implemented in ADAPT software, has proven to be particularly suitable as the prime vehicle for handling the structural engineering aspects of this movement. For its application to post-tensioning, however, the general purpose routines developed in industry over the years and implemented in many commonly available general purpose software had to be reformulated to account for post-tensioned building structures.[5,6]

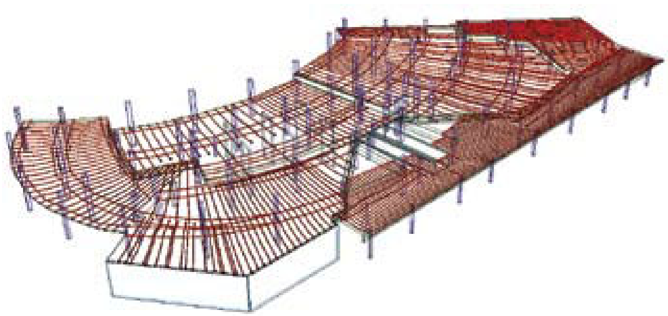

Fig. 5: Post-tensioned podium slab with irregular support layout and multiple steps on the top and bottom of the slab

BUILDING CODES

Unlike many other aspects of engineering practice where a technology introduced in industry is oftentimes the outcome of work in universities and research facilities, post-tensioning in building construction was developed in the field through the efforts of pioneering engineers and contractors. It was not until 1963 that prestressed concrete was first introduced in ACI 318.[7] Although ACI 318's treatment of the design of post-tensioned buildings is the most comprehensive of any concrete design code currently

Extended load balancing accounts for changes in thickness of a post-tensioned member: (a) a post-tensioned structure of nonuniform thickness; (b) the tendon is assumed to be removed and replaced with equivalent loads that consist of distributed uplift forces due to the parabolic tendon profiles and concentrated axial loads at the ends of the tendons. Lack of alignment of the axial forces results in added bending of the beam; (c) to maintain the concept of decoupling axial and bending effects, a moment is introduced at the change in member geometry (step in the member); and (d) the vertical forces from tendon geometry (1), and the moment(s) introduced at the change in member geometry (2) result in reactions at the supports (3). Note that the concentrated loads resulting from discontinuities in the tendon as well as the moment due to the change in geometry affect the reactions (3). For the in-service evaluation of a member, all of the illustrated forces [load (1), moment(s) (2), and reactions (3)], are used in conjunction with dead and live loads. For the strength check, however, only the reactions (3) shown in (d) are used in conjunction with the factored dead and live loads

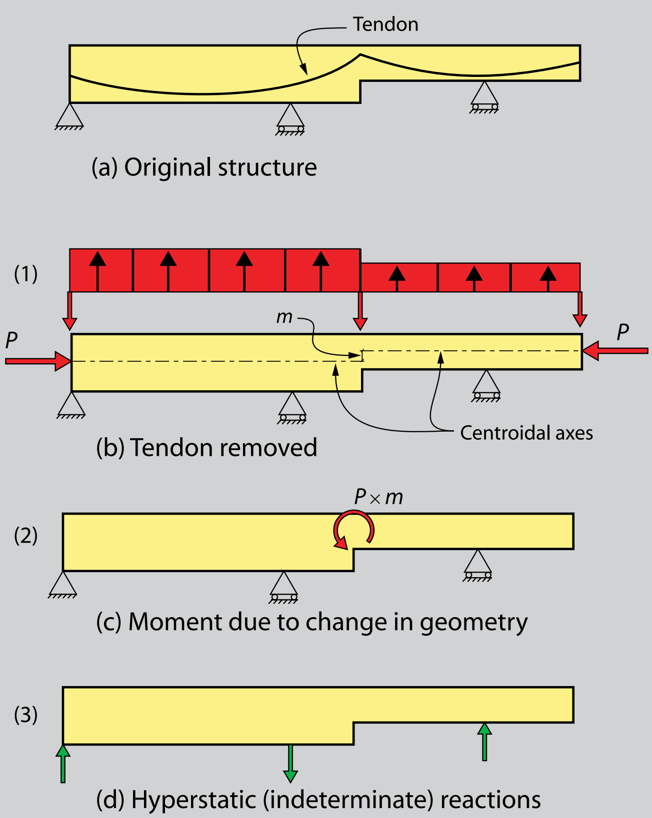

Fig. 6: Extended load balancing

available, it is still catching up in addressing some design aspects of post-tensioned construction in buildings. Among other considerations, the next obvious issue to be addressed in ACI 318 is the inclusion of the industry practice of using finite element methods to design concrete floor systems, in particular for post-tensioned buildings. The practice has reached a fine degree of refinement in industry, but is yet to be handled in the code. Finally, it should be noted that, with the increased application of post-tensioning throughout the world, there has been a clear interest in implementing post-tensioning in building codes outside the U.S.

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Selected for reader interest by the editors.

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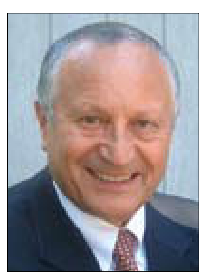

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