Chapter 2
Contemporary Post-tensioned Concrete Construction

In our fire test specifications we require certain minimum sizes of specimens in order to have a fairly standard test. These are comparatively large and represent an average if not maximum of what will be used in the [real] structure.

—Simon Ingberg, chief of Fire Resistance Section National Bureau of Standards and former chair of ASTM E05 as corresponded to Carl Menzel in relation to his standard fire tests on concrete members (1943).

2.1 Defining a Post-tensioned Structure

Post-tensioned (PT) concrete is an increasingly popular technology since it allows for rapid construction using less material than conventional concrete. While its use has been widespread in the United States since the late 1950s, it has recently seen wider popularity in Europe, China, and the Middle East. PT concrete uses high strength cold-drawn prestressing steel tendons. The tendon configurations for PT concrete are bonded and unbonded. In both configurations, prestressing steel is used to pre-compresses the concrete slab before loading and results in longer spans without deformation. In comparison to conventional reinforced concrete slabs, PT concrete provides excellent control of in-service deflections (Khan and Williams 1995). Figure 2.1 illustrates simplified tensioning and compression mechanics used in PT concrete.

In order to explain how optimization of PT concrete construction is achieved, an understanding of load balancing is necessary (Lin 1963; Aalami 2007). In load balancing the prestressing tendon, which typically follows a parabolic profile within

J. Gales et al., *Structural Fire Performance of Contemporary Post-tensioned Concrete Construction*, SpringerBriefs in Fire,
DOI 10.1007/978-1-4939-3280-1_2

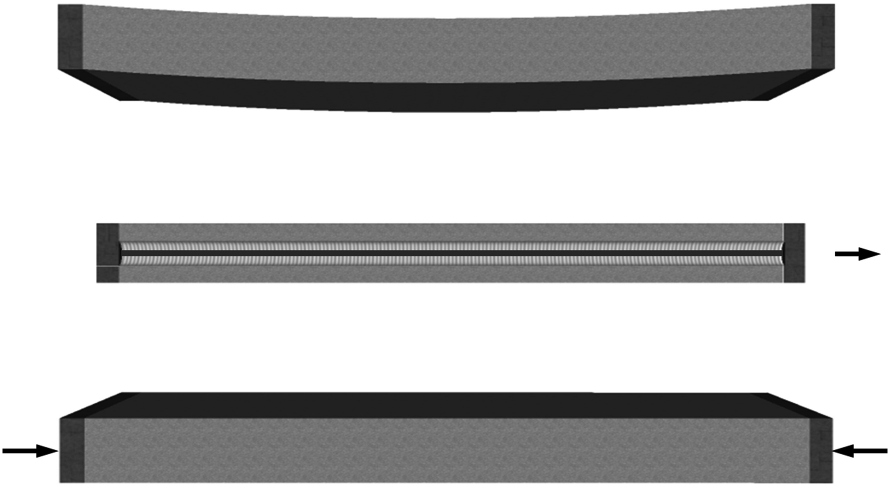

Fig. 2.1 Post-tensioning concrete where the tendon is shown in blue and the forces are shown in *black*

the concrete, acts as a 'distributed force' applied on the entire structural element. This distributed force is a function of the tendon's degree of tension and its drape (the prestressing steel's eccentricity with respect to the neutral axis of the structural element). The distributed force acts to 'balance' the net loading that contributes to service deflection. Figure 2.2 provides a visual representation of load-balancing by tensioning reinforcement.

Figure 2.2 is a highly idealized schematic of loading behavior in PT slabs; in reality the secondary loading exerted by the stressed prestressing steel is more complicated. This complication is partially due to the fixity of support conditions, the compressive reactions at slab ends, and the amount of tendon draped above and below the structure's neutral axis. The decreased deflection in PT structures helps minimize the concrete used by enabling shallower, and optimized structural elements. This enables a designer to specify additional space and open plan compartments for hi-rise buildings.

2.2 Design and Construction Is Changing

Today a typical multi bay, hi rise PT construction consists of a shallow floor (150–200 mm) and long spans of 7–14 m (see Fig. 2.3), creating span to depth ratios of 40 or more. The complexity of this type of building requires special consideration and most guidance available is dated and not be applicable for modern fire engineering design.

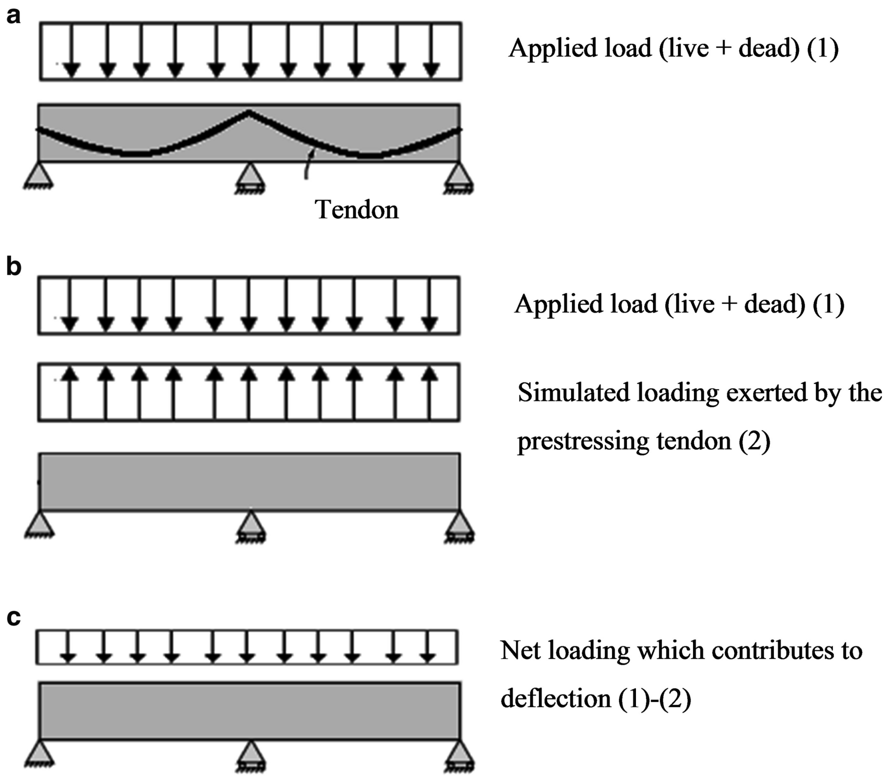

Fig. 2.2 Load balancing after Lin (1963) and Aalami (2007) with (**a**) applied load (**b**) applied load amd simulated loading exerted by prestressing tendon and (**c**) net loading contributing to deflection

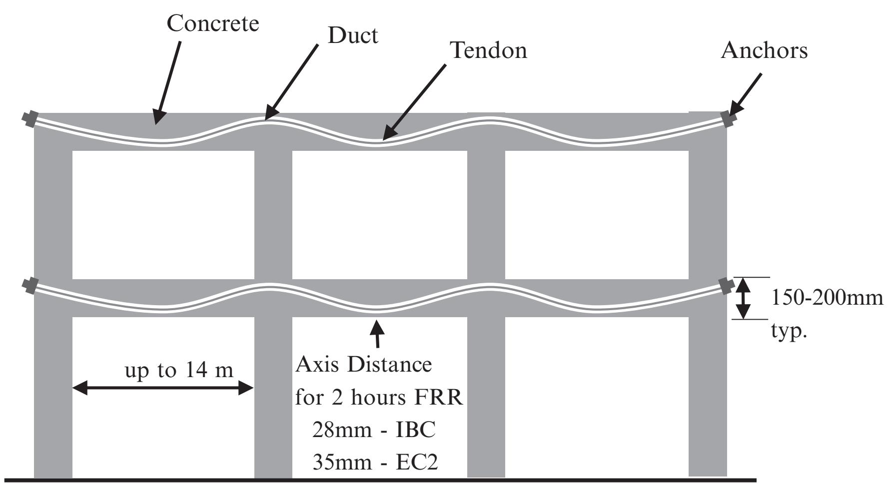

Fig. 2.3 Typical configuration of a multi bay post-tensioned slab

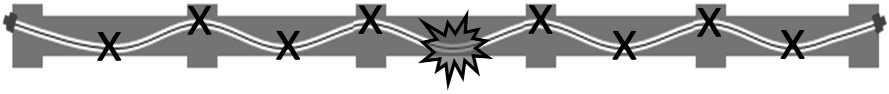

Fig. 2.4 Unbonded tendon continuity

In the 1960s when post-tensioning was in its infancy, designers traditionally relied on simplified load balancing procedures. Today, computer-aided structural design software helps optimize the concrete material usage by calculating the optimal placement and position of tendons. This advancement has permitted designs of flat slabs with span to depth ratios of 40 or more. The tensioning strands have also changed over time. Older structures were cast with isolated monostrand tendons, today's post-tensioned structures are highly pre-compressed using banded tendons, usually in groups of four. These multi strand tendons help reinforce flat slabs to carry primary loads to the structure's columns. To complement the high degree of tensioning and to meet faster construction demands, the use of high strength concrete in PT slabs is becoming more common today.

Beyond changing the number of strands in the tendons, the physical properties have also been altered. Most innovations in prestressing steel have largely been driven by corrosion resistance. For example ACI 318-14 now pushes for full encapsulation of unbonded tendons to help alleviate this concern. Corrosion causing any localized damage can effect adjacent bays in unbonded post-tensioned construction. These concerns have led to changes in the way tendons are being made. Tendons can be alloyed and controlled to increase corrosion resistance, such as through the addition of chromium and copper. Corrosion resistance is especially important in bridges, as stressed tendons in bridge girders are more susceptible. Tendons are now also made to achieve higher strengths. Tendons from the 1970s were typically of 1700 MPa strength, today most tendons are produced to meet a minimum strength of 2000 MPa.

2.3 Contemporary Fire Design

Prestressing steel has a lower critical temperature, the temperature at which it loses half its strength in fire, than mild steel reinforcement. Typically these temperatures are about 100 °C different (ASTM 2014; CEN 2004). The fire design of a PT concrete member is based upon providing a concrete cover that acts as a thermal barrier and protects the prestressing steel from reaching critical temperatures. These cover requirements are largely based on a series of dated standard fire tests from the 1960s that used different materials and structural configurations than their modern constructed counterparts (these are reviewed in Chap. 3). Based on the assumption that concrete is fully restrained, the cover for interior spans is reduced in some jurisdictions. Good practice for fire design is to include a bonded reinforcing mesh to mitigate spalling, although it is not required by some codes based on in-service stress conditions and there is scant

Table 2.1 Concrete axis distance covers as specified in design guidance for floor slabs

	Required fire resistance axis distance (mm)				
	Prescribed by EN 1992-1-2 (2004)			Prescribed by the IBC (2012)	
Fire resistance rating (min)	Simply supported slabs	Continuous slabs	Flat plate slabs[a]	Simply supported slabs[b]	Continuous slabs[b]
30	25	25	25	–[c]	–[c]
60	35	25	30	–[c]	–[c]
90	45	30	40	–[c]	28
120	55	35	50	47	28
180	70	45	60	59	34
240	80	55	65	–[c]	41

[a] 15 mm additional axis distance was added to tabulated data from CEN (2004)
[b] Clear cover adjusted to axis distance, by adding 3 mm sheathing and ½ bar diameter of 12.7 mm
[c] The IBC (2012) does not tabulate values for these fire resistances

evidence as to its effectiveness in this regard. Table 2.1 details the prescriptive axis-cover requirements for PT concrete slab systems.

Current cover requirements found in design guidance come from dated experimental test regimes that do not resemble contemporary construction, and limited efforts have been made to develop new guidance that meets the needs of contemporary construction (see Chap. 3).

A comprehensive set of papers (Gales et al. 2011a, b, c) detail the origins of these guidelines. Outlined in these papers were several concerns relating to contemporary PT concrete construction. In particular, floor construction with respect to fire is examined to show why renewed research attention is essential for fire safety in contemporary construction. These concerns are subsequently outlined below.

2.3.1 Tendon Continuity Across Multiple Bays

In unbonded PT (UPT) buildings the prestressing steel tendons are free to move longitudinally through ducts within beams and/or slabs, unlike in the bonded case. Since the same tendon is used across the entire slab, any localized heating and resulting damage has consequences across all bays of the structure.

In PT construction the length of the unbonded tendon can be up to 70 m (Taranath 2010). This is problematic as research has shown that the longer the total length of an unbonded tendon between anchors, the greater the likelihood of the prestressing tendon rupturing due to localized heating (Gales et al. 2011b, c). This is because of a complex combination of accelerating plastic strains and loss of ultimate tensile strength of the tendon. The consequences of premature tendon rupture during fire have received limited research attention to date, despite the fact it has led to the progressive failure of several floors (Post and Korman 2000), and the forced demolition of several UPT structures after real fires (Barth and Aalami 1992; Brannigan and Corbett 2009).

2.3.2 Higher Strength Concretes

Research has shown that high strength contemporary concrete mixes are more likely to experience fire-induced explosive spalling than their low strength counterparts (Kodur and Phan 2007). The satisfactory performance of PT elements in fire resistance tests conducted decades ago and used to define code should not be taken as evidence of adequate fire resistance for modern PT structures, where spalling is likely to occur.

2.3.3 Pre-compression

PT slabs and beams are axially pre-compressed (see Fig. 2.1), which means that a greater portion of the soffit will be subjected to higher compressive stresses in service than in a non-prestressed member. Since compressive stress is a widely acknowledged risk factor for spalling in fire (Hertz 2003), it is reasonable to assume that that PT beams and slabs are more likely to spall.

2.3.4 Large Span-to-Depth Ratios

A primary advantage of PT structures is that they enable span-to-depth ratios greater than ratio of 40 allowed by non-prestressed flooring systems (CPCI 2007). There is a risk that a PT slab could experience proportionally greater deflections during fire, due to thermal bowing caused by uneven heating gradients in the slab and smaller lateral restraint forces. Since compressive membrane action only occurs for a certain level of deflection, there may be less chance of developing this beneficial behavior which provides additional support against collapse. Inability to engage compressive membrane action is a credible concern for PT slabs in fire. This is particularly true in the case of UPT tendons as they can rupture during fire and some design guidelines allow zero mild steel reinforcement in sagging moment regions (CEN 2004; CSA 2004; ACI 2011), see Fig. 2.5.

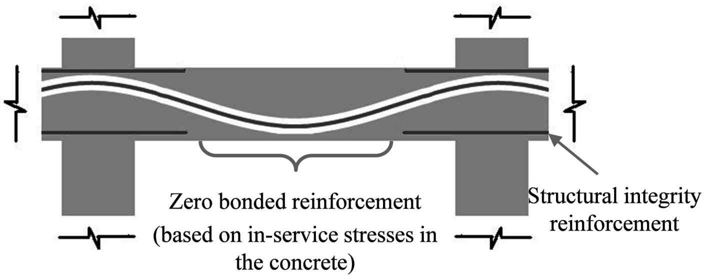

Fig. 2.5 Lack of bonded reinforcement in some service stress conditions

Worth noting is that the span-to-depth ratios used in available furnace tests on UPT members have generally been unrealistically small due to available furnace sizes.

2.3.5 Fire Resistance Based on Concrete Cover

The code prescribed covers are based largely on results of standard fire tests conducted on isolated PT slabs and beams in the 1950s and 1960s (Troxell 1959; UL 1966; Gustaferro et al. 1971), although some codes have been revised based on more recent furnace testing (see Purkiss and Kelly (2008) for discussion pertaining to the development of EN 1992-1-2 (CEN 2004) requirements). In some cases these tests used concrete that had been pre-conditioned before fire testing, did not adequately define the degree of restraint, or used a light steel mesh within the concrete cover to prevent or arrest spalling. Cover spalling was thus explicitly excluded from many of the tests, yet these important details are routinely omitted when using test data to justify current prescriptive cover requirements. Clearly, use of light steel mesh in the cover and pre-drying of the concrete is non-representative of typical PT construction. Additionally, the restraint used in standard fire test furnaces does not always represent a structure's true stiffness, which varies between building configurations and will affect how the structure behaves in fire. In instances where 'total' restraint is achieved, premature failure of a PT structure could be observed due to explosive spalling (see Bletzacker 1967). For these reasons, the wisdom of relying on prescriptive concrete cover thickness as the sole means of achieving fire resistance in UPT buildings is clearly questionable.

2.3.6 Inadequacies of Standard Fire Tests

It is widely recognized that fire exposures used in standard fire tests (e.g. ASTM E119 2014; ISO 834 1999) are unrealistic, particularly for the large compartments or open floor plans found in many modern buildings (Stern-Gottfried et al. 2010). It is generally argued that standard fires are conservative representations of worst-case fires for most types of construction. This rationale cannot be applied to UPT concrete beams or slabs because unbonded prestressing steel tendons are continuous over multiple bays, and localized or travelling fires is more likely to result in premature tendon rupture (Chap. 3 will provide greater details on this issue).

2.4 Summary

The challenges we face in safely designing a PT concrete structure are growing as we use new materials and design technologies to make contemporary structures more complex. The above discussion addresses numerous concerns and inadequacies of current knowledge on the fire performance of PT concrete buildings, particularly with unbonded tendons. To further highlight the apparent disconnect between existing knowledge, available guidance, and industry practice, Chap. 3 summarizes and critically appraises the 46 fire tests on UPT concrete structural members that are currently available in the literature. A brief discussion of bonded PT concrete structural members is also provided.

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http://www.springer.com/978-1-4939-3279-5

Structural Fire Performance of Contemporary
Post-tensioned Concrete Construction
Gales, J.; Hartin, K.; Bisby, L.A.
2016, XI, 91 p. 43 illus., 31 illus. in color., Softcover
ISBN: 978-1-4939-3279-5