State-of-the-Art Report on Partially Prestressed Concrete

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Partially prestressed concrete construction uses prestressed, or a combination of prestressed and nonprestressed, reinforcement. Partially prestressed concrete falls between the limiting cases of conventionally reinforced concrete and fully prestressed concrete, which allows no flexural tension under service loads. When flexural tensile stresses and cracking are allowed under service loads, the prestressed members have historically been called partially prestressed. This report is presented as an overview of the current state of the art for partial prestressing of concrete structures. Research findings and design applications are presented. Specific topics discussed include the history of partial prestressing, behavior of partially prestressed concrete members under static loads, time-dependent effects, fatigue, and the effects of cyclic loadings.

Keywords: bridges; buildings; concrete construction; corrosion; cracking; crack widths; cyclic loading; deflections; earthquake-resistant structures; fatigue; partially prestressed concrete; post-tensioning; prestressing; prestress losses; shear; stresses; structural analysis; structural design; time-dependent effects; torsion.

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CHAPTER 1—INTRODUCTION

1.1—Historical perspective

Application of prestressing to concrete members imparts a compressive force of an appropriate magnitude at a suitable location to counteract the service-load effects and modifies the structural behavior of the members. Although the concept of prestressed concrete was introduced almost concurrently in the U.S. and in Germany before the turn of the 20th century (Lin and Burns 1981), its principle was not fully established until Freyssinet published his classical study (Freyssinet 1933). Freyssinet recognized that as the load on a prestressed member is increased, flexural cracks would appear in the tensile zones at a certain load level, which he referred to as the transformation load. Even though the cracks would close as the load was reduced and the structure would recover its original appearance, Freyssinet advocated avoiding cracks under service load so that the concrete would behave as a homogeneous material.

A different design approach, however, was proposed by von Emperger (1939) and Abeles (1940). They suggested using a small amount of tensioned high-strength steel to control deflection and crack width while permitting higher working stresses in the main reinforcement of reinforced concrete. Most of the early work in support of this design concept was done by Abeles (1945) in England. Based on his studies, Abeles determined that eliminating the tensile stress and possible cracking in the concrete is unnecessary in many designs. Abeles also realized that prestress can be applied to counteract only part of the service load so that tensile stress, or even hairline cracks, occur in the concrete under full service load. Abeles did specify that under dead load only, no flexural tension stress should be allowed at any member face where large flexural tensile stresses occurred under maximum load, so as to ensure closure of any cracks that may have occurred at maximum load. Additional bonded and well-distributed nonprestressed reinforcement could be used to help control cracking and provide the required strength. Abeles termed this design approach as "partially prestressed concrete." Therefore, the design approach advocated by Freyssinet was then termed as "fully prestressed concrete." In actual practice, nearly all prestressed concrete components designed today would be "partially prestressed" as viewed by Freyssinet and Abeles.

Interest in partial prestressing continued in Great Britain in the 1950s and early 1960s. Many structures were designed by Abeles based on the principle of partial prestressing, and examinations of most of these structures around 1970 revealed no evidence of distress or structural deterioration, as discussed in the technical report on *Partial Prestressing* published by the Concrete Society (1983). Partially prestressed concrete design was recognized in the *First Report on Prestressed Concrete* published by the Institution of Structural Engineers (1951). Provisions for partial prestressing were also included in the *British Standard Code of Practice for Prestressed Concrete* (CP 115) in 1959. In that code, a permissible tensile stress in concrete as high as 750 psi (5.2 MPa) was accepted when the maximum working load was exceptionally high in comparison with the load normally carried by the structure. Presently, the British Code (BS 8110) as well as the *Model Code for Concrete Structures* (1978), published by CEB-FIP, defines three classes of prestressed concrete structures:

Class 1—Structures in which no tensile stress is permitted in the concrete under full service load;

Class 2—Structures in which a limited tensile stress is permitted in the concrete under full service load, but there is no visible cracking; and

Class 3—Structures in which cracks of limited width (0.2 mm [0.008 in.]) are permitted under full service load. Calculations for Class 3 structures would be based on the hypothetical tensile stress in the concrete assuming an uncracked section. The allowable values of the hypothetical tensile stress vary with the amount, type, and distribution of the prestressed and nonprestressed reinforcement.

Elsewhere in Europe, interest in partial prestressing also developed in the 1950s and 1960s. In the mid-1950s, many prestressed concrete structures in Denmark, especially bridges, were designed using the partial prestressing concept. Their performance was reported as satisfactory after 25 years of service (Rostam and Pedersen 1980). In 1958, the first partially prestressed concrete bridge in Switzerland (Weinland Bridge) was completed near Zurich. Provisions for partial prestressing were introduced in SIA Standard 162, issued by the Swiss Society of Engineers and Architects (1968), and since 1960, more than 3000 bridges have been designed according to this concept with highly satisfactory results (Birkenmaier 1984). Unlike the British Code and CEP-FIP Model Code, the limit of partial prestressing in the Swiss Code was not defined by the hypothetical tensile stress. Instead, it was defined by the tensile stress in the prestressed and nonprestressed reinforcement, and calculated using the cracked section. Under full service load, the allowable stress in the nonprestressed reinforcement was 22,000 psi (150 MPa), and in railroad bridges, the stress increase in the prestressed reinforcement was not to exceed 1/20 of the tensile strength. This value was taken as 1/10 of the tensile strength in other structures. It was required, however, that the concrete be in compression when the structure supported only permanent load.

In the U.S., the design of prestressed concrete in the early 1950s was largely based on the *Criteria for Prestressed Concrete Bridges* (1954) published by the Bureau of Public Roads, which did not permit tensile stress and cracking in concrete under service loads. The ACI-ASCE Joint Committee 323 report (1958), however, recognized that "complete freedom from cracking may or may not be necessary at any particular load stage." For bridge members, tensile stress was not allowed in concrete subjected to full service load. For building members not exposed to weather or corrosive atmosphere, a flexural tension stress limit of $6\sqrt{f'_c}$ psi* was specified with the provision that the limit may be exceeded if "it is shown by tests that the structure will behave properly under service load conditions and meet any necessary requirements for cracking load or temporary overload." Thus, partial prestressing was permitted in that first definitive design guide for prestressed concrete, and designers were quick to embrace the idea. When the balanced load design concept was published by Lin (1963), it provided a convenient design tool and encouraged the practical application of partial prestressing.

In 1971, the first edition of the *PCI Design Handbook* was published. Design procedures allowing tension stresses are illustrated in that guide. The second edition (1978) mentioned the term "partial prestressing," and by the third edition (1985), design examples of members with combined prestressed and nonprestressed reinforcement were included. Presently, ACI 318 permits a tensile stress limit of $12\sqrt{f'_c}$ psi with requirements for minimum cover and a deflection check. Section 18.4.3 of ACI 318 permits the limit to be exceeded on the basis of analysis or test results. Bridge design guidelines or recommendations, however, did not follow the development until the publication of the *Final Draft LRFD Specifications for Highway Bridges Design and Commentary* (1993), even though most bridge engineers had been allowing tension in their designs for many years.

The concept of partial prestressing was developed half a century ago. Over the years, partial prestressing has been accepted by engineers to the extent that it is now the normal way to design prestressed concrete structures. Bennett's work (1984) provides a valuable historical summary of the development of partially prestressed concrete.

1.2—Definition

Despite a long history of recognition of the concept of partial prestressing, both in the U.S. and abroad, there has been a lack of a uniform and explicit definition of the term, "partial prestressing." For example, Lin and Burns (1981) state: "When a member is designed so that under the working load there are no tensile stresses in it, then the concrete is said to be fully prestressed. If some tensile stresses will be produced in the member under working load, then it is termed partially prestressed." On the other hand, Naaman (1982a) states: "Partial prestressing generally implies a combination of prestressed and nonprestressed reinforcement, both contributing to the resistance of the member. The aim is to allow tension and cracking under full service loads while ensuring adequate strength." According to Nilson (1987), "Early designers of prestressed concrete focused on the complete elimination of tensile stresses in members at normal service load. This is defined as full prestressing. As experience has been gained with prestressed concrete construction, it has become evident that a solution intermediate between full prestressed concrete and ordinary reinforced concrete offers many advantages. Such an intermediate solution, in which a controlled amount of concrete tension is permitted at full service, is termed partial prestressing."

A unified definition of the term "partial prestressing" should be based on the behavior of the prestressed member under a prescribed loading. Therefore, this report defines partial prestressing as: "An approach in design and construction in which prestressed reinforcement or a combination of prestressed and non-prestressed reinforcement is used such that tension and cracking in concrete due to flexure are allowed under service dead and live loads, while serviceability and strength requirements are satisfied."

For the purposes of this report, fully prestressed concrete is defined as concrete with prestressed reinforcement and no flexural tension allowed in the concrete under service loads. Conventionally reinforced concrete is defined as concrete with no prestressed reinforcement and generally, there is

* In this report, when formulas or stress values are taken directly from U.S. codes and recommendations, they are left in U.S. customary units.

flexural tension in concrete under service loads. Partially prestressed concrete falls between these two limiting cases. Serviceability requirements include criteria for crack widths, deformation, long-term effects (such as creep and shrinkage), and fatigue.

By the previous definition, virtually all prestressed concrete that uses unbonded tendons is "partially prestressed," as codes require that a certain amount of bonded reinforcement be provided to meet strength requirements. Most pretensioned members used in routine applications such as building decks and frames, and bridges spanning to approximately 100 ft (30 m) will allow flexural tension under full service load. The addition of nonprestressed reinforcement is used only in special situations, such as unusually long spans or high service loads, or where camber and deflection control is particularly important.

1.3—Design philosophy of partial prestressing

The basic design philosophy for partial prestressing is not different from that of conventionally reinforced concrete or fully prestressed concrete. The primary objective is to provide adequate strength and ductility under factored load and to achieve satisfactory serviceability under full service load.

By permitting flexural tension and cracking in concrete, the designer has more latitude in deciding the amount of prestressing required to achieve the most desirable structural performance under a particular loading condition. Therefore, partial prestressing can be viewed as a means of providing adequate control of deformation and cracking of a prestressed member. If the amount of prestressed reinforcement used to provide such control is insufficient to develop the required strength, then additional nonprestressed reinforcement is used.

In the production of precast, pretensioned concrete members, serviceability can be improved by placing additional strands, as this is more economical than placing reinforcing bars. When this technique is used, the level of initial prestress in some or all of the strands is lowered. This is also a useful technique to keep transfer stresses below the maximum values prescribed by codes. At least for purposes of shear design, the ACI Building Code treats any member with effective prestress force not less than 40% of the tensile strength of the flexural reinforcement as prestressed concrete.

1.4—Advantages and disadvantages of partial prestressing

In the design of most building elements, the specified live load often exceeds the normally applied load. This is to account for exceptional loading such as those due to impact, extreme temperature and volume changes, or a peak live load substantially higher than the normal live loads. By using partial prestressing, and by allowing higher flexural tension for loading conditions rarely imposed, a more economical design is achieved with smaller sections and less reinforcement.

Where uniformity of camber among different members of a structure is important, partial prestressing will enable the designer to exercise more control of camber differentials. In multispan bridges, camber control is important in improving riding comfort as a vehicle passes from one span to the next. The relatively large mild steel bars used in partially prestressed members result in a transformed section that can be significantly stiffer than a comparable section that relies solely on prestressing strand, thus reducing both camber and deflection.

Nonprestressed reinforcement used in partially prestressed members will enhance the strength and also control crack formation and crack width. Under ultimate load, a partially prestressed member usually demonstrates greater ductility than a fully prestressed member. Therefore, it will be able to absorb more energy under extreme dynamic loading such as an earthquake or explosion.

Because mild steel does not lose strength as rapidly as prestressing strands at elevated temperature, it is sometimes added to prestressed members to improve their fire-resistance rating. See Chapter 9 of the *PCI Design Handbook* (1992) and *Design for Fire Resistance of Precast Prestressed Concrete* (1989) for more information.

Partial prestressing is not without some disadvantages. Under repeated loading, the fatigue life of a partially prestressed member can be a concern. In addition, durability is a potential problem for partially prestressed members because they can be cracked under full service load. Recent studies (Harajli and Naaman 1985a; Naaman 1989; and Naaman and Founas 1991), however, have shown that fatigue strength depends on the range of stress variation of the strand (refer to Chapter 4) and that durability is related more to cover and spacing of reinforcement than to crack width, so these concerns can be addressed with proper design and detailing of the reinforcement (Beeby 1978 and 1979).

1.5—Partial prestressing and reinforcement indexes

Several indexes have been proposed to describe the extent of prestressing in a structural member. These indexes are useful in comparing relative performances of members made with the same materials, but caution should be exercised in using them to determine absolute values of such things as deformation and crack width. Two of the most common indices are the degree of prestress λ, and the partial prestressing ratio (*PPR*). These indexes are defined as

$$\lambda = \frac{M_{dec}}{M_D + M_L} \tag{1-1}$$

where

M_{dec} = decompression moment (the moment that produces zero concrete stress at the extreme fiber of a section, nearest to the centroid of the prestressing force, when added to the action of the effective prestress alone);

M_D = dead-load moment; and

M_L = live-load moment

and