An Overview on Tendon Layout for Prestressed Concrete Beams

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Abstract

Construction of structures using prestressed members is becoming a common practice in various parts of the world. Prestressing of structures is gaining popularity in engineering fraternity because of its better stability, serviceability, economy, aesthetic appearance and structural efficiency. Prestressing of structures can be done in two ways which are pre-tensioning and posttensioning. Various types of losses occur out of which some are immediate and some are time dependent. These are the losses due to elastic shortening, friction losses, relaxation losses, losses due to creep and shrinkage. Due to these losses the prestress will be reduced as with time. The profile of the tendon has a great effect in the reduction of tension from concrete. The curvature of cable exerts force on the concrete to counterbalance the forces causing tension. The main aim in construction of a structure is to achieve greater strength and at the same time making the structure economic. This paper aims in studying the various tendon profiles and the cable curvature which is the parameter in designing an economical section. Many such parameters are analysed in the previous studies and thus the optimization problem is the combination of many individual variables which has been reviewed in the present work.

KEYWORDS: Prestress, Tendon Profile, Cable Layout, Post-tensioning, Pre-tensioning, Optimization

1. Introduction

Concrete plays a major role in the field of construction being the most important construction material. But still concrete faces the problem of its weakness in tension. To overcome this weakness reinforced concrete system was developed. Thus the development of prestressed concrete structures and its use in the recent world is increasing. The principle included in the concept of prestressing is that the compressive stresses induced by the high-strength steel tendons in a concrete member before loads are applied will balance the tensile stresses imposed in the member during service. For this purpose prestressing tendons (generally of high tensile steel cable or rods) are used which produces a compressive stress that offsets the tensile stress that the concrete compression member would otherwise experience due to self–weight and gravity loads.

Prestressed concrete can be of many types based on five different criteria

1. Based on sequence of casting concrete and applying tension to the tendons
   a. Pre-tensioning
   b. Post-tensioning
2. Based on location of prestressing tendons
   a. External prestressing
   b. Internal prestressing
3. According to shape of members
   a. Linear prestressing
   b. Circular prestressing
4. Based on amount of prestressing force
   a. Full prestressing
   b. Partial prestressing
   c. Limited prestressing
5. Based on directions of Prestressing
2. Pre-Tensioning and Post-Tensioning

Pre-tensioning is the system wherein the tension is applied to the tendons before casting of the concrete. The prestressing is transferred to the concrete through the bond between the concrete and tendons.

In post-tensioning, the prestressing is done against hardened concrete. When the concrete has been hardened, the prestressed tendons are passed through ducts cast into the concrete and locked with mechanical anchors. The tendon force is thereby transferred to the structure through the anchorage wedges.

Prestressing can be accomplished in three ways:
1. Pre-tensioned concrete
2. Bonded post-tensioned concrete
3. Unbonded post-tensioned concrete

2.1. Pre-Tensioned Concrete

In this method the tendons are first tensioned between rigid anchor blocks cast on the ground or pretensioning bed. The concrete is cast around the steel tendons, cables or bars which are under tension. The concrete then bonds to the tendons as it hardens. When the tension in tendons is released, it is transferred to the concrete as compression by static friction. The tension forces imposed on the concrete is transferred directly to the tendons.

2.2. Bonded Post-Tensioned Concrete

In post tensioning system, the concrete is first cast by incorporating ducts to house the tendons. In bonded system the compressive forces are applied after casting and curing of concrete in situ. Steel or aluminium ducts are provided in the area where tension forces are expected to occur. A set of tendons are introduced into these ducts and the concrete is cast and is allowed to harden. The tendons are now tensioned by means of hydraulic jacks and anchored in position by wedges or nuts once the sufficient stretching of tendons is attained. The forces are transmitted to the concrete by the end anchorages while the cable is curved due to the radial pressure between the cable and duct. The space between the concrete and the tendons is grouted after tensioning to prevent corrosion of tendons. The tendons form a continuous bond along its length with concrete surrounding it.

The grout is provided to serve the following functions
- It provides a continuous bond between the strand and the duct.
- It increases protection against corrosion by acting as a physical barrier against moisture and chemicals.
- Through its alkalinity it acts a nonconductor for corrosion.

The duct serves the following functions
- Maintains a voided path for the strands in the concrete member during construction
- Transfers the bond between the grout and the surrounding.
- Acts as additional protection against penetration of moisture and chemicals

2.3. Unbonded Post-Tensioned Concrete

This method also is a type of post-tensioning system, but it differs from bonded post-tensioning by providing each individual cable the permanent freedom of movement relative to the concrete. Unbonded tendons are generally made of single strand high strength steel, covered with a corrosion inhibiting coating and encased in a plastic sheathing. These tendons does not form a bond along its length with the concrete. The force in the stressed tendons is transferred to the concrete by the anchors provided at the ends. Variation in force along the tendon is affected by the friction between the strands and the tendon profile in the concrete member. The long term integrity of anchors throughout the service life of the unbonded tendon is important. Plastic sheathing is provided
- to act as a bond breaker
- to provide protection against damage by mechanical handling
- to form a barrier against intrusion of moisture and chemicals

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The main disadvantage over bonded post-tensioning is the fact that a cable can distress itself and burst out of the slab if damaged.

2.4. External and Internal Prestressing

External prestressing technique is one where the tendons are placed on the outer section of the region being stressed. The tendon lie outside or inside the hollow space of a box girder and forces are only transferred at the deviations or anchorage blocks. External prestressing technique require a great deal of accuracy in planning, executing and maintenance; therefore it is not more common. This external prestressing technique is most widely suited for the strengthening of buildings and constructing bridges. Internal prestressing is a technique where the tendons are placed within a structure. Prestressing applications use internal technique because it is easy to achieve a greater degree of accuracy.

2.5. Linear and Circular Prestressing

Linear prestressing is a type of prestressing used in straight, bent or flat structures. The technique can even be used on curved structures as long as the tendons don't go round in circles because they are linearly prestressed. For example, prestressing of poles, slabs and beams can be done using the linear prestressing technique. In contrast, curved or circular structures employ the circular prestressing technique. The tendons are wound in circles. Examples include pipes, silos and tanks.

2.6. Full, Limited And Partial Prestressing

The technique where no restrictions are placed on concrete tensile stresses under service conditions is called partial prestressing. The part under tension is reinforced using additional mild steel bars to control the cracks and hence the crack width is within allowable limit. Deviations from the set prestressing can cause deformation, cracking and fatigue on the structure; therefore, when using this technique during construction, you must always monitor the prestressing force carefully. On the other hand, full prestressing is a technique where no tensile stress is allowed in concrete under service loads. Whereas limited prestressing is where the level of prestressing is such that the tensile stress under service loads is within the cracking stress of concrete. In case of partial prestressing, the crack width occurring due to tensile stress due to service loads is within the allowable limit.

2.7. Uniaxial, Biaxial and Multiaxial Prestressing

When the prestressing cables are parallel to one axis, it is called uniaxial prestressing (longitudinal prestressing of beams). If the prestressing cables are parallel to two axes, it is termed as biaxial prestressing (prestressing of slabs). In multiaxial prestressing, the prestressing cables are parallel to more than two axes (prestressing of domes).

3. Tendon Profile

The layout of cable plays a vital role in reducing tension from concrete. The curvature of the cable exerts force on the concrete to counterbalance the forces causing tension. In most of the prestressed beams, the tendons are located with eccentricities towards the soffit of the beam to counteract the sagging bending moments due to transverse loads. Consequently the prestressed beams deflect upwards (camber) on the application of prestress. Since the bending moment is the product of the prestressing force and eccentricity, the tendon profile itself will represent the shape of the bending moment diagram.

The profile of the tendons can be provided in various ways. Some of them are:

1. Straight tendons
2. Trapezoidal tendons
3. Parabolic tendons (Central anchors)
4. Parabolic tendons (Eccentric anchors)
5. Sloping tendons (Eccentric anchors)
6. Parabolic and straight tendons
7. Parabolic and straight tendons (Eccentric anchors)

The tendons are usually laid as continuous curve, but for analysis they are modelled by curves following mathematical equations. The most
important modelling includes parabolic modelling, reverse parabolic modelling and modelling using B-spline curves. These curves ensure smooth profile in continuous beams and also provide realistic stress values. The deflection due to prestress depends on the c.g.s line.

**Fig 1a**: Straight Tendon Profile with constant eccentricity  
**Fig 1b**: Parabolic tendon profile with maximum eccentricity at midspan

4. Base Papers

**Chaitanya Kumar J.D. and Lute Venkat** (2013) presented the genetic algorithm based optimum design of prestressed concrete beams. This paper deals with the optimization of a simply supported prestressed beam subjected to live and dead loads using genetic algorithm technique. Genetic Algorithm helps in finding the global optimum solution. It is to be noted that cost of any material is not constant factor at all times. But the ratio of cost of cable to cost of concrete is going to remain almost constant. Cost ratio is considered as objective function in the present problem. The cost ratio for cable to concrete is taken as 8. The different parameters considered are the effect of size of population on cost ratio, effect of beam length on optimum cost, effect of beam length on optimum cost, effect of profile of cable on optimum cost. The percentage variation in optimum cost from 14m and 15m beam length is 21.7%. The percentage difference in optimum cost from 50kN/m to 60kN/m of live load is 16.8%. There is no effect of restraining the cable profile up to a length of 13m but for 14m and 15m beam lengths parabolic cable profile gives higher optimum cost as compared to straight cable profile. For beam length of 15m, the percentage increase in Optimum cost is 4.22% for the parabolic cable profile as compare to straight cable profile.

**Ahmad Ali Khan, K.K.Pathak and N.Dindorkar** (2010) presented the cable layout design of one way prestressed concrete slabs using FEM. In this paper, B-Spline approach for cable layout design of prestressed concrete structures is presented. Cable thrust on concrete is related to curvature of cable layout. The stresses in the structure are computed using finite element method. The cable concrete interactions are precisely accounted using vector calculus formulae. The paper states that the method of modelling cables as parabola and varying their eccentricities to reduce tensile stresses of the concrete lags behind because the cables are not truly parabolic especially in continuous structures and also because this technique is very expensive since separate parabola has to be defined for each span. Thus the shape of the cable can be represented by a B-spline. By varying the ordinates of the B-spline, cable shape is changed to get the desired profile. The cable layout is developed so that stresses in the structural element be below the limiting tensile stress. A check on the compressive stresses will be made in order to avoid crushing of the concrete. Based on stress results obtained from finite element analysis, cable profile is changed in iterative manner. Using the proposed technique a two span pre-stressed concrete slab has been successfully designed for friction as well non friction conditions. The limiting tensile stress is considered as 0.25 MPa. For non-friction case the initial prestressing force is 480KN which takes 12 iterations to limit the tensile stresses below limiting value that provides the final prestressing force to be 494 KN. For friction condition the initial prestressing force is 560 KN which takes 7 iterations to limit the tensile stress below limiting value that provides the final prestressing force to be 588 KN. The percentage increase in the final load with respect to that of non-friction case is 19% which is required to overcome friction. The eccentricity of the cable at mid span is more for the non-friction case than the friction condition.

**Piero Colajania, Antonino Recupero and Nino Spinella** (2013) presented the design procedure for prestressed concrete beams. The design procedure, which attempts to provide the optimal layout of ordinary reinforcement in prestressed concrete beams, subjected to bending moment and shear force are presented. The difficulties encountered in
simulating the actual behaviour of prestressed concrete beam in presence of coupled forces - bending moment - shear force are discussed. A unified model for reinforced and prestressed concrete beams under axial force - bending moment - shear force interaction is provided. This analytical model is validated against both experimental results numerical analyses.

*Samer Barakat, Khaldoon Bani-Hani, Mohammed Q. Taha (2004)* presented the multi-objective reliability based optimization of prestressed concrete beams. In this study the optimum design of a prestressed concrete structures is done by the method of multi-objective reliability based optimization (MORBO) technique. This method considers all side constraints and behaviour specified in (American Concrete Institute) ACI code for prestressed concrete. Variables are selected randomly and they include, loading conditions, material properties, prestressing force and the models used in predicting structural performance at various stages. In this method, the values of design variables are simultaneously obtained as when the objective functions are optimized. A pareto optima set is obtained by this technique. Here only bi- and tri-multi-objective formulations are considered which are subjected to eleven reliability constraints and four geometrical constraints. The competing objectives in the multi-objective optimization of PCB are selected from, Minimization of the overall cost of the PCB, Maximization of the system reliability index, Maximization of the flexural strength reliability index, Maximization of the tensile stress reliability index at service stage.

5. CONCLUSIONS

Though prestressed concrete structures are widely used now-a-days, they lag behind due to their heavy weight which makes them expensive. As a result the cost of launching of the structure increases resulting in the increase of the cost of the entire structure. Thus the cost is optimized to provide an economical section. The element is optimized to get global optimum solution. The stresses in the member is simultaneously checked for during optimization. The service limit states and ultimate limit states are used for evaluation. Many number of constraints are placed on the optimization technique. They are broadly categorized as explicit and implicit constraints. There are various methods of optimization techniques. The prestressing tendons are subjected to losses due to friction that occur between the tendons and the concrete. The tendon is designed such as to have either a constant eccentricity or with a varying eccentricity so as to form a rectangular or parabolic profiles respectively. Arrangement of tendons depend on Duct size, Anchorage Spacing Anchorage edge distance. Every method proves to be effective in their own perspective. Most of the studies find out that a parabolic profile is most economical when compared to rectangular profile. And similarly a trapezoidal profile is most economical than a parabolic profile. The cost and weight of PSC slab unit depends on the span of the slab. The cost increased exponentially with respect to span whereas weight of PSC slab unit increased linearly with respect to span. Though larger concrete strength values correspond to more expensive concrete, the total manufacturing cost of the beam decreases as fck grows up. Hence concrete having larger fck values lead to cheaper prestressed concrete beam design.

6. REFERENCE