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Full Length Article

Ultimate stress increase in unbonded tendons in post-tensioned indeterminate I-beams cast with high strength normal and self compacting concrete

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ABSTRACT

The use of un-bonded tendons is prevalent in post-tensioned concrete structures. Equations for prediction of stress in un-bonded tendons of post-tensioned normal (vibrating) concrete flexural members have been given in various codes. They are based on experience and don't account all of important parameters such as concrete strength (normal and high strength) and its type (vibrating and non-vibrating concrete). Since self-compacting concrete (SCC) is nearly a new innovation therefore, understanding the implementation of this type of non-vibrating concrete on the ultimate unbonded tendon stress is critical. For this aim, in this paper there are presented experimental results of six continuous un-bonded post-tensioned I-beams in two groups were casted and monitored by different electrical strain gauges. In the first tested group, the beams (UPN1-12, UPN1-18, UPN1-22) were consisting of high strength normal concrete (HSNC) where as in the second group (UPS1-12, UPS1-18, UPS1-22) high strength self-compacting concrete (HSSCC) were tested. The variables included the type of concrete and percentage of bounded non-prestressed steel. Experimental monitored results of ultimate stress increase in unbonded tendons are compared with predicted equations of different researchers and standards. It was found that, the proposed equation is in better agreement with the test results. The results of standard error of estimate $S_{y/x}$, indicates that for two types of HSCs, the ACI 318-2011 provides better estimates than AASHTO-2010 model whereas this model provides better estimates than BS 8110-97.

1. Introduction

Since the theory of strain compatibility cannot be applied to the strain of un-bonded tendons in pre-stressed concrete beams subjected to loading, estimation of stress increase in the tendons due to external loading is difficult. According to strain compatibility analysis and assumption that between pre-stressing steel and concrete exists perfect bond, stress changes in bonded tendons can be determined in any section along the span. This rule does not apply to unbonded tendons, because lack of continuity between prestressing steel and concrete. Analysis methods and empirical equation are available to predict the change in stress in an unbonded pre-stressed tendon due to external loading. Many researchers have developed some prediction equations to calculate the tendon stress at ultimate, which have been evaluated and reviewed by Harajli and Kanj [17], Naaman and Alkhairi [28], Ament et al. [5], Harajli [16], Manisekar and Senthil [25], Dall'Asta et al. [11]; He and Liu [43]. However, all mentioned researchers worked with vibrated nearly low strength concrete. Except theoretical studies, there were carried out many researches especially for normal (vibrated) concrete. Hundreds of elements, both slabs and beams cast with normal (vibrated) concrete were tested. Through these investigations, there were separated parameters that have influence on the stress increment in unbonded tendons. These are span-to-depth ratio, concrete compressive strength (normal strength and high strength concrete), yield strength, tendon profile, tensile strength and amount of non-prestressed and prestressed reinforcement, type of loading (single point load, third-point loading and uniformly distributed load), loading pattern in continuous members (uniform loading, alternate spans, adjacent spans, external span or internal span) and stress in the tendon after time dependent losses.

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Warwaruk et al. [41] conducted an extensive investigation comprising tests on 82 simply supported partially pre-stressed rectangular beams. Of these beams, 41 contained unbonded tendons. The main variables were the amount of reinforcement, the type of loading and the concrete compressive strength. They reported that, beams containing no supplemental reinforcement, failed by developing only one major crack, while those with supplemental reinforcement developed multiple cracking before failure. The stress in the unbounded steel remained in the elastic range up to failure. They predicted too conservative equation for prediction of stress in tendon at an ultimate state.

Another investigation, based on analytical and experimental data, was carried out by Cooke et al. [10] who studied how the stress at ultimate in unbonded tendons follows the changes of the span-to-depth ratio and the amount of pre-stressing steel. They tested 9 simply supported fully prestressed slabs with unbonded tendons, and it was concluded that the $f_{ps,u}$ (stress in tendon at an ultimate state) equation of ACI 318-77 [3] overestimates in the pre-stressing steel at low reinforcement indexes. The influence of different pre-stress forces on the flexural strength of unbonded partially pre-stressed concrete beams has been studied by Elzatany and Nilson [15]. They used 8 scale models of two series: under-reinforced (U-series) and over-reinforced (O-series). It was concluded that: 1) beams both of U and O series showed a high ductility at failure; 2) the increasing of pre-stress force leads to a major flexural capacity in O-series, since $\Delta f_{ps,u}$ (increase in tendon stress at an ultimate state) remains constant; 3) the ACI 318-77 equation for $f_{ps,u}$ was too conservative for O-series and non-conservative for U-series; 4) bonded reinforcement was effective in distribution of cracks; 5) there was a need to change the equations for prediction of $f_{ps,u}$ in the ACI codes to consider all the important factors that influence it and a procedure to predict $f_{ps,u}$, based on the effective moment of inertia concept, was developed.

Du and Tao [14] worked out an experimental research to investigate the effects of the presence of non-pre-stressed reinforcement on the $f_{ps,u}$ value. In total, they tested 22 partially pre-stressed simply supported beams, with unbonded tendons and under third point loading. The variables were the area of pre-stressed and ordinary steel and compressive concrete strength, whereas the span-to-depth ratio was constant. They concluded that, unbounded beams, which have an adequate amount of bonded nonprestressed reinforcement in the form of medium grade deformed bars, distribute cracks and compressive concrete strains almost the same as bonded prestressed concrete beams. In addition they indicated that the ultimate tendon stress, $f_{ps,u}$ can be computed from the moment-curvature relationship, but they did not clarify the underlying assumptions used in their analysis and how the relationship was obtained. Chouinard [9] worked out an experimental research to investigate the effects of different amounts of non-pre-stressed reinforcement on 6 partially pre-stressed beams with unbonded tendons loaded at their third point. He concluded that the addition of high quantity of non-pre-stressed steel implied a reduction of $f_{ps,u}$ and he also observed the strain distribution at the level of the pre-stressing tendons in the constant moment zone. There were uniformaly distributed strains at mid-span with only one or two wide cracks formed in the beams without supplementary reinforcement, while in beams with non-pre-stressed steel multiple cracks occurred. The development of cracks is an indication of the extension of the plastic zone along the top fiber of the beam. An experimental research on 26 partially pre-stressed with unbonded tendons concrete beams was carried out by Harajli and Kanj [17], the aim was to investigate the influence of important factors, such as the reinforcing index, the span-to-depth ratio and the loading type on the behavior of these kind of beams. It was observed that the effect of the length of the plastic hinge is important on $f_{ps,u}$.

Self-compacting concrete, SCC is a type of concrete that is able to flow and compact under its own weight; completely fill the formwork even in the presence of dense reinforcement, whilst maintaining homogeneity without need of any additional type of compaction. This has generated tremendous interest since initial development in Japan by Okamura in the 1986s in order to reach durable concrete structures. The good workability, high rate of production and durability assurance of SCC create wide acceptance by the prestressed and precast concrete industry where congestion of reinforcement is the norm [34]. Numerous researches have contributed to investigate the characteristics of SCC compared to NC (Normal Concrete). A comparison between mechanical properties of self-compacting concrete and the corresponding properties of normal concrete was done by Persson [35]. The results show that elastic modulus, creep and shrinkage of SCC did not differ significantly from the corresponding properties of NC. The study on the shear resistance of flexural members without stirrups for NC shows that there is no significant difference between SCC and NC regarding the crack pattern, crack width and failure mode [18]. The study by Dolatabad and Maghsoudi [12] shows the amount of experimental time-dependent losses in beams consisting of HSSCC was slightly lower than that of beams prepared using HSNC with almost the same concrete strength.

Many prestressed and precast concrete producers currently use SCC for a considerable part or 100% of their production [40]. SCC shortens the construction period and assures full compaction in the confined zones in the prestressed concrete structures especially the end-blocks of prestressed concrete structures, where concrete compaction by vibration, due to large amount of steel reinforcement is difficult.

With recent advancements in concrete technology, and the availability of various types of mineral and chemical admixtures and very powerful superplasticizers, concrete with a compressive strength of up to 100 MPa can now be produced commercially with an acceptable level of variability using ordinary aggregates. These developments have led to increased applications of high-strength normal and self-consolidating concrete (HSNC, HSSCC) all around the globe. Although HSC offers many advantages over conventional concrete, as the strength of concrete increases some of its characteristics and engineering properties become different from those of normal-strength concrete (NSC) [44,45]. Material properties may have important consequences in terms of the structural behavior and design of HSC members [46,4,39]. Maghsoudi et al. [21] studied some of these structural behavior such as flexural ductility but a very limited research is carried out in unbounded tendon post-tensioned HSSCC [38] and [22]. Some studies have presented variations in mechanical property behavior of HSSCC compared to HSNC mixtures in the 55–103 range. Specifically, Schindler et al. [36] and Naito et al. [29] have shown lower modulus of elasticity values for HSSCC when compared to HSNC.

Post tensioning with unbounded tendon is increasingly used in the rehabilitation of concrete bridges, which in engineering practice are usually continuous beams or slabs. For the rational design of this type of structures, a good understanding of the behavior of continuous concrete beams with unbounded tendon is needed. This study was carried out to experimentally investigate the flexural performance of continuous beams with unbounded tendons. As a result of continuity, the behavior of continuous beams may be different from that of simple beams. In this paper increase in tendon stress at ultimate state for continuous beam is studied. Moreover, continuous prestressed concrete beams have some additional characteristics, such as redistribution of moments in the post elastic range and secondary moments as a result of prestressing that the prestress moment redistribution and serviceability of tested beams has presented by second author in the other published papers [24,23].