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Accurate finite element modeling of pretensioned prestressed concrete beams

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ABSTRACT

This paper presents a nonlinear finite element model for pretensioned prestressed concrete beams. The study presented here is an important step because it is, perhaps, for the first time that a prestressed concrete beam has been successfully modeled by nonlinear finite element analysis, allowing for plasticity and damage behavior of concrete and slip-bond failure behavior for strands. The model faithfully follows the actual loading history realistically, allowing for the construction sequence including the process of transfer of strand force. Existing results of finite element analysis are not reliable in the critical regions. Even the very recent ones do not seem to have been successful. In this study, all material and bond models used are based on experimental data. The simulation results are validated with data from actual load testing. Apart from examining the behavior of the beam up to the limit state, the response of the damaged beam after local bonded composite patch repair is also considered. For this purpose, the prestressed concrete beam specimens are manufactured and tested in the laboratory before and after they have been repaired with bonded composite patches. Satisfactory agreement between finite element predictions and test results of the virgin beam is noted.

1. Introduction

In prestressed concrete structures, flexural tensile resistance capacity is induced by creating initial compressive stresses in concrete using high strength steel tendons. In precast construction, the pre-compression is induced in the concrete due to the shortening tendency of the released strand, by mobilizing the bond resistance between the two. The conventional mechanics based methods to determine the stress distribution in a prestressed concrete beam caused by various external effects is accurate enough for practical design purposes in the elastic range, except perhaps near the end regions. The main objectives of this paper are (i) to accurately predict the behavior of a precast prestressed concrete beam for all loading stages, and (ii) to predict the performance of a damaged beam subjected to bonded composite patch repair, using nonlinear finite element modeling and simulation. The simulation model needs to reflect the true mechanics of a precast prestressed concrete beam for all stages of loading: manufacture, service condition, and limit state. The simulation model should consider nonlinear material properties reflecting concrete plasticity and damage, interfacial bond characteristics between concrete and steel, and that between concrete and bonded composite patch repair, if used. Interfacial slippage, Poisson radial expansion of the strands, and wedging (or, Hoyer) effect at the ends also need to be accounted for. For the purpose of this study, a test prestressed concrete beam is considered. A four-point load test is first undertaken on the prestressed concrete beam till it reaches the limit state. The flexural and/or shear cracks appearing in the damaged state are then repaired by bonding composite patches and the repaired beam is load-tested again. Test results of such actual loading tests are then used to verify model predictions.

Since anchorage zone cracking is a commonly observed phenomenon in prestressed concrete beams, critical investigation of the end zone stresses of such beams is also aimed in this study, because such cracks tend to shorten the service life of such beams in exposed situations, as in the case of a highway bridge structure [1]. In exposed situations, such cracks tend to get wider as the embedded steel gets corroded.

Several past studies on anchor zone stresses in post-tensioned beams have been reported in the published literature. The earliest

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approaches as put forward by Magnel and Guyon treated the problem as two dimensional [2,3]. Several efforts followed these two studies viewing the same problem in the 3-D context [4–6]. A survey of previous studies did not reveal any significant effort leading to better understanding of the actual state of stress in the anchor zone or end region of, especially, pretensioned prestressed beams. Some of the early studies did, however, investigate the effects of vertical reinforcement in such regions for the prevention of horizontal cracks [7–11]. For instance, Padmarajaiah and Ramaswamy [9] undertook experimental studies on such beams incorporating short steel fibers as supplemental reinforcement. They also undertook nonlinear finite element analysis using the commercial software Ansys for predicting the load vs. deformation behavior, validating with the experimental data. Concrete was modeled with hexahedral solid elements using William and Warnke characterization and truss elements were used for steel. The interfacial bond effect was characterized by tangential linear spring elements located at the nodal points. The focus of the study was the influence of steel fibers on quasi-static load vs. deformation behavior of such beams. Another group of researchers [10] tried to improve the prediction using the layered beam approach. Markovic et al. put forward a computationally efficient analysis scheme for nonlinear analysis of such beams based on Euler–Bernoulli theory, smeared crack concept, tendon slippage and material softening accounted for by the arc-length method. The results appeared to follow the trend of experimental data available in the literature.

In modern prestressed concrete construction, the main approaches used for the control of stresses at the ends of pretensioned members, besides adding vertical reinforcement, have been – reducing eccentricity of the strands at the ends; deliberate debonding of selected strands with concrete at and near anchorage zones; introducing supplemental steel rods for reinforcement; adding top strands, which can be debonded in the center portion of the girder, as needed; releasing the strands when the concrete has reached higher compressive strength.

For better prediction of the state of stress and the nature of damage in the critical regions of pretensioned concrete beams, this study focuses on determining the state of stress in the end-zone of prestressed concrete beams using the proposed finite element modeling and simulation scheme so that more effective steps can be taken in the design to control such cracking.

As the pretensioned beams used in practice tend to be deep and slender, stress predictions, even away from the ends, based on conventional Euler–Bernoulli assumptions may not be valid in all cases. As a consequence, both ACI-318 [12] and AASHTO LRFD [13] recommend a simplistic semi-empirical approach called the strut-and-tie method for designing the secondary reinforcement, especially, near the anchor zone. The basic premise of the strut-and-tie method is that near limit state a complex structural member can be treated as an equivalent truss structure. Although the approximate representation of the limit state in the method makes sense, according to the recent studies, however, designs based on this method are found to be inefficient and overly conservative [14]. Since 1960's, finite element simulation to predict the response of prestressed concrete beams has been widely used. But some of the finite element models used for this purpose were grossly inadequate and were not representative of the real mechanics of prestressed concrete beams and most recent attempts to improve the situation [15–17] were not quite successful.

In their study, Ayoub and Filippou [15] implemented a mixed formulation based model to represent the prestressed concrete beam in the general purpose Finite Element Analysis Program (FEAP) [18]. The model of the prestressed concrete beam comprised of three components. First, a fiber beam-column element is used to represent the behavior of concrete and embedded reinforcement. Secondly, a 1-D truss element is used to represent the prestressing tendon. Finally, bond elements defined at the nodal points accounted for the transfer of interfacial forces between concrete and prestressing strand. The pretensioning operation is considered in two stages at discrete times. First, the pretension is induced in the tendons which is followed by the transfer of prestress to concrete. In the first stage of the analysis, only the 1-D tendon elements are active. Also for representing the bedding element, a linear stiff spring is used at one end of the tendon. The prestressing force is applied at the other end. In the second stage of analysis, the beam-column elements and bond elements are activated. Thereafter, the applied prestressing force in the tendon is reduced to zero, to simulate the release of the strands. The bedding element at the other end is also removed at the same time. In this stage, the prestressing force in the tendon element is transferred to the concrete fiber based beam-column elements via the idealized bond elements. This study makes a number of sweeping assumptions which may have questionable validity. First, 1-D representation of the tendon ignores one of the main stress transfer mechanisms between the strand and the concrete which is 3-D in nature. This mechanism is called wedge effect or "Hoyer effect". This is caused by the tendency of the strand to return to its original size from the reduced diameter resulting from the initial pretensioning force (Fig. 1). Also, the model does not adequately account for cracking and tension stiffening effects.

As an attempt to further unravel the important issues of finite element modeling of prestressed beams, Arab et al. [16] used the Concrete Damaged Plasticity (CDP) model in the commercial software 'Abaqus' [19]. In modeling the interaction between the prestressing strand and the concrete, Arab, et al. tried two methods, terming them as (a) the extrusion technique, and (b) the embedment technique. In the first technique, a coefficient of friction is used to define the tangential behavior and hard contact is used for normal behavior. While preventing penetration between steel and concrete, the hard contact model prevented tensile stress transfer through interfacial interaction. In the embedment technique, however, the prestressing strands are assumed to be embedded into the concrete matrix with the prestressing strands modeled by 1-D truss elements and the concrete matrix by solid elements. In the interface model, the degrees of freedom of the prestressing strand element nodes are supposedly constrained with respect to the interpolated values of the corresponding degrees of freedom of the concrete host elements.

Arab et al. also used a steel casting bed model to provide support to the beam without restraining longitudinal and transverse movements. The interface between the casting bed and the beam is assumed to be frictionless and of hard contact type, allowing for separation. Pretensioning is accomplished in two steps. In the first step, the strands are pretensioned and no relationship is established between strand and concrete. In the second step, the strain-compatibility is applied between strand and concrete to simulate release of the strands.

Acute lack of accuracy of the predictions by this model may be attributed to some of the assumptions made by Arab et al., appearing to defy the basic mechanics of the problem. For instance, the assumption of strain compatibility at steel and concrete interface in both extrusion and embedment techniques do not appropriately allow for the possibility of slippage due to bond failure. Another area of concern centers on the mesh. The elements around the prestressing strand appear to have quite high aspect ratios and this is expected to introduce errors in representing the interfacial bond behavior. For numerical stability, according to the contact sub-module of Abaqus [19], the concrete matrix at the interface should have been meshed finer than the strand, which is contrary to the model used by Arab et al. Furthermore, the experimental