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A two-stage modelling approach for the analysis of the stress distribution in anchorage zones of pre-tensioned, concrete elements

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ABSTRACT

An innovative strategy for the analysis and design of the anchorage zones of pre-tensioned, concrete girders is presented. In this approach, the bond behaviour of the prestress strands is first characterised in a small-sized beam model. A new relation between the slip and radial strain of the prestress strand is introduced and used together with the radial stress–strain relation resulting from a thick-walled cylinder model to establish the bond-slip behaviour at the steel–concrete interface. This bond behaviour is implemented in a numerical model and validated via a comparison of the computed transfer length with the results of two experimental campaigns. Next, the bond-slip relation of the small-scale model is applied in full-scale models of pre-tensioned, concrete girders to derive the stress distribution in the anchorage zones. The non-linear material behaviour of concrete is taken into account and a comparison of the numerical results with full-scale experimental data is made. An acceptable agreement is achieved between the experimental results and the numerical calculations regarding the bond behaviour and transfer lengths as well as the crack patterns and the stress values in the reinforcement bars. This efficient modelling approach allows for a full analysis of the anchorage zone based solely on the geometrical and material properties known at the design stage.

1. Introduction

Although the use of prestressed concrete girders for structures involving large spans is widespread nowadays, field observations show that some of these elements still exhibit non negligible cracking in the anchorage zone due to a combination of large prestress forces and inadequate anchorage zone reinforcement design. The transfer of the prestress force from the prestress tendon to the surrounding reinforcement and the spreading of these forces over the height of the element cause a non-linear stress distribution in the anchorage zone which is not easily controlled. Furthermore, the commonly used Euler-Bernouilli beam theory is not suited to describe the stress field in this zone since the cross-section of the element under prestress load does not remain plane and does not stay perpendicular to the neutral axis. Therefore, characterising the stress distribution in the anchorage zones is often tackled by resorting to specifically derived analytical or numerical approaches, often involving simplifications.

Advanced numerical models, validated against empirical data, have recently been applied in order to get a better understanding of the behaviour of these zones in view of a more efficient and economic design of anchorage zone reinforcement. Tuan et al. [1] studied analytical models of the anchorage zone using conventional methods like the strut-and-tie method and Gergely-Sozen method but also more advanced numerical finite element models. Okumus [2–4] also used the finite element method to analyse the stress distribution of the end zones of pre-tensioned elements but included non-linear concrete material behaviour. A study of the tensile stresses in the anchorage zones of four full-scale beams was conducted by O'Callaghan [5] who investigated the tensile stresses in the anchorage zone empirically. Resulting from these researches, the value of the prestress force, the eccentricity at which it is applied and the value of the transfer length are identified as being the main parameters governing the cracking behaviour in the end zones. Furthermore, an insight is provided into the cause of anchorage zone cracks and suggestions concerning the anchorage zone reinforcement lay-out are made.

As just stated, proper evaluation of the tensile stresses in the anchorage zone and a consequent effective design of the corresponding reinforcement lay-out in this zone require a correct assessment of the transfer length. This transfer length is the length, measured from the extremity of the member, necessary to lead to the full transfer of the prestressing force from the tendon to the

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surrounding concrete [6]. A short transfer length will induce high tensile stresses within the anchorage zone and may thus lead to cracks which may deteriorate the structural integrity of the element. The transfer length is essentially governed by the bond behaviour at the steel concrete interface and the value of the bond strength depends on a range of parameters. Extensive experimental research has been performed in order to identify and investigate these influences. It is found that concrete confinement is one of the most important aspects governing the bond behaviour, as evidenced by the experimental campaigns of Galvez et al. [7], Marti-Vargas et al. [8], Benitez et al. [9] and Torre-Cassanova et al. [10]. This concept of concrete confinement incorporates geometrical parameters, such as concrete cover and strand diameter, and material parameters, such as the concrete strength.

The mechanical action of the strand also affects the bond behaviour. Gustavson [11] and Moon et al. [12] notice a significant contribution of the indentations and helical shape of the strand to the bond strength. The experimental campaign of Marti-Vargas [13] also showed that other factors like the water/cement ratio of the concrete mixture influences the value of the transfer length. Moreover, this influence is higher for concrete mixtures with a high cement content. However, most formulae for the evaluation of the transfer length available in current codes and standards are still based on empirical formulations and only take into account a limited part of the numerous influencing parameters [14–17]. Furthermore, Royce et al. [18] and Marti-Vargas et al. [8] showed that these different normative formulae are providing a substantial range of values for the transfer length and thus lack accuracy.

Modelling the transfer of the prestress force in pre-tensioned, concrete elements has also been investigated extensively over the past decade. Ayoub and Fillippou [19] used a bond-slip relation similar to the one that can be found in the CEB Fib Model code 2010 [17]. Some of the parameters applied in this bond model were evaluated beforehand by Tabatabai and Dickson [20] through an experimental campaign.

Lundgren [21] advocated that the bond behaviour should not be inserted into the model as a fixed input but that it should result rather from an analysis. Galvez et al. [7,22] simulated the bond behaviour by implementing a non-associative yield function representing the relation between the bond strength and the compressive stress at the steel–concrete interface. The confinement of the surrounding concrete was taken into account in the model using a cohesive crack model. The confinement effect can alternatively be taken into consideration using a thick-walled cylinder model. This approach is based on the work of Timoshenko [23] and describes the constitutive behaviour of the concrete surrounding a prestressing strand based on the geometric and material parameters of the specimen. The resulting stress–strain relation is then used as an input for determining the bond-slip relation. This way of assessing the bond-behaviour and the confinement of the surrounding concrete was applied by Den Uijl [24], Fellinger [25], Oh et al. [26] and Benitez et al. [27].

Very recently, Abdelatif et al. [28] presented a comparison of three different models of the prestress transfer. The first model was an analytical model using a thick-walled cylinder approach. The two other models consisted of a 2D axi-symmetric finite element model with linear elastic material behaviour and of a full 3D finite element model with non-linear concrete constitutive behaviour. From this research, an analytical formulation of the stress distribution along the transfer length is proposed. Furthermore, it is concluded from the non-linear finite element model that the thick-walled cylinder concept is justified to describe the confinement of the prestress tendon.

Arab et al. [29,30] compared several modelling techniques concerning the prestress tendons. One model uses an extrusion technique, a second model is built following the concept of embedded reinforcement in which the prestress tendons are implemented using one-dimensional elements which are embedded in the concrete continuum elements. For both models, bond-slip behaviour is achieved by implementing the frictional nature at the concrete-strand interface. However, in the extruded model, this is achieved through contact surface algorithms while the embedded model uses nodal constraints and master–slave connections It is concluded that a correct assessment of the overall behaviour of the pre-tensioned elements can be achieved with both techniques [29]. However, the local behaviour surrounding the strand was better approximated with the extrusion technique even though this latter approach was numerically more expensive. To allow for the correct evaluation of the self-weight of the elements, the prestress bed was also modelled together with contact formulations. This time the frictional behaviour was minimised in order to limit the influence on the modelled girder in the axial direction. In the vertical direction, hard contact behaviour is implemented which prevents the girder from merging with the prestress bed but allows for the uplift from the casting bed.

As a conclusion of the review of available references dealing with the transfer of the prestress force and with the bond behaviour in pre-tensioned elements, it can be stated that focus is mostly set on the modelling of the bond-slip behaviour at a local scale, evaluating the transfer length and its influences for small beams with one strand.

In this general context, the present paper proposes an efficient modelling strategy aiming at characterising the non-linear stress distribution within the anchorage zone of pre-tensioned girders on the base of the limited number of geometric and material parameters that can be identified at the design stage. This is achieved by the application of a decoupled two-stage analysis. In the first stage, the bond-slip behaviour is evaluated by modelling a small-sized prestressed beam with only one strand using equivalent strand confinement and material properties to those of the full-scale girder. The equivalent strand confinement is achieved by evaluating an effective concrete cover using the actual geometric values of the concrete cover and of the clear spacing between the prestress strands of the full-scale model. This effective cover is then used in the small-scale model to compute the bond-slip behaviour at the steel strand interface. As a result, the appropriate bond-slip behaviour and transfer lengths of the strand can be determined through the use of a simple and numerically affordable model. In the second stage, the computed bond-slip behaviour is implemented into a full-scale model with non-linear material behaviour which in turn allows for the correct portrayal of the stress state in the anchorage zone. This includes the stress behaviour of the reinforcing steel as well as the concrete material, including crack prediction if relevant. The proposed approach is compared with experimental results in order to validate the prediction of the transfer length and of the bond-slip behaviour of the pre-tensioned strands. The appropriate strain distribution in the anchorage zone is also checked by referring to existing experimental data.

2. Modelling bond behaviour

2.1. Bond mechanism of 7-wire strands

The bond behaviour of 7-wire strands differs quite significantly from that of plain wires, as can be concluded from experimentally identified bond-slip relations [31] (Fig. 1). The bond strength at the steel–concrete interface is attributed to three aspects; chemical adhesion, mechanical resistance, and frictional forces between steel and concrete [32]. The chemical adhesion at the steel–concrete interface is very small and can be neglected [21]. Mechanical