Finite Element Modelling of Concentrated Anchorage Load in Early Age Concrete

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Abstract. Analyses of end-block and beam-end specimens have been undertaken based on the finite element models. The purpose of the analyses is to investigate the effects of concrete early age properties on the response behaviour of the anchorage zone. Time dependent strains and stresses in the anchorage zone are evaluated. The mechanical concentrated load represents the anchorage in post-tensioning of slab or beam during construction where the load is transferred typically at 1 and 4-days ages. The analyses incorporate thermal, creep and shrinkage effects. The double power law (DPL) is adopted to represent the creep effects. The ACI 209 and the CEB-FIP shrinkage models in FE TNO DIANA were also adopted to account for shrinkage. The models are validated based on experiments. Results indicate that early ages concrete effects need to be considered for design of sensitive elements in particular such as anchorage zones of post-tensioned elements.

Keywords: Early age concrete, post-tensioning, anchorage, load transfer.

1 Introduction

During the early ages, concrete experiences a significant amount of volume change, primarily due to the cementitious materials' hydration reaction (chemical shrinkage), available moisture (autogenous shrinkage) and temperature evolution (thermal deformations). These volume changes generate compressive and tensile stresses when the concrete member is restrained. These stresses are intensified with the higher rate of creep at early ages. Heavy reinforcements and adjoining structural members can act as internal and external restraints, respectively. Stresses associated with effects of early age concrete simultaneously occur at the time when the concrete is developing strength.

Early age dilatations and the associated stresses become significant during construction when post-tensioning loads are transferred to the element. To account for the early age stresses, a conservative design approach is normally adopted for the anchorage zone concrete.

In post-tensioning applications, the tendon forces are transferred to the concrete using an anchorage device that are often proprietary. They are supplied with special bearing plates that have a complex geometry and rely on local confinement reinforcements to resist higher bearing pressures than normally imposed on concrete. Post-tensioning load transfer is completed within a space of 7 days after the concrete pour. Therefore an accurate characterisation of the state of concrete during this time is essential. Current design standards intrinsic thermal stresses.

This paper reports on the finite element modelling of anchorage zone concrete behaviour taking into consideration the early age concrete effects. Finite element models of two different types of specimens are described, where in addition to simulation of early age properties as first part of the analysis, an external mechanical load is applied in the second part. The first type of specimen "end-block" model is validated on published literature. The more complex type "beam-end" model includes the dead-end anchor and considered detailing of the geometry of an anchor. The beam-end specimen model is validated by comparisons with the experimental results.

2 Review of literature

In 1953, Guyon presented a solution based on the theory of elasticity to the problem of determining the bursting force in a concentrically loaded rectangular member [1]. Guyon's approach to the determination of stresses in the anchorage zone has been widely used to date and can be found in most textbooks covering design of concrete structures [2, 3].

The transverse stresses in the anchorage zone are well elaborated in Warner et al. [2]. In considering the transverse stresses set up in an end-block, it is important to keep in mind that the stress field is essentially three-dimensional. The anchorage applies a compressive force to the concrete in the longitudinal direction (x-direction). This fans out in the lead length and, in doing so, it sets up transverse stresses in both the vertical direction and the lateral direction. These stresses are radial, but for design purposes they are resolved into 2 dimensions.

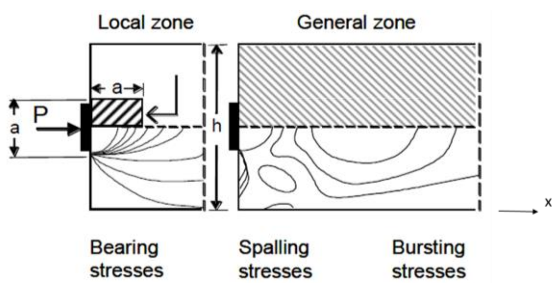

Figure 1: Local and general anchorage zones [4]

According to Breen et al. [4], the objectives of the anchorage zone design are to assure the safe introduction of the tendon force into the structure and to control crack width under service load. Transverse tensile stresses and some concrete cracking in the anchorage zone, particularly along the tendon path is expected.

The problem associated with introducing a concentrated load into a pseudo-elastic structural member (such as concrete) has existed as long as the concept of post-tensioning has been around over a century ago. Different approaches have been adopted towards a solution to the problem. Initially, the problem was treated based on linear elastic theory and the equilibrium method of analysis. Although, this approach forms the basis of analysis recommended by the standard code of practice to date and is deemed to be safe [4], it ignores the fact that cracking of the structure introduces significant stress redistributions. In practice, one added problem for concrete properties during the construction is that the concrete is not fully cured and it is at the same time subjected to early age effects.

3 FE Model Description of Anchorage Specimens

Non-linear finite element code DIANA has been used to simulate the structural response of anchorage in concrete. Program TNO DIANA has been used to simulate the anchorage zone behaviour. The FE model of a push-in specimen (end-block) according to the Zielinski and Rowe [5] experiments are presented first. The second model (beam-end) is a more elaborate version of a dead-end anchor. The FE model of beam-end specimen is validated by experimental results. As for early age properties, it is assumed that concrete is fully restrained in both cases.

For this study adopted the modified Newton-Raphson iteration. In the modified Newton-Raphson iteration, the stiffness matrix is calculated at each time-step.

3.1 End-block Model

The current model presented by the Australian Standards to estimate the bursting stresses is a modified version of the equation proposed by Zielinski and Rowe [5]. In order to consider the concrete early age effects, it was deemed important to study a model that is a replica of the end-block specimen experimentally tested [5]. The FE model consists of an end-block with a circular loading anchorage surface (type CIII, no embedded anchorages, no Ductubes), as shown in Figure 2a.

3.2 Beam-end Model

In order to consider the early age properties of concrete and to study the effect of these on the anchorage zone, a robust beam-end analytical model is presented in this section. The model can simulate both the early age effects and the mechanical action due to the application of the anchorage pullout load. The model is conveniently presented such that it can simulate: a) the early age properties, including the concrete hydration associated thermal and time-dependent effects in view of the thermal boundary conditions and external conditions (heat flow analysis); and b) the mechanical action due to the application of pullout load on the anchor (structural analysis). The purpose of this model was to simulate the interaction of an actual dead-end anchor within the concrete. The model can simulate a) and b) as these two are exclusively independent analyses, or alternatively, combine the two effects and simulate the thermal analysis of concrete while the mechanical load is imposed simultaneously.

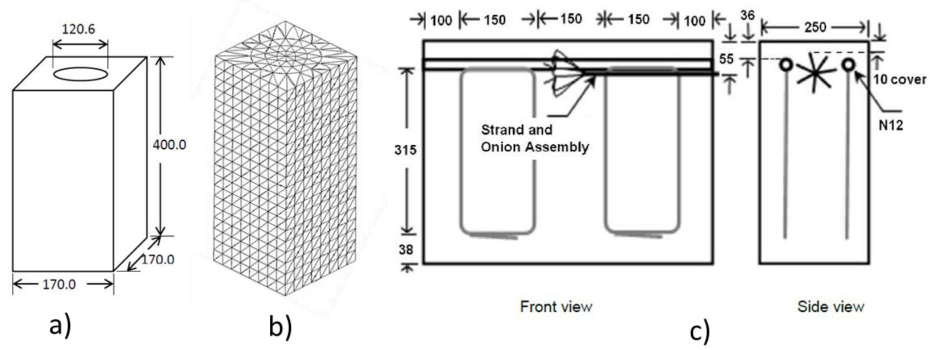

Figure 2: a) End-block; b) FE Model End-block; c) Beam-end geometry

The embedded anchorage "onion" has a 90 × 90 × 90 mm dimensions. One of the most complicated features of the beam-end model is the onion. The location of the onion is set next to the 'exposed' concrete surface. The connection between the steel elements (strand and wire) and the surrounding concrete is done via the interface elements. The truss lines representing the wires are made of very small lines, all interconnected. This is to provide flexibility of displacement when the specimen is subjected to the pullout load. The lines representing the wires are joined together on the left and the right sides. On the right side, the lines are joined again with the line representing the strand. The wire and the strand is made up of truss elements connected to the concrete blocks surrounding it, via the interface elements. The lines representing the 7 mm wires and the 12.7 mm strands are each given a cross-sectional dimension representative of their actual diameters. A detailed description of the experimental work and FEM approach is reported in Ref. [7].

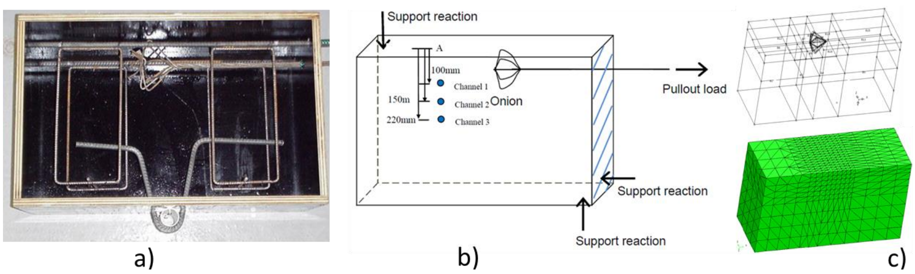

Figure 3: a) Beam-end mould, reinforcements and the anchor; b) Beam-end support reactions and the location of thermal sensors (Channel 1 to 3); c) Beam-end FE model

3.3 Temperature Development in Hydrating Concrete: Theoretical Background

The temperature development in hardening concrete due to hydration may be described by the Fourier differential equation for heat conduction in a homogeneous and isotropic body.

$$div(q) + \rho c\dot{T} = Q \quad (1)$$

$$q = -K\nabla T \quad (2)$$

where q is the heat flux, T is the temperature, $\dot{T}$ is the rate of temperature rise, ∇T is the temperature gradient, ρ is the mass density, c is the specific heat, Q is the rate of internal heat generation per unit volume, and K is the conduction coefficient.

Convection refers to the heat transfer that occurs between the concrete surface and a moving fluid (usually air) when a temperature gradient is installed between both materials. According to Newton's cooling law, the convective heat transfer can be expressed as shown in Equation (7.3) [6]:

$$q \cdot n = h(T_f - T) \quad (3)$$

where q is the convective heat flux per unit area, n is the vector pointing outwards normal to the boundary, h is the heat transfer coefficient, T is the boundary temperature, and T_f is the temperature of the surroundings.

3.4 Material Properties

A 32 MPa commercial concrete specially designed for post-tensioning of slabs in multi-story building is considered for this work. In the experimental work, 16 mm plywood was used as the formwork for curing the concrete (Figure 3a).

Table 1: Thermal properties of concrete and the boundary conditions

Parameter	Value
Concrete thermal conductivity (W/m°C)	2
Concrete volumetric heat specific capacity (J/m^3°C)	4.6×10^6
Convection-radiation coefficient between concrete and air (W/m^2°C)	7.5
Plywood thermal conductivity W/(m°C)	0.1154
Heat transfer coefficient concrete-air W/(m^{2}K)	10
Equivalent convection-radiation coefficient between concrete and formwork (W/m^2°C)	6
Arrhenius constant Ea/R	4000

The adiabatic temperature rise of the mix is presented in Figure 4.

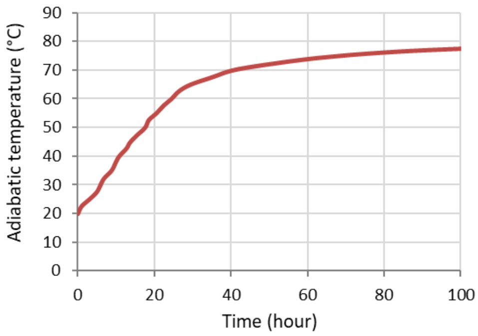

Figure 4: Adiabatic temperature of the concrete mix

4 Model Validation and Results

Figure 5 presents a comparison between the recorded temperature profile and that simulated from FE model. Only one temperature location in the concrete block is pretend. The model was shown to be in good agreement with the experimental results. Temperature profiles recorded from the experiment and the analyses were found to be very similar, with a maximum temperature difference of about 2°C. It is noted that the values of the input parameters were found to vary quite significantly in the literature.

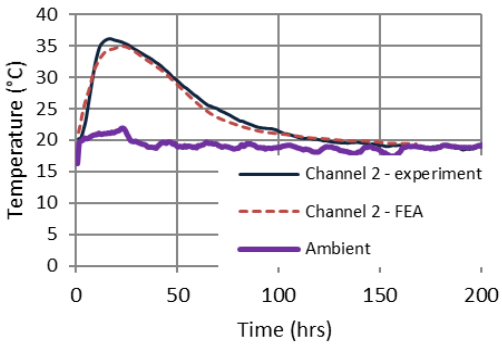

Figure 5: Comparison of temperatures between the FEM and experimental results

The thermal stresses and the cracking tendency of cast in-situ concrete at early ages under restrained condition is a concern. The interim findings of a research program that is aimed to investigate the in situ thermal stresses at early ages. The intrinsic thermal stresses including the effects of creep and shrinkage associated with early age concrete have been investigated. A degree of reaction approach is adopted to account the evolution of material properties of concrete [8].

4.1 Material Properties Anchorage Zone Strains in Early Age Concrete

The beam end model presented in (Figure 3) has been shown to be able to simulate the anchor-concrete interaction with a reasonable accuracy. This highly complex model involves the anchorage assembly, which consists of the wires and the strands, the concrete volumes which surrounds the anchorage, and the interface elements representing the connection between the steel elements and the surrounding concrete. Investigation of early age concrete include extensive number of parameters associated with early age properties on strains and stresses that occur on the concrete surface as a result of mechanical actions. To bring the computation time to a manageable level, the simpler end block model is chosen for the parametric studies presented.

The end block model has been used by numerous researchers to investigate the development of bursting stresses under post tension load [1, 5]. The model was validated against experimental data in order to ascertain that the end-block model can simulate the response behaviour of the more sophisticated beam-end model, the stress distributions in the transverse direction were compared. As the helical and transverse reinforcements in the local and general anchorage zone, respectively, are designed to prevent the occurrence of cracks, finite element analyses were conducted on both models assuming linear elastic behaviour. Figure 6 presents the stress distributions along the central line on the face of end block (z direction) and beam (y direction) models.

The stress values normalised with respect to the imposed stress were plotted against the distance (x) from the location of the plate normalised with respect to the width of the specimen (h). The stress values on the end block and beam end models are shown to be similar (Figure 6). Given the complexity of the analysis, the smaller end-block model is considered adequate for the analysis of the anchorage zone behaviour.

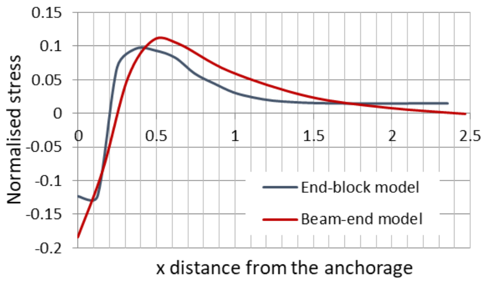

Figure 6: Comparison of stress distributions between end block and beam end models

Further, in order to adjust the size effects between the beam-end and the end-block models, the thermal properties of the FE models can be adjusted such that the temperature development and degree of hydration obtained from the model are similar to that from the beam-end model. Comparison of the temperature development and degree of hydration values between the end-block and beam-end models is presented in Figure 7. The results of Figure 7 are based on the ambient temperatures presented in Figure 5.

The compressive forces imposed on the end-blocks were determined based on common tendon unit types supplied by VSL, with a breaking load of 184 kN for a 12.7 mm wire strand. The post-tensioning load is applied up to 80% of the breaking load of the strands in accordance with AS3600 (2009).

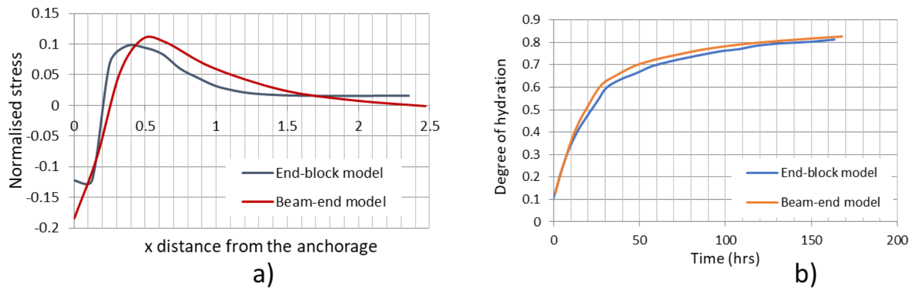

Figure 7: Comparison of: a) temperature development; and, b) degree of hydration between end block and beam end model

4.2 Strain Increment due to a 2 Stage Post-tensioning Load

The push-in stress imposed on the end-block was determined based on common tendon unit types supplied by VSL Australia Pty Ltd, with a breaking load of 184 kN for a 12.7 mm wire strand. The post-tensioning load is applied up to 80% of the breaking load of the strands in accordance with AS3600 (2009). Depending on the strength gain of concrete, it is also a requirement that the post-tensioning load be introduced in two stages: 25% of the post-tensioning load imposed 1 to 2 days after casting the concrete member; and the remaining 75% applied 4 to 7 days after.

It is postulated that strain levels in the highly stressed zone of concrete increase significantly during the time when the load is first introduced to the second stage of loading. Therefore, it is important to investigate whether the strain levels in the anchorage zone increase between the two stages of the loading process. For simplicity, it is assumed that the post-tensioning load is applied at 1 and 4-days age. The stress values corresponding to an anchorage plate areas 11500 mm^2 is calculated to be 10 MPa and 38.5 MPa for 1 and 4-days age concrete. The strain and stress values were calculated for a duration of 7 days.

To investigate the effects of creep, shrinkage and temperature development in concrete on its response behavior in the anchorage zone, the variation in ambient temperature is initially excluded. The concrete end-block is subject to a constant temperature of 20°C. The preliminary analysis was undertaken using ACI 209 models to describe the effects of creep and shrinkage.

Figure 8 presents the strain development in the concrete when shrinkage is ignored. Instantaneous increase in tensile strain observed at 1 and 4-days age represents the instantaneous increase in loads applied when concrete is at 1 and 4-days age. The total strain value decreases between 1 day and 4-days, but increases from 4-days onwards Figure 8(a). The total strain consists of thermal and creep strains, as presented in Figure 8(b). The reduction in the strain values between 1 to 4-days is as a result of rapid reduction in the thermal strain in the concrete block from 1 to 4 days. The high rate of reduction in the thermal strain is expected as the in-situ temperature of the concrete block decreases rapidly from 1 to 4-days.

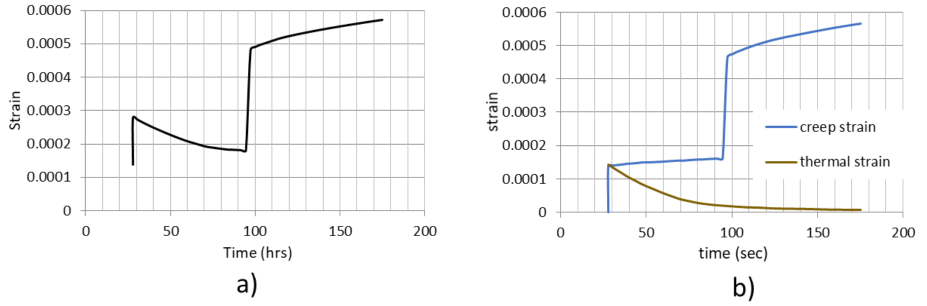

Figure 8: Strain results based on ACI 209 creep model (ignoring shrinkage): a) total strain; and, b) Creep strain and thermal strain

The analyses show that the rate of reduction in compressive strain due to temperature is higher than the increase in tensile strain due to creep between 1 and 4 days. Therefore, the concrete experiences a reduction in total tensile strain. On the other hand, the effects of temperature on the concrete block of 4-days age onwards are not significant due to a much less pronounced decrease in the temperature after 4 days. The increase in the tensile strain due to creep is higher than the decrease in the thermal strain. As a result, an increase in the total tensile strain was observed in the concrete block at 4 days onwards. It was also observed from the analyses that initial strain exists at 1 day, prior to the application of the load. The initial strain was contributed to by the thermal strain developed as the temperature increases to a peak value at around 1 day.

5 Concluding remarks

Finite element approach for two different specimens representing anchorage zone of concrete at early ages is presented. It is shown that the simpler model “end-block” model yields similar results to that of beam-end specimen which takes into consideration all detailing of a typical anchorage zone concrete. Therefore, to conduct parametric studies looking into the effects of early age concrete, it is end-block model is preferred as it will take less run time.

The end-block model is then used to simulate the two stage post-tensioning load application at 1 and 4-days age. The tensile strain at the anchorage zone is then plotted against time (representing duration of the time since the load is applied).

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