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An Experimental Study on Pre-tensioned Concrete Members

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Abstract: Prestressed concrete elements are highly being used in the construction industry. For these kind of precast members, exposure to the loading starts at the fabrication processes. There might be high level of stress fields inside the element because of the prestressing. Exact values of these stresses are being assumed according to the linear homogenous design criteria. However, modeling a pre-tensioned prestressed concrete member via photoelastic experimental procedure could lead to make exact stress analysis in a pointwise manner. The analogy between the prestressing phenomena with photothermoelasticity led to make a pretensioned concrete model with using the "frozen-stress" method of photoelasticity. Two sorts of three-dimensional photoelastic models are prepared and analyzed with using the experimental techniques of three-dimensional photoelasticity and aimed to deal with the investigation of the pre-stress distribution after the fabrication process of the pre-tensioned reinforced concrete members. With considering the technical literature, insufficient information requires to make an investigation of the stress distribution at the vicinity of the free edges and bonding area of the reinforcing material of the pre-stressed structural members. Finally, obtained results show that some regions in a prestressed member have to endure high level of compressive and shear forces immediately after the release of prestress. This study mainly deals with the determination of the critical regions in a prestressed member and taking some precautions in order to keep the safe design margins.

Keywords: Pretensioned concrete, photothermoelasticity, photoelastic modelling, anchorage zone.

1. Introduction

Limited tensile strength of reinforced concrete made the large-span system constructions impossible to undertake in the past. Highly utilized compressive strength of concrete is facilitated by prestressing phenomena. The concept has experienced essential developments with high technology in response to the architectural needs [1, 2]. Partially PC, external PC, highly eccentric prestressing and extradosed prestressing are among the viable innovative advancements [3]. The prestressed concrete as a major structural material has still some problems despite to contributions to technological improvement of its constituent materials. Steel corrosion, concrete creep, prestress loss and environmental effects deteriorate the structural durability in decades. Particularly, prestress loss, bond slips and transfer length assumptions are being made for pretensioned concrete materials in order to ensure the structural safety [4, 5]. Regarding the bond mechanism of pretensioned concrete members, a much more sophisticated analysis is required to handle with this kind of self-equilibrated internal stress state at the fabrication process. A photoelastic experimental procedure is able to tackle with a pointwise stress analysis.

A pretensioned concrete material is a type of composite member consists of concrete and steel tendons. Photoelastic modeling of a composite structure is possible with using the "frozen-stress" method of 3-D photoelasticity. If a birefringent material is loaded at its critical temperature, T_c, and then cooled down to room temperature in a slow rate, internal stresses are locked after this freezing cycle. This type of behaviour allows to make the photoelastic analysis of 3-D models with using slice method [6, 7].

2. Experimental Procedure

In this study, two types of three-dimensional photoelastic models (3DModel1 and 3DModel2) are implemented in addition to a two-dimensional photoelastic stress analysis (2-DModel) made before [8]. Let the composite structure made in n dissimilar materials. For a proper photoelastic modelling the Eq. [1] must hold at the freezing temperature (T_f), between the materials used in prototype and model.

$$\frac{E_{pi}}{E_{p(i+1)}} = \frac{E_{mi}}{E_{m(i+1)}}; \quad i = 1,2, \dots n \qquad (1)$$

where E denotes the elastic moduli of the ith material, p and m the prototype and model. Models presented herein consist of 2 types of birefringent material (araldite1 and araldite2) and an opaque plastic material (nylon6). Young moduli variation of the used materials according to temperature change are shown in Fig. 1.

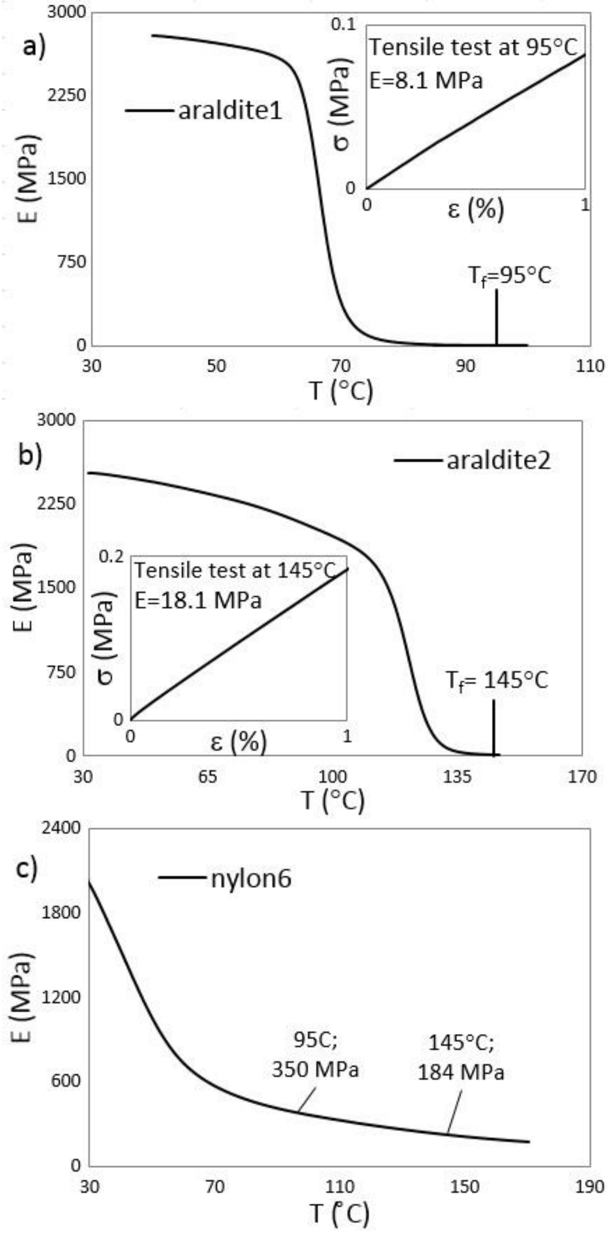

Figure 1: Temperature-Young Modulus curves for a) araldite1, b) araldite2, and c) nylon6 with tensile test results at freezing temperatures

Based on the test results, implemented by DMA (Dynamical Mechanical Analyzer), nylon6 and araldite2 compliance the aforementioned modular ratio for the prototype which consist of concrete and steel materials. These two materials form the 3DModel1. For the sake of comparison another 3-D Model (3DModel2) is made by araldite1 and nylon6 with having a modular ratio of E_n/E_a=43.

Calibration is needed to make the photoelastic analysis. Optical sensitivities of both araldite specimens are determined with photoelastic disk specimens for each material (Fig.2).

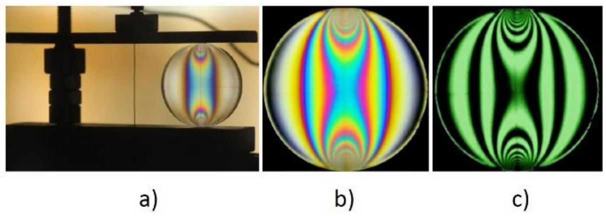

Figure 2: a) Loading frame in digitally controlled oven, b) fringe pattern of the disks in white light, c) monochromatic light

With using the polarizer microscope the centroid fringe numbers are obtained. Following relationship is used to assess the optical sensitivity constant which holds for the center point of the disk.

$$\sigma_0^{1.0} = \frac{4P}{\pi \mu \mathrm{R}} \qquad (1)$$

where $\sigma_0^{1.0}$ is the optical sensitivity constant, P the applied load, μ fringe number and R radius. Using the Eq. [1] optical constants of araldite1 and araldite2 is found as 0.25 and 0.22 respectively.

The preparation of the models consists of the following steps.

2.1 Prestressing

Applying the prestress forces to the model is conducted via “freezing cycle”, which leads to lock the stresses in the photoelastic materials (Fig. 3a). Frozen-stress work is made with regarding the critical temperatures of the optical materials which are 95°C and 145°C for araldite1 and araldite2, respectively. There is an analogy between the photothermoelasticity and stress distribution of the prestresses pretensioned concrete members. In line with this analogy the prestress forces are applied on the birefringent materials via compressive loads which are representing the concrete part of the prototype. The stability and compressive yield strength controls are made with analytical and experimental work to determine the weights. It is supposed that the stress level of a prestressed member immediate after the fabrication process are below the strength limits of used materials.

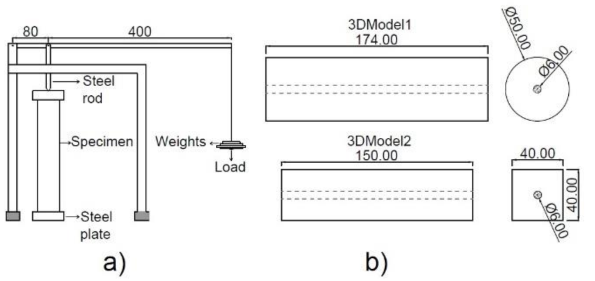

Figure 3: a) Loading frame, b) 3-D Models

Therefore the compressive stresses frozen in the araldite specimens are 0.20 MPa and 0.15 MPa for the 3DModel1 and 3DModel2 respectively (Fig. 3b).

2.2 Drilling

In regard with the defined geometrical similarity ratio, ¼, araldite specimens are drilled with 6mm diameter drilling bit. Only a single hole at the center of the cross sections, created for each 3-D models.

2.3 Placing the bars

Nylon6 rods, with having a diameter of 6mm, is sited inside the holes with using a claw mechanism and prepared epoxy glue (Fig. 4 a-c).

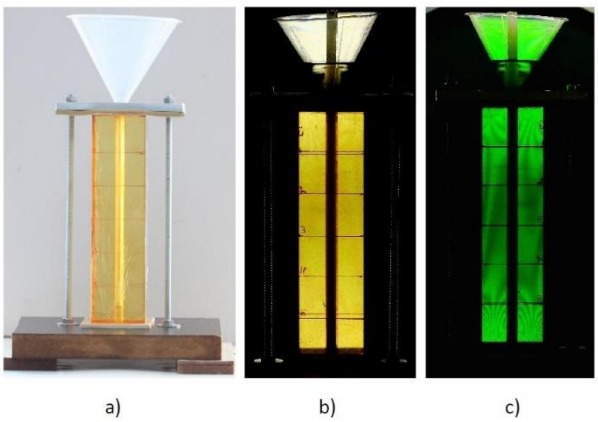

Figure 4: a) Placing and gluing the inclusion, and polariscopic photographs of 3DModel2 on b) white, c) monochromatic light

2.4 Releasing

After the completion of the models, another freezing cycle is implemented in order to release the prestresses which are already locked in the araldite part of the specimens. To fulfil the freezing operation, models are heated with 3°C/h rate to its freezing temperature, halt at this temperature for 3 hours and cooled down to the room temperature consecutively at the same rate with heating up. The generated interference fringe pattern of the models after the release of prestresses is shown in Fig. 5 a, b.

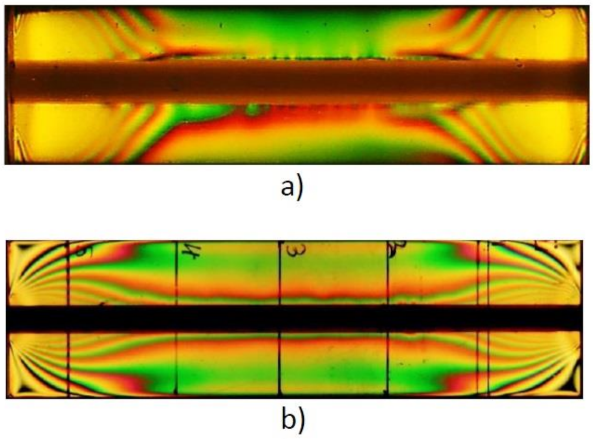

Figure 5: Fringe pattern of the a) 3DModel1 and b) 3DModel2 after the release

Frozen stress phenomena leads to make a comprehensive photoelastic analysis of 3-D models with using slicing method of photoelasticity. Regions of interest are sliced from the 3-D models and defined points are measured with Leica polarizing microscope.

3. Experimental Analysis

Stress results of the models are obtained with the aforementioned photoelastic work. Stress values of the model must be transformed to prototype correspondent. Thus following relationship holds for the model-prototype relationship.

$$\sigma_p = \frac{1-\vartheta_p \varepsilon_{0p} E_p}{1-\vartheta_m \varepsilon_{0m} E_m} \sigma_m \tag{2}$$

where ϑ, ε_{0p}, E and σ represent for the Poisson's ratio, initial pre-strain, Young modulus and stress respectively. Suffixes of p and m refer to prototype and model. With using Eq. [2] conversion factors, $n=\sigma_p/\sigma_m$, are found and shown in Table 1.

Table 1: Model-prototype conversion parameters

Model	ε_{0m}	ε_{0p}	n
2DModel	0.014	0.0015	162
3DModel1	0.011	0.0015	205
3DModel2	0.019	0.0015	266

3.1 2D Model

The detailed information about the 2DModel can be found in [8, 9], which is a model of prestressed concrete slabs. It consists of araldite2 for concrete and nylon6 for prestressing tendon. Experimental analysis results along the interface is shown in Fig.4.

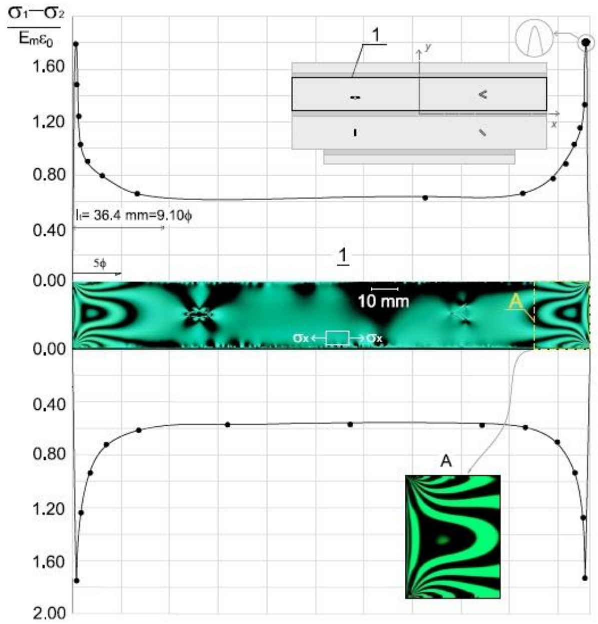

Figure 4: Normalized stress distribution along the interface of 2DModel, (ϕ= 4 mm, l_t: transfer length, E_m: Young modulus araldite2, ε_0: initial value of frozen strains on the araldite part of the model)

In the Fig. 4, σ_1 and σ_2 define the principal stresses at the certain points on the concrete steel interface. The normalization is made by initial prestress value (frozen-prestress), which equals to $E_m\varepsilon_0$ (0.28 MPa for 2-DModel). The difference of the principal stress values is called as Tresca stresses. Half of the Tresca stress values equal to the maximum shear stress. It can be deduced from the figure shown above that maximum shear stresses are 0.9~1 times of initial prestress. Considering the converted stress, this value is much higher than the shear strength limit, assuming that the shear strength is equal to $\sqrt{f_c}$, in which f_c is the compressive strength of concrete. And the transfer length is measured about 9.1 times of used tendon diameter.

3.2 3DModel1

The concrete part of 3DModel1 is represented by araldite2. Modular ratio of the materials comply with the prototype. The model has *50 mm* diameter cross section with *6 mm* diameter nylon6 rod which represents the tendon. Sample1 from the 3DModel1 is cut during the slicing operation (Fig. 5)

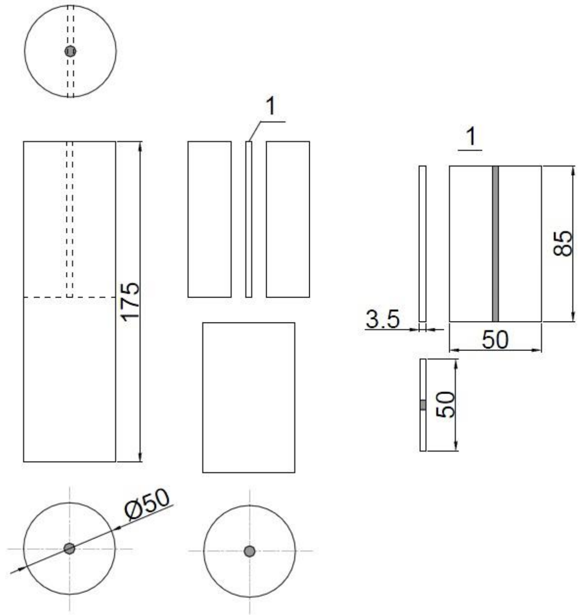

Figure 5: Sliced sample1 from 3DModel1

Sample1 represents the anchorage zone of the model. Stress concentrations are located at the free ends of the interface region. The graphical representation of the measured stress values on sample1 is shown in Fig. 6.

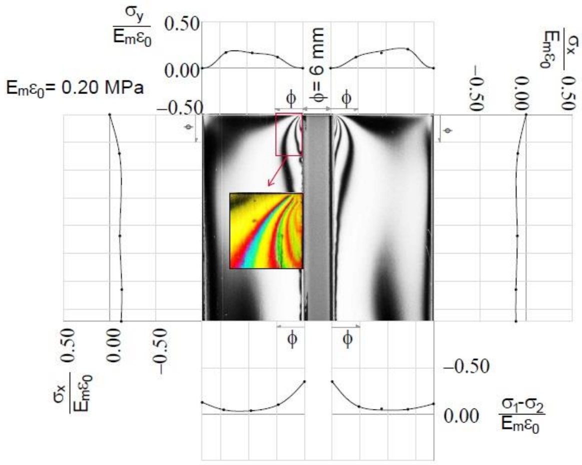

Figure 5: Experimental stress analysis of 3DModel1 at its edges (σ_1, σ_2: principal stresses)

Principal stress differences at the edges of 3DModel1 is shown in Fig. 6. The stress values called as Tresca stresses normalized with the initial prestress which is *0.20 MPa* for this case. As a result of the investigation of the stress field yielded at the edges of the prestressed member, attention is called at the edges on anchorage zone. The top end of the member undergoes high tensile stresses on concrete part (more than *8 MPa*). This value is much higher than the assumed tensile strength of a regular concrete. High concentration of stress in the anchorage zone threatens the structural safety. Maximum shear stress in this field could be as higher as more than *41 MPa*. Interface regions would bear overloaded transmission forces at the transfer length. This problem may come out as tendon slips after the fabrication process.

3.3 3D Model2

3DModel2 consists of araldite1 and nylon6 materials. The concrete part is simulated by araldite1 and nylon6 for steel. Modular ratio is about 40. The model has square cross-section with a 6 mm tendon diameter.

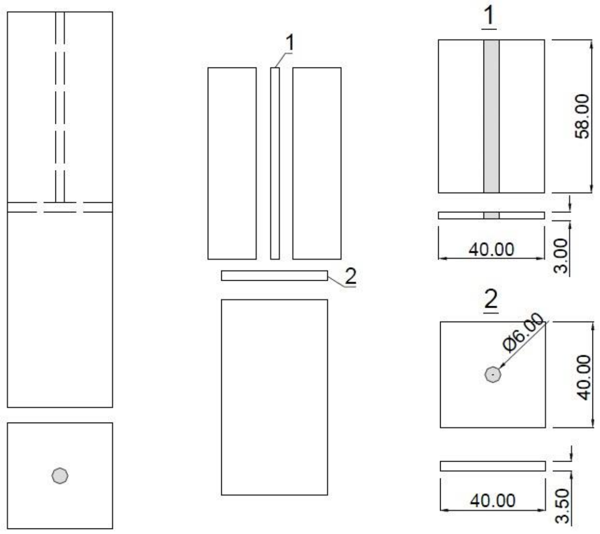

Figure 5: Cut samples of 3DModel2 via slice method

The geometry and dimensions of sample 1 and sample2 of 3DModel2 are shown in Fig. 5. The anchorage zone analysis is made on sample 1. Concentrated fringe pattern at the free ends of the interface can be seen on Fig. 6. Sample 2 is cut at the transverse plane to the applied prestress load (Fig. 7). The slice operations are made with using milling machine. Precautions are taken in order to provide the sample against residual stresses which could be generated at the cutting operations.

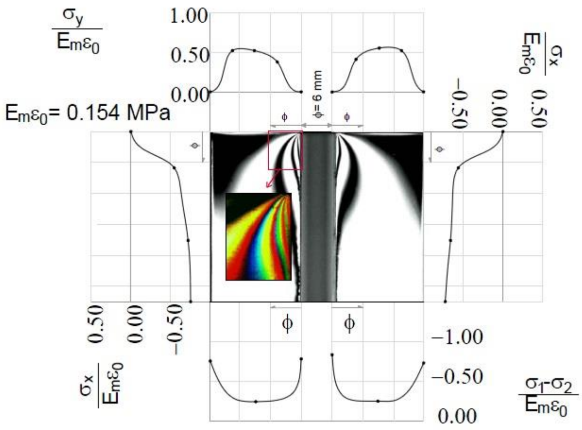

Figure 6: Cut sample 1 from 3DModel2 via slice method

It can be seen from Fig. 6 that tensile forces at the anchorage end of the member can reach up to half of the initial prestress force. According to Eq. [2] and Table 1, tensile stress at this part is about 20 MPa which certainly can cause the cracking. The tensile stress value at these regions is 8 MPa for 3DModel1 which has the proper modular ratio with the prototype. The maximum shear stress at the anchorage zone is approximately 60 MPa. Which is 41 MPa for the previous 3-D model. These values are much higher than the elastic limits if one consider a regular normal weight concrete.

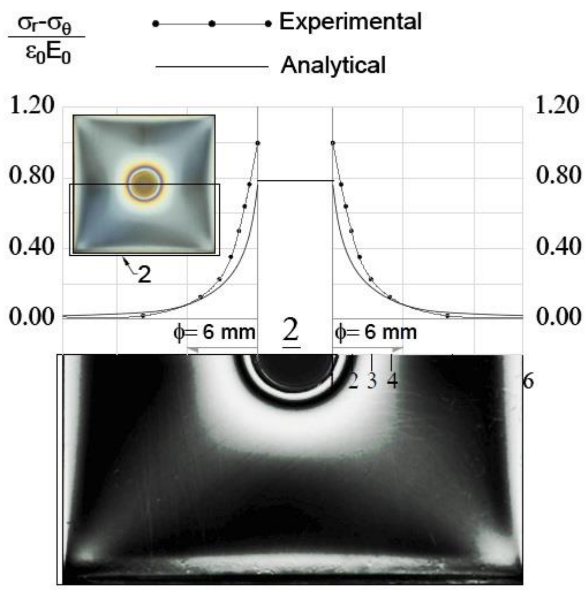

Figure 6: Cut sample 1 from 3DModel2 via slice method

Fig 6 represents for the transverse cut sample 2 of 3DModel2. It can be deduced from the analysis of sample 2 that with releasing the prestress forces contact interface bears considerably high radial stress.

4. Conclusions

Experimental simulations of prestressed concrete members are made by using the thermoelastic analogy. The mechanism of stress transmissions of different material joints in a uniform heat flow led to use the frozen-stress method of photothermoelasticity for the simulations of prestressed elements. The photoelastic analysis with help of the conversion to prototype techniques yield in significant results about the stress levels of prestressed materials, immediate after the fabrication process. The most notable conclusions are derived at the anchorage zone and at the free ends of the member. The bond regions between concrete and prestressed tendons acquires considerably high shear and radial stress values which may result in reinforcement slips with prestress loss.

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