

Parameter identification for coupled elasto-plasto-damage model for overheated concrete

Andrey Benin^{1*}, *Sergey Semenov*¹, *Artem Semenov*² and *Galina Bogdanova*¹

¹Emperor Alexander I St. Petersburg State Transport University, N.A. Belebouski Laboratory of Mechanics, 190031, Moskovsky pr. 9, St. Petersburg, Russia.

²Peter the Great St. Petersburg Polytechnic University, Mechanics and control processes, 195251, Polytechnicheskaya st. 29, St. Petersburg, Russia.

Abstract. The methodology of experimental acquisition and subsequent processing of data for identification of nonlinear elasto-plasto-damage concrete model parameters are considered. Typical measurement equipment and data acquisition process are described. The experiments were carried out on standard specimens of cubic and prismatic form under compression and dog-bone-shaped specimens under tension. Elasticity modulus in tension and compression, ultimate strengths in compression and tension, damage evolutions during deformations process and other mechanical characteristics were obtained. The results of parameter identification and validation for typical structural concrete including regular and overheated concrete are presented and discussed.

1 Introduction

The elasto-plastic models with account of damage [1-3] provides effective tools for the modelling nonlinear concrete behavior with taking into account irreversible deformation, softening effect, inelastic volumetric expansion and stiffness degradation. There are many implementations of such type models, for example, in commercial software ABAQUS [4]. One of the main difficulties is an identification of the model parameters for the computation of real concrete and reinforced concrete structures [5-8]. There are few recent researches aimed to obtain all parameters for elasto-plasto-damage model [9, 10]. Calibration of concrete parameters based on digital image correlation was proposed in [11]. Aims of the current research are:

- design of test setup for the correct control test and obtaining stress-strain curves;
- developing of identification methodology for model parameter obtaining (excepting biaxial loading) for finite-element computations;
- carrying out experiments using recommended standard specimens [12], identifying model constants;
- validation of identified parameters using finite-element computations.

* Corresponding author: benin.andrey@mail.ru

2 Test setup

The test setup (Fig. 1a) is based on Shimadzu AGX300 electromechanical test machine. The fixtures (Fig. 1b) for tensile tests and deformation sensor frame (Fig. 1c) were designed and produced.



Fig. 1. Test machine (a), tensile test fixtures (b) and deformation sensor frame (c).

There are two Heidenhain ST1278 length gauge sensors used for strain measurement. The sensors were interfaced with test machine controller and result strain was calculated as average of two sensors measurements for neglecting influence of bending effect. The strain sensor frame was installed directly on the specimen. This approach allows obtaining the direct strain measurement during testing and as result to measure correctly elastic modulus (see, for example, comparison of modules measured by different methods in table 2 [10]). Such design allows to perform experiments in the temperature chamber and using quartz glass tubes for precisely strain measurement.

3 Specimens

Specimens were prepared according to the recommendation of Russian standard [12]. There are three types of specimens:

- cubes $100 \times 100 \times 100$ mm for concrete class (cube strength) definition,
- prisms $100 \times 100 \times 400$ mm for compression experiments,
- dog-bone specimens for tension experiments.

Concrete mixture recipe is 400 kg/m^3 of CEM I 42.5R, 700 kg/m^3 of 0/4 gabbro sand, 1125 kg/m^3 of 5/10 gabbro coarse aggregate, 120 kg/m^3 of fly-ash, 230 kg/m^3 of water and 35 kg/m^3 of plasticizers and modifiers. Specimens were casted in standard steel forms, extracted from forms after 3 days and cured in the 95% humidity and 20°C temperature environment during 28 days. The standard cube strength class of prepared specimens is B50.

A part of specimens have a heating treatment up to the maximum temperature 600°C during 1 hour. The heating rate was 10°C/h.

4 Experimental results and parameter identification

Fig. 2a and b represent typical cyclic stress-strain diagrams containing the post-peak behaviour under compression and tension for the specimens from the overheated concrete. These curves are basis for the parameter determination of the evolution law for the plastic strain and damage.

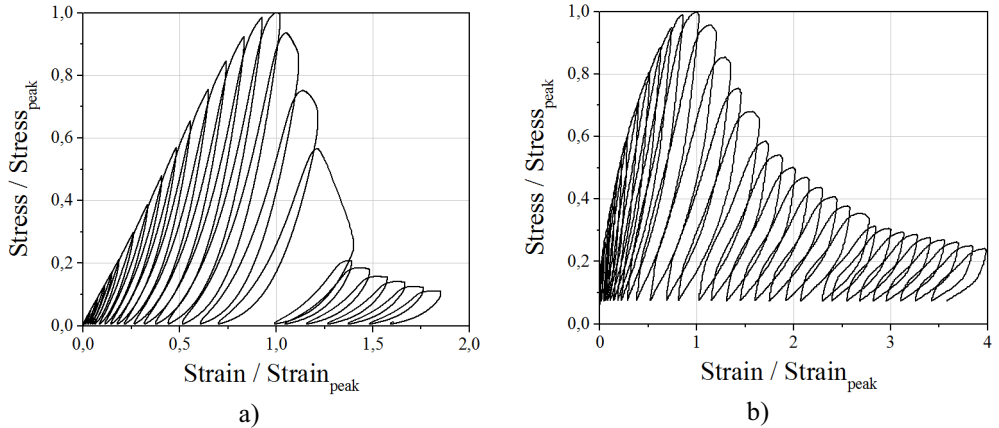


Fig. 2. Typical compression (a) and tension (b) cyclic diagrams for overheated concrete.

The progressive elastic stiffness degradation from cycle to cycle provides information for the damage calculation. The damage (in compression) is considered as a scalar variable D , which is equal to 0 for virgin material and equal to 1 at the failure. The damage variable at k -th cycle can be evaluated as:

$$D_k = 1 - E_k / E_0, \tag{1}$$

where E_0 is the value of the undamaged modulus and E_k is the values of the damaged moduli at the at k -th cycle (see Fig. 3).

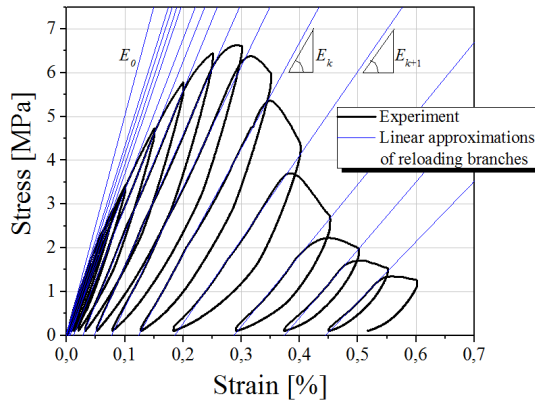


Fig. 3. Illustration of the determination of the elastic reloading moduli of the damaged material.

Due to non-linear character of both unloading and reloading branches of cyclic stress-strain curve it is non-trivial problem to calculate appropriate elastic moduli of the damaged material. The loading and reloading branches, tangential, averaged and secant slopes can be used. The results of multivariant computations show that the elastic reloading moduli of the damaged material determined as the slopes of linear best-fit approximations of the ascending parts of the experimental reloading branches (see Fig. 3) provide the best variant.

For the further analysis it is rational to recalculate the damage as function of inelastic strain instead of function of number of cycles. The axial inelastic strain is determined as

$$\varepsilon^{in} = \varepsilon - \sigma / E_0, \tag{2}$$

The results of damaged elastic moduli and damage calculation as function of inelastic strain is given in Fig. 4 for regular and overheated concrete.

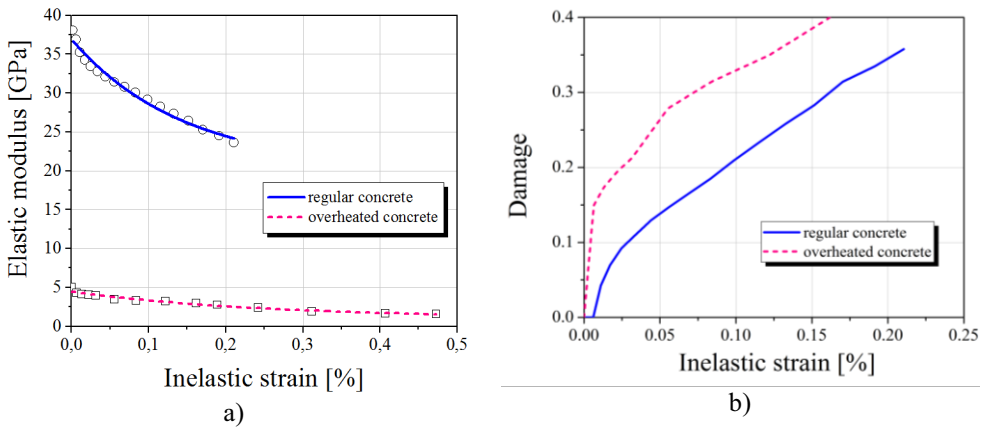


Fig. 4. Elastic modulus degradation (a) and damage evolution (b) with increasing of inelastic strain for regular and overheated concretes.

5 Constitutive equations

The constitutive equation of elastic-plastic material with scalar isotropic damage for three dimensional general case takes the following form:

$$\boldsymbol{\sigma} = (1 - D) \cdot {}^4\mathbf{C}_0^e \cdot (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^p) = {}^4\mathbf{C}^e \cdot (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^p), \tag{3}$$

where $\boldsymbol{\sigma}$ is Cauchy stress tensor, $\boldsymbol{\varepsilon}$ is the strain tensor, $\boldsymbol{\varepsilon}^p$ is the plastic strain tensor, ${}^4\mathbf{C}_0^e$ the initial (undamaged) elastic stiffness of the material, while ${}^4\mathbf{C}^e = (1 - D) \cdot {}^4\mathbf{C}_0^e$ is the degraded elastic stiffness tensor. The effective stress tensor is defined by the relation $\bar{\boldsymbol{\sigma}} = {}^4\mathbf{C}_0^{el} \cdot (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^p) = (1 - D)^{-1} \boldsymbol{\sigma}$.

The evolution of the scalar degradation variable is defined by the function $D = D(\bar{\boldsymbol{\sigma}}, \tilde{\varepsilon}^{in})$, governed by a set of the effective stress tensor $\bar{\boldsymbol{\sigma}}$ and hardening (softening) variables $\tilde{\varepsilon}^{in}$. In the used in further Lubliner model [2], the stiffness degradation is initially isotropic and defined by degradation variable D_c in a compression zone and variable D_t in a tension zone.

Plastic flow is governed by a flow potential function $G(\bar{\boldsymbol{\sigma}})$ according to non-associative flow rule:

$$\frac{d\boldsymbol{\varepsilon}^p}{dt} = \lambda \frac{\partial G(\bar{\boldsymbol{\sigma}})}{\partial \bar{\boldsymbol{\sigma}}} \tag{4}$$

The flow potential G is accepted in the form:

$$G = \sqrt{(f_c - m \cdot f_t \cdot \tan \beta)^2 + 3\bar{J}_2} + \frac{1}{3}\bar{I}_1 - \tan \beta, \tag{5}$$

where f_t and f_c are the uniaxial tensile and compressive strengths of concrete, respectively, β is the dilation angle measured in the $\frac{1}{3}\bar{I}_1 - \sqrt{3\bar{J}_2}$ plane at high confining pressure, while m is an eccentricity of the plastic potential surface, $\bar{I}_1 = \mathbf{1} \cdot \bar{\boldsymbol{\sigma}}$ and $\bar{J}_2 = \frac{1}{2} dev \bar{\boldsymbol{\sigma}} \cdot dev \bar{\boldsymbol{\sigma}}$.

6 Validation

The results of comparison of simulation results with experimental data under monotonic compression for regular and for overheated concrete are given in Fig. 5. A good agreement is observed in both cases. The model parameters are identified with help of the relations (1) and (2). The constitutive equations (3)-(5) are used in simulations. Note that the considered approach allows to describe strain hardening, softening and post-peak behaviour under compression and tension

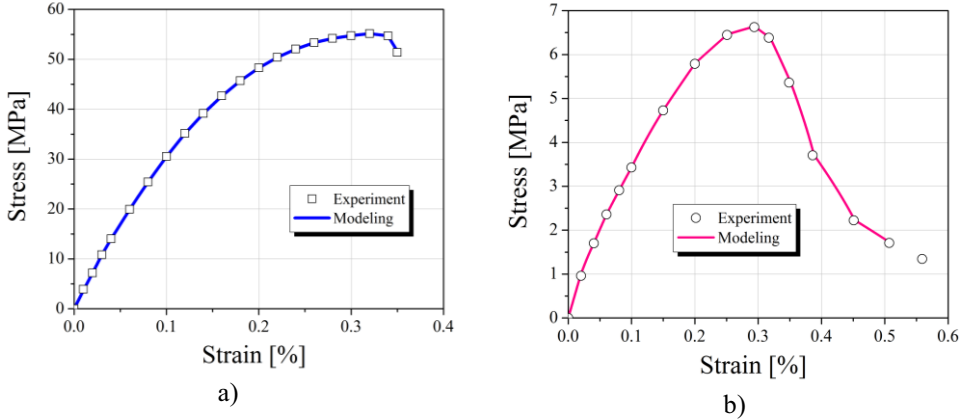


Fig. 5. Comparison of simulation results with experimental data under compression for regular concrete (a) and for overheated concrete (b).

The validation results of proposed identification procedure under cyclic loading for regular and for overheated concrete are given in Fig. 6. Prediction accuracy is lower in comparison with monotonic case, but a satisfactory agreement results of experiment and simulations is observed in this case too.

The considered model is limited by the possibility to predict only the linear unloading. This reduces the accuracy of the computations. One of the possible ways to further improve the material model is to consider structural or multisurface models.

Examples of further application of the considered elasto-plasto-damage model in solving real problems of practice are given in [5-8].

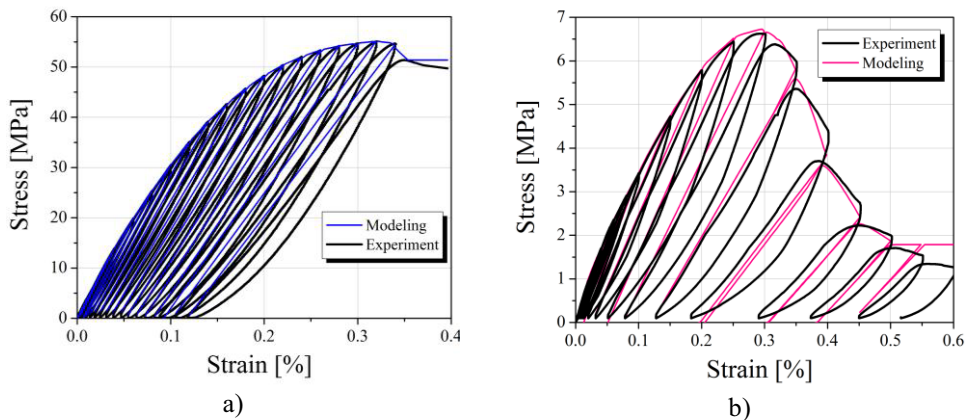


Fig. 6. Comparison of simulation results with experimental data under cyclic compression for regular concrete (a) and for overheated concrete (b).

7 Conclusion

The parameter identification procedure of nonlinear elasto-plasto-damage concrete model is proposed and validated. The results of multivariant calculations of damage on the base of experimental cyclic stress-strain curves under compression show that the elastic reloading moduli of the damaged material determined as the slopes of linear best-fit approximations of the ascending parts of the experimental reloading branches provide the best variant. Comparison of simulation results with experimental data under monotonic and cyclic compression demonstrates a good agreement for regular and for overheated concrete.

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