Available online at www.sciencedirect.com
SciVerse ScienceDirect
journal homepage: www.elsevier.com/locate/acme

Original Research Article

Calibration of concrete parameters based on digital image correlation and inverse analysis

T. Gajewski, T. Garbowski*

Poznan University of Technology, Institute of Structural Engineering, ul. Piotrowo 5, 60-965 Poznan, Poland

ARTICLE INFO

Article history:
Received 6 April 2013
Accepted 30 May 2013
Available online 11 June 2013

Keywords:
Lubliner model
Digital image correlation
Inverse analysis

ABSTRACT

The main goal of this paper is to present a robust calibration procedure of essential material parameters of concrete models, based on both full-field measurements and inverse analysis. The proposed method uses a simple laboratory test and home-made correlation software alongside a fast camera. Usually, a full set of material model parameters of concrete can be determined through application of several different tests and specimen conditions. A recent method requires just one test for identification of most of the model constants. It reduces the time needed for testing and provides a relatively fast calibration of the selected parameters through minimization of discrepancies both of experimentally measured displacement fields on the specimen surface and of the numerically computed corresponding quantities. A study of an efficient correlation algorithm and of a reliable minimization gradient-based algorithm is also presented.

1. Introduction

Concrete has a wide application in civil engineering, being used as a typical construction material for modern buildings, structure foundations, arch-gravity dams and soil stabilization systems, to list just a few. Often, engineers need to design or analyze concrete structures, working not only in the linear elastic range but also far beyond that. Such advanced analyses require appropriate constitutive modeling of the material in order to capture its main characteristic and behavior. Constitutive modeling of concrete has attracted a lot of attention in many research fields in the last decades. Researchers have developed a wide variety of models in an attempt to capture and mathematically describe many important features of concrete. Unfortunately, due to the heterogeneous nature of such material, there is no single model capable of mimicking all of its characteristics, therefore great care needs to be taken in the selection of an appropriate material model that has been designed to emulate expected behavior.

Concrete is a composite pressure-sensitive material with a dramatically lower tensile strength than compressive strength. An analysis of a structure that is majorly subjected to tensile loading (which typically leads to the formation and propagation of cracks normal to the axis of maximum principal stress) will probably be done using the simple Rankine criterion [28], which can reasonably well describe such a failure mode. Alternatively, if respectively greater compressive loads are expected, the Drucker–Prager criterion in its original form [7] or enhanced with a cap yield surface [29] would be more suitable choice. For structures both under tension and compression loading criteria which combine these two models might be selected [8,11].

*Corresponding author. Tel.: +48 616652099.
E-mail addresses: tomasz.gajewski@put.poznan.pl (T. Gajewski), tomasz.garbowski@put.poznan.pl (T. Garbowski).

1644-9665/$ - see front matter © 2013 Politechnika Wrocławska. Published by Elsevier Urban & Partner Sp. z o.o. All rights reserved.
http://dx.doi.org/10.1016/j.acme.2013.05.012

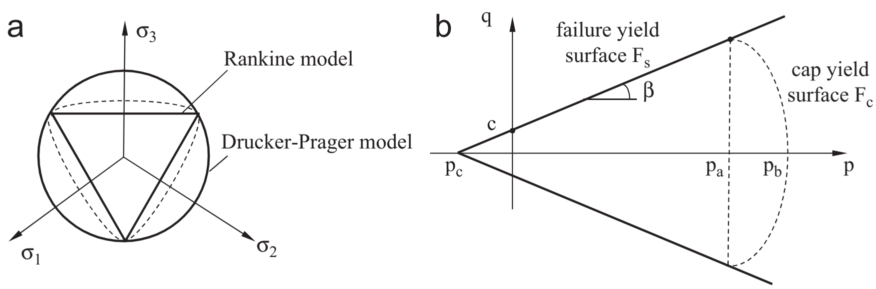

Fig. 1 – Typical yield surfaces of deviatoric sections for: (a) both the Rankine and the Drucker–Prager model and (b) the Drucker–Prager model alone with a cap in the meridian plane.

Typically, experimental results for concrete tend to indicate that the strength envelope (failure surface) within principal stress space is a deformed cone with three planes of symmetry, which all intersect at the hydrostatic axis. The deviatoric sections (octahedral plane projections) take the form of rounded triangles whose shapes vary from almost triangular with tensile and low compressive hydrostatic pressures to almost circular with high compressive hydrostatic pressures (see Fig. 1a). Triangularly shaped deviatoric sections correspond to the Rankine criterion and circularly shaped sections correspond to the Drucker–Prager criterion. Such variations in the deviatoric section's shape can also be described in terms of the so-called meridians, i.e. intersections of the failure surface with the half-planes that begin at the hydrostatic axis (see Fig. 1b). Such variations in the meridians of deviatoric sections usually have exponential, hyperbolic or linear relations, depending on the failure criteria [1,18,26,27].

Additionally the tensile cracking or compressive crushing of concrete usually leads to a degradation in its elastic stiffness, which is not reflected by the standard plasticity models that unload with an initial slope. Stiffness degradation can be handled within the framework of fracture mechanics or damage mechanics (using a proper localization limiter). The so-called smeared crack models [31], popular in engineering applications, can be interpreted as a special type of damage model [4,17]. However, provided that the energy dissipation caused by localized fracture and the existence of a characteristic length are properly taken into account, the cracking of concrete under monotonic loading can also be approximated using a model based exclusively on the theory of plasticity.

A group of constitutive models that suitably describes these complex phenomena is based on a combination of the flow theory of plasticity and damage mechanics. Plasticity models alone [5,6,8,19,23] are unable to capture the stiffness degradation that has been observed in experiments. On the other hand, damage models are unsuitable for describing both the irreversible deformations and inelastic volumetric expansion that occur during compression. Combinations of plasticity models and damage models [14–16,21] usually consider plasticity with isotropic hardening and enrich it with either isotropic or anisotropic damage.

The problem of selecting a proper material model suitable for this specific kind of numerical analysis is complicated further when taking into consideration another aspect, which is how difficult the model is to calibrate. A compromise would be to use a model that reasonably reflects the main features of the material and has a relatively easy calibration procedure. However, the more sophisticated the model is, the more parameters there are to identify and the more complicated the tests are. Using a simpler model, which thus has smaller set of parameters to characterize, one can attempt to design a simple and straightforward experiment, which could possibly be enhanced by new measurement techniques that help to extract more information from the test. A number of modern techniques that enrich the standard tests can be applied, using equipment that is available on today's market (e.g. thermal imaging, vibrations registration, body motion tracking and waveguide sensors). Among these techniques is digital image correlation (DIC), which belongs to a group of visual non-contacting methods that track the deformation or motion of recorded objects [30]. DIC is often used as a measurement tool within an inverse procedure for the characterization of material properties (cf. e.g. [9,10,12]). This primarily is because a certain amount of information taken from such measurements helps, not only to regularize the inverse problem but also to extend the number of possible to identify parameters from a single test.

2. Experimental setup

The proposed procedure is based on a simple compression uniaxial test of a normalized cubic concrete specimen. The compression test is performed under standard conditions, e. g. with the specimen compressed on top of a rigid base the quasi-static loading velocity ranging from 0.2 to 1.0 MPa/s, and the strain rate not exceeding 10^{-6} 1/s.

The experiment is carried out on an Instron 8500 (http://www.instron.tm.fr) four-column frame servohydraulic fati gue testing machine with compressive force capacities of up to 1000 kN (see Fig. 2a). These electronically controlled and versatile systems can perform static, fatigue and dynamic tests on various materials.

From the experimental data (i.e. experimental curve) resulting from a standard displacement-controlled test, one can determine the elastic modulus E, the compressive strength σ_c, possibly the crushing energy G and the stiffness degradation d so long as cycling loading is applied (see Fig. 3). However, our goal is to determine more parameters (without involving other experiments). Therefore the standard compression test must be improved through additional experimental techniques. Here, non-contacting full-field measurements of displacements on