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Identification of material properties using indentation test and shape manifold learning approach

L. Meng[a,*], P. Breitkopf[a], B. Raghavan[b], G. Mauvoisin[c], O. Bartier[c], X. Hernot[c]

[a] *Sorbonne Universités, Université de Technologie de Compiègne, CNRS, Laboratoire Roberval, UMR 7337, Centre de Recherches de Royallieu, CS 60319, 60200 Compiègne Cedex, France*
[b] *Laboratoire de Génie Civil et Génie Mécanique EA 3913, INSA de Rennes, 20 Avenue des Buttes de Coesmes, 35708 Rennes Cedex, France*
[c] *Laboratoire de Génie Civil et Génie Mécanique EA 3913, Université de Rennes 1, 9 rue Jean Macé, 35000 Rennes, France*

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Highlights

- We construct a lower-dimensional space in which a smooth manifold is approximated.
- We develop a family of algorithms to identify material properties in the shape space.
- Our protocol is verified by a real indentation test starting from different initial points.

Abstract

The conventional approach for the identification of the work hardening properties of a material by an indentation test usually relies on the force–displacement curve. However, finite element modeling of the indenter–specimen system is a complex task, and the unicity of the solution to the inverse problem of identifying material parameters using the force–displacement curve is not always guaranteed. Also, the precise measurement of the displacement of the indenter tip requires the determination of the indenter frame compliance and indenter tip deformation. To alleviate these problems, we propose in this work an approach based solely on the 3D indentation imprint shape measured after indenter withdrawal, rather than relying on the minimization of the pointwise discrepancy between the experimental and simulated indentation curve. We first build a mathematical "shape space" of indentation shapes in which a lower-dimensional manifold of imprints admissible according to a postulated material constitutive law is approximated. Then, we solve the inverse problem by using a series of predictor–corrector algorithms minimizing the distance between the estimated solution and the experimental imprint in this shape space. We finally apply the proposed approach to indentation tests using a spherical tip indenter on two different materials: a C100 steel specimen and a specimen of the AU4G (AA2017) aluminum alloy.

Keywords: Identification; Shape manifold learning; Indentation test; Reduced order modeling

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[*] Corresponding author.
E-mail address: liang.meng@utc.fr (L. Meng).

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1. Introduction

The identification of material work hardening properties by an indentation test [1,2] is considered as non-destructive, especially when compared to the tensile test. With the help of indentation tests carried out on different scales, a wide range of materials can be characterized: metals, alloys, ceramics, concrete [3] or even graded materials [4–8] and the test can also be applied to an actual structure without the need for cutting-out a specimen for tensile testing.

Indentation-based assessment of material properties usually relies on the recorded force–displacement curve (P–h curve) [9–12] obtained in two main phases. In the loading phase, a hard indenter is pressed against the specimen surface. The applied load is increased while the indenter penetrates into the specimen. This phase lasts until the force (or penetration depth) reaches an *a priori* defined value and is followed by removing the indenter from the specimen (unloading phase). The force exerted on the indenter is recorded against the penetration depth over a series of time instants. This P–h curve (Fig. 1) is then the primary information used for the identification of material properties. A conventional deterministic identification approach is then applied to minimize the pointwise discrepancy between the simulated and measured P–h curves

$$J_h(\mathbf{c}) = \sum_{i=1}^{N_1} \left(\frac{h_i^s(\mathbf{c}) - h_i^e}{h_{max}^e} \right)^2, \tag{1}$$

where $\mathbf{c}$ is the vector of material parameters to be identified; h_i is the instantaneous penetration depth of indenter at time instant $i = 1, 2, 3, \ldots, N_1$; the superscript 's' refers to 'simulated' by the Finite Element Method (FEM), while the superscript 'e' denotes 'experimental'. Mathematical programming procedures are then used to identify the material properties $\mathbf{c}$ by solving

$$\mathbf{c}^* = \text{Argmin}\Big(J_h(\mathbf{c}) \Big). \tag{2}$$

However, nearly identical P–h curves [13,14] can often be obtained for different materials and this makes the solution to the inverse problem non-unique. Another approach consists in taking into account the residual deformation of the specimen's surface at the conclusion of the indentation test, as additional information to complement the P–h curve [15,16] since different materials generally exhibit diverse plastic piling-up (Fig. 2) or elastic sink-in effects. A review of existing literature reveals extensive research on combining the traditional indentation test with the mapping of residual deformation (indentation imprint) in order to provide more reliable information for the identification of material properties [4,17–22]. An atomic force microscope was adopted by [4] to measure the maximum piling-up observed at the end of the test and eventually obtain a well-defined inverse problem for the Al2024 alloy. Imprint mapping was also employed for the identification of bi-dimensional states of stress [22]. This method was later applied to the identification of graded material properties of thin layers on a substrate in [21]. In the inverse problem of property identification using the imprint shape, the cost function J_h in Eq. (1) is replaced by

$$J_u(\mathbf{c}) = \sum_{j=1}^{N_2} \left(\frac{u_j^s(\mathbf{c}) - u_j^e}{u_{max}^e} \right)^2, \tag{3}$$

where u_j denotes the vertical coordinate of a measured point j with the initial surface of specimen serving as the reference plane; N_2 is the number of sample points chosen from the specimen surface, and this value depends both on the resolution of the imprint scanning instrument and the density of the FE mesh used.

The traditional approach for determination of plastic mechanical properties requires that the indentation load/Penetration depth (P–h) response be obtained with sufficient accuracy and precision [23–25]. Two factors that can greatly affect this are the indentation frame/machine compliance and the deformation of the indenter tip. As a result, the behavior of indenter has also been investigated. The indenters were mainly simulated as perfectly rigid bodies to eliminate the nonlinear deformation during the indentation test [26,27], while [28] corrected a possible elastic deformation of the indenter by a system reduced modulus computed from Young's modulus and Poisson's ratio of both the indenter and the specimen. Machine compliance can easily be influenced by tilting or deforming the specimen [24]. The determination of the imprint area, which must be known for the estimation of the machine compliance, is not easy, especially in nanometer scale [25,29]. Various methods used for the determination of machine compliance can lead