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Quantitative assessment of resilience for earthen structures using coupled plasticity-damage model

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ABSTRACT

In this work, structural resiliency is revisited as a composite term which consists of three interrelated capacities. A computational platform for quantitatively assessing the disaster-resilience of earthen structures is introduced with the use of a coupled plasticity-damage constitutive model. This numerical framework addresses the collapse resistance, damage sequences, strength residual state as well as resilience metrics. In particular, the plasticity model is furnished with combined isotropic-kinematic hardening internal variables accounting for the adaptive capacity of structural resilience. To simulate the transformative capacity at structural level, the model adopts the enhanced strain finite element method capturing the propagating fracture through the structural elements. Localized failure is detected by a bifurcation analysis. A cohesive based failure criterion is also incorporated to accurately represent the constitutive softening response in the case of progressive failure. Finally, we analyzed the factors that shape the structural resilience of earthen wall in the face of lateral loading. The performance of the structural system is examined for two conditions, namely fully intact structure and pre-damaged state.

1. Introduction

Earth-based materials have been used for millennia in construction. Some earthen structures built centuries ago are still performing satisfactorily. For instance, The Great Wall of China was built nearly 2000 years ago using local materials: rammed earth, stones, baked bricks and wood. As far as strength is concerned, it is well known that natural soil, with no reinforcement or stabilizer, may not be suited for the construction of very tall structures. Nevertheless, it has been vastly used for load-bearing structures with 1–3 stories high in Australia, Brazil, Europe, USA, India, China and many other countries Foster et al. [22], Silva et al. [50], Reddy and Kumar [41], and Zami and Lee [64]. Traditional rammed earth houses in France is a good example which were built more than 100 years ago and are still in good condition today Bui et al. [12]. Over the last decade, earth has been garnering increased attention as a revival structural material for a modern construction technique. Compared to conventional mineral building materials, earth possesses particularly positive ecological qualities such as having low carbon content, low embodied energy, highly efficient hygric-thermal behavior and inherent recyclability Schroeder [49]. Not only are these aspects driving the resurgence of the earthen buildings, but the fact that in locations with relatively cheap labor and high material costs, these structures are the most cost-effective option.

However, earthen buildings are particularly vulnerable to lateral loading induced by natural hazards such as floods and earthquakes Silva et al. [50]. The presence of cracks is a type of damage often present in these constructions, which has particular influence on the structural performance. Cracks constitute preferential paths for rainfall infiltration, directly moistening the internal structural elements, substantially reducing its mechanical properties. The presence of structural cracks in earthen walls decreases their bearing capacity and stiffness, and disrupts the overall monolithic behavior of the structure (see Fig. 1) Foster et al. [22] and Tennant et al. [56].

Numerical simulation of earthen structures, especially in the platform of the finite element (FE) method, has attracted much research interest with the advent of modern computational resources. One crucial part of an FE simulation is the selection of an appropriate constitutive material model, since earth-based materials can exhibit many complex and interacting behaviors Qi et al. [40], Tonge and Ramesh [58], Motamedi and Foster [35], Lou et al. [31], Wong and Baud [61], Xie and Shao [63,62]. At low confining pressure, localized deformation in the form of shear and/or dilation bands or fractures may occur due to the growth and coalescence of micro-cracks and pores. At high confining pressure, on the contrary, delocalized irreversible deformation may occur in the form of shear-enhanced compaction. The latter response, generally accompanied by material hardening, is the result of pore collapse, grain crushing, internal locking and other microphysical mechanisms.

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Fig. 1. Damages, in form of cracks, observed in earthen buildings due to hazard-related lateral loading.

The remainder of this paper is organized as follows: Section 2 reviews the idea of resiliency and its growing application as a metric to evaluate the performance of structural systems. Section 3 briefly demonstrates a recently modified cap plasticity model for analyzing geomaterials behavior. In Section 4 first, the kinematics of a strong discontinuity are outlined. Second, to capture the initiation of the crack and its orientation, bifurcation theory is introduced. Section 5 summarizes a mixed-mode cohesive fracture model which is suitable to represent damage evolution and softening behavior of monolithic earthen structure. In Section 6, the finite element approximation using assumed enhanced strain (AES) method is briefly discussed.

Finally in Section 7, the structural performance of an earthen wall for two case scenarios, namely being structurally intact or having some level of initial damages, when is subjected to lateral load has been examined. In addition to the metric available in the literature (including maximum capacity differentiation and residual strength ratio), the proposed multi-stage structural resiliency measure has been utilized to describe the full-range nonlinear response of the structure.

2. Resilience: from conceptual frameworks to quantitative assessment

The concept of resilience has recently been widely promoted in many fields such as urbanization, social protection, ecosystems analysis as well as structural engineering. Resilience harbors different meanings in different contexts. Some authors trace back the first ‘scientific’ application to the concept of modulus of resilience adopted in the context of 19th century warship design. This idea became progressively apparent in the 1970s, where resilience was then formally defined as “the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading to have this energy recovered.” Callister and Rethwisch [13]. However, in the last decade, a more elaborate conceptualization emerged where resilience is no longer simply about resistance to change and conservation of existing structures, but instead viewed as a characteristic that includes also two other dimensions: (1) the adaptive capacity of the system components, that is leading to incremental adjustments/changes in response to increasing external impact to continue operating and (2) transformative capacity leading to transformational responses. The latter response can be regarded as a process which results from insufficient adaptive resilience. These responses are said to be transformative because they aim at altering fundamentally the systems performance such that it makes the initial system untenable. These three different types of responses can be linked (at least conceptually) to different intensities of external load or impact, as shown in Fig. 2a.

The transition from conceptual frameworks to quantitative assessment of structural resilience remains controversial due to its integrative nature. In this work, structural resiliency associated with damages induced by severe loadings is revisited as a composite term which consists of three interrelated capacities (absorptive, adaptive and transformative.) Therefore, a computational platform for quantitatively assessing the disaster-resilience of earthen structures has been developed using a coupled plasticity-damage constitutive model.

3. Three-invariant cap plasticity model

In this section, the formulation and numerical implementation of a nonassociated, three-invariant cap plasticity model are briefly described. The model comprises of a pressure-dependent shear yield surface, hardening compaction cap and newly added elliptical tension cap accounting for the tensile yielding as shown in Fig. 3. This modified model allows us to better replicate complex mechanical behaviors of earthen materials under various loading conditions. For more details and motivation of the model, the reader is referred to Motamedi and Foster [35] and the references therein.

3.1. Non-associated plastic flow rule

The generalized Hooke’s law for linear isotropic elasticity can be written as:

$$\dot{\boldsymbol{\sigma}} = \boldsymbol{C}^e : \dot{\epsilon}\,; \quad \boldsymbol{C}^e = \lambda \mathbf{1} \otimes \mathbf{1} + 2\mu \boldsymbol{I} \tag{3.1}$$

where $\mathbf{1}$ is the second order identity tensor, $\boldsymbol{I}$ is the fourth-order symmetric identity tensor, λ and μ are the Lamé parameters and $\boldsymbol{C}^e$ is the fourth-order isotropic elasticity tensor. The hypothesis of small deformations and rotations allows an additive decomposition of the total strain rate $\dot{\epsilon}$ into the elastic and plastic parts:

$$\dot{\epsilon} = \dot{\epsilon}^e + \dot{\epsilon}^p \tag{3.2}$$

For geomaterials, nonassociated plasticity is usually needed to realistically describe volumetric deformation Borja [8] and Collins [16]. As pointed out by McDowell [33], non-associativity in geological materials is attributed to the procedure of structural rearrangement. This physical phenomenon has been observed in conjunction with growth of microcracks, propagation of shear bands, and frictional shear resistance of geological materials. Moreover, Borja [6] demonstrates that non-associative flow rule enhances liquefaction instability in fluid-saturated granular soils. This imperative feature also allows for bifurcation (onset of strain localization) in the material from a computational standpoint Motamedi et al. [34] and Regueiro and Foster [43]. Hence, a non-associative flow rule is introduced for plastic flow as below

$$\dot{\epsilon}^p = \dot{\gamma} \frac{\partial g(\boldsymbol{\sigma}, \boldsymbol{q})}{\partial \boldsymbol{\sigma}} \tag{3.3}$$

where g stands for a plastic potential function and $\boldsymbol{q}$ represents the stress-like plastic internal variables characterizing the hardening response of the material. $\dot{\gamma}$ is a plastic consistency parameter satisfying the Kuhn-Tucker complementary conditions Borja [8]. In addition, the continuum elasto-plastic tangent $\boldsymbol{C}^{ep}$ can be derived as the following

$$\dot{\boldsymbol{\sigma}} = \boldsymbol{C}^{ep} : \dot{\epsilon}\,; \quad \boldsymbol{C}^{ep} = \left(\boldsymbol{C}^e - \frac{1}{\chi} \boldsymbol{C}^e : \frac{\partial g}{\partial \boldsymbol{\sigma}} \otimes \frac{\partial f}{\partial \boldsymbol{\sigma}} : \boldsymbol{C}^e \right) \tag{3.4}$$

in which

$$\chi = \frac{\partial f}{\partial \boldsymbol{\sigma}} : \boldsymbol{C}^e : \frac{\partial g}{\partial \boldsymbol{\sigma}} - \frac{\partial f}{\partial \boldsymbol{\alpha}} : \boldsymbol{h}^{\alpha} - \frac{\partial f}{\partial \kappa} h^{\kappa} \tag{3.5}$$