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A hierarchical elasto-plastic constitutive model for rammed earth

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HIGHLIGHTS

- A hierarchical constitutive model based on elasto-plasticity is developed and presented.
- A level is chosen given the quantity of information for model parameter identification.
- The first level is able to capture some basic features of rammed earth behaviour.
- The second level is able to quantitatively retrieve the non-linear behavior of rammed earth.

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ABSTRACT

A hierarchical constitutive model based on the framework of elasto-plasticity is developed to model the mechanical behavior of rammed earth which is a quasi-brittle material. This model holds two mechanisms of plastic deformation, one related to shear failure and another one to a tensile mode of failure. Different hierarchies for the model, which are merely levels of complexity, are proposed according to the amount of information available to identify the model parameters. The model was validated simulating a diagonal compression test and a pushover test on a wallette. The simple elasto-plastic model (level-1) was able to capture some basic features of the rammed earth behaviour essentially for a rather small range of deformations, it can be used for a first estimate of the loading capacity of a system. The more sophisticated model (level-2) was able to quantitatively retrieve the non-linear behavior of rammed earth over a larger range of deformations.

1. Introduction

Rammed earth structures are obtained by successively compacting layers of moist earth within formworks. The definitive mechanical strength of these structures is obtained after some weeks of drying when the capillary tensions within the pore networks provides a strong bonding effect between the different particles constituting the material. Sometimes, rammed earth is mixed with cementitious materials to obtain impermeable and more durable walls. This construction method is currently becoming more popular because it meets the requirement of sustainable development such as a low embodied energy for the production and the processing of the materials which are locally extracted. Recent studies also showed that the material contributes to the inner comfort of rammed earth houses [24]. In the past, rammed earth was used in areas where stones were not available, for example in large sedimentary basins or large valleys. At present, it is not only used for building walls, but also for roofs, foundation, and garden ornaments [32]. In France, there is no regulation yet that rules the design, construction, and also the preservation of rammed earth structures which tend to slow down the development of this constructive technique. This building technique has not benefited from a century of studies, researches and feedback like more conventional technique including reinforced concrete.

Nevertheless, there exists a certain amount of scientific works devoted on the basic mechanical of rammed earth including compression, tensile, and other deviatoric stress paths even if not comprehensive. First, on the basis of compression tests, Champiré et al. [11] found that humidity strongly influences the mechanical behaviour of rammed earth. In addition, a decrease of the elastic moduli were observed when unloading is performed from different compression stress levels. Unloadings also evidenced the existence of irreversibilities in the material which rate of creation are different from a given earth to another one. By using compression tests with different layers orientations with respect to the loading compression, Bui and Morel [6] found that rammed earth can be considered as a quasi isotropic material if the layers are adherent one to each

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other. This finding confirmed another study by Bui et al. [8] in which they found that the tensile strength in earthen layers and interface are very similar.

Bui et al. [8] performed non homogenous tests, namely Brazilian tests to study the tensile behaviour of rammed earth. They found that the tensile strength of rammed earth can be taken equal to 10% of the corresponding compression strength which is similar to the relationship derived for concrete. More recently, Araki et al. [2] carried out homogenous uniaxial tensile tests and also Brazilian tests on both unstabilised and stabilised earth. The homogenous uniaxial tensile tests showed a pattern typical of quasi-brittle material like concrete with a quasi linear behaviour for the stress-strain curve until a peak, followed by a very sharp softening. They revealed that the tensile strength can vary between 5% to 12.5% of the corresponding compression strength for unstabilised rammed earth and between 15% until 20% of the corresponding compression strength for stabilised one. These extended range of values comes from the natural heterogeneity of the material.

Finally, geotechnical shear tests such as the triaxial test and the shear box test can be used to estimate the shear strength of rammed earth. Jaquin et al. [20] used triaxial tests to study the source of shear strength in rammed earth and focused on the contribution of the matrix suction. They found that shear strength will increase as suction increases. Similar results were also obtained by Bui et al. [7]. The shear strength of the material can also be measured at a scale larger than the Representative Volumetric Element by means of a diagonal compression test [30,29,23], though it corresponds to a non homogenous test.

To conclude, even if few different homogenous tests are available including unconfined compression tests and confined tests, there is not a comprehensive set of tests for a same material questioning different homogenous stress paths (compression and extension paths with different confining pressures).

To model the mechanical behavior of earth, it is not clear whether the available constitutive models for concrete which is like earth (when the water content is as low as 2%) a quasi brittle material can be directly used for rammed earth without any modification. Some authors used simple elasto-plastic models to model the mechanical behavior of rammed earth systems, for example Jaquin [19] or Bui et al. [9] which cannot model the degradation of elastic stiffness observed when unloading. Other authors used models designed within the framework of damage elasticity [8,23] which cannot model the existence of permanent deformations in the material.

Phenomena observed throughout experiments incite the use of an elasto-plastic model with damage elasticity. However, this complexity implies the involvement of a numerous set of model parameters that may be hard to identify in the absence of experimental data. In this context, a constitutive model denoted CJS-RE is specifically developed for rammed earth. It is inspired from CJS model which is a hierarchical constitutive model based on the elasto-plasticity theory that was originally designed by Cambou, Jafari, and Sidoroff [10] for granular materials. Different works have improved or extended the usage of this model for complex loadings such as cyclic one-way or two-ways cyclic loadings [16,27,21,4,14]. The interesting idea of this model lies in the hierarchical approach where the appropriated level (of complexity) of the model can be selected according to the information (generally experimental tests) available to identify the model parameters [28] and to the complexity of phenomena to model. This hierarchical framework was also used by Marzec and Tejchman [22] to model the mechanical behaviour of concrete samples in the context of cyclic laboratory tests. Herein, two first levels are given in the framework of elasto-plasticity. This constitutive law can be used for the prediction of the behaviour of rammed earth under monotonous loading. A third level which would involve an elasto-plastic model with damage elasticity is out of the scope of this work.

First, some reference experimental tests on rammed earth that were used in this study are exposed. After introducing the two levels of the proposed elasto-plastic model, the process for the identification of the model parameters is given. Finally, the constitutive model CJS-RE is validated by simulating a diagonal compression test and a push-over test which are two different boundary value problems.

2. Reference experiments for the simulations

2.1. Diagonal compression test

Experiments are generally required for the modeller to have a better insight onto the mechanical behaviour of a material and onto the variety of phenomena that must be modeled. As important is the necessity of a certain set of experimental data which are required for the identification of the model parameters and the validation of the constitutive model. Herein, the study is based from a set of experiments performed by Silva et al. [29] on unstabilised rammed earth (MAT-1) sourced from Alentejo in Portugal (Fig. 1). The dry density of the material used was around 2100 kg/m^3. Fig. 1a depicts shear stress-shear strain curves obtained on different wallettes throughout diagonal compression tests. Fig. 1b gives the typical crack patterns after the test where a vertical crack crosses the whole system and other cracks can also be observed at the edges of the specimen. Eleven wallettes with $550 \times 550 \times 200\ \text{mm}^3$ size were loaded under a displacement control with a rate of 2 μm/s. In Fig. 1a, the global behaviour shows a first peak reached at the average level of 0.13 MPa and small deformations followed by a small re-increase of the resistance. One can note that repeatability is not easy to achieve due to the inherent heterogeneity of the system composed of different compacted layers.

2.2. Pushover test

The second reference experiment consists of pushover test performed on wallette [15]. Rammed earth materials were sourced from the demolition of an old farmhouse located in Dagneux (Auvergne-Rhône-Alpes region, France). A wallette measuring $1500 \times 1500 \times 250\ \text{mm}^3$ (wallette-3) was pushed laterally until failure while a vertical pressure on the wallette equal to 0.3 MPa was used to represent the typical pressure of a two storeys house. The obtained load-displacement curves are depicted in Fig. 2a. In Fig. 2a, the wallette exhibit nonlinear responses until the horizontal resistance of 40 kN at displacement of 9 mm before it reaches yield plateau. Fig. 2b shows cracks pattern where horizontal cracks at the interfaces were found at the bottom left of the wallette and a quasi diagonal cracks at the center part of the wallette.

3. Constitutive equations for CJS-RE

3.1. CJS-RE1: a level-1 model

The first level of the model holds the basic features of an elasto-plastic model such as Mohr-Coulomb model, adapted to take into account the specificities of quasi brittle materials. The advantage of CJS-RE1, unlike Mohr-Coulomb model, lies in the shape of the shear failure surface which is continuously differentiable. Plasticity is generated whenever the current state of stress reaches the shear failure surface which also acts as a yield surface.

There exists two kinds of failures for quasi brittle materials including a failure due to excessive shearing and a failure due to