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Research Paper

Application of a coupled homogenization-damage model to masonry tunnel vaults

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ABSTRACT

This paper presents an approach developed to study the behavior of the masonry vaulted tunnels in order to evaluate the serviceability state and failure load. An appropriate homogenization technique is used to simulate the global anisotropic behavior across the vault. The model takes into account isotropic damage in each component of the masonry and the variations of the directions of anisotropy in case of a vault. A set of comparisons with experimental tests allowed the validation of the proposed approach. Failure loads and deformation states are correctly assessed. The present model was programmed in the finite element code CESAR-LCPC.

1. Introduction

Masonry vaults are very common in numerous historical buildings, bridges and tunnels. The use of masonry for new constructions declined considerably since the second half of the 20th century, but these structures still exist and their maintenance necessitates the study of their behavior. In particular, the objective of this paper is to develop a model to study the behavior of the masonry vaulted tunnels of the Paris metro, whose infrastructure is mostly underground and was built predominantly in the early 20th century. Such structures can withstand displacements in the order of few centimeters without reaching failure, and this is not properly accounted for by numerical models (notably elastoplastic models).

Masonry is a heterogeneous material made of elementary blocks (bricks or stone blocks) and mortar joints. Its behavior has been studied in numerous scientific publications (see for instance the survey provided by [3]). Before the 20th century, the calculation methods developed for masonry vaults were focused on the evaluation of their bearing capacity [5], on the basis of graphic analysis of the static equilibrium of the structure. More recently, masonry vaults have been analyzed by means of limit analysis [14,15,23] and of the yield design theory [38,10]. However, such stability analyses do not allow to compute the deformation of the structure when the applied load brings it close to failure.

The development of modern displacement computation approaches and numerical methods permits to evaluate the deformation of any structure under complex conditions, in all stages of an incremental loading. Among the different numerical techniques to model masonry structures [37], the finite element method is frequently used. It is especially adapted to discuss the interaction between the masonry vault of a tunnel and the surrounding ground, which generally exhibits a complex behavior that can be conveniently taken into account in the framework of the finite element method. Three modeling strategies can be distinguished for masonry structures [24]:

(1) detailed micro-modeling: each component of the masonry, i.e. blocks, joints and interfaces are modeled separately, with a constitutive law for each component;
(2) simplified micro-modeling, where the blocks are geometrically expanded to account for mortar, while the mortar behavior is reflected in the interface constitutive law;

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(3) macro-modeling, in which all components of the masonry are represented as a continuous homogeneous medium and "equivalent" to the masonry.

Given the computational effort required and the large number of necessary experimental data, the first two approaches are reserved for small masonry structures and for situations in which the local heterogeneities of the stress field are investigated. The macro-modeling is suitable for large structures. Several examples of these three approaches can be found in [3,37].

The objective in our study is to develop a model for masonry vaults. To this end, a macro-modeling approach was adopted using a homogenization technique proposed by [45] to transform the masonry into an equivalent continuum medium. Then, an isotropic damage model is used to represent the nonlinear behavior of the masonry components, which describes the degradation of the material as a stiffness reduction before the macroscopic failure [33]. Variations of the directions of the block-mortar bond in the vault are also taken into account.

Damage models have been used by several authors to study masonry structures under various loading conditions: walls under seismic loads [7,28,34,41,43]; walls under a point shear load [1,2,6,42,46]; walls under in-plane vertical or horizontal loads [13,27,29,36,40,44,45,48]; vaults under different loads [8,35,39]; and bridges [11,12]; among others. Most of the studies on masonry using damage models consider a wall subjected to in-plane loads or earthquake motions; the case of vaults (bridge or buried arches) is not commonly discussed. Old masonry tunnels are even more rarely studied: the analysis of buried masonry vaults is the focus of our study.

The model for masonry vaults was programmed in the finite element code CESAR-LCPC [17] a software package dedicated to civil engineering and geotechnical engineering applications, developed since the 1980s by the French Institute of science and technology for transport, development and networks (IFSTTAR).

In this paper we present the numerical implementation of a homogenized masonry model, followed by a set of comparisons with experimental tests which validates of the proposed approach.

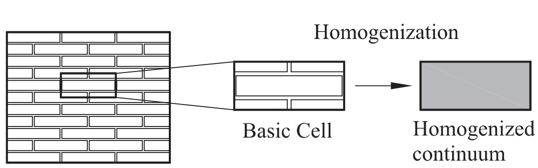

Fig. 1. Basic cell of a masonry wall [47].

2. Homogenization-damage model for masonry

2.1. Masonry homogenization

The process of homogenization consists in replacing a heterogeneous medium by an equivalent homogeneous one. In the case of masonry, the very regular geometrical pattern of bricks or blocks and mortar joints makes it possible to assume that the heterogeneous masonry material is comparable to a composite one with a periodic microstructure. Such a medium is defined by a "basic cell" whose graphic repetition represents the whole structure (Fig. 1).

The geometry of the basic cell and the behavior of its components, i.e. blocks and joints, are used to derive the constitutive law of the homogenized continuum. This procedure is referred as a micro-mechanical model for the homogenization of masonry by [47], and gives the homogenized macroscopic stiffness matrix H that connects the macroscopic stresses Σ^0 to the macroscopic strains E^0 in the basic cell. This matrix is then used to compute forces and displacements in the structure.

A state of the art on the homogenization techniques for masonry can be found in [25]. Homogenization can be carried out by numerical or analytical means. In this paper a simplified analytical approach was used.

2.2. Nonlinear homogenization

Among the homogenization techniques, the analytical engineering approach proposed by [47] for the masonry was chosen. This technique aims to replace the complex behavior of the basic cell with a simplified one. Initially developed for the elastic range, the approach was extended to the nonlinear range in [45,48,46] for various loading situations. This technique will be referred as the model of Zucchini and Lourenço in the following.

The approach is based on the superposition principle. The elastic response to the basic cell subjected to a uniform macroscopic stress state is determined by studying separately six basic loading conditions: three cases of normal loading and three cases of pure shear loading, along the axes of the local coordinate system (LCS) (Fig. 2a). For each load case, the value of one component of the macroscopic stress tensor is imposed to the basic cell, the other components being zero.

Because of symmetry conditions, only one quarter of the basic cell is studied. It is divided into four components: in one hand the blocks, and in the other hand, the mortar joints, with the horizontal, vertical and cross joints (Fig. 2b).

By introducing the equilibrium between micro and macro forces in the basic cell boundaries and interfaces, the compatibility of the deformation of the components and using Hooke's law, together with other simplifying assumptions, a system of equa-

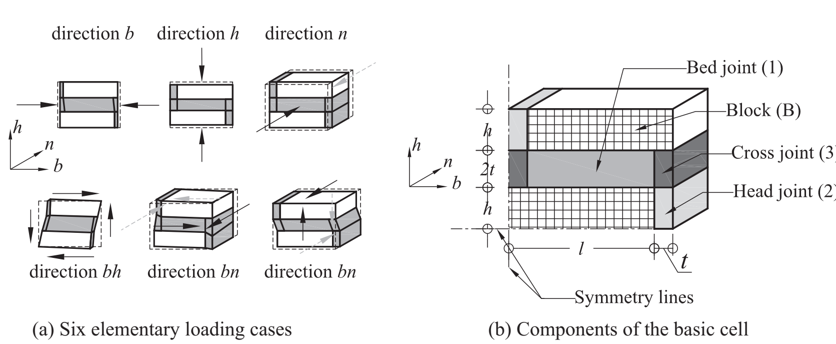

Fig. 2. Quarter basic cell in the masonry of the model of Zucchini and Lourenço [47].