FINITE ELEMENT MICRO-MODELING OF EARTH BLOCK MASONRY SYSTEMS

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Abstract

Earth block masonry (EBM) is attracting interest as an affordable and sustainable alternative to other mainstream materials and systems for low-rise buildings. However, most of the research available in the literature focuses on characterizing the mechanical properties of earth blocks, whereas only a few studies investigate the structural behavior of EBM systems. In addition, existing numerical studies of the mechanical behavior of EBM mostly use finite element (FE) simplified micro-model (SMM), which were originally developed for fired-clay and cinder-block masonry. SMMs are based on the hypothesis that the masonry inelastic behavior and cracking are concentrated along the masonry joints, whereas the blocks are assumed elastic. This hypothesis is satisfied when the blocks are stronger than the mortar. However, EBM typically exhibits significant cracking through earth blocks, whose compressive and tensile strength is often similar to those of the mortar. This study shows that SMMs cannot accurately simulate the mechanical response of EBM. Therefore, a new FE detailed micro-model (DMM) is developed to model EBM systems. This model is preliminarily validated through a comparison of the FE response and experimental results for EBM wallettes subject to diagonal compression forces. The FE results show that the DMM can accurately simulate the mechanical behavior of EBM systems.

Introduction

Earth block masonry (EBM) is attracting interest as an affordable and sustainable alternative to other mainstream materials and systems (e.g., reinforced concrete, fired masonry, concrete masonry, and wood construction) for low-rise buildings because of their low cost, low carbon footprint, use of indigenous materials, and inherent simplicity [1,2]. However, most of the engineering research available in the literature focuses on understanding the mechanical characteristics of earth blocks, and only a few studies investigate the structural behavior of EBM systems [3]. Therefore, material-specific design standards for EBM systems are lacking because of the limited understanding of their structural behavior. In fact, earthen building codes around the world (i.e., Standards New Zealand 4297-4298, 2019 International Building Code (Section 2109), and 1993 Indian Standard 13827) depend heavily on established methods for ordinary masonry and reinforced concrete structures when providing guidance on engineering analysis of earthen structures [3]. In addition, numerical studies to simulate the behavior of EBM are limited [4,5], and mostly use finite element (FE) simplified micro-model (SMM) originally developed for ordinary masonry. Over the last three decades, FE SMMs have been commonly employed to investigate the local and global mechanical response of masonry structures [6,7]. In SMMs, the mortar joint and the two adjacent block-mortar interfaces (referred to as masonry joints) are lumped into zero-thickness interfaces (referred to as masonry joint interfaces), which connect expanded masonry blocks (with dimensions equal to those of the earth block and half of the mortar thickness) [4,6,7]. The expanded masonry blocks are augmented with an additional zero-thickness interface (referred to as potential crack interface), which is vertically placed in the middle of the blocks to model the potential crack that is often experimentally observed within the masonry blocks [6]. SMMs are based on the hypothesis that the masonry inelastic behavior and cracking are concentrated along the masonry joints (i.e., within the mortar and along the block-mortar interfaces), whereas the expanded masonry blocks are assumed elastic [6]. However, this assumption is valid only when the geometry of masonry blocks and mortar joints is regular, and the masonry blocks are significantly stronger in compression and shear than the masonry joints. However, specific instances exist in which the compressive and shear strengths of masonry blocks are similar to or smaller than those of the masonry joints, e.g., in EBM, for which significant cracking through the earth blocks has been experimentally observed [8].

This study investigates the limitations of SMMs to simulate the mechanical response of EBM. A detailed micro-model (DMM) is proposed to accurately simulate the behavior of EBM systems, in which both masonry blocks and mortar are modeled by continuum elements, and the block-mortar interfaces are represented by zero-thickness interface elements. DMMs explicitly model the behavior of the individual masonry constituents and address the intrinsic discontinuity and heterogeneity of masonry structures. Generally, DMMs are computationally expensive and, thus, have been rarely employed to simulate the behaviors of masonry systems [7]. This paper describes the benchmark experimental test and the corresponding SMM and DMM. The FE responses of the SMM and DMM are compared with the corresponding experimental response, and then conclusions are presented.

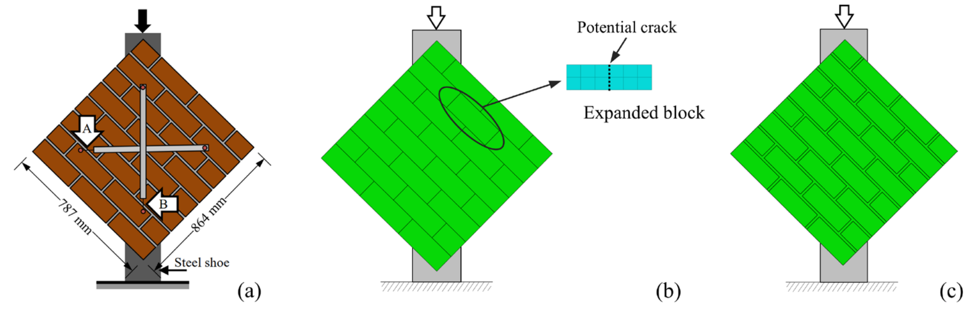

Figure 1. EBM wallette: (a) test setup, (b) SMM discretization, and (c) DMM discretization.

EBM wallettes subjected to diagonal compression

A diagonal compression test performed on three replicate EBM wallettes, as reported in [8], was selected as validation example for this investigation. Each specimen comprised a single-leaf, eight-course wallette with dimensions of 864 mm × 787 mm × 178 mm, as shown in **Figure 1**. The masonry wallettes were tested under diagonal compression force, as illustrated in **Figure 1**(a). The experimental test involved a monotonically increasing vertical displacement applied downward to the steel shoe at the top of the masonry wallettes, while keeping the boundaries of the steel shoe at the bottom of the masonry wallette fixed. The horizontal extension and vertical contraction were recorded using two displacement transducers, which are labeled as “A” and “B”, respectively, in **Figure 1**(a).

Figure 2 shows the experimental crack patterns of the three wallettes at the end of the diagonal compression test. All the specimens exhibited a consistent failure mode, with diagonal cracks parallel to the direction of the load and inclined approximately 45° with respect to the bed joints. The cracks at failure were observed mainly through earth blocks and to a lesser extent along the head and bed joints.

Description of the FE models for the EBM wallette

Figure 1(b) and (c) present a schematic of the SMM and DMM, respectively, which were developed to simulate the response of the EBM wallettes using the FE software ABAQUS 6.14 [9]. All the FE models were constructed using two-dimensional elements under the assumption of plane stress and analyzed using an explicit dynamic FE solver with a time step equal to the critical time step of 10^{-6}s. In the SMM, the masonry joints and potential cracks interface were modeled using COH2D4 elements [9], and the expanded masonry blocks were modeled using CPS4R elements [9]. The mesh used for the SMM of the masonry wallettes comprised 12 interface elements employed for each bed joints (i.e., six interface elements for the bed joint of each half-expanded masonry block), five interface elements for each head joint and for the potential vertical cracks, and 30 elements for each half of the expanded masonry blocks. For the DMM, earth blocks and mortar were modeled using CPS4R elements [9], and the block-mortar interface was discretized using COH2D4 elements [9]. The mesh discretization of the DMM comprised 27 and nine elements employed across the length and thickness of each earth block, respectively, for a total of 243 elements for each block. Three elements were employed across

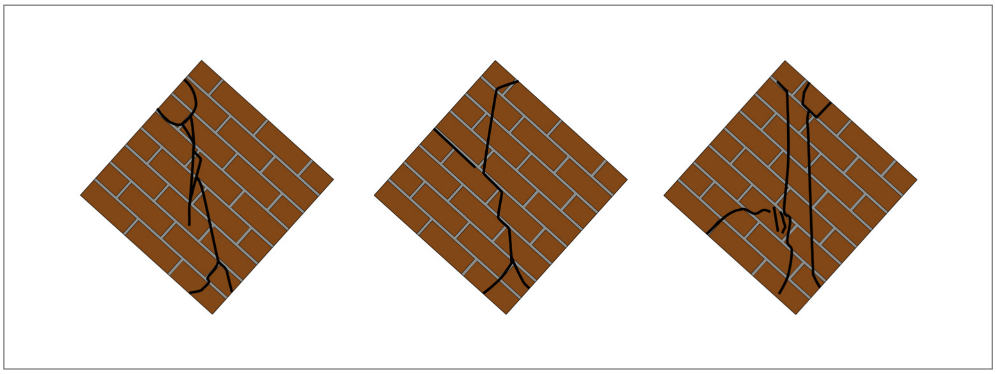

Figure 2. Experimental crack patterns of the EBM wallettes.

the mortar thickness. The size of the elements in the blocks was kept constant except for the regions in the middle of the earth blocks, where the element size was reduced to match the dimension of the elements in the head joints. The block-mortar interfaces were discretized using zero-length elements of the same length as the adjacent continuum elements. The coupled tension-shear interface model presented in [10] was employed for simulating the behavior of the masonry joint and potential crack interface in the SMM, and of the block-mortar interface in the DMM. The concrete damaged plasticity model (which is available in ABAQUS 6.14 [9]) was used for simulating the material constitutive behavior of earth blocks and mortar in the DMM. In addition, the steel shoes were modeled as linear elastic in both the SMM and DMM, with a surface-based tie constraint [9] imposed between the masonry and the steel shoes. The steel shoes were modeled using CPS4R elements [9]. The mesh of the steel shoes was extruded from the masonry wallettes in order to get a continuous mesh. Two elements were used across the thickness of the steel shoes.

All degrees of freedoms at the bottom edge of the bottom steel shoe were fixed in the FE models, and a constant vertical velocity of $V = 0.1$ mm/s (i.e., with zero acceleration) was applied downward to the top edge of the top steel shoe. A density $\rho_b = 1.8\times10^3$ kg/m^3 and a mass-proportional damping corresponding to a damping ratio $\zeta = 5\%$ were used for the solid elements of the wall to model inertia and damping effects, respectively. The material properties of the different components used in the SMM and DMM were obtained from existing experimental results on tension, shear, and compression tests available in [8,11,12].

Comparison of FE and experimental results

Figure 3 compares the FE force-displacement responses obtained using the SMM and DMM with the corresponding experimentally-measured responses of the EBM wallettes subjected to a diagonal compression test. Positive and negative displacements correspond to horizontal extension and vertical contraction, respectively, which were experimentally recorded using the displacement transducers A and B shown in **Figure 1**(a). The SMM significantly overestimates the peak vertical load, which is 68.44% higher compared to the average of the experimentally-measured peak vertical loads of the three EBM wallettes. By contrast, the DMM accurately estimates the peak vertical load, which is only 3.10% lower than the average of the experimentally-measured peak vertical loads of the masonry wallettes. Both FE models under-estimate the initial stiffness (defined as the secant stiffness measured

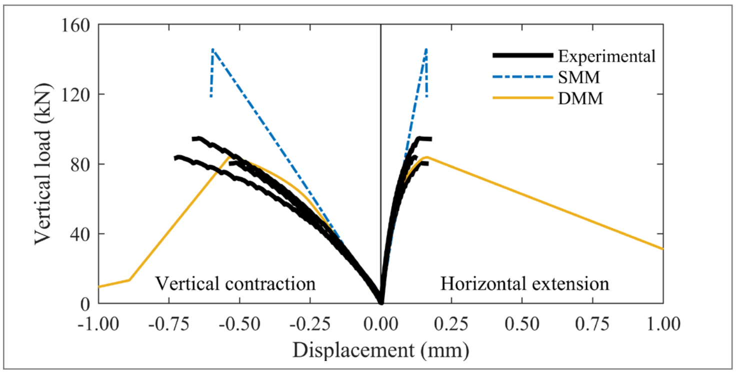

Figure 3. Comparison of the experimental and FE load-displacement responses for EBM wallettes.

at 1/10 of the average experimentally-measured peak vertical load), which is 25.67% to 31.01% lower than the average of the experimentally-measured initial stiffnesses for both horizontal extension and vertical contraction.

The crack patterns and the distribution of the in-plane minimum principal stress observed in correspondence to the displacement at failure for the SMM and DMM of the EBM wallettes are presented in **Figure 4**(a) and (b), respectively. **Figure 4**(c) presents the crack patterns and the in-plane maximum principal plastic strains observed in correspondence to the displacement at failure for the DMM. In order to make the cracks visible, the deformed shapes in **Figure 4** are magnified by a factor 10. The FE crack patterns of the SMM do not match the experimental crack patterns of the EBM wallettes, as shown in **Figure 2**. The cracks observed in the SMM are mostly concentrated at the bottom two masonry bed joints, at the head joints, and at the potential crack interfaces of the bottom two courses of the masonry wallette. In the DMM, a narrow diagonal band of high plastic strain almost parallel to the loading direction is observed. This diagonal band represents the cracks forming across the EBM wallettes and is similar to the experimental crack patterns of the wallettes, as reported in **Figure 2**. Therefore, it is concluded that the DMM accurately matches the experimental crack patterns of the EBM wallettes, whereas the SMM cannot capture their experimental failure mode.

The SMM is unable to simulate the mechanical behavior of these EBM wallettes because they do not satisfy the hypothesis that mortar and block-mortar interfaces are significantly weaker than the masonry blocks. In fact, the assumption that the inelastic behavior is concentrated along the masonry joints and the middle plane of the masonry blocks is not valid for EBM, where the experimental evidence shows cracking patterns that are similarly distributed across joints and masonry blocks. Therefore, a DMM (in which each component of a masonry system is modeled separately from the others through an appropriate nonlinear constitutive model) is needed to simulate the mechanical behavior of EBM walls. In fact, the FE simulation presented in this paper for the EBM wallettes subjected to a diagonal compression test shows that the DMM can accurately simulate the mechanical behavior of EBM systems.

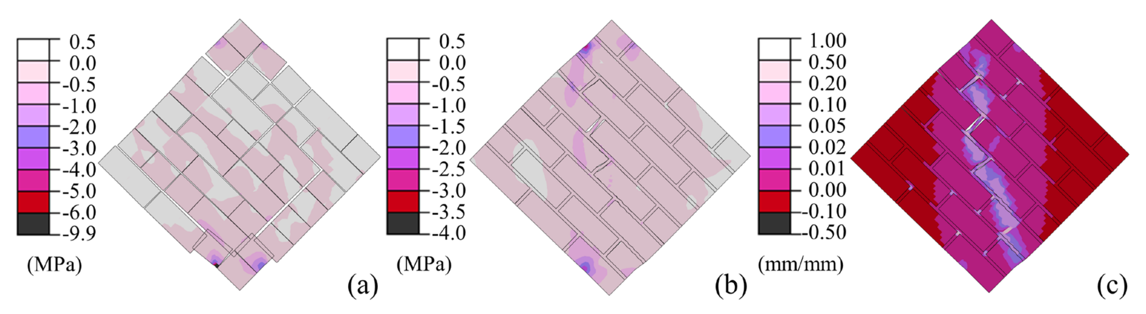

Figure 4. FE responses of EBM wallettes at failure: (a-b) FE crack patterns and distribution of in-plane minimum principal stress for SMM and DMM, respectively; and (c) FE crack patterns and distribution of in-plane maximum principal plastic strain for DMM.

Conclusion

It is concluded that: (1) finite element simplified micro-model is unable to simulate the mechanical behavior of earth block masonry (EBM), which are characterized by earth blocks and mortar joints with similar strength and stiffness properties, and for which cracks are evenly distributed across mortar and blocks; (2) a detailed micro-model is necessary to capture the crack propagation through the earth blocks and the mortar that is typically observed in EBM; and (3) the proposed detailed micro-model can accurately simulate the mechanical behavior of EBM.

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