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Analysis of the shear failure process of masonry by means of a meso-scopic mechanical modeling approach

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Abstract. The masonry is a complex heterogeneous material and its shear deformation and fracture is associated with very complicated progressive failures in masonry structure, and is investigated in this paper using a mesoscopic mechanical modelling, Considering the heterogeneity of masonry material, based on the damage mechanics and elastic-brittle theory, the newly developed Material Failure Process Analysis (MFPA) system was brought out to simulate the cracking process of masonry, which was considered as a three-phase composite of the block phase, the mortar phase and the block-mortar interfaces. The crack propagation processes simulated with this model shows good agreement with those of experimental observations by other researchers. This finding indicates that the shear fracture of masonry observed at the macroscopic level is predominantly caused by tensile damage at the mesoscopic level. Some brittle materials are so weak in tension relative to shear that tensile rather than shear fractures are generated in pure shear loading.

Keywords: meso-scopic damage model; elastic damage mechanics; fracture process; masonry.

1. Introduction

The masonry is a complex heterogeneous material and its shear deformation and fracture is associated with very complicated progressive failures in masonry structure. The researches on the cracking mechanism of the masonry composite were concentrated on the static property analysis based on the assuming model by virtue of some simplified models coming from the finite element method (Chiou *et al.* 1998, 1999, Lotfi and Shing 1991, Lourenco *et al.* 1999, Miha 1996, Milad *et*

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al. 1999, Park *et al.* 1999, Paulo *et al.* 1998, Briccoli Bati *et al.* 1999, Shi 1992, Sutcliffe *et al.* 2001, Wang *et al*. 2003, Wang and Tang 2003). At present, the analysis research on the related masonry failure mode, owing to the complexity of dealing with the failure problem, it is difficult to simulate the whole process from deformation to cracking of the masonry material, and more difficult to draw the laws.

Now researches try to find an approximate method, which can combine the theory experiment and numerical simulation to research the capability of the masonry or concrete structure, a good way to relate the meso-scopic crack propagation to the macroscopic mechanics capability.

The numerical method is regarded as one of the more effective ways to settle that problem. Thereinto, finite element method is one of the most important numerical tools. Finite element method is applicability of different numerical techniques for the analysis of masonry structures, and compared the computed results with the experimental test data obtained on a full-scale masonry specimen (Chiou *et al.* 1999, Miha 1996, Wang *et al.* 2003). As other researchers pointed out, homogenization is one of the most important steps in the numerical analysis of masonry structures where the continuum method is used (Wang and Tang 2003). And equivalent elastic properties, strength envelope, and different failure patterns of masonry material are homogenized by numerically simulating responses of a representative volume element (RVE) under different stress conditions (Massart *et al.* 2004, Agioutantis *et al*. 2002, Cluni and Gusella 2004, Giuseppe *et al.* 2001, Mazars and Pijaudier-Cabot 1987). Pegon *et al.* (2001) showed how 2D and 3D numerical modeling could be used in order to design a representative model of a built cultural heritage structure to test at the laboratory and to characterize its behavior. A 3D model was proposed to study masonry walls subject to in plane and out of plane actions through a rigorous homogenization procedure (Pegon *et al.* 2001). The numerical methods above have a number of advantages over traditional limiting equilibrium approaches for masonry analysis. Most importantly, the critical failure surface can be found automatically. Nevertheless, the currently widely accepted numerical methods do not take into account the heterogeneity of masonry material at mesoscopic level with complicated conditions. However, during fracturing, the heterogeneity plays a marked influence in determining the fracture paths and the resulting fracture patterns of masonry. The influence of heterogeneity is pronounced on the progressive failure process.

The great advantage of numerical tools is its flexibility in simulating all kinds of boundary conditions. In recent years, there has been growing interest in numerically modeling the meso-scale behavior during the fracture process and evaluating the macroscopic response of masonry subjected to external loading. For example, the random particle model presented by Bažant *et al.* (1990), UDEC used by Vonk *et al.* (1991), micromechanical model proposed by Mohamed and Hansen (1999), the lattice model that have used in the Stevin laboratory (Mohamed and Hansen 1999), and discontinuous deformation analysis (DDA) modeling framework of (Pearce 2000, Schangen and Van Mier 1992) are all typical mesoscopic mechanical models that can simulate the fracture process of masonry. In many micromechanical models such as lattice model, and micromechanical model proposed by Mohamed and Hensen (1999), Schangen and Van Mier (1992), Van Mier and Van Vliet (1999), Abrams and Paulson (1991), Guinea *et al.* (2000), Marfia and Sacco (2001), the fracture process is simulated based on the assumption that tensile cracking at the micro level is the only failure criterion associated with the masonry materials. However, the shear fracture really exists at macroscopic level, whether is there shear cracking at the meso-level? Because of the heterogeneity of masonry, the stress distribution in the masonry is actually very complex even if very simple external load is applied. Its micromechanical failure mechanism is certainly related to its stress conditions.

The failure mechanism of masonry at mesoscopic level is certainly related to its stress conditions. Because of the heterogeneity of masonry, the stress distribution in the masonry is actually very complex even if very simple external load is applied. In this paper, an elastic damage-based mesoscopic model that can deal with both tensile damage and shear damage at the meso level is used to reappraise the fracture mechanism of the regular shear test.

The numerical simulation has become the third powerful tool in studying the mechanical behaviors of masonry material. Numerical tools can give an approximate behavior at best.

In this paper a three-phase composite model that the masonry was considered as a three-phase composite of the block phase, the mortar phase and the block-mortar interfaces, is simulated from mecroscropic level conducted in the Northeastern University, China, by using the Material Failure Process Analysis (MFPA^{2D}). This numerical approach to the masonry structure sheds some new light on the understanding of the shear fracture process (Guinea *et al.* 2000, Marfia and Sacco 2001, Zhu and Tang 2002, Wang *et al.* 2002).

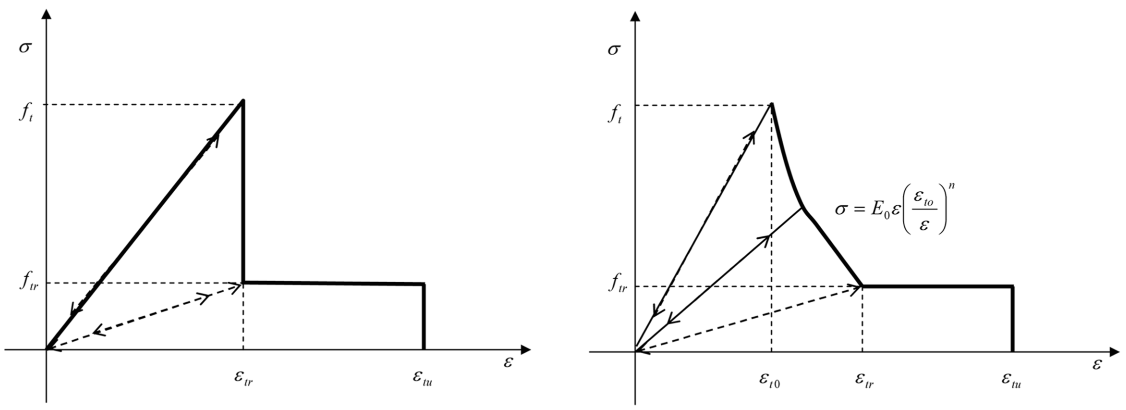
As an alternative approach to the failure process related to masonry structures. Mathematically, MFPA is completely a continuum mechanics method for numerically processing nonlinear and discontinuum mechanics problems in masonry failure. The code has been developed by considering the deformation of a heterogeneous material containing a randomly initial distribution of meso-fractures. As load is applied the fractures will grow, interact, and coalesce, resulting in nonlinear masonry behavior and in the formation of macroscopic fractures. MFPA not only satisfies the global equilibrium, strain consistent and nonlinear constitutive relationship of masonry materials but also takes into account the heterogeneous characteristics of materials at mesoscopic level. In an attempt to model tension failure, a tension cut-off criterion was incorporated. The code has been successfully applied in failure process analysis of brittle material (Wang *et al.* 2003). In the present work, an introduction on mesoscopic mechanical model is proposed to simulate the behavior of masonry. Considering the heterogeneity of masonry material, based on the damage mechanics and elastic-brittle theory, the new developed Material Failure Process Analysis (MFPA^{2D}) system was brought out to simulate the cracking process of masonry, which was considered as a three-phase composite of the block phase, the mortar phase and the block-mortar interfaces.

2. Mesoscopic mechanical model

In order to simulate the shear fracture process of masonry subjected to external loading, the heterogeneity of mesoscopic structures of masonry must be considered and included in the numerical model. Here the failure process simulation is attained when using FEM as the basic stress analysis tools, where the four-node isoparametric element is used as the basic element in the finite element mesh, and the elastic damage constitutive relationship of meso-level elements is incorporated in it. Masonry is assumed to be a three-phase composite composed of the block phase, the mortar phase and the block-mortar interface. The mechanical parameters such as Young's modulus, strength and Poisson's ratio of each phase in masonry are heterogeneous and assumed to be conformed to specific Weibull distribution. This kind of randomness used in the assignment of mechanical properties of elements is quite different from that of stochastic finite element method, because the mechanical and geometrical parameters of an element are actually definite after the assignment is finished; no probability is incorporated in the finite element analysis. The mesoscopic element is assumed homogeneous and isotropic, whose damage evolution meets with the specific elastic damage constitutive law.

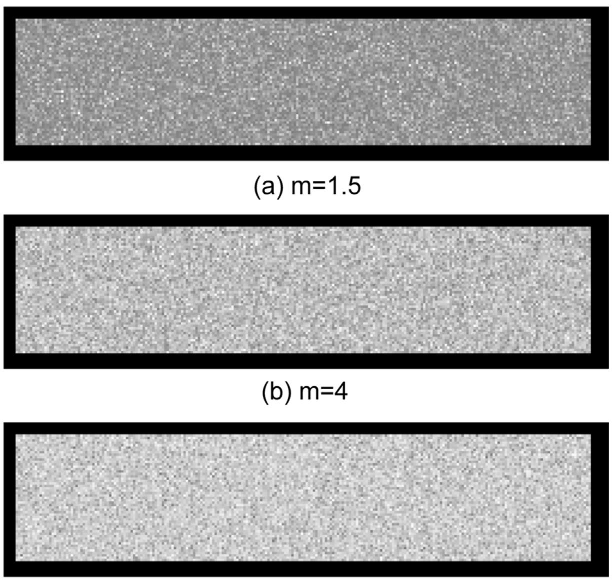
2.1 Assignment of material properties

In order to capture the heterogeneity of quasi-brittle materials at meso-level, the mechanical parameters of materials, including the Young's modulus, strength and Poisson's ratio are assumed to conform to Weibull distribution as defined in the following probability density function:



(a) Brittle with residual strength (b) Power function softening with residual strength

Fig. 1 Elastic damage constitutive law of element under uniaxial tensile stress



(a) m=1.5

(b) m=4

(c) m=8

Fig. 2 Distributions of elastic modulus of specimens with different homogeneity indices (53 × 240 elements)

$$f(\sigma_c) = \frac{m}{\sigma_0}\left(\frac{\sigma_c}{\sigma_0}\right)^{m-1}\exp\left(-\frac{\sigma_c}{\sigma_0}\right)^m \tag{1}$$

Where σ_c is the parameter of element (such as strength or elastic modulus); the scale parameter σ_0 is related to the average of element parameter and the parameter m defines the shape of the distribution function. The parameter m defines the degree of material homogeneity, is called homogeneity index. In Fig. 1 elastic damage constitutive law of element under uniaxial tensile stress is given. In Fig. 1, E and E_0 are Damaged and Undamaged (initial) elastic moduli of element, respectively; f_t and f_{tr} are Tensile strengths of element and Residual tensile strengths of element, respectively; σ is Stress; ε is Strain; ε_{t0}, ε_{tr}, and ε_{tu} are Strain at the peak tensile stress; Maximum tensile strain at the residual tensile strength; and Ultimate tensile strain.

According to the definition of Weibull distribution, the value of parameter m must be larger than 1.0. Fig. 2 show three single-phase numerical specimens, which are all composed of 53×240 elements, produced randomly by the computer according to the Weibull distribution with different homogeneity indices. As the homogeneity index m increases, material properties become more homogeneous and approach that of the homogeneous body; the Young's modulus and strength of every element approach their mean value given in the Weibull distribution (as shown in Fig. 3). In Fig. 3 the values of calculated elastic modulus and strength of the numerical specimens are all normalized with respect to their mean values of Weibull distribution parameter μ_0. We find that the homogeneity index m has much more influence on the macroscopic strength than that on elastic modulus.

Only when all the mesoscopic elements in the specimen have the same mechanical parameters would all elements in the numerical specimen damage simultaneously when subjected to uniaxial compression, and the stress-strain curve of numerical specimen would exactly coincide with the constitutive law of elements (Fig. 3). This also proves that the finite element analysis used in MFPA is correct (the detailed discussion seen in Wang and Tang 2003).

Here the specimen produced numerically with given distribution of material properties is called "numerical specimen". In Fig. 4 the different gray degree of color corresponds to different magnitude of strength of elements. It can be found that the strengths of more elements are concentrated and closer to σ_0 with the increase of homogeneity index. So the increase of homogeneity index leads to more homogeneous numerical specimens. In general, we assumed that

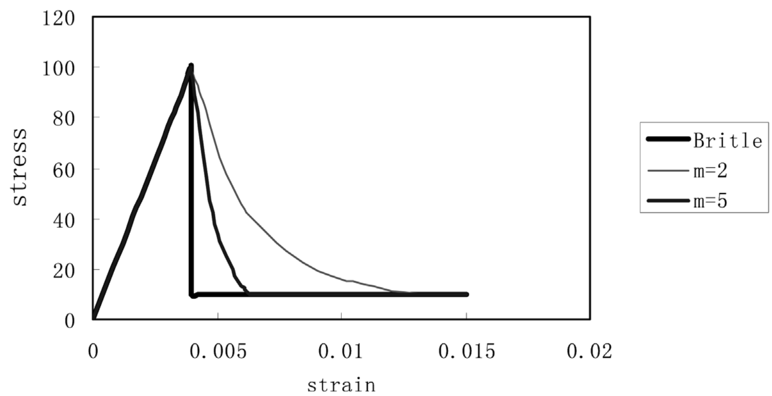


Fig. 3 Stress-strain curve of homogeneous specimens for different schemes of constitutive law (simulated with MFPA) (Wang and Tang 2003)

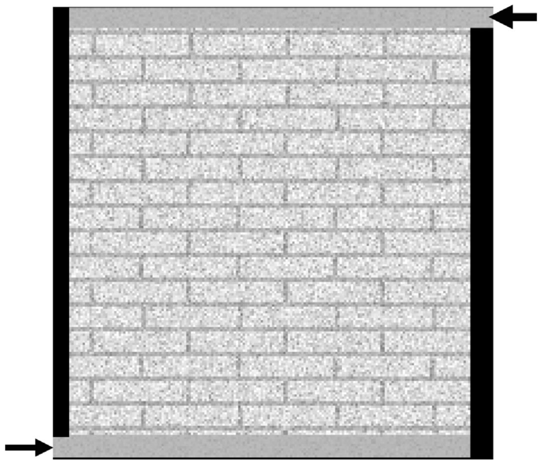


Fig 4 The model of numerical simulation

Young's modulus and strength conform to two individual distributions with the same heterogeneity index. The distribution of Poisson's ratio is not very dispersing in reality; therefore, a high homogeneity index of 100 is specified in the following numerical simulations. In previous literature (Wang and Tang 2003), how the homogeneity index affects the macroscopic mechanical response has been discussed and found that the homogeneity index is a very important Weibull distribution parameter to control the macroscopic response of numerical specimen.

Based on the above assumption, we can numerically produce the heterogeneous material using this model, and the material is composed of many mesoscopic elements. Here the mesoscopic element is also acted as the element of finite element analysis. The mesoscopic element is assumed to be isotropic and homogeneous. This heterogeneous material produced by computer is usually used to indicate the real specimen used in the laboratory, so it is called numerical specimen in this investigation. The mesoscopic elements in the specimen must be relatively small enough to reflect the mesoscopic mechanical properties of materials under the conditions that current computer can perform this analysis because the number of mesoscopic elements is substantially limited by the computer capacity. No local heterogeneous part is included; the nonhomogeneity of this numerical specimen is specified only according to a Weibull distribution with the above given parameters.

2.2 Constitutive relations of element

Continuum damage mechanics has proved to be an efficient tool for the understanding and the description of structural evolutions, so here we use it to describe the mechanical behavior of a meso-scopic element. In the paper, the material is analyzed at meso-scopic level. At the beginning, the element is considered to be elastic, and its elastic properties can be defined by Young's modulus and Poisson's ratio. The stress-strain curve of element is considered linear elastic till the given damage threshold is attained, and then is followed by softening. We choose the maximum tensile strain criterion and Mohr-Coulomb criterion respectively as the damage threshold. In the previous paper (Wang and Tang 2003, Agioutantis *et al.* 2002, Cluni and Gusella 2004, Giuseppe *et al.* 2001, Mazars and Pijaudier-Cabot 1987, Pegon *et al.* 2001, Bazant *et al.* 1990, Vonk *et al.* 1991, Mohamed and Hansen 1999, Schangen and Van Mier 1992, Van Mier and Van Vliet 1999, Abrams and Paulson 1991, Guinea *et al.* 2000), it has been proved that the macroscopic mechanical response of masonry at macroscopic level can be simulated effectively even if very simple constitutive law (such as elastic-brittle) of mesoscopic element is used. At any event, the tensile strain criterion is preferential. If the maximum tensile strain criterion is met and the element damages are in tensile mode, it will not decide whether the element will damage according to Mohr-Coulomb criterion. Contrariwise, if the element does not damage in tensile mode, we will use Mohr-Coulomb criterion to judge whether the damage of the element occurs in shear mode.

In elastic damage mechanics, the elastic modulus of element may degrade gradually as damage progresses, the elastic modulus of damaged material defined as follows.

$$E = (1 - D)E_0 \tag{2}$$

Where D represents the damage variable. E and E_0 are elastic modulus of the damaged and the undamaged material, respectively. Here the element as well as its damage is assumed isotropic elastic, so the E, E_0 and D are all scalar. A total (secant) rather than incremental (tangential) form is used for the proposed constitutive law.

We had discussed the influence of different softening schemes for elastic damage constitutive law on the macroscopic response of numerical specimen and found that the simple elastic-brittle constitutive relationship is sufficient to describe the mechanical behavior of mesoscopic element when the heterogeneity is considered.

In this paper, the sign convention used through out this paper is that tensile strain is positive. When the mesoscopic element is under uniaxial tensile stress, the constitutive relationship that is elasto-brittle damage with given specific residual strength of elements is shown in Fig. 1. No initial damage is incorporated in this model, thereafter, at the beginning, the stress-strain curve is linear elastic, no damage occurs, i.e., $D = 0$. When the maximum tensile strain criterion is met, the damage of element occurs. Herein this kind of damage is called tensile damage.

According to the constitutive relationship of mesoscopic element under uniaxial tension as shown in Fig. 1 the damage evolution of element can be expressed as

$$D = \begin{cases} 0 & \varepsilon < \varepsilon_{t0} \\ 1 - \dfrac{\lambda\varepsilon_{t0}}{\varepsilon} & \varepsilon_{t0} \le \varepsilon < \varepsilon_{tu} \\ 1 & \varepsilon \ge \varepsilon_{tu} \end{cases} \tag{3}$$

Where σ_t and λ are uniaxial tensile strength and residual strength coefficient (abbreviated as RSC), respectively. Where ε_{t0} is the strain at the elastic limit, which is the so-called threshold strain. And ε_{tu} is the ultimate tensile strain of element, which indicates that the element would be completely damaged, when the tensile strain of element attains this ultimate tensile strain. The ultimate tensile strain is defined as $\varepsilon_{tu} = \eta\varepsilon_{t0}$, where η is called ultimate strain coefficient.

Additionally, we assume that the damage of mesoscopic element in multiaxial stress field is also isotropic elastic. According to the method of extending one-dimensional constitutive law under uniaxial tensile to complex tensile stress condition, which was proposed by Mazars *et al.*, we can easily extend the constitutive law described above to use for three-dimensional stress states. Under multiaxial stress states the element still damages in tensile mode when the combination of major tensile strain attains the above threshold strain ε_{t0}. The constitutive law of element subjected to multiaxial stresses can be easily obtained only by substituting the strain ε in above (3), with equivalent strain $\bar{\varepsilon}$.

It must be emphasized that when $D = 1$, it can be calculated from Eq. (2) that the damaged elastic modulus is zero, which would make the system of equations ill-posed, therefore, in this model a relatively small number, i.e., 1.0e-05 is specified to the elastic modulus under this condition.

In fact, the above constitutive law only considers the situation when element is damaged in tensile mode. But the compressive softening also occurs when masonry subjected to compressive and shear stress. In order to study the damage of element when it is under compressive and shear stress, Mohr-Coulomb criterion as expressed follows is chosen to be the second damage threshold.

$$F = \frac{1 + \sin\phi}{1 - \sin\phi}\sigma_1 - \sigma_3 \geq f_c \tag{4}$$

Where σ_1 and σ_3 are major and minor principal stress respectively. Again, compressive stresses are negative and tensile stresses are positive. As a matter of fact, the numerical value of σ_3 and σ_1 respectively indicate the magnitude of maximum and minimum compressive stress when these two principal stresses are both compressive. Moreover, f_c is uniaxial compressive strength and ϕ is the internal friction angle of the element. Here, the effect of the intermediate principal stress σ_2 on the damage is not included in the model.

This kind of damage is called shear damage because the stress conditions of element meet the Mohr-Coulomb criterion.

In the same way, similar constitutive law is given when the element is under uniaxial compression and damaged in shear mode according to the Mohr-Coulomb criterion. The damage variable D can be described as follows.

$$D = \begin{cases} 0 & \varepsilon > \varepsilon_{c0} \\ 1 - \dfrac{\lambda\varepsilon_{c0}}{\varepsilon} & \varepsilon \leq \varepsilon_{c0} \end{cases} \tag{5}$$

Where λ is also residual compressive strength. We assumed that $f_{cr}/f_c = f_{tr}/f_t = \lambda$ is true when element is under uniaxial compression or tension.

The mechanical behavior of masonry in multiaxial compression is mainly characterized by a considerable increase of strength and pre-peak strain at high confinement level. When element is under multi-axial stress state and satisfies the Mohr-Coulomb criterion, the damage occurs, and we must consider the effect of other principal stress in this model during damage evolution process.

When the Mohr-Coulomb criterion is met, we can calculate the minor principal strain (maximum compressive principal strain) ε_{c0} at the peak value of minor principal stress.

$$\varepsilon_{c0} = \frac{1}{E_0}\left[-f_c + \frac{1 + \sin\phi}{1 - \sin\phi}\sigma_1 - \mu(\sigma_1 + \sigma_2)\right] \tag{6}$$

In addition, we assume that the damage evolution is related to the maximum compressive principal strain ε_3. Therefore, we use the maximum compressive principal strain ε_3 of damaged element to substitute the uniaxial compressive strain ε in Eq. (5).

From the above derivation of damage variable D, which is generally called damage evolution law in damage mechanics, as well as the Eq. (2), we can calculate the damaged elastic modulus of element at each stress or strain level. The unloaded element keeps its original elastic modulus and strength. That is to say, the element will unload elastically and no residual deformation is incorporated in the numerical model.

The simulation of crack is just as method used in smeared crack model, the crack is smeared over the whole element, which has the advantage of leaving untouched the mesh topology, and no special singular element is adopted. When the stress states of an element meet the damage threshold, the element will damage in tensile or shear mode. Only when the maximum tensile strain of the damaged element attains given ultimate tensile strain, the damaged element will become totally cracked and displayed as crack in the post-processing figures.

2.3 Numerical simulation process

Based on the mesomechanical model presented in the preceding sections, computer program named MFPA (Material Failure Process Analysis) was developed based on RFPA (Rock Failure Process Analysis) under the Microsoft Visual C++ and the Fortran Power-Station environment. The program provides a user-friendly interface so that the numerical simulation process, including the setting-up of the numerical model, execution of the finite element analysis, the processing of outputs, can all be accomplished easily and efficiently. Outputs from the computer program include stress distributions, the stress-strain response, and the crack propagation process. The entire process of numerical simulation using this computer program may divided into the three common stages of pre-processing, finite element analysis and post-processing as described below.

(1) Pre-processing: the pre-processing stage is aimed at the creation of a numerical model of a masonry specimen for use in a subsequent finite element analysis (numerical specimen). As mentioned earlier, the masonry is considered as a three-phase composite. Before generating a finite element mesh, material properties for each of the three phases have to be specified first. In principle, the mechanical properties including the elastic modulus and strength of each phase should be determined from meso-level experiments. The meso-level properties of the block phase and the mortar phase should be obtained form meso-level experiments on the block and mortar respectively. The properties of the block-mortar interfaces should also be similarly based. However, there are few results from experiments on the block-mortar interfaces that are carried out at the meso-level. In the present study, the Weibull distribution parameters of the three phases were chosen to give realistic macroscopic responses of masonry under uniaxial compression when compared with results from laboratory experiments.

(2) Finite element analysis: this stage involves finite element stress analysis that is generally executed with a large number of steps corresponding to different load or deformation levels. Both load control and displacement control are possible during the analysis, with the latter being generally adopted to trace the entire fracture process. Within each step corresponding to a pre-defined load or deformation level, several iterations are carried out until on new damage is detected or the number of newly damaged elements is below a small percentage of the total number of elements. Each iteration involves a linear elastic finite element analysis of the numerical specimen under the total applied load/deformation, with the elastic modulus of each element being that determined by the previous iteration, the results of which are then used to evaluate the state of damage of each element and the degraded material properties considering the new damage. Once convergence is achieved, the analysis proceeds to the next step with a small increment in the load or deformation level. In addition, similar screen displays of the

distributions of elastic modulus and damaged elements are also possible.

(3) Post-processing: Following the completion of the finite element analysis, a variety of outputs are available for an examination of the entire fracture process. Phenomena such as deformation localization, stress redistribution, load-displacement responses, and crack patterns can then be examined.

3. Numerical simulation and its results

Fig. 4 is the numerical specimens, which is composed of 200×198 elements with geometry of $1000\,\text{mm} \times 990\,\text{mm}$ in size. All the elements have the same size in scale (square in shape). The mechanical parameters of masonry such as Young's modulus, strength and Poisson's ratio are heterogeneous and assumed to be conformed to Weibull distribution.

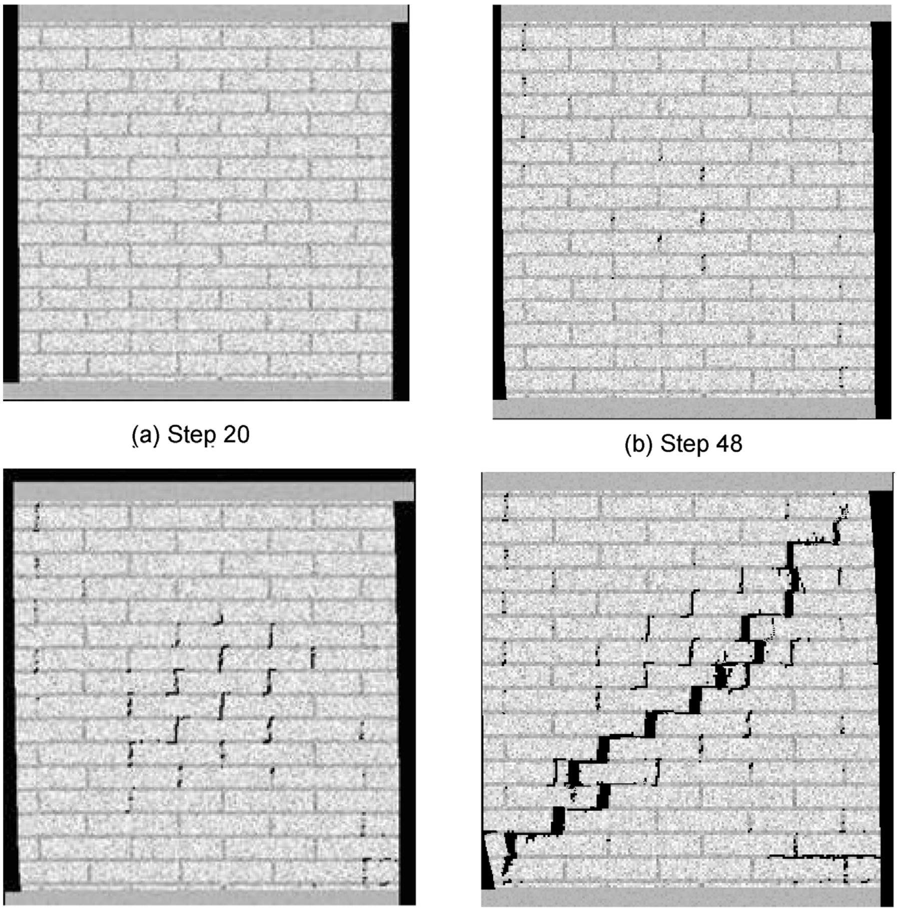
The heterogeneity of the masonry structure must be considered to investigate the fracture process of the masonry structure at meso-scopic scale. Therefore, the heterogeneity of the material is incorporated into the numerical model at small scale to investigate the localization of the fracture and the initiation, propagation and coalescence of the cracks in the masonry, and even the whole fracture process of the masonry. Similar to other numerical methods, the crack are randomly distributed in the whole element, the mechanical property of the element is still isotropic and homogeneous. As for the damaged element, it can be taken as completely fractured and assigned to a very small value (1.0E-05) until the maximum tensile strain reaches to the specified limit strain. In the Figures of elastic modulus, the newly formed cracks can be obviously observed. In the numerical model, tensile damage is the main reason for the initiation and propagation of cracks. Shear damage can also lead to the degradation of the mechanical properties of elements and cracks cannot be formed in the model. Even so, shear damage can cause the redistribution of stress and induce cracks due to newly concentrated tensile stress.

Based on the above considerations, the homogeneity indexes list in Table 1 were used in this numerical simulation presented in this section.

The boundary conditions of the problems are set as plane strain state. The parameter value is selected according to the related handbook, and the elastic modulus and strength of the bondages are small, which are similar to those of the concrete and mortar. The values of mechanical parameters of the material are randomly assigned for a given material with a given homogeneity index. In order to research the influence of the cracking path in the masonry structure, the strength of mortar is given a low value, about 20 percent of the block strength. The numerical model is shown in Fig. 4. Displacement control manner is adopted. The loading step is 0.004 mm/step and 200 steps in total.

Table 1 Weibull distribution parameters of the three phases for masonry

Phase	Scale parameter of elastic modulus (GPa)	Scale parameter of compressive strength (GPa)	Homogeneity index (m)
Block	50	100	5
Mortar	20	40	3
The block-mortar interfaces	26	60	3



(a) Step 20 (b) Step 48

(c) Step 87 (d) Step 91

Fig. 5 Fracture process of masonry wall (Numerical results)

The elastic modulus of the failed elements will be reduced to a small value in MFPA^{2D}, thus the propagation track of the cracks can be obviously observed. As a convention, compressive stress is regarded as positive value and tensile stress negative value. The numerically simulated results (step 20, step 48, step 87 and step 91) of the masonry structure under loading are given in Figs. 5(a)-(d).

As shown in Fig. 5(a), tensile failure firstly occurs along perpendicular cracks and then shear failure occurs along horizontal cracks, the failure pattern is symmetrical along the midline of the masonry. Numerically simulated results reproduced the whole process of the masonry. Compared with the Fig. 6 in experimental test (see Raijmakers and Vermeltfoort 1992), the numerical results agree well with the experimental results, which reveals that the numerical model can well replicate the failure process of the masonry.

The heterogeneity of masonry is incorporated in the numerical simulations of this investigation, those phenomena such as deformation localization, stress redistribution and curvilinear crack propagation path observed in experiments can be numerically retrieved. Besides, the maximum load obtained from numerical simulation is 186.7 KN, which is quite close to the values tested in

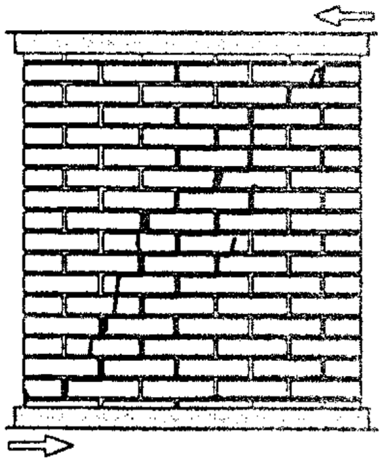


Fig. 6 The progress of masonry wall failure progress observed in experiment (Raijmakers and Vermeltfoort 1992)

experiment (Wang and Tang 2003). Because both the maximum tensile strain criterion and Mohr-Coulomb criterion are utilized as damage threshold, the shear damages of few mesoscopic elements are also observed from numerical simulation of masonry specimen subject to shear loading. But the numerical result in the paper further proves that the shear damage is predominantly caused by tensile damage at the mesoscopic level.

In fact, the failure process of the masonry structure is the mutual interaction and coalescence of multiple cracks. Numerical simulation is characterized by quick visualization and feasible manipulation, and it can not only track the whole process of initiation, propagation and coalescence of the crack, but also clearly show the stress field, displacement field and damage evolution in the masonry and obtain the failure mechanism of masonry with different geometries and loading conditions. It is shown that the MFPA method is a very promising tool to study the failure and seismicity of the masonry structure.

Using the numerical method mentioned above, not considering the change of the damage and the element grid structure, it can simulate the complex process of the cracking and the interaction in compound material effectively.

4. Conclusions

The implementation of a mesoscopic mechanical model has been discussed in this paper; an elastic damage mechanical model is proved to be effective in simulating the fracture process of masonry.

The recently proposed mesoscopic numerical model is capable of capturing the crack propagation path and other fracture characteristics found in the shear tests of masonry.

Numerical simulation is characterized by quick visualization and feasible manipulation, and it well reproduces the whole process of initiation, propagation and coalescence of the crack. Compared with the experimental tests, it can easily obtain the stress field and damage evolution in the fracture process of the masonry.

From this work, in 2D space, these are a very good agreement between results on real materials and simulation. It is the first step in this direction and the method must be refined, particularly to extend for 3D space by a way, which seems easy to imagine. This opens up a new, very promising, approach of research.

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