論文の内容の要旨

論文題目 Application of Continuumnization for the Analysis of Dynamic Characteristics of Brick Structures

(連続体化の組積造構造物動的特性解析への適用)

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Although discrete models like DEM or RBSM are commonly used in numerical simulation of brick structures, equivalent continuum form can provide us advantages. Continuum form allows us to analytically study dynamic characteristics of brick structure for given brick-mortar geometric and material properties. The predicted dynamic characteristics can be useful to verify numerical codes. In design propose, it is possible to analytically select proper brick mortar properties for desired dynamic characteristics. With the governing equations of the equivalent continuum form, FEM models for brick structures can be constructed. With the FEM model, it is convenient to use commercial software to analyze brick model using proper structural elements such as beam or shell without writing computational code.

According to literature survey, discrete models, such as DEM or RBSM, of brick structures are use due to their good representation of brick movement. However it is difficult to obtain analytical solution to verify these kinds of model.

To obtain additional advantage, continuum form of brick structures is also developed. For simplicity, some researches average brick-mortar properties assuming the system to be isotropic and homogeneous which can reduce computational cost. However, there are lack of accuracy since this approach ignores effects of brick arrangement. For more accurate method, governing equations of the equivalent continuous systems are obtained by the approximation of relative translation and rotation based on Taylor's expansion. In this approach, dynamic characteristic can be well predicted since the effects of arrangement are considered. With governing equations obtained by this approach, FEM which include the rotational degree of freedom is obtained. However, moment of inertia is not well defined. Regarding to damping in continuum model, Rayleigh damping is commonly used. However, there is no physical explanation of damping mechanism.

According to the study of obtaining continuum form of spherical mass-spring system based on continuumnization, it is hypothesized that high frequency rotation may cause damping in particle system. This hypothesis could provide us an opportunity to discover a rational source of damping. This study aims to obtain equivalent continuum form of brick-mortar systems. In this thesis, there are 3 main approach to obtain governing equations of the equivalent continuum form. First approach is based on continuumnization. For the second, the Tayler's expansion is applied. Third, the infinite Tayler series is used.

After obtaining continuum form, this study aims to apply this form for three main applications. The first target is to predict dynamic characteristics like wave frequency and velocity for verification propose. Second, Particle Discretization Scheme Finite Element Method (PDS-FEM) is to be developed instead of standard FEM since bricks themselves are particles. For the third application, the hypothesis that high frequency rotation may cause damping in particle systems is to be investigated.

For discrete brick system, bricks are assumed to be rigid blocks and mortar are assumed to be tiny linear springs with normal and tangential constant. Based on Hamilton principle, discrete equations of motion of the system are obtained.

The equations of motion consist of coupling term which are the equation of translation and equation of rotation. In this form of equations, though it is convenient to simulate the particle system, it is difficult to predict dynamic characteristics of the system. To predict dynamic characteristic equivalent continuum form of the systems is required

In continuumnization, it is assumed that the particle size is relatively small such that the particle system can be assumed to be continuum. Taking limit of the particle size closed to zero, the relative translation and rotation are approximated to be the equivalent gradient terms. Substituting the gradient terms to the governing equations of the discrete system, the governing equations of the equivalent continuum form is obtained

Based on the Tayler's expansion, it is assumed that there are at least twice differentiable smooth functions that can represent the discrete translation and rotation of particles. Using second order Tayler's expansion to approximate the relative motions, the governing equations of the equivalent continuum form is obtained

One advantage of the governing equations obtained by both methods described above is that it allows us to predict dynamic characteristic of the brick-mortar systems. Using Fourier transform with respect to length and time, a characteristic equation in frequency-wavelength domain can be obtained. Solving the characteristic equation, the relation between frequency and wave number is obtained. For relatively long wavelength, analytical wave phase velocities of p-wave and s-wave predicted. Also the corresponding modes including rotational wave is obtained

To verify the analytical solutions, a numerical RBSM model of 2d brick wall is constructed. The numerical model is subjected by 2 cases of input condition at the center of the model. First is translational input to compare the wavefronts for a given travel time. Second is rotational input to compare the relation between wave frequency and wavenumber for givens length domain.

According to the verification, the analytical wavefront are in good agreement with numerical wavefront in horizontal and vertical propagation of waves which is 4% error. For the frequency-wavenumber relation, the numerical relation and the analytical relation are in good agreement for wavelength 7 times longer than the size of bricks which is sufficient for civil engineer.

For some applications where the verification of short wavelength is required, continuum form based on infinite series can also be applied. Without truncation, this method provide the accurate prediction of frequency-wavenumber relation which is applicable for wavelength 2 times longer than brick size. Note that this wavelength is the shortest meaningful wavelength in discrete particle systems.

With the governing equations of the equivalent continuum systems, FEM of brick structures can be derived. Since bricks are rigid particles, PDS-FEM can be implemented properly. With PDS-FEM, the functions of translation and rotation of a brick are approximate to be a zero order such that the characteristic function is 1 for inside the brick and 0 for outside. Unlike standard FEM, the derivatives of translation and rotation are approximate on a triangle formed by a center of three neighboring bricks such that characteristic function is 1 for inside the triangle and 0 for outside.

To obtain the range of applicability of the PDS-FEM, numerical simulations of PDS-FEM were verified with analytical solutions of the continuum form based on second order Tayler's expansion. Comparing the frequency-wavenumber relations, the PDS-FEM is applicable for wavelength 7 times longer than of the size of bricks which is also the applicable range of the continuum form based on second order Tayler’s expansion.

According to the analytical solution of continuumnization and numerical solution of PDS-FEM, high frequency of rotation which is about 200000 rad/s is observed. However, this such high frequency should not occur in practices. Thus, it is possible that the rotational mode could be one of the sources of damping. To study the effect of the rotational damping, the special care of damping model is required instead of using Rayleigh damping

To study the effect of rotation in continuumnization based governing equations, rotation is derived in term of translation in equation of rotation and substituted into equation of translation With this approach, governing equations which include damping term is obtained

To study effects of the damping term in the equation. A numerical simulation is required. However, the equivalent weak form of the damped governing equation contain second order derivative, the formulation of the second derivative is required. Based on PDS, a function is approximated using a brick itself as the tessellation. Then, the conjugate tessellation which is a triangle connected by three neighboring brick is used for the approximation of the first derivative. Expanding this idea, the conjugate tessellation of the triangle which is the brick tessellation can be used to discretize the second derivative of the translation

Substituting the PDS-FEM based approximation above, into the equivalent weak form and taking the variation to be zero, the matrix equation of damped systems is obtained.

Back to the numerical simulation of the brick wall with PDS-FEM, the wall is fixed on the based and is subjected to a static force on the top of the wall. After the static force is released, the wall freely vibrates.

It is observed that in damped systems there is the dissipation of the total energy of the wall. Also, acceleration of a brick wall with some decayed amplitude is observed. This can be concluded that the damping term can cause the energy dissipation.

In addition to the results above, it is observed that the wall vibrates with high frequency in the beginning. Around a half of second later, the vibration of acceleration become more smooth. This may because the high frequency terms starts to disappear during the vibration and then the low frequency modes become dominant.

To conclude, this study formulate the governing equations of the equivalent continuum brick mass-spring system and applied them for three main applications. First, frequency-wavenumber relation of p-, s- and rotational waves and corresponding wave speed are predicted. Second, PDS-DEM for brick wall is formulated. According to its verification, PDS-DEM for brick wall is applicable for civil engineering applications. Finally, the damping term which include brick mortar properties unlike empirical damping is obtained.