Dynamic model reduction in the nonlinear interaction simulation of the neighboring high-rise buildings on the soil base

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Abstract

The new method of reduction of dynamic freedom degrees for finite element models (FEM) are presented in the article. The reduction method is based on the spectral superelements (SES) used together with the method of normal coordinates. The developed SES-superelements preserve the property of the SES's matrix of masses to be diagonal, that allowed to efficiently apply the explicit integration schemes. The comparative analysis was performed by analysing the dynamic response of a highrise building. The calculations were executed in the nonlinear conditions by direct integration over the time by using the explicit method with the help of Automated System of Scientific Research (ASSR) "VESNA-DYN". The results obtained without reduction and with the use of spectral superelements showed a high convergence.

Keywords: finite element method, dynamical reduction, spectral superelement, explicit direct method, VESNA-DYN, high-rise building

1. Introduction

The construction of modern high-rise buildings poses a number of problems related to the assessment of a stress-strain state under the action of seismic loads, large number of equations, necessity to get the reliable input data, including the data on seismic loads, account for the real nonlinear properties of media, reasonable value of duration of calculations, etc.

There are many methods are available for the assessment of the effect of seismic loads on the stress-strain state of structures, such as methods of the static theory, spectral methods, and the group of direct dynamical methods. But only direct dynamical methods can give the most complete information about the behavior of a construction. Most building structures are characterized by the presence of multiple structural elements. The finite-element models of subconstructions called the superelements are developed independently with the formulation of contact conditions for the joint operation in the composition of the construction under study. This allows one to apply the methods most efficient for the corresponding superelements and to significantly improve the parameters of efficiency of the calculations on the whole due to such combined approach.

2. Dynamic FEM reduction for building analysis

The practice has shown that the superelements constructed on the eigenmodes of oscillations of the sub-constructions with a diagonal matrix of masses are the most efficient from the viewpoint of the application of explicit methods (below, we call them spectral superelements (SES) [1, 2]). The construction of the superelement is based on the Craig-Bampton method of normal coordinates, where the reduction is carried on with the use of a non-complete collection of the subconstruction eigenmodes.

2.1. *Dynamic superelements of the spectral type*

The nodes, by which the subconstruction contacts with other parts of construction, are called external (Fig. 1.), and the elements, which include at least one external node are called external elements. The nodes and elements, which remain in the subconstruction, are referred to as internal ones.

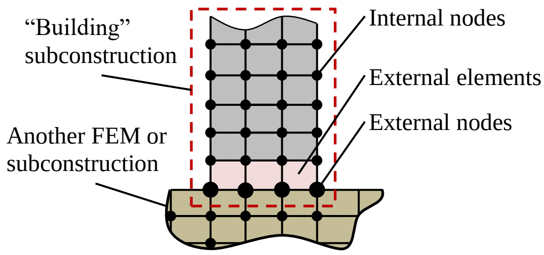

Figure 1: Separation of external and internal nodes of a superelement for the given subconstruction

According to the work [1], the matrix of reduction [S] is formed by the method of normal coordinates from the eigenmodes of a subconstruction for the internal nodes and by the method of static condensation for the external nodes. For this purpose, the eigenmodes of a subconstruction are determined and normalized in the first turn at fixed external nodes $[\mathrm{R_{ii}}]$. Then the matrix [S] is supplemented by the displacements caused by the unit displacements of the external nodes $[\mathrm{X_{ei}}]$:

$$[\mathrm{S}]^{\mathrm{T}} = \begin{bmatrix} [\mathrm{R_{ii}}] & 0 \\ [\mathrm{X_{ei}}] & [\mathrm{E_{ee}}] \end{bmatrix} \tag{1}$$

where: $[\mathrm{R_{ii}}]$ – is the collection of vector-rows of the normalized eigenmodes of a subconstruction for internal nodes; $[\mathrm{X_{ei}}]$ – are the displacements of internal nodes under unit displacements of external ones; and $[\mathrm{E_{ee}}]$ – is the identity matrix, whose order is equal to the number of external displacements.

However, while forming the reduced matrix of masses $[\tilde{M}]$ with the use of (1) we obtain the "framed" matrix of masses, which does not allow one to efficiently apply the explicit integration schemes.

In the proposed approach, we have that the matrices of masses of external elements of the subconstruction possess the diagonal structure, and the matrix of reduction [S] has the form:

$$[S] = \begin{bmatrix} [R_{ii}] & 0 \\ 0 & [E_{ee}] \end{bmatrix} \qquad (2)$$

where $[R_{ii}]$ – is the collection of vector-rows of the normalized eigenmodes of the subconstruction for internal nodes obtained with regard for the possibility to change the stiffness of external elements from a given magnitude to zero. In the case where the stiffness of external elements is nonzero, the matrix $[R_i]$ is supplemented by rows of the vectors of tough displacements of internal nodes; and $[E_{ee}]$ – is the identity matrix.

To take into account the peculiarities of the subconstruction interaction with other parts of the FEM, k_z factor of matrices of stiffness of external elements is used with $0 \le k_z \le 1$. The successful choice of k_z can only decrease the number of involved modes needed for the necessary accuracy of results.

3. Nonlinear seismic simulation of group of the buildings

The proposed method of dynamical reduction was applied to the study of oscillations of a high-rise building complex based on a real object in a seismically hazardous area. The buildings have a frame-monolithic construction (Fig 2.). The calculations were executed in a nonlinear settings by the direct integration over the time by using the explicit method of central differences with discrete steps in the spatial coordinates [3] using Automated System of Scientific Research "VESNA-DYN". The developed FEM includes a system of 1'505'383 algebraic equations. For SES superelement composed for overhead part of building used up to 390 eigenmodes (up to 30Hz of subconstruction eigenfrequency).

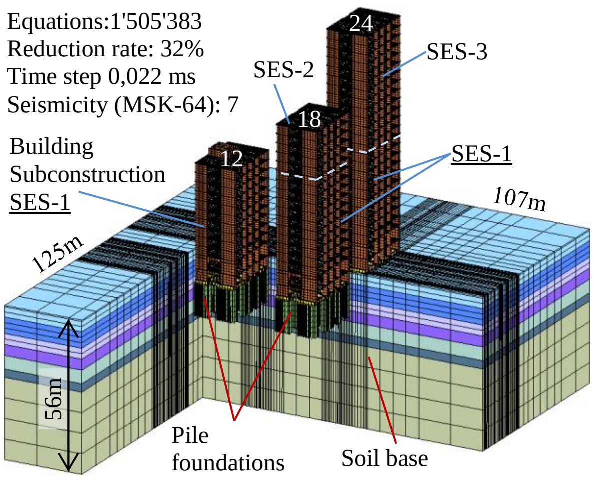

Figure 2: The finite element model of the system "soil base – foundation – building" with the indicated spectral superelement of subconstructions (SES)

The comparative analysis of the results obtained for the tallest building with and without reduction showed a high convergence. Maximum errors (less than 12%) mainly occur on the short-term peaks of fluctuations. Meanwhile dimensionality of the system was reduced by 2.8 times.

Using SES dynamic reduction for the whole complex led to the reduction of the number of degrees of freedom by 32% - resulting in 1'025'766 equations and allowing to perform an efficient dynamic analysis.

The result has shown that the behavior and deformations of the complex significantly differ for each building. Lowest 12-story building had maximum amplitudes, that lead to the large nonlinear deformation at the soil base (with piles). This is typical for the resonance mode. Predicted residual settlements for this foundation were about 5 cm. On the other hand, settlements under 18- and 24-storey sections were about 3 cm and 1 cm respectively.

Thus, the executed studies allow us to recommend the use of spectral superelements in the modeling of the dynamic behavior of buildings with the soil base, as well as accounting for a nonlinear deformation of the soil.

4. Conclusions

Based on the results of our research, we have reached the following conclusions:

A new version of spectral superelements (SES) is proposed. They are developed on the basis of the method of normal coordinates, ensuring the conservation of the property of the matrix of masses of a superelement to be diagonal, and allowing one to significantly decrease the order of the system of equations.

By utilizing real building as the example, it is shown that the application of spectral superelements ensures the triple reduction of the number of dynamic degrees of freedom while providing the result has a high degree of convergence with results obtained without the reduction. The level of error depends on the number of used modes for the specific SES elements.

The proposed method of solution of dynamic problems with the use of spectral superelements allows one to perform the efficient dynamic analysis, including the seismic one, of the interaction of elements of the "soil base – foundation – building" system while accounting for the nonlinear deformation of soils of the base with the use of explicit integration schemes.

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