doi: 10.18720/MCE.78.14

Adaptive finite-element models in structural health monitoring systems

Адаптивные конечноэлементные модели в системах мониторинга зданий и сооружений

A.M. Belostotsky,
P.A. Akimov,
StaDyO Research & Engineering Centre, Moscow, Russia
O.A. Negrozov,
N.O. Petryashev,
S.O. Petryashev,
S.V. Sherbina,
National Research Moscow State Civil Engineering University, Moscow, Russia
D.K. Kalichava,
OOO "Pixar", Moscow, Russia
T.B. Kaytukov,
Russian Academy of Architecture and Construction Sciences, Moscow, Russia

Д-р техн. наук, генеральный директор А.М. Белостоцкий,
д-р техн. наук, заместитель директора по науке П.А. Акимов,
ЗАО "Научно-исследовательский центр СтаДиО", Москва, Россия
ассистент О.А. Негрозов,
инженер Н.О. Петряшев,
инженер С.О. Петряшев,
инженер С.В. Щербина,
Национальный исследовательский Московский государственный строительный университет, Москва, Россия,
канд. техн. наук, генеральный директор Д.К. Каличава,
ООО "ПИКСАР", Москва, Россия,
канд. техн. наук, заместитель главного ученого секретаря Т.Б. Кайтуков,
Российская академия архитектуры и строительных наук, г. Москва, Россия

Key words: structural health monitoring; finite element method; adaptive models; unique buildings; seismometric approach; standing wave method; natural frequencies

Ключевые слова: мониторинг строительных конструкций; метод конечных элементов; адаптивные модели; уникальные здания и сооружения; сейсмометрический подход; метод стоячих волн; собственные частоты

Abstract. The design and construction of unique buildings, facilities and complexes of “modern” architectural forms and constructive solutions in Russia began less than 20 years ago in the conditions of a shortage of national design codes and experience of such construction. Thus these objects were not provided with proper scientific and technical support and structural health monitoring (SHM) systems. Generally only the instrumental monitoring system, based on results of finite element analysis and comparison with measured data allows performing planning activities to prepare for and respond to changes in state of critical structures and drawing conclusions about the actual state and the possibility of further safe operation of the building. Theoretical foundations of methodology of such SHM have been developed. Parameterized finite element models of buildings, special algorithm of adaptation (calibration) in accordance with results of measurements, methodology of measurements of natural frequencies and modal shapes and algorithm of structural evaluation are proposed in this paper. So-called “start” finite element model is normally developed to study the load-bearing capacity of the current version of the project. Parameterized “monitoring-oriented” three-dimensional dynamic finite element model for each significant stage of life cycle of the building (the stages of construction and operation) is constructed or modified, verified and adapted in accordance with the measured data. The main criterion for the adaptation is the correspondence of calculated and measured spectrum of the natural frequencies and mode shapes in the entire frequency range, significant for the assessment of system-wide changes and for identification – localization of possible defects.

Белостоцкий А.М., Акимов П.А., Негрозов О.А., Петряшев Н.О., Петряшев С.О., Щербина С.В., Каличава Д.К., Кайтуков Т.Б. Адаптивные конечноэлементные модели в системах мониторинга зданий и сооружений // Инженерно-строительный журнал. 2018. № 2(78). С. 169–178.

Аннотация. Расчетное обоснование, проектирование и строительство уникальных зданий, сооружений и комплексов «современных» архитектурных форм и конструктивных решений в Российской Федерации начинались менее двадцати лет назад в условиях дефицита национальной нормативной документации и опыта подобного строительства, в результате чего не были обеспечены надлежащим научно-техническим сопровождением и мониторингом соответствующих несущих конструкций. Вообще, лишь система инструментального мониторинга, построенная на основе анализа результатов конечноэлементного моделирования в сопоставлении с данными измерений, позволяет выполнять планирование мероприятий по подготовке и реагированию на изменения состояния ответственных конструкций, сделать выводы о фактическом состоянии и возможности дальнейшей безопасной эксплуатации здания (сооружения). Теоретические основы соответствующей методики разработаны и представлены в настоящей статье. Описываются параметризованные конечноэлементные модели зданий, алгоритм их адаптации (калибровки) по данным инструментальных наблюдений, методика измерения собственных частот и форм колебаний, подход к оценке несущей способности для фактического состояния объекта. «Стартовая» конечноэлементная модель используется, как правило, для обоснования несущей способности актуального проектного варианта. Для каждой значимой стадии «жизненного цикла» здания (этапы строительства и эксплуатации) строится, модифицируется (актуализируется), верифицируется и адаптируется по текущим данным инструментальных наблюдений параметризуемая пространственная динамическая «мониторинговая» конечноэлементная модель. Основным адаптационным критерием здесь принимается соответствие расчетного и измеренного спектра собственных частот и форм колебаний во всем диапазоне частот, значимом как для оценки общесистемных изменений, так и идентификации-локализации возможных дефектов.

1. Introduction

The main target of research of this paper is unique buildings, facilities and complexes of “modern” architectural forms and constructive solutions. The design and construction of unique buildings, facilities and complexes of “modern” architectural forms and constructive solutions in Russia began less than 20 years ago in the conditions of a shortage of national design codes and experience of such construction.

The systematic process of observing, tracking and logging data over a period of time in order to characterize the health state of structures and to detect any possible change due to damage occurrence is referred to as structural health monitoring (SHM) [1]. SHM is nowadays a field of great concern. The main aim of SHM is to prevent and avoid fatal structural damages through the determination of stresses and deformations (i.e. displacements) of whole structure or a specific component. It is clear that external loads and boundary conditions should be previously identified [2].

Due to the above-mentioned reasons, unique buildings, facilities and complexes in Russia were not provided with proper scientific and technical support and SHM systems [3]. Corresponding consequences of this situation include, in particular, inadequacy of the structural analysis and the poor quality of the construction works [4, 5]. The problem of SHM (at the construction and operation stages) takes on special significance, the importance of which has already been recognized by designers, builders and specialists of supervisory organizations [6, 7]. However, there is no algorithm for the solution of this problem in the Russian design codes. Besides, SHM systems of erected unique buildings and structures exist, as a rule, only on papers, approved by the Russian State Expertise [8].

In the last decades, SHM technology has emerged creating an exciting new field within various branches of engineering. This technology integrated remote sensing [9], smart materials, and computer based knowledge systems to allow civil engineers see how built up structures are performing over time. Since the emergence of this technology, it became more and more useful for large infrastructures, such as bridges, buildings, tunnels, pipelines, offshore platforms, wind turbines, and railway infrastructure where performance is critical but onsite field test is difficult or even impossible [10, 11]. Besides, the request for damage detection by means of non-destructive methods is greatly increasing in order to reduce the maintenance costs and to increase the safety level of the structures [12].

As is known, there are four basic methods of instrumental monitoring at the present time: geodetic measurements; geotechnical monitoring the state of foundation; measuring loads and strains in the substructure and superstructure; dynamic (seismometric) approach [13–15]. Special mention should go to seismometric method that allows investigator to explore the whole building and to identify significant changes in the load-bearing structures without instrumental actions and visual inspections of each structure [16, 17]. The experiments on real objects confirmed the potential of this method, however, revealed a number of problems [18, 19]. It is necessary to note complex specify of unique buildings and

Belostotsky A.M., Akimov P.A., Negrozov O.A., Petryashev N.O., Petryashev S.O., Sherbina S.V., Kalichava D.K., Kaytukov T.B. Adaptive finite-element models in structural health monitoring systems. *Magazine of Civil Engineering*. 2018. No. 2. Pp. 169–178. doi: 10.18720/MCE.78.14.

advantages of seismometric method in the context of the monitoring problems (high dimensionality and variability (relative to loads, masses and stiffness) of object; difficulty of corresponding instrumental measurements (online access to the majority of load-bearing structures in residential and other premises is difficult or impossible [17]).

Instrumental monitoring of unique buildings without corresponding correct and adequate “monitoring-oriented” mathematical and computer models has random nonsensical nature and therefor it is not of practical interest. These “monitoring-oriented” models (several models or parameterized one) have a number of specific differences from the conventional design models, which are normally used to justify design decisions (input of real (actual measured instead of design) physical and mechanical parameters of construction materials (steel, concrete, reinforcement etc.) and geometry of structures; input of real (actual measured instead of design) loads; inclusion of non-bearing structures (dividing walls, facades, etc.) in static and dynamic operation of structures under weak “background” loads; modelling of work of several joints in accordance with schemes, different from design ones (for example, elastic restraint instead of hinge joint); adaptability (calibration, “learning”) of model in accordance with data obtained from instrumental measurements (including detected defects).

The main objective of this paper is the development of correct adaptive finite element models in SHM systems of unique buildings. Thus, the following tasks are solved:

1. Formulation of basic theoretical foundations of advanced methodology of structural health monitoring.
2. Development of parameterized finite element models of buildings (so-called “design” and “monitoring-oriented” models).
3. Adaptation (calibration) of finite element models in accordance with results of measurements.
4. Introduction of effective technology of measurements of natural frequencies and modal shapes.
5. Introduction of correct approach to structural evaluation in real situation of building.
6. Approbation of advanced methodology of structural health monitoring.

2. Methods

2.1. Formulation of basic theoretical foundations of advanced methodology of structural health monitoring

Block diagram and content of developed computational and experimental methodology of structural health monitoring dealing with load-bearing structures of unique buildings, is presented in Figure 1.

So-called “start” (“design”) finite element model is normally developed to study the load-bearing capacity of the current version of the project. Parameterized “monitoring-oriented” three-dimensional dynamic finite element model for each significant stage of life cycle of the building (the stages of construction and operation) is constructed or modified, verified and adapted in accordance with the measured data. The main criterion for the adaptation is the correspondence of calculated and measured spectrum of the natural frequencies and mode shapes in the entire frequency range, significant for the assessment of system-wide changes and for identification – localization of possible defects.

Computational assessment of load-bearing capacity of structures is carried out in accordance with design codes with the use of “design” and “monitoring-oriented” finite element models based on design and measured parameters of structures, foundation, loads etc. Basic peculiarities of components of proposed methodology of structural health monitoring are discussed in the distinctive paper.

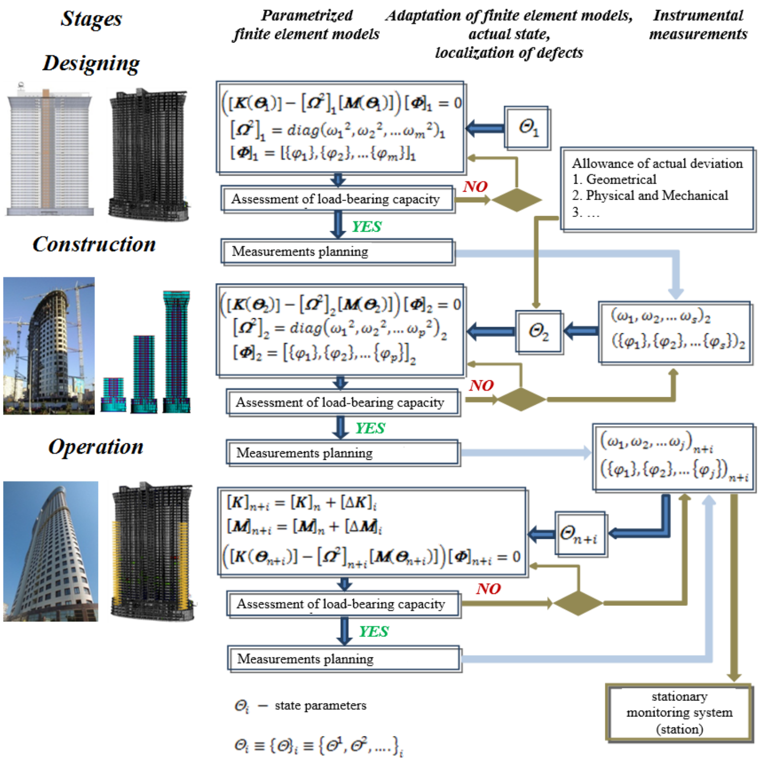

Figure 1. Block diagram and content of developed computational and experimental methodology of structural health monitoring dealing with load-bearing structures of unique buildings

2.2. Parameterized finite element models of buildings (“design” and “monitoring-oriented” models)

Three-dimensional shell-beam finite element model (models) of coupled systems “foundation – building” are normally constructed for strain-stress state analysis and load-bearing capacity of actual design version. It is so-called “start” (“design”) model for subsequent parameterization and adaptation.

Vector of parameters of model has the form

$$\theta_l=\{\theta\}_l=\{\theta_1\;\theta_2\;\theta_3\;\ldots\}_l, \tag{1}$$

where l is the number of stage of construction and operation $(l=1{,}2\ldots)$ with corresponding instrumental SHM.

Vector (1) can contain the following measured parameters, which normally differ from design ones: $\theta_1$is dynamic parameters of foundation; θ_2 is physical and mechanical parameters of construction materials (concrete, reinforcement, steel, etc.); θ_3 is geometrical parameters of load-bearing structures (particularly eccentricities and inclinations of walls and columns; θ_4 is measured loads and impacts; θ_5 is stiffness and mass of nominally non-bearing structures (dividing walls, façade structures), included in dynamic operation of structures under weak “background” loads; θ_6 is modeling of structural behavior of several joints in accordance with schemes, different from design ones (for instance, elastic restraint instead of hinge).

Well-known methods of construction of three-dimensional shell-beam dynamic finite element models [20, 21] with allowance for above mentioned factors are realized. Thus, the reduction of the actual class of the concrete in comparison with the project one are taken into account by corresponding reduction in the modulus of elasticity, deviations of the geometric positions of the columns, walls and other load-bearing elements are taken into account by introduction of so-called “rigid inserts” allowing displacement of the elements in the plan, and their inclination.

The most problematic is the allowance for stiffness of dividing walls (especially located inside apartment) and façade structures included in the dynamic operation of the system for the operation stages, under weak background loads. We can use “integrated” approach (a proportional increase of stiffness of the vertical load-bearing structures), and introduction of each non-bearing structure with reduced dynamic stiffness in finite element model (this approach can substantially (at times) increase computational dimension of the model).

Partial eigenvalue problem is formulated and solved for parameterized finite element model (computing of natural frequencies ω_i and mode shapes $\{\varphi_i\}$) of dynamic system has the form

$$[K(\theta_l)][\Phi] = [\Omega^2][M(\theta_l)][\Phi], \tag{2}$$

where

$$[\Phi] = [\{\varphi_1\} \dots \{\varphi_n\}];\ [\Omega^2] = diag(\omega_1^2 \dots \omega_n^2); \tag{3}$$

$[K(\theta_l)]$ is the global stiffness matrix of system; $[M(\theta_l)]$ is the global mass matrix of system.

The following parameters (criteria) of the solution of partial eigenvalue problem can be used: the number ($\leq n$) of computing lower natural frequencies and mode shapes; frequency range (from Ω_1 to Ω_2), within which all natural frequencies (mode shapes) must be computed; frequency range (from Ω_1 to Ω_2), and the number of computing lower natural frequencies and forms within this range.

If the frequency range is given, shift σ of stiffness matrix within triangulation procedure and eigenvalue analysis must be done. Recommended value of this shift σ can be defined by formula

$$\sigma = -0.5 \cdot (\Omega_1^2 + \Omega_2^2). \tag{4}$$

In accordance with recommendations from [4] the most advanced and competitive methods of solution of generalized and partial eigenvalue problems (subspace iteration method, and block Lanczos method) can be used as basic methods. Numerous computational experiments (including samples with “contrasting” ill-conditioned systems and systems with multiple eigenvalues) showed reliability and efficiency of current implementations of these methods. Experience has proven that Lanczos method had undeniable advantages in high speed of computing of the given number of eigenvalues and eigenvectors for practical problems (of high dimension; up to 10 million of unknowns (dynamic degrees of freedom)) of finite element analysis of unique buildings.

2.3. Adaptation (calibration) of finite element models in accordance with results of measurements

Two main groups of approaches are used for adaptation of finite element models in accordance with results of dynamic monitoring data: “intuitive-engineering” approaches and mathematically formalized approaches. The first group of approaches, which is the most popular at this time in Russia, leaves wide scope for interpretation of the calculated and measured dynamic characteristics. We should note the most severe and challenging approach from the second group, which is based on numerical solution of incorrect inverse problems by Tikhonov regularization method. It should be noted that algorithms and software, enabling identification of the actual status and localization of defects for simple linear-elastic structures (beam and plate on elastic (Winkler) foundation, frame, framework etc.) have been already developed.

Let’s consider one of the versions of corresponding algorithm based on solution of nonlinear optimization problem (i.e. minimization of objective function):

$$\min_{\theta} \Pi(\theta) = \frac{1}{2}\sum_{i=1}^{N_{md}} a_i \,\|\varphi_i - \hat{\varphi}_i\|^2 \text{on condition that } R(\theta) \geq 0. \tag{5}$$

Sensitivity function is defined by formula

$$\Pi_{,\theta} = \sum_{i=1}^{N_{md}} a_i \,\|\varphi_i - \hat{\varphi}_i\|\, \varphi_{i_{,\theta}};\ \ \varphi_{i_{,e}} = -\sum_{i \neq j}^{N_{md}} \frac{\varphi_i^T K_{,\theta} \varphi_j}{(\lambda_i - \lambda_j)\varphi_i^T M \varphi_i} \varphi_i \ (i \neq j) \tag{6}$$

Regularization has the form

$$\min_{\theta} \Pi(\theta) = \frac{1}{2}\sum_{i=1}^{N_{md}} a_i \,\|\varphi_i - \hat{\varphi}_i\|^2 + \frac{\beta}{2}\|K(\theta) - K(\theta_0)\|^2 \text{on condition that } R(\theta) \leq 0, \tag{7}$$

where $\theta = \{\theta\}$=$\{\theta_1\, \theta_2\, \theta_3\, \dots\}$ is previously user-defined vector of parameters of model; α is weight coefficients; φ_i and $\hat{\varphi}_i$ are computered and measured natural mode shapes; $R(\theta)$ is constrain with respect to parameters; λ_i is computered eigenvalues (angular frequencies squared); θ_0 is initial state; β is parameter of regularization; K is the global stiffness matrix; M is the global mass matrix.

It is necessary to note specific requirements to accuracy of structural design and instrumental measurements (including modal analysis in corresponding significant frequency range).

2.4. Technology of measurements of natural frequencies and modal shapes

As follows from the common engineering sense and confirmed by formal above-mentioned mathematical manipulations, seismometric method of measurement should provide reasonable accuracy of computing of not only lower total-system performance natural frequencies [22] and mode shapes but also natural frequencies and mode shapes corresponding to local deviations of state of structure (including structural failures). Besides, efficiency and economic competitiveness are also provided.

Analysis of available sources showed that so-called standing wave method, proposed by Professor A.F. Emanov, is fully consistent with these principles and criteria. Standing wave field, different from other waves by coherence property in time, is always formed in closed spaces. Standing waves extraction from recorded wave fields on filtering basis by coherence in time and conversion of nonsimultaneous observations in simultaneous standing waves records in studied objects forms the basis of standing wave method. The method performs well in study of self-induced buildings vibrations. Amplitudes and phases maps of standing waves in set of natural frequencies fully characterize object and allow to determine not only seismic stability, but realize physical state diagnostics at a constructional elements level. In microzoning the standing wave method performs well as direct research method of resonant properties of section. As a result of standing wave method use we have set of section natural frequencies and vibration amplification maps. On the basis of maps of standing wave phases a resonance type is simply set. The resonances, formed as multiples between horizontal boundaries, have the same close phase on area, whereas in lenses and block mediums horizontal resonances may appear characterized by banded change of areal phase. Combination of high-accuracy study of resonant properties of areas and buildings provides a new echelon of accuracy in seismic risk assessment [4, 15, 18].

Russia already has positive experience of using this method to determine the dynamic characteristics of dams, bridges and buildings. However, there is no such experience for high-rise buildings, complexes and long span structures. It is planned to fill this gap in research on real objects.

2.5. Structural evaluation in real situation of building

Analysis of stress-strain state and load-bearing capacity of structures is carried out in accordance with the design codes and corresponding criteria with the use of finite element model comprising parameters of “monitoring-oriented” and design models.

Static and dynamic (including seismic) stress-strain state for stage number *l* can be obtained after solution of system of linear algebraic equations. In particular, we have displacement equations of equilibrium

$$[K(\Theta_l)][\{u\}_1 \dots \{u\}_m] = [\{F(\Theta_l)\}_1 \dots \{F(\Theta_l)\}_m] \tag{8}$$

and displacement equations of motion

$$[M(\Theta_l)]\{\ddot{u}\} + [C(\Theta_l)]\{\dot{u}\} + [K(\Theta_l)]\{u\} = \{F(\Theta_l)\}. \tag{9}$$

Stability analysis (computing of lower critical loads λ_i and modes of buckling φ) can be done as a result of solution of partial eigenvalue problem

$$[K(\Theta_l)][\Phi] = [\Lambda][K_G(\Theta_l)][\Phi], \tag{10}$$

where

$$[\Phi] = [\{\varphi_1\} \dots \{\varphi_n\}]; \;\; [\Lambda] = diag(\lambda_1 \dots \lambda_n). \tag{11}$$

This enables the additional (as compared with the dynamic model), the properties, namely, parameters of foundation, stiffness and loads (set of parameters Θ_l). The model is complemented by data measures within SHM.

The proposed approach allows verification of results of progressive collapse analysis at each stage of SHM based on the actual state of the object.

Planning for measurement at the current stage of SHM should be done with the use of results of the previous stage. Thus, the detection of “suspicious” of natural frequencies and mode shapes requires installation of a sufficient number of sensors for the measurements for the qualitative identification of these frequencies and shapes. However it should be noted that for most SHM applications, the number of available sensors for monitoring is usually significantly less than the number of potential monitoring locations.

3. Results and Discussion

We considered so-called Evolution Tower as a vital object for approbation of proposed methodology of SHM. One of the most ambitious skyscraper projects in Moscow, Evolution Tower is part of the Moscow International business center Moscow City. The impressive design of this 255 meters high skyscraper, its well-developed facilities and efficient state-of-the art engineering services form most comfortable conditions for work and rest (Figure 2).

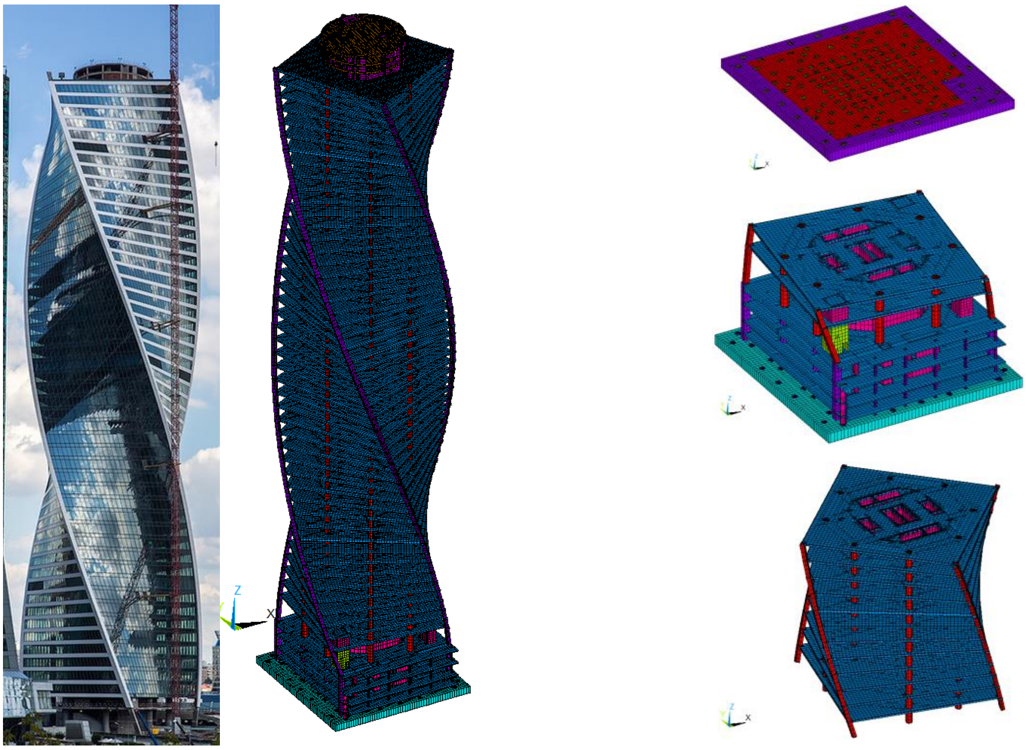

Figure 2. Evolution tower. Building and corresponding finite element models

Basing on the files of the research activity customer in the form of AutoCAD and the set of drawings in the software ANSYS, a “design” shell-beam finite element model (FE model) of a building was constructed (Figure 1). Then basing on the “design” (ideal) model another two models were developed: “actual no. 1” – finite element model of an object, in which the deviations of piles from the designed positions were taken into account, that were found out as a result of investigation; “actual no. 2” – finite element model of an object, in which the deviations of walls from the designed positions were taken into account, that were found out as a result of investigation.

In frames of verification of finite element models the natural frequencies and vibrational modes of the considered system were estimated (for “design” and “actual no. 1” models), which means almost most informative test tasks were solved, which, from the one hand, integrate many factors and parameters of the design models, and, from the other, allow detecting their difference. Thus determined natural frequencies and vibration modes of the building were expectable characteristic (for the objects of a similar type) in quality and quantity senses (in terms of natural frequencies spectrum and systemic forms), which allowed making a conclusion on the correctness and adequacy of the created finite element models to the “design” variant of the building (“actual no. 1” model is dynamically equivalent to the “design” one).

The comparative analysis of the corresponding results for “design” and “actual” finite element models revealed the slight “sensitivity” of the stress-strain state parameters, which predetermine the reliability of the bearing structures (piles, columns and walls), to the considered deviations of the columns and walls from the designed positions, detected as a result of the investigations. It was established, that the design reinforcement of the piles and walls generally possesses an essential reserve compared to the corresponding design parameters for “design” and “actual” models.

Basing on the results of the investigations the authors made a conclusion on the correspondence of the design parameters of the stress-strain state and reliability of the bearing structures of a high-rise building to the specified criteria of stability and deformability at set actual deviations of the reinforced concrete structures from the designed positions, detected as a result of field measurements (account for eccentricities and vertical deviations [17, 20].

The obtained results of the mathematical simulation of a building – static displacements, natural frequencies and vibration modes – may (и and as authors believe, should) be used at developing and implementing the program and methods of monitoring the state of the foundation and bearing structures of a building on all the stages of its operating life [4, 23, 24].

4. Conclusion

Generally the finite element method (FEM) method is nowadays a very powerful computer aided simulation technique, allowing the user to study any kind of problem virtually without limitation in model size and complexity.

Finally we can formulate the main results.

1. Formulation of basic theoretical foundations of advanced methodology of structural health monitoring is presented

2. Parameterized finite element models of buildings (so-called “design” and “monitoring-oriented” models) are proposed.

3. Algorithm of adaptation (calibration) of finite element models in accordance with results of measurements is described.

4. Effective technology of measurements of natural frequencies and modal shapes and correct approach to structural evaluation in real situation of building are introduced.

5. The results of the approbation of advanced methodology of SHM were very satisfactory and were discussed in this paper. Since the investigated cases are taken from real structures, it can be concluded that the proposed advanced methodology can be a valuable tool for SHM.

6. Thus only the instrumental monitoring system, based on results of finite element analysis and comparison with measured data allows performing planning activities to prepare for and respond to changes in state of critical structures and drawing conclusions about the actual state and the possibility of further safe operation of the building.

As we have already mentioned, the monitoring of building structures is rather complicated due to complex relationship between various loads and structural members. However, if the proposed advanced methodology of SHM is developed, it will have a positive effect on the maintenance of structures.

5. Acknowledgements

The Reported study was funded by Government Program of the Russian Federation “Development of science and technology” (2013-2020) within Program of Fundamental Researches of Ministry of Construction, Housing and Utilities of the Russian Federation and Russian Academy of Architecture and Construction Sciences, the Research Projects 7.1.1, 7.1.2 and 7.4.17”.

References

1. Masciotta M.-G., Ramos L.F., Lourenco P.B. The importance of structural monitoring as a diagnosis and control tool in the restoration process of heritage structures: A case study in Portugal. *Journal of Cultural Heritage.* 2017, http://dx.doi.org/10.1016/j.culher.2017.04.003.
2. Papa U., Russo S., Lamboglia A., Del Core G., Iannuzzo G. Health structure monitoring for the design of an Innovative UAS fixed wing through inverse finite element method (iFEM). *Aerospace Science and Technology*. 2017, http://dx.doi.org/10.1016/j.ast.2017.07.005.

Литература

1. Masciotta M.-G., Ramos L.F., Lourenco P.B. The importance of structural monitoring as a diagnosis and control tool in the restoration process of heritage structures: A case study in Portugal // Journal of Cultural Heritage. 2017, http://dx.doi.org/10.1016/j.culher.2017.04.003.
2. Papa U., Russo S., Lamboglia A., Del Core G., Iannuzzo G. Health structure monitoring for the design of an Innovative UAS fixed wing through inverse finite element method (iFEM) // Aerospace Science and Technology. 2017.

3. Belostotskiy A.M., Akimov P.A. Obzorno-analiticheskoye issledovaniye normativno-metodicheskoy literatury v oblasti monitoringa zdaniy i sooruzheniy [Review and analysis of design codes and methodological literature in the field of structural health monitoring]. *International Journal for Computational Civil and Structural Engineering.* 2016. No. 2(12). Pp. 42–64.
4. Belostotsky A.M., Akimov P.A. Adaptive finite element models coupled with structural health monitoring systems for unique buildings. *Procedia Engineering.* 2016. No. 153. Pp. 83–88.
5. Belostotsky A.M., Akimov P.A., Kaytukov T.B., Petryashev N.O., Petryashev S.O., Negrozov,O.A. Strength and stability analysis of load-bearing structures of Evolution tower with allowance for actual positions of reinforced concrete structural members. *Procedia Engineering.* 2016. No. 153. Pp. 95–102.
6. Brownjohn J.M.W. Structural health monitoring of civil infrastructure. *Philosophical Transactions of the Royal Society A*. 2007. No. 1851(365). Pp. 589–622.
7. Belostotskiy A.M., Akimov P.A., Afanasyeva I.N., Kaytukov T.B. Contemporary problems of numerical modelling of unique structures and buildings. *International Journal for Computational Civil and Structural Engineering*. 2017. No. 2(13). Pp. 9–34.
8. Belostotskiy A.M., Akimov P.A. Nauchno-issledovatelskiy tsentr StaDiO. 25 let na fronte chislennogo modelirovaniya [25-th Anniversary of scientific research centre StaDyO]. *International Journal for Computational Civil and Structural Engineering.* 2016. No. 1(12). Pp. 9–34. (rus).
9. Suhaimi S.A., Azemi S.N., Jack S.P. Evolution of structural health monitoring. *Journal of Built Environment, Technology and Engineering.* 2016. No. 1. Pp. 76–80.
10. Kim J.-T., Sim S.-H., Cho S., Yun C.-B., Min J. Recent R&D activities on structural health monitoring in Korea. *Structural Monitoring and Maintenance.* 2016. No. 1(3). Pp. 91–114.
11. Ryu H.-H., Kim J.-S., Choi E.-G., Lee S.-H. Preliminary design of structural health monitoring for high-rise buildings. *International Journal of High-Rise Buildings.* 2017. No. 3(6). Pp. 279–284.
12. Mordini A., Savov K., Wenzel H. The finite element model updating: A powerful tool for structural health monitoring. *Structural Engineering International.* 2007. No. 4. Pp. 352–358.
13. Brownjohn J.M., Pan T.C., Deng X. Correlating dynamic characteristics from field measurements and numerical analysis of a high rise building. *Earthquake Engineering & Structural Dynamics.* 2000. No. 29(4). Pp. 523–543.
14. Novikov P.I. Identifying Real Stiffness Properties of Structural Elements of Adapted Finite-Element Models of Buildings and Structures - Part 1: Problem Setting. *Applied Mechanics and Materials.* 2014. No. 670-671. Pp. 732–735.
15. Yemanov A.F., Krasnikov A.A. Primeneniye metoda stoyachikh voln dlya issledovaniy seysmoizolirovannykh zdaniy [The use of standing waves method in study of seismically isolated buildings]. *Voprosy inzhenernoy seysmologii.* 2015. No. 4(42). Pp. 37–64. (rus)
16. Chang P.C., Flatau A., Liu S.C. Review paper: Health monitoring of civil infrastructure. *Structural Health Monitoring.* 2003. No. 2(3). Pp. 257–267.
17. Zhou H.Z. Recent advances in research on damage diagnosis for civil engineering structures. *China Civil Engineering Journal.* 2003. No. 36(5). Pp. 105–110.
18. Krasnikov A.A., Yemanov A.F., Bakh A.A. Otsenka polnoty konechnoelementnykh modeley inzhenernykh sooruzheniy po eksperimentalnym dannym metoda stoyachikh voln [Finite element model of engineering structures

3. Белостоцкий А.М., Акимов П.А. Обзорно-аналитическое исследование нормативно-методической литературы в области мониторинга зданий и сооружений // International Journal for Computational Civil and Structural Engineering. 2016. № 2(12). С. 42–64.
4. Belostotsky A.M., Akimov P.A. Adaptive finite element models coupled with structural health monitoring systems for unique buildings // Procedia Engineering, 2016. № 153. Pp. 83–88.
5. Belostotsky A.M., Akimov P.A., Kaytukov T.B., Petryashev N.O., Petryashev S.O., Negrozov,O.A. Strength and stability analysis of load-bearing structures of Evolution tower with allowance for actual positions of reinforced concrete structural members // Procedia Engineering. 2016. № 153. Pp. 95–102.
6. Brownjohn J.M.W. Structural health monitoring of civil infrastructure // Philosophical Transactions of the Royal Society A. 2007. № 1851(365). Pp. 589–622.
7. Белостоцкий А.М., Акимов П.А., Афанасьева И.Н., Кайтуков Т.Б. Contemporary problems of numerical modelling of unique structures and buildings // International Journal for Computational Civil and Structural Engineering. 2017. № 2(13). С. 9–34.
8. Белостоцкий А.М., Акимов П.А. Научно-исследовательский центр СтаДиО. 25 лет на фронте численного моделирования // International Journal for Computational Civil and Structural Engineering. 2016. № 1(12). С. 9–34.
9. Suhaimi S.A., Azemi S.N., Jack S.P. Evolution of structural health monitoring // Journal of Built Environment, Technology and Engineering. 2016. № 1. Pp. 76–80.
10. Kim J.-T., Sim S.-H., Cho S., Yun C.-B., Min J. Recent R&D activities on structural health monitoring in Korea // Structural Monitoring and Maintenance. 2016. № 1(3). Pp. 91–114.
11. Ryu H.-H., Kim J.-S., Choi E.-G., Lee S.-H. Preliminary design of structural health monitoring for high-rise buildings // International Journal of High-Rise Buildings. 2017. № 3(6). Pp. 279–284.
12. Mordini A., Savov K., Wenzel H. The finite element model updating: A powerful tool for structural health monitoring // Structural Engineering International. 2007. № 4. Pp. 352-358.
13. Brownjohn J.M., Pan T.C., Deng X. Correlating dynamic characteristics from field measurements and numerical analysis of a high rise building // Earthquake Engineering & Structural Dynamics. 2000. № 29(4). Pp. 523–543.
14. Novikov P.I. Identifying Real Stiffness Properties of Structural Elements of Adapted Finite-Element Models of Buildings and Structures - Part 1: Problem Setting // Applied Mechanics and Materials. 2014. № 670-671. Pp. 732–735.
15. Еманов А.Ф., Красников А.А. Применение метода стоячих волн для исследований сейсмоизолированных зданий // Вопросы инженерной сейсмологии. 2015. № 4(42). С. 37–64.
16. Chang P.C., Flatau A., Liu S.C. Review paper: Health monitoring of civil infrastructure // Structural Health Monitoring. 2003. № 2(3). Pp. 257–267.
17. Zhou H.Z. Recent advances in research on damage diagnosis for civil engineering structures // China Civil Engineering Journal. 2003. № 36(5). Pp. 105–110.
18. Красников А.А., Еманов А.Ф., Бах А.А. Оценка полноты конечноэлементных моделей инженерных сооружений по экспериментальным данным метода стоячих волн // Интерэкспо Гео-Сибирь. 2017. № 4(2). С. 179–184.
19. Friswell M.I., Mottershead J.E., Ahmadian H., Experimental test data: Parameterization and regularization // Transactions of the Royal Society of London, Series A,

Белостоцкий А.М., Акимов П.А., Негрозов О.А., Петряшев Н.О., Петряшев С.О., Щербина С.В., Каличава Д.К., Кайтуков Т.Б. Адаптивные конечноэлементные модели в системах мониторинга зданий и сооружений // Инженерно-строительный журнал. 2018. № 2(78). С. 169–178.

completeness assessment by standing waves method experimental data]. *Interekspo Geo-Sibir.* 2017. No. 4(2). Pp. 179–184. (rus)

19. Friswell M.I., Mottershead J.E., Ahmadian H., Experimental test data: Parameterization and regularization. *Transactions of the Royal Society of London, Series A, Special Issue on Experimental Modal Analysis*. 2001. No. 359(1778). Pp. 169–186.
20. Ebrahimian H., Astroza R., Conte J.P. De Callafon R.A. Nonlinear finite element model updating for damage identification of civil structures using batch Bayesian estimation. *Mechanical Systems and Signal Processing*. 2017. No. 84(B). Pp. 194–222.
21. Kefal A., Tessler A., Oterkus E. An enhanced inverse finite element method for displacement and stress monitoring of multilayered composite and sandwich structures. *Composite Structures.* 2017. No. 179, Pp. 514–540.
22. Sartorato M., De Medeiros R., Vandepitte D., Tita V. Computational model for supporting SHM systems design: Damage identification via numerical analyses. *Mechanical Systems and Signal Processing.* 2017. No. 84(A). Pp. 445–461.
23. Ursos M.E., Tingatinga E.A., Longalong R.E. A finite element based method for estimating natural frequencies of locally damaged homogeneous beams. *Procedia Engineering.* 2017. No. 199. Pp. 404–410.
24. Zhong R., Zong Z., Niu J., Liu Q., Zheng P. A multiscale finite element model validation method of composite cable-stayed bridge based on Probability Box theory. *Journal of Sound and Vibration.* 2016. No. 370. Pp. 111–131.

Special Issue on Experimental Modal Analysis. 2001. № 359(1778). Pp. 169–186.

20. Ebrahimian H., Astroza R., Conte J.P. De Callafon R.A. Nonlinear finite element model updating for damage identification of civil structures using batch Bayesian estimation // Mechanical Systems and Signal Processing. 2017. № 84(B). Pp. 194–222.
21. Kefal A., Tessler A., Oterkus E. An enhanced inverse finite element method for displacement and stress monitoring of multilayered composite and sandwich structures // Composite Structures. 2017. № 179. Pp. 514–540.
22. Sartorato M., De Medeiros R., Vandepitte D., Tita V. Computational model for supporting SHM systems design: Damage identification via numerical analyses // Mechanical Systems and Signal Processing. 2017. № 84(A). Pp. 445–461.
23. Ursos M.E., Tingatinga E.A., Longalong R.E. A finite element based method for estimating natural frequencies of locally damaged homogeneous beams // Procedia Engineering. 2017. № 199. Pp. 404–410.
24. Zhong R., Zong Z., Niu J., Liu Q., Zheng P. A multiscale finite element model validation method of composite cable-stayed bridge based on Probability Box theory // Journal of Sound and Vibration. 2016. № 370. Pp. 111–131.

Alexander Belostotsky,
+7(499)706-88-10; amb@stadyo.ru

Pavel Akimov,
+7(499)706-88-10; pavel.akimov@gmail.com

Oleg Negrozov,
+7(958)819-64-30; genromgsu@gmail.com

Nikolay Petryashev,
+7(499)929-50-17; stadyo@stadyo.ru

Sergey Petryashev,
+7(499)929-50-17; petsero@mail.ru

Sergey Sherbina,
+7(499)929-50-17; serg_msk89@mail.ru
Dmitry Kalichava,
+7(495)120-04-05; 2109962@gmail.com

Taymuraz Kaytukov,
+7(495)625-81-53; tkaytukov@gmail.com

Александр Михайлович Белостоцкий,
+7(499)706-88-10; эл. почта: amb@stadyo.ru

Павел Алексеевич Акимов,
+7(499)706-88-10;
эл. почта: pavel.akimov@gmail.com

Олег Александрович Негрозов,
+7(958)819-64-30;
эл. почта: genromgsu@gmail.com

Николай Олегович Петряшев,
+7(499)929-50-17; эл. почта: stadyo@stadyo.ru

Сергей Олегович Петряшев,
+7(499)929-50-17; эл. почта: petsero@mail.ru

Сергей Викторович Щербина,
+7(499)929-50-17;
эл. почта: serg_msk89@mail.ru

Дмитрий Котэвич Каличава,
+7(495)120-04-05;
эл. почта: 2109962@gmail.com

Таймураз Батразович Кайтуков,
+7(495)625-81-53;
эл. почта: tkaytukov@gmail.com

Belostotsky A.M., Akimov P.A., Negrozov O.A., Petryashev N.O., Petryashev S.O., Sherbina S.V., Kalichava D.K., Kaytukov T.B. Adaptive finite-element models in structural health monitoring systems. *Magazine of Civil Engineering*. 2018. No. 2. Pp. 169–178. doi: 10.18720/MCE.78.14.