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EARTHQAUKE OF BUILDINGS AND STRUCTURES: REGULATORY "MUST-DO" OR SCIENTIFICALLY SUBSTANTIATED RESULTS

Alexander M. Belostotsky, Alexander I. Nagibovich, Pavel I. Novikov, Vladislav V. Vershinin

National Research Moscow State University of Civil Engineering, Moscow, RUSSIA

Abstract: Within the present article the problem of selection and substantiation of "compensating measures" to provide earthquake resistance of buildings and structures which have deviations from structural regulatory requirements is considered. The authors proposed and tested a theoretical approach to substantiation of earthquake resistance of buildings and structures as opposed to unreasonable utilization of seismic isolation devices. The proposed approach is demonstrated through validation of seismic resistance of the Choreographic Academy building located in Sevastopol city with the use of a numerical (finite element) analysis performed in a physically nonlinear dynamic formulation, taking into account the structural solution compensating extra factor.

Keywords: mathematical modeling, numerical methods, finite element method, earthquake resistance, seismic protection, stress-strain state, structural solutions compensating factor, scientific and technical support

СЕЙСМОСТОЙКОСТЬ ЗДАНИЙ И СООРУЖЕНИЙ: НОРМАТИВНАЯ "ОБЯЗАЛОВКА" ИЛИ НАУЧНО-ОБОСНОВАННЫЕ РЕЗУЛЬТАТЫ

А.М. Белостоцкий, А.И. Нагибович, П.И. Новиков, В.В. Вершинин

Национальный исследовательский Московский государственный строительный университет,
г. Москва, РОССИЯ

Аннотация: в статье представлена проблема выбора и обоснования «компенсирующих мероприятий» для обеспечения сейсмостойкости зданий и сооружений с отступлениями от нормативных конструктивных требований. Авторами предложен и апробирован расчетный подход к обоснованию сейсмостойкости зданий и сооружений в противовес необоснованному применению сейсмоизолирующих устройств. Предложенный подход демонстрируется на примере обоснования сейсмостойкости здания Хореографической академии в г. Севастополь с реализацией численного (конечно-элементного) моделирования в физически-нелинейной динамической постановке с учетом дополнительного компенсирующего коэффициента конструктивных решений.

Ключевые слова: математическое моделирование, численные методы, метод конечных элементов, сейсмостойкость, сейсмозащита, напряженно-деформированное состояние, компенсирующий коэффициент конструктивных решений, научно-техническое сопровождение

PROBLEM RELEVANCE

For unique buildings, structures and complexes with bold modern architecture, designed and constructed in earthquake-prone regions, it is a common issue of compelled deviations from structural requirements prescribed by current building codes [9]. In such cases certain compensating measures are usually designed.

One of the ways to decrease seismic forces is to construct a specific seismic protection system. There is a view that installation of seismic isolation devices (seismic isolation pads, dampers, etc.) by itself is enough to provide sufficient earthquake resistance. Such design solutions are often proposed without any theoretical substantiation. Evidently, installation of seismic isolation and (or) damping devices will change the eigen spectrum of a structure, but, without a sophisticated theoretical analysis, it is impossible to determine whether corresponding changes of the structure dynamic response will provide its better earthquake resistance or not.

An alternative proposed and tested on several unique structures by the authors [2] is to use the following measures as compensating ones:

- *Detailed accounting of loads and excitations*, in particular their actual areas of application, seismological parameters, potential earthquake focuses, possible earthquakes and their spectra. Design response spectra and ground acceleration histories are developed basing onto seismic microzonation of a construction site.
- *Structural solutions extra factor* $\boldsymbol{K_2}$ *is taken into account* during design earthquake analysis and maximum considered earthquake analysis when there are deviations from the requirements of SP 14.13330 [9].
- *Sophisticated theoretical substantiation of structural safety parameters for special load combinations including the seismic loading.* A theoretical substantiation of structural safety is prescribed by SP 14.13330 [9] which requires to account of current standards. Among design parameters are: a location of the construction site, a structure type according to its function, a structure risk category (K_0), a design level of structural damage during an earthquake (K_1), energy dissipation factor (K_ψ), and structural solutions factor (K_2). Also, the following factors altering the stress-strain state of the structural system shall be taken into consideration: foundation bed stiffness, soil-structure interaction, three-dimensional response of the structural system, orientation of the structure relative to the seismic sources, heterogeneous damping in structural elements, and, where necessary, nonlinear properties of structural materials, large deformations and large strains of structural elements and their erection sequence.
- *Scientific and technical support during design and construction* with eventual determination of actual earthquake resistance of a structure using its dynamic characteristics obtained from thorough microseismic-based investigations.

The mentioned issues can be illustrated by a representative example of the Choreographic Academy located in Sevastopol city.

BUILDING DESCRIPTION

The construction site of the educational facility is located in the coastal zone with significant difference of local topography. The building has a planform of open rectangle (114.8×104.9 m) and is divided into six dynamically independent blocks with various number of stories (up to 8 stories), functions and architecture. The general view of the Choreographic Academy is shown in Fig. .

The structural system of the Academy is classified as wall-frame with stiffness cores. The cast-in-place reinforced concrete frame is formed by vertical bearing elements – columns, walls, and stiffness cores (staircase and elevator blocks) – and horizontal floor slabs.

All connections of structural elements are rigid. The foundation is made of cast-in-place reinforced concrete and underlain by natural bed.

The construction site is located in the earthquake-prone region. According to the map OSR-2015-A and SP 14.13330 [9], the seismic intensity at the construction site is 8 grade with a mean return period of 500 years and the probability of 0.90 for the seismic intensity to stay within its nominal value within a 50-years period (risk level “A”). The construction site is classified as Category II based on the seismic behavior of foundation soils.

a) Architectural rendering б) Construction stage

Figure 1. The general view of the Choreographic Academy

DEVIATIONS FROM THE REGULATORY REQUIREMENTS

The most critical deviation from the requirements of SP 14.13330 [9] refers to *the limit height (number of stories)* of the building. In such cases when the limit number of stories is exceeded due to functional requirements, it is prescribed to utilize a specific seismic protection system. Also, there are deviations concerning the shape of expansion joints as compared to the required one in the cases when separated blocks have significantly different stiffness and (or) mass, foundation type, layout of walls, diaphragms, bracing, stiffness cores and columns.

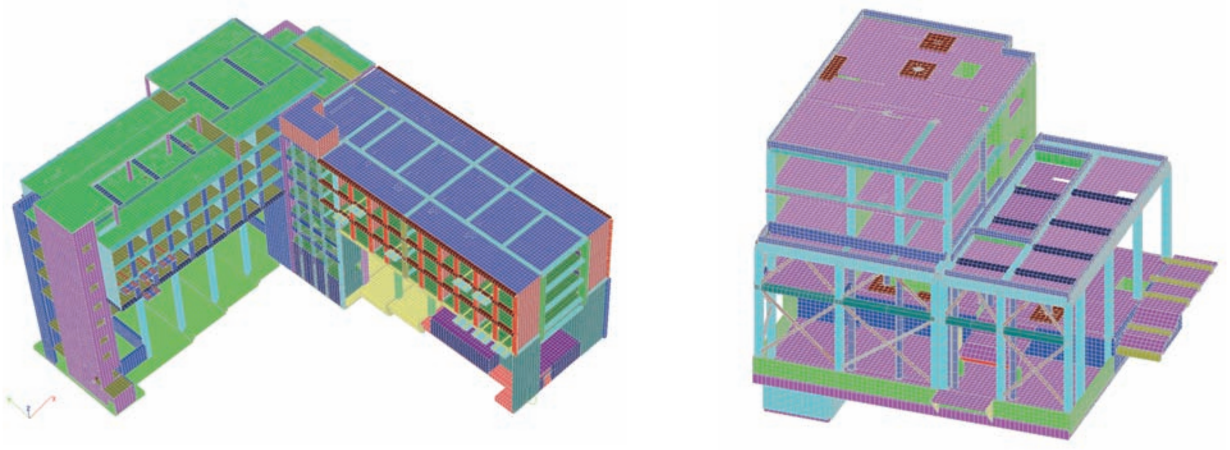
COMPENSATING MEASURES

Initially, at the behest of "seismic marketers", to reduce seismic forces, it was decided to design and construct a special seismic pad beneath the foundation slabs of the building blocks. Also, the building frame was intended to be provided with damping system.

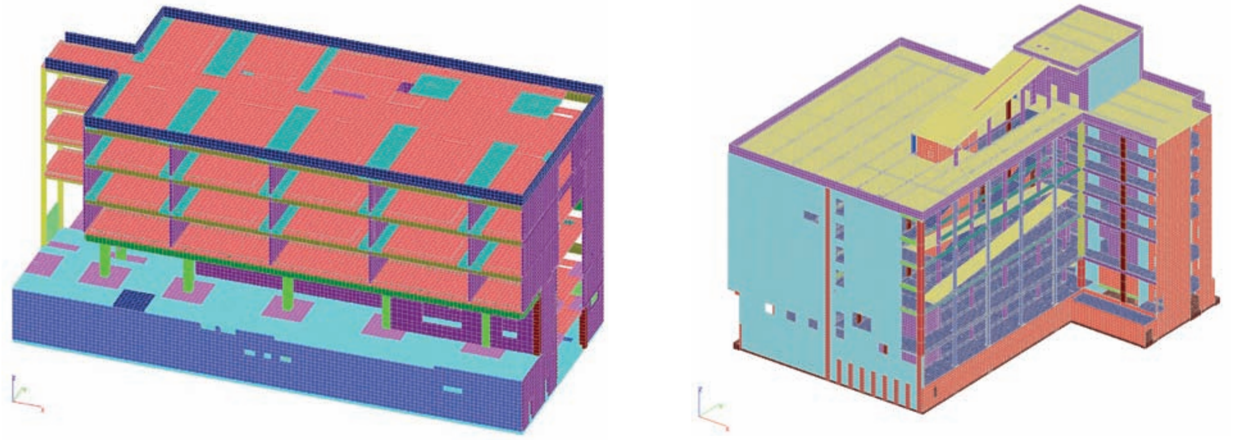
The interesting point is that the Choreographic Academy building locates in the immediate proximity to a unique structure – the Opera and Ballet Theater (Sevastopol city, Fig. 2) which earthquake resistance in the absence of any seismic protection system was successfully substantiated by NIC StaDyO JSC [2]. The results of an elaborated dynamic analysis of the Opera and Ballet Theater building validated the earthquake resistance of the designed structural system without any seismic protection system, which has arisen certain questions concerning necessity of "enforced" measures to provide earthquake resistance of the Choreographic Academy.

The authors proposed an alternative – utilization of "compensating measures" that do not require mandatory seismic isolation. The proposed approach is based onto real (not "fake") complex scientific and technical support including sophisticated theoretical analysis of major structural safety parameters, performed independently of the design analysis.

Figure 2. Architecture rendering of the Opera and Ballet Theater in Sevastopol city



a) Blocks 1 and 2 model *b) Block 3 model*



c) Block 4 model *d) Block 6 model*

Figure 3. Mathematical (finite element) models of the Choreographic Academy blocks

STRUCTURAL MODELING

Three-dimensional finite element structural models of the Choreographic Academy blocks were constructed in SCAD Office 21.1 software using shell type and beam type finite elements. Reinforced concrete columns, beams and bracing were modeled with beam type finite elements, while reinforced concrete foundation slabs, floors, bearing walls were meshed with triangular and quadrilateral shell type finite elements of constant thickness. Foundation bed elastic properties required for the static analysis were determined using KROSS software. Mathematical models of blocks having joint foundation were assembled together, and the full model was analyzed.

Design earthquake effects were determined through modal response spectrum analysis. Three directions of a seismic ground motion were considered: along X and Y horizontal axes and along Z vertical axis. The corresponding response spectra ignoring K_0, K_1, K_ψ, K_2 factors are shown in Fig. 4.

Dead and live gravitational loads were considered according to Table 5.1 of SP 14.13330 [9].

Requirements of SP 13.13330 [9] concerning the minimum value of a combined modal mass participation were fulfilled as well.

Due to the deviations from the requirements of SP 14.13330 [9] (caused by the challenging construction site conditions and functional requirements) design earthquake effects were calculated using structural solutions extra factor K_2 = 1.2. Adopted values of seismic load factors K_0, K_1, K_ψ, K_2 are given in Table 1.

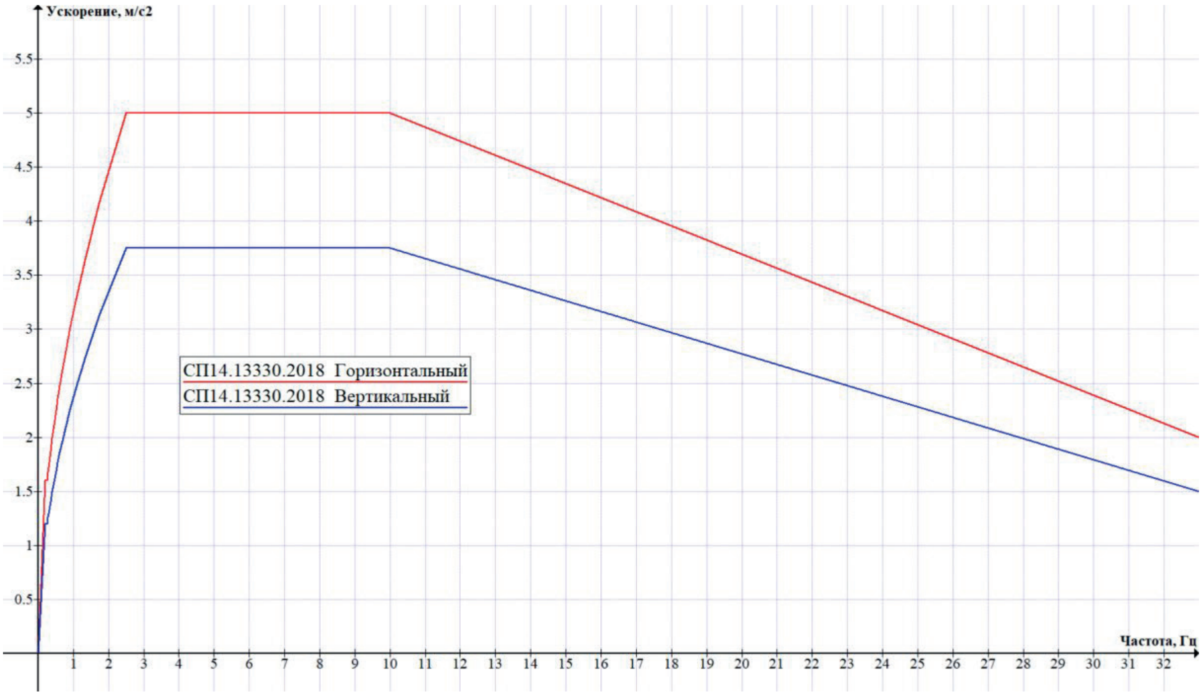


Figure 4. Spectral response acceleration (ignoring K_0, K_1, K_ψ, K_2 factors) for horizontal (colored in red) and vertical (colored in blue) components of the design earthquake according to SP 14.13330.2018

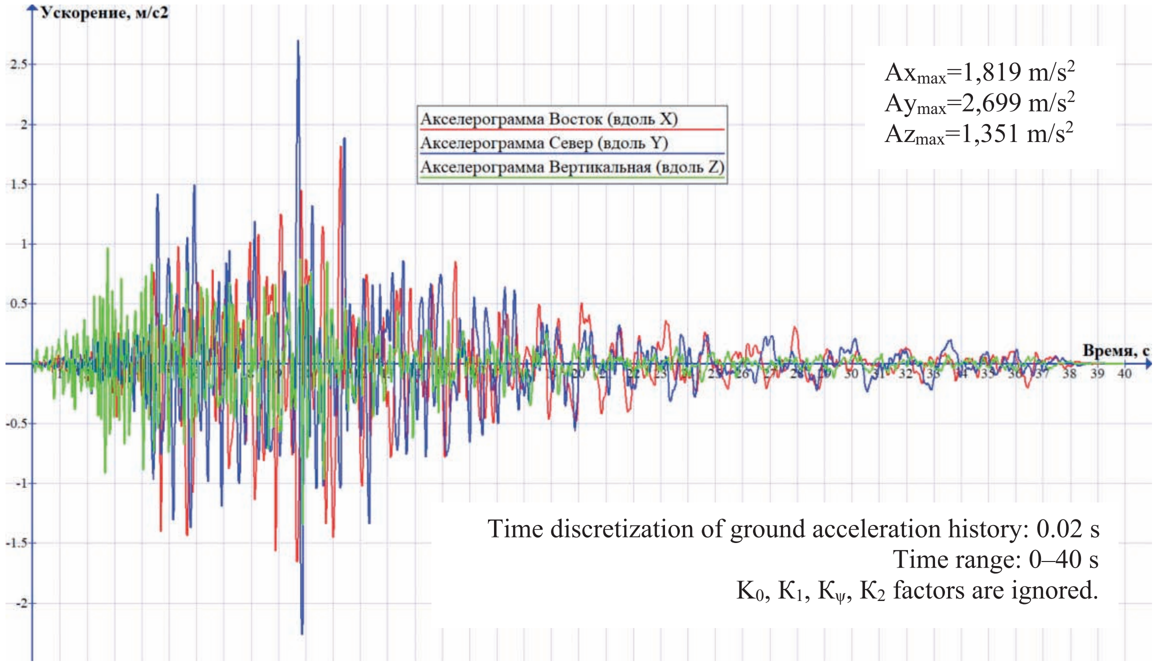
Table 1. Adopted values of seismic load factors

No.	Factor	Design earthquake	Maximum considered earthquake
1	K_0	1,1	1,5
2	K_1	0,3	1,0
3	K_ψ	1,0	1,0
4	K_2	**1,2**	**1,2**

Maximum considered earthquake effects were calculated through nonlinear dynamic analysis with seismic excitation applied in the form of the ground acceleration history having three independent components. To integrate the equations of motion over time, the implicit Newmark scheme was used with a time increment set equal to 0.005 s. Damping in the structural model was defined as the Rayleigh one corresponding to 5% of the critical damping. Within the nonlinear dynamic analysis, reinforcement and concrete of vertical bearing elements were modeled taking their physically nonlinear properties defined as bilinear stress-strain curves into account. Horizontal structural elements were modeled as elastic ones.

The analysis was performed in two stages. At the first stage, dead and live loads were statically applied and retained in the further analysis. At the second stage, a ground displacement history having three independent components and time duration of 25 s came into action. An example of ground displacement history and corresponding ground acceleration history having three independent components and used in calculations are shown in Fig. 5.

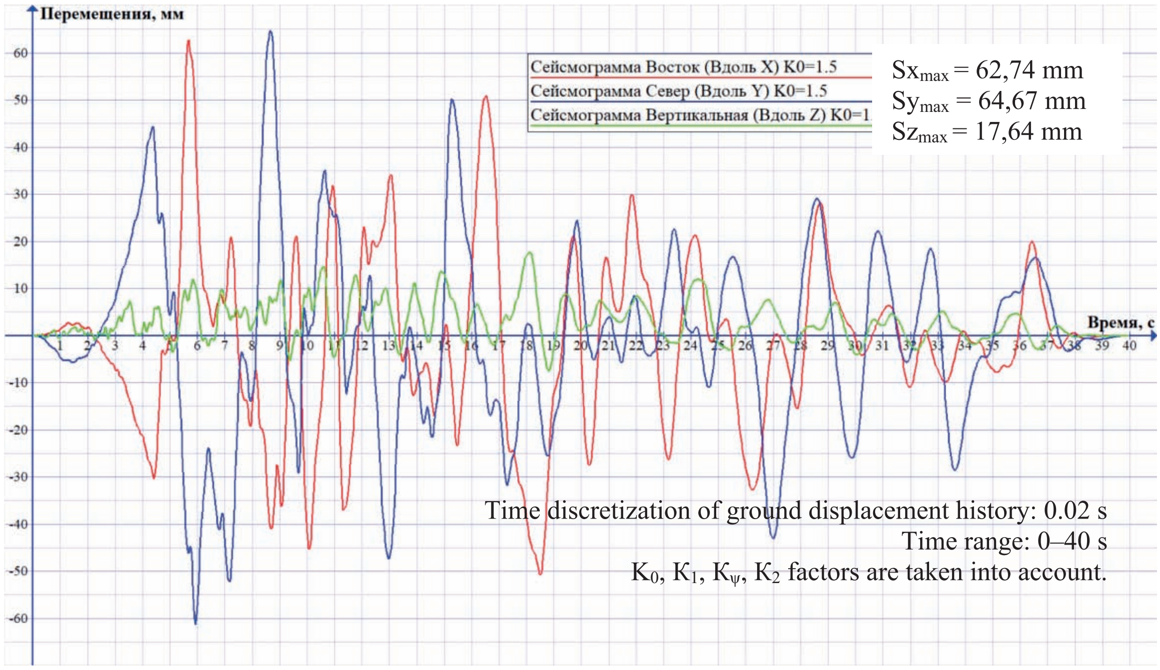
Reinforcement of concrete structural elements was defined in the mathematical model according to design drawings (see, for instance, Fig. 6).



Ax_{max}=1,819 m/s^2
Ay_{max}=2,699 m/s^2
Az_{max}=1,351 m/s^2

Time discretization of ground acceleration history: 0.02 s
Time range: 0–40 s
K_0, K_1, K_ψ, K_2 factors are ignored.

a) Ground acceleration history [m/s^2]

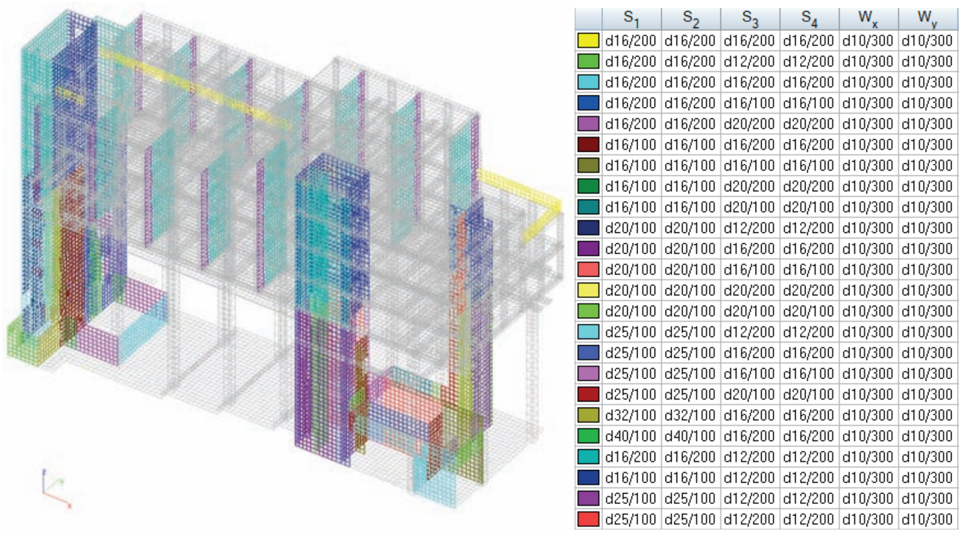


Sx_{max} = 62,74 mm
Sy_{max} = 64,67 mm
Sz_{max} = 17,64 mm

Time discretization of ground displacement history: 0.02 s
Time range: 0–40 s
K_0, K_1, K_ψ, K_2 factors are taken into account.

b) Ground displacement history [mm]

Figure 5. Ground acceleration (Ax, Ay, Az) and displacement (Sx, Sy, Sz) histories



	S_1	S_2	S_3	S_4	W_x	W_y
🟨	d16/200	d16/200	d16/200	d16/200	d10/300	d10/300
🟩	d16/200	d16/200	d12/200	d12/200	d10/300	d10/300
🟦	d16/200	d16/200	d16/200	d16/200	d10/300	d10/300
🟦	d16/200	d16/200	d16/100	d16/100	d10/300	d10/300
🟪	d16/200	d16/200	d20/200	d20/200	d10/300	d10/300
🟥	d16/100	d16/100	d16/200	d16/200	d10/300	d10/300
🟫	d16/100	d16/100	d16/100	d16/100	d10/300	d10/300
🟩	d16/100	d16/100	d20/200	d20/200	d10/300	d10/300
🟦	d16/100	d16/100	d20/100	d20/100	d10/300	d10/300
🟦	d20/100	d20/100	d12/200	d12/200	d10/300	d10/300
🟪	d20/100	d20/100	d16/200	d16/200	d10/300	d10/300
🟥	d20/100	d20/100	d16/100	d16/100	d10/300	d10/300
🟨	d20/100	d20/100	d20/200	d20/200	d10/300	d10/300
🟩	d20/100	d20/100	d20/100	d20/100	d10/300	d10/300
🟦	d25/100	d25/100	d12/200	d12/200	d10/300	d10/300
🟦	d25/100	d25/100	d16/200	d16/200	d10/300	d10/300
🟪	d25/100	d25/100	d16/100	d16/100	d10/300	d10/300
🟥	d25/100	d25/100	d20/100	d20/100	d10/300	d10/300
🟫	d32/100	d32/100	d16/200	d16/200	d10/300	d10/300
🟩	d40/100	d40/100	d16/200	d16/200	d10/300	d10/300
🟦	d16/200	d16/200	d12/200	d12/200	d10/300	d10/300
🟦	d16/100	d16/100	d12/200	d12/200	d10/300	d10/300
🟪	d25/100	d25/100	d12/200	d12/200	d10/300	d10/300
🟥	d25/100	d25/100	d12/200	d12/200	d10/300	d10/300

Figure 6. Wall reinforcement in Block 1 model

RESULTS

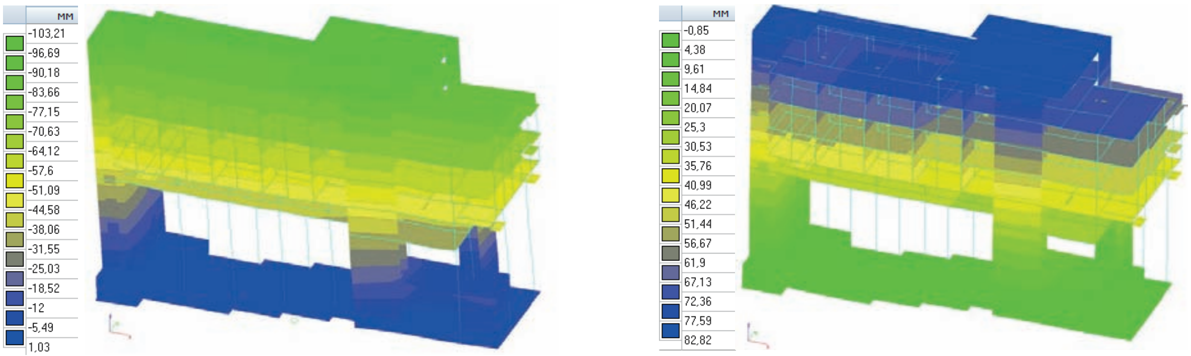
Results of the conducted analyses exhibited consistent distribution of displacements and forces (Figs. 7, 8, 9) in foundation and superstructure structural elements of the Choreographic Academy blocks under special load combinations including the seismic load.

It was determined that design parameters of the building (geometry (layout and cross-sections), material properties, characteristics of element connections, values and combinations of loads) provided compliance with the requirements concerning strength, stability and limited deformations of the structural system and its individual elements.

Nonlinear dynamic analysis of the building response to the special load combination including the maximum considered earthquake applied in the form of the ground motion history (see Fig.5) revealed its spatial and time complexity. Nevertheless, the design reinforcement with the structural solutions compensating extra factor K_2=1.2 taken into account appeared to be enough to provide structural safety.

Some of the results for the block 1 are presented in Figs. 7-11 below.

Zones where the reinforcement reached its yield stress are depicted in Fig. 10. Also, using the SCAD postprocessor tools normal stresses in the most severely strained cross-sections of individual reinforced concrete elements were determined (see Fig.11).



a) Ux, mm, time instant t = 14.20 s

b) Uy, mm, time instant t = 12.70 s

Figure 7. Horizontal displacements induced by the special load combination including the maximum considered earthquake (the presented time instants correspond to the maximum absolute values of the displacement components)

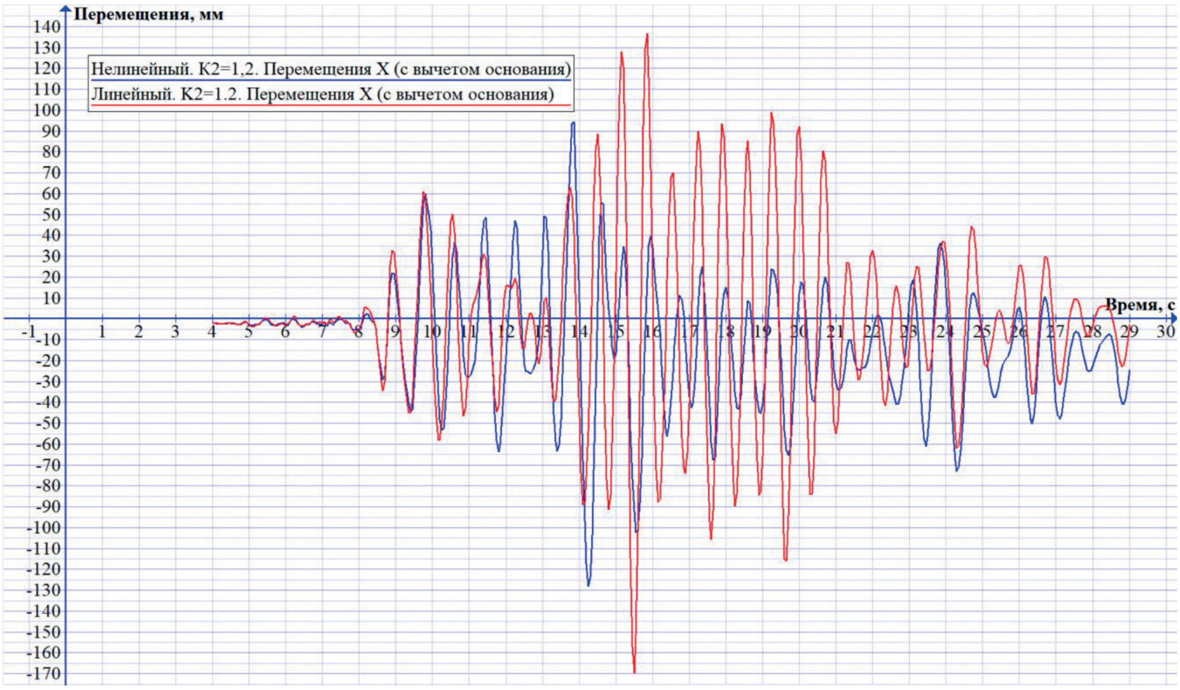


Figure 8. Horizontal displacements along X axis at the top of the block 1 induced by the special load combination including the maximum considered earthquake with the structural solutions extra factor K_2=1.2 taken into account

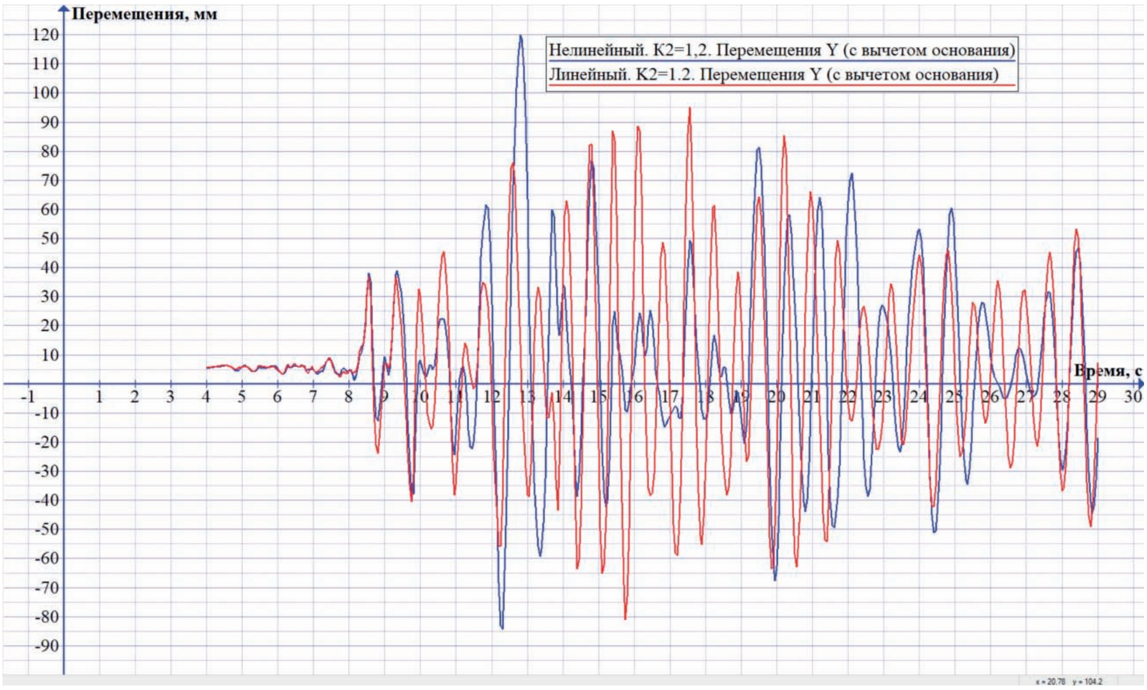
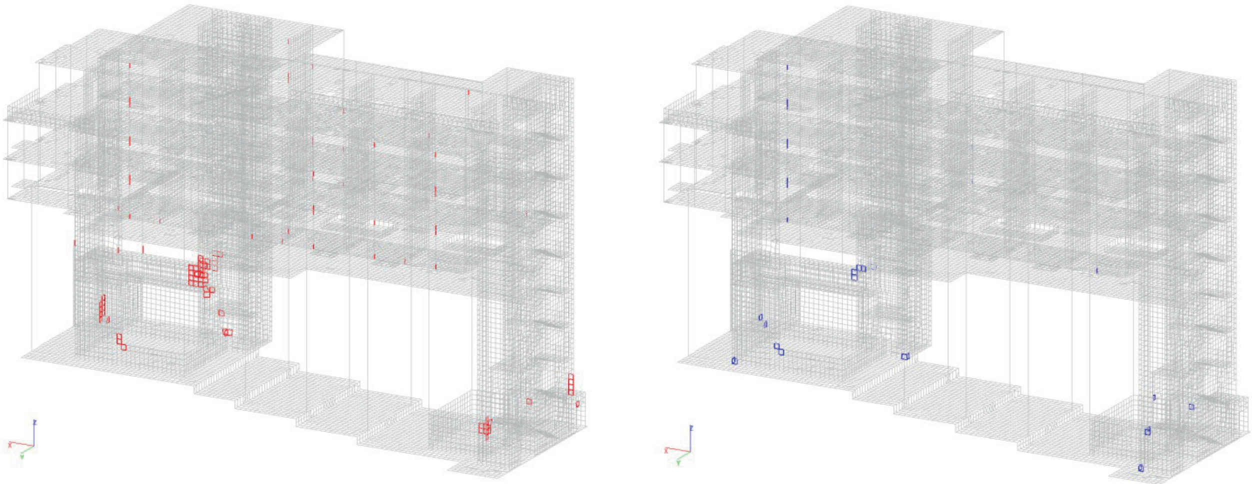


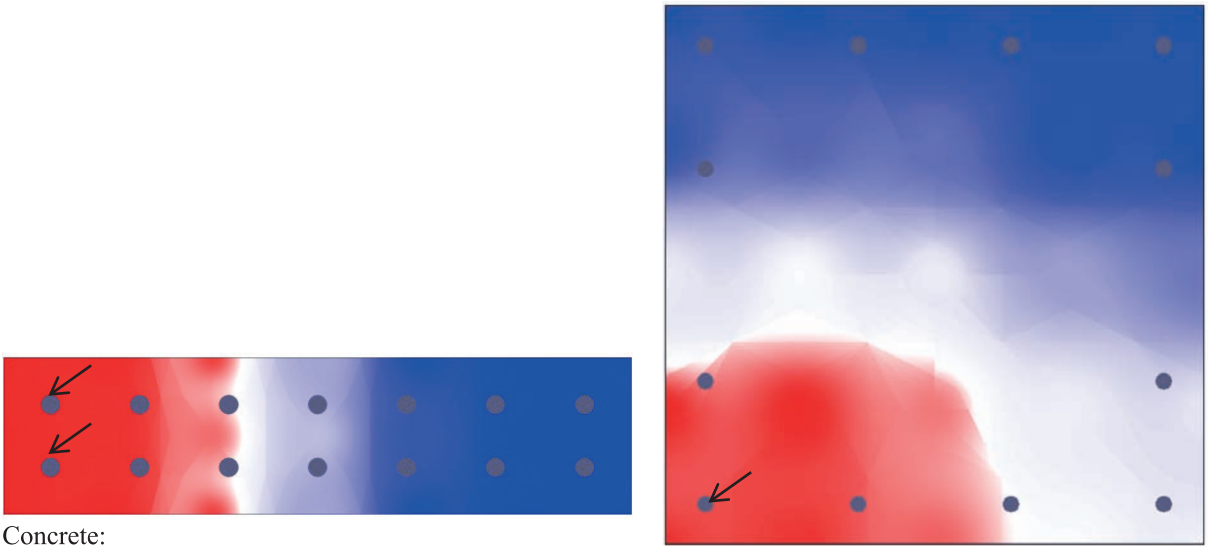
Figure 9. Horizontal displacements along Y axis at the top of the block 1 induced by the special load combination including the maximum considered earthquake with the structural solutions extra factor K_2=1.2 taken into account



a) Finite elements in which the reinforcement reached its yield stress under tension

b) Finite elements in which the reinforcement reached its yield stress under compression

Figure 10. Finite elements in which the reinforcement reached its yield stress due to action of the special load combination including the maximum considered earthquake with the structural solutions extra factor $K_2=1.2$ taken into account



Concrete:

🟦 Compression. The minimum of -17.3 MPa

🟥 Tension. The maximum of 1.29 MPa

Reinforcement rods in which the yield stress of 522 MPa was reached are shown by the arrows

a) Column 800×200 mm on grid lines 16-17/E

Concrete:

🟦 Compression. The minimum of -17.1 MPa

🟥 Tension. The maximum of 1.05 MPa

Reinforcement rods in which the yield stress of 522 MPa was reached are shown by the arrows

b) Column 800×800 mm on grid lines 18/D

Figure 11. Normal stresses in the cross-sections of the reinforced concrete elements induced by the special load combination including the maximum considered earthquake with the structural solutions extra factor $K_2=1.2$ taken into account

CONCLUSION

1. Nonlinear dynamic analysis of the Choreographic Academy response to the special load combination including the maximum considered earthquake (applied in the form of the ground motion history, see Fig.) conducted using elaborate three-dimensional finite element model revealed spatial and time complexity of the building response. Nevertheless, the design reinforcement with the structural solutions compensating extra factor K_2=1.2 taken into account appeared to be enough to provide structural safety (preventing progressive collapse of the building).
2. The very utilization of the “compensating measures” (we had not coined this term and believe there is a better one) which do not require mandatory seismic isolation enabled to perform the design and the scientific and technical support at a high level, and ensure the structural safety of the one considered within the present article and other truly unique buildings located in the earthquake-prone regions without groundless installation of a seismic isolation devices. Among famous and the latest approved by the FAI “Glavgosexpertiza of Russia” are the Opera and Ballet Theater located in Sevastopol city (in the immediate vicinity to the Choreographic Academy) and the Opera and Ballet Theater located in Kaliningrad city.
3. The structural safety of unique, highly dangerous, and technically sophisticated permanent facilities shall be substantiated by a real scientific and technical support including detailed and independent analysis of major structural safety parameters, not by its “imitation” usually come down to uncountable references to highly imperfect Russian building codes (a very gentle characteristic when considering its part related to the earthquake resistance of buildings and structures), and (or) “juggling” with regular “acts of the party and the government”.
4. The considered one and other plentiful examples of theoretical substantiation of the earthquake resistance of buildings and structures performed by NIC StaDyO JSC and Zolotov Research and Educational Center for Computational Modelling of the National Research Moscow State University of Civil Engineering state with absolute certainty that superiority of structural requirements over results of an elaborate theoretical analysis, which takes place in the current Russian seismic building design code [9], is desperately backward and hazardous. Perhaps, such requirements should be fulfilled only by underqualified design engineers; on second thoughts, it is more rational to keep such engineers off the substantiation of the earthquake resistance of permanent facilities.

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Alexander M Belostotsky – DSc, Professor, Full Member of the Russian Academy of Architecture and Construction Sciences, Scientific adviser at A.B. Zolotov REC CM of the National Research Moscow State University of Civil Engineering; 129337, Russia, Moscow, Yaroslavskoe shosse, 26. e-mail: amb@stadyo.ru

Alexander I. Nagibovich – CSc, Director at A.B. Zolotov REC CM of the National Research Moscow Stale University of Civil Engineering; 129337, Russia, Moscow, Yaroslavskoe shosse, 26. e-mail: nagibovich@yandex.ru

Pavel I. Novikov – CSc, Senior Researcher at A.B. Zolotov REC CM of the National Research Moscow Stale University of Civil Engineering; 129337, Russia, Moscow, Yaroslavskoe shosse, 26. e-mail: novikov.mgsu@gmail.com

Vladislav V. Vershinin – Senior Lecturer at the Department of Structural Metal and Timber of the National Research Moscow Stale University of Civil Engineering; 129337, Russia, Moscow, Yaroslavskoe shosse, 26. e-mail: vlodya_91@mail.ru

Белостоцкий Александр Михайлович – д.т.н., профессор, академик РААСН, научный руководитель НОЦ КМ им. А.Б. Золотова Национального исследовательского Московского государственного строительного университета; 129337, Россия, г. Москва, Ярославское шоссе, д. 26. e-mail: amb@stadyo.ru

Нагибович Александр Игоревич – к.т.н, директор НОЦ КМ им. А.Б. Золотова Национального исследовательского Московского государственного строительного университета; 129337, Россия, г. Москва, Ярославское шоссе, д. 26. e-mail: nagibovich@yandex.ru

Новиков Павел Игоревич – к.т.н., старший научный сотрудник НОЦ КМ им. А.Б. Золотова Национального исследовательского Московского государственного строительного университета; 129337, Россия, г. Москва, Ярославское шоссе, д. 26. e-mail: novikov.mgsu@gmail.com

Вершинин Владислав Владимирович – старший преподаватель кафедры Металлических и деревянных конструкций Национального исследовательского Московского государственного строительного университета; 129337, Россия, г. Москва, Ярославское шоссе, д. 26. e-mail: vlodya_91@mail.ru