DOI:10.22337/2587-9618-2023-19-3-165-172

NUMERICAL SIMULATION OF THE STRESS-STRAIN STATE OF A LARGE-SPAN STRUCTURE WITH JOINTS WITH GAP UNDER THE SEISMIC LOADS IN A TRANSIENT DYNAMIC

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Abstract: The article presents the results of numerical simulation of a unique long-span structure subjected to seismic loads. The roof and facade of structures were connected to reinforced concrete base with joints with gaps. The simulation was realized for ideal model and model with gap imperfections. Various modeling approaches for the joints and the resulting dynamic response were examined.

Keywords: Long-span structures, seismic response, joints with gaps

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ БОЛЬШЕПРОЛЕТНОГО СООРУЖЕНИЯ С ЛЮФТАМИ В ОПОРАХ С УЧЕТОМ СЕЙСМИЧЕСКИХ ВОЗДЕЙСТВИЙ В НЕЛИНЕЙНОЙ ДИНАМИЧЕСКОЙ ПОСТАНОВКЕ

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Аннотация: В актуальной статье представлены результаты численного моделирования уникального сооружения, подвергающегося сейсмическому воздействию, включающего большепролетные конструкции покрытия и другие ограждающие конструкции, связанные с железобетонным основанием через опорные части с конструктивными люфтами/зазорами. Проведена оценка динамической реакции сооружения в идеализированной постановке и при наличии несовершенств узлов. Рассмотрены различные варианты моделирования узлов и реализуемой динамической реакции.

Ключевые слова: Большепролетные конструкции, сейсмическая реакция сооружения, опорные части с люфтами

1. INTRODUCTION

Current modern approaches to numerical modeling of unique buildings and structures are oriented towards detailed and physically accurate reproduction of the construction itself, taking into account initial imperfections and the actual operational scheme of the components.

The consideration of imperfections becomes especially important for tasks involving the direct modeling of the behavior of a structure subjected to dynamic influences, such as seismic loads of the ultimate level or emergency actions leading to progressive collapse. These situations may force the structure to operate in a critically unstable state, for which standard methods of assessing load-bearing capacity have limited applicability. It is necessary in these cases to ensure the stability and survivability of the structure and to eliminate the possibility of its collapse.

Based on various domestic and international normative documents and research, two main types of imperfections can be identified:

– Imperfections of the shape of structural elements (various deviations from straightness or theoretical shape);

– Imperfections of the joints (the actual stiffness of joints, structural nonlinearity of joints in the form of contact opening, or the possibility of free movement due to clearances).

Accounting for shape imperfections in modern normative documents, such as Russian Codes, Eurocodes, ACI, and others, can be done through coefficients determined based on initial eccentricities and element sizes or through direct modeling of imperfections by adjusting the shape of the analytical model.

Research related to the consideration of the actual project scheme of joint operation has been conducted by teams from the Melnikov Central Research and Design Institute of Steel Structures (CNIIIPSK), including the work of N.N. Streletsky, VNIIPI Promstalkonstruktsiya, and the work of V.V. Kalenov and A.B. Pavlov [4]. G.G. Kashevarova's work [5] is also relevant in this context. Expert assessments of the actual joint operation schemes in the collapse of large-span structures have been the focus of research by A.M. Belostotsky [1-3] and teams from the R&D Center StaDyO and NOC KM MGSU, and among others.

In this current article, we will consider one of the numerical modeling approaches for the behavior of joints, the structural design of which allows for clearances or gaps, resulting in limited free movement of the structure.

2. PROBLEM'S FORMULATION

The large-span structure is located in a seismic zone. The normative seismicity of the construction site is assessed at 9 points for soils of category II in terms of seismic properties. According to the results of geophysical studies, the revised seismicity of the construction site is numerically rated at 8 points.

The object is a building with a complex geometric shape, featuring an outstanding cantilevered open terrace with a length of 35.2 meters. The building's roof is designed as a spatial steel truss structure supported by steel columns, with overhanging edges on all sides and a canopy over the main entrance and terrace. The approximate overall dimensions in plan are 124.8 by 207.0 meters.

The steel roof elements span the entire volume of the building and consist of a spatial grid structure comprising longitudinal and transverse trusses. The support for the roofing is provided by a reinforced concrete frame and steel columns, which, in turn, rest on the reinforced concrete structure of the frame and the steel structure of the cantilever.

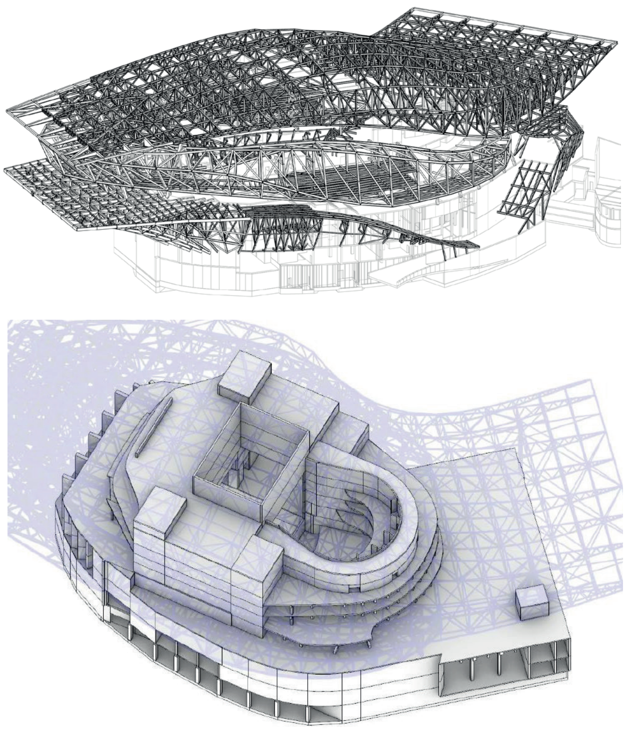

Figure 1. Structural views

The steel elements of the 35.2-meter cantilever consist of longitudinal and transverse trusses made of welded elements. Support for the facade is provided through steel inclined struts on the reinforced concrete frame and the cantilever structure, as well as through cantilever support of the facade elements on the reinforced concrete frame. The steel elements of the structure are made of welded I-beam sections and circular pipes.

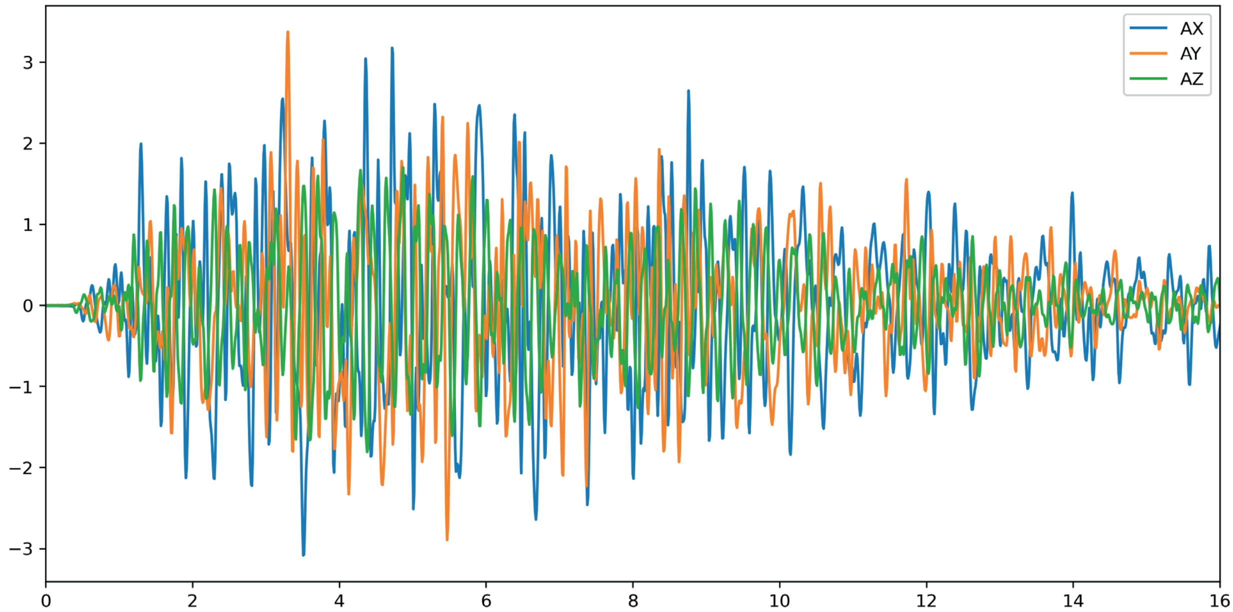

Figure 2. Accelerograms for seismic loads for X, Y, Z directions (acceleration, m/sec^2 vs time, sec)

The joints that connect the steel roof and facades with the reinforced concrete structures of the operational part of the structure are designed as hinged movable and fixed joints with clearances/gaps normal to the base of the joint. Preliminary calculations using linear spectral theory have shown that, in addition to compressive reactions, tensile forces may occur at these joints, leading to cyclic opening/closing of the gap and essentially bidirectional impact loads. Assessing the contribution of the dynamic impact component to the overall stress-strain state of the structure and joints within the framework of linear spectral theory is impossible.

Taking this into account, experimental numerical modeling of the structure was performed in a transient dynamic using direct integration of dynamic equations in time with an implicit scheme, considering physical, geometric, and structural nonlinearities.

The base excitation considered was seismic loading based on a three-component ground motion record of the ultimate level (Level KZ) with a structure responsibility factor (K0) of 1.3, in accordance with current regulatory requirements.

3. MODELS AND THEIR PROPERTIES

The analysis of the structure's behavior was performed in a dynamic setup using the Newmark method with standard integration parameters [7], considering physical and geometric nonlinearities. Damping was implemented in the analytical model using Rayleigh damping. For steel structures, the determination of the "alpha" and "beta" parameters was performed with damping set at 2% of critical damping, while for reinforced concrete; it was set at 5% of critical damping.

Considering the complexity of the structural design and the independent vibrations of structural segments, the Rayleigh damping range was considered in the range of f_1 = 1.381 Hz, up to 33 Hz.

Number of natural mode	Natural frequency, Hz
1	1.381
2	1.5744
3	1.6095
4	1.9641
5	2.0974
6	2.1176

Number of natural mode	Natural frequency, Hz
7	2.183
8	2.2404
9	2.2691
10	2.2841

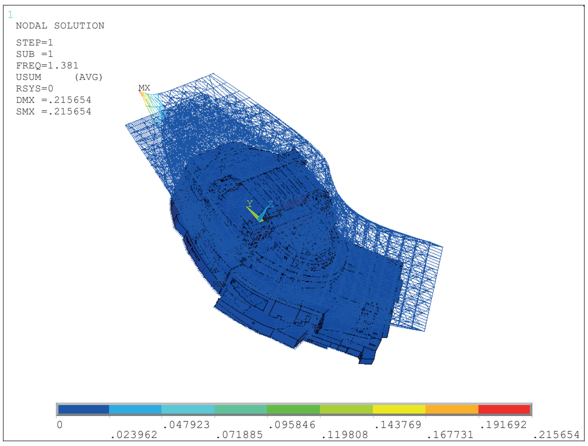

Figure 3. First natural mode of structure

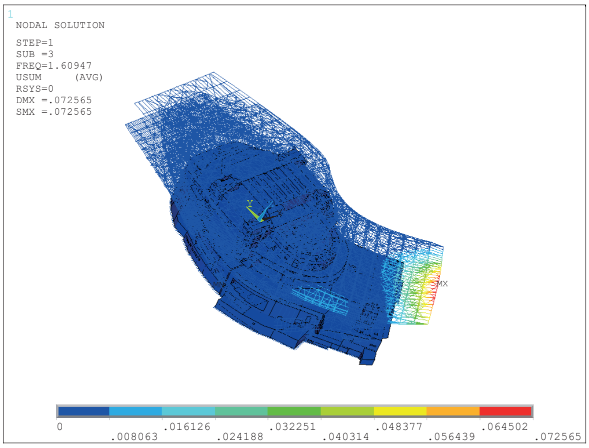

Figure 4. Third natural mode of structure

The calculations were realized with ANSYS Mechanical software package. In the analysis the following elements were used:
– structural beam elements BEAM188 based on Timoshenko's theory with corrections for shear and seven degrees of freedom at each node (three translations, three rotations, and one out-of-plane degree of freedom)
– thin-walled shell elements SHELL181 in the Mindlin-Reissner form with full integration (for representing wall and slab reinforced concrete structures).

The modeling of joints was done using discrete spring elements. Several options were considered beforehand:

- A variable stiffness spring elements (multilinear form) COMBIN39.
- Two springs oriented in different directions along local axes with clearances, using COMBIN40 elements.
- The combination of the COMBIN40 spring element with a contact element node-to-node.

Table 1. Axial stiffness of springs for middle range of triaxial displacement-force curve for COMBIN39

Joint type	Axial stiffness, kN/m	Gap, mm
A	744580	1.8
B	372080	2
G	764050	2.6
D1	1583440	2.6
D2	1187500	2.6
D3	791560	2.6
D4	372080	1.7
D5	372080	1.7
E	555670	2.4

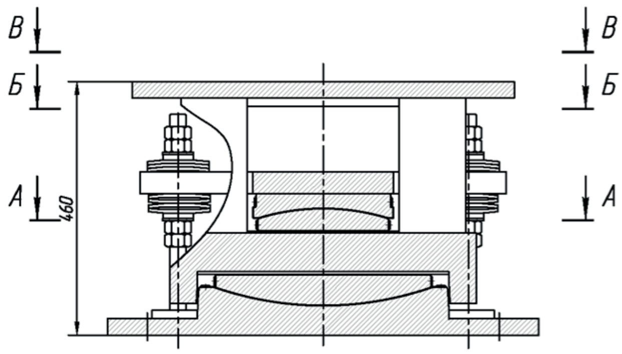

Figure 5. Section of Joint type A

The COMBIN40 options showed a good force-displacement relation during verification modeling. However, during the actual dynamic analysis, they encountered unconvergence issues.
The use of finite elements of the COMBIN39 type was chosen as optimal. The behavior of the supporting joints with clearances was represented in the form of a three-linear displacement-stiffness diagram. The stiffness of the extreme

segments was equivalent to the longitudinal stiffness of the connected structures, while the middle segment was assumed to have the stiffness of disc springs introduced into the structural node to reduce the influence of clearances on the stress-strain state of the structure.

Figure 5 displays a graph of force verification in the element relative to the displacement of one of the structure's nodes. In the 0-2 interval, a compressive load is applied to the node, followed by unloading. In the 2-3 interval, a displacement equal to the clearance is applied, followed by equivalent tensile loading in stage 1.

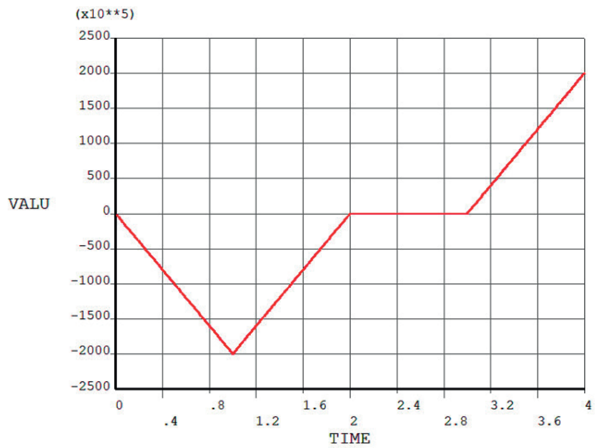

Figure 6. Force-loading stage relationship for COMBIN39 as joint with gaps

It's worth noting that the stiffness ratio between the middle and extreme segments of the diagram spans several orders of magnitude, which, in turn, affects the convergence of the solution when transitioning from the "stiff" portion of the curve to the "soft" portion and vice versa.

4. RESULTS AND DISCUSSION

The conducted computational studies indicate that small clearances/gaps in the joints, allowing limited movement of the structure as a rigid body, have a minimal impact on the resulting stress-strain state of the entire system.

According to the performed computational studies, the joints with clearances have relations describing the stress-strain state over time that are similar to those of the model without them (top diagrams in Figure 7 and 8).

Some joints only work in compression, while others experience momentary detachments accompanied by dynamic impact. Such dynamic loading of the system does not qualitatively affect the overall deformation over time, but it leads to local rapidly decaying high-frequency oscillations (visible in the graphs as local densifications of the deformation curves).

It's worth noting that the high-frequency noise generated by the "impacts" of the structure after introducing clearances is more pronounced for joints with higher contact stiffness. Additionally, for these temporary segments, convergence issues arise, necessitating a reduction in the integration step.

To improve convergence and maintain a stable time integration step in this case, two approaches can be applied:

1. Adjust the reduced stiffness of the deformation curve segments for COMBIN39 elements that represent the behavior of joints with closed gaps.
2. Use non-standard integration parameters for the Newmark method [7] to smooth the solution for high-frequency oscillation regions:

$$\alpha = \frac{1}{4}(1+\gamma)^2$$

$$\beta = \frac{1}{2} + \gamma ,$$

γ — amplitude decay factor with recommended value between 0.05 and 0.1 for high and moderated speed dynamic processes [6].

For some joints, accounting for the behavior of disc springs and gaps results in a reduction of detachment forces if the displacement does not reach the gap size. For certain elements, such as joint B (element 510493), E (506798), and E (506792), the detachment forces increase from 8.6% to 31.5%. For elements D2 (506805), D2 (506788), D4 (506787), D3 (506806), D2 (506803), and D4 (506804), the increase in compressive forces ranges from 7.3% to 37.8%. Large values correspond to joints with initially small support reactions.

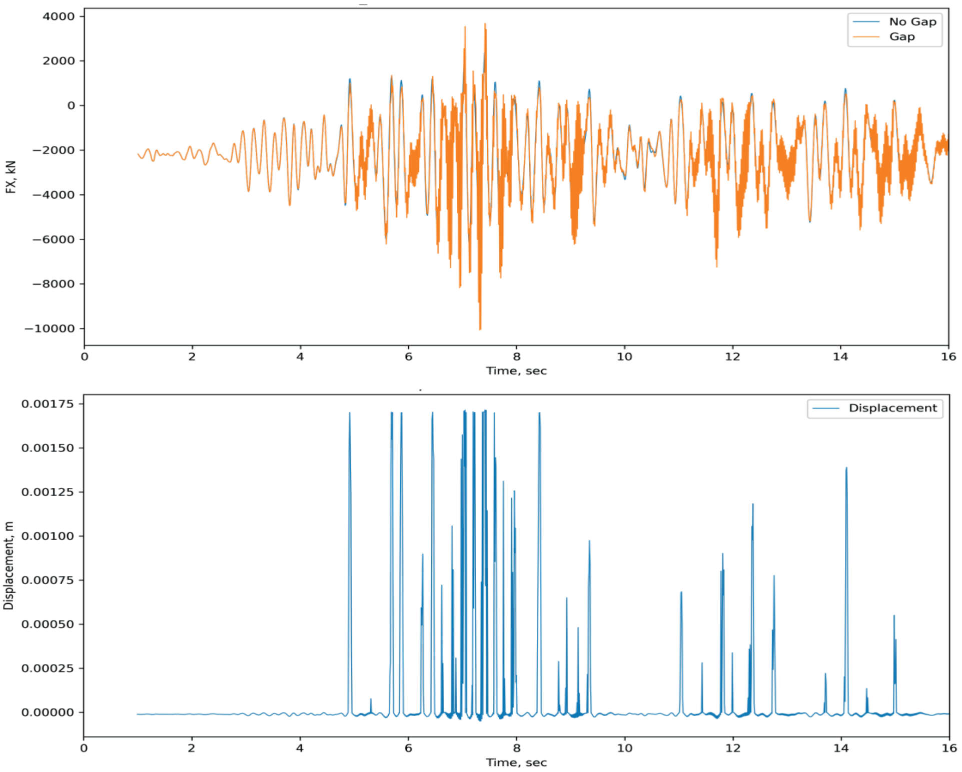

Figure 7. Joint reaction and gap displacement versus time for element 506791 (top — axial reaction vs time, bottom — axial displacement between joint plates vs time)

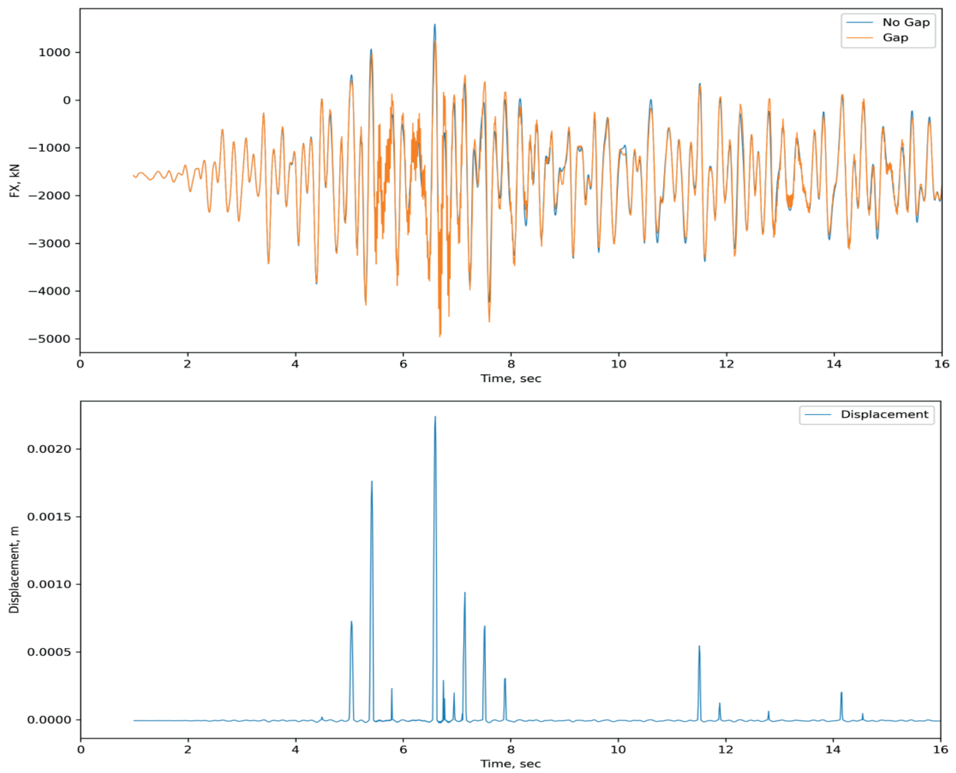

Figure 8. Joint reaction and gap displacement versus time for element 506808 (top — axial reaction vs time, bottom — axial displacement between joint plates vs time)

In most cases, the amplitude of compression/detachment forces is close to those obtained from the model without accounting for the behavior of joints with clearances.
The influence on shear reactions and the change in their amplitude values is insignificant and does not exceed an average of 2%.

CONCLUSION

A methodology for modeling buildings and structures with joints that have clearances/gaps, subjected to cyclic dynamic seismic loading, has been proposed. Approaches for maintaining a stable time step and reducing the computational costs of the iterative solution process have also been presented.
Based on the results of the performed calculations of large-span structure under seismic loading using three-component ground motion records with direct integration of dynamic equations over time, considering physical, geometric, and structural nonlinearities, it is currently possible to use linear elastic models, calculated using linear spectral theory, for modeling structures that include joints with small clearances/gaps.

ACKNOWLEDGEMENTS

This research was supported by Ministry of Science and Higher Education of the Russian Federation (project No. FSWG-2023-0004, “A system of territorial seismic protection of critical infrastructure facilities based on granular metamaterials with the properties of wide-range phonon crystals”).

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