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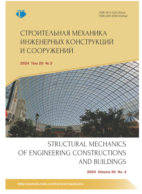

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Influence of Damage Level on Dynamic Characteristics of Reinforced Concrete Structures when Assessing their Seismic Resistance

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Abstract. Many buildings during their operational period incur damage of different origin: man-made, natural, operational, etc. Dynamic tests are performed for detailed assessment of the technical condition of buildings and structures in accordance with the regulatory documents for general analysis of the building damage state. In a large number of papers, the results of comparison of full-scale tests and numerical analysis using finite element method are presented. When analyzing the results, it can be concluded that the dynamic method is reliable, but has several limitations. The advantage of the dynamic method of building damage assessment is the possibility to adjust finite element models in software systems taking into account results obtained from in-situ tests, which allows to obtain more accurate results for the assessment of bearing capacity under seismic loading. To examine the effect of damage to buildings on their seismic resistance, an experiment with corrosion-damaged reinforced concrete columns was performed. The result of the first stage of the experiment is the assessment of the change in dynamic characteristics (eigenfrequency, vibration decrement, vibration damping coefficient, etc.) of reinforced concrete column specimens subjected to corrosion damage.

Keywords: vibration frequency, corrosion, reinforced concrete, vibration decrement, experimental studies, damage, dynamic method

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Влияние уровня повреждений на динамические характеристики железобетонных конструкций при оценке их сейсмостойкости

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Аннотация. Большое количество зданий за свой эксплуатационный период приобретают повреждения различного происхождения: техногенного, природного, эксплуатационного и др. Для детальной оценки технического состояния зданий и сооружения в соответствии с нормативными документами проводят динамические испытания для общего анализа состояния поврежденности здания. Во многих работах отечественных и зарубежных авторов приведены результаты сопоставления натурных испытаний и численных расчетов методом конечных элементов. При анализе результатов можно сделать выводы, что динамический метод является достоверным, однако имеет ряд ограничений. Преимуществом динамического метода оценки повреждений зданий является возможность корректировки конечно-элементных моделей в программных комплексах с учетом полученных результатов по натурным испытаниям, что позволяет получить более точные результаты для оценки несущей способности в условиях сейсмических воздействиях. Для уточнения сведений о влиянии повреждений зданий на их сейсмостойкость был поставлен эксперимент на коррозионно-поврежденных железобетонных колоннах. Результатом первого этапа эксперимента является оценка изменения динамических характеристик (собственная частота, декремент колебаний, коэффициент затухания колебаний и др.) железобетонных образцов колонн, подверженных коррозионным повреждениям.

Ключевые слова: частота колебаний, коррозия, железобетон, декремент колебаний, экспериментальные исследования, повреждение, динамический метод

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1. Introduction

During operation, buildings and structures sustain damage, the origin of which can be divided into two main categories: man-made (explosions, fires, removal of structural elements, accidents) and natural. In the modern world, reinforced concrete buildings and structures account for 70–80% of the total volume of construction. Due to the influence of aggressive media, as well as man-induced factors, the process of corrosion of load-bearing reinforced concrete elements can start, which in turn leads to a decrease in the

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rigidity and load-bearing capacity of the building. Special attention should be paid to the assessment of the technical condition of existing buildings located in seismic regions of the Russian Federation. Considering the reduction of stiffness parameters of buildings due to existing damage, integral dynamic characteristics are noticeably reduced. Assuming unchanged mass characteristics of the object, the eigenfrequencies of vibration become lower, which in turn affects such parameters as the period and shape of free vibrations, which characterize the degree of dynamic impact on the object and the change in shape at various points under study [1–5].

The main regulatory document in the field of monitoring and technical inspection of buildings and structures is GOST 31937-2011[1] interstate standard. This document regulates the definition of dynamic parameters of buildings and structures, which characterize the dynamic properties that are exposed under dynamic loads. The definition of dynamic properties includes frequencies, periods, decrements (X, Y, Z axes) of vibrations, transfer functions of the structure (as well as its individual parts and elements) [6].

Measurement of dynamic parameters should be performed after the construction of the facility, as well as 2 years after. If the measurement results of the dynamic characteristics do not differ by more than 10% from the previous inspection, the subsequent measurement must be repeated after 2 years. If the deviation of 10% from the original parameters is exceeded, a full mandatory unscheduled inspection should be carried out.

In addition, these dynamic parameters can be used for the following tasks:

- refinement (validation) of the numerical model;
- evaluation of the actual seismic resistance;
- implementation of seismic strengthening measures;
- determination of the damage degree;
- localization of damage locations.

The main measurement rules and instrumental methods for determining eigenfrequencies, periods and logarithmic decrements of vibrations are established by GOST R 54859-2011[2] national standard of the Russian Federation.

The main purpose of the study is to investigate the influence of the level of corrosion damage of reinforced concrete structures on the change of their dynamic characteristics. Based on the obtained and analyzed data on the influence of corrosion on the dynamics of reinforced concrete structures located in earthquake-prone regions, it is possible to predict their earthquake resistance.

2. Methods

In [7], seismic resistance of a cast-in-situ reinforced concrete building was evaluated based on experimental data from the Polytechnic University in Hong Kong. The tower-type building was subjected to structural damage. At each stage, the fundamental vibration frequency was measured at each damage level, and the results are summarized in Table 1.

The building was modeled in Abaqus CAE, and according to the calculation results, the building collapse occurs at the degree of reduction of natural vibration frequency $\geq 15\%$. The calculation results confirm the results of the field experiment.

In [8], short-term monitoring of 6 multistory buildings of different years of construction (from 1973 to 2014), with different number of storeys and sections was performed. Monitoring was conducted between July and October 2017. Based on the test results, the author concludes that the method of dynamic monitoring can be applied to assess building damage as an integral method with mandatory additional technical inspection.

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[1] GOST 31937-2011. Buildings and constructions. Rules of inspection and monitoring of the technical condition. Moscow: Standartinform Publ.; 2014.

[2] GOST R 54859-2011. Buildings and constructions. Determination of the parameters of the basic tone of free oscillations of buildings. Moscow: Standartinform Publ.; 2012.

Table 1

Results of the experiment in paper

Degree of damage	Value of fundamental vibration frequency, Hz	Decrease in frequency of natural vibration, %
No damage	4.61	0
Light	4.55	1.3
Moderate	4.32	6.3
Serious (severe)	3.70	19.7
Catastrophic (before complete destruction)	2.58	44.0

S o u r c e : Chauskin A.Yu. [7]

In [9], an experimental evaluation of an 11-storey frame building of the KUB-2.5 series was performed to analyze the level of seismic resistance of residential buildings. The research results are based on the parametric analysis of forced vibrations (microseismic vibrations), which allowed to estimate the change in the integral stiffness of load-bearing structures due to damage accumulation. The initial dynamic characteristics were determined, which will allow further monitoring of the technical condition of the building.

The author of [10] states that the advantage of the dynamic control method is its “integrality”, which reflects the deformation of bond of reinforcement with concrete in reinforced concrete structures, and allows to evaluate strength, stiffness and crack resistance. The author investigated a reinforced concrete beam with a length of 6 meters and a cross section of 40×70 cm. The beam had a 15×15×3 cm defect located at a distance of 3 meters from one of the supports. The modeling was performed in ANSYS PC (Figure 1). The experiment showed that with the increase of the defect size there is a decrease in the eigenfrequencies of vibration. The best result about the location of the defect was shown by the method of changing the shape of vibrations, the basis of which is the modal convergence criterion (*MAC*):

$$MAC(x) = \frac{\left| \sum_{j=1}^{n} \varphi(x)_j \cdot \varphi(x)_j^* \right|^2}{\sum_{j=1}^{n} \varphi(x)_j^2 \cdot \sum_{j=1}^{n} \varphi(x)_j^{*2}}, \tag{1}$$

where x is the distance to the measurement point, n is the number of vibration measurement points, φ and φ* are the values of vibration shape displacements without and with damage. The error of the method amounted to 2.33%, which is a positive result.

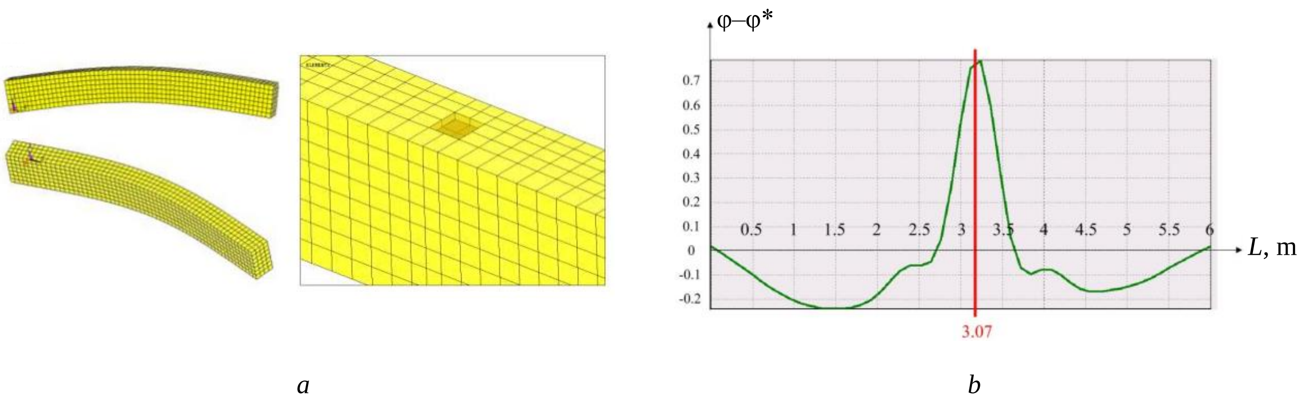


Figure 1. Defect detection by modal convergence method:
a — FE model of beam with defect (first and second eigenfrequencies);
b — location of the defect along the length of the beam
S o u r c e : Kadomtsev M.I. et al. [10]

The modal convergence criterion (*MAC*) varies from 0 (no correlation between modes of vibration) to 1 (100% matching).

Paper [11] considers the problem of predicting the consequences of earthquakes, man-made accidents, natural factors, and other impacts on the load-bearing structures of operating buildings. It is recommended to use eigenfrequencies, decrements, and periods of vibration as the main parameters for verification of the analysis model. To predict the seismic resistance of buildings with damage, it is necessary to create a model with the closest possible values of dynamic characteristics. As an example, the author considers a large-panel building located in St. Petersburg. Based on the results of the survey, the frequencies of natural vibrations were determined, and the model was created in ANSYS. The results are summarized in Table 2.

Table 2

Results of the calculation in paper

Shape of vibration according to the model	Vibration frequency recorded during testing, Hz	Frequency of vibration according to the model adjusted by dynamic characteristics, Hz	Mismatch of vibration frequency in relation to the design frequency, %
1	1.25	1.291	3.1
2	1.92	1.944	1.2
3	1.94	2.045	5.1
4	5.96	5.604	5.9
5	6.98	6.832	2.1
6	7.812	7.456	4.5

Source: Savin S.N., Smirnova E.E. [11]

Based on the obtained data, calculations were performed considering the damage to buildings from the unevenness of building settlement with subsequent partial failure.

The author concluded that this method could solve various problems, both in evaluating the technical condition of the building, and for forecasting the residual life of damaged objects.

To evaluate the reduction of dynamic characteristics of corrosion-damaged structures, an experiment is conducted on reinforced concrete columns with dimensions of 100×100×700 mm [12–17]. Damage to reinforcement is achieved by electrocorrosion of specimens in salt solution. The undamaged specimen is fixed by the widening in the base to the floor. At a distance of 150 mm from the free edge of the column, a displacement sensor parallel to the impact is installed, and a force sensor is fixed to the end of the column above the displacement sensor (Figure 2).

The test methodology and processing of the results are as follows:

1. The force sensor is struck with a hammer to excite forced vibrations in the column.
2. Recording equipment reads the impact force and records at a frequency of 1000 Hz.
3. Based on the test results, the time graph of the vibration amplitude is plotted and the first eigenfrequency of vibration, vibration period, logarithmic decrement of vibration and damping coefficient are analytically determined (Figure 3).

The first eigenfrequency for the intact sample was 37.037 Hz, and the vibration period was 0.027 s.

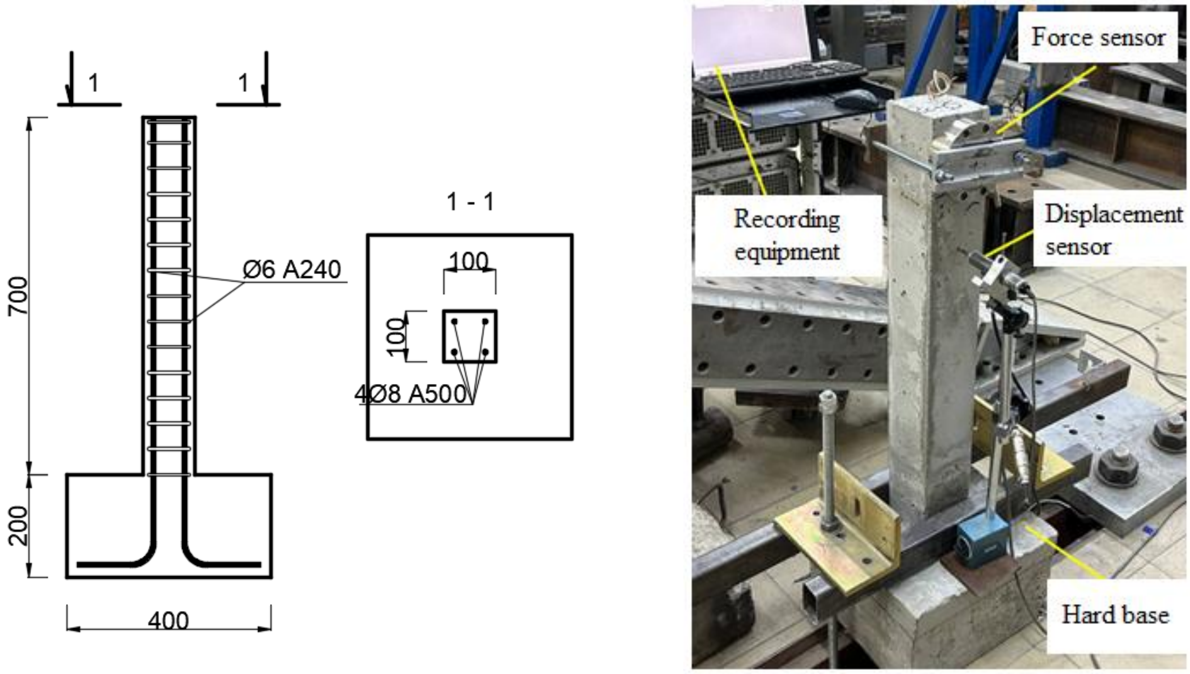
To estimate the damping of the system, we introduce the logarithmic decrement of vibration — δ. The rate of damping is defined as the natural logarithm of the ratio of peak vibration amplitudes spaced by one period:

$$\delta = ln\frac{y_i}{y_{i+1}} = \alpha T. \quad (2)$$

Also, in dynamic analysis, important characteristics are the coefficient of energy absorption ψ characterizing the cyclicity of deformation process, which in the form of the ratio to the number 2π gives inelastic deformation coefficient γ. The inelastic drag coefficient (equation (3)) and energy absorption coefficient (equation (4)) were determined based on the experiments performed [18–25].

$$\gamma = \frac{\psi}{2\pi} = \frac{\delta}{\pi}, \tag{3}$$

$$\psi = -2\int_{t}^{t+T} \frac{dy_0}{y_0} = 2ln\frac{y_i}{y_{i+1}} = 2\pi. \tag{4}$$



a *b*

Figure 2. Specimen testing:
a — reinforcement model; *b* — testing of samples
S o u r c e : made by A.G. Tamrazyan, M.V. Kudryavtsev

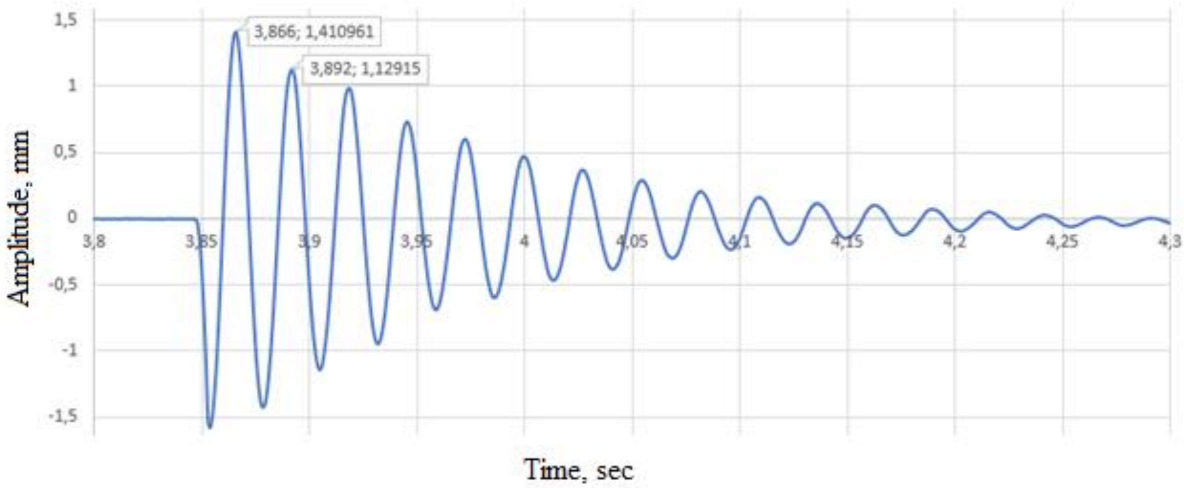


Figure 3. "Amplitude, mm vs time, s" graph
S o u r c e : made by A.G. Tamrazyan, M.V. Kudryavtsev

3. Results and Discussion

Equations (2)–(4) were used to calculate the main dynamic characteristics obtained experimentally on reinforced concrete column specimens undamaged by corrosion. The results of calculations are presented in Table 3.

Table 3

Results of the authors' calculations

№	Sample ID	Impact along the axis	Vibration period	Vibration frequency	Logarithmic decrement of vibration	Circular frequency	Inelastic drag coefficient	Energy absorption coefficient
			T	ν	δ	ω	γ	ψ
1.	1c-1	X	0.027	37.04	0.263	232.6	0.0837	0.525
		Y	0.031	32.26	0.173	202.6	0.0552	0.347
2.	1c-2	X	0.027	37.04	0.369	232.6	0.1175	0.738
		Y	0.026	38.46	0.133	241.5	0.0423	0.266
3.	1c-3	X	0.024	41.67	0.230	261.7	0.0734	0.461
		Y	0.028	35.71	0.236	224.3	0.0750	0.471
4.	1c-4	X	0.026	38.46	0.246	241.5	0.0784	0.492
		Y	0.026	38.46	0.808	241.5	0.2572	1.615
5.	1c-5	X	0.031	32.26	0.468	202.6	0.1491	0.937
		Y	0.029	34.48	0.911	216.6	0.2903	1.823
6.	1c-6	X	0.026	38.46	0.156	241.5	0.0496	0.311
		Y	0.027	37.04	0.308	232.6	0.0982	0.617
7.	1c-7	X	0.028	35.71	0.400	224.3	0.1274	0.800
		Y	0.027	37.04	0.355	232.6	0.1130	0.710
8.	2c-1	X	0.028	35.71	0.169	224.3	0.0537	0.338
		Y	0.035	28.57	0.122	179.4	0.0389	0.244
9.	2c-2	X	0.031	32.26	0.330	202.6	0.1052	0.661
		Y	0.03	33.33	0.423	209.3	0.1348	0.846
10.	2c-3	X	0.026	38.46	0.289	241.5	0.0921	0.579
		Y	0.027	37.04	0.271	232.6	0.0865	0.543
11.	2c-4	X	0.026	38.46	0.644	241.5	0.2049	1.287
		Y	0.029	34.48	0.402	216.6	0.1282	0.805
12.	2c-5	X	0.026	38.46	0.344	241.5	0.1095	0.687
		Y	0.029	34.48	0.201	216.6	0.0639	0.401
13.	2c-6	X	0.03	33.33	0.144	209.3	0.0459	0.288
		Y	0.03	33.33	0.264	209.3	0.0840	0.527
14.	2c-7	X	0.026	38.46	0.223	241.5	0.0710	0.446
		Y	0.029	34.48	0.216	216.6	0.0687	0.432
			Mean value:	35.89	0.325	225.4	0.1035	0.650

S o u r c e : made by A.G. Tamrazyan, M.V. Kudryavtsev

Since the experimental study with artificial corrosion of reinforced concrete takes a long time, the test results with a comparison of the obtained results will be presented in the upcoming articles.

4. Conclusion

1. Based on the scientific studies using methods of mathematical analysis, computer modeling and in-situ tests, conclusions were made about the significant effect of reducing the frequency of natural vibrations on the degree of damage to the building under dynamic action such as seismic loading. This effect arises due to the accumulation of damages of different nature in the nodes of structures and elements of buildings, making them less rigid and more compliant, which affects the overall degradation of the rigidity of the structure.

2. The method of dynamic assessment of the technical condition of buildings and structures is popular among surveyors, but there are difficulties in comparing measured values with the original indicators, because the latter, in turn, have not been measured. This problem can be solved by designing a high quality model in a CAE software. Also, to estimate the residual life of buildings and to assess the seismic resistance of buildings, the results of measurements can be introduced into the calculation to refine the FEM model considering the technical condition of the building.

3. Conducting the experiment will allow to expand the field of assessment of the technical condition of buildings considering the corrosion damage of load-bearing structures, which will increase the accuracy of solving the problems of earthquake resistance.

References

1. Savin S.Yu., Fedorova N.V. Stability exposure of building structural systems under environmental damage. *Structural Mechanics of Engineering Constructions and Buildings.* 2022;18(6):564–572. https://doi.org/10.22363/1815-5235-2022-18-6-564-572

2. Klyueva N.V., Kolchunov V.I., Gubanova M.S. Strength criterion of the loaded and corrosion-damaged concrete under the plane stressed state. *Housing Construction*. 2016;(5):22–27. (In Russ.) EDN: WEFACB

3. Shamshina K.V. Experimental research results of deformation properties of compressible reinforced concrete structures with corrosion longitudinal cracks in the protective layer of concrete. *Engineering and Construction Bulletin of the Caspian Region.* 2020;(1):26–33. (In Russ.) EDN: LEQCNP

4. Dangwal S., Singh H. Behavior of corrosion damaged non-seismically and seismically detailed reinforced concrete beam-column sub-assemblages under cyclic loading. *Engineering Failure Analysis*. 2023;146:107135. https://doi.org/10.1016/j.engfailanal.2023.107135

5. Kanchanadevi A., Ramanjaneyulu K. Effect of corrosion damage on seismic behaviour of existing reinforced concrete beam-column sub-assemblages. *Engineering Structures.* 2018;174:601–617. https://doi.org/10.1016/j.engstruct.2018.07.094

6. Shakhramanian M.A., Nigmetov G.M., Gaifullin Z.G., Babusenko M.S. Methodology of assessment and certification of engineering safety of buildings and structures. *Civil security technologies.* 2004;(2):5–15. (In Russ.) EDN: KVUNYV

7. Chauskin A.Yu., Pshenichkina V.A., Leichu F.F. Failure criteria of buildings as nonlinear systems under earthquake load. *FEFU: School of Engineering Bulletin.* 2018;(2):120–127. (In Russ.) https://doi.org/10.5281/zenodo.1286040

8. Ulybin A.V. Measurement of periods and decrements of vibrations of multistory buildings. *Inspection of buildings and structures: problems and ways of their solution. Materials of the VIII International Scientific and Practical Conference*. St Petersburg, 2017. p. 192–202. (In Russ.) EDN: YQYCBV

9. Bazarov A.D., Lundenbazar B., Ivanov I.A. Dynamic response assessment of a frame building affected by micro-seismic noise in the city of Ulan Bator. *Proceedings of Universities. Investment. Construction. Real estate*. 2020;(1): 198–205. (In Russ.) https://doi.org/10.21285/2227-2917-2020-2-198-205

10. Kadomtsev M.I., Lyapin A.A., Shatilov Yu.Yu. Vibrodiagnostics of building structures. *Ingineering journal of Don.* 2012;(3):576–579. (In Russ.) EDN: PJZXHZ

11. Savin S.N., Smirnova E.E. Predicting the service life of buildings in the conditions of natural and technogenic emergency situations. *Modern problems of civil protection*. 2019;(2):33–42. (In Russ.) EDN: XYVCJB

12. Avetisyan L.A., Tamrazyan A.G. Experimental research in eccentrically compressed reinforced concrete elements during short-term dynamic loadings under fire conditions. *Industrial and Civil Engineering.* 2014;(4):24–28. (In Russ.) EDN: SAZOJD

13. Tamrazyan A.G. Livability as a degree of serviceability of structures under damage. *Industrial and Civil Engineering*. 2023;(7):22–28. (In Russ.) https://doi.org/10.33622/0869-3019.2023.07.22-28

14. Tamrazyan A.G. Conceptual approaches to the assessment of survivability of building structures, buildings and facilities. *Reinforced Concrete Structures.* 2023;3(3):62–74. (In Russ.) https://doi.org/10.22227/2949-1622.2023.3.62-74

15. Matseevich T.A., Tamrazyan A.G. Reliability analysis of reinforced concrete slab with corroded reinforcement. *Construction and Reconstruction.* 2022;(1):89–98. (In Russ.) https://doi.org/10.33979/2073-7416-2022-99-1-89-98

16. Kolchunov V.I., Al-Hashimi O.I., Protchenko M.V. Rigidity of reinforced concrete structures in bending with transverse and longitudinal forces. *Construction and Reconstruction.* 2021;(6):5–19. (In Russ.) https://doi.org/10.33979/2073-7416-2021-98-6-5-19

17. Tamrazyan A.G., Chernik V.I., Matseevich T.A., Manaenkov I.K. Analytical model of deformation of reinforced concrete columns based on fracture mechanics. *Structural Mechanics of Engineering Constructions and Buildings.* 2022;(18):573–583. https://doi.org/10.22363/1815-5235-2022-18-6-573-583

18. Trekin N.N., Kodysh E.N., Trekin D.N. Calculation of the formation of normal cracks based on the deformation model. *Industrial and Civil Construction.* 2016;(7):74–78. (In Russ.) EDN: WHKJXN

19. Belov N.N., Yugov N.T., Kopanitsa D.G., Kabantsev O.V., Yugov A.A., Ovechkina A.N. The design and experimental approach to the analysis of dynamic strength of reinforced concrete constructions. *Earthquake Engineering. Constructions safety.* 2006;(4):40–46. (In Russ.) EDN: HUJJPT

20. Tonkikh G.P., Kabantsev O.V., Dorofeev M.L. Experimental studies of the influence of non-structural elements on the periods of natural vibrations of frame buildings. *Earthquake Engineering. Safety of constructions.* 2002;(6):12–16. (In Russ.) EDN: UIEBJR

21. Kabantsev O.V., Useinov E.S., Sharipov Sh. On the methodology for determining the damage tolerance factor of earthquake-resistant structures. *Bulletin of Tomsk State University of Architecture and Civil Engineering.* 2016;(2): 117–129. (In Russ.) EDN: VSTVTV

22. Nazarov Yu.P., Poznyak E.V. Estimation of Amplification Factor in Earthquake Engineering. *Construction: Science and Education.* 2015;(1):2. (In Russ.) EDN: TMPKTT

23. Sosnin A.V. About dissipation properties of multi-storey RC frame buildings of large-scale-construction projects at their earthquake-resistance estimation. *Modern Science and Innovations.* 2017;(1):114–131. (In Russ.) EDN: YTFHIB

24. Li D., Wei R., Xing F., Sui L., Zhou Y., Wang W. Influence of Non-uniform corrosion of steel bars on the seismic behavior of reinforced concrete columns. *Construction and Building Materials*. 2018;(167):20–32. https://doi.org/10.1016/j.conbuildmat.2018.01.149

25. El-Joukhadar N., Dameh F., Pantazopoulou S. Seismic Modelling of Corroded Reinforced Concrete Columns. *Engineering Structures*. 2023;275(Part A):115251. https://doi.org/10.1016/j.engstruct.2022.115251

Список литературы

1. *Savin S.Yu., Fedorova N.V.* Stability exposure of building structural systems under environmental damage // Structural Mechanics of Engineering Constructions and Buildings. 2022. Vol. 18. No. 6. P. 564–572. https://doi.org/10.22363/1815-5235-2022-18-6-564-572

2. *Клюева Н.В., Колчунов В.И., Губанова М.С.* Критерий прочности нагруженного и коррозионно поврежденного бетона при плоском напряженном состоянии // Жилищное строительство. 2016. № 5. С. 22–27. EDN: WEFACB

3. *Шамшина К.В.* Результаты экспериментальных исследований деформационных свойств сжимаемых железобетонных конструкций с коррозионными продольными трещинами в защитном слое бетона // Инженерно-строительный вестник Прикаспия. 2020. № 1 (31). С. 26–33. EDN: LEQCNP

4. *Dangwal S., Singh H.* Behavior of corrosion damaged non-seismically and seismically detailed reinforced concrete beam-column sub-assemblages under cyclic loading // Engineering Failure Analysis. 2023. Vol. 146. https://doi.org/10.1016/j.engfailanal.2023.107135

5. *Kanchanadevi A., Ramanjaneyulu K.* Effect of corrosion damage on seismic behaviour of existing reinforced concrete beam-column sub-assemblages // Engineering Structures. 2018. Vol. 174. P. 601–617. https://doi.org/10.1016/j.engstruct.2018.07.094

6. *Шахраманьян М.А., Нигметов Г.М., Гайфуллин З.Г., Бабусенко М.С.* Методика оценки и сертификации инженерной безопасности зданий и сооружений // Технологии гражданской безопасности. 2004. № 2. С. 5–15. EDN: KVUNYV

7. *Чаускин А.Ю., Пшеничкина В.А., Лейчу Ф.Ф.* Критерии отказа зданий как нелинейных систем при сейсмическом воздействии // Вестник Инженерной школы Дальневосточного федерального университета. 2018. № 2 (35). С. 120–127. https://doi.org/10.5281/zenodo.1286040

8. *Улыбин А.В.* Измерение периодов и декрементов колебаний многоэтажных зданий // Обследование зданий и сооружений: проблемы и пути их решения: материалы VIII Международной научно-практической конференции. Санкт-Петербург. 2017. С. 192–202. EDN: YQYCBV

9. *Базаров А.Д., Лундэнбазар Б., Комаров А.К., Иванов И.А.* Оценка динамической реакции каркасного здания под воздействием микросейсмического шума в г. Улан-Баторе // Известия вузов. Инвестиции. Строительство. Недвижимость. 2020. № 2 (33). С. 198–205. https://doi.org/10.21285/2227-2917-2020-2-198-205

10. *Кадомцев М.И., Ляпин А.А., Шатилов Ю.Ю.* Вибродиагностика строительных конструкций // Инженерный вестник Дона. 2012. № 3 (21). С. 576–579. EDN: PJZXHZ

11. *Савин С.Н., Смирнова Е.Э.* Прогноз ресурса зданий в условиях природных и техногенных чрезвычайных ситуаций // Современные проблемы гражданской защиты. 2019. № 2 (31). С. 33–42. EDN: XYVCJB

12. *Аветисян Л.А., Тамразян А.Г.* Экспериментальные исследования внецентренно сжатых железобетонных элементов при кратковременном динамическом нагружении в условиях пожара // Промышленное и гражданское строительство. 2014. № 4. С. 24–28. EDN: SAZOJD

13. *Тамразян А.Г.* Живучесть как степень работоспособности конструкций при повреждениях // Промышленное и гражданское строительство. 2023. № 7. С. 22–28. https://doi.org/10.33622/0869-3019.2023.07.22-28

14. *Тамразян А.Г.* Концептуальные подходы к оценке живучести строительных конструкций, зданий и сооружений // Железобетонные конструкции. 2023. Т. 3. № 3. С. 62–74. https://doi.org/10.22227/2949-1622.2023.3.62-74

15. *Мацеевич Т.А., Тамразян А.Г.* Анализ надежности железобетонной плиты с корродированной арматурой. *Строительство и реконструкция.* 2022. № 1 (99). С. 89–98. https://doi.org/10.33979/2073-7416-2022-99-1-89-98

16. *Колчунов В.И., Аль-Хашими О., Протченко М.В.* Жесткость железобетонных конструкций при изгибе поперечной и продольной силами // Строительство и реконструкция. 2021. № 6 (98). С. 5–19. https://doi.org/10.33979/2073-7416-2021-98-6-5-19

17. *Tamrazyan A.G., Chernik V.I., Matseevich T.A., Manaenkov I.K.* Analytical model of deformation of reinforced concrete columns based on fracture mechanics // Строительная механика инженерных конструкций и сооружений. 2022. № 6. С. 573–583. https://doi.org/10.22363/1815-5235-2022-18-6-573-583

18. *Трекин Н.Н., Кодыш Е.Н., Трекин Д.Н.* Расчет образования нормальных трещин на основе деформационной модели // Промышленное и гражданское строительство. 2016. № 7. С. 74–78. EDN: WHKJXN

19. *Белов Н.Н., Югов Н.Т., Копаница Д.Г., Кабанцев О.В., Югов А.А., Овечкина А.Н.* Расчетно-экспериментальный метод анализа динамической прочности железобетонных конструкций // Инженерная сейсмостойкость. Безопасность сооружений. 2006. № 4. С. 40–46. EDN: HUJJPT

20. *Тонких Г.П., Кабанцев О.В., Дорофеев М.Л.* Экспериментальные исследования влияния неконструктивных элементов на периоды собственных колебаний каркасных зданий // Инженерная сейсмология. Безопасность сооружений. 2002. № 6. С. 12–16. EDN: UIEBJR

21. *Кабанцев О.В., Усеинов Э.С., Шарипов Ш.* О методике определения коэффициента допускаемых повреждений сейсмостойких конструкций // Вестник Томского государственного архитектурно-строительного университета. 2016. № 2 (55). С. 117–129. EDN: VSTVTV

22. *Назаров Ю.П., Позняк Е.В.* Определение коэффициента динамичности в расчетах на сейсмостойкость // Строительство: наука и образование. 2015. № 1. С. 2. EDN: TMPKTT

23. *Соснин А.В.* К вопросу учёта диссипативных свойств многоэтажных железобетонных каркасных зданий массового строительства при оценке их сейсмостойкости // Современная наука и инновации. 2017. № 1 (17). С. 114–131. EDN: YTFHIB

24. *Li D., Wei R., Xing F., Sui L., Zhou Y., Wang W.* Influence of Non-uniform corrosion of steel bars on the seismic behavior of reinforced concrete columns // Construction and Building Materials. 2018. Vol. 167. P. 20–32. https://doi.org/10.1016/j.conbuildmat.2018.01.149

25. *El-Joukhadar N., Dameh F., Pantazopoulou S.* Seismic modelling of corroded reinforced concrete columns // Engineering Structures. 2023. Vol. 275. Part A. https://doi.org/10.1016/j.engstruct.2022.115251