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The Buildings' Reliability Calculating Method Using a Simple Seismic Impact Model

Vladimir Lapin [1*], Yeraly Shokbarov [1], Yerken Aldakhov [1]

[1] *Kazakh Research and Design Institute of Construction and Architecture JSC, 21 Solodovnikova, Almaty, Kazakhstan*.

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Abstract

Non-canonical spectral representation of seismic activity is employed to assess the reliability of nonlinearly modeled buildings. Seismic impact is modeled using a random process, represented by simple functions with random parameters. We consider random processes with correlation functions expressed as a sum of cosine-exponential terms. Reliability, defined as the probability of failure-free operation, is determined using statistical testing methods. The reliability calculation algorithm is implemented in MATLAB. As an illustrative example, we calculate the reliability of a section of a one-story industrial building frame modeled by a nonlinear system. Failure is defined as exceeding experimentally determined permissible displacement limits. Our calculations involve up to 2000 realizations of the random process. We analyze histograms, empirical distribution functions, and reliability values of maximum fragment movements. We find that using 100 realizations of the random process yields satisfactory accuracy in determining reliability. This reliability calculation method is recommended for rapid reliability estimates across various structure types, including those employing seismic isolation systems. We also observe a correlation between displacement magnitudes calculated under accelerograms and a random process represented in a non-canonical form. Thus, we recommend this method for reliability assessments in multi-story buildings.

Keywords: Artificial Accelerograms; Earthquake-Resistant Construction; Seismic Impact; Reliability; Probability of Failure-Free Operation.

1. Introduction

The cornerstone of seismic safety lies in earthquake-resistant construction, which proves to be a highly reliable and steadfast survival strategy in regions prone to frequent earthquakes. However, the commonly employed spectral calculation method falls short in adequately assessing seismic resistance and determining seismic risk values for buildings and structures. These encompass stationary, non-stationary, or Markov random processes, spectral representations of random processes, canonical or non-canonical representations of random processes, and various methods for digitally modeling random functions.

The first case of applying a non-canonical spectral representation of a random process was noted in the study by Chernetsky when calculating nonlinear control systems [1]. At that time, the method did not gain wide acceptance. In the study by Zhunusov et al. [2], quasi-stationary random processes were used for modeling seismic impact, with realizations generated using the shaping filter method. In Bolotin's study [3], stationary random processes were applied to various tasks in building mechanics, while in another article by Bolotin [4], different schemes for statistical modeling of seismic impact using non-stationary random processes were proposed. The classic study by Pugachev [5] examines various canonical representations of random processes that can describe different dynamic processes. Approximations of stationary and non-stationary random functions using uncorrelated elementary random functions are of significant interest.

* Corresponding author: lapin_1956@list.ru; vlapin@kazniisa.kz

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In the study by Alderucci et al. [6], fully non-stationary random processes were proposed for modeling seismic impacts, considering the evolution of spectral characteristics over time. This model better represents actual seismic impacts. The procedure for generating artificial accelerograms based on Gaussian random processes is investigated by Cacciola & Zentner [7]. A method for modeling artificial accelerograms compatible with the specified response spectrum, corresponding to the mean value and target response spectrum of the mean + standard deviation, is proposed. The response spectrum is derived from a set of 67 accelerograms from the European Strong Motion Database (ESD) with similar magnitudes and epicentral distances. It is claimed that this method better matches real accelerograms.

In the study by Rezaeian & Der Kiureghian [8], a method for creating artificial accelerograms for specific earthquake and construction site characteristics is presented. A parameterized stochastic model based on a modulated "white noise" process is used. The model parameters consider seismic intensity, predominant frequency, and spectral width with characteristics of the "reference accelerogram" on solid ground. This method is recommended for generating artificial accelerograms for design calculations. A simple but interesting way of probabilistically defining seismic impacts for extended systems is proposed in the study by Falamarz-Sheikhabadi & Zerva [9]. The probability distribution function of wave velocity values and the non-synchronous oscillation of the extended structure's base are considered. This method of defining the impact is recommended for project work within the framework of Eurocode 8.

It is also necessary to address the method of modeling seismic impacts using random processes with wavelet transformations. A wavelet transformation is an integral transformation that represents the convolution of a wavelet function with the original signal. Wavelet transformation translates the signal from the time domain to the time-frequency domain. In the study by Mamaghani & Lui [10], a comprehensive algorithm for applying wavelet analysis to real accelerograms is proposed. The wavelet analysis determines the frequency characteristics of the impact, the frequency window, and the duration of the impact. An artificial accelerogram is generated as a realization of a random process using a Chebyshev filter, adjusting the frequency composition of the impact. Then, an envelope is applied to the accelerogram, and the artificial accelerogram is ready for use in building and structure calculations.

Naturally, the accuracy of determining artificial accelerograms depends on which accelerograms are taken as the initial or reference for building and structure calculations. It is recommended to use instrumental recordings of earthquakes obtained by engineering seismometric service stations, as in the studies by Lapin et al. [11]. Specific accelerograms of certain earthquakes, the parameters of which correspond to the regional characteristics of local earthquakes, can be used. For example, accelerograms recorded during the 1994 Northridge earthquake [12] are often used.

It is worth noting a successful example of using a non-canonical representation of a random process to construct the reaction spectrum of a specific earthquake in the study by Yerzhanov & Lapin [13]. Thus, there are numerous models of seismic impact using the theory of random functions. For tasks assessing the seismic resistance of buildings considering nonlinearity of deformation and determining seismic risk values for buildings and structures, the commonly employed spectral calculation method proves insufficient. The spectral method fails to address "failures" within dynamic systems that accurately simulate real buildings and cannot monitor nonlinear effects contingent upon impact amplitude. Consequently, there is a growing body of works focusing on direct dynamic calculations, particularly within models based on nonlinear dynamic systems.

For ordinary buildings with nonlinear seismic isolating foundations, as well as extended structures featuring non-uniform acceleration fields, the use of real or artificial accelerograms is imperative. The use of real or artificial accelerograms is mandatory when calculating ordinary buildings with nonlinear seismic isolating foundations, as well as extended structures with non-uniform acceleration fields. Similarly, calculations for high-rise buildings, especially those employing a deformed scheme, necessitate the utilization of real, artificial (representations of a random process), or synthetic accelerograms.

A new class of tasks has emerged, related to determining the reliability of buildings as the probability of failure-free operation of a given construction object. Building failures can be understood as exceeding a specified floor displacement or other kinematic characteristics that occur during the building's oscillation in an earthquake. Numerous studies delve into determining the reliability of buildings and structures from a probabilistic perspective. In the study by Lapin [14], an interpolation method for reliability calculation is considered, allowing significant refinement in determining the probability of failure-free operation using a relatively small number of realizations of a stationary random process.

In the study by Mkrtichev et al. [15], a probabilistic method for assessing the reliability of buildings and structures is developed, which, in principle, allows designing construction structures with a given reliability level. The model of a five-story building, which considers the interaction effect between the building and the ground foundation, is examined. The Monte Carlo method (statistical testing) is used in the calculations of the building's reliability.

In the study by Drozdov et al. [16], a simple method for analyzing the reliability of a 16-story building under high-magnitude seismic impact is proposed. The article analyzes the reliability level implemented using the method recommended by SP 14.13330.2014 (Rules for the Design of Earthquake-Resistant Buildings). The results of the probabilistic analysis of a 16-story earthquake-resistant building in terms of seismic load corresponding to a design earthquake are presented.

Of particular interest is the study by Der Kiureghian & Zhang [17], which directly addresses reliability issues where a failure event is defined in a spatial domain, such as exceeding the damage measure beyond an acceptable threshold anywhere within the construction body. Uncertainties in the problem can arise due to the stochastic nature of the material, load, geometry, and boundary conditions of the structure. The classical finite element method is applied to determine the probability of failure.

An analysis of nuclear power plant safety is performed in the study by Guo et al. [18]. The criterion for failure is the formation of through cracks in the reactor containment structures. The Monte Carlo method and the ABAQUS modeling program are used for reliability calculation. Numerical values of the probability of failure are obtained.

Various numerical methods are applied in Pavani et al. [19] and Wu et al. [20] for analyzing the reliability of different objects. The aim of the study by Pavani et al. [19] is the application of two numerical models describing the destruction process of masonry subjected to aggressive environmental impacts to predict the time required to reach a specified damage level. The results of the probabilistic analysis are compared with the deterministic method results. It is found that the results of both types of analysis do not contradict each other.

In the study by Wu et al. [20], a nonlinear calculation of the aqueduct structures is performed using the Monte Carlo method. One hundred realizations of the random process (artificial accelerograms) were generated. The seismic impact had a random nature. Specific nonlinear effects were noted in the study of the reliability of aqueduct structures. The Monte Carlo method is also applied in the study by Kim and Wallace [21] for analyzing the reliability of a high-rise building with reinforced concrete walls. The analysis considers buildings with 20 and 30 stories. The criteria for failure are taken as the property of the structures to work under shear. A quantitative and fairly high assessment of the buildings' reliability level is obtained.

Thus, the probabilistic description of seismic impact using random functions allows considering a class of tasks with reliability assessment (probability of failure-free operation). The main method for solving such tasks is primarily the Monte Carlo method. Therefore, considering the complexity of practical reliability calculation tasks for construction structures with damageability and nonlinearity, it is advisable to propose a maximally economical way to generate realizations of the random process.

Let us solve the problem of applying a seismic impact model in the form of a random process represented by a non-canonical spectral representation [1]. In Yerzhanov & Lapin [13], such a seismic impact model was used to construct spectral curves of specific earthquakes. Let us consider and solve a new problem of determining the reliability of a building as a nonlinear system under a given model of seismic impact, and also estimate the number of realizations of the random process necessary to solve this problem. Previously, such problems were not solved.

It is also necessary to assess the extent to which there is a correlation between the magnitudes of displacements of a fragment of a frame building, calculated in two ways - under the influence of accelerograms and a random process in the form of a non-canonical representation.

So, we need to solve the following problem:

- To propose a method for modeling seismic impact to determine the reliability of a building modeled by nonlinear systems;
- To assess the accuracy of the specified method for modeling seismic impact using the example of calculating the probabilistic characteristics of displacement (skew) of a nonlinear building model;
- To compare the values of displacements of a nonlinear system for different values of viscous friction;
- To investigate the influence of the number of realizations of a random process on the reliability values W for different numbers of realizations of a random process;

To determine the number of realizations of a random process for calculating the highest moments of displacement values of a nonlinear building model.

2. Methods and Objects

Let us consider the results of applying the seismic impact model in the form of a random Equation 1. We take the correlation function of the random process in cosine-exponential form:

$$r_x(\tau) = \sigma^2 e^{-a|\tau|} \cos \beta\tau \tag{1}$$

where α, β – parameters of the correlation function, σ – the root means square values of acceleration.

A profoundly general theorem, as established in reference [1], asserts that a stationary random function, denoted as $X(t)$, can be impeccably represented within the realm of correlation theory in the following form:

$$X(t) = m_x(t) + \lambda_1 \sin \omega t + \lambda_2 \cos \omega t \tag{2}$$

The envelope of a stationary random process is adopted in the form of a fractional rational expression by Aptikayev [22].

In this context, it is assumed that $m_x(t) = 0$. The values of λ_1 and λ_2 are distributed according to the normal distribution. Digital modeling of such quantities can be easily achieved using computer mathematics systems like MATLAB, MATHCAD, and MAPLE.

The values of ω are determined by solving the nonlinear equation [13].

$$\frac{1}{2} + \frac{1}{2\pi}\left[arctg\frac{\omega+\beta}{\alpha} + arctg\frac{\omega-\beta}{\alpha}\right] = \frac{z+1}{2} \tag{3}$$

where random numbers z have a uniform distribution on the interval [-1, 1].

Consequently, for each implementation of a random process, calculations involve only three random variables.

Before this study, dynamic tests were conducted on a fragment of a one-story industrial building [23]. These tests utilized a robust vibration machine, VZ, enabling the observation of the structure's behavior until failure. From these test results a nonlinear deformation diagram was constructed (Figure 1), revealing the frame building's significant nonlinear characteristics. As per Eurocode 0 standards, a nonlinear calculation considering actual deformations and a probabilistic method for specifying seismic impact is necessary.

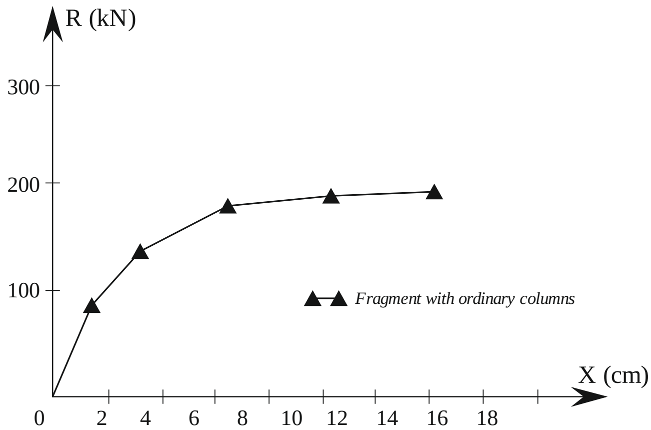

Figure 1. Deformation diagram of a fragment of an industrial building

The experimental fragment constitutes a cell of a one-story frame building with a 6x12 m column grid. The building's calculated seismicity is 8 points. The fragment's plan dimensions are also 6x12 m. The design of the flooring aims to create a longitudinal force on the column ranging from 20 to 25 EHL, aligning with values typical for buildings with a 6x18 m column grid. The fragment's height to the bottom of the truss structure is 4.2 m. The columns are made of prefabricated reinforced concrete, featuring a standard size with a cross-section of 40x40 cm and a concrete grade design of 200. Column foundations consist of monolithic reinforced concrete with base dimensions of 2.4x2.4 m. The flooring comprises prefabricated bridge slabs measuring 1.0x6.0 m in plan, with a section height of 30 cm along steel rafter beams. The junction of rafter beams follows standard practices for buildings with a calculated seismicity of 7 and 8 points. The total longitudinal reinforcement for the column section consists of 4x22 AIII bars.

Let us perform a probabilistic calculation of the indicated fragment for pseudo-earthquakes of various magnitudes. We approximate the deformation diagram by a piecewise linear curve with five linear sections. The accumulation of plastic deformations is taken into account.

For convenience of calculation, it is convenient to set the interpolation points of the deformation diagram (Table 1). When $R \geq 190\ kN,\ R = 190\ kN$ is taken. For the case of a negative branch of the diagram, all data from Table 1 is multiplied by “-1”.

Table 1. Characteristic points of the nonlinear deformation diagram of a building fragment

Displacement, cm	0	1.7	3.4	6.0	8.0	10.0	12.0	15.0
Reaction, kN	0	80.0	140.0	160.0	170.0	180.0	185.0	190.0

The nonlinear differential equation is integrated:

$$m\ddot{x} + \mu\ddot{x} + R(x) = -m\ddot{x}_{0i} \tag{4}$$

where $R(x)$ – the nonlinear restoring force, $\ddot{x}_{0i}$ – the i-th accelerogram, μ – the coefficient of inelastic resistance (Voigt’s hypothesis).

The fragment has the following static and dynamic characteristics:

$Q = 880\ \text{kN};\ C_1 = 47.06\ \text{kN/cm}; C_2 = 37.50\ \text{kN/cm};\ C_3 = 1.50\ \text{kN/cm};$

$P_1 = 80\ \text{kN};\ P_2 = 140\ \text{kN/cm},\ \ [x_{max}] = 15\ \text{cm}, \mu = 0.26\ \text{kN s/cm}.$

The achievement of maximum permissible displacements is taken here as a failure criterion $[x_{max}]$.

3. Results

Let's proceed with a nonlinear calculation of a frame industrial building subjected to seismic impact in the form of a non-stationary random process, as well as the impact of real accelerograms. The parameters of cosine-exponential correlation functions have been previously established. In the probabilistic calculation, we implement the classical scheme of the statistical test method. One hundred implementations of the random process (1) with zero mathematical expectation are generated. By averaging over all implementations, we determine the average values of the maximum displacements, velocities, and accelerations.

Table 2 presents the names of recorded instrumental records of California earthquakes, along with the magnitude of acceleration at the base and the results of calculations performed using the MATLAB computer mathematics system.

Table 2. Maximum displacements of a building fragment under the influence of real accelerograms and a model in the form of a random process

Earthquake, date	Acceleration at the base, cm/s^2	Displacement (random process), cm	Displacement (real accelerogram), cm
Kern County, 21.07.52	152.7	2.44	2.50
Kern County, 21.07.52	175.9	2.40	2.76
Eureca, 21.12.54	164.5	2.39	1.95
Eureca, 21.12.54	252.7	2.59	2.53
San Fernando, 9.02.71	110.8	2.91	2,13
San Fernando, 9.02.71	309.4	1.34	1.60
San Fernando, 9.02.71	265.4	3.86	4.33
San Fernando, 9.02.71	250.0	3.82	3.21
San Fernando, 9.02.71	104.6	4.37	1.60
Northern California, 3.10.41	118.6	1.41	1.14
Northern California, 3.10.41	113.5	0.84	0.74
Long Beach, 10.03.33	192.7	1.63	3.53
Long Beach, 10.03.33	156.0	2.13	1.78

Figure 2 illustrates a graph of displacements and velocities obtained from calculations using one of the implementations of the non-canonical representation of a random process.

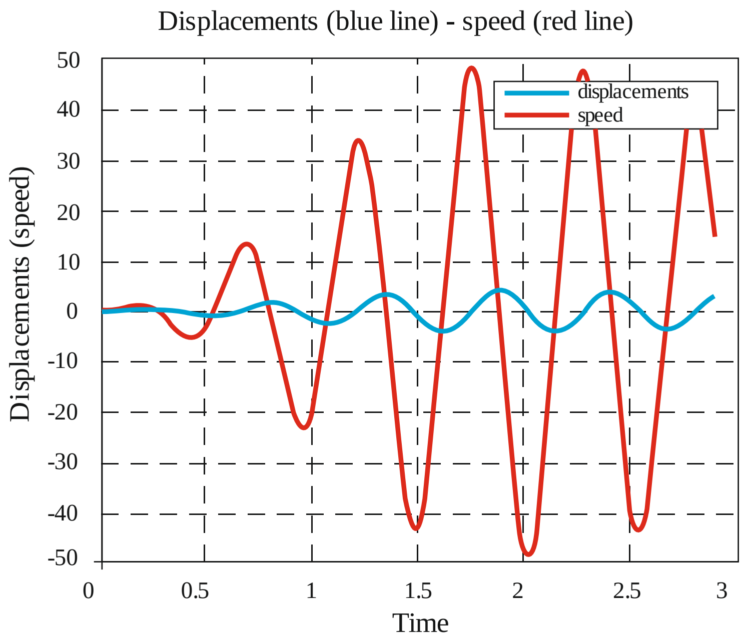

Figure 2. Displacement and speed of a building fragment under the influence of the implementation of a random process

An analysis of Table 2 shows that there is a correlation between the displacement values of a fragment of a frame building, calculated in two ways - under the influence of accelerograms and a random process in the form of a non-canonical representation. The amount of movement of the building model was obtained using the Monte Carlo method and is presented in Table 2 as the average value (mathematical expectation). Comparing the average displacement values (third column) with the displacements obtained when calculating with real accelerograms, it can be noted that for the Kern County, Eureca, San Fernando, and Northern California earthquakes, the non-canonical spectral representation of the random process models the frequency characteristics of real accelerograms quite well. For the Long Beach earthquake, the mentioned representation of the random process models the characteristics of real accelerograms less accurately. Table 3 shows the probabilistic characteristics of the displacement values from Table 2 - average values, root-mean-square values and coefficients of variation. The difference between the average displacement values calculated by the two methods is about 7%. In general, the non-canonical representation of a random process can be assessed as a convenient means of modeling seismic impact for express analysis of the behavior of nonlinear dynamic models. Within the framework of the application of statistical modeling methods using finite element design diagrams of a building, the benefits from the use of such impact models can be significant.

Table 3. Probabilistic characteristics of displacement values

Parameters	Accelerograms	Random process
Average, cm	2.29	2.47
RMS value, cm	1.0	1.06
The coefficient of variation	0.44	0.43

Table 4 shows the results of calculations of the maximum displacements of the fragment at various values of the viscous friction parameter μ. From the analysis, it follows that when the value of the coefficient μ changes by 13 times, the values of the maximum displacements change by approximately 2-3.5 times. The results of Table 3 also make it possible to evaluate the influence of the error in assigning the value of the viscous friction parameter on the displacement values.

Table 4. Influence of the coefficient value of viscous friction μ on the values of maximum displacements, in cm

№	μ kN s/cm	Non-canonical representation, x_1	Kern County Accelerogram, 21.07.52, $\ddot{x} = 152.7\ cm/s^2$	Non-canonical representation, x_2	Kern County Accelerogram, 21.07.52, $\ddot{x} = 175.9\ cm/s^2$
1	0.39	1.44	1.92	1.86	2.24
2	0.26	2.44	2.50	2.40	2.76
3	0.13	3.61	3.87	3.11	3.93
4	0.07	4.13	5.28	4.01	4.60
5	0.03	5.47	6.51	4.17	4.63

Using the least squares method, we approximate the 3rd and 5th columns, respectively, by linear dependencies

$$x_1 = -10.16\mu + 5.21 \tag{5}$$

$$x_2 = -6.60\mu + 4.27 \tag{6}$$

Using expressions 5, it is possible to predict the maximum displacements of a fragment at intermediate values of the viscous friction parameter μ.

Since the use of a non-canonical representation of a random process does not require the generation of a significant number of random numbers as in the case, for example, of the forming filter method, it begs the consideration of this representation in problems of calculating the probabilities of failure-free operation of buildings modeled by nonlinear systems. Calculations were performed for the case of the San Fernando earthquake, 09.02.71 (the average value of the maximum acceleration at the base was chosen similar to that indicated).

Table 5 presents the results of determining the reliability values (probability of failure-free operation) W of a fragment of a frame industrial building, where

$$W = 1 - \frac{n}{N} \tag{7}$$

where N – total number of realizations, n – number of realizations under the influence of which the failure condition $x > [x_{max}]$ is satisfied.

Table 5. Probabilities of failure-free operation (reliability) *W* of a fragment of a frame building

$[x_{max}]$	Number of realizations of a random process				
	100	**200**	**500**	**1000**	**2000**
8	0.97	0.975	0.956	0.945	0.945
10	0.95	0.960	0.956	0.975	0.961
12	0.94	0.955	0.982	0.972	0.9635
15	0.99	0.99	0.964	0.972	0.9745
17	0.97	0.985	0.972	0.974	0.9815
20	1.00	0.975	0.988	0.992	0.9825

The number of generated implementations varied from 100 to 2000. Table 5 shows the reliability values Was a function of the number of implementations of the random process and the magnitude of the limiting displacement $[x_{max}]$. Starting from 500 implementations, the dependence of the increase in the reliability value as the maximum skew of the building increases. The actual value of the limiting skew according to experimental data is 15 cm. Even with 100 implementations of the random process, the accuracy of determining the reliability value W100 is satisfactory. The difference from the same value for 2000 sales is 1.5%.

Figure 3 shows the displacement distribution functions as the number of implementations used in the calculation increases. Differences are visible only in the "tail" region of the distribution.

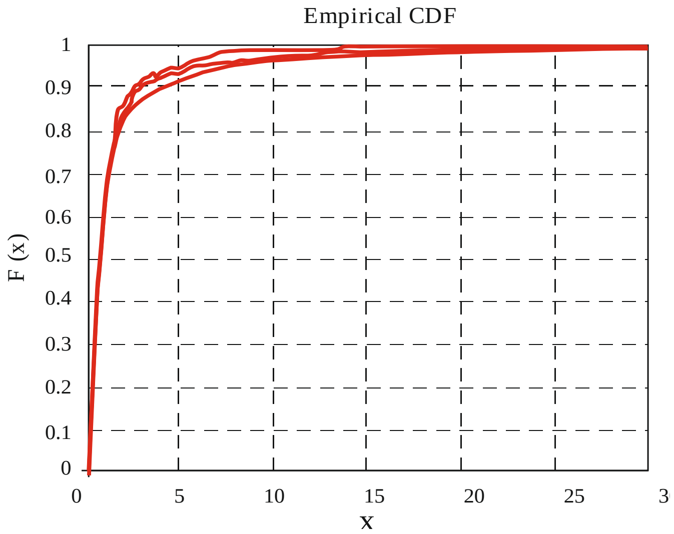

Figure 3. Distribution function of maximum displacements of a building fragment depending on the number of realizations

Figure 4 shows the histogram and the empirical distribution function of the maximum fragment displacements. Due to the nonlinearity of deformation, the normal distribution (blue line) poorly approximates the empirical dependences (red line).

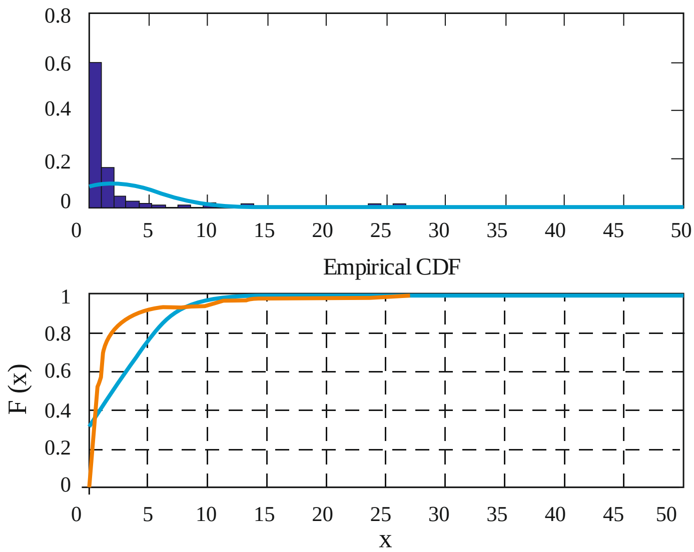

Figure 4. Histogram and empirical distribution function of maximum fragment displacements

In Figure 5, a graph of the lognormal distribution is plotted to assess the closeness between the empirical cumulative and theoretical distributions. The analysis reveals a very satisfactory correspondence between the two curves.

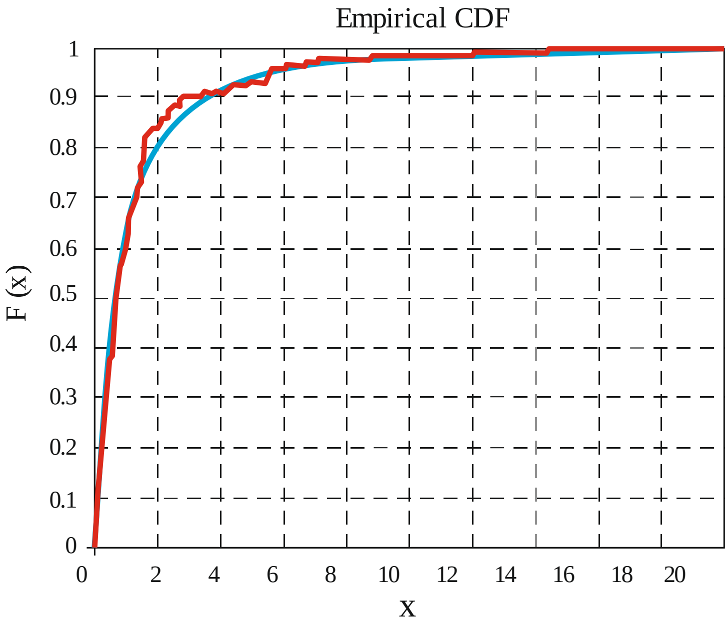

Figure 5. Cumulative empirical distribution function (red line) and cumulative lognormal distribution function (blue line)

Next, in Figure 6, the upper and lower estimates of the cumulative function of the tested distribution are depicted. A qualitative visual assessment confirms the lognormality of the distribution of maximum displacement values.

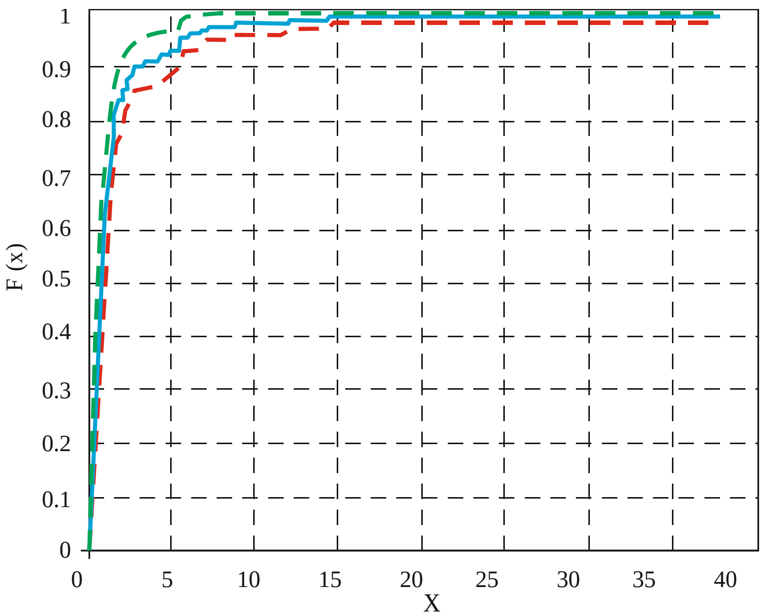

Figure 6. Confidence limits for the cumulative distribution

To further assess the closeness of the empirical distribution to normal, it is convenient to calculate the values of skewness and kurtosis, respectively

$$A = \frac{\sqrt{N}}{\sqrt{(N-1)^3 S^3}} \sum_{i=1}^{N} (x_i - \overline{x})^3 \quad (8)$$

$$E = \frac{N}{(N-1)^2 S^4} \sum_{i=1}^{N} (x_i - \overline{x})^4 - 3 \quad (9)$$

where S sample standard deviation, $\bar{x}$ – sample mean.

Table 6 presents the values of asymmetry and kurtosis as a function of the number of realizations of the random process. With 2000 implementations, the values of these quantities practically do not change.

Table 6. Values of probabilistic characteristics

Probabilistic characteristics	Number of realizations				
	500	**1000**	**2000**	**5000**	**10000**
$\bar{x}$, cm	1.72	2.44	2.02	2.07	2.09
A	10.28	7.50	8.12	8.28	8.56
E	138.92	68.76	88.98	83.61	95.01

In general, the sample average displacement values stabilize relatively quickly, particularly at the onset. However, the values of asymmetry and kurtosis exhibit minimal change until approximately 2000 realizations.

Both the skewness and kurtosis coefficients deviate significantly from zero. The positive kurtosis coefficient indicates that the empirical distribution is more peaked than a normal distribution, implying that the histogram bars at the distribution's center are higher than the corresponding values of the normal curve.

It is worth noting that the proposed method for determining reliability values (i.e., the probability of failure-free operation) can naturally be applied to seismic isolating systems, whose dynamics are governed by nonlinear differential equations [24].

4. Discussion

The application of methods of reliability theory in construction design makes it possible to create buildings and structures that are very economical and reliable. Regulatory documents of the Republic of Kazakhstan are based on Eurocodes. Eurocode 1990 regulates the concept of reliability of structures and establishes their quantitative values depending on the responsibility of the structure [25]. The application of methods of reliability theory within the framework of Eurocode 0 will make it possible to reasonably design various types of steel and reinforced concrete structures that are optimal in terms of parameters under any static and dynamic influences [26, 27]. For example, the scheme for applying the Monte Carlo method can be used to calculate buildings for wind impacts, so non-canonical representations of the impact can also be used when modeling wind impacts [28].

All seismic isolating structural systems, as a rule, turn out to be nonlinear. Sometimes nonlinearities have a very complex form. Therefore, the Monte Carlo Method scheme with a description of the influence (1), (2) turns out to be useful [27, 28]. Any seismic isolation systems can be calculated using this seismic impact model [29, 30].

The method developed in this article will make it possible to determine the values of reliability and failure of buildings modeled by nonlinear systems within the framework of Pushover analysis [31, 32].

The simple method of modeling the impact in the form (2) facilitates the generation of random process realizations at a minimal cost. For each implementation, only 3 random number values need to be generated. Consequently, it becomes feasible to produce numerous implementations of a random process within a relatively short amount of time. This approach to generating influence renders the Monte Carlo method (statistical tests) an effective tool for studying nonlinear systems that simulate construction objects [28, 33].

Moreover, this impact modelling method is recommended for calculating multi-mass discrete systems that simulate high-rise multi-story buildings [34]. As shown above, despite the simplicity of expression (2), the non-canonical representation of the random process has broad capabilities even for studying significantly nonlinear dynamic systems. For a 30-40 story building and a multi-mass dynamic model of a construction object, the time savings in determining reliability values using the Monte Carlo method will be significant.

Impact models are successfully used in algorithms for determining seismic risk [35]. The concept of seismic risk is based on the concept of structural failure. Seismic risk is the probability of losses due to seismic impact. The more accurately the seismic impact is described, the more adequately the risk value is determined.

A simple and effective impact model (2) can apparently find wide application when working with Eurocode 8, which allows the application of reliability theory methods for alternative design of construction structures in seismic areas. Ultimately, the reliability value is a quantitative assessment of the seismic resistance of a building. By determining the probability of failure-free operation of two design solutions for a building, a more reliable or economical design solution can be identified.

5. Conclusion

The non-canonical representation of a random process is a simple way to model seismic impact. To generate one realization, only 3 random variable values are needed. Its use is quite effective for determining the probabilistic characteristics of displacements, velocities, and reactions of buildings and structures modeled by nonlinear non-stationary systems. An effective way to calculate reliability values for this method of seismic impact modeling is the method of statistical tests (Monte Carlo method). Determination of reliability values (probability of failure-free operation) using this method has sufficient accuracy, starting with the use of 100 implementations of a random process. The failure probability values are also established using from 100 to 500 realizations of a random process. The realization of a non-canonical spectral representation of a random process is very economical from a computational point of view and is very convenient for use, especially using computer mathematics systems MATLAB or MATHCAD. The distribution function of displacement values in essentially nonlinear calculations is very close to lognormal.

6. Declarations

6.1. Author Contributions

Conceptualization, V.L., Y.S., and Y.A.; methodology, V.L., Y.S., and Y.A.; writing—original draft preparation, V.L. and Y.S.; writing—review and editing, V.L., Y.S., and Y.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Chernetsky, A. I. (1968). Analysis of the accuracy of nonlinear control systems. Mechanical Engineering, Moscow, Russia. (In Russian).

[2] Zhunusov, T. Z. Pak, E.F. & Lapin V.A. (1990). Earthquake resistance of frame buildings. Gylym, Almaty, Kazakhstan. (In Russian).

[3] Bolotin, V.V. (1965). Statistical methods in building mechanics Publishing house of literature on construction, Moscow, Russia. (In Russian).

[4] Bolotin, V.V. (1981). Statistical modeling based on earthquake resistance. Mechanics and Calculation of Structures, (1), 60-64.

[5] Pugachev, V. S. (1965). Theory of Random Functions and its Application to Control Problems. Fizmatgiz, Moscow, Russia.

[6] Alderucci, T., Muscolino, G., & Urso, S. (2019). Stochastic analysis of linear structural systems under spectrum and site intensity compatible fully non-stationary artificial accelerograms. Soil Dynamics and Earthquake Engineering, 126, 105762. doi:10.1016/j.soildyn.2019.105762.

[7] Cacciola, P., & Zentner, I. (2012). Generation of response-spectrum-compatible artificial earthquake accelerograms with random joint time–frequency distributions. Probabilistic Engineering Mechanics, 28, 52–58. doi:10.1016/j.probengmech.2011.08.004.

[8] Rezaeian, S., & Der Kiureghian, A. (2010). Simulation of synthetic ground motions for specified earthquake and site characteristics. Earthquake Engineering & Structural Dynamics, 39(10), 1155–1180. doi:10.1002/eqe.997.

[9] Falamarz-Sheikhabadi, M. R., & Zerva, A. (2018). Two uncertainties in simulating spatially varying seismic ground motions: incoherency coefficient and apparent propagation velocity. Bulletin of Earthquake Engineering, 16(10), 4427–4441. doi:10.1007/s10518-018-0385-x.

[10] Mamaghani, M., & Lui, E. M. (2023). Use of Continuous Wavelet Transform to Generate Endurance Time Excitation Functions for Nonlinear Seismic Analysis of Structures. CivilEng, 4(3), 753–781. doi:10.3390/civileng4030043.

[11] Lapin, V. A., Yerzhanov, S. Y., & Essenberlina, D. I. (2020). Dynamics of a 16-storey building with a core of rigidity in a local earthquake. IOP Conference Series: Materials Science and Engineering, 953(1), 012086. doi:10.1088/1757-899x/953/1/012086.

[12] Fischer, E. G., & Fischer, T. P. (1998). Quasi-resonance effects observed in the 1994 Northridge earthquake, and others. Shock and Vibration, 5(3), 153–158. doi:10.1155/1998/418528.

[13] Yerzhanov, S. Y., & Lapin, V. A. (2021). Non-Canonic Representation of the Random Process in Tasks of Simulating Seismic Impacts for Calculating Buildings and Structures. IOP Conference Series: Materials Science and Engineering, 1079(3), 032055. doi:10.1088/1757-899x/1079/3/032055.

[14] Lapin, V., & A. (1998). Method for calculating the reliability of a nonlinear system under seismic influence. Earthquake-Resistant Construction, 5, 11–13.

[15] Mkrtychev, O. V., Dzhinchvelashvili, G. A., & Busalova, M. S. (2015). Assessing the reliability of a multi-storey monolithic concrete building with a base. Procedia Engineering, 111, 550–555. doi:10.1016/j.proeng.2015.07.041.

[16] Drozdov, V. V., Pshenichkina, V. A., & Sukhina, K. N. (2016). Evaluation of Reliability of the Earthquake Resistant Building Provided by Means of the Analysis for Design-Basis Earthquake. Procedia Engineering, 150, 1841–1847. doi:10.1016/j.proeng.2016.07.180.

[17] Der Kiureghian, A., & Zhang, Y. (1999). Space-variant finite element reliability analysis. Computer Methods in Applied Mechanics and Engineering, 168(1–4), 173–183. doi:10.1016/S0045-7825(98)00139-X.

[18] Guo, Q., Wang, S., Chen, S., & Sun, Y. (2020). Structural safety reliability of concrete buildings of HTR-PM in accidental double-ended break of hot gas ducts. Nuclear Engineering and Technology, 52(5), 1051–1065. doi:10.1016/j.net.2019.10.015.

[19] Pavani, R., Calio', F., & Garavaglia, E. (2003). Numerical modelling in building reliability using both a probabilistic approach and a delay differential model. Mathematical and Computer Modelling, 38(5–6), 551–558. doi:10.1016/s0895-7177(03)90026-4.

[20] Wu, C., Xu, J., Zhang, C., & Wang, J. (2023). Overall seismic reliability analysis of aqueduct structure based on different levels under random earthquake. Structures, 58. doi:10.1016/j.istruc.2023.105469.

[21] Kim, S., & Wallace, J. W. (2022). Reliability of structural wall shear design for tall reinforced-concrete core wall buildings. Engineering Structures, 252, 113492. doi:10.1016/j.engstruct.2021.113492.

[22] Aptikaev, F. F. (1979). The shape of the envelope of amplitudes of accelerations from records of strong motions: Sat. Soviet-American earthquake prediction works. – Dushanbe T. 2. – Book 2.139-147.

[23] Zhunusov, T. Z., Ashimbayev, M. U., Kravchenko, A. A., & Odonovich, V. F. (1979). Study of the inelastic work of reinforced concrete frames of one-story industrial buildings under dynamic impacts such as seismic. Collection: "Research on the seismic resistance of buildings and structures." Almaty, issue 11(22).,48-61.

[24] Bulat, A. F., Dyrda, V. I., Lysytsya, M. I., & Grebenyuk, S. M. (2018). Numerical Simulation of the Stress-Strain State of Thin-Layer Rubber-Metal Vibration Absorber Elements Under Nonlinear Deformation. Strength of Materials, 50(3), 387–395. doi:10.1007/s11223-018-9982-9.

[25] Gulvanessian, H., & Holicky, M. (2012). Designers' Guide to Eurocode: Basis of Structural Design (2nd Ed.). Thomas Telford Ltd, London, United Kingdom. doi:10.1680/bsd.41714.

[26] Mkrtychev, O.V. & Raiser, V.D. (2016). Reliability theory in the design of building structures. M.: ASV. 978-5-4323-0189-5. 1-906.

[27] Thoft-Cristensen, P., & Baker, M. J. (2012). Structural reliability theory and its applications. Springer Berlin, Heidelberg, Germany. doi:10.1007/978-3-642-68697-9.

[28] Zhang, L., & Caracoglia, L. (2021). Layered Stochastic Approximation Monte-Carlo method for tall building and tower fragility in mixed wind load climates. Engineering Structures, 239, 112159. doi:10.1016/j.engstruct.2021.112159.

[29] Dyrda, V., Kobets, A., Bulat, I., Lapin, V., Lysytsia, N., Ahaltsov, H., & Sokol, S. (2019). Vibroseismic protection of heavy mining machines, buildings and structures. E3S Web of Conferences, 109, 22. doi:10.1051/e3sconf/201910900022.

[30] Montazeri, M., Namiranian, P., Pasand, A. A., & Aceto, L. (2023). Seismic performance of isolated buildings with friction spring damper. Structures, 55, 1481–1496. doi:10.1016/j.istruc.2023.06.116.

[31] Yang, K., Tan, P., Chen, H., Li, J., & Tan, J. (2024). Prediction of nonlinear seismic demand of inter-story isolated systems using improved multi-modal pushover analysis procedures. Journal of Building Engineering, 82, 108322. doi:10.1016/j.jobe.2023.108322.

[32] Bové, O., Golla, V. K., Oliver-Saiz, E., Bonada, J., & López-Almansa, F. (2024). Seismic pushover analysis of unbraced adjustable pallet racks in the down-aisle direction. Need for multimode analysis. Thin-Walled Structures, 195, 111444. doi:10.1016/j.tws.2023.111444.

[33] Khan, M. M., & Roy, A. K. (2024). Interference effect of buildings on high rise power station chimney subjected to wind: a numerical modelling approach. Innovative Infrastructure Solutions, 9(8), 327. doi:10.1007/s41062-024-01642-y.

[34] Zhao, H. (2023). Research on the Health Detection and Seismic Performance Evaluation of High-Rise Buildings. Procedia Computer Science, 228, 21–28. doi:10.1016/j.procs.2023.11.004.

[35] Paolacci, F., Giannini, R., Nam, P. H., Corritore, D., & Quinci, G. (2022). Scores: an algorithm for records selection to employ in seismic risk and resilience analysis. Procedia Structural Integrity, 44, 307–314. doi:10.1016/j.prostr.2023.01.040.