Građevinski materijali i konstrukcije
Building Materials and Structures
journal homepage: www.dimk.rs

doi: 10.5937/GRMK2203105S UDK: 624.042.7:699.841
624.131

Technical paper

Analysis of the simultaneous influence of the horizontal seismic load components on buildings

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Article history
Received: 14 July 2022
Received in revised form: 18 August 2022
Accepted: 22 August 2022
Available online: 30 September 2022

Keywords
directions of the earthquake action,
collinear seismic load,
simultaneous horizontal seismic load components,
Eurocode 8

ABSTRACT

Earthquake records indicate that earthquake motion is an irregular oscillatory soil movement as a consequence of the heterogeneity of the soil material, as well as due to reflection, refraction, and interference of seismic waves. The trajectories of soil particle movement during an earthquake are proven to be chaotic, so the approximation of seismic effects by a simplified collinear model is very rough from an engineering point of view. The directions of the earthquake during the duration of the earthquake event affects the results of the seismic calculation. In this paper, the simultaneous influence of horizontal seismic load components on buildings has been analyzed. Actual seismic norms deal with this issue and define recommendations that should be applied in the design. This paper discussed how realistic and applicable these recommendations are in standard engineering design. A series of time history analyses of the horizontal stiffness of reinforced concrete regular and irregular structures were performed. Two earthquake events with a markedly changing direction of the ground acceleration vector were taken as the load. Significant differences in the influence values of the adopted representative parameters were determined for the two considered cases of collinear and simultaneous effects. In the conclusion, a critical review of the usual seismic calculation and the provisions of Eurocode 8, related to the effect of the horizontal components of the seismic load, is given. Finally, the paper comments on the introduction of corrective factors in cases where simultaneous action is not considered.

1 Introduction

In seismically active areas, a seismic design is performed to ensure adequate safety and bearing capacity of the building due to seismic load. A seismic load is specific when compared to the other types of loads. Characteristics such as the probability of occurrence, the dynamic characteristics of the load, the intensity of action, and the duration of the earthquake are unknown values at the time when the seismic design is performed. In that sense, the values that determine the seismic load are obtained not through a deterministic but rather a probabilistic approach. This approach requires a greater amount of objective data and a significantly larger number of measured data points related to the effect of earthquakes.

The analysis of these data reveals the characteristics of the seismic load that assert the need to re-examine common engineering practices and procedures. The direction, i.e., the directions of the earthquake action during the earthquake event, have been insufficiently researched. In this paper, the simultaneous effect of horizontal seismic load components on high-rise buildings has been analyzed. Actual seismic norms deal with this issue and define recommendations that should be applied in the design. This paper will discuss how realistic and applicable these recommendations are in standard engineering design. The regularity of the building structure, the stiffness of the structure, and the ratio of frequency characteristics of the forced load to the structure have been adopted as important parameters for analysis. A series of time-history analyses of the horizontal stiffness of reinforced concrete regular and irregular structures were performed. Two earthquake events with a markedly changing direction of the ground acceleration vector were taken as the load.

The results of the performed calculations have been analyzed, and a critical review of the usual seismic design and the provisions of Eurocode 8 [1], related to the effect of horizontal seismic load components is presented in the conclusion. Finally, the paper comments on the introduction of corrective factors in cases wherein the simultaneous impacts are not considered.

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2 Overview of previous research

The direction of seismic actions has been studied by several authors, applying various methods in the process. Within this subchapter, a brief overview of normative recommendations and previous research will be given.

The proposed orthogonal combination rule for multi-component ground motions was first considered by O'Hara and Cunnif (1963) [2], while Chu et al. (1972) [3] proposed the application of the SRSS (Square Root of the Sum of the Squares) procedure. The type of orthogonal combination procedure, known as the 100% + XX% rule, was introduced by Newmark (1975) [4]. He considered 100% of responses in one direction and an additional 40% in the other direction, in order to conservatively capture a bidirectional load. Rosenblueth and Contreras (1977) [5], based on previous work by A.S. Velestos and Newmark, proposed the 100% + 30% rule, which has been widely used in modern regulations.

Menun and Der Kiureghian (1998) [6] proposed extending the well-known rule of modal combination CQC (Complete Quadratic Combination) to a modal and directional combination rule named CQC3 (Complete Quadratic Combination with Three Components). Hisada et al. (1988) [7] used the ratio of response spectra constructed using both horizontal components of ground motion to those constructed using only one ground motion component as a measure of seismic effects, which was applied in Regulations ASCE/SEI 7-10. MacRae and Mattheis (2000) [8] considered the SRSS rule, the 100% + 30% rule, and the SAV rule (Sum of Absolute Values) for a steel frame building using direct nonlinear dynamic analysis with a varying ground motion angle. The SAV rule uses the sum of the absolute maximum values of the structure response for each direction of the earthquake. The structure displacements were chosen as a comparative parameter, given the fact that in the nonlinear analysis, the forces in elements may not change significantly when the parts of the structure reach yield strength. It was concluded that SRSS, 100% + 30%, and SAV rules depend on the angle at which seismic forces act on the object (rotation of the direction of seismic loading concerning the principal axes of the building) and that all methods produce unconservative results in terms of relative inelastic floor displacements. The conclusions were interpreted in UBC-97 (Uniform Building Code provisions). In their work, Lopez et al. (2001) [9] compared the SRSS rules 100% + 30% and 100% + 40% with the CQC3 rule. Within the CQC3 method, the critical response of the structure was determined, which was compared with the responses of the structure obtained using other methods, and ratios up to 25% difference were obtained. It was found that the critical response increases in cases where the modes with the highest effective mass have close frequency characteristics, so the CQC3 rule should not be applied in that case.

Zaghlool (2001) et al. [10] considered the 100% + XX% rule by applying linear and nonlinear direct dynamic analysis. They analyzed the structure response in the *x*-direction at the time of the maximum response in the *y*-direction, and vice versa. The obtained corresponding component of the response is then divided by the maximum from the same direction, yielding XX% participation. This procedure can be described as the percentage activated of the maximum "strong"-axis response at the time of the maximum "weak"-axis response. As a conclusion of this analysis, the use of 100% + 45% rules was proposed. Sherman and Okazaki (2010) [11] analyzed spatial brace frames by using the nonlinear time integration method. Two criteria were applied for designing corner columns shared by orthogonal frames that resist the effects of earthquakes in both directions. In the first one, corner columns were designed to take 100% of the forces from one direction and 30% from the other direction. In the second one, columns were designed at 100% of the forces from both directions. This approach is analogous, but not completely the same, as the 100% + 30% rule because the column forces were obtained based on the bearing capacity of the whole system and not based on design forces caused by the horizontal effect of the earthquake. They noted that the first approach proved to be unconservative in several cases in terms of the results obtained. For the second approach, they noted that for all calculations, the results were on the side of safety, with more conservative results observed when increasing the height of the building since this change reduces the possibility that all braces will be yielding at the same moment. Bisadi and Head (2011) in their work [12] assessed the 100% + 30%, 100% + 40%, and SRSS rules using nonlinear direct dynamic analysis of bridge structures. They analyzed two cases. In the first case, only the major component of the seismic ground motion record was applied, which is defined as the one with the largest amplitude of the ground motion record (PGA, Peak Ground Acceleration) in the longitudinal and transverse directions of the bridge individually, and then the structure responses were combined using adopted rules. In the second case, the primary and secondary components of the earthquake were applied simultaneously. Next, they combined the responses for both directions using combination rules. After that, they determined the probability of underestimation for each of the combination rules, for each of the two loading cases. It should be noted that the probability of underestimating the results varies depending on whether the force capacity or the displacement capacity of the structure is considered. Cimellaro (2014) et al. [13] proposed the application of a modified nonlinear static analysis that would use the factors of 1.0 and 0.6 for two orthogonal seismic actions. The factor with a value of 60% that differs from the usual 30% was obtained by the calibration of six distinctly irregular models with reinforced concrete spatial frames, using nonlinear direct dynamic analysis. The authors found that the difference between these factors arose as a consequence of observing the nonlinear response, instead of the linear response that the 100% + 30% rule was based on.

3 Seismic load

Earthquakes occur at irregular intervals in space and time. For the assessment of seismic risk, certain laws of earthquake occurrence can be observed, if a sufficient amount of objective data is available. This primarily refers to the basic characteristics of seismic loadings, such as the predominant period, the duration of the earthquake, peak ground acceleration, peak ground velocity, peak ground displacement, and the direction of the earthquake [14]. In this paper, only one parameter will be analyzed in detail, namely the direction of the earthquake in the horizontal plane $x0y$. The effect of the earthquake concerning the z-axis is disregarded in this paper and was not subject to analysis.

An earthquake is a natural phenomenon caused by an abrupt release of energy in the earth's crust, which spreads in the form of seismic waves and manifests itself on the surface as shaking of the ground. Earthquake records indicate that it is an irregular oscillatory movement. It is a consequence of the inhomogeneity of the material through which seismic waves travel. Due to reflection and refraction, on the surface they manifest as three-component oscillatory movements without a stable period and amplitude. Due to earthquakes, ground vibrations occur that have two horizontal components and one vertical component. Vector-wise, ground displacements $x0y$ can be analytically defined by the displacement vector (Figure 1a). It is necessary to adopt a time interval for which the displacement is monitored, since data is collected at discrete moments of time, as a consequence of the impossibility to present the stochastic function as an analytical function. Each moment of time t_i corresponds to the vector r_i. (Figure 1a).

In previous engineering practice, the effect of an earthquake was usually considered a load caused by the collinear displacement of ground particles, since all displacement vectors are on one line. This direction is defined by the angle β of the previously arbitrarily adopted orthogonal global coordinate system (Figure 1b).

As earthquake records are obtained via data (displacement, velocity, or ground acceleration) for two orthogonal directions, the input data for the numerical calculation can be component values of the ground displacement u_x and u_y, that is, ground acceleration a_x and a_y caused by an earthquake (Figure 1c). How the components of this load will be used in calculations, independently or simultaneously, affects the essential result of the calculation. Modern-day software and hardware development has made it possible to consider the simultaneous actions of seismic action components relatively easily today.

Based on the data for a large number of examined earthquakes, the ground particle displacement trajectories can be illustrated by diagrams (Figure 2).

The analysis of the presented diagrams shows that the action of earthquakes in the horizontal plane is usually chaotic, with a significant change in the direction of the displacement vector, so rarely can the action of the earthquake be approximated with the effect in one direction alone. Out of all the trajectory diagrams presented, a single-direction approach can only be acceptable in the case of the diagrams corresponding to the Nicaragua, 1972, and Montana, 1935, earthquakes. The diagram analysis concludes that a rough approximation of the load effect is performed if the earthquake load is considered to be acting only in one direction. One direction cannot realistically describe the majority of the seismic load.

Having that in mind, the regulations have introduced a mandatory consideration of the seismic load in two orthogonal directions, primarily led by the fact that the direction of the future earthquake is not known.

It is recommended that a calculation for each excitation direction be made separately, and then, after assuming the linear behavior of the structure, the final results be determined by the superposition of the results for both orthogonal directions. In cases where we calculate only the maximum values for each direction separately using the response spectrum, the procedure is similar to the problem of determining the resultant effects of various vibration tones.

Since it is quite unlikely that the maximum excitation values in both directions will occur simultaneously, simply adding up the maximum values for individual directions gives overestimated effect values, so it is usually suggested that the square root of the sum of the squares (SRSS) method be applied, which is also used in the modal analysis [14]:

$$\begin{aligned} u_{imax} &= \sqrt{u_{ixmax}^2 + u_{iymax}^2} \\ f_{Eimax} &= \sqrt{f_{Eixmax}^2 + f_{Eiymax}^2} \end{aligned} \tag{1}$$

Expressions (1) represent the displacement and force values, and the indices “x“ and “y“ indicate the direction of excitation. The directions of x and y axes must be orthogonal and are most often adopted as the main axes of the structure. In applying this approach, the results are independent of the chosen excitation directions. The approach is not applicable if the excitation in different directions causes different types of loads in individual elements (e.g. axial forces from vertical load, transverse forces, and moments from horizontal load) [14]. Then a combination of 100% load in one direction and 30% or 40% load in the other direction is recommended.

Applying these problem setups, Eurocode [1] prescribes that horizontal seismic load components act simultaneously. The combination of horizontal components of seismic action can be determined in several ways. The first is that the structure response for each component must be calculated separately, using combination rules of modal responses. The second, the maximum value of each impact in the structure due to the two horizontal seismic components, is determined as the square root of the sum of the squares of the seismic effect for each horizontal component:

$$\sqrt{E_{Edx}^2 + E_{Edy}^2} \tag{2}$$

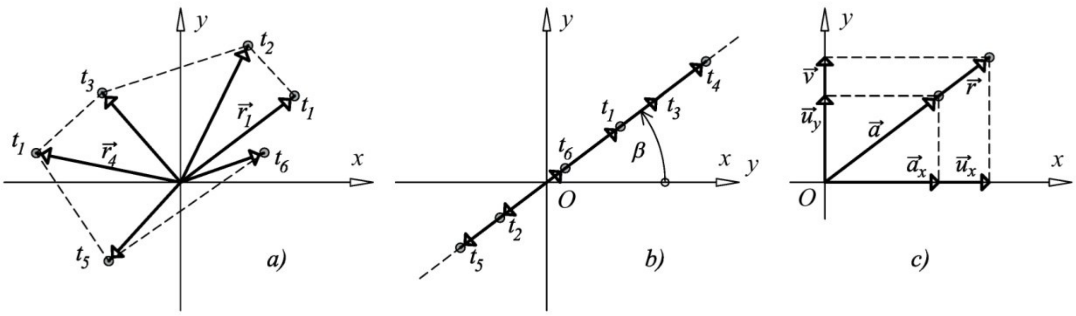

Figure 1. a) Ground particle displacement vector during an earthquake b) Collinear ground displacement during an earthquake c) Components of ground displacement and acceleration due to an earthquake

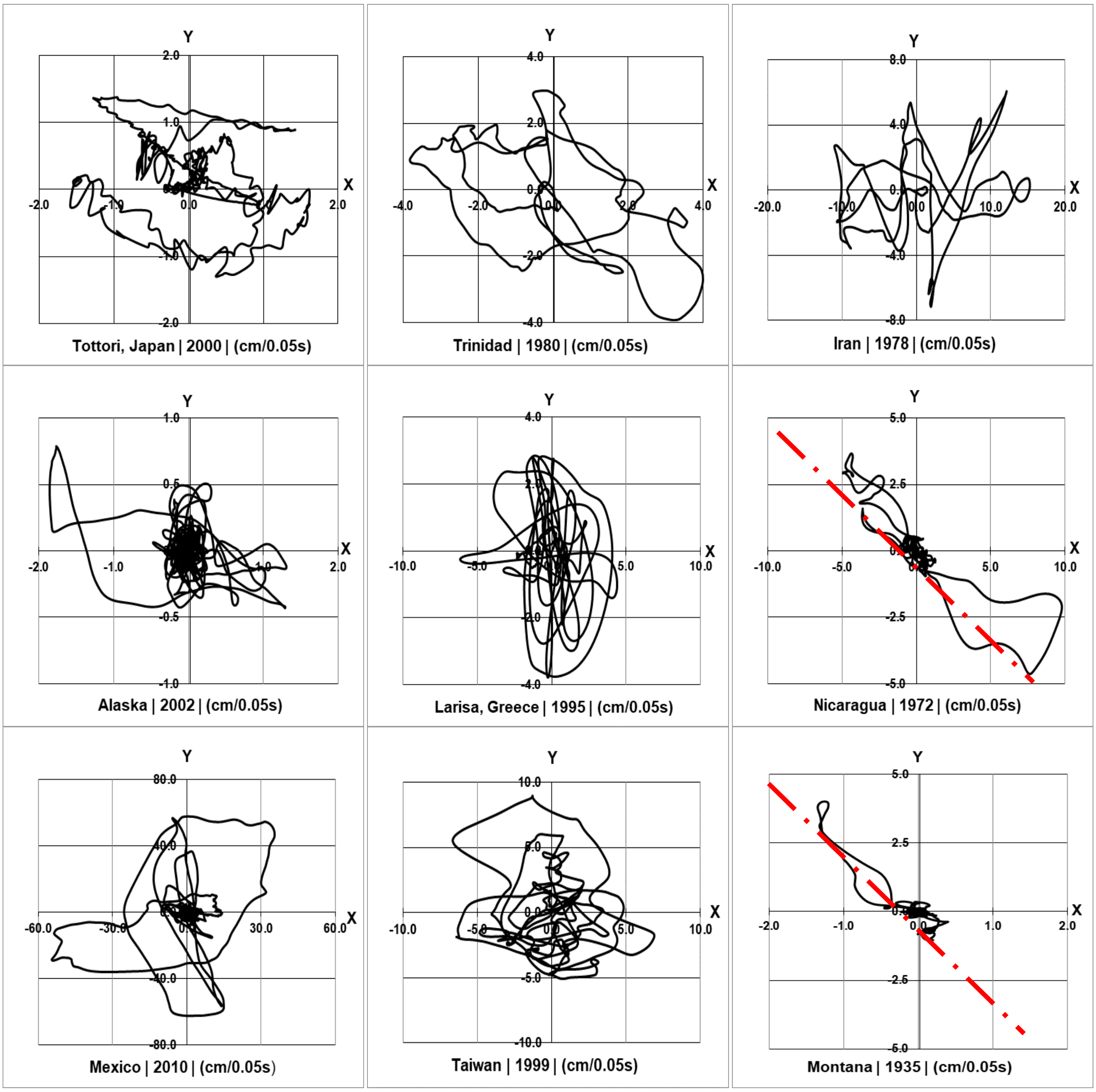

Figure 2. Horizontal action for various earthquake events [15]

The third, less conservative way, assumes governing influences according to the combination of the values of the seismic effects:

$$\mathrm{E_{Edx}} \text{ "+" } 0.3\ \mathrm{E_{Edy}} \qquad \mathrm{E_{Edy}} \text{ "+" } 0.3\ \mathrm{E_{Edx}} \tag{3}$$

where:

$\mathrm{E_{Edx}}$ - is the value of effects due to the application of seismic action along the x axis of the structure

$\mathrm{E_{Edy}}$ - is the value of effects due to the application of seismic action along the y axis of the structure

In particular, for the nonlinear time history analysis and the spatial model of the structure, the simultaneous effect of the acceleration components in both horizontal directions should be analyzed.

4 NUMERICAL ANALYSIS

4.1 Models for numerical analysis

Numerical analysis was performed for four models of a reinforced concrete multi-story (10-story) structure. The first two models, A and B, represent regular structures with lower and higher horizontal stiffness. Models C and D represent irregular structures with different horizontal stiffness. Different horizontal stiffness was obtained by adding a reinforced concrete core to the frame structure (Figures 3 and 4).

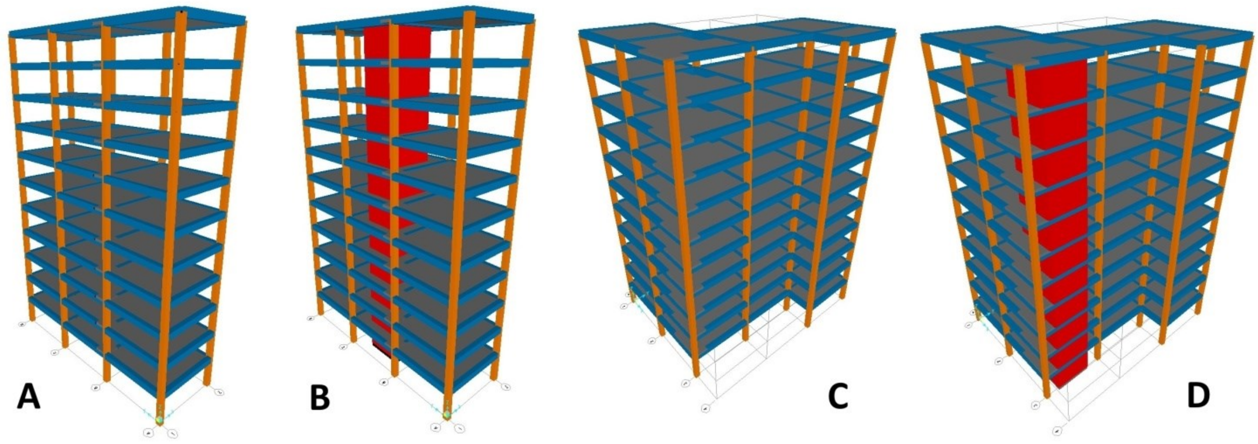

Figure 3. Considered structure models

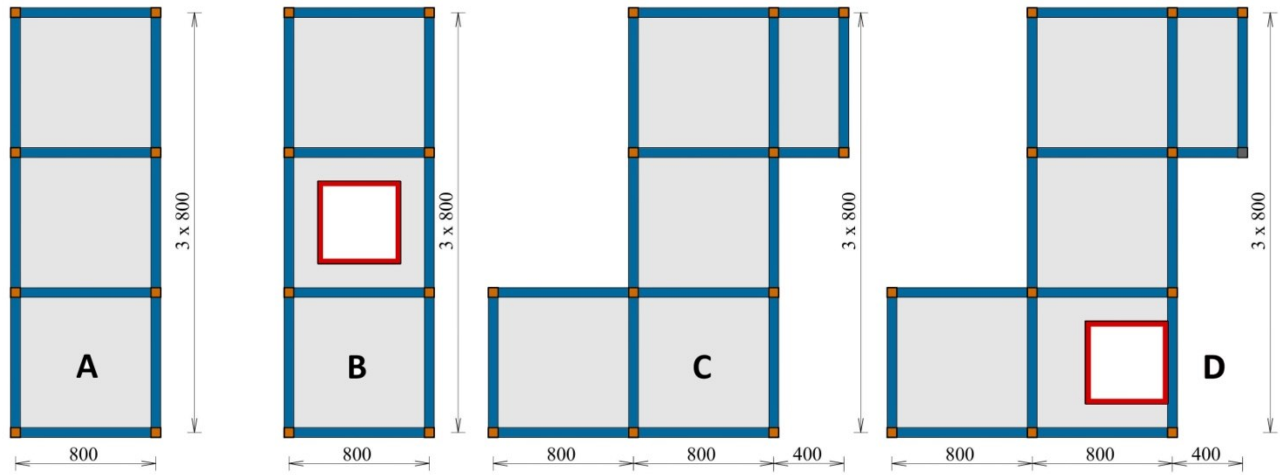

Figure 4. Plan view of the considered models

During the modeling of the structures, given the fact that it is an RC structure, reduced stiffnesses were adopted, which differ depending on the structural element, which is considered to correspond to the behavior of the real structure under the action of seismic loading. For vertical structural elements, columns and walls, the stiffness correction value of 0.70 was adopted, while for horizontal structural elements, beams and ceilings, the stiffness correction value of 0.50 was adopted. The dynamic characteristics for each of the models are given in Table 1.

4.2 Seismic load applied

Analysis was carried out for two earthquake events for which the accelerograms were available for two orthogonal directions, the Gulf of California 2001 and the Lazio-Abruzzo 1984 earthquakes (Figures 5 and 6). The basic data of the record are given in Table 2. The aforementioned earthquakes were chosen for analysis because their ground particle displacement trajectories are markedly chaotic in the horizontal plane (Figure 7).

Table 1. The first three periods of oscillation of the considered models

Structure models	**Oscillation periods** *(s)*		
	T_1	T_2	T_3
A – Regular in plain without RC core	2.35	2.08	1.81
B – Regular in plain with RC core	1.06	0.99	0.78
C – Irregular in plain without RC core	2.17	2.11	1.73
D – Irregular in plain with RC core	1.38	1.13	0.82

Table 2. Earthquake record data

Earthquake record	Gulf of California	Lazio - Abruzzo Italy
Year	2001	1984
Station	El Centro - Meadows Union School	Athens
Magnitude	5,7	5,8
V_{s30} (m/s)	276,25	585,04
PGA (direction 1)	0,011 g	0,0956 g
PGA (direction 2)	0,0099 g	0,0956 g
Closest distance to rupture – R_{rup} (km)	96,28	18,89
Duration *D5 - 95* (s)	64,7	10,0

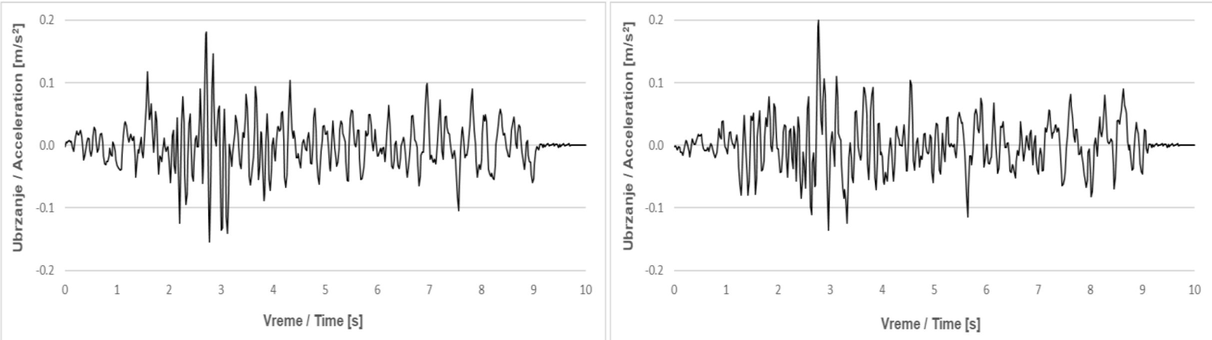

Figure 5. Accelerogram of the Gulf of California earthquake in the direction of both x *and* y *- axes [15]*

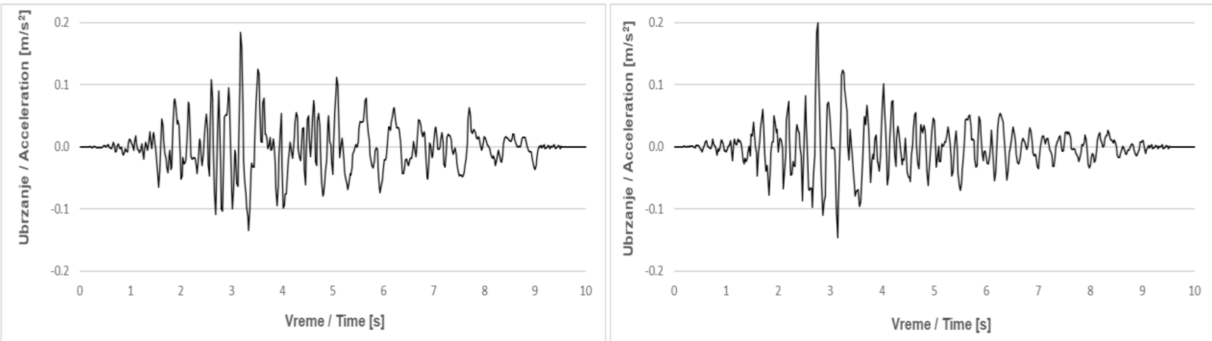

Figure 6. Accelerogram of the Lazio earthquake in the direction of x *and* y *- axes [15]*

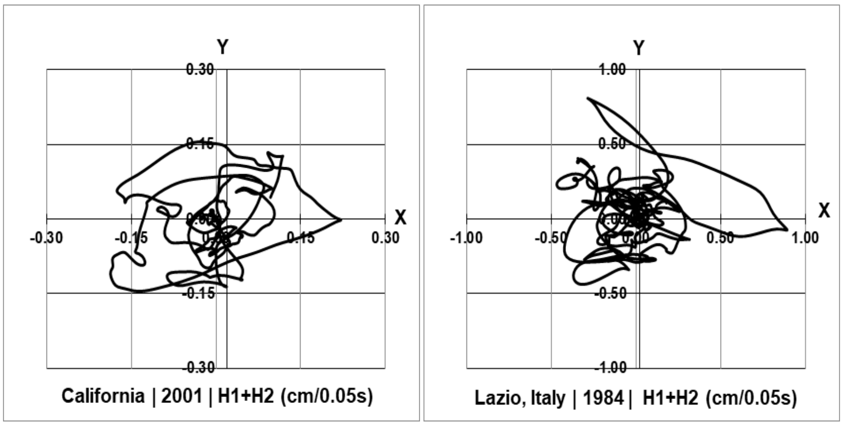

Figure 7. Representation of the ground displacement trajectory in the horizontal plane for the selected earthquakes [15]

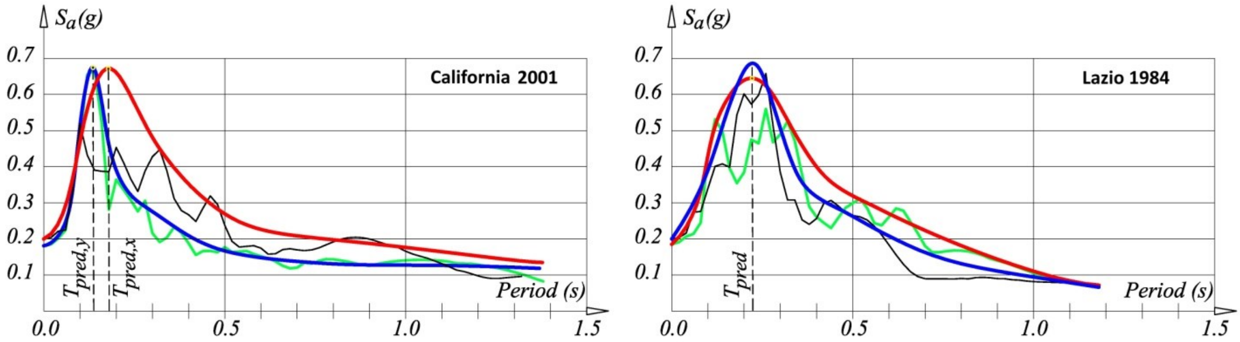

Figure 8. The spectrum of the California and Lazio earthquake response [16]

Ground acceleration records are normed to a value of 0.2g for the more intense direction, and then the acceleration values for the other direction were modified with the same multiplier to maintain the same ratio of ground acceleration components both in x and y directions.

In the case of the California earthquake record in the x-direction, the predominant period is 0.17 s, while in the y-direction it is 0.14 seconds. Different values of predominant periods could be due to inadequate earthquake recording or due to a numerical error in the integration procedure. In the case of the Lazio earthquake record, in both directions the predominant period is 0.22 s. Figure 8 presents the original spectrum for two directions (black line - x direction, green line - y direction) and their envelopes (red line - x direction, and blue line - y direction).

4.3 Results of the calculation

The calculation was carried out using the method of linear direct dynamic analysis with the software package SAP2000 ver. 14 [17]. In this study we did not analyze the vertical component of the seismic action and used the assumption that earthquake records, given in orthogonal directions, coincide with the longitudinal and transverse axes of the base of the building. For each of the formed structure models, the seismic load was assigned using three different approaches:

1) according to the EC8 standard, EN 1998-1: 2004 [1],
2) independent collinear effect of seismic loading,
3) simultaneous effect of seismic loading for two seismic load components.

Calculations were performed for each of the assigned loads, to determine the governing deformation and static values. The first calculation is following the provisions of EC8 by applying equations (3). The second calculation, the collinear effect, considered the seismic load in the x-direction and y-direction as acting independently, so the load that causes greater effect was chosen as the governing one. The third calculation refers to the simultaneous action of the acceleration components corresponding to the obtained accelerograms for the two orthogonal directions of the selected earthquakes.

After conducting the analysis using the software package SAP2000 [17], the obtained values of the following components were observed to consider the structure response:

- the resulting displacements in the nodes on the roof slab, (Figure 9)
- columns' bending moments at the building base, (Figure 10)
- total base shear forces.

The resulting displacements in the nodes on the roof slab are determined as the vector sum of the component displacements, which are obtained in the results of the software calculation. These displacements of the roof slab were obtained in all nodes of the slab as a same values, given the fact that the adopted reinforced concrete ceiling was rigid in its plane (Tables 3 and 4).

For the base bending moments, the values that have the largest differences in the calculation values according to Eurocode 8, and the calculation with simultaneous effect are presented (Tables 3 and 4). Differences are given in percentages $\Delta[\%] = ((R_{1,2}-R_3))/R_3$, and R indicates the considered parameter, and the index is the chosen calculation of seismic load.

The total base shear force is equal to the total seismic force. It represents a single global quantity that characterizes the earthquake and is often used to control and analyze the results obtained from a numerical seismic design. Results for total seismic force differences is given in Table 5.

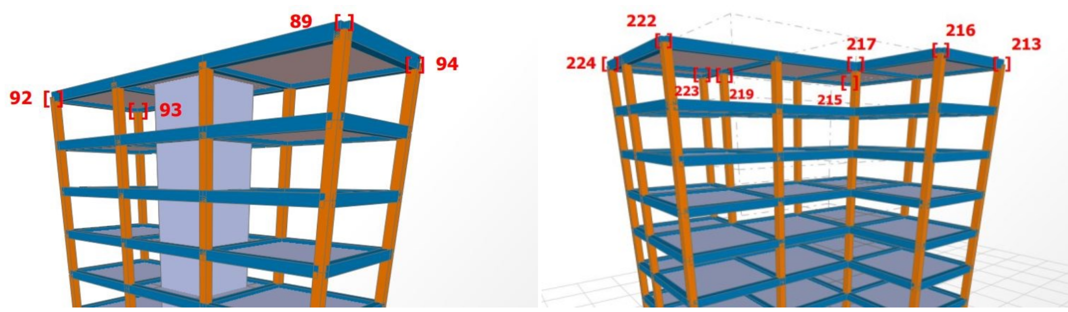

Figure 9. FEA (Finite Element Analysis) model nodes for which the resulting displacements are considered

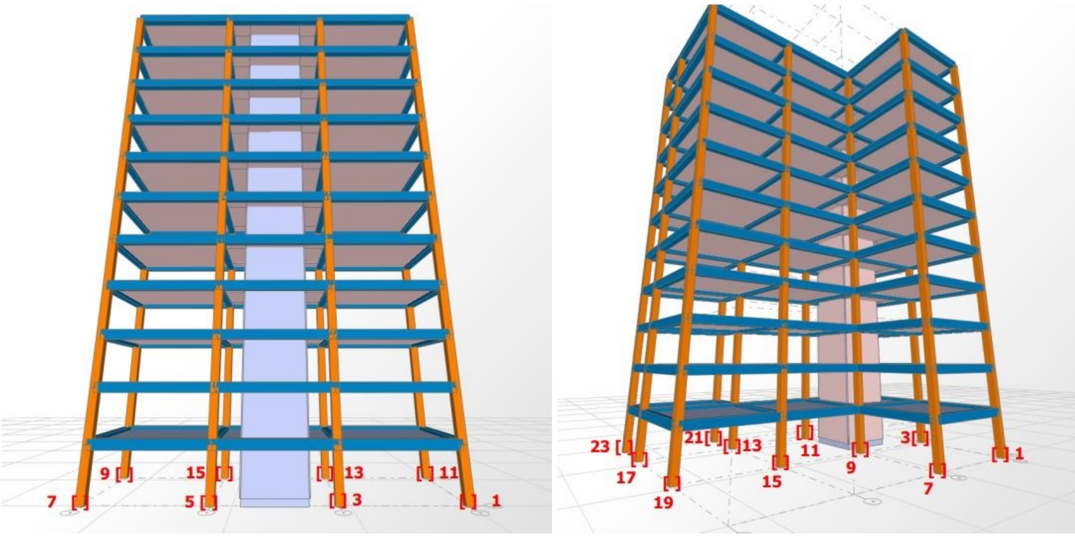

Figure 10. FEA model nodes for which the base bending moment values are considered

Table 3. Results of roof ceiling displacement and bending moments in columns in regular models

		Displacement [cm]				**Bending moment** [kNm]			
	California	**A**	**Δ** [%]	**B**	**Δ** [%]	**A**	**Δ** [%]	**B**	**Δ** [%]
1	EC8	3.40	3.0	3.70	-8.6	144.2	-13.0	66.9	-13.5
2	Collinear	3.27	-0.9	3.56	-12.1	138.3	-16.5	61.2	-20.8
3	Simultaneously	3.30	-	4.05	-	165.7	-	77.3	-
	Lazio	**A**	**Δ** [%]	**B**	**Δ** [%]	**A**	**Δ** [%]	**B**	**Δ** [%]
1	EC8	2.90	0.7	2.73	-14.7	141.6	2.5	38.4	-16.7
2	Collinear	2.80	-2.8	2.61	-18.4	135.9	-1.7	36.9	-20.0
3	Simultaneously	2.88	-	3.20	-	138.2	-	46.1	-

Table 4. Results of roof ceiling displacement and bending moments in columns in irregular models

		Displacement [cm]				**Bending moment** [kNm]			
	California	**C**	**Δ** [%]	**D**	**Δ** [%]	**C**	**Δ** [%]	**D**	**Δ** [%]
1	EC8	3.40	6.6	4.17	-25.4	133.8	-24.9	148.4	-27.7
2	Collinear	3.24	1.6	4.17	-25.4	138.6	-22.2	126.2	-38.5
3	Simultaneously	3.19	-	5.59	-	178.1	-	205.3	-
	Lazio	**C**	**Δ** [%]	**D**	**Δ** [%]	**C**	**Δ** [%]	**D**	**Δ** [%]
1	EC8	2.61	-7.1	2.68	-31.3	155.9	7.2	123.6	41.4
2	Collinear	2.50	-11.0	2.77	-29.0	150.8	3.7	110.4	26.3
3	Simultaneously	2.81	-	3.90	-	145.4	-	87.4	-

Table 5. Results of total seismic force components in irregular models

		Components of total seismic force [kN]							
	California	**C**	**Δ_x** [%]	**C**	**Δ_y** [%]	**D**	**Δ_x** [%]	**D**	**Δ_y** [%]
		S_x		S_y		S_x		S_y	
1	EC8	675.1	-1.7	656.6	-1.8	1831.0	-12.0	2109.4	-10.2
2	Collinear	675.1	-1.7	656.5	-1.8	1877.0	-9.8	2195.5	-6.6
3	Simultaneously	687.0	-	668.4	-	2080.6	-	2349.4	-
	Lazio	**C**	**Δ_x** [%]	**C**	**Δ_y**[%]	**D**	**Δ_x** [%]	**D**	**Δ_y** [%]
		S_x		S_y		S_x		S_y	
1	EC8	727.9	2.6	723.8	2.6	1196.7	-8.9	1393.5	-22.4
2	Collinear	725.9	2.3	721.8	2.3	1214.0	-7.6	1469.5	-18.1
3	Simultaneously	709.4	-	705.3	-	1313.6	-	1795.0	-

4.4 Analysis of the numerical analysis results

Analyzing the displacement of the roof slab and column's bending moments in the case of regular structures, there is a difference in the results for the calculation according to Eurocode 8 and the calculation with simultaneous action, for displacement of up to 13.5% while for bending moments it increases to 20.8% (Tables 3, 4). The same parameters for irregular structures have a difference of 25.4% for displacement and 41.4% for bending moments.

The differences in the total seismic force components of regular structures are negligible (2.6%), while in irregular structures they are 22.4% at the most.

When comparing the predominant record periods used in the design of structures, we can conclude that the main oscillation periods of flexible models (Models A and C) are quite distant from the resonant range. The situation is different when analyzing the oscillation periods of stiff models (Models B and D).

We can notice that the oscillation tones of the rigid models are closer to the predominant periods of the considered earthquakes. The periods obtained for the models under consideration are expected. The identical seismic load was assigned to all models, and there is the effect of increasing acceleration in the nodes of rigid models whose oscillation periods are closer to the predominant earthquake period, which indicates the effect of amplification.

If the calculation is performed in accordance with the provisions of the current Eurocode 8, the obtained differences in the results indicate an obvious underestimation of the impact in the seismic calculation. Differences in results from 10% to 20%, even exceptionally up to 41%, indicate that engineering calculations must pay special attention to this fact. This conclusion is in line with previous research on the simultaneous effect of earthquakes, based on both linear and nonlinear analysis. The analysis herein was linear, which may provide a relevant response at the beginning of the earthquake action, before the appearance of nonlinear effects.

Important input data for numerical analysis of the time response of the structure are primarily accelerograms. As the two records define one earthquake event, the dynamic characteristics of the excitation should be the same for both accelerograms in both x and y directions. A certain deviation certainly exists due to the discretization of the input data. A special analysis needs to be conducted in order to determine the sensitivity of the results to the choice of integration time interval, in order to define the criteria for the applicability of the accelerogram record in seismic design.

5 Conclusion

After the analysis of earthquake records, it is obvious that the earthquakes whose action can be approximated by collinear influences have occurred in very small numbers. The trajectories of movement of soil particles during an earthquake are proven to be chaotic, so the approximation of seismic effects by a simplified collinear model is very rough from an engineering point of view. Actual regulations, primarily the Eurocode, prescribe for which cases of seismic calculation it is necessary to carry out an analysis with the simultaneous effect of ground acceleration components. Those normative provisions refer only to more complex and irregular constructions. The problem remains unsolved when calculation with simultaneous action is not mandatory.

Common procedures based on the combination of effects due to collinear effects of earthquakes hide the effects of real earthquake action, because underestimated values of seismic effects are increased by mathematical procedures and not based on the actual response of the structure.

In the paper, the results for the selected types of structure were analyzed in detail, and important differences were determined in the impact values of the adopted representative parameters for the two considered cases of collinear and simultaneous action. Differences were noted in a wide range, from 1% to 40%. The presented difference in results is so significant for some influences that it undoubtedly affects the change in the behavior of the system that absorbs seismic energy with the plastification of the most stressed elements of the system. In the case of irregular building systems, as well as other systems that do not fully meet the requirements of aseismic design, the aforementioned differences may cause unwanted consequences.

The previous conclusion raises the issue of introducing a correction factor for calculations that do not take into account the simultaneous effect of two components of earthquake acceleration. The corrective factor would have the role of increasing the underestimated impacts obtained based on the collinear effect. In this way, for simpler objects, there would be no need to introduce a more complex calculation. Its value should be determined based on the knowledge of the actual impact values compared to underestimated ones, for different categories of objects and types of calculations (regular, irregular, high, low buildings, linear and non-linear design).

In the design which takes into account simultaneous action, special attention should be paid to the analysis of the available records of the ground acceleration components in the x and y directions, i.e. accelerograms. They represent a single earthquake event, and the frequency characteristics of the records for both records should be matched. These errors most often occur due to an inadequate earthquake record or time step in the accelerogram record.

References

[15] Eurocode 8: Design of structures for earthquake resistance - Part 1 : General rules, seismic actions and rules for buildings EN 1998-1:2004

[16] G.J. O´Hara, P.F. Cunnif, Elements of Normal Mode Theory, Report 6002, Naval Research Laboratory, Washington, DC, USA, 1963

[17] S.L. Chu, M. Amin, S. Singh, Special Treatment of Actions of Three Earthquake Components on Structures, Nuclear Engineering and Design, 1972, 126-136

[18] N.M. Newmark, Seismic Design Criteria for Structures and Facilities – Trans – Alaska Pipeline System, Proceedings of the U.S. National Conference on Earthquake Engineering, Ann Arbor, USA, 1975, 94-103

[19] E. Rosenblueth, H. Contreras, Approximate Design for Multicomponent Earthquakes, Journal of the Engineering Mechanics Division, Proceedings of ASCE, 1977, 881-893

[20] C. Menun, A. Der Kiureghian, A Replacement for the 30%, 40% and SRSS Rules for Multicomponent Seismic Analysis, Earthquake Spectra, 1998, 153-163

[21] T. Hisada, M. Miyamura, S. Kan, Y. Hirao, Studies on the Orthogonal Effects in Seismic Analyses, Proceedings of Ninth World Conference on Earthquake Engineering, Tokyo, Japan, 1988

[22] G. MacRae, J. Mattheis, Three – Dimensional Steel Building Response to Near – Fault Motions, Journal of Structural Engineering, 2000, 117-126
[23] O. A. Lopez, A. K. Chopra, J. J. Hernandez, Evaluation of Combination Rules for Maximum Response Calculation in Multicomponent Seismic Analysis, Earthquake Engineering and Structural Dynamics, 2001, 1379-1398
[24] B. S. Zaghlool, A. J. Carr, P. J. Moss, Inelastic Behavior of Three – Dimensional Structures under Concurrent Seismic Excitations, Proceedings of 12th World Conference on Earthquake Enginnering, EQC, Auckland, New Zeland, 2001
[25] J. Sherman, T. Okazaki, Bidirectional Loading Behavior of Buckling – Restrained Braced Frames, Proceedings of ASCE Structures Congress, Orlando, Florida, 2010
[26] V. Bisadi, M. Head, Evaluation of Combination Rules for Orthogonal Seismic Demands in Nonlinear Time History Analysis of Bridges, Journal of Bridge Engineering Special Issue: AASHTO – LRFD Bridge Design and Guide Specifications: Recent, Ongoing and Future Refinements, 2011, 711-717
[27] G. Cimellaro, T. Giovine, D. Lopez – Garcia, Bidirectional Pushover Analysis of Irregular Structures, Journal of Structural Engineering, 2014
[28] D. Aničić, P. Fajfar, B. Petrović, A. Szavits – Nossan, M. Tomažević, Zemljotresno inženjerstvo – visokogradnja, DIP Građevinska knjiga, Beograd, 1990
[29] PEER Ground Motion Database, URL: https://ngawest2.berkeley.edu/
[30] Seismosoft (2021) "SeismoStruct 2021 – A computer program for static and dynamic nonlinear analysis of framed structures", URL: https://seismosoft.com/
[31] CSI SAP2000 Version 14.2.0 (2010), Integrated Software for Structural Analysis and Design, Computers and Structures Inc., Berkeley, California, URL: https://csiamerica.com/products/sap2000