Seismic Analysis of a School Building With Reinforced Concrete Panels

Praštalo, Gordan

***Abstract:* This paper aims to present, on the example of a reinforced concrete school building, a comparative analysis of its behavior due to the effects of an earthquake through 4 fundamentally different models. The school building has a frame structural system with reinforced concrete walls, while the other models were created by adding and subtracting vertical and horizontal structural elements. The most prominent problem of this structure of the school building is the very high stiffness, which is the result of the existence of a dense system of underground and above-ground walls. This paper includes the calculation of required and adopted reinforcement, as well as displacement control, and inter-storey drift control, respecting the provisions of Eurocode 8 [5]. Based on the calculation results, certain conclusions were drawn, and some possible solutions were also proposed to potentially improve the building.**

Index Terms: ***Earthquake, stiffness, displacement, reinforced concrete, seismic analysis***

1. INTRODUCTION

The earthquake is a natural phenomenon of ground shaking that occurs due to the sudden release of a large amount of energy in the earth's crust. The release of energy in the earth's crust is a consequence of the movement of tectonic plates, volcanic activity or other geological changes, while seismicity is the frequency of earthquakes in an area [9].

The geographical position of Serbia is such that it is located in the area of the central Balkans, which is not known as the most remote Balkan area. The most destructive earthquakes on the Balkan Peninsula are characteristic of the Adriatic coast and its immediate surroundings, as shown in Figure 1. Nevertheless, relatively strong earthquakes, with a magnitude (M) greater than 5, occur relatively often in the region [4]. On average, once every 10 to 15 years, a very devastating earthquake occurs in the region of Serbia, which causes very large-scale damage, both economic and social. As examples of such earthquakes, we can cite the earthquakes in Skopje in 1963 and Banja Luka in 1969, after which the engineers began to pay much more attention to the design of seismically resistant structures. Until then, the aseismic design of structures was a rather remote and scientifically unexplored entity.

Over the past 150 to 200 years, seismic activity on the Balkan Peninsula has been increasing, especially in the central part where Serbia is located [3]. A devastating earthquake, such as Earthquake in Petrinja, Croatia 12/29/2020. years of magnitude (M 6.4). As a result of this earthquake, many buildings were badly damaged or collapsed.

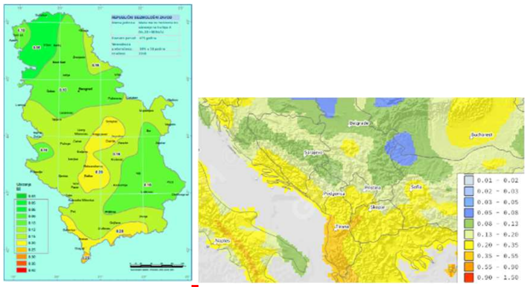


Figure 1. Seismic hazard map of the Republic of Serbia and the Balkan Peninsula [2]

Nowadays, structures are designed according to Eurocodes [5], [6], and special attention is paid to structures that are in seismically active areas. According to Eurocode 8 [5], the displacement of a point because of an earthquake is represented by the elastic response spectrum of ground acceleration. The shape of the elastic response spectrum is the same for the requirement that the structure does not collapse and the requirement for limited damage to the structure, which are two authoritative requirements that must be met from the aspect of the aseismic design of structures [1],

Manuscript received November, 2022.

[7], [8]. [9]. Elastic response spectra are useful for evaluating the displacement of structures of certain dynamic characteristics, such as the period of oscillation of the structure. They are obtained based on the response of linear elastic systems with one degree of freedom under the action of an earthquake.

Eurocode 8 [5] distinguishes two levels of seismic resistance of buildings, which are based on the ductility of the observed structure. The first type is medium ductility structure (DCM) and the second type is high ductility structure (DCH). Ductility is the ability of a material to plastically deform under the influence of an external load before the material breaks. We say that a material is more ductile if it can deform more plastically before a fracture occurs. If we take a look at reinforced concrete structures, concrete is a very brittle material, while reinforcement is very ductile.

2. *Problem Definition*

Knowing the characteristics of reinforced concrete as a material, during the aseismic design of reinforced concrete structures, it is necessary to find a balance between sufficient resistance to the effects of earthquakes and the cost of the structure itself. The first option is for the structure to have very large dimensions of cross-section and not to be ductile, but for the stresses in the structural elements to remain in the elastic zone, while the second option is for the structure to be ductile, i.e. that it has smaller dimensions of cross-section, but specially shaped details, with which we introduce the structure into the field of plastic behavior. It is up to the designer to decide which approach to apply, considering all the parameters that serve as input data.

As mentioned earlier, before the well-known earthquakes of 1963 and 1969, structures were not designed to withstand the effects of earthquakes. Most of the structures were designed to be very stiff and had very massive elements. Also, it is not a rare case that in the structures that were built in the post-war period, an atomic shelter is found, i.e. very stiff underground basement structure. Such is the case with the reinforced concrete structure of the school, which is the subject of this work. The analyzed building was built in 1973 in Smederevska Palanka. As the school structure was built shortly after the introduction of aseismic regulations, the structure itself is very stiff, which causes it to generate very large impacts due to the effects of earthquakes.

The building is a combined structural system, with walls in both directions. The school building has two floors with a gymnasium that is seismically expanded relative to the school. It is irregular, with overall dimensions of approximately 70x35 m. Also, the building is irregular in height and has three different heights in different parts of the building.

A dense system of walls with a thickness of 25 cm is noticeable in the basement floors, which makes this structure very stiff, and for this reason, the buried part of the structure, i.e. basement floors. The simplification adopted is to analyze only the part of the structure that is above the ground, due to the problem of activating 90% of the mass in the modal analysis. Another simplification adopted is not to analyze the gym, due to pronounced second-order effects in the tall and slender columns of the gym.

Observing the foundation of the school building, it can be concluded that the system of walls is much denser in the global y direction, while in the global x-direction there are only three reinforced concrete walls that accept the impacts due to the action of the earthquake. Of course, the frames that are present in both global directions, along the entire height of the school building, participate in accepting the impact of the earthquake to a certain extent. Walls and frames placed in the global x direction are more loaded in in-plane bending than walls placed in the global y direction, which will be shown in the further elaboration of this paper. A big role in accepting the influence of the ground plan, as well as a very stiff element of the school building, are the two stair cores that also serve for the vertical transport of people inside the building.

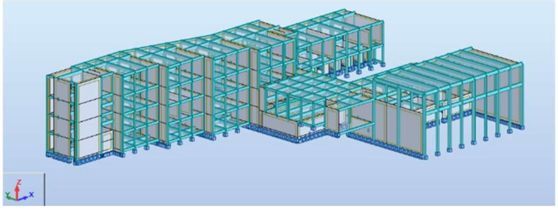


Figure 2. Structure of the reinforced concrete school building

The mathematical model of the structure used for the analysis of the real structure of the school building is spatial (3D), shown in Figure 2, and was created in the Robot Structural Analysis software package. For the class of concrete, class C 30/37 was adopted, and for the class of reinforcement, class B500 B was used. The behavior of the material was modeled as linear in the Robot Structural Analysis program, respecting the working diagrams of reinforcing steel and concrete and the rules defined in Eurocode 2 [6].

The simplified basic model of the school building, on which all the analyzes were performed, is shown and described in detail in the further elaboration of the thesis, as well as all the variations of the simplified basic model.

The idea of this paper is to analyze two constructive school systems. The constructive systems of the school that will be tested are:

- structure of a school building with walls,

- The frame structure of the school building.

Both structural systems of the school building were developed on four different models, two for each system:

- Model 1a - a structure of a school building with reinforced concrete walls: This model is a simplified basic model and it is the most complex of all that were analyzed. It is modeled as a combined system of walls, spatial frames and solid slabs. Considering that the simplified version of the structure has no underground floors, there are three different floor heights. The floor height of the ground floor and the first floor of the main part of the structure is 3.30 m, while the floor height of the attic floor is 3.80 m. The height of the entrance hall is 3.90 m. The main part of the school building is the highest at 10.40 m, while the height of the eastern part of the school is slightly lower at 7.55 m.
- Model 1b – a structure of a school building with reinforced concrete walls (smaller number of modes of oscillations): Numerical model 1b is in all respects identical to model 1a. The only difference is in the number of main modes of oscillation that are taken into account in the modal analysis. When defining the modal analysis, it is assumed that the structure oscillates with the number of modes required by model 2 to achieve activation of 90% of the mass of the structure during oscillation. The idea behind this is that supposedly the impacts occurring in a structure oscillating with a different number of modes are very little different, even though the same percentage of the mass of the structure has not been activated.
- Model 2 - a structure of a school building with fewer reinforced concrete walls: The difference between this model and the first model is that certain walls have been removed. The walls were removed in order to reduce the stiffness of the model, and the walls that were removed were mainly from the middle of the school building, so as not to cause the model to become torsionally sensitive. The result of reducing the number of walls is a smaller number of oscillation modes required to activate 90% of the mass of the structure.
- Model 3 - frame structure of the school building: the frame model of the structure of the school building was made by removing all the walls, and in the places where two or more beams meet, columns were placed to support the beams. The skeletal system of beams and columns, i.e. the spatial multi-story frame that represents the structure of the school building is responsible for receiving the forces resulting from the action of the earthquake. This version of the school model is the most flexible and represents the model with the largest displacements analyzed.
- Model 4 - frame structure of a school building with stair cores: The last model of the school that was analyzed is a frame model of the structure of a school building with stair cores. There are two staircase cores inside the school and they act as very stiff elements that accept a very large part of the forces generated as a result of the earthquake. Model 4 is neither the stiffest nor the most flexible, but is somewhere in between, but has significant displacements that make it interesting for further analysis.

3. EXISTING SOLUTIONS

There are various ways and methods that can be applied to analyze the impact on the structure due to the action of the earthquake.

The method that is the basis for all further analyzes of the impact due to earthquakes is modal analysis. In addition to it, the response spectrum method is also very often used, where the design response spectrum is used on the linear-elastic model of the structure. Depending on the type of building structure and the complexity of the model, there are two types of linear-elastic methods:

- The method of equivalent lateral forces, for buildings that meet certain conditions,
- Multimodal spectral analysis, which can be applied to all types of buildings.

Also, as a substitute for the above methods, there are two more complex non-linear types of analysis:

- Nonlinear static "Pushover" analysis,
- Nonlinear dynamic analysis of time response - "Time history".

3.1. Modal Analysis

Modal analysis is a prerequisite for any other analysis of the structure's behavior due to earthquakes. Modal analysis is a method used by engineers to easily, quickly and efficiently calculate the periods of oscillation and the main mode shapes of a structure. To adequately analyze the structure, it is necessary to take as many modes of oscillation as possible in the modal analysis to obtain the most accurate and precise results related to deformations and displacements, because these results are the basis that serves as input data for all other analyses. The modal analysis uses the mass and stiffness of the structure to determine the oscillation periods with which the structure will oscillate. In earthquake engineering, it is very important that the frequency of oscillation of the structure does not coincide with the frequency of the earthquake because this causes the structure to enter into resonance and thus it can be damaged or even collapse. The mass of the structure that the software takes into account is its weight and additional permanent load, i.e. permanent load throughout, 30 % useful load and 20 % snow load, in all respects the provisions of Eurocode 2 [6]. The influence of the inherent forms of free oscillations contributing to the global response of the structure must be taken into account if:

- The sum of the effective modal masses for the considered characteristic forms of vibrations amounts to a minimum of 90% of the total mass of the structure,
- All oscillation modes with an effective modal mass greater than 5 % of the total mass of the structure must be taken into account.

3.2. Multimodal Spectral Analysis

Multimodal spectral analysis is the type of analysis that was used to obtain the influence in the structure due to the action of the earthquake in this paper. Multimodal spectral analysis is a linear-elastic analysis that shows the maximum possible response of the structure to the effect of an earthquake, using the forms of oscillation known from the modal analysis and the elastic or design spectrum of ground acceleration, which are an integral part of the regulations according to which the calculation was made, i.e. in this case according to Eurocode 8 [5]. The multimodal spectral analysis provides insight into the dynamic behavior of a structural model by measuring pseudo-acceleration, velocity or displacement as a function of the period of oscillation of the structure for a given damping and time record. This method is practical because the response envelope of the structure can be made and approximated accurately enough by a smooth curved line, it is also very useful for deciding on the appearance of the structure itself because it very well relates to the type of structural system used to the dynamic performance of that structure.

4. PROPOSED SOLUTION

Modal and multimodal spectral analysis are defined in the Robot Structural Analysis software [10], using the dynamic characteristics of the school structure, such as stiffness, mass, and damping, but also the reference ground acceleration a_{gR}, which is read from the seismic hazard map for a given location, must also be defined. for the earthquake return period of T_{DLR}=475 years. In this case, the reference ground acceleration value for Smederevska Palanka is a_{gR}=0.15g, i.e. design ground acceleration $a_g=\gamma_{I*}a_{gR}$=0.18g. Importance factor γ_I=1.2 for school building structures. In addition to the seismic load, there are permanent, additional permanent and useful loads, which participate in the mass of the object that oscillates under the action of an earthquake. The software in which the calculation was performed first performed a modal analysis, as explained earlier, according to Eurocode 8 [5], from where it was possible to see the results in terms of the values of the periods of oscillation corresponding to the main forms of oscillation, as well as the main forms of oscillation of the structure. After reviewing the above results, it is analyzed whether all the conditions prescribed by Eurocode 8 [5] have been met. The main condition that must be met is that the periods of oscillation of the structure in the first mode should be less than *4Tc*, but also less than *2s*. The period of oscillation *Tc* is defined by the category of soil on which the observed object is founded. For different categories of soil, there are different shapes of the spectrum of soil acceleration, where all characteristic periods of oscillation are defined.

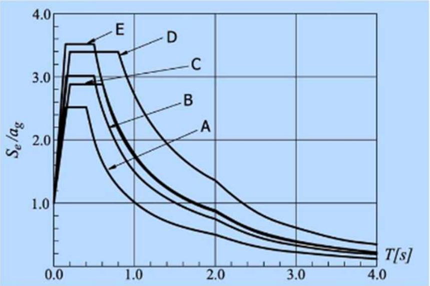


Figure 3. Acceleration response spectrum [5]

After reviewing and verifying the results of the modal analysis, it is necessary to define a multimodal spectral analysis, for which the results of the modal analysis serve as input data. In addition to the stiffness and period of oscillation of the structure, which the Robot Structural Analysis software itself draws from the results of the modal analysis, it is necessary to define the soil category, which for the analyzed school facility is soil type C, according to Figure 3.

Performing a multimodal spectral analysis provides insight into the size of the total seismic forces that occur in two orthogonal directions, as well as the size of the structure's movement due to the effect of the earthquake.

Taking into account the magnitude of the generated seismic forces and the total stiffness of the object, in two orthogonal directions, each element accepts its part of the total seismic force, according to its stiffness in the observed direction. It is necessary, in an adequate way defined in Eurocode 8 [5], to design the elements of the structure, so that they can accept a primarily seismic load, but also other gravity loads, as well as wind load.

Displacements are the most visible effect of earthquake action in a structure, so it is most important to ensure that the structure has sufficient displacement capacity so that it can follow the displacements that occur during the action of the earthquake. In other words, it is necessary to ensure that the structure is sufficiently ductile. Ductility is achieved by appropriately shaping details for local ductility.

After this, the control of the movement of the structure must be carried out, which includes the condition that the structure must not collapse or be fatally damaged so that it loses its functionality, due to the effect of an earthquake with a return period of T_{DLR}=95 years and thus endangers the people inside it.

For designers, it is perhaps more important to know what the values of the inter-storey drifts are because there are very strict conditions that limit the values of the inter-storey drifts, depending on the type of non-structural elements in the observed structure.

The last remaining control is the control of second-order effects, which, according to Eurocode 8 [5], must be taken into account if the factor θ is greater than 0.1 but less than 0.2. In that case, it is necessary to scale all cross-section forces in the designed elements by multiplying the original influences by $\frac{1}{1-\theta}$ and in this way increase the influences and re-design everything. If the factor θ is greater than 0.2, then Eurocode 8 [5] does not define what next steps should be taken, so such an outcome should definitely be avoided when designing reinforced concrete structures.

It is especially necessary to pay attention to the results obtained by performing all the previously described calculation procedures and analyzing the advantages and disadvantages of each of the structure models.

5. *ELABORATION*

For all models, the same dimensions of cross-sections of mezzanine ceilings, beams, columns and walls were adopted. After modeling in the Robot Structural Analysis software, each of the previously described school building structure models was subjected to the previously mentioned test procedure.

5.1. Modal Analysis Results

As already mentioned, for the analysis of the structure, it is necessary to take a sufficient number of modes of oscillation in order to describe the deformations and movements of the structure as precisely as possible, because the results of the modal analysis serve as the initial parameters of many other analyzes that are performed to know how the structure behaves due to the action of an earthquake . Oscillation periods and forms of oscillation depend on the basic characteristics of the structural system, i.e. mass, stiffness and damping of the structure. Using the model of the structure of the school building, it was shown, in the attached results from Robot, that for a stiff structure, the periods of oscillation are small, while with progressive reduction of stiffness, the periods of oscillation of the structure increase significantly. The main form of oscillation of the structure dominantly depends on the ratio of the stiffness of the two vertical directions and the torsional stiffness of the structure. The reduction of stiffness and the change in the constructive system of the building has a great influence on the main forms of oscillation.

Model	1a	1b	2	3	4
1st mode [s]	0,18	0,18	0,18	0,64	0,31
2nd mode [s]	0,16	0,16	0,16	0,58	0,21
3rd mode [s]	0,12	0,12	0,12	0,52	0,19
4th mode [s]	0,10	0,10	0,11	0,32	0,15
5th mode [s]	0,09	0,09	0,10	0,28	0,14

Table 1. Oscillation period values for the first five modes

It is visible from the attached Table 1 that with the increase in the number of oscillation modes, the oscillation period decreases. Also, it can be concluded that all models are generally quite stiff, but also that if you go from model 1a, which is a model with walls, to model 3, which is a purely frame model, the stiffness decreases, i.e. to increase the period of oscillation of the school building structure. While model 4 is stiffer than model 3, but more flexible than models 1a, 1b and 2, due to the core walls.

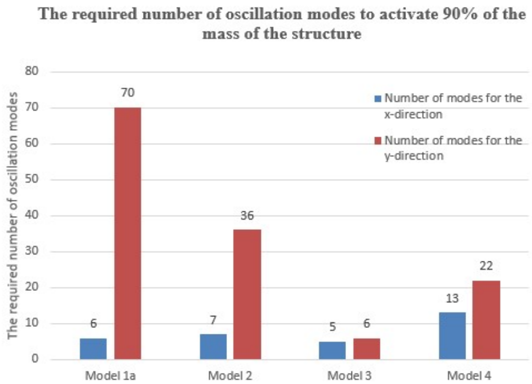
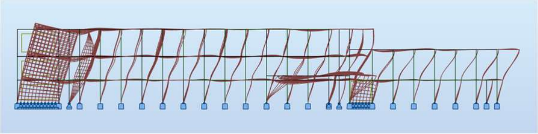


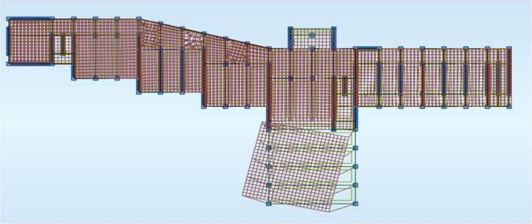
Figure 4. The required number of oscillation modes to activate 90% of the mass of the structure

As expected, according to Figure 4, the number of required modes of oscillations to activate 90% of the mass, for model 1a, is the highest and this is confirmed by the fact that this model is the stiffest because it has the most walls in it. Model 1b was not analyzed in this graph because it was not even assigned a sufficient number of modes to activate 90% of the mass. Model 3 needs the least number of modes, which is logical because it is a frame model of the structure of the school building and is therefore the most flexible. A large number of required oscillating modes is also a consequence of the fact that the structure of the school is extremely irregular, both at the base and at the height. What can also be seen from the attached graph is that in general in each model a higher number of oscillation modes is needed to activate 90% of the mass for the global y direction. This happens because the structure is many times stiffer in the y direction, so it needs more modes to activate 90% of the mass, oscillating modes, as well as enhanced torsional effects. With the frame model of the school structure, it can be observed that the number of modes required to activate 90% of the mass during oscillation is almost the same, which means that the stiffness is very similar for both directions.

5.2 Main Modes of Oscillation

Attention is paid to the forms of oscillation in the first few modes of the oscillation, while the modes are predominantly translational. In higher modes of oscillation, as mentioned earlier, local oscillation modes are available and torsion occurs.





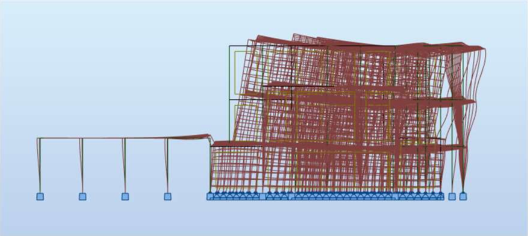
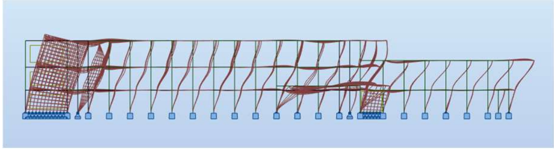
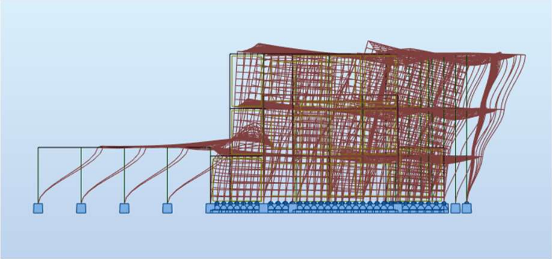


Figure 5. The first, second and eighth modes of oscillation of model 1a

What can be observed and concluded from Figure 5 is that the first mode of the structure oscillation in model 1a is predominantly translational in the x direction with small torsional effects occurring in the left stair core and entrance hall. Torsion in the left stair core occurs due to its large distance from the center of stiffness around which the structure of the school building rotates, while in the entrance hall it occurs due to the low stiffness of that part of the school building. The reason why the structure behaves like this can be cited as a distinct irregularity and disproportionate distribution of stiffness within it. The structure of the school is many times stiffer in the y direction due to the very dense arrangement of the walls, while in the x direction there are only three walls that resist the effect of the earthquake, of course with the help of frames, but still, the walls accept most of the impact due to the dominant stiffness. Also, the arrangement of stiffness in height is not the same, the entrance hall stands out as the "weak link" of the structure of this school building and that part suffers the most. The forms of oscillation of model 1b are identical to those of model 1a because it is a characteristic of the structure that depends exclusively on the mass and stiffness of the structure.





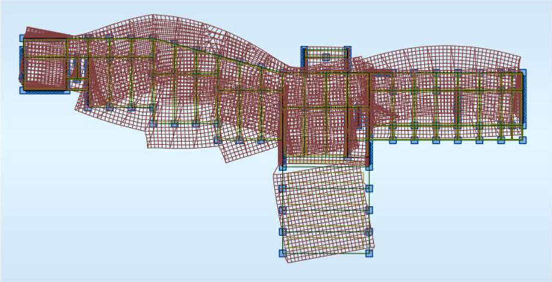
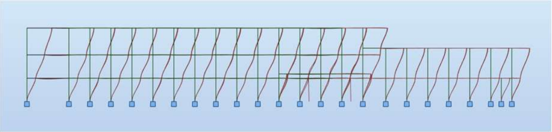
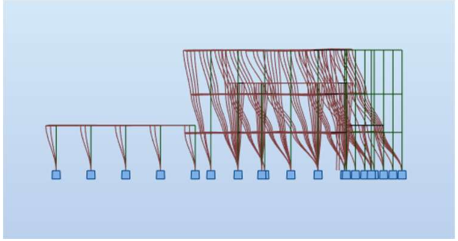


Figure 6. The first, fourth and tenth modes of oscillation of model 2

What can be noticed, in Figure 6, in the first mode is that it looks almost identical to the shape of the oscillation of model 1a in the first mode. The reason behind this is that the first mode is dominantly a translational mode in the x direction, so since the arrangement of the walls in the x direction remains the same, then this too remains unchanged in model 2. The next form of oscillation of the structure is almost so pure translation in the y direction. The fact that the translational mode occurs earlier than in the previous model indicates that this model behaves more flexibly, i.e. that the stiffness of the school building model has decreased a lot and that the center of stiffness has moved closer to the center of mass. This arrangement of stiffness is better and more uniform, although the stiffness is still greater in the y direction. The dominant rotational form of oscillation of the structure appears only in the tenth mode, which is later than in model 1a where the torsional mode appears very early, like the second, and from the picture that shows that form of oscillation it can be concluded that the main problem in the structure is again flexibility entrance hall.





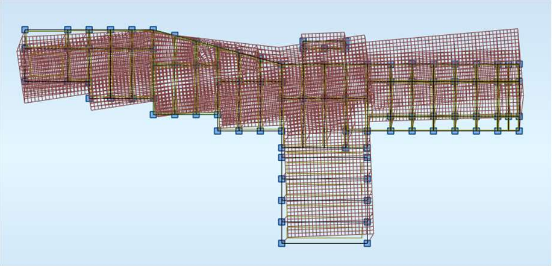
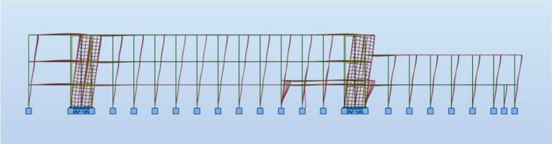


Figure 7. The first, second and third modes of oscillation of model 3

The framework model, i.e. model 3 of the structure of the school building is the most flexible model processed in this work. The main forms of oscillation, shown in Figure 7, are very clear and the first two modes are purely translational, while the third mode of the oscillation is torsional. In the first mode, close to 85% of the mass is activated and translated in the x direction, while in the second mode, close to 60% of the mass is activated to translate in the y direction. The different behavior of this school model compared to the previous ones is a consequence of the almost uniform distribution of stiffness for both main directions and the fact that there is no very large stiffness concentrated in one place, such as, for example. staircase core. At the third mode of oscillation, we notice that the center of mass and the center of stiffness are very close to each other and that the effects of torsion are generally small for this model of a school building structure. Edge frames, which are the most resistant to torsional influences, contain elements of sufficient dimensions, which can be seen from the fact that the movements that occur at the edges of the object are not large. It can be noticed that in this model of the school building structure there is not any deviation in the oscillation of the entrance hall relative to the oscillation of the main part of the building, which occurred in the first two models of the structure of the school. This is because the stiffness of the entrance hall does not differ too much from the stiffness of the main part of the building, so the impact is more or less evenly distributed.



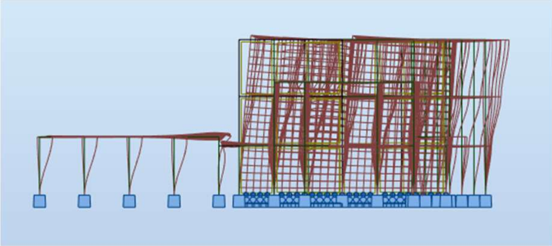


Figure 8. The second and fourth modes of oscillation of model 4

Model 4, i.e. the frame model with staircase cores behaves differently compared to the previous model. The mode in which a significant part of the mass is activated during oscillation is the second mode, which is translational and in the x direction, according to Figure 8. It can be noticed that model 4 behaves much stiffer than model 3 from which it was created, from which it can be concluded that the stair cores that were additionally inserted are very stiff elements and that they significantly affect the behavior of the structure. Stair cores, as extremely stiff structural elements, were added at both ends of the school and they resist the rotation of the school building quite strongly. The next mode, which is characteristic of this model, is the fourth mode of oscillation, which is predominantly a translational mode in the y direction, but with the effects of torsion, because the problem from before appears again, which is a more pronounced rotation of the entrance hall, as an element that for such a constructive system it is not stiff enough to follow the translation of the main part of the building. This occurs as a consequence of the introduction of staircase cores in the structure of the school building, and this again makes it irregular from the aspect of the distribution of stiffness inside it.

5.3. Total Seismic Force

As a result of the action of the earthquake, seismic forces of very high intensity are generated in the structure and are transmitted to the walls, columns or frames in the structure, which serve to accept these forces and carry them to the foundation. The forces are distributed among the elements in the structure, according to their stiffness. When the total force is distributed among the supporting elements of the structure, then the seismic elements are designed to accept the impact due to the action of the earthquake.

Model	1a	1b	2	3	4
Total seismic force in the x direction [kN]	3550,53	3380,94	3865,70	3046,51	3299,37
Total seismic force in the y direction [kN]	5929,32	5928,80	5524,26	4253,21	4654,47

Table 2. Total seismic force

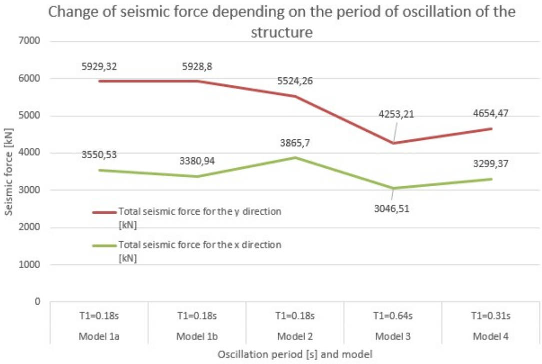


Figure 9. Change of seismic force depending on the oscillation period of the structure

From the attached data in Table 2 and Figure 9, it can be observed that the total seismic force changes depending on the type of structural system that is applied in a certain model of the school building structure, i.e. it mostly depends on the stiffness of the structure, as well as the period of oscillation. If the periods of oscillation of the structure model and their total seismic forces generated during the action of the earthquake are connected. It can be seen from the graph that for the school model that has the smallest period of oscillation in the first mode, i.e. for the stiffest model, the highest seismic force occurs, while the opposite is true for the most flexible model. It can be concluded that the absolute greatest force occurs in the models that contain a dense system of reinforced concrete walls, and the smallest in the frame model of the school building. It is also a logical conclusion, because, in addition to everything already mentioned, the seismic force is a function of the mass of the oscillating structure. An excellent example to show that the mass of the structure significantly affects the magnitude of the seismic force is model 2 of the school building structure, which has an identical period of oscillation as model 1a and therefore similar stiffness, but significantly less mass, because the number of walls is reduced, which on the total the seismic force is affected so that they differ by about 500 kN. One very important conclusion of this analysis is that the force intensity changes significantly for the x and y directions because there is a big difference in the stiffness of the model, for those two directions, especially for models 1a and 2, which have a large number of walls in the y direction, and only 3 in the x direction. However, with the framework model of the school. If we now connect the results of the multimodal spectral analysis with the results of the modal analysis, one very interesting fact can be observed, namely that the magnitude of the total seismic force generated in models 1a and 1b does not change significantly, for the same structure model that is once reached a sufficient number of modes to activate 90% of the mass, and the second did not. Model 1b was built precisely to compare the magnitude of the seismic force for different percentages of the activated mass of the structure. In model 1a, the software was allowed to do the modal analysis until it has activated 90% of the mass of the structure, i.e. 70 modes, while in model 1b a modal analysis was performed with a given number of modes, in which 90% of the mass of the structure is activated in model 2, i.e. 36 modes. Although in model 1a more than 90% of the mass is activated for both directions, the magnitude of the total seismic force in the y direction differs by about 4.8%, which is a very small difference. From this, it can be concluded that the number of modes of oscillation, i.e. the percentage of the activated mass of the structure during the oscillation of the analyzed structure of the school building affects the size of the seismic force, but not too significantly, which may mean that if there are any problems during the execution of the modal analysis, it is not necessary to activate 90% of the mass of the structure, as required by the Eurocode 8 [5], and that errors in the dimensioning of structural elements can be avoided.

5.4. Displacements

Probably the most important information about structures that accept impacts due to earthquakes is the movement of the structure. Movements largely depend on the stiffness of the structure, but of course also on its irregularity, i.e. eccentricity of the center of mass from the center of stiffness. Torsion can greatly affect displacement magnitudes. The size of the displacement and its limitation are significantly influenced by the behavior factor *q* and the type of applied structural system. Specifically related to the case of the school that is the subject of this paper's analysis, the frame model of the school building structure has the absolute largest displacements, which makes sense due to the flexibility of that model, while the model with reinforced concrete walls is the stiffest and thus has the smallest displacement values.

Model	Model 1a	Model 1b	Model 2	Model 3	Model 4
Displacement in x direction [cm]	0,8	0,8	0,8	7,3	0,9
Displacement in y direction [cm]	0,2	0,2	0,3	6,9	2,1
Displacement in z direction [cm]	2	2	2	3	2

Table 3. Displacements

Analyzing the results of horizontal displacements, given in Table 3, the first three models, we can conclude that by reducing the number of walls, the magnitude of horizontal displacements practically did not change. The frame model of the structure is therefore much more flexible and the displacements have increased many times. Also, it can be noticed that in general the displacements of the structure in the x direction are greater than the displacements of the structure in the y direction. Such behavior of the structure is expected due to the dominant stiffness of the school structure in the y direction, but also due to the greater total seismic force acting in the x direction. Also, as already mentioned, with the frame model of the structure, the stiffness in two orthogonal directions is approximate, so the magnitudes of displacement are quite close.

5.5. Inter-storey Drift

When talking about inter-storey drifts, the most common interest is focused on satisfying the conditions in Eurocode 8 [5], [7], [8], [9], which is related to the requirement of damage limitation. Specifically related to the structure of the school building, the inter-storey drifts of the structure model with walls were not analyzed because the horizontal displacements of those models are generally very small. The focus is on the analysis of the inter-storey drifts of the frame models of the school building.

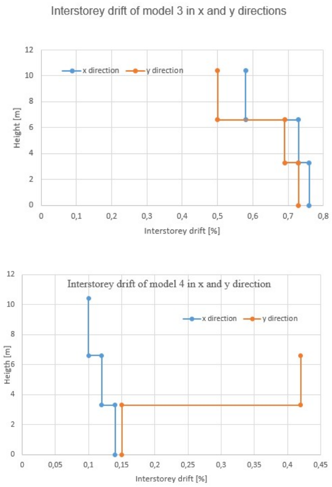


Figure 10. An inter-storey drift of model 3 and model 4

From the attached diagram in figure 10, it can be seen that model 3 of the school building structure behaves quite stiffly and that the values of inter-storey drifts are within the upper limit of 1%. Also, it can be seen that the structure behaves similarly in both global directions, while the y direction is a shade stiffer than the x direction. With model 4, the situation is a little different, the school structure behaves quite differently in the x and y directions. Due to the presence of staircase cores, the main part of the structure moves very little in the x direction, so the values of the inter-storey drifts are very small, i.e. it has been proven that this model of the school is very stiff and it is visible how much the staircase cores affect the overall stiffness of the structure. As for the movement in the y direction, it can be noted that the second floor has moved more in relation to the first, than the first in relation to the ground floor, but this is a consequence of the fact that the floor height is higher, so, logically, it will move more.

5.6. *Required and Adopted Reinforcement*

Designing the elements so that they can accept the impacts that occur in the structure due to the effect of the earthquake is extremely important because it very often depends on what the outcome will be after the effect of the earthquake on the structure. Also, a very important thing related to designing is the correct shaping of details for local ductility, otherwise, there may be very large damage or even collapse of the structure.

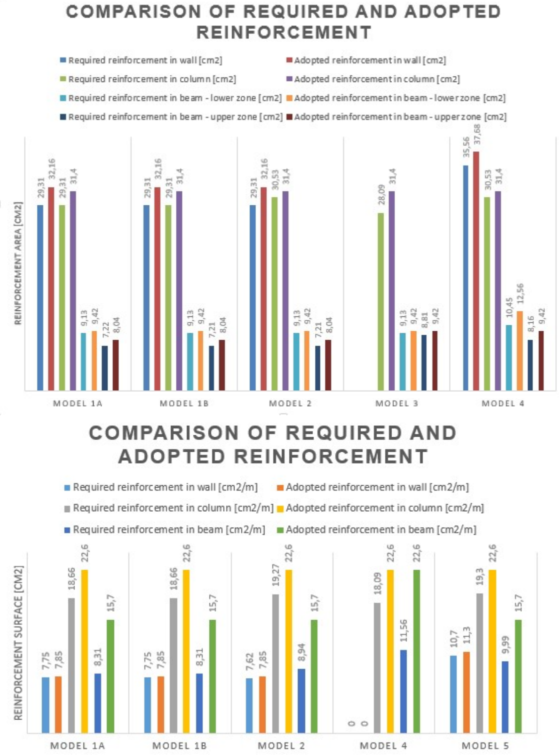


Figure 11. Required and adopted reinforcement

The first graphic, shown in figure 11, shows a graphic comparison of the required and adopted longitudinal reinforcement in the relevant elements of the structure, while the second graphic shows a comparison of the required and adopted transverse reinforcement of the relevant elements of the school structure. From the attached figures and tables, we can conclude that the final adopted reinforcement in most cases does not differ at all. The conclusion is that, from the perspective of the adopted reinforcement in the relevant elements, there is no single school model that we could single out as economical. The results are like this because all 5 models are designed according to relatively similar crosssectional forces, which are so due to the small oscillation periods of the structure. After all, the structure in the "linear" part is close to the "plateau" of the design acceleration spectrum according to Eurocode 8 [5]. It is very important to emphasize that the analysis of the total amount of reinforcement for the entire model of the school was not carried out in this paper due to the technical shortcomings of the computer on which the analyzes were performed.

6. CONCLUSION

As part of this work, a numerical analysis of the reinforced concrete structure of the school building in Smederevska Palanka was performed. The numerical models considered were chosen to illustrate the behavior of different structural systems under earthquake action. Based on all performed analyses, the following conclusions were drawn:

- The originally constructed structure of the school is too stiff and this would potentially cause a brittle fracture at the junction with the basement walls because the part of the structure that is buried is still at rest, while the part of the structure above ground level oscillates under the action of an earthquake. Although the displacement values are relatively small, for a system with walls, they can cause great damage, because at the time the structure was built, the ductile behavior of the structure was not taken into account.
- Due to the irregularity of the structure of the school, both in the base and in height, the construction generally behaves very unevenly and has noticeable effects of torsion due to the large eccentricity of the center of mass and the center of stiffness. What could be a potential solution to this problem is the expansion of the right, lower, part of the building in relation to the main part of the building, because then they would become two independent structures and their behavior would change drastically.
- The main problem with the structure of this school is the enormous stiffness in the y direction, i.e. a very large number of reinforced concrete walls, which is unnecessary in such a large number. By changing the structural system to a frame system, it was shown that the stiffnesses in two orthogonal directions are approximate, as well as that the structure has larger displacements, which leads to the fact that the school as a frame system can behave ductilely during earthquakes.
- The dimensions of the tall columns in the entrance hall are very small. The dimensions of those columns should be increased so that they are oriented with the longer side in the global x direction, to increase the stiffness of that part of the school building.

A potential earthquake would point out all the mistakes that occurred during the design and execution of the structure, which certainly exists, but it would definitely be very difficult with an object with very large-scale stiffness, such as this school.

7. REFERENCES

[1] - V. Alendar - Projektovanje seizmički otpornih armiranobetonskih konstrukcija kroz primere, 2004.

[2] – Republican Seismological Association of the Republic of Serbia. Available at https://www.seismo.gov.rs/.

[3] – Radovanović S. – Seizmički hazard u Srbiji, 2020.

[4] – Nikolić-Brzev S., Marinković M., Milićević I., Blagojević N., Isufi B. – Consequences of the earthquake in Albania from November 26, 2019. year on facilities and infrastructure, 2020.

[5] - SRPS EN 1998-1/NA: 2018 (2018). Eurocode 8: Design of seismically resistant structures - Part 1: General rules, seismic actions and rules for buildings. Institute for Standardization of Serbia, Belgrade, Serbia

[6] - SRPS EN 1992-1-1: 2004 (2004). Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings. Institute for Standardization of Serbia, Belgrade, Serbia.

[7] – Prof. dr Branko Milosavljević - Predavanja iz predmeta: Projektovanje i građenje betonskih konstrukcija 2, 2022. Available at http://imksus.grf.bg.ac.rs/.

[8] – Ivan Milićević, MSc of Civil Eng. – Vežbe iz predmeta: Projektovanje i gradjenje betonskih konstrukcija 2, 2022. Доступно на http://imksus.grf.bg.ac.rs/.

[9] – Prof. dr Ratko Salatić – Dinamika konstrukcija i zemljotresno inženjerstvo – Priručnik, Beograd, 2021.

[10] – Robot Structural Analysis – User’s guide, 2021.

Gordan Praštalo is an MSc student, Faculty of Civil Engineering, University of Belgrade, Serbia (e-mail: gordan.prastalo.11@gmail.com).