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COMPARATIVE ANALYSIS OF GLOBAL STABILITY OF THE TYPICAL STRUCTURAL SYSTEMS OF MULTI-STOREY STEEL BUILDINGS

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Abstract. *The paper presents global stability comparative analysis of two distinctive structural systems for one 25 - storey high steel building. These are the system with rigid and the system with hinged joint connections between beams and columns in the steel structure. The analysis focuses on the basic structure which was designed only to carry vertical loads, and on the corresponding structure which was stabilized with vertical bracings in the façade walls. Additionally, the paper shows several intermediate steps in the designing of stabilized systems. Static and dynamic design of the relevant structural systems, as well as the control of stress, deformation and stability under the seismic forces of seismic intensity VIII, was done on a computer, on the 3D computation models using Finite Element Method.*

Key words: *global stability, steel structure, multi-storey building, vertical bracings, belt truss, space frame.*

1. Introduction

1.1. General

One of the main characteristics of multi-storey buildings in steel, which has a great influence on the global stability of the building, is a low stiffness of the main load bearing structure, which is a consequence of the small cross-sections of the support elements of steel, the small base of the building compared to its height, mostly large free spaces in the building and the use of lightweight walls and façades. In addition, large values of horizontal forces, especially the seismic forces, in cases of the buildings with greater heights, may disturb their global stability and safety of people staying in them. With that in mind, the global stability of the building becomes a priority in the design and construction of such buildings, particularly in seismic active areas. Designing the appropriate type of structural system, which includes an adequate bracing system, is important not only for structural safety, but also for its

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efficiency and speed of construction and mounting of its elements. The choice of the correct method of bracing is of mayor importance to the structural design and may even govern the whole design concept of a high-rise building [4].

Bracing system provides the necessary rigidity and global stability of the building, and is therefore an integral part of most structural systems in steel. In many cases it represents the whole structural system. Stiffening system plays an important role of reception of horizontal forces acting on an object and their transmission to the foundation and soil. It prevents the excessive horizontal deflection and limits vibrations of tall buildings [2]. This system undoubtedly has a considerable influence on the global stability of the building and is also one of the few factors that can be influenced in order to increase global rigidity and in that way improve the stability of the building [1].

For achieving the global stability of the analyzed three-dimensional computational models of the building, in the practical part of this work, the stiffening system with vertical bracings and belt trusses was applied. This system is explained in detail in [2].

1.2. The subject and the aim of the paper

The multistory building usually consist of beams and columns, either rigidly connected or having simple end connections along with diagonal bracing to provide stability. Even though a multistory building is three-dimensional, it usually is designed to be much stiffer in one direction than in the other; thus it may reasonably be treated as a series of plane frames. However, if the framing is such that the behavior of the members in one plane substantially influences the behavior in another plane, the frame must be treated as a three-dimensional space frame [3].

This paper is an example of global stability comparative analysis for 25 - storey high steel building, with two distinctive structural systems - the system with rigid and the system with hinged joint connections between beams and columns in the steel structure (in further text rigid system and hinged system). In both cases there were rigid connections between columns and foundation. The analysis was performed on the three-dimensional computational models of the building, using Finite Element Method. The aim of the paper was to broaden the knowledge and to gain a deeper understanding of the behavior of these structural systems in space during the seismic load and eventually to give advantage for practical use of one treated system.

First, the basic structural systems were analyzed. These systems were designed to receive only the vertical loads. After that, design and analysis of globally stable structural systems was started, in several steps, by laying the vertical bracings in the façade walls. The bracings were disposed only in the façade walls for architectural reasons, not to disturb the use of the interior space. Often, it is more advantageous to install the bracing in the external walls, as this eliminates structural restrictions upon the freedom of internal layout [4].

During the work the maximum horizontal deflections of the building due to seismic forces in two orthogonal directions (X and Y) were tested, as well as the natural periods of vibrations of the building in the same directions (T_{1x} and T_{1y}). The analyzed systems were considered stable when the maximum horizontal deflections were in the limits prescribed by The Serbian Rules of Technical Standards for Construction of Buildings in Seismic Active Areas, H/600 (H-building height), which in this case is 15,17 cm, and when the state of stress and strain in all elements of the structure was within tolerable limits.

1.3. Description of the building structure

The analyzed building has rectangular shaped base with dimensions 40x45m. The height of the building is 91 m. There are two basement floors, ground floor and twenty five floors above. Storey height is 3,5 m. Axial distance between columns in both orthogonal directions is 5,0 m. In the central part there is a reinforced - concrete core with dimensions in the base 5x10 m and 25 cm thick walls. Between the main columns on the façade there are façade columns that extend through all storeys above the ground floor. All beams in the floor structure have the same rank and they are connected directly to main columns. The cross-sections of beams are classic I profiles and the cross-section of columns are two connected IPB profile. Each floor has monolithic, 16 cm thick reinforced - concrete slab. The foundation structure was modeled as a full foundation slab on an elastic base, thickness of 1 m. Foundation depth is 7 m. The basement floors have reinforced concrete walls 0,5 m thick, which extend around the base. The concrete class is MB30, and steel is S235.

2. Global Stability Analysis

2.1. Basic structural systems

During the design of the basic structural systems the minimum required dimensions of steel and concrete elements were adopted, in order to receive only vertical loads, both for the system with hinged, and the system with rigid joint connections. Afterwards, the modal analysis was done and the natural periods of vibrations for both orthogonal directions of the building were calculated (T_{1x} and T_{1y}).

Then the seismic design was done. Seismic forces were calculated for two orthogonal directions, X and Y, according to the Method of Equivalent Static Loads for the level of seismic intensity VIII. The building structure was classified in construction with flexible ground floor (Kp = 2), because of the greater rigidity of the structure above ground floor, due to existence of façade columns in other floors.

This analysis of the basic structural systems was performed to found what are their dynamic characteristics and sizes of horizontal displacements due to earthquakes, as well as to see the state of stress in the structure after the seismic load. Table 1 presents the results of this analysis.

Table 1. Natural periods of vibration and maximum horizontal deflection - Basic Systems

Structural system	Natural period of vibration [s]		Maximum horizontal deflection [cm]	
	T_{1X}	T_{1Y}	f_X	f_Y
Hinged	4,819	4,284	64,7	57,4
Rigid	4,099	3,890	45,8	46,0
Difference Δ0	0,72	0,394	18,9	11,4

In the following, bracings that will provide the global stability of the basic structural systems were designed up to the level that was set in the introduction.

2.2. Stabilized structural systems

Bearing in mind that the analyzed basic structural systems were very flexible, with high values of natural periods of vibrations and significantly higher horizontal displacements than the allowable ones, it was decided to form bracings entirely of crossed diagonals which will be rigidly connected to the bracing nodes. The stiffness of the lattice girder can be increased by constructing it with rigid joints, so that a combination of lattice and rigid framework is obtained [4]. This decision is based on the previous experience and knowledge about the problems of multistory steel buildings stability. These kind of bracings represent the stiffening system combined of a truss and a rigid frame, which is several times statically indeterminate structure and much more efficient in stiffening the multistory steel buildings [1]. The bracings were placed only in façade walls. The cross-section of the diagonal bracings was 2U profiles connected as a box.

In the following, the three-dimensional models with bracings were designed, both for the rigid and the hinged system. It was done in several steps with the same arrangement of bracings in both systems. During this work results of modal analysis and the values of maximum horizontal deflection due to designed seismic forces were examined as it was done for the basic structural systems.

2.2.1. Step – 1

In the first step the class of the concrete elements was increased to MB40, as well as the thickness of reinforced - concrete core walls to 30 cm. Bracings were placed as in Figure 1 in all façade walls and cross-sections of diagonal bracings were 2U200. Than the analysis of free oscillations and seismic design was done. As Figure 1 shows, vertical bracings pass through the ground floor, so ground floor was no longer considered to be flexible, and ductility and damping coefficient Kp for seismic forces was Kp=1,6, since the natural period of vibrations was greater than 2,0 seconds. This value for Kp was kept until the end of the analysis. The analysis, as already mentioned, included both types of structural systems, hinged and rigid. The Table 2 presents the results of this analysis.

Table 2. Natural periods of vibration and maximum horizontal deflection - Step 1

Structural system	Natural period of vibration [s]		Maximum horizontal deflection [cm]	
	T_{1X}	T_{1Y}	f_X	f_Y
Hinged	4,027	3,575	36,8	32,7
Rigid	3,601	3,363	28,8	28,1
Difference Δ1	0,426	0,212	8,0	4,6

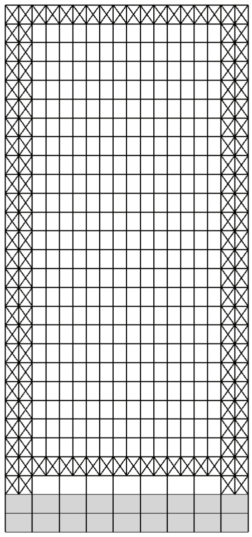

Fig. 1. Arrangement of vertical bracings for Step - 1

2.2.2. Step – 2

In the second step vertical bracings of the same type and size were added in the middle of the façade walls, as Figure 2 shows. The same analysis was performed and the results are shown in Table 3.

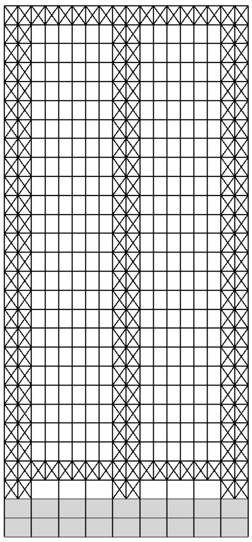

Fig. 2. Arrangement of vertical bracings for Step - 2

Table 3. Natural periods of vibration and maximum horizontal deflection - Step 2

Structural system	Natural period of vibration [s]		Maximum horizontal deflection [cm]	
	T_{1X}	T_{1Y}	f_X	f_Y
Hinged	3,881	3,467	33,6	29,2
Rigid	3,484	3,263	26,6	25,5
Difference Δ2	0,397	0,204	7,0	3,7

2.2.3. Step – 3

Since the vertical bracings added to the façade walls in the Step 2 did not have a greater effect, it was decided to set belt trusses around certain storeys, as in Figure 3. Results of analysis are given in Table 4.

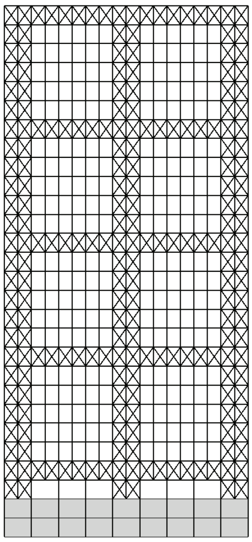

Fig. 3. Arrangement of vertical bracings for Step - 3

Table 4. Natural periods of vibration and maximum horizontal deflection - Step 3

Structural system	Natural period of vibration [s]		Maximum horizontal deflection [cm]	
	T_{1X}	T_{1Y}	f_X	f_Y
Hinged	3,062	2,914	22,5	21,9
Rigid	2,905	2,823	19,7	20,1
Difference Δ3	0,157	0,091	2,8	1,8

2.2.4. Step – 4

Bearing in mind that belt trusses added in the previous step were very efficient, the following systems were formed by placing additional belt trusses around every third floor, as in Figure 4. Cross-section of diagonal bracings was increased to 2U300. In this way the maximum horizontal deflections of the building in both treated structural systems were taken to the limit allowed. As the state of stress in some steel elements was not in tolerable limits, cross-sections of these elements were increased. Analysis results are presented in Table 5.

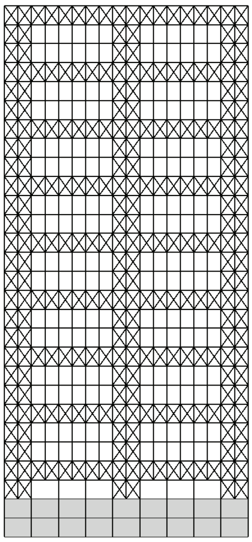

Fig. 4. Arrangement of vertical bracings for Step - 4

Table 5. Natural periods of vibration and maximum horizontal deflection - Step 4

Structural system	Natural period of vibration [s]		Maximum horizontal deflection [cm]	
	T_{1X}	T_{1Y}	f_X	f_Y
Hinged	2,379	2,359	13,8	14,6
Rigid	2,345	2,307	12,9	13,9
Difference Δ4	0,034	0,052	0,9	0,7

The following Table 6 shows the dimensions of the columns for both treated structural systems, which were adopted at the beginning of the analysis for the basic structural systems and at the end of the analysis for stabilized structural systems.

Table 6. Column cross-sections for Basic and Stabilized Systems

Storey	Basic systems (hinged and rigid)	Stabilized systems (hinged and rigid)
	Column cross-section	
Basement	2IPB 450, 2IPB 500, 2IPB 550	2IPB 600, 2IPB 700
Ground floor and 1. floor	2IPB 400	2IPB 500
From 2. to 5. floor	2IPB 340	2IPB 340
From 6. to 9. floor	2IPB 300	2IPB 300
From 10. to 13. floor	2IPB 260	2IPB 260
From 14. to 17. floor	2IPB 240	2IPB 240
From 18. do 21. floor	2IPB 220	2IPB 220
From 22. to 25. floor	2IPB 200	2IPB 200

In the Table 6 we can see that adopted cross-sections of the columns are identical for both systems examined at the beginning of the analysis, as well as for stiffened structural systems obtained at the end of the analysis. During the work, until the end of analysis when spatially stable structural systems were formed the class of the reinforced concrete core was increased from MB30 to MB40 as well as the wall thickness from 25 cm to 30 cm. Also increased were the cross-sections of façade columns from 2U200 to 2U300. The adopted cross-sections of diagonal bracings are 2U300. Dimensions of beams in the system with hinged joint connections were retained on I260, while in the rigid system some cross-sections of beams were increased to I320 and I340.

3. Analysis Results

3.1. Comparison of the results for systems with the same structural type

When comparing the results of analysis of the systems in Step - 1 which have vertical bracings placed at the corners of the building façade and belt trusses around the first and the last floor, with the results of analysis of the basic structural systems, which is given in the Table 7, it may be observed that there was a significant reduction of natural period of vibration. However, the significant reduction of horizontal deflection can be noticed.

Table 7. Comparison of the results Basic systems – Step 1

Structural system	Natural period of vibration [s]		Maximum horizontal deflection [cm]	
	ΔT_{1X}	ΔT_{1Y}	Δf_X	Δf_Y
Hinged	0,792	0,709	27,9	24,7
Rigid	0,498	0,527	17,0	17,9

In the Table 8, the differences between the system obtained in Step - 2, where the vertical bracings were added in the middle of façade walls, and the systems in Step -1 are given.

Table 8. Comparison of the results Step 1 – Step 2

Structural system	Natural period of vibration [s]		Maximum horizontal deflection [cm]	
	ΔT_{1X}	ΔT_{1Y}	Δf_X	Δf_Y
Hinged	0,146	0,108	3,2	3,5
Rigid	0,117	0,100	2,2	2,6

As it can be seen, the differences are insignificant for the values of the natural period of vibration as well as for the horizontal deflection. It might be expected, because the main central axis of the building base cut these new added bracings and they do not have a greater effect in stiffening of the building.

Comparing the results of analysis of the systems obtained in Step - 3, in which belt trusses were added around some storeys, with the results in Step - 2 in Table 9, we can see significant reduction of the natural period of vibration in X direction, the greatest of all, and a great reduction of the natural period of vibration in Y direction. There is also a great reduction of horizontal deflections.

Table 9. Comparison of the results Step 2 – Step 3

Structural system	Natural period of vibration [s]		Maximum horizontal deflection [cm]	
	ΔT_{1X}	ΔT_{1Y}	Δf_X	Δf_Y
Hinged	0,819	0,553	11,1	7,3
Rigid	0,579	0,560	6,9	5,4

The Table 10 shows the differences between structural systems in Step - 4 in which the global stability is achieved by placing additional belt trusses, compared to the previous Step – 3.

Table 10. Comparison of the results Step 3 – Step 4

Structural system	Natural period of vibration [s]		Maximum horizontal deflection [cm]	
	ΔT_{1X}	ΔT_{1Y}	Δf_X	Δf_Y
Hinged	0,683	0,555	8,7	7,3
Rigid	0,560	0,516	6,8	6,2

It is clear that additional belt trusses in Step - 4 effected a significant reduction of natural periods of vibrations and the maximum horizontal deflections, so the analyzed systems contented the criteria set for achieving the global stability.

3.2. Comparison of the results between the hinged and the rigid structural system

Table 11 Difference of the results between the hinged and the rigid system

Hinged / Rigid	Natural period of vibration [s]		Maximum horizontal deflection [cm]	
	T_{1X}	T_{1Y}	f_X	f_Y
Difference Δ0	0,720	0,394	18,9	11,4
Difference Δ1	0,426	0,212	8,0	4,6
Difference Δ2	0,397	0,204	7,0	3,7
Difference Δ3	0,157	0,091	2,8	1,8
Difference Δ4	0,034	0,052	0,9	0,7

Looking at Table 11, large differences in the results obtained for hinged and rigid structural system at the beginning of the analysis can be observed, drastically decreasing at the end of the analysis. The differences obtained between the maximum horizontal displacements of these two systems are in the final, for stabilized systems, as it can be seen, very small. In X direction the difference was 0,9 cm, and in Y direction only 0,7 cm. Also these two systems have very small differences in the natural periods of vibration. For the period T_{1y} the difference is 0,034 s and for the period T_{1x} 0,052 s.

4. Final Remarks

Bearing in mind all the issued and done, especially comparison given in sections 3.1. and 3.2. of this paper which are shown in Tables 7-10 and Table 11, it was concluded the following.

Acording to results obtained during examination of the basic structural systems to the effects of seismic forces at the beginning of this paper it was noticed that the rigid system had much lower horizontal deflections than the hinged system, so it was expected that allowed horizontal deflections in the rigid system would be reached before than in the hinged system.

From the Table 11 it can be seen that basic system with rigid connections had smaller horizontal displacement for 18,9 cm in X direction and 11,4 cm in Y direction than basic system with hinged connections, which was obviously a result of higher stiffness of applied joint connections.

But, from the results presented in Tables 7-10, which show that the reduction in displacement for the rigid system in every step of the analysis was less than the reduction in the system with hinged connections, it was concluded that the effects of bracings in the rigid systems were weaker than in the hinged system. The logical consequence is that at the end, in the same step of analysis, using the same arrangement of bracings, we get horizontal deflections in the acceptable limits in both systems examined and obtained differences between the horizontal displacements and natural periods of vibration insignificant (Table 11). These differences in the maximum horizontal deflections is less than 1 cm, and in the natural periods of vibration less than 0,1 s. This shows that the type of designed joint connections between beams and columns in the steel structure was less important in achieving global stability than applied bracing system, which is one of the most important conclusions of this paper. Considering the complexity of the design and construction of rigid connections the advantage of use, in this case, should be certainly given to the hinged system. The hinged systems are more effective than the rigid systems for receiving a horizontal load because the majority of the columns are discharged of receiving of horizontal forces and thus requires less consumption of steel, making them suitable for higher buildings [5].

During the analysis, it was also concluded that belt trusses placed around certain storeys and connected to vertical bracings in façade corners had very good results in stiffening the building structure when building also have the reinforced concrete core in the middle of its base.

Although the structural systems designed in the last iteration satisfy the requirements for global stability, they are still considered quite flexible, because of the small sizes of the adopted structural elements, which show the values of obtained maximum horizontal displacements. Table 12 shows the effects of stiffening with the applied type of bracing system.

Table 12 The effects of stiffening with the applied type of bracing system

Structural system		Natural period of vibration [s]		Maximum horizontal deflection [cm]	
		T_{1X}	T_{1Y}	f_X	f_Y
Hinged	Basic	4,8	4,3	64,7	57,4
	Stabilized	2,4	2,4	13,8	14,6
Rigid	Basic	4,1	3,9	45,8	46,0
	Stabilized	2,3	2,3	12,9	13,9

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UPOREDNA ANALIZA PROSTORNE STABILNOSTI KARAKTERISTIČNIH KONSTRUKCIJSKIH SISTEMA ČELIČNIH VIŠESPRATNIH ZGRADA

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U radu je izvršena uporedna analiza prostorne stabilnosti dva karakteristična konstrukcijska sistema 25 – spratne čelične zgrade. To su sistem sa zglobnim i sistem sa krutim vezama čeličnih nosača i stubova. Analizom su obuhvaćeni osnovni noseći sistemi koji poseduju armirano – betonsko jezgro oko vertikalnih komunikacija i odgovarajući sistemi stabilizovani vertikalnim rešetkastim spregovima u fasadnim zidovima. Takođe je dat i prikaz nekoliko međufaza u formiranju prostorno ukrućenih sistema. Određivanje statičkih i dinamičkih uticaja u predmetnim konstrukcijskim sistemima, perioda sopstvenih oscilacija, kao i kontrola stanja napona, deformacija i stabilnosti usled dejstva seizmičkih sila, za VIII stepen seizmičkog intenziteta, izvršena je na računaru, na prostornim računskim modelima, primenom Metoda konačnih elemenata.

Ključne reči: *prostorna stabilnost, čelična konstrukcija, višespratna zgrada, vertikalni spregovi, pojasne rešetke, prostorni ram.*