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Original Scientific Paper

ANALYSIS OF 3D MULTI-STOREY BUILDING NUMERICAL MODELS INCLUDING FLOOR SLABS AND SHEAR WALLS DEPENDING ON THE CONNECTION TYPE IN THE STEEL STRUCTURE

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Abstract. *Multi-storey steel buildings are usually designed with rigid connections between beams and columns or with simple hinged connections and a stiffening system. The paper focuses on the 3D structural design of multi-storey steel buildings including floor slabs and shear walls. The method of numerical modelling has been applied to investigate the influence of rigid connections between certain structural elements on the lateral stiffness of the multi-storey building structure, when floor slabs and shear walls are considered in the structural design. Four building heights and six structural system types, having the same floor plan have been examined. 3D numerical models have been configured in FEM software to evaluate the lateral stiffness of the structures exposed to gravity and seismic loads. The maximum horizontal deflections and natural periods of vibrations are presented in the paper. It has been concluded that the connection type in the multi-storey steel structure has no significant influence on the lateral stiffness of the structure when structural design considers floor slabs and shear walls.*

Key words: *multi-storey buildings, shear walls, floor slabs, lateral stiffness, connections, steel structures*

1. INTRODUCTION

Supporting the steel structure of multi-storey buildings can be designed by using a large number of structural systems [1]. Multi-storey steel buildings usually consist of beams and columns, either rigidly connected (moment resisting frames) or having simple end connections along with diagonal bracing to provide the lateral stability [2]. Both groups of systems are equally applicable for buildings up to 30 storeys high, knowing that the most of

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the typical multi-storey steel buildings such as schools, universities, residential buildings, office buildings, hospitals, etc. have been built in hinged or rigid structural systems.

Even though a multi-storey building is three-dimensional and in addition to beams and columns contains floor slabs and walls, the structural strength provided by walls and slabs is usually neglected while modelling the building structure and it is commonly designed as a pure skeletal structure. However, consideration of walls and slabs in three-dimensional models of multi-storey buildings improves the lateral stiffness, which leads to a more economical structural design [3].

Reinforced concrete shear walls are vertical structural components with generally high stiffness and strength that increase the buildings' lateral resistance against horizontal loads [4]. Stiffness is one of the three basic parameters that significantly influences the behavior of structures during earthquakes, besides carrying capacity and ductility. The stiffer the structure, the less it deflects under a seismic force, although a smaller natural period of vibration caused by a stiffer structure will usually result in a structure attracting a greater seismic force [5]. Stiffness directly depends on the type of structural system and it affects the values of the natural period of vibrations. The response of the structure to the effect of the dynamic load depends primarily on the value of the natural period of vibrations.

In addition, stiffness significantly affects the structural deformation. If a structure's stiffness is so low that it deflects excessively, its non-structural elements will suffer damage [5]. High values of horizontal forces, especially the seismic forces, in cases of buildings with greater heights, may disturb their stability and safety of people staying in them. Earthquakes show that the behavior of stiffer structures (with shear walls), on average, is better than the behavior of flexible systems (pure skeletal structure). The deformations of the stiffer system are smaller than the flexible system deformation and therefore the damage to non-structural elements in a building is smaller. Bearing in mind that the building structure has a lower cost than non-structural elements, destroying all non-structural elements in a flexible system means a considerable economic loss, although the structure is not physically destroyed. There is no doubt that the structures with reinforced concrete shear walls can not be sufficiently ductile, so a large number of experts in seismic construction considers that it is better to build structures with greater stiffness in the seismic areas [6].

In most cases, multi-storey buildings have walls around elevator and stairway cores. These walls, especially when they are made of reinforced concrete, provide a considerable lateral stiffness that resists horizontal forces. For tall buildings, centrally located reinforced concrete shear wall systems are typically used as the main seismic force resisting system [7]. Furthermore, floor slabs participate in the whole system by accepting the horizontal forces and transferring them to the vertical system. Research on the topic related to walls and/or slabs has been conducted by many authors such as [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [3]. These studies have shown that consideration of walls and floor slabs plays an important role in the design of multi-storey building structures. These important parts of a building contribute to greater lateral stiffness, thereby creating a more economical design.

2. The Subject and the Aim of the Research

The paper focuses on multi-storey steel buildings having height up to 25 storeys, exposed to gravity loads and seismic forces of seismic intensity VIII. Six structural system types of steel buildings having the same floor plan with the central reinforced concrete core, and four different heights of 10, 15, 20 and 25 storeys, have been examined. These systems differed by the selected type of connection between the structural elements, hinged or rigid, or their disposition in the structural system of the building. The systems with exclusively hinged or rigid connections have been analyzed, as well as the combined systems with a different arrangement of the hinged and rigid connection between the structural elements.

The aim of this study is to investigate whether the use of rigid connections between certain structural elements may increase the lateral stiffness of the whole structure, when the structural design considers floor slabs and shear walls of the central reinforced concrete core. The assumption is that the rigid connections will not contribute much to the lateral stiffness of the system in this case, which would give priority to hinged connections. Hinged connections have a number of benefits. Among them, unification of beams in floors and standardization of joints in the structure are very important for tall buildings.

The use of standardized joints where the fittings, bolts, welds and geometry are fully defined offers the following benefits [18]: reduces buying, storage, and handling time; improves availability and leads to a reduction in material costs; saves fabrication time and leads to faster erection; leads to a better understanding of their performance by all industrial branches ; leads to fewer errors.

Bearing in mind that multi-storey buildings are not pure skeletal systems, but complex systems composed of beams and columns, floor slabs, foundation slab and shear walls, three-dimensional numerical models have been configured for all examined systems. In this way, the behavior of the structure under load has been analyzed as a spatial system and interaction of all significant elements of the structure has been covered. It can be considered that the results obtained are more accurate than in the conventional design.

The maximum horizontal roof deflections and natural periods of vibrations are presented in the paper. Based on these parameters of structural stiffness, the conclusions of this paper have drawn. Also, based on the results obtained, the recommendations for more economical systems have been given.

3. The Numerical Models

3.1. Structural System Types

Six structural system types were examined for all the building heights. The model labels with the appropriate system type are given below.

- MODEL 1 – The system with rigid connections between all structural elements (Fig. 1);
- MODEL 2 – The system with rigid connections, except hinged connection between columns and foundation slab (Fig. 2);
- MODEL 3 – The systems with rigid connections between beams and columns and hinged connections between columns and foundation slab and beams and central core (Fig. 3);
- MODEL 4 – The system with hinged connections between beams and columns and rigid connections between columns and foundation slab and beams and central core (Fig. 4);
- MODEL 5 – The system with hinged connections except rigid connection between columns and foundation slab (Fig. 5);
- MODEL 6 – The system with hinged connections between all structural elements (Fig. 6).

The following Fig. 1-6 show an internal frame and a frame including core wall for the systems having height of 10 storeys. The systems having height of 15, 20 and 25 storeys have the same arrangement of rigid and hinged connections as the 10 storey models.

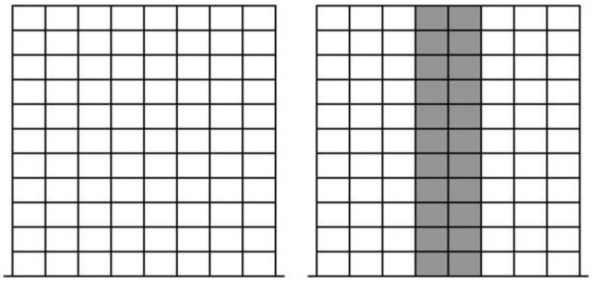

Fig. 1 An internal frame and a core wall frame in Model 1

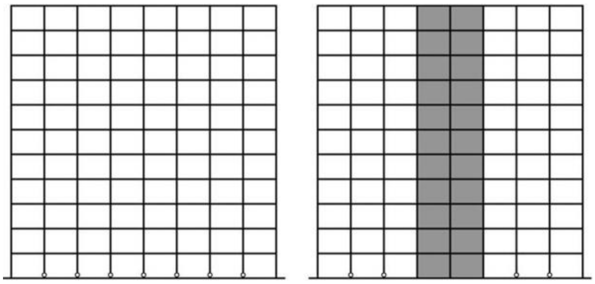

Fig. 2 An internal frame and a core wall frame in Model 2

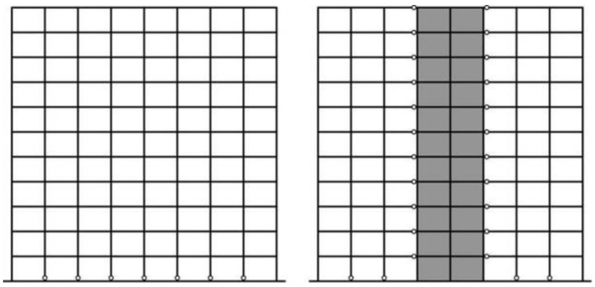

Fig. 3 An internal frame and a core wall frame in Model 3

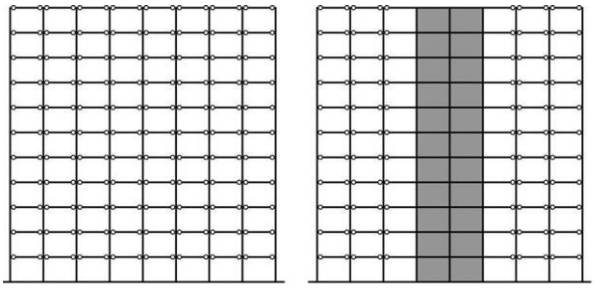

Fig. 4 An internal frame and a core wall frame in Model 4

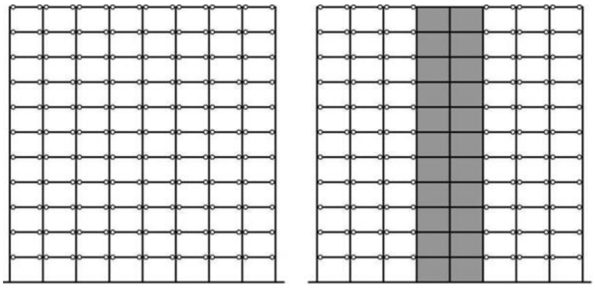

Fig. 5 An internal frame and a core wall frame in Model 5

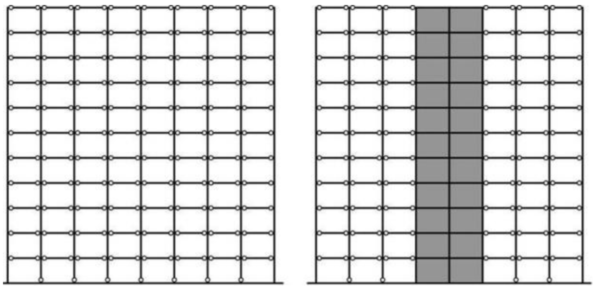

Fig. 6 An internal frame and a core wall frame in Model 6

3.2. Model Description

In this research the method of numerical modelling was applied, using a FEM computer software [19], to investigate the behavior of the structures. Three-dimensional models have been configured for all structural systems.

The analysis was done for the buildings of four heights: 10 storeys (30m), 15 storeys (45m), 20 storeys (60m) and 25 storeys (75m). For each of the four heights, six models have been designed according to defined structural system types. Total number of models is 24. All the designed models contain supporting steel structure, reinforced concrete core walls, reinforced concrete floor slabs, reinforced concrete foundation slab on elastic foundation and outer reinforced concrete basement walls. The models do not contain partition walls, stairways and landings and the façade structure (it is assumed that the façade type is a curtain wall).

All numerical models have identical floor plan, with the total area of 32 x 32 m. The Fig. 7 shows the disposition of columns, beams and reinforced concrete core. Distance between columns in both orthogonal directions is 4 m. All beams in the analyzed models have the same rank, there are no secondary beams. Reinforced concrete core occupies the central part of the building and runs continuously through all floors. The core was modelled as a hollow tube. The walls of the core are 25 cm thick.

Floor slabs were modelled as monolithic reinforced concrete slabs 12 cm thick. Cross-sections for all beams are IPE 200 profiles, and all cross-sections for columns are IPB profiles. The cross-sections of the columns gradually change at every 3-4 storeys. The largest cross-sections of the columns in the basement floor are given in the Table 1.

The outer walls of the basement floors are reinforced concrete walls having thickness of 50 cm. The foundation structure is 1 m thick reinforced concrete foundation slab.

Table 1 Design parameters

Parameter	Value
Plan Area	32 x 32 m
Storey Height	3 m
Floor Slabs	Concrete C30; 0.12 m thick
Foundation Slab	Concrete C30; 1.0 m thick
Core Walls	Concrete C30; 0.25 m thick
Basement Walls	Concrete C30; 0.50 m thick
Beams	Steel S235; IPE 200
Columns	Steel S235; 10 storeys IPB (HE-B) 260
(maximum cross-section)	Steel S235; 15 storeys IPB (HE-B) 340
	Steel S235; 20 storeys IPB (HE-B) 450
	Steel S235; 25 storeys 2IPBv (HE-M) 450

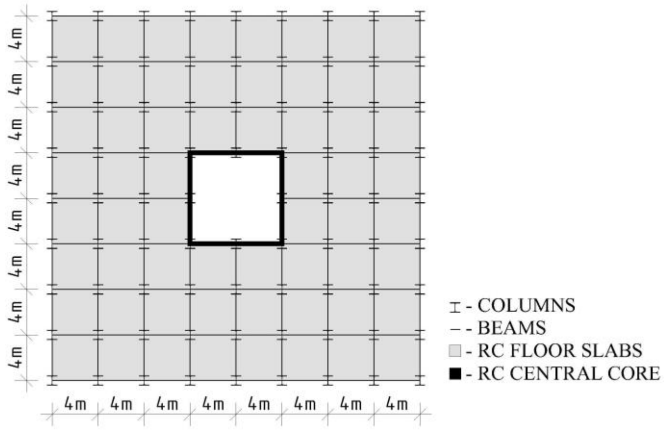

Fig. 7 Common plan view of the examined models

The storey height of each storey is 3 m. The analyzed buildings have one or two basement levels depending of the building height. All steel elements were designed of steel S235 and all reinforced concrete elements were designed of concrete class C30.

Considering the possibilities of the applied software, three types of finite elements were used: plate, beam and boundary. Plate finite elements were used for modelling of walls and slabs in order to consider both membrane and bending stiffness. Beam finite elements were used for modelling of beams and columns.

3.3. Material Properties

Two kinds of materials were used for modelling the building structures. Steel S235 was used for skeletal structure, and concrete C30 for walls, floor slabs and foundation slabs. The properties of these materials are given in the Table 2.

Table 2 Material properties

Material	Properties
Steel S235	f_e=235 MPa E=210 GPa ρ=7850 kg/m^3 ν =0.3
Concrete C30	f_c=30 MPa E=31.5 GPa ρ=2500 kg/m^3 ν=0.2

3.4. Loading Data

In all analyzed models both gravity loads and the lateral seismic load were taken into account. The software calculates the self-weight of the modelled structure automatically. The intensities of dead and imposed floor loads were taken according to reference [20]. The intensity of the dead floor load applied is 2.5 kN/m^2, and the intensity of the imposed floor load, according to the type of occupancy of the building is 2.0 kN/m^2. Also, applied load of the façade weight is 10 kN/m (façade walls were not modelled, curtain wall façade was assumed).

The design of seismic forces was done according to reference [21], using the Method of Equivalent Static Loads for the level of seismicity VIII (MCS scale). As the standards require, the seismic forces were calculated for two orthogonal directions.

4. The Numerical Investigation

The design of the models in this paper was done according to references [22] and [23].

The total number of models which were configured according to the defined structural types, loads and materials is 24. For each of four building heights six models were designed. The eigenvalue analysis was performed to determine natural periods of vibration for all numerical models. Then all models were analyzed under the seismic load.

The maximum horizontal deflections and natural periods of vibrations are presented in the paper. Based on these parameters, the conclusions of this research were drawn.

For all the building heights, first the system with rigid connections between all structural elements (Model 1) was designed to accept only the gravity loads. Then the eigenvalue analysis was done and the natural periods of vibrations (T_{1X} and T_{1Y}) were calculated. After that seismic forces were calculated for two orthogonal directions with corresponding values of natural periods.

The total horizontal seismic force S is determined by the equation (1):

$$S = K \cdot G \tag{1}$$

where G is the total weight of the building and equipment and K is the total seismic coefficient for the horizontal direction, given by the equation (2):

$$K = K_o \cdot K_s \cdot K_d \cdot K_p \tag{2}$$

Calculation of the total seismic coefficient was done with the following values of the individual coefficients:

- Coefficient of object categories, Category II, $K_o = 1.0$;
- The coefficient of seismic intensity of VIII seismicity zone, $K_s = 0.05$;
- The dynamic coefficient, for the first category of soil, $K_d = 0.5/T$, with the limit values $1.0 > K_d > 0.33$;
- Ductility and damping coefficient, K_p=1.3.

The total horizontal seismic force was distributed at the height of the building as follows. Amount of 15% of the total seismic force was concentrated on the top of a building and 85 % was distributed in other floors by equation (3):

$$S_i = S \cdot \frac{G_i \cdot H_i}{\sum_{i=1}^{n} G_i \cdot H_i} \tag{3}$$

where S_i is the seismic force in i-floor, G_i is the weight of i-floor and H_i is the height of i-floor from the upper edge of the foundation slab.

Due to the effects that the horizontal deflections of the building have on the comfort of the building's users and also on the functional aspects of the building, during an earthquake, a stricter criterion than in the standards has been defined for the control of the maximum horizontal deflection, with the value of H/1000, where H is the height of the building.

During the design of 3D models to the effects of the seismic load, the state of stress, strain and stability of individual steel elements and the maximum horizontal deflections of the structure were controlled. Besides, the natural periods of vibrations, as an important indicator of stiffness, were tested too.

After designing the system with rigid connections (Model 1), the 3D models of the remaining five systems (Models 2 - 6) were designed respectively for all the heights, by replacing certain rigid connections in Model 1 with hinged connections. Replacing was done in the software [19] by releasing the connection from the reception of the bending moment M_z around the stronger axis – z. These models retained the same dimensions of all structural elements as in Model 1, for the purpose of credible comparison of the results obtained. For all models, natural periods of vibrations and the seismic forces were calculated as for the Model 1.

After analyzing the results obtained, it was found that for all systems tested, for all the heights, the state of stress and strain was within acceptable limits, although identical cross-sections were kept as in the systems with rigid connections.

5. Results and Discussion

In order to compare the results obtained for different models of the buildings with the same height, in the paper the maximum horizontal deflections D [cm] and natural periods of vibrations T_1 [s] are presented. These parameters are very good indicators of structural performance. Results are presented in the Table 3.

The Table 3 shows that periods of free vibration have expected values which increase with the height rise. The results also show that the differences of natural periods of vibrations between the tested systems having the same height, are extremely small. Precisely, for the systems having the height of 10 storeys, natural periods of vibrations are in the range from 0.9895 s for the system with rigid connections (Model 1) up to 1.002 s for the system with hinged connections (Model 6). The difference ΔT_1, shown in Table 4, between these two systems is only 0.0125 s (1.25 %).

Table 3 Results of the research for all the models

Model	Storeys/ height	Parameters		Relation $D_{max} \sim H$
		Natural period of vibration T_1 [s]	Maximum horizontal deflection D_{max} [cm]	
Model 1	10	0.9895	2.379	H/1261
	15	1.6897	4.245	H/1060
	20	1.9390	5.414	H/1108
	25	2.1040	7.243	H/1035
Model 2	10	0.9896	2.380	H/1261
	15	1.6899	4.248	H/1059
	20	1.9400	5.417	H/1108
	25	2.1050	7.258	H/1033
Model 3	10	0,9901	2.382	H/1259
	15	1.6920	4.259	H/1057
	20	1.9410	5.416	H/1108
	25	2.1100	7.308	H/1026
Model 4	10	1.0010	2.438	H/1231
	15	1.7510	4.676	H/962
	20	1.9730	5.694	H/1054
	25	2.1340	7.629	H/983
Model 5	10	1.0020	2.439	H/1230
	15	1.7530	4.688	H/960
	20	1.9750	5.693	H/1054
	25	2.1440	7.668	H/978
Model 6	10	1.0020	2.440	H/1230
	15	1.7530	4.692	H/959
	20	1.9750	5.696	H/1053
	25	2.1450	7.685	H/976

For the systems having height of 15 storeys, natural periods of vibrations are in the range from 1.6897 s for the system with rigid connections (Model 1) up to 1.753 s for the system with hinged connections (Model 6). The difference ΔT_1 between these two systems is only 0.0633 s (3.61 %), which is shown in the Table 4.

Table 4 Differences between hinged systems (Model 6) and rigid systems (Model 1)

Height / Storeys	Difference ΔT_1 [s]	Difference ΔT_1 [%]	Difference ΔD [mm]	Difference ΔD [%]
10	0.0125	1.25	0.61	2.50
15	0.0633	3.61	4.47	9.53
20	0.0360	1.82	2.82	4.95
25	0.0410	1.91	4.42	5.75

For the systems having height of 20 storeys, natural periods of vibrations are in range from 1.939 s for the system with rigid connections (Model 1) up to 1.975 s for the system with hinged connections (Model 6). The difference ΔT_1 between these two systems is only 0.036 s (1.82 %), also shown in the Table 4.

For the systems having height of 25 storeys, natural periods of vibrations are in range from 2.104 s for the system with rigid connections (Model 1) up to 2.145 s for the system with hinged connections (Model 6). The difference ΔT_1 between these two systems is only 0.041 s (1.91 %), Table 4.

The results in the Table 3 also show that the differences of the deflections between the tested systems with the same height are very small. For the systems having height of 10 storeys the maximum horizontal deflections are in range from 2.379 cm for the system with rigid connections (Model 1) up to 2.440 cm for the system with hinged connections (Model 6), so that the maximum difference ΔD which occurs between these completely opposite systems according to types of connections in the structure, is only 0.061 cm (2.5%), Table 4.

For the systems having the height of 15 storeys the maximum horizontal deflections are in the range from 4.245 cm for the system with rigid connections (Model 1) up to 4.692 cm for the system with hinged connections (Model 6). The maximum difference ΔD which occurs between these completely opposite systems according to types of connections in the structure is only 0.447 cm (9.53 %), Table 4.

For the systems having the height of 20 storeys the maximum horizontal deflections are in the range from 5.414 cm for the system with rigid connections (Model 1) up to 5.696 cm for the system with hinged connections (Model 6). The maximum difference ΔD which occurs between these completely opposite systems according to types of connections in the structure is only 0.282 cm (4.95 %), Table 4.

For the systems having the height of 25 storeys the maximum horizontal deflections are in range from 7.243 cm for the system with rigid connections (Model 1) up to 7.685 cm for the system with hinged connections (Model 6). The maximum difference ΔD which occurs between the completely opposite systems according to types of connections in the structure is only 0.442 cm (5.75 %), Table 4.

6. Conclusions

Many authors have shown that the inclusion of walls and slabs in the structural design leads to a more economical structure. Material cost for connections in the structure can significantly affect the price of the whole structure. In a typical braced multi-storey frame, the share of joints may account for less than 5 % of the frame weight, but 30 % or more of the total cost. Efficient joints will therefore have the lowest detailing, fabrication and erection labour content [18].

In this research the method of numerical modelling has been applied to investigate the influence of rigid connections between certain structural elements on lateral stiffness of the multi-storey steel building structure, when structural models contain floor slabs and shear walls. Four building heights and six structural system types having the same plane view have been examined. Three-dimensional numerical models have been configured in FEM software [19] to assess lateral stiffness of the structures exposed to gravity and seismic loads. Static and free vibration analyses have been performed. The maximum horizontal deflections due to seismic action and natural periods of vibrations, have been used to draw reliable conclusions.

In all the models analyzed, for all the building heights, the unification of beams has been accomplished. The results show that the values obtained for the natural periods as well as for the maximum horizontal deflections are very similar for the systems having the same height. The analysis results given in the Table 3 clearly show that differences of natural periods of vibration and maximum horizontal deflections between the analyzed systems with the same height are extremely small. These values are such that, practically, can be neglected, because the differences between fully hinged (Model 6) and fully rigid system (Model 1), as totally opposite systems according to the type of connections, are also negligible, Table 4. This has been confirmed for all the analyzed building heights. Based on these results, it can be concluded, that the application of rigid connections in the systems that contain reinforced concrete shear walls in the form of the central core and reinforced concrete floor slabs, did not increase the lateral stiffness of the system, and also did not cause a significant reduction of the maximum horizontal deflection.

This is an important conclusion, because the design of joints in steel structures is a complex and time-consuming task. The type of connections has an impact not only on the static system of the structure and its behavior, but also on its economy. So, already at the stage of their design, an easy setup of basic elements and fast construction works should be provided. These requirements can be achieved only by using a simple supporting systems with hinged connections, whenever possible, which also allow the unification of beams in floors, standardization of joints in the structure and less consumption of steel. When rigid connections are in question, it is necessary to predict specific structural elements to ensure the transfer of the bending moment. Rigid connections are more complex and require higher consumption of steel and construction time.

Considering the established fact in this research, that rigid connections did not improve the lateral stiffness of the steel building structure, in the systems that contain reinforced concrete shear walls and floor slabs [24], the main conclusion of this paper can be drawn:

- The type of applied connections between the structural elements, rigid or hinged, as well as their different arrangement in the structure, has no significant influence on the lateral stiffness of the steel building structure, if the reinforced concrete core and floor slabs are considered in the structural design. Therefore it can be concluded that the
- Systems with hinged connections, because of their simplicity and other benefits stated in the paper, have significant advantage compared to the systems with rigid connections, for all the analyzed building heights, and they can be recommended for economical design.
- Contemporary calculation methods, based on FEM and engineering software enable reliable and relatively easy modelling and calculation of complex structural systems that include as line, as well as plate structural elements, and such modelling is highly recommended, since it gives more reliable and cost-effective steel structures, especially regarding the connections.

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ANALIZA 3D NUMERIČKH MODELA VIŠESPRATNIH ZGRADA KOJI SADRŽE MEĐUSPRATNE PLOČE I SMIČUĆE ZIDOVE U ZAVISNOSTI OD TIPA VEZA U ČELIČNOJ KONSTRUKCIJI

Višespratne čelične zgrade obično se projektuju sa krutim vezama između greda i stubova ili sa zglobnim vezama i sistemom za ukrućenje. Rad je fokusiran na 3D proračun višespratnih čeličnih zgrada koji uključuje međuspratne ploče i smičuće zidove. Primenjen je metod numeričkog modelovanja da bi se istražio uticaj krutih veza između određenih nosećih elelmenata na bočnu krutost višespratne konstrukcije, kada se pri proračunu uzimaju u obzir međuspratne ploče i smičući zidovi. Testirano je šest nosećih sistema koji imaju isti raspored elemenata u osnovi za četiri različite visine. Formirani su 3D numerički modeli u MKE softveru kako bi se procenila bočna krutost konstrukcija izloženih gravitacionom i seizmičkom opterećenju. U radu se prezentovani maksimalni horizontalni ugibi i periodi sopstvenih oscilacija. Zaključeno je da tip veza u višespratnoj čeličnoj konstrukciji nema većeg uticaja na bočnu krutost konstrukcije kada proračun uzima u obzir postojanje međuspratnih ploča i smičućih zidova.

Ključne reči: *višespratne zgrade, smičući zidovi, međuspratne ploče, bočna krutost veze, čelične konstrukcije*