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Static and Dynamic Analysis in Design of Exoskeleton Structure

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Abstract. This paper introduces a numerical experiment of creating the load bearing system of a high rise building. When designing the high-rise building, it is always an important task to find the right proportion between the height of the building and its perceptive width from the various angles of street view. Investigated high rise building in this article was designed according to these criteria. The load bearing structure of the analysed object consists of a reinforced core, plates and steel tubes of an exoskeleton. Eight models of the building were created using the spatial variant of FEM in Scia Engineer Software. Individual models varied in number and dimensions of diagrids in the exoskeleton. In the models, loadings due to the own weight, weight of external glass cladding, and due to the wind according to the Standard, have been considered. The building was loaded by wind load from all four main directions with respect to its shape. Wind load was calculated using the 3D wind generator, which is a part of the Scia Engineer Software. For each model the static analysis was performed. Its most important criterion was the maximum or minimum horizontal displacement (rotation) of the highest point of the building. This displacement was compared with the limit values of the displacement of the analysed high-rise building. By step-by-step adding diagrids and optimizing their dimensions the building model was obtained that complied with the criteria of the Limit Serviceability State. The last model building was assessed also for the Ultimate Limit State. This model was loaded also by seismic loads for comparison with the load due to the wind.

1. Introduction

For structural designers, there is a constant challenge of proper choice of structural systems of high rise buildings, to find optimal solutions, to assess their response to wind and seismic effects, etc. In the past, it was only possible to obtain such data about high rise buildings by means of substitute models like consoles, plane frames, etc. Presently the advanced computer technology enables us to create spatial computational models, which are very close to the real structures, as far as the load, structure, material and subsoil are concerned. By numerical experiment, e.g. step-by-step increasing of stiffness of elements, it is possible to obtain the optimal design of load bearing system of the building.

2. Models of the high rise building

Particular models of the high rise building were created by spatial variant of FEM using the Scia Engineer software. Eight models with different types of exoskeleton were made. The floor plan of high rise building is square shaped with dimension of one side 30 m. Two sides of the building taper towards the top along the height of the building. Resulting shape of the top floor is an irregular tetragon. The height of the building is the same in all models – 165.4 m; there are 44 above ground floors. The structural height of the single floor is 3.6 m except for first two above ground floors with structural height 7.4 m and one top technological floor with structural height 3.0 m. Vertical support system of the high rise building is created by reinforced concrete core with shear walls 300 mm thick (concrete C40/50) and the steel exoskeleton with various dimensions in particular models. Horizontal support structures are created by composite steel concrete slabs with thickness 200 mm (concrete C40/50). The external cladding of the building is supposed to be a curtain wall with thickness 200 mm and volume weight 300 kg/m^3. The dimensions and arrangement of the exoskeleton are different in particular models. All models were subjected to wind load from each side of the building in 90 angles. The wind load was calculated using the 3D wind generator, implemented in the Scia Engineer software. The structure had to be covered for creating the model envelope with particular areas, loaded by wind load in the 3D generator where the wind excitation on the model is simulated. After input of all data, the 3D wind generator calculated pressure coefficient of the external cladding and subsequently the planar load.

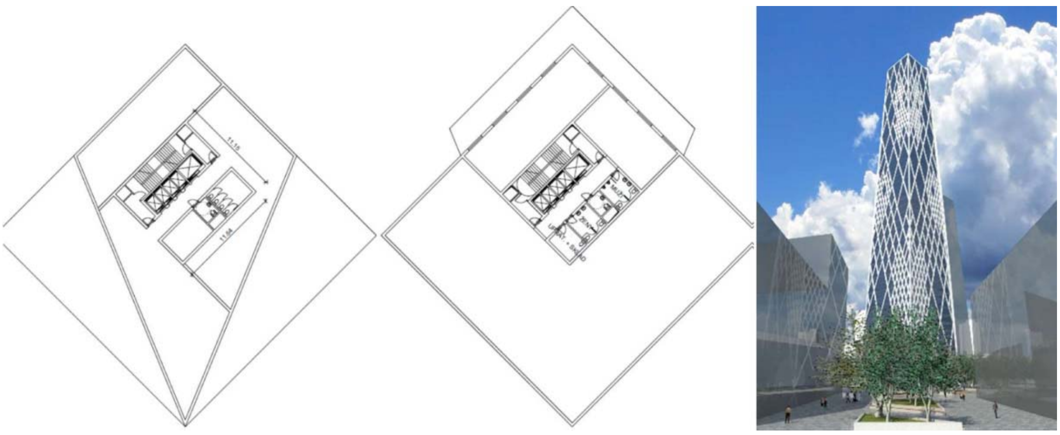

Figure 1. Top floor plan, ground floor plan, visualization according architectural study

Variant 1: High rise building with steel concrete coupled slabs and reinforced concrete core, see figure 2a.
Variant 2: Variant 1 with added columns in edges along the whole height of the building. The steel tubes with diameter 914/14.2 mm were used, see figure 2b.
Variant 3: According to the architectural proposal main diagonals of exoskeleton were added. In this variant tubes with diameter 508/10 mm in edges and tubes with diameter 244.5/10 mm for diagonals were used, see figure 2c.
Variant 4: Exoskeleton was modelled with steel tubes with diameter 762/12.5 mm in edges of the building and wall diagonals with diameter 355.6/12.5 mm, see figure 2c.
Variant 5: The same dimensions of steel tubes in edges (diameter 914/14.2 mm) as in Variant 2 were used, the diameter of wall diagonals used was 457/12.5 mm, see figure 2c.

Within the creation of high rise building's models, the value of limit deformations was monitored. Even in Variant 5 was not achieved the sufficient stiffness to resist the horizontal wind loads. The value of limit deformations was still exceeded. The investigation continued and other three models were created.

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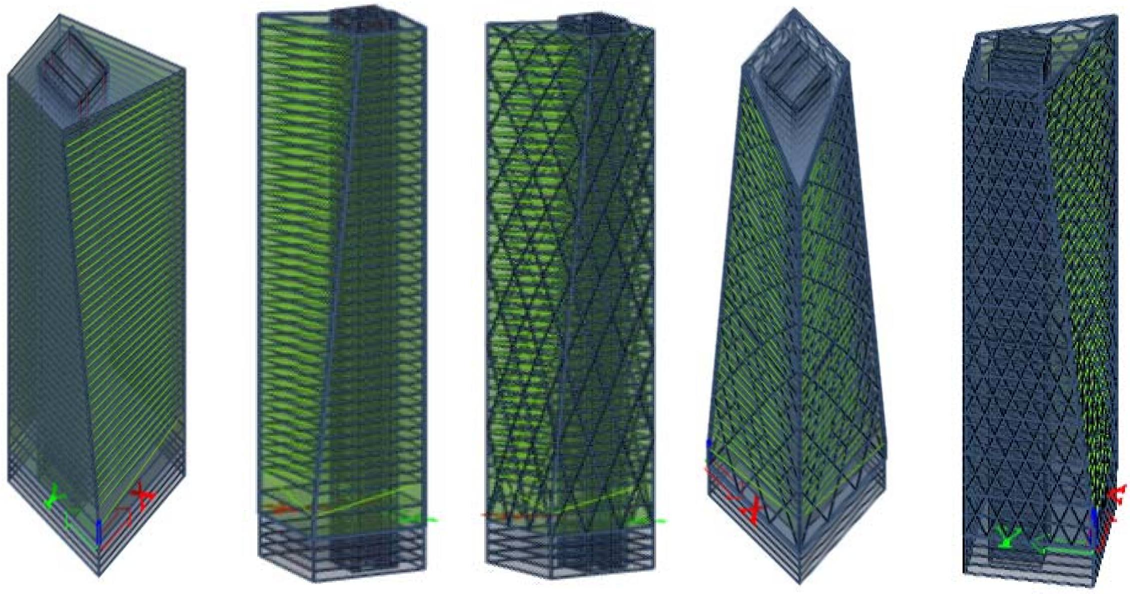
Variant 6: The stiffness of Variant 5 was increased by addition of further diagonals with diameter 457/12.5mm, figure 2d.
Variant 7: In this model all steel elements were used the same as in Variant 6, however the diagonals were more concentrated and situated in all arrays of the exoskeleton grid, see figure 2e. This model complied values of limit deformations.
Variant 8: In this model a massive coupled steel concrete column was placed between the reinforced concrete core and the most distant edge of the exoskeleton in the middle of the span. The purpose of this modification was the elimination of excessive displacement of the slab.



a) Variant 1 b) Variant 2 c) Variants: 3, 4, 5 d) Variant 6 e) Variant 7

Figure 2. Variants of spatial models

3. Static analysis

For static analysis the calculated and characteristic loads were determined [1]. Models of the high rise building were loaded by own weight of the structure, other permanent load and wind load [2]. Design situations for Limit Serviceability State and Ultimate Limit State were formed from combination of these loads. Scia Engineer Software with its component the 3D wind generator was used for modelling of wind load and wind effect's simulations.

Table 1. Maximal and minimal displacements and rotations of the top floor slab for all variants.

Variant	$u_{x,max}$ (mm)	$u_{x,min}$ (mm)	$u_{y,max}$ (mm)	$u_{y,min}$ (mm)	$u_{z,max}$ (mm)	$u_{z,min}$ (mm)	$\varphi_{x,max}$ (mrad)	$\varphi_{x,min}$ (mrad)	$\varphi_{y,max}$ (mrad)	$\varphi_{y,min}$ (mrad)	$\varphi_{z,max}$ (mrad)	$\varphi_{z,min}$ (mrad)
1	253.1	-72.1	84.5	-237.7	0.5	-70.8	7.0	-8.0	7.1	-8.0	1.4	-1.3
2	199.7	-69.7	79.6	-187.4	0.6	-58.2	7.0	-8.0	7.0	-8.0	1.4	-1.4
3	197.6	-69.5	79.5	-185.5	0.6	-56.8	6.4	-6.8	6.4	-6.8	1.1	-1.1
4	113.6	-10.0	17.9	-103.7	0.6	-50.2	5.7	-5.8	5.8	-5.7	0.8	-0.8
5	152.0	-64.3	72.2	-142.6	0.7	-45.5	5.7	-5.6	5.7	-5.6	0.9	-0.9
6	99.3	-10.0	17.1	-90.6	0.6	-45.6	5.4	-5.4	5.4	-5.4	0.7	-0.7
7	80.3	-14.7	21.3	-73.0	0.6	-40.2	5.1	-5.0	5.2	-5.0	1.1	-1.1
8	75.6	-19.2	25.9	-68.3	0.6	-37.2	4.0	-4.1	4.0	-4.1	0.9	-0.9

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4. Evaluation of horizontal displacements

The results of static analysis due to the wind effect are maximal and minimal horizontal displacements of the building. Results have been presented in table (table1) and figure 3, 4, with respect to wind direction and to particular displacements and rotations along the axes x, y, and z. The limit value of displacements must not exceed 1/2000 of building's height [3], in our case this value was 82.7mm.

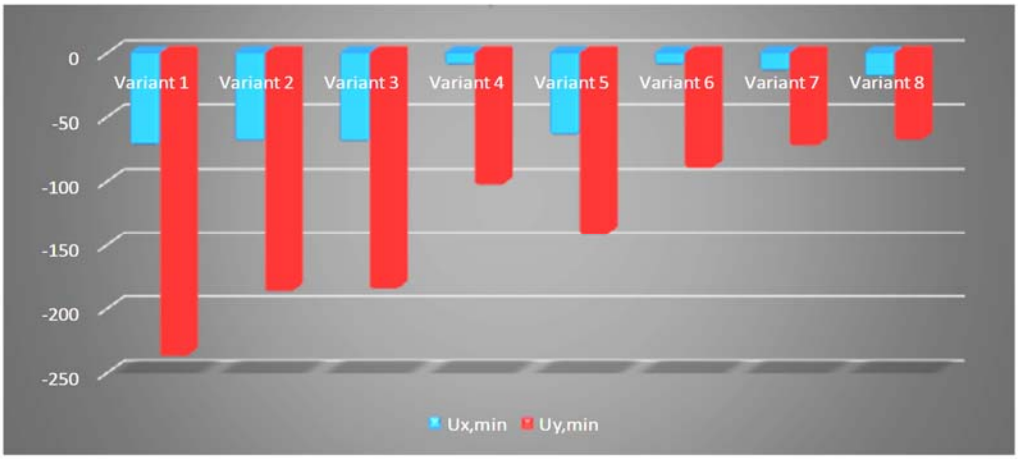

Figure 3. Minimal displacements of top floor slab for all variants

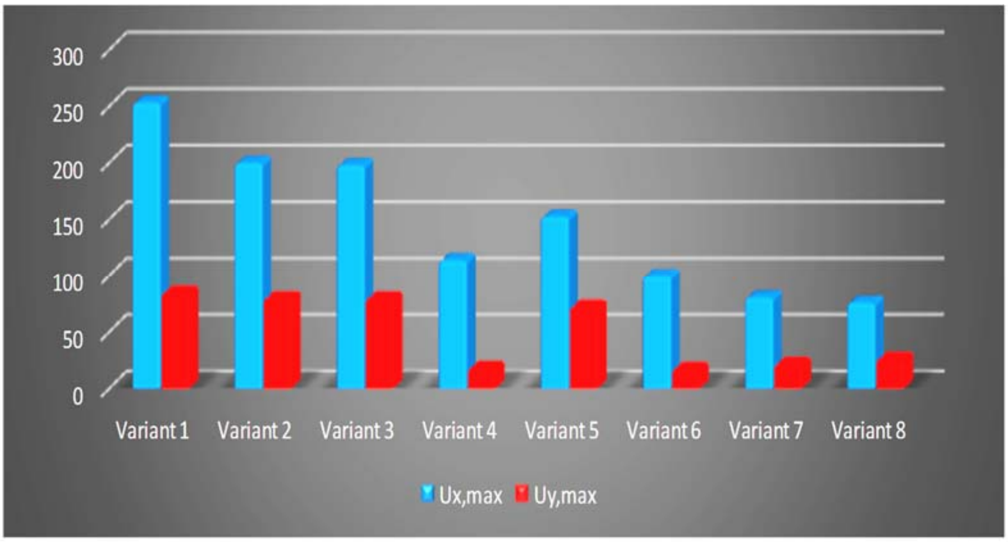

Figure 4. Maximal displacements of top floor slab for all variants

5. Dynamic analyses

Within the scope of investigation of the seismic response in Variant 8, eigenshapes of vibration as well as corresponding frequencies were analysed. 265 eigenshapes have been calculated. The amount of mass included to vibration formed 90% of total mass and frequency range was from 0 to 33Hz. Participation coefficient of Eigen modes is also important, denoting a ratio between the mass vibrating in corresponding eigenshape and the total mass. It is a basis for determination of dominant frequencies. These are: 1st and 2nd in *x* and *y* axis directions; and 7th frequency in *z* axis direction (table 2). Values of displacements were calculated in dynamic analysis with the combination of static and dynamic loads (seismicity effects), see figure 5. Maximum value of displacements in axis direction *x* is

41.7 mm and in axis direction *y* is 49.9 mm. These horizontal deflections were compared with the limit value *H*/500 [4], where *H* is defined as the total height of the structure from the foundation to the top (in this case *H* = 165.4 m and *H*/500 = 0,331 m).

Table 2. First 20 eigenfrequencies for Variant 8

N	**f (Hz)**	**ϖ (1/s)**	**ϖ^2 ($1/s^2$)**	**T (s)**	**N**	**f (Hz)**	**ϖ (1/s)**	**ϖ^2 ($1/s^2$)**	**T (s)**
1	0.32	2.02	4.08	3.11	11	4.72	29.66	879.72	0.21
2	0.34	2.15	4.62	2.92	12	4.85	30.50	930.20	0.21
3	1.46	9.17	84.10	0.69	13	4.87	30.61	937.25	0.21
4	1.59	9.97	99.31	0.63	14	4.93	30.98	960.04	0.20
5	1,63	10.24	104.83	0.61	15	4.96	31.16	970.68	0.20
6	3.41	21.45	460.03	0.29	16	4.99	31.37	984.01	0.20
7	3.51	22.06	486.82	0.28	17	5.02	31.51	992.93	0.20
8	3.77	23.68	560.73	0.27	18	5.04	31.68	1003.58	0.20
9	4.47	28.10	789.74	0.22	19	5.05	31.73	1006.92	0.20
10	4.68	29.43	865.87	0.21	20	5.07	31.87	1016.01	0.20

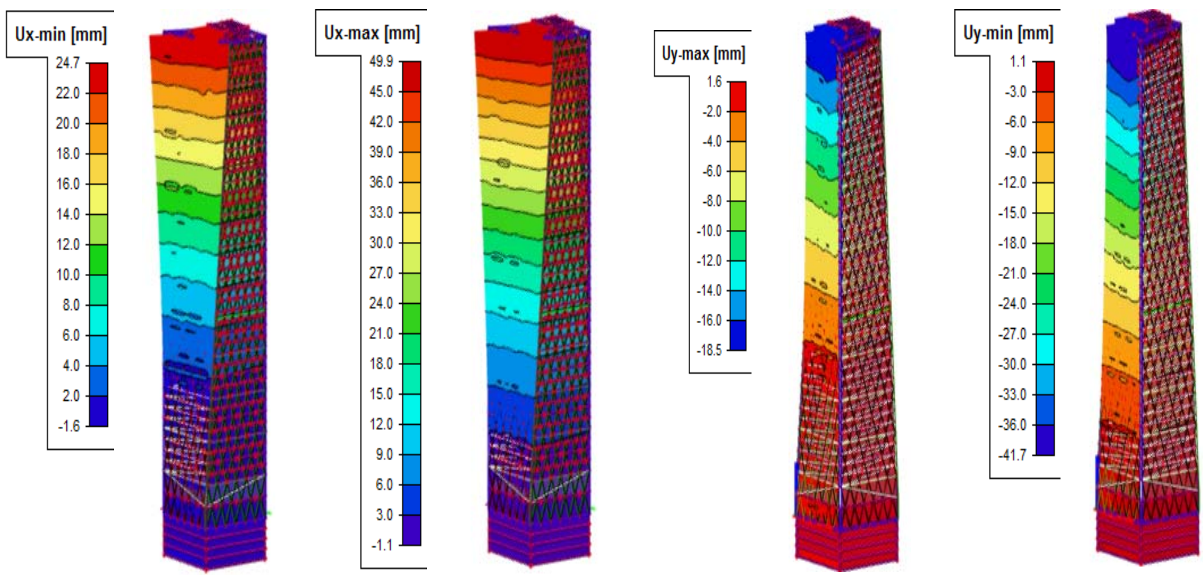

Figure 5. Maximal and minimal displacements for Variant 8

6. Results and discussions

It is obvious from the obtained results, that progressive modelling brought us to a proper design that complies with limit displacements. An improper design might cause over-limit displacement of higher floors and cause failures in external cladding: glass cracking and rain water leaks. Exoskeleton in Variant 7 contains the smallest number of steel tubes still being able to carry all loads acting upon the high rise building. The resulting reinforcement is sufficient from the static and dynamic viewpoints. Architectural design of the building according to figure 1 was achieved by inserting of further tubes. This has no effect on the load bearing capacity of the exoskeleton.

7. Conclusion

Exoskeleton, as a visible primary structural element of the building, affects the arrangement of façade: its density, scale, and configuration. Design of the exoskeleton requires close collaboration between architects and structural engineers in order to arrange the entire façade properly. The exoskeleton and

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minimal concrete core allow creating the column-free slabs to expand the usable space. Functional utilization of designed multipurpose high rise building can be arranged as a flexible open space, which can be modified according to individual needs of future tenants.

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