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The influence of wind on the work of the structure of columnar elements in reinforced concrete tall buildings

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ABSTRACT:
The methods of designing tall buildings are based mainly on the analysis of the influence of aerodynamic effects on the work of cross-sections of individual reinforced concrete elements: columns, slabs and beams. On the example of a building on a rectangular plan with dimensions of 36 × 60 meters and a height of 400 meters, a detailed analysis of the operation of selected reinforced concrete columns was carried out. Six models of buildings, differing in the location of internal walls as the concentration of the load-bearing structure, were analyzed. Static calculations with aerodynamic simulation were performed in Autodesk Robot Structural Analysis Professional 2022. On this basis, the final results were prepared and the most optimal layout of walls in tall buildings was selected.

KEYWORDS:
tall buildings; wind load; aerodynamic simulations

1. Introduction

Already in the years 1884-1885, the eleven-story Home Insurance Building was constructed in Chicago, designed by William LeBaron Jenney as an iron and steel structure. The building was demolished in 1931 (Fig. 1a).

In 1890-1994, attempts were made in Chicago to build the Reliance Building of considerable height (Fig. 1b). The building had 14 floors and was designed by Daniel Burnham. Restored in 1995 and now houses the Burnham Hotel. The first skyscraper of the Chrysler Building was built in New York in the first half of the 20th century, with a total height of 318.9 m and 77 floors (Fig. 1c). For this purpose, the skeleton system of the building was used, consisting of load-bearing elements (columns, beams, ceilings, internal walls and bracings), which was supposed to transfer permanent and variable loads (functional and climatic). The opening of the building took place in May 1930. A year later, the construction of the Empire State Building began, a skyscraper with a total height of 443.2 m (Fig. 1d).

The twentieth and twenty-first centuries are the time when the world-famous skyscrapers were built. The currently tallest Burj Khalifa building is located in Dubai, United Arab Emirates (Fig. 2a). Construction began on September 21, 2004 and was completed on August 16, 2009. The building is 827.9 meters high and has 163 floors.

In the Pudong district of Shanghai, China, there is the second tallest Shanghai Tower, 632 meters high. Construction started on November 29, 2008 and was completed in 2015 (Fig. 2b).

In the years 2004-2011, the Abraj al-Bayt hotel complex was built in Mecca, Saudi Arabia, the height of which is 559 meters (Fig. 2c). In the following years 2010-2016, Ping An Finance Center was built in Shenzhen, China, a building with a height of 599 meters. (Fig. 2d).

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From 2011 to 2017, the 129-story, 555.7-meter-high Lotte World Tower was built in Seoul, South Korea (Fig. 2e).

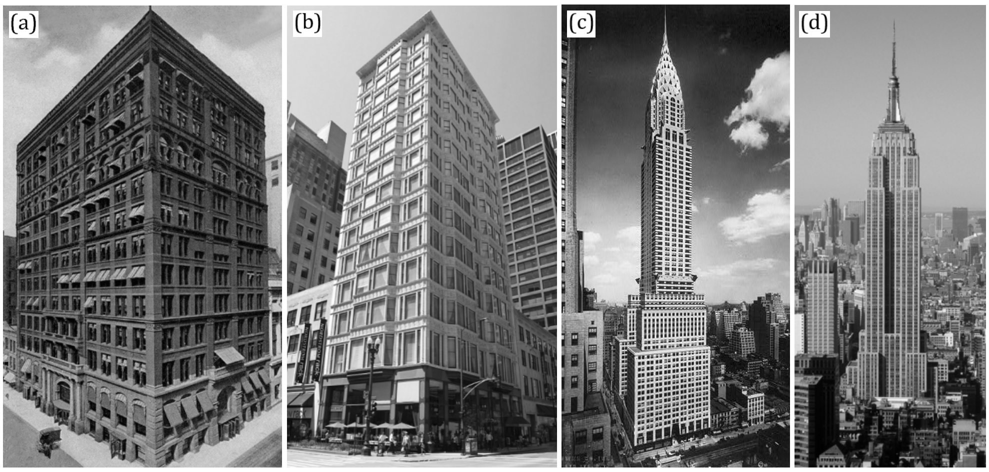

Fig. 1. First tall buildings: **a)** Home Insurance Building in Chicago [1]; **b)** Reliance Building in Chicago [2]; **c)** Chrysler Building in New York [3]; **d)** Empire State Building in New York [4]

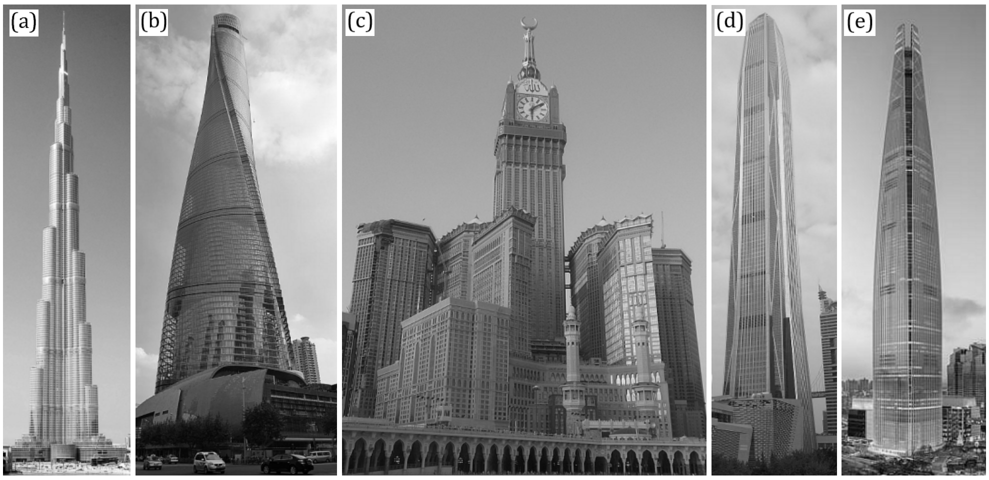

Fig. 2. The tallest buildings in the world: **a)** Burj Khalifa, Dubai – United Arab Emirates [5]; **b)** Reliance Building in Chicago [6]; **c)** Abraj al-Bajt hotel complex [7]; **d)** Ping An Finance Centre [8]; **e)** Lotte World Tower [9]

2. Characteristics of the analyzed building

The building was analyzed on a rectangular plan with dimensions of 36×60 meters and a height of 400 meters. The building has 100 storeys with a height of 4.0 meters each. The load-bearing elements are reinforced concrete columns, beams and slabs, which are ceilings with a thickness of 22 cm. The cross-section of the poles was diversified, i.e.

- 80×80 cm columns are adopted from the 1st to the 25th storeys,
- 70×70 cm columns are adopted from the 26th to the 50th storeys,
- 60×60 cm columns are adopted from the 51st to the 75th storeys,
- 50×50 cm columns were adopted from 76 to 100 storeys.

Reinforced concrete elements are made of concrete class C35/45 and reinforcing steel class "C" B500SP EPSTAL. The building is in the first wind load zone and the second snow load zone. According to [10] Tables 6.1 and 6.2, the building use category was assumed as C2, and on this basis the service load use equal to 4.0 kN/m^2.

The building is founded on a reinforced concrete grate connected monolithically with the foundation slab. The elements of the building bracing are 25 cm thick reinforced concrete walls arranged according to a specific scheme presented in Figure 3. The basic (base) system is a floor without internal FP-1 stiffening walls. The second variant of the building cross-section is FP-2 with a reinforced concrete core located in the central part of the building. Schemes FP-3 and FP-4 are the placement of reinforced concrete walls along the shorter and longer side of the building, respectively. The FP-5 diagram is a combination of the FP-3 and FP-4 diagrams. An alternative solution to bracing the building is to use reinforced concrete walls in the corners of the building – diagram FP-6. Six characteristic columns marked in Figure 3 as C-1÷C-6 were analyzed.

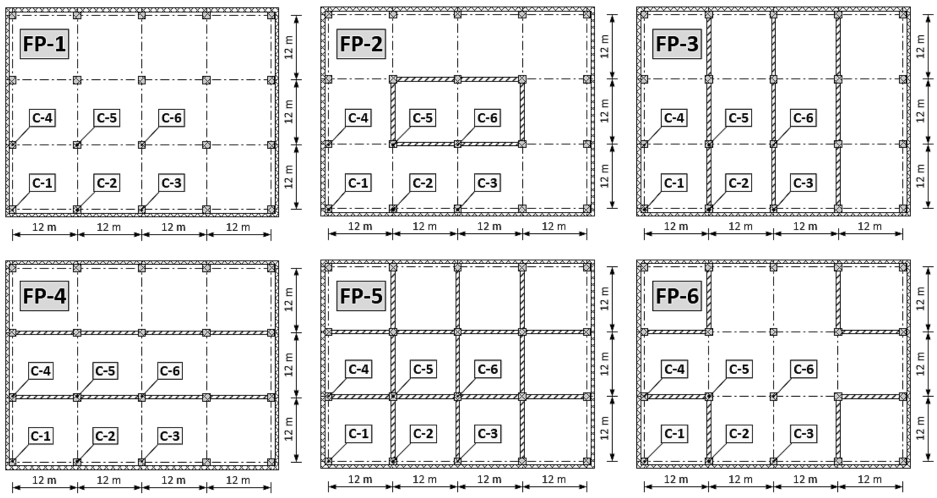

Fig. 3. Horizontal projections of the structural systems of a tall building: **FP-1** basic structural system without internal walls; **FP-2** structural system of the ceiling with a central reinforced concrete core; **FP-3** structural system of the ceiling with transverse walls (along the shorter edge of the building); **FP-4** structural system of the ceiling with longitudinal walls (along the longer edge of the building); **FP-5** structural system of the ceiling with transverse and longitudinal walls; **FP-6** structural system of the ceiling with corner walls

3. Analysis of the building's structural system

The building was modeled in Autodesk Robot Structural Analysis Professional 2022 as a shell model with bar elements of a beam and columns. The shell elements are external and internal walls and ceilings. Composite Delaunay meshing was used in static calculations. The view of the model is presented in Figure 4. Wrza with the division into elements and nodes of the separated columns C-1 to C-6. The permanent and service load applied to the ceilings were assumed to be surface loads. As the wind load, the aerodynamic simulation for the first wind zone was adopted, in which the wind affects the building from all sides. The self-weight of the structure elements was automatically generated in the program.

The analysis of the building structure was carried out for six variants (Fig. 3). The analysis compared the axial forces FX in the separated columns C-1 to C-6 in the building and the total deflection of the columns in characteristic sections. The characteristic sections are the places where the cross-sections of the columns change at the level of ±0.0; +100 m; +200 m; +300 m; +400 m.

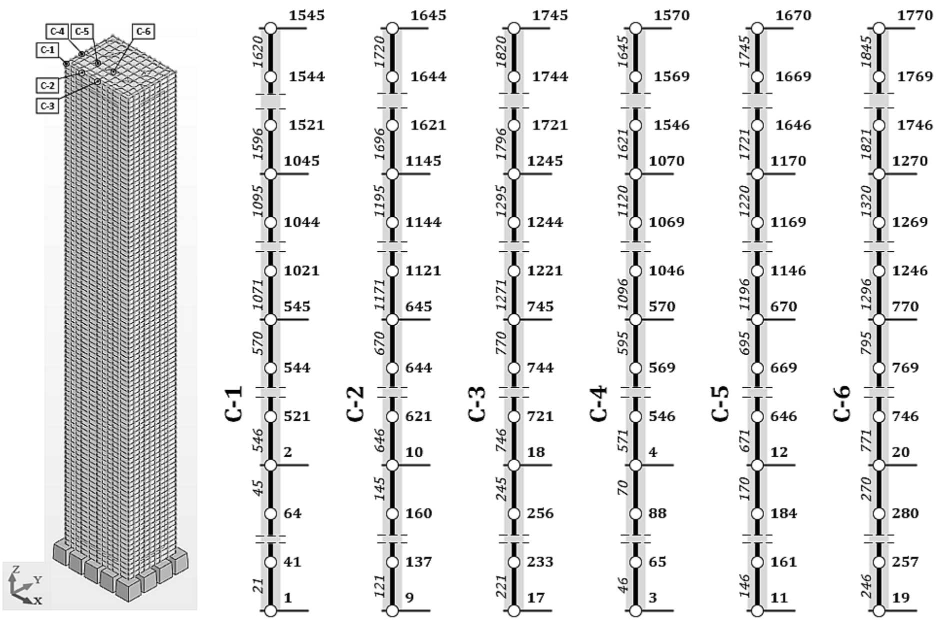

Fig. 4. Calculation model of a tall building. Place of the analyzed C-1÷C-6 reinforced concrete columns

Table 1
Calculation results of axial forces in individual C-1÷C-6 columns

Columns					Axial force FX [kN]					
Bottom node	No of bars	Top node	No of column	Cross section [cm]	PF-1	PF-2	PF-3	PF-4	PF-5	PF-6
1544	1620	1545	C-1	50x50	-84.78	-2.37	33.65	17046.00	20.64	-146.58
1045	1596	1521		60x60	4983.53	3535.41	3664.44	3821.02	2982.48	3873.85
545	1071	1021		70x70	13850.11	10056.06	10494.88	10979.83	8597.82	10526.15
2	546	521		80x80	26752.65	20060.14	21148.71	22155.89	17475.5	20629.58
1	21	41		80x80	103491.52	70774.56	75305.95	85103.77	64032.91	76822.94
1644	1720	1645	C-2	50x50	86.04	56.49	25.72	72.35	46.54	-20.27
1145	1696	1621		60x60	4932.22	3484.84	3583.01	3784.23	2915.08	3764.38
645	1171	1121		70x70	13794.2	9928.44	10265.34	10910.21	8462.03	10359.52
10	646	621		80x80	26815.28	19897.02	20744.94	22100.67	17269.59	20463.00
9	121	137		80x80	96825.37	69922.00	78153.86	82319.67	66759.81	86433.92
1744	1820	1745	C-3	50x50	94.04	51.59	44261.00	70.86	35.33	107.85
1245	1796	1721		60x60	4958.59	3500.04	3583.07	3790.21	2925.49	3785.13
745	1271	1221		70x70	13934.32	10010.49	10281.2	10963.54	8507.33	10565.52
18	746	721		80x80	27255.66	20158.07	20845.74	22280.58	17434.01	21075.51
17	221	233		80x80	99925.99	75557.72	79873.51	83907.94	70921.6	76168.14
1569	1645	1570	C-4	50x50	83.4	26.59	32.5	18.16	42.8	-22.18
1070	1621	1546		60x60	4936.27	3470.04	3609.8	3732.32	2912.79	3761.29
570	1096	1046		70x70	13839.98	9884.46	10377.85	10680.04	8377.12	10345.16
4	571	546		80x80	26953.15	19771.65	21003.51	21619.08	17075.55	20423.16
3	46	65		80x80	95338.92	69962.67	75215.45	84594.8	64572.84	87845.7
1669	1745	1670	C-5	50x50	468.69	100.22	-84.73	-154.94	-173.59	-69073.86
1170	1721	1646		60x60	18710.8	5307.08	3611.07	3800.19	2934.78	-4582.6
670	1196	1146		70x70	48030.94	15296.75	10341.52	10881.05	8360.06	23991.58
12	671	646		80x80	95798.2	31231.62	21119.27	22096.78	16955.07	63705.17
11	146	161		80x80	166587.92	110692.89	81903.77	84732.19	69603.71	129083.83
1769	1845	1770	C-6	50x50	600.79	-122.26	-160.31	-155.15	-184.34	-172.48
1270	1821	1746		60x60	23777.49	5170.69	3603.29	3754.3	2954.63	9372.99
770	1296	1246		70x70	61976.99	15106.07	10337.16	10973.04	8404.4	33246.76
20	771	746		80x80	124505.68	31107.00	21160.5	22266.83	17121.42	74973.04
19	246	257		80x80	208700.23	106205.27	82576.65	87618.88	72162.6	141346.87

Table 2
Results of deformation of tall columns depending on the analyzed model

Columns					Column top deformation u [cm]						Considered height storeys
Bottom node	No of bars	Top node	No of column	Cross section [cm]	PF-1	PF-2	PF-3	PF-4	PF-5	PF-6	H [m]
1544	1620	1545	C-1	50x50	42.4	35.7	30.0	40.6	29.9	31.5	400
1045	1596	1521		60x60	35.0	27.8	25.3	31.5	23.4	26.0	300
545	1071	1021		70x70	25.6	19.0	19.6	21.3	16.6	19.6	200
2	546	521		80x80	14.5	10.9	11.6	12.3	9.7	11.6	100
1	21	41		80x80	0.0	0.0	0.0	0.0	0.0	0.0	0
1644	1720	1645	C-2	50x50	42.8	35.8	30.5	40.7	30.0	31.8	400
1145	1696	1621		60x60	35.5	28.1	25.8	31.6	23.5	26.2	300
645	1171	1121		70x70	26.1	19.3	19.7	21.5	16.7	19.8	200
10	646	621		80x80	14.8	11.1	11.8	12.4	9.9	11.8	100
9	121	137		80x80	0.0	0.0	0.0	0.0	0.0	0.0	0
1744	1820	1745	C-3	50x50	43.2	36.0	31.0	40.8	30.1	31.9	400
1245	1796	1721		60x60	36.1	28.3	26.3	31.8	23.6	26.5	300
745	1271	1221		70x70	26.7	19.5	20.2	21.7	16.9	20.1	200
18	746	721		80x80	15.2	11.3	11.9	12.5	10.0	12.0	100
17	221	233		80x80	0.0	0.0	0.0	0.0	0.0	0.0	0
1569	1645	1570	C-4	50x50	43.4	36.5	30.5	41.6	30.6	32.3	400
1070	1621	1546		60x60	36.1	28.8	25.9	32.6	24.2	26.8	300
570	1096	1046		70x70	26.6	20.0	20.1	22.6	17.0	20.2	200
4	571	546		80x80	15.0	11.1	11.9	12.4	9.7	11.8	100
3	46	65		80x80	0.0	0.0	0.0	0.0	0.0	0.0	0
1669	1745	1670	C-5	50x50	112.6	45.7	31.2	41.8	30.7	34.4	400
1170	1721	1646		60x60	102.6	38.9	26.5	32.9	24.4	60.7	300
670	1196	1146		70x70	80.8	30.0	20.3	22.9	17.1	54.5	200
12	671	646		80x80	47.0	17.6	12.0	12.6	9.7	34.1	100
11	146	161		80x80	0.0	0.0	0.0	0.0	0.0	0.0	0
1769	1845	1770	C-6	50x50	143.3	45.9	31.6	41.9	30.8	81.0	400
1270	1821	1746		60x60	131.4	39.1	26.9	33.1	24.5	77.2	300
770	1296	1246		70x70	103.9	30.3	20.7	23.1	17.3	63.6	200
20	771	746		80x80	60.3	17.8	12.1	12.8	9.9	38.6	100
19	246	257		80x80	0.0	0.0	0.0	0.0	0.0	0.0	0

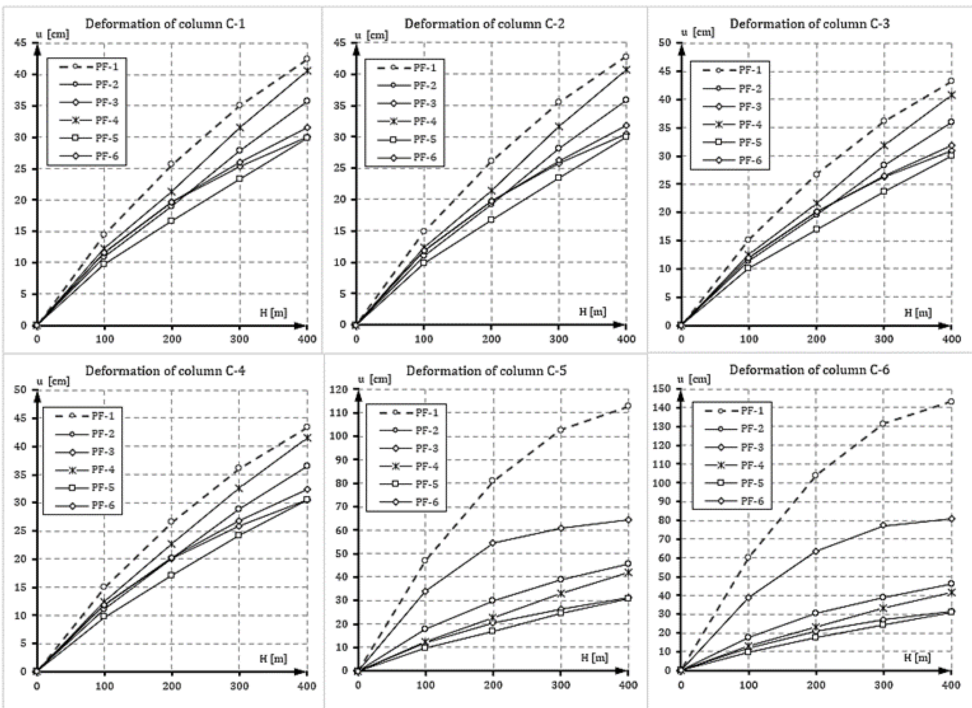

Fig. 5. Graphical presentation of the results of deformation tall building's columns, depending on the analyzed model

The results of the analysis are presented in Tables 1 and 2 and graphically in Figures 5, 6. Based on the values of the axial forces FX, it is possible to estimate the optimal cross-section of the columns on individual levels. Knowing the deflection of the tops of the columns in the building, it is possible to assume the optimal arrangement of bracings of internal walls in the building. The permissible deflection of tall buildings in accordance with [11] is H/500, which for the analyzed object is $\mathbf{u_{lim} = 40000/500 = 80\ cm}$.

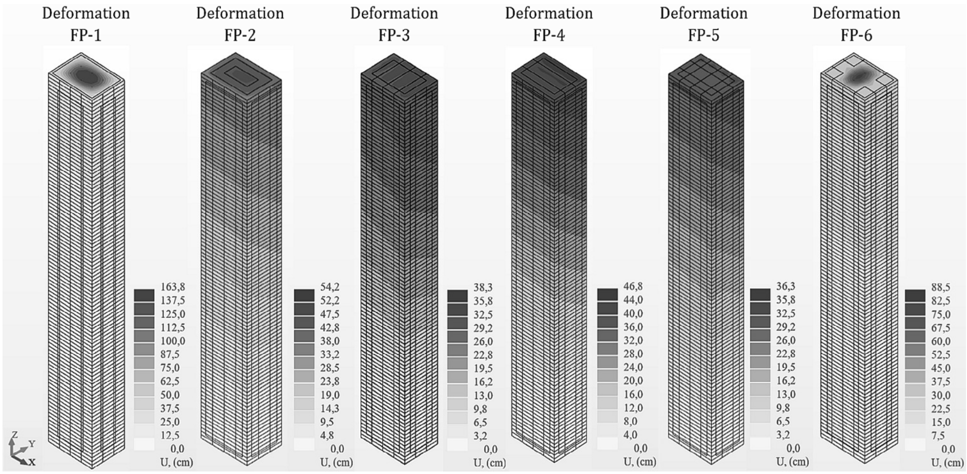

Fig. 6. The results of deformation of the tall building depending on the analyzed model

Table 3
The results of deformation of C-1÷C-6 columns in tall buildings are presented in [%] depending on the arrangement of internal walls (Fig. 3)

No of column		Column top deformation $\delta = u/u_{lim}$ [%]					u_{lim} = 80 cm
		PF-1	**PF-2**	**PF-3**	**PF-4**	**PF-5**	**PF-6**
external colums	**C-1**	53,0	44,6	37,5	50,8	37,4	39,4
	C-2	53,5	44,8	38,1	50,9	37,5	39,8
	C-3	54,0	45,0	38,8	51,0	37,6	39,9
internal colums	**C-4**	54,3	45,6	38,1	52,0	38,3	40,4
	C-5	140,8	57,1	39,0	52,3	38,4	80,5
	C-6	179,1	57,4	39,5	52,4	38,5	101,3

4. Conclusion

The main aim of the article was to show the influence of the arrangement of internal walls in the building (Fig. 3) on the size of internal forces in selected columns (Fig. 4) according to ULS and deformation of these elements (Fig. 6) according to SLS. The geometric parameters of the building (width, length, height and number of storeys) have been selected in accordance with the guidelines applicable to the design of high-rise buildings. The location of the building was selected for the first wind load zone and the second snow load zone.

The analysis of the building's operation (mainly columnar elements), in which a detailed areodynamic simulation in all directions was taken into account, showed:

– The share of columns in operation of the entire building is dominant and the values of the compressive axial forces and the final deformation depend on the location of the columns (Fig. 4) and the dimensions of the columns on individual storeys directly depend on the arrangement of internal walls in the building (Fig. 3). The C-6 splitter in the PF-1 diagram is the most loaded and the lowest axial force FX is in the C-1 column in the PF-5 diagram (Table 1).

- The arrangement of internal walls, constituting the bracing of the entire building, has a significant impact on the operation of the entire tall building. In the absence of internal walls (FP-1 diagram), the value of axial forces FX in internal C-4÷C-6 columns increases from **196.5** to **289.2%** compared to systems with internal walls (FP-2÷FP-6 diagrams). In the C-1÷C-3 external columns it increases from **119.1** to **140.9%**.
- Due to the arrangement of internal walls in the building, the optimal solution is to use walls in the longitudinal and transverse directions (FP-5 diagram). The lack of internal walls (PF-1 diagram) and the use of walls only in the corners of tall buildings (FP-6 diagram) is an insufficient solution for the operation of the structure. Removal of transverse or longitudinal walls increases the value of forces in individual columns.
- The displacement of the top of the C-6 internal column in the PF-1 diagram is exceeded by **179.1%**, which suggests an insufficient solution due to the lack of bracing of the building with internal walls (Table 3).
- The optimal solution is the PF-5 scheme with the longitudinal and transverse arrangement of internal walls, in which the maximum displacements constitute **37.6%** of the permissible value for the C-3 outer column and **38.5%** of the permissible value for the C-6 inner column (Table 3).

In conclusion, constructions of the column and beam skeletal systems, which are devoid of internal walls constituting the concentration of the entire high building, should not be used.

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Wpływ oddziaływań wiatru na pracę konstrukcji elementów słupowych w żelbetowych budynkach wysokich

STRESZCZENIE:

Sposoby projektowania budynków wysokich opierają się głównie na analizie wpływu oddziaływań aerodynamicznych na pracę przekrojów poprzecznych poszczególnych elementów żelbetowych: słupów, płyt i belek. Na przykładzie budynku na rzucie prostokąta o wymiarach 36×60 metrów i wysokości 400 metrów, przeprowadzono szczegółową analizę pracy wybranych żelbetowych słupów. Analizie poddano 6 modeli budynków różniących się między sobą położeniem ścian wewnętrznych jako stężenia konstrukcji nośnej. Obliczenia statyczne wraz z symulacją aerodynamiczną wykonano w programie Autodesk Robot Structural Analysis Professional 2022. Na tej podstawie opracowano wyniki końcowe i wybrano najbardziej optymalny układ ścian w budynkach wysokich.

SŁOWA KLUCZOWE:

budynki wysokie; obciążenia wiatrem; symulacje aerodynamiczne