MODERN COMPUTER METHODS OF MULTIVARIANT ANALYSIS OF A TALL BUILDING

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Summary:
At the beginning of this material to familiarize the reader with the definition of a high building and shows how modern, dynamically developing urban centers and with their growth, increasing the demand for housing high. This is confirmed by the examples presented in the article, the tallest buildings in the world. In this paper we present a variant static analysis of building construction high. It was carried out on the computational model described in point. 2 Calculations were performed in Autodesk Robot Structural Analysis 2012. In the first embodiment focuses on the calculation adopted discretization effects. The analysis was four computational models vary in terms of the finite element shape (square or triangular) and the maximum dimension of the finite element (0.50 m or 1.00 m). We analyzed the behavior of the structure according to the modeled subsoil on which it was set. In this variant, have been studied in two models of the object. In one model was taken into account susceptibility of the ground, while the second vulnerability is omitted and assumed the rigid connection. Another important problem that the stiffness of the building is analyzed, namely the effect of increasing stiffness are located inside the object individual components. Another element that was tested in the calculation of their time and memory occupation. In the last paragraph of articles presents the results of analyzes with figures obtained from the calculation. Selected elements more fully described in the tables. Analysis results were compared with each other and makes appropriate proposals, which were presented in the results of the subsequent variants of the analysis.

Keywords: high building, finite elements, discretization

Introduction

In this work, a multivariant analysis of a tall building, which is more and more common in the urban development, is presented. The definition of a tall building is a controversial issue and generally it is considered to be a building with more than several levels. In accordance with the Order of the Minister of Infrastructure of 12 April 2002 regarding the technical requirements that must be met by the buildings and their location [6], the buildings are classified into the groups in terms of height in order to determine the technical and usage requirements:

- low buildings – up to and including 12 m above the ground level or housing buildings with a height of up to and including 4 above-ground levels;
- mid-low buildings – from above 12 to and including 25 m above the ground level or housing buildings with a height of above 4 up to and including 9 above-ground levels;
- tall buildings – from above 25 up to and including 55 m above the ground level or housing buildings with a height of above 9 up to and including 18 above-ground levels;
- high-rise buildings – from above 55 m over the ground level.

Since tall buildings are used as office or residential blocks, the service loads are not high. However, one of the basic issues is their foundation - the transfer of very high total loads to the ground. As a solution, the foundation is usually a stiffened slab or reinforced concrete box that transfers the pressure to the ground and prevents an uneven foundation of the structure. The other equally important issue is to ensure the appropriate stiffness of the structure, its protection against the effects of operation of horizontal loads (caused by the wind pressure as well as seismic and para-seismic forces). This stiffness is achieved through a proper structure of the building, use of vertical and horizontal membranes – plates formed by walls, cores, pillars and ceilings. There are plenty of unique construction solutions for tall buildings but the most common should be considered the monolithic framework with a stiffened core usually used as a passageway or installation path.

Despite the hardships and costs related to the design and operation of tall buildings, these are erected more and more, with Poland being no exception. Tall buildings ceased to be the pride of rich shopping malls and became the omniscient type of housing and office blocks. Due to the development of conurbations, which entailed the reduction of land for development, the demand for tall buildings has grown. Such buildings have many advantages, such as: housing of a substantial amount of people and large usable area on are latively small portion of land.

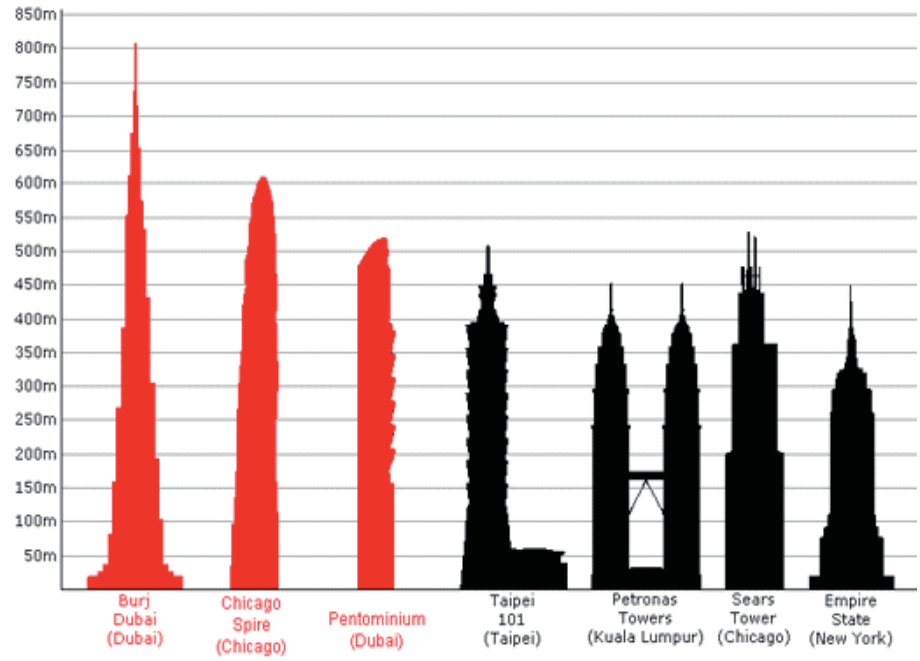


Fig. 1. Classification of the tallest buildings in the world

The examples of tall buildings can be easily found in every larger city. The tallest building in the world is Burj Khalifa in Dubai, the United Arab Emirates. The building has a height of 829 m and boasts 163 service levels. The general appearance and design of the tower reflects the character of the flower of desert and the Islamic architecture (ornaments, decorations, etc.). This tower block consists of the central core and 3 "arms" –the higher the height of the block, its "arms" get smaller, making the block slender and having necessary aerodynamics. On the very top, the central core goes into a spire that finishes the building. The second tallest building in the world is Abraj Al Bait, located in Mecca, Saudi Arabia. This complex of buildings, completed in 2012, has a height of 601 m. It holds several world records: it is the tallest hotel in the world and has the tallest clock tower with the largest clock face. The third tallest building is the famous Taipei 101, the skyscraper with a height of 509.2 m and 101 levels, located in Taiwan. It is also the first building in the world to exceed the height of half a kilometre. It was commissioned in 2004, thus, taking away from Petronas Towers in Kuala Lumpur the title of the tallest building. The greatest challenge was to protect Taipei 101 against earthquakes. This was even harder since at the distance of 200 m from the building is a 10-cm wide tectonic offset. For Taipei 101 to be able to sustain the quakes, the engineers designed a massive structure. The internal core of the building is connected with eight external columns through a net of horizontal trusses. The columns are the backbone of the building allowing its inclination as needed but protecting from fracture. Each building section is independent to other, transferring the weight of the building from external portions towards inside. This idea has already been put in practice but the supporting columns have not been so large ever. The "competition" for the tallest building in the world is still underway. Presently, in Saudi Arabia, the construction of Kingdom Tower is being prepared, the height of which is to exceed one kilometre, while in the United Arab Emirates, a giant with a height of up to 1 mile is planned to be constructed. We may wonder how high are the limits of human capability.

The static analysis of buildings of this type uses the method of folded cantilevers, equivalent frame method, coefficient methods or more universal method of finite elements in computer implementation.

Today, we can use multiple software to perform calculations, design, drawing of the structure, which in combination with the efficiency of the modern computer equipment makes that the time needed to calculate and even design of the majority of types of structures that are common in the engineering practice boils down to a few or several minutes of work. Most time consumes the preparation of the calculation model for analysis. This allows for the projection of the actual structure in the calculation model in the manner as accurate as possible and the possibility not to use a series of simplifications, as well as the long-hour solving of mathematic equations. The problem is, however, in the correct formulation of the calculation model of a structure to be able to obtain as reliable results as possible. Even a seemingly small change in the calculation model can give completely different results of the static analysis of the discussed issue.

Description of the analysed building

The analysed object is a tall, 15-level building, designed based on the monolithic technology of the mixed slab and column construction with a core. Each of the nine levels of the housing part has six flats. The building also has five levels for service and office use, on the 5. floor is a café with a viewing terrace, while the first level is the basement located under the whole area of the object. In the central part of the object is the core with the walls having a thickness of 30 cm, which serves as a passageway. The top of the building is finished with a green flat roof, which is to be the viewing terrace. On the circumference of each level is an edge beam with a rectangular cross section of 35cm x 60cm as functioning in a continuous arrangement. The ceiling slabs are designed as monolithic with a thickness of 20 cm, supported by the columns with a square cross section of 60 cm x 60 cm. The thickness of the flat root slabs was increased to 25 cm due to the higher load operating. The foundation is a monolithic reinforced concrete slab with a height of 1.00 m. Figure 2 shows the view and cross-section of the analysed building.

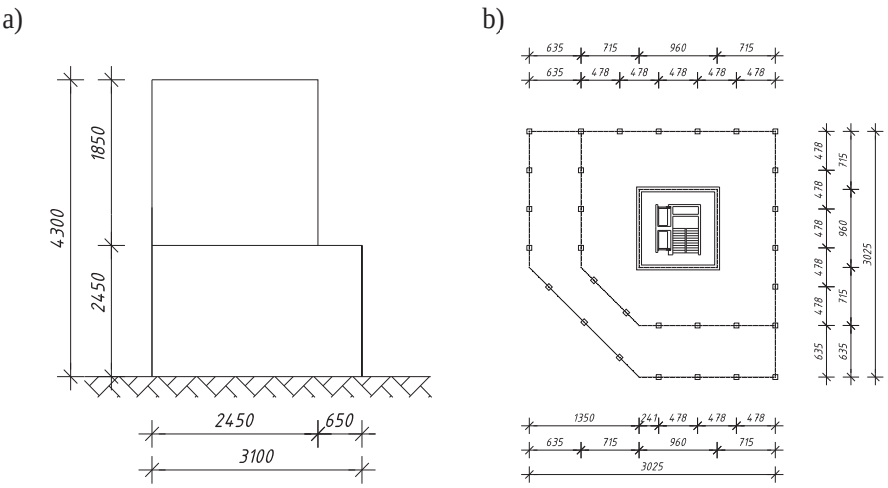


Fig. 2. Analysed tall building a) vertical cross-section b) office level view

Multivariant static analysis of building's structure

In this work, we will present the multivariant static analysis of the structure of the above-described tall building. The calculations were performed in Autodesk Robot Structural Analysis 2012. Robot is an integrated graphic software for modelling, analysis and design of various types of structure. This software allows for modelling of a structure, static calculations, verification of the results, norm calculations of the elements of a structure and creation of a construction documentation.

In the first variant of calculations, the focus is one the impact of the adopted discretisation (shape and size of finite elements). In each of the analysed cases, the complex discretisation in the form of Delaunay + Kang was adopted. The Delaunay triangulation method can be used to form a net of finite elements for any flat surface. If the Kang method is selected, the net will

be generated only near the emitters (user-defined points around which the net is condensed) according to the set parameters. The combination of these two methods means that around these emitters the net will be formed with the Kang method and outside these areas with the Delaunay method. Four calculation models were adopted for analysis, diversified in terms of shape of finite elements (quadrangular or triangular) and maximum size of the finite element (0.50 m or 1.00 m). The net was condensed twice in the points of concentration of stresses, i.e. in edges and support nodes, to the size of a finite element, that is, to 0.25 m or 0.50 m, respectively. Ultimately, in the analysed calculation model the following finite elements were adopted:

- quadrangular with a maximum size of 0.50m;
- triangular with a maximum size of 0.50m;
- quadrangular with a maximum size of 1.00 m;
- triangular with a maximum size of 1.00 m;

Figure 3 below shows the net with quadrangular elements with a maximum size of the element of 1.00 m.

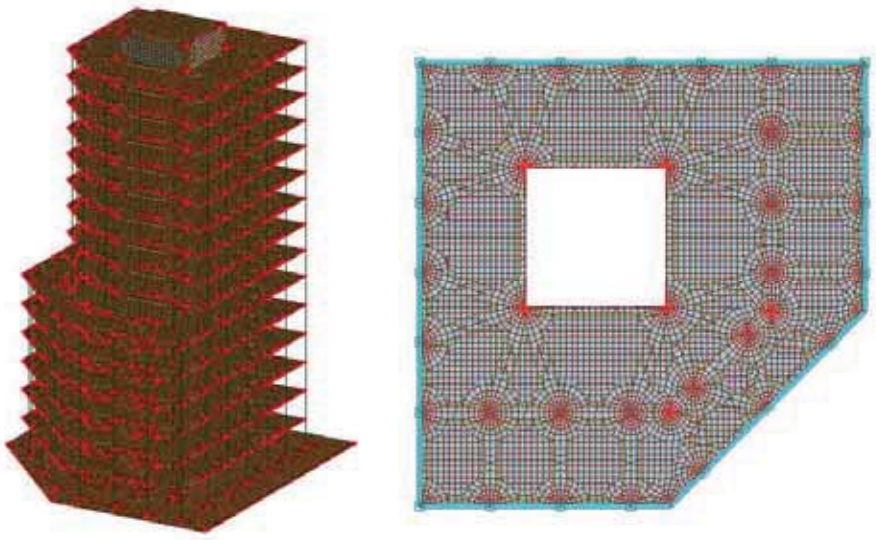


Fig. 3. Adopted discretisation in the calculation software

In the table below the main characteristics is shown for the sizes of the calculation models:

Tab. 1. Characteristics of the calculation models

DISCRETIZATION	quadran. 0,50m	trian. 0,50m	quadran. 1,00m	trian. 1,00m
NUMBER OF NODES	23873	63892	23873	63892
NUMBER OF RODES	732	732	732	732
NUMBER OF AREA	149	149	149	149
NUMBER OF ROD FINITY ELEMENTS	4362	4362	4362	4362
NUMBER OF AREA ES	68227	100575	68227	100575

The behaviour of the structure as a function of the modelled subgrade, on which it was founded, was analysed as well. In this variant, the two models of the above-described object were put to analysis. Both of them were modelled on a square base plate with a length of sides of 10.00 m and a height of cross-section of 1.00 m, with the susceptibility of the subgrade considered in one of them and omitted in the other, where a stiff joint was used. The results of this analysis are shown in the next section of this work.

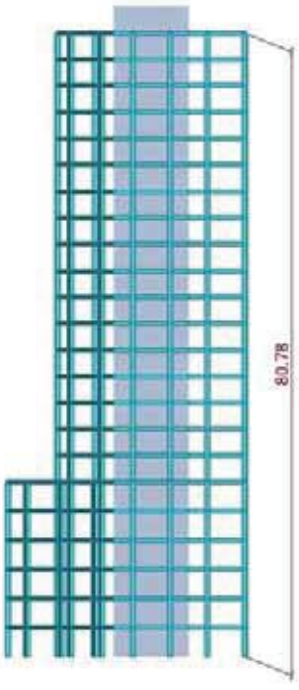


Fig. 4. Analysed building view

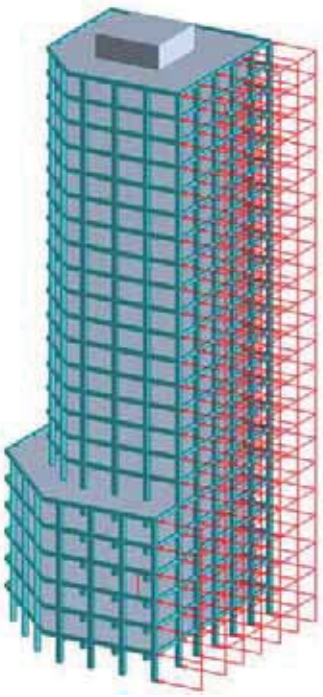


Fig. 5. Wind load on the structure

The next important issue that was analysed is the stiffness of the building. For the purpose of this analysis, the height of the building was increased from 43 m to 80 m (Fig. 4). The building was loaded equally distributed load with a value of 30 kN/m, operating horizontally on the columns and beams situated in the plane of one façade, which is shown on Figure 5.

Initially, the building designed without the walls inside the core was analysed, as shown on Fig. 6 below.

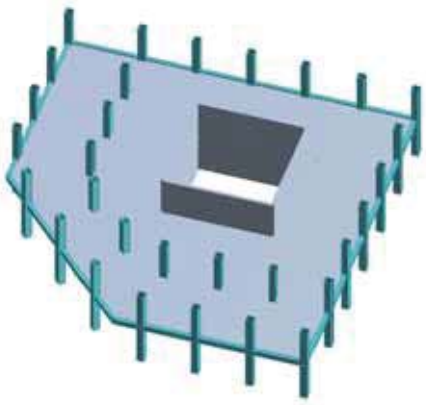


Fig. 6. A level of the analysed building (variant 1) with all the structure elements

The second variant of the structure adopted for calculations has an additional stiffening in the form of walls dividing the inside of the core. The purpose of this analysis is to examine how these walls affect the inclination of the building and hence, the stiffness of the structure. The inserted walls are shown on Fig. 7.

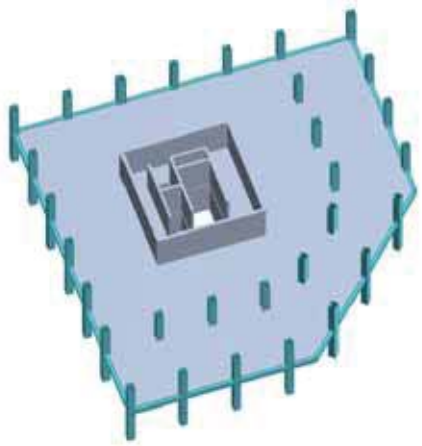
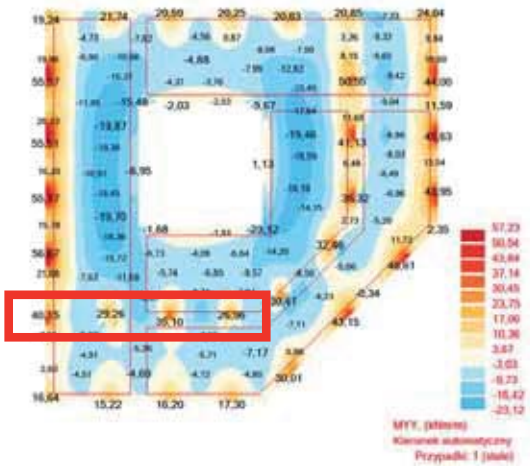


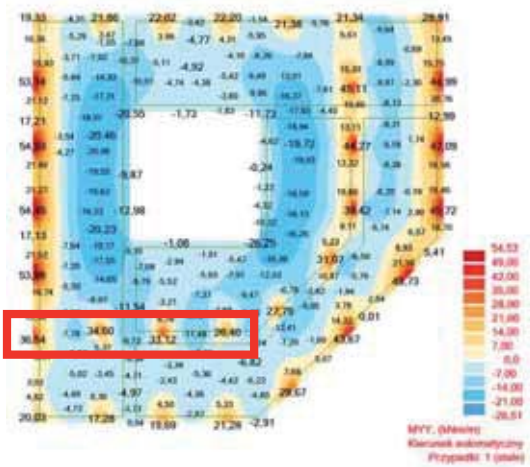
Fig. 7. A level of the analysed building (variant II) with all structure elements

Comparisons and final conclusions

After the static calculations were made, the values of internal forces in the analysed structure with a height of 43 m were obtained. For comparison purposes, the figures below show the maps of bending moments caused by dead loads with various shape and size of finite elements. As can be seen, the description of the structure significantly affects the obtained results. The comparison of the results is shown in Table 2.

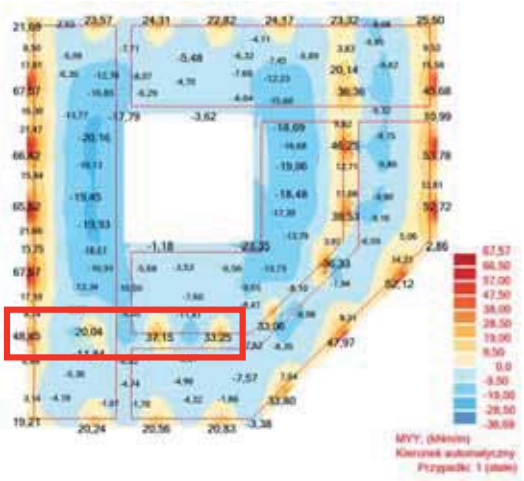
a) Quadrangular elements





Triangular elements

b) Quadrangular elements



Triangular elements



Fig. 8. Maps of bending moments M_y in the analysed ceiling plate; a) dimension of the net element 0.50 m; b) maximum size of the net element 1.00 m.

Tab. 2. Comparison of the obtained values of bending moments in the analysed internal field marked with a frame on Fig. 8.

TYPE FINITY ELEMENTS	support A [kNm]	span 1 [kNm]	support B [kNm]	span 2 [kNm]	support C [kNm]	span 3 [kNm]	support D [kNm]
Quadran. 0,50m	40,15	8,53	29,26	9,67	35,10	9,21	26,96
Trian. 0,50m	36,54	7,78	34,60	9,73	33,12	11,48	26,40
Quadran. 1,00m	48,45	9,56	20,04	9,91	37,15	11,68	33,25
Trian. 1,00m	39,43	9,01	21,49	9,99	35,97	10,93	37,54

The analysis of the structure of a tall building is significantly affected by its deformation due to the vertical and, for the most part, horizontal loads. As it has already been mentioned, the foundation of such a building is of great importance. Below are the results of the analysis of deformation of the structure of a tall building with consideration of the susceptibility of the subgrade, with the full stiff restraint of the base plate. On the figures below marked are the maximum values of the net vector of vertical and horizontal dislocation of nodes, where the dislocations are extreme. The table below shows extreme dislocations towards the axes x, y, z depending on the type of finite elements in a low building.

Tab. 3. Extreme dislocations of nodes in the model with consideration of susceptibility of the subgrade

	UX (cm)	UY (cm)	UZ (cm)	RX (Rad)	RY (Rad)	RZ (Rad)
MAX	0,4	1,6	-0,4	0,003	0,003	0,000
Nod	22132	22140	10234	15062	15140	19253
MIN	-1,7	-1,0	-3,7	-0,003	-0,003	-0,000
Nod	22128	22092	15150	15478	15550	18705

Tab. 4. Extreme dislocations of nodes in the model without consideration of susceptibility of the subgrade

	UX (cm)	UY (cm)	UZ (cm)	RX (Rad)	RY (Rad)	RZ (Rad)
MAX	0,1	0,3	0,0	0,003	0,003	0,000
Nod	21988	22145	310	5889	15400	15057
MIN	-0,3	-0,1	-1,3	-0,003	-0,003	-0,000
Nod	22121	22228	15146	15304	5712	15228

a)



b)



Fig. 9. Deformation of the object a) with consideration of susceptibility of the subgrade b) with a stiff restraint of the base plate

The fig. 9 shows the deformations of the structure due to the susceptibility of the subgrade. As it can be noted, the structure elements of the designed tall building are subject to much greater deformations assuming the susceptibility of the subgrade under the foundation.

As implied by the performed analyses, the size of the finite elements affects the accurate determination of the result of calculations. It is noted that at the greater size of the elements, the moments are greater as well. The size of the calculation elements should be selected not to allow the values of the forces operating in the structure exceed 5% [2]. The greater size of the finite element causes less accurate results and greater deviation, therefore the smaller size of finite elements should be used. Thus, the selection of the correct size of the element depends on the accuracy of the projected results and reasonable condensation of the partition net, which afterwards, affects the calculation time and transparency of results. Based on these results of calculations, we also found that the shape of the element does not affect that much the results of bending moments as obtained here.

Below are the results of two variants of analysis of stiffness of a tall building. Variant I does not consider the walls inside the central core of the building, and variant II was analysed with vertical partitions modelled, located inside the passageway. Table 2 shows the results of maximum dislocations of nodes caused by the applied operational and wind load.

Tab. 5. Maximum dislocation of structure nodes (variant I)

	UX (cm)	**UY (cm)**	**UZ (cm)**	**RX (Rad)**	**RY (Rad)**	**RZ (Rad)**
MAX	0,4	0,5	1,9	0,003	0,003	0,000
Nod	49423	49458	44900	26436	38539	241
MIN	-25,4	-0,4	-1,9	-0,003	-0,004	-0,000
Nod	49609	49604	38612	38318	26259	502

Tab. 5. Maximum dislocation of structure nodes (variant II)

	UX (cm)	**UY (cm)**	**UZ (cm)**	**RX (Rad)**	**RY (Rad)**	**RZ (Rad)**
MAX	0,4	0,5	1,8	0,003	0,003	0,001
Nod	49423	49458	44900	26436	38539	241
MIN	-24,6	-0,5	-1,8	-0,003	-0,004	-0,001
Nod	49609	49604	38612	38318	26259	502

UX dislocations are horizontal dislocations parallel to the operation of wind pressure, UY – horizontal dislocations perpendicular to the operation of wind pressure, UZ – vertical dislocations. As can be read from Table 2, subject to the greatest horizontal dislocation is the node no 49609, which was marked on Figure 4 below. The dislocation obtained is quite significant and exceeds the permissible standard deviation, however, it is done on purpose through the increase of a height of the building and the value of the horizontal load operating on the structure to make the difference between variant I and II more noticeable.

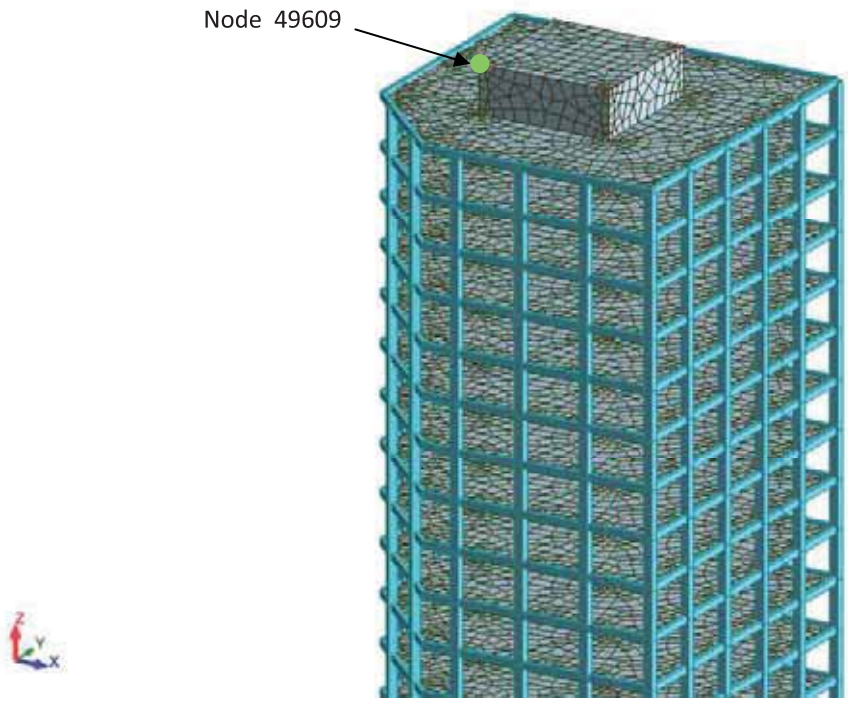


Fig. 10. The node subject to greatest dislocation

By comparison of the results obtained from two variants of analysis of stiffness of the building, it was found that the greatest stiffness in the analysed tall building is achieved by the columns designed on the external circumference of the object, having a significantly greater moment of inertia due to their position against the centre of gravity of the horizontal view of a building's level. Additional stiffness is achieved by the core designed at the centre of the object, while the vertical partitions in the inside of the structure indeed provide extra stiffness but not that much. After the insertion of additional walls to the model, the maximum dislocation of a node decreased by just 0.3 cm.

The additional element tested during the measurements was their duration and usage of memory. As already mentioned, with the today's equipment and software available, the effect of these two factors on the design of the structure is virtually negligible. The time needed to carry out the measurements for the above-described analyses was around 8 minutes, and the usage of memory – around 135000000 B. The recorded time values obviously do not consider the time used for modelling of this structure in the calculation software, where it is as long as from a few to several days depending on the complexity of the structure.

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