Application of Numerical Methods for the Analysis of a Concrete-Steel Tower Subjected to Multiple Load Factors

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Abstract

The conducted research reveals the behaviour of a concrete-steel tower subjected to vertical and lateral loads and actions taking into account the complexity of multiple factors including wind, temperature, ice and soil settlement. The stress-strain state of the concrete-steel tower structure has been analyzed applying the state-of-the-art numerical analysis and computer simulation methods. Two calculation models for investigating and analyzing the impact of wind actions on the structure of the tower have been developed. The obtained results have been compared to evaluate the importance level of these factors as variations in static and dynamic actions of the wind, changes in temperature material properties and requirements for design code.

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Selection and peer-review under responsibility of the Vilnius Gediminas Technical University.

Keywords: concrete; steel; tower; wind load; numerical analysis; finite element method; computational fluid dynamics.

Nomenclature

| Symbol | Description               |
|--------|---------------------------|
| s      | coefficient of an orthographic position |
| c₀     | holliness coefficient     |
| Φ      | windward slope obtained from slope height to length ratio |

1. Introduction

The evaluation of residual load-bearing capacity of a number of buildings appears to be a burning issue, particularly after facing natural disasters such as hurricanes, earthquakes or some other hardly predictable actions, including terrorist attacks etc. The establishment of residual load-bearing capacity plays a crucial role in the long-lasting exploitation of unique buildings. The qualities of materials increasingly influenced by an aggressive environment can be reduced, and therefore breaches and deformations of load-bearing elements may occur, which reduces the bearing capacity of structures. To assess the behaviour of residual buildings, the methods similar to those applied for designing new constructions are used. Reserves of the bearing capacity of extensively exploited buildings can be established employing the latest techniques for numerical modelling, calculating the values of an actual load and evaluating an impact and design response [1-3]. Similar procedures can be applied for reinforcing constructions and buildings having insufficient load-bearing capacity [4-5].

Vilnius TV Tower, as the tallest building in Lithuania, has been chosen as an object of research. The tower counts 32 years of exploitation.

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The main purpose of numerical studies on an engineering basis was to complexically perform calculations of the tower evaluating all possible impact factors that could influence the behaviour of tower constructions.

The experiment involved complexically applied numerical methods for analyzing constructions of the steel-reinforced concrete tower impacted by complicated stress-strain status and showed the most realistic simulation of strain impact distribution over the building as well as a response of the building to that structure. With reference to the obtained results using numerical methods, besides a detailed analysis of structural behaviour and condition, the article focuses on forecasting the upcoming stages of the building life cycle.

On the basis of data on numerical analysis and analytical methods, and along with issued normative documents, an expert evaluation of the building regarding analytical methods was performed following the requirements for normative documents.

The calculations primarily focused on dominating wind load and its consequences that could determine the after-effects of such impact. Therefore, the following aspects were considered:

- to create an authentic geometrically close to the real building model of a tower and highly accurately evaluate factors that can define the consequences of the impact created by wind etc. loads;
- to assess the terrain and aerodynamic factors that depend on that particular area;
- to analyze determining wind loads and establish design and actual wind loads for control calculations;
- to calculate computational fluid dynamics (CFD) evaluating normative requirements for wind loads and perform analysis using the revised data.

2. Construction of the Tower

The TV Tower is made of reinforced concrete and steel structures. The tower is 326.5 m in height and weights about 28 000 tons.

![Fig. 1. The calculated spatial model of the complete tower (a) and a steel mast (b) made of shell and beam finite elements; construction fragments of a lower wing of the reinforced concrete tubular structure (c) and an upper structure (d)](image)

A lower supporting part of the tower – reinforced concrete tubular structure – is 190 m in height (Fig. 1 a) and has a form of a thin-walled cylinder tapering towards the top. The diameter of the concrete tubular structure at the bottom reaches 15 m
and wall thickness – 500 mm, whereas in the upper part, the diameter decreases up to 8 m and wall thickness – up to 300 mm.

The upper part (mast) of the tower is made of steel (Fig. 1a). The overall height makes 136,47 m. The constructions of the mast are produced from thin-walled steel cylinders tapering towards the top. TV and radio antennas are placed in this part of the tower. The total weight of the part, including antennas makes approximately 260 tons.

The lower reinforced concrete part and the upper metal part of the tower are joined using a special mounting clamp at a height of 190 m.

At a height of 160 m, the arranged superstructure (the so called bowl) includes technical and viewpoint facilities as well as a restaurant with a rotating deck (Fig. 1b). The lower part of the bowl is formed of 16 prefabricated reinforced concrete elements weighing 3500 tons. The bowl contains steel-bearing constructions of a machinery hall built on the rotating deck and is overlapped with radial girders. The constructions of the superstructure are made of steel. The weight of this particular part of the building is 100 tons.

A basement slab of the TV tower is a reinforced concrete ring with a diameter of 38 m, the thickness of 1,5 m, the weight of 11 500 tons and a trench into the ground of 10m. The constructions of the lower part of the building are assembled on the basement slab (Fig. 2b) and are separated from the reinforced concrete foundations using a deformation joint, and therefore have not been modelled and examined.

3. Analysis Model

To thoroughly evaluate all factors (first of all, an individual weight of constructions, areas and volumes of surfaces) that can determine the consequences of load impact and should allow fully analyze the behaviour of the whole or certain parts of the building, a 3D computational model made of shell and beam finite elements has been created. The geometric parameters of the model have remained very close to the real prototype (see Figs 1 and 2a).

The basic detailed shell-like model of the conducted analysis has been prepared using documents on the tower project as well as referring to project supervision records. Project discrepancies have been evaluated according to the current situation.

To maintain an equivalent level of the details of the computational model, the size of the finite element gradually changes from 500×500 mm at the bottom up to 50×50 mm at the top of the steel mast.

The inner non-bearing elements such as an elevator shaft, staircase and service places have not been designed and accepted as loading.

According to the project, the steel mast and reinforced concrete foundations are tightly connected placing one part into other and stiffening with massive horizontal diaphragms that ensure the general behaviour of the construction.

The connection of reinforced concrete tubular structure of the tower and the foundation slab has been modelled as rigid. The model has presented the bottom slab propped against an elastic soil.

Soil properties have been accepted with reference to the performed research. Calculations used two different models for an elastic foundation: for a static analysis, the elastic foundation properties were found according to the deformation modulus of the ground, whereas for dynamic deformation actions, a stiffer base was developed applying the elastic modulus of the ground.
To calibrate a solid model and compare the obtained results, a validation model composed of 1D beam elements has been created and used for establishing dynamic parameters of the building, identifying the mode shapes, Eigen values and evaluating the general deformed shape.

Another detailed 3D solid model geometrically similar to a real building has been created for dealing with computational fluid dynamics. Accurately modelled antennas, service places and the elements of stiffness allowed properly evaluate the behaviour of the tower under the impact of the wind (Fig. 2b). Also, the terrain has been modelled to assess aerodynamic factors that depend upon the area.

For creating and calculating models, different software has been applied: SCAD Office (for analyzing the main shell-like model and the one composed of beam elements, for static and dynamic analysis), KROSS (for modelling an elastic foundation), VEST (for defining normative parameters of the wind load), SolidWorks Flow Simulation (for computational fluid dynamics) and Bentley Micro Station (for creating a 3D solid model of the tower and terrain) [8-9].

4. Vertical Strains and Effects

One of the most important qualities of the buildings of a special purpose is that they must remain safe, reliable and long-lived objects throughout the history of their lifetime independently on changes in requirements for design standards. The discussed building has experienced four periods of changes in design standards. The project was launched in 1962 under SNiP Loads & Actions, was designed following the same SNiP edition in 1974, was used under SNiP issued in 1985 and now must be investigated and assessed following the requirements Loads & Actions [6] according to STR 2.05.04:2003. Moreover, the authors considered requirements for Euro codes.

An individual weight of constructions and its distribution across the height of the tower has been automatically evaluated taking into account precise measurements of the model and the density of materials. Individual weights of non-bearing constructions (internal and external service sites, the inner lift shaft, the weights of antennas, etc.) have been received from the project documentation and added as external loads. Imposed loads have been evaluated examining the areas of the restaurant, viewpoint facilities, servicing and ancillary premises.

Snow loads on the roof of the lower and upper superstructure have been assessed. The evaluated ice load varied across the whole height of the mast from the 15 mm layer of ice at the bottom of reinforced concrete tubular structure up to a thickness of 42 mm at the top of the steel tower.

To establish the exact behaviour, the effect of temperature has been considered. The bend effect of temperature can be noticed in the summer time when the sun burns the surface of only one side of the tower.

Shrinkage deformation of monolithic reinforced concrete has been modelled to evaluate construction technology. The works of concreting the tower were done in the sliding formwork putting concrete in 5 metre-wide stretches. Shrinking concrete has been imitated by the impact of temperature.

The made calculations have assessed base deformation to establish possible inclination of the tower due to the different sedimentation of the soil. Thus, the interaction between the building and ground received from the analysis of the detailed computational model has been examined.

5. Wind Effects

Wind pressure for the buildings of a similar type is a dominant load. Therefore, for calculation purposes, wind load and analysis of load effects have been given particular attention. To examine wind load effects, specific analysis has been conducted. To evaluate wind loads, several methods have been employed:

- according to the region of wind speed indicated in design standards, computational wind loads have been established;
- according to the observed wind speed data received from metrological stations, actual wind loads have been identified;
- with reference to computational fluid dynamics (CFD) and considering the above mentioned standard and actual wind speeds, wind loads have been discovered.

On the basis of the obtained values of wind effects and confining to the requirements for normative documents, the static and dynamic components of wind load have been found out making calculations of the tower and accompanying loads affecting the tower. Also, the analysis of the effect of a the self-oscillation excitation of tower structures in turbulent wind flow on the behaviour of tower constructions has been conducted.

The base value of wind load has been calculated referring to normative documents. The evaluated reference wind speed measured at a height of 10 metres for the period of 10 minutes in the 'A' type locality equals \( v_{ref} = 24 \) m/s, (likelihood of exceeding annual indexes makes 0.02). Wind effect has been evaluated in all four directions: West, East, South and North.
The terrain effect (Fig. 3) has been evaluated applying hilliness coefficients calculated according to LST EN 1991-1-4:2005 directions. The rising slope situated on the east side of the 600 m section reaches 70 m. The most significant increase in wind speed appears near the top of the slope and is established applying the hilliness coefficient:

\[ c_0 = 1 + 2s\Phi \]  

where \( s \) – the coefficient of an orthographic position received from the below presented empiric diagrams, \( \Phi \) – a windward slope obtained from slope height to length ratio. Under the East wind, rather than under stronger West wind, due to the terrain, in the reinforced concrete part of the tower up to 160 m altitude, higher wind pressure can be observed.

![Fig. 3. Scheme for defining the coefficient of the windward slope (a) and a scale for setting the coefficient of an orthographic position (b)](image)

For actual analysis showing the condition of the tower, wind speed measurements from the closest to the tower meteorological stations have been received. For the period from 1971 to 2012, Vilnius region meteorological station recorded cases when two times, in 1981 and 2007, wind speed reached 18 m/s, which is the highest wind speed ever. However, according to the data (1964-2012) collected by Vilnius Meteorological Aviation Centre, the maximum wind speed was recorded in 1983 and reached 14 m/s. Instant wind gusts were 30 m/s and 28 m/s respectively. To evaluate a real load affecting the tower, an actual wind speed of 18 m/s was accepted.

Two components have been used for discovering the load of wind pressure calculated applying the method based on design codes:

- a distributed part of wind pressure on the reinforced concrete tubular structure and steel upper tower part calculated for the body of a cylindrical surface with certain aerodynamic coefficients considering a shallow conical shape (Fig. 4);
- a part of wind pressure on the antennas of the tower mast.

![Fig. 4. The establishment of the load of wind pressure on the reinforced concrete tubular structure and steel part: location parameters (a), wind speed parameters (b), distribution of wind pressure (c)](image)

6. Numerical Wind Modelling

Numerical wind modelling applying software SolidWorks Flow Simulation [7] has to objectively assess the aerodynamic effects of an outer loop of the tower on the actions of the wind power and to find out detailed distribution of wind pressure on the surfaces of the building (Fig. 5).

The main primary data on imitating wind effects using computational fluid dynamics (CFD) were as follows: a detailed volumetric model, a local landscape model, the initial wind speed, a diagram for wind dependence on height, a diagram for dependence of turbulence on height.

The researched object of the model for computational fluid dynamics is the volume around the obstacle (investigated object) as if the building is cut in space and the rest part of the volume is further examined. The studied volume is
segmented into volumetric finite elements the move of which, depending on the details of the investigated construction, is splintered up to the required level of accuracy.

Analysis has been performed under the standard wind speed of 24 m/s and wind speed of 18 m/s according to the data received from meteorological stations.

The indexes of wind load calculated employing the methods of computational fluid dynamics (CFD) and taking into consideration the aerodynamics of the building have been applied for analyzing the shell-like model and the one composed of 1D beam elements. The obtained results have been compared with calculations made following the requirements for design standards.

![Fig. 5. A general view of the computational model of the wind with a vertical section of finite elements (a) and the trajectories of wind flows in the hollow area of the tower](image)

### 7. The Main Results

Following the analysis of determining wind loads and referring to the identification of design and actual wind loads, analytical and numerical methods have been applied for tower analysis evaluating all possible impact factors influencing the behaviour of constructions. For making tower calculations, 387 combinations of loads and effects have been investigated. At the final stage, two main load combinations have been used:
- individual weight of constructions, applied loads, temperature effects and wind pressure;
- individual weight of constructions, applied loads, snow, icing and wind pressure making 25% of intensiveness considering the total wind load.

The detailed analysis of wind loads indicates that under the predominating West wind, a load affecting the lower reinforced concrete part is lighter than that observed investigating the East wind that is not very influential.

The total horizontal load considering the predominating wind has been established employing two methods – analytical and numerical and calculating wind speed regarding the location area and measurement results and is provided in Table 1.

| Method                                | Wind speed | Measurement results |
|---------------------------------------|------------|---------------------|
| Analytical method - the first simplified model | 1321 kN    |                     |
| Analytical method - a detailed model   | 1205 kN    | 681 kN              |
| CFD detailed model                    | 905 kN     | 510 kN              |

A comparison of the total values of wind loads has disclosed that the values obtained using the method of computational fluid dynamics (CFD), according to the detailed model of the tower, are significantly lower than those calculated employing
analytical methods. The revised total value of wind load has been reduced by 10%. The results received applying the method of computational fluid dynamics (CFD) allow decreasing wind load by approximately 30%.

The analysis of the shell-like model and the one composed of 1D beam elements has offered 32 forms of fluctuations (Fig. 7). Further calculations evaluate the modes of Eigen values having frequency not less than $\leq 2.9$ Hz when a period lasts not longer than $\geq 0.34$ s. Therefore, 8 basic forms of individual fluctuations have been investigated.

Vertical deformations, foundation settlements and deviations have been established and investigated. The received values have been compared with the allowed ones according to the requirements set for design standards. Horizontal deformations of the tower caused by wind impacts and other actions (temperature, foundation settlements) have been compared with the allowed values of design codes.

According to the analysis results of the shell-like model, internal forces in reinforce concrete structure and bowl constructions have been established and assessed (Fig. 7). Also, the required and actual amount of reinforcement used in the tubular structure of the tower has been identified and compared. The analyzed concentration zones of critical stresses have been examined close to the slots and at the joint between the upper steel part and reinforced concrete tubular structure.

Considering the results of the analysis, model composed of 1D beam elements, the internal forces of the steel part have been identified (Fig. 7b). On the basis of the results obtained calculating the shell-like model, the load-bearing capacity of
all steel elements of the upper superstructure has been verified. Moreover, the stresses of the steel elements above the slots of the changing cross-section at the joints have been examined (Fig. 7b) evaluating steel fatigue due to a dynamic impact.

8. Conclusions

The application of recent numerical analysis methods assists in making tower calculations to evaluate all possible impact factors that can influence the behaviour of constructions.

To analyze reinforced concrete tower constructions affected by complex loads, numerical methods have been combined and successfully employed highly realistically imitating the impact of loads on the building and a response of the building to the made impact, thus creating conditions for a detailed analysis of the behaviour and stress-strain state of constructions and for predicting the forthcoming stages of the building lifecycle.

On the basis of data received from numerical analysis and analytical methods as well as with reference to normative documents, the behaviour of the tower has been investigated making an expert evaluation of the building and establishing residual load-bearing capacity.

Computational fluid dynamics (CFD) shows that, according to the detailed model of the tower and evaluated design code requirements for wind loads, lighter loads have been received.

In accordance with design code based methods, the results of the correction analysis of wind loads allow reducing the total value of wind load up to 10%.

Computational fluid dynamics (CFD) has established that the wind impact of the tower constructions reaches approximately 30% and is lower than that found applying the analytical method, which results in a remarkable reduction on the loads of the whole construction.

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