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Evaluation of Highrise Building Fundamental Frequency – a Case Study

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The paper proposes a relatively simple tool to evaluate the precision of the developed FEM model by using the measurements of MEMS accelerometers of a high-rise building during its construction process. It is very important to precisely model the stiffness properties and geometry of the whole building with adequate simplifications in order to choose the correct dimensions of the load bearing elements of the building. The finite element models of two 33 story high-rise buildings were verified against the real high-rise building structure using the experimental data. The two high-rise building fundamental frequencies data were experimentally obtained during different stages of the construction process. The experimentally obtained data were compared with the numerically calculated data to evaluate the precision of the assumptions made during the FEM model creation process.

Keywords: *finite element method, high-rise building, oscillations, reinforced concrete, vibration*.

1. Introduction

Cost of the error in structural design of high-rise building can be very high and therefore should be eliminated. One of the ways to discover serious inaccuracies early is by measuring the accelerations and fundamental frequencies of structure during the ongoing construction process on-site. Micro electro-mechanical system (MEMS) accelerometers may be utilized. Then experimental natural frequencies can be compared with theoretical values obtained from finite element method (FEM) calculation model. The stiffness and dynamic parameters of FEM calculation model can be checked. Therefore, FEM model overall adequacy and admissibility can be controlled. This includes checking of simplifications usually done in calculation process (the geometry of structure, loads, stiffness and other parameters).

Fig. 1. *Multifunctional complex “Z-Towers” during construction*

Since the year 2007 in Riga, Latvia the multifunctional complex “Z-Towers” that consists of four underground levels and two cylindrical towers above them has been built (office “O” tower and hotel “H” tower.).

The complex main load bearing structures are made of in-situ reinforced concrete (RC). The foundation is the drilled RC piles based on the dolomite rock layer. Both tower structures consist of the central core and perimeter columns. The “O” tower has the outer diameter of 37,2m, 12 perimeter columns and the cylindrical core with the outer diameter of 17,8m. And the smaller “H” tower has the outer diameter of 30,9m, 14 perimeter columns and the cylindrical core with the outer diameter of 13,8m. The “O” tower RC structure height above the ground without the roof steel structure is 124,600m and 117,870m for the ‘H’ tower.

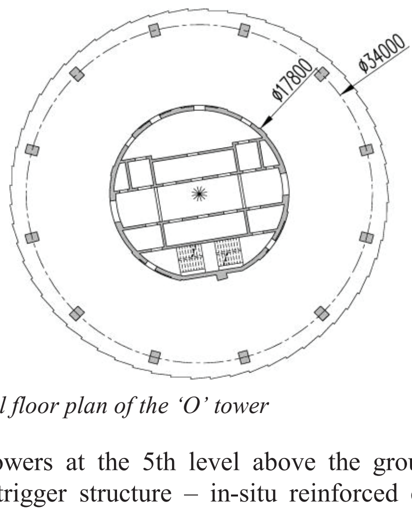

Fig. 2. *Typical floor plan of the ‘O’ tower*

Both towers at the 5th level above the ground will have the outrigger structure – in-situ reinforced concrete walls of 600 mm and 500 mm thickness between the central core and perimeter columns (Fig. 3). These walls will provide translation of the internal forces between the columns and the core, hence it promotes combined work to in-crease the global stiffness of the building, reduces wind induced dynamic effects, reduces loads on the piles under the central core and provides greater security level against progressive collapse.

The dynamic characteristic precise estimation of such a high structure is vitally important. This directly affects the structural solutions of the building.

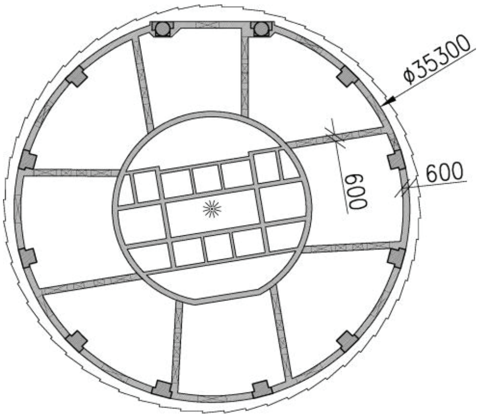

Fig. 3. *Plan of the 'O' tower outrigger level walls*

The structural dynamic behavior denotes modal parameters of the structure (natural frequencies, damping ratios and mode shapes). The field of the research the so called "modal analysis" is dealing with identification of these parameters. Basically, there are two ways of extracting them.

First way is experimental modal analysis that starts with the measurement of the input forces and output responses of the structure of interest (Heylen, *et al.* 2007).

Second way is theoretical modal analysis where the stiffness matrix, mass matrix and damping matrix are known, and by solving the eigenvalue problem the required dynamic parameters of the structure can be obtained (used in FEM analysis software).

In case of tall buildings it is almost impossible to measure the input forces, therefore the output or operational modal analysis should be used that aims to determine the dynamic characteristics of the structure under operational conditions. Usually, the operational analysis drawback is that the method assumes the input signal to be a white noise sequence but the peaks in an input spectrum will yield in responses that might not be the structural mode.

This drawback might be utilized in a positive way. The usual assumption in response calculations of tall structures like high-rise buildings is that it will mainly respond in fundamental modes (Zhou, 1999) due to wind loading. This assumption might be confirmed by many case studies, for example (Li, Wu, *et al.* 2007), (Li, Fu, *et al.* 2006), (Zhao 2011), (Gu 2009). Therefore, to identify only the fundamental frequency of the structure extracted from measurements in time domain (e.g., accelerations) does not require expensive dynamic testing methods but still it provides a valuable tool for checking assumptions made during the numerical model construction.

The wind induced displacement of a structure mainly consists of a mean component and dynamic fluctuating component.

To measure the output response of the structure accelerometers that generally are capable to measure the resonant components can be utilized (Li, Wu 2007).

In this way, the measurements of the tower response during the construction process using simple accelerometers might give the confidence of the finite element model reliability.

In engineering practice for multi-storey buildings fundamental flexural frequency estimation is used rough empirical formula (EN 1991-4-1:2005):

$$f = 46 / h \quad (1)$$

where: f – fundamental flexural frequency in Hz, h – building height in meters. Measurements carried out allow to verify this formula it in particular case.

Aim of the study is to check possibility to verify the correspondence of the calculation models with the real structure behavior using MEMS accelerometers.

2. Tower natural oscillation frequencies estimation

2.1. On-site measurements

The on-site oscillations measurements were periodically conducted during the tower construction. It allows controlling the dynamic characteristics of the towers and observes changes depending on the tower height and construction work progress.

The measurements were conducted in windy weather, when the wind gusts provoked significant horizontal deformations of the towers due to natural oscillations.

One of the aims of on-site experiments was to identify weather without the expensive dynamic testing methods and instruments it is possible to identify the fundamental mode frequency of the structure. Therefore, simple 3-axis light-weight (55g) USB accelerometers (GCDC Model X6-1A, Fig. 4) were used to record the accelerations. The measurement sample rate was 40Hz.

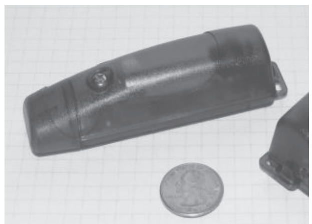

Fig. 4. *Model X6-1A accelerometer (www.gcdataconcepts.com/ xlr8r-1.html (accessed 1 July 2014))*

This MEMS accelerometer includes elastically restrained seismic mass, which moves under acceleration forces influence, and sensors, that measures changes of electric capacity (Fig. 5). Acceleration causes displacement of a seismic mass resulting in a change in capacitance. A circuit, detects and transforms changes in capacitance into an analog output voltage, which is proportional to acceleration. The sense element design utilizes common mode cancellation to decrease errors from process variation and environment (Andrejasic 2008, Pedley, 2013).

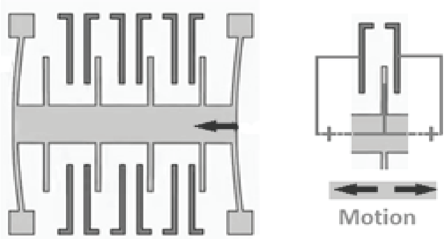

Fig. 5. *MEMS accelerometers working principle (Gujarati P. What is Accelerometer and how does it work on smartphones.* Available at: *www.techulator.com/resources/8930-How-does-smart-phone-accelerometer-work.aspx (accessed 1 July 2014))*

The placement of the accelerometers was chosen after examination of the existing FEM model. The maximum and minimum vertical stiffness planes of each of the two towers were found. Accelerometers were tightly attached to the upper floor outer perimeter columns that were built at the particular construction stage and crossed these planes. One of the accelerometers was attached to the main lateral stiffness element - central core of the tower. Already from the raw accelerometer readings it is possible to identify the presence of harmonic oscillations (Fig. 6).

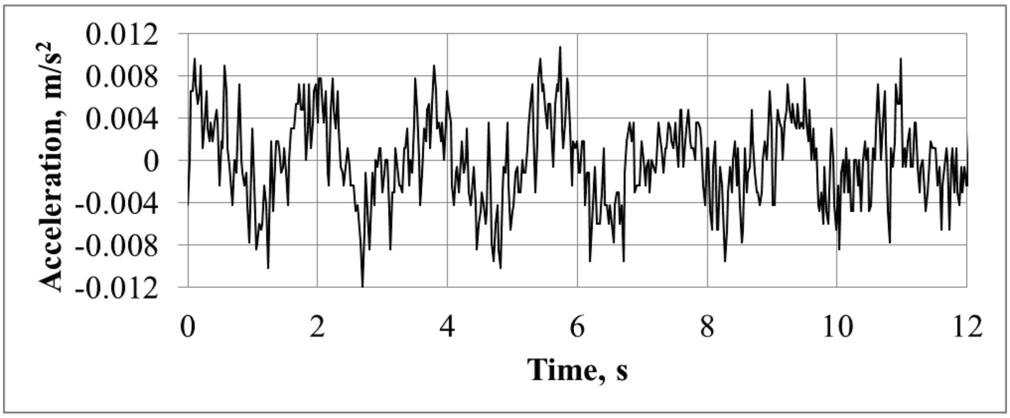

Fig. 6. *An example of the recorded measurements by accelerometer (conducted at level 124.600m of the "O" tower)*

The autocorrelation function (2) shows how the mean power in a signal is distributed over frequency. It is also a very handy tool to detect harmonic signals buried in the noise (Heylen, et.al., 2007).

$$G_{AA}(f) = A(f) \cdot A^{*}(f), \tag{2}$$

where A(f) is the Fourier transform of the time trace a(t) and "*" indicates the complex conjugate.

To reduce the leakage effects due to the non-periodicity of the time signal records the "Hanning window" was applied to each sampling window before the FFT (Fast Fourier Transform) was applied. In the next step Auto Spectrum was "normalized" by the frequency resolution of the Auto Spectrum and thereby the power spectral density was obtained (PSD). The PSD is very useful even if data do not contain any pure oscillatory signals and it is the easiest way to identify the peaks. In the experiments 3-axis accelerometers that simultaneously measured accelerations in three directions were used, and then the obtained frequency response function amplitudes were summed to improve the identifying process of the physical and meaningful poles. As a check the stabilization diagram that subsequently assumes an increasing number of poles was used. Physical poles (exited frequencies) always appear as "stable poles", consequently unrealistic poles are filtered out.

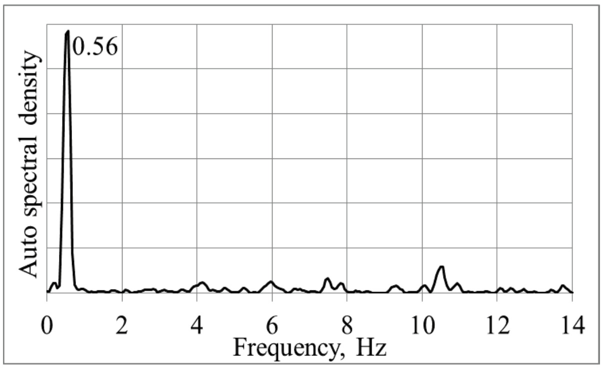

Fig. 7. *Power spectral density of acceleration along stiffer axis of the structure*

Fig. 7 presents the example of the obtained acceleration response spectra for the largest lateral stiff-ness direction.

To compare the numerically obtained frequencies with the experimentally ones the FEM model was loaded only with permanent load – RC self-weight because during the experiment generally only this load was represented.

2.2. FEM analysis

High-rise FEM analysis was made using Lira 9.4 computer program. The calculation model consists of linear (beams, columns and piles) and shell (walls and slabs) finite elements. The structure dimensions were assumed according to nominal project dimensions. In-situ reinforced concrete structure dead weight was assumed regarding the density 2.5t/m³.

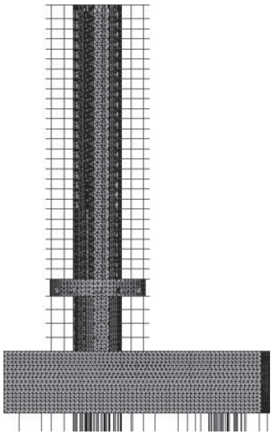

Fig. 8. *FEM calculation model of the "O" tower for full height*

The tower overall calculations were carried out in the linear elastic phase. The modulus of elasticity for mainly compressed vertical elements (columns and walls) was assumed based on the concrete elasticity properties and reinforcement amount. The modulus of elasticity of homogeneous cross-sections for mainly bended horizontal elements (slabs, plates and beams) was determined by calculations to take into account cracking of the elements under the characteristic self-weight load. In the FEM model of the structure the supports are located at the bottom ends of the piles. The pile modulus of elasticity was reduced to provide equal load-deformation relationship as it was obtained in the full scale static pile tests.

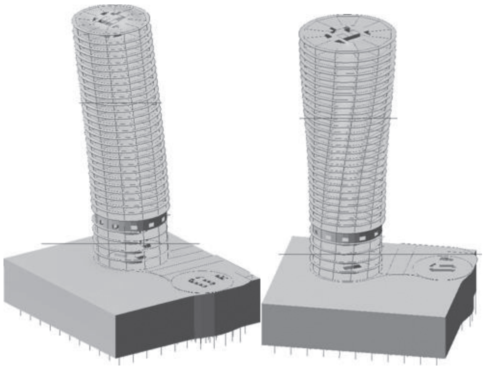

Fig. 9. *The FEM calculation model of the "O" tower; natural oscillations in the 1st (bending) and 3rd (torsion) modes. Displacement scale is increased*

A number of simplifications were made during the FEM analysis:

1. Taking into account the amount of levels and complex configuration some geometry features were ignored, such as one slab elevation local changes, small openings in walls and slabs, etc. The calculation models were made maximally close to the design project, but some simplifications were made to decrease the amount of the finite elements to get the model of the whole building in order to calculate the natural frequencies.
2. Stiffness values should be specified for RC elements during the FEM modeling. They are different for cracked and non-cracked sections. The cracked section stiffness reduction varies depending on the current loads and loading history, used materials, section geometry, used RC analysis model, etc. This complicates a precise estimation of the stiffness parameters. Also the RC stiffness can vary depending on the specific concrete compound, compacting quality, climatic conditions during concrete works and hardening process, etc. All of these factors are difficult to predict and can be evaluated only in a simplified way.
3. The towers are supported by a 12m deep underground structure that is loaded with the ground water pressure from the bottom. The RC piles are drilled to the dolomite layer and work in compression or tension depending on the load from the supported structure. Geotechnical data and deformation characteristics of the piles can vary in a very wide range and the stiffness of the supports is difficult to predict precisely.

All these factors influence the theoretical calculations; therefore behavior of the real building can be different. That is why the FEM analysis should be checked with on-site measurements. The estimation of the structure natural frequency can be obtained theoretically and experimentally. These dynamic parameters can be used to validate the FEM model.

To compare the natural frequencies obtained from the FEM model with on-site measurements at the particular construction stage the finite elements of the model that were not built yet at the relevant stage were deleted.

3. Results

Generally, the FEM analysis results show a good correspondence with on-site measurements for the first oscillation mode. According to the FEM analysis the first two oscillation modes of both towers are bending in two perpendicular directions. The performed measurements do not allow to receive precise oscillation mode shapes but generally there is no doubt that oscillations could happen in a different manner as it was estimated by the FEM calculations.

Similar measurements were also conducted earlier when the heights of the towers were smaller. When the structure with a smaller height and fundamental frequencies close to 2.0Hz was measured using the same devices, there were no clear results obtained and extraction of the building fundamental frequency was problematic. The first reliable results were obtained when the first 11 levels above the ground were built.

The experimentally obtained fundamental frequency of the full height "O" tower was 0.51Hz, on the other hand the FEM calculation result was 0.43Hz which makes the difference of 19% (Fig. 10 and Table 1).

The experimentally obtained fundamental frequency of the 17 built levels of "H" tower was ~1.0 Hz and the FEM calculation result was 1.10 Hz which makes the difference of 10% (Fig. 11 and Table 2).

The experimentally obtained fundamental frequency of the full height "H" tower was 0.60Hz, on the other hand the FEM calculation result was 0.45Hz which makes the difference of 30%. Larger difference can be caused by partition wall and facade partly assembled at measurements moment, which influence overall stiffness, but are not included in FEM calculations (Fig. 11 and table 2).

The dynamic behavior of both towers is similar. It appears in the similar acceleration levels and dominating natural frequencies.

Both full height towers real behavior is better than estimated by the FEM analysis (oscillation frequency is greater). The "H'' tower real behavior was slightly worse as it was estimated by the FEM analysis (oscillation frequency is smaller) at first construction stages. Generally, there was good correspondence between the on-site measurements and the FEM analysis showing that the adopted simplifications of the numerical calculation model are adequate. The information extracted from the experimental measurements reveals that foundation restrain of the real structure is better than modeled in the FEM model. The fact, that the "H'' tower at first construction stages has lower values of the numerically calculated fundamental frequencies than the experimentally obtained ones could be explained with the assumption that the slabs real stiffness is smaller than modeled. The "H" tower stiffness of the slabs and column involvement in overall stiffness have a bigger role than in the "O" tower case.

Table 1. *The fundamental frequencies of the "O" tower*

Construction stage	Oscillation mode	Oscillation frequency according to FEM analysis, Hz	Oscillation frequency according to on-site measurements, Hz	Oscillation frequency according to empirical formula 46/h, Hz
"O" tower 58.400m above the ground (16.07.2012; 14 levels without outrigger walls)	1st	1.04	1.11	0.79
	2nd	1.11	1.18	
"O" tower 79.750m above the ground (28.12.2012; 20 levels with partly constructed outrigger walls)	1st	0.768	0.9	0.58
	2nd	0.833	1.15	
"O" tower 124.600m above the ground (full structure)	1st	0.427	0.51	0.37
	2nd	0.474	0.56	

Table 2. *The fundamental frequencies of the "H" tower*

Construction stage	Oscillation mode	Oscillation frequency according to FEM analysis, Hz	Oscillation frequency according to on-site measurements, Hz	Oscillation frequency according to empirical formula 46/h, Hz
"H" tower 46.050m above the ground (16.07.2012; 11 levels without outrigger walls)	1st	1.57	1.3	1.00
	2nd	1.59	1.4	
"H" tower 65.720m above the ground (28.12.2012; 17 levels with partly constructed outrigger walls)	1st	1.10	1.00	0.70
	2nd	1.13	1.16	
"H" tower 117.87m above the ground (full structure)	1st	0.447	0.60*	0.39
	2nd	0.507	0.66*	

* – Building partition wall and facade partly assembled at measurements moment. This non-structural elements influence overall stiffness, but are not included in calculations.

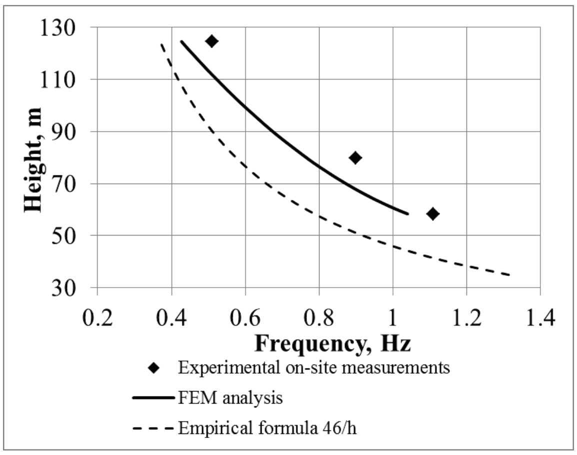

Fig. 10. *The fundamental frequencies of the "O" tower*

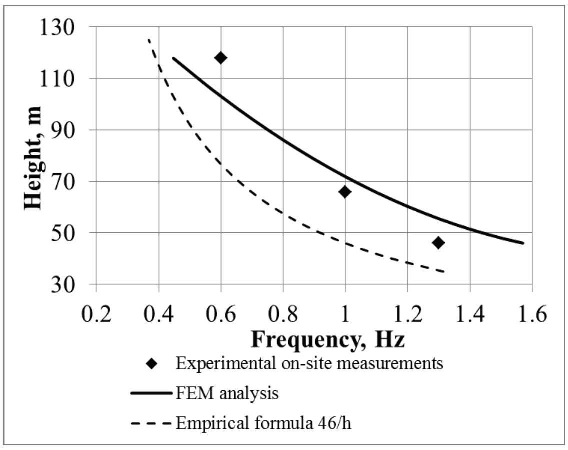

Fig. 11. *The fundamental frequencies of the "H" tower*

The obtained results can be used as the basis for the existing FEM model update that allows getting more precise calculation results.

In case if significant difference between the FEM calculations and the experimentally obtained results would be found, the assumptions made during the FEM model construction should be analyzed and the model revised.

Rough empirical formula f=46/h for building fundamental flexural frequency estimation shows for 30-40% more conservative values than FEM analysis or on-site measurements. It can be used in engineering practice.

4. Discussion

The accuracy of the developed calculation model of the structure with relatively small natural frequencies can be evaluated by conducting the on-site frequency measurements.

Usually the dynamic testing is performed for the finished building when non-structural parts (e.g., partition walls or facades) add additional stiffness to the whole building. A simplified dynamic testing with MEMS accelerometers (when there is an aim to determine only the fundamental frequencies of the building) during the different stages of the load bearing structure construction process creates the possibility to verify the correspondence of the existing calculation model with the real structure behaviour by comparing the stiff-ness parameters. In this case if there a necessity arises, the FEM model could be corrected in relatively early stage. And strengthening of the real structure can be performed before the building is finished so avoiding the extensive additional expenses.

This method has its restrictions – the structures must have uncoupled natural frequencies that are well separated. Therefore, the method of calculation model verification cannot be used for the buildings with a low-rise structure and non-consistent structural element arrangement. Still, a large amount of the engineering judgment and experience is necessary to extract proper dynamic parameters from the accelerometer measurements.

Such simplified calculation model evaluation is specifically applicable for high-rise buildings, tall towers and other similar line – like vertical structures.

5. Conclusions

During construction stage of two high-rise concrete towers a simplified dynamic testing with MEMS accelerometer was performed and a good correlation between finite element method and on-site measurement were obtained. Consequently, no significant imperfections were applied in analytical calculations. Several assumptions were assumed during the design stage, such as linear elastic behaviour of the structure, homogeneous cross-sections of the main concrete members, geometrical simplifications in order to reduce the FEM model size and complexity and approximate modulus of elasticity. These assumptions confirmed as adequate and admissible in this case. Imperfections discovered are acceptable for engineering practice.

Nevertheless, it is recommended to control stiffness parameters of high-rise buildings during the construction stage by determining the fundamental frequencies of bare load bearing structure to ensure the assumptions and simplifications made during the design stage are valid. It can be effectively done with simple MEMS accelerometers.

This particular case proves, than empirical formula f=46/h for building fundamental flexural frequency estimation shows conservatively reliable results and can be used in engineering practice.

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