Long-Term Monitoring of High-Rise Buildings in Moscow

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ABSTRACT

A long-term structural health monitoring program started in 2000 with a seismometrical monitoring station installed in 44-storey "Edelweiss" tower. Since then several high-rise residential buildings in Moscow were equipped with monitoring systems. The research includes both practical and scientific purposes. The practical one is to increase the structural safety by detecting anomalies in structural behaviour. The scientific one is to gain knowledge about the evolution of reinforced concrete structures stress-strain state during the construction and operation of buildings. The large amounts of data have been obtained using various types of equipment (seismometers, pressure cells, extensometers and vibrating wire strain gauges). Based on results it was possible to establish main factors that influence the stress-strain state of structures. The actual data was compared to simulation results and the most appropriate computer models were determined. The redistribution of stresses between parts of a construction turned out to be impossible to reproduce by means of finite element analysis in current software suites was found. Finally, a technique of long-term forecast of the stress-strain state of reinforced concrete structures was developed.

KEYWORDS : *high-rise buildings, reinforced concrete, experimental data, stress-strain state.*

INTRODUCTION

Monitoring of load-bearing structures is acknowledged in Russia as a reliable method for the safety of constructions. Building boom in 1990s and 2000s along with government acts prescribing monitoring to be conducted on high-rise and unique buildings gave birth to a large amount of investigations in this field. Russian codes describe the tasks monitoring should be capable of performing, which are:

- inspection of stress-strain state of structures;
- comparison of acquired construction parameters with critical values;
- conclusion on the actual technical condition of an object in study and the forecast on the future progression of its technical state.

The stress-strain analysis is performed for every building design by means of creation and analysis of the computer model of the building. While the initial state in calculation is always the fresh construction state, the changes in its state over the exploitation are mostly neglected. The mathematical model used in simulation does not allow the incorporation into the calculation of all factors affecting reinforced concrete. These factors include construction conditions, stress level and the redistribution of stresses between structural elements.

Monitoring of bearing structures is an effective mean to estimation of both non-regular structural responses to an external impact (which are not included into models) and long-time evolution of the stress-strain state. However, several tasks are to be completed if a forecast has to be made:

- acquisition of a statistically meaningful collection of detailed data on the stress-strain state of load-bearing structures;
- estimation of influence of soil base behavior and thermal changes in construction during the year on overall stress-strain state.

These conditions define the principle differences between this investigation and other well-known studies [1, 2], they are:

- automated monitoring systems with tunable measurement length;
- strain gauges that have in-built temperature compensation;
- pressure-cells measuring the pressure under the foundation slab.

1 BUILDING CONSTRUCTION

The building studied with the novel monitoring system is 43-storey triangular-shaped apartment with dual-store car parking to the side. The address is Dybenko, 38, Moscow (Fig.1). The foundation slab is box-sectioned, the structural system of the overground part is a frame-wall and constructional elements are reinforced concrete. The house was built in several stages (Table 1).

Table 1: Stages of construction

stage	time
Underground part	December 2007 – April 2008
Stores 1-22	April 2008 – December 2008
No construction	December 2008 – March 2010
Stores 23-43	March 2010 – August 2010

Figure 1: 43-storey apartment at Dybenko, 38 in Moscow

2 MONITORING

2.1 Measurement system

Several parameters of the high-rise part of the building are monitored: pressure under the foundation slab, strain in the foundation slab and strain in the walls of the ground floor. Vibrating wire strain gauges by SISGEO®, Italy were used and their specifications are given in Table 2. The tension gauges have in-built thermal sensor so that the temperature compensation can be easily applied.

Table 2: Vibrating wire strain gauges specifications

Active gauge length	150 mm
Range (nominal)	3000 µs
Sensitivity	1.0 µs
Accuracy	±0.5% FS
Stability	0.1% FS/yr

Sensor placement is based on the building design and structural analysis. The most loaded walls also have sensors attached. The choice of positions was dictated by that the full picture of vertical deformations of the store had to be acquired. Thus the wall thickness and its position in plan was an important parameter for the sensor placement choice (Fig.2).

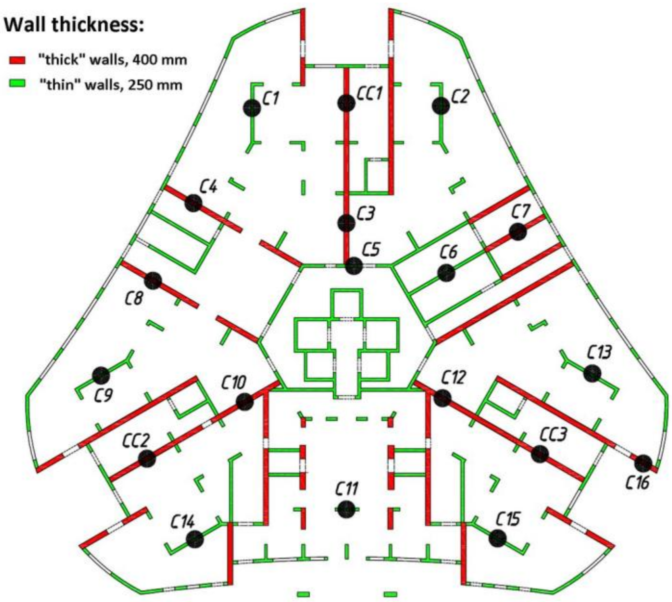

Figure 2: Monitored walls and columns, ground floor

First batches of data were acquired in a manual regime. During the construction period every measurement corresponds to the construction of five floors. During the downtime period one measurement was conducted every month. After the end of construction work a centralized automated system was installed and all sensors were connected to it. From September 2011 till nowadays data from all sensors are collected automatically every 6 hours.

2.2 Computer model

A simulation model of the building was composed to calculate axial forces and bending moments. Every measurement point was related to a finite element of the model. Eleven stages of construction were considered with spacing equal to 5 floors. Self-weight loads of bearing and enclosing structures were applied at the stages by their characteristic values. Two stages are related to loading of finishing materials and imposed loads. This sequence in the model represents the real construction schedule.

3 RESULTS AND DISCUSSION

3.1 Construction stage

Strains in bearing structures were derived from forces acquired in simulation. Reinforced concrete deformations were defined as a sum of elastic ε_e, creep ε_{pl} and shrinkage ε_s deformations. Creep deformation was calculated in accordance with the superposition principle: total creep deformation at alternating stress is defined as a sum of creep deformations caused by corresponding stress increments:

$$\varepsilon_{pl} = \sum_{i=1}^{n} \varepsilon_{pl,i}\left(\Delta\sigma_i, t - t_i\right), \tag{1}$$

where $\Delta\sigma_i$ – stress increase at i stage of loading, n – total amount of simulated loading stages, t_i – time of loading stage i, t – time, at which creep deformation is calculated.

Shrinkages and creeps were determined according to Russian codes. The evolution of simulated strains in bearing structures during the construction is given in Fig.3 along with experimentally obtained values. The values are given for the walls of the ground floor (thicknesses of 250 and 400 mm) for the four year period (2008-2012). The range of strain change reflects the probability-based load behavior.

The agreement of calculated and experimental plots is both qualitative and quantitative thus conclusions can be drawn regarding the correspondence of the real construction behavior to the designed one (Fig.4).

Intervals of stress-strain changes are estimated based on plots of simulated strains (Fig.3) with the multitude of stages not taken into consideration. This approach leads to a major deviation from the experimental values during the construction phase; however the final values are determined within an acceptable accuracy.

The comparison given reveals the discrepancy between the real and forecasted stress-strain states of bearing structures. These deviations are due to simplifications of the simulation. Several notable features of experimental plots are:

- Spasmodic changes (25% of average level) of strains for ground floor walls occurring at construction downtime;
- The delay of experimental deformation graph compared to the simulated one;
- Experimental excess of deformation growth is lower than the simulated for some elements (C3 wall for example).

These differences are partly attributed to the omission of redistibution of the load between walls with different thickness. The real relative deformations vary slightly for vertical elements across the given floor. The simulated variation is more intense with higher deformation of thin and lower of the thick walls.

3.2 Exploitation

The apartment entered exploitation in 2011 and was inhabited at a low rate: 12% of flats were sold during the first two years resulting in less than 3% increase of the load. Fig.5 contains data for the 2.5 year period from October 2011 to February 2014. Plots for various sensors are similar but have some significant variations: the average deformation change across this time interval (difference in minimal and maximal values in plot) is $\Delta\varepsilon = 130\cdot10^{-6}$ and approximately 35% of the average value. The nature of observed variation has to be determined because it relates to inner cyclic processes.

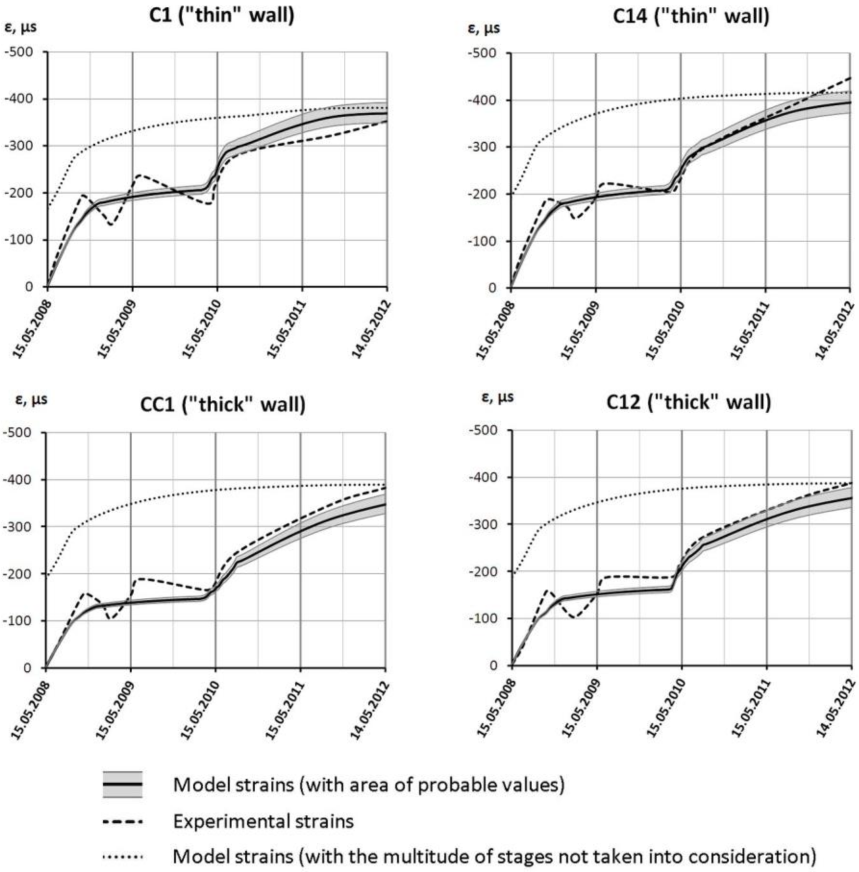

Figure 3: Comparison of experimental and simulated plots of strains in walls of the ground floor that occur during the construction and exploitation phases.

As it was stated above the load increase is negligible and thus is not the cause for the aforementioned structural changes. The reinforced concrete is known to change its properties over time and can be the trend for the deformation growth over the considered period. Additional factors influencing the deformation and bringing in the deviation are thermal cycles and the interaction of structural elements and the soil base.

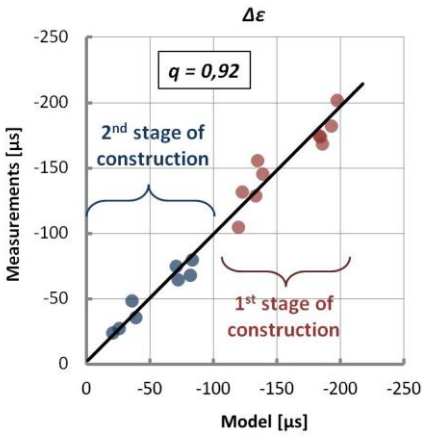

Figure 4: Comparison of model and measured increments of strains in walls

In order to reveal other possible regularities in the deformational evolution the autostructural function (ASF) method was applied. It is widely employed in physics for statistical analysis of processes with complicated temporal composition. ASF is functionally tied with spectral characteristics of a stochastic process and can be used for the determination of its components that have periodic behavior.

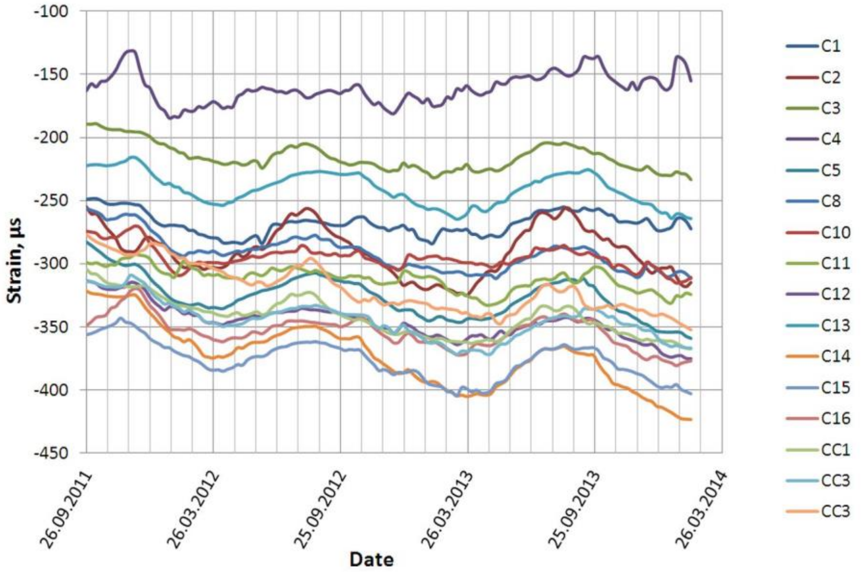

Figure 5: Evolution of strains of the ground floor walls during the exploitation of the apartment

ASF $S(\tau)$ for the stohastic function $X(t)$ is defined using mean M as following:

$$S(\tau)=M\left[\left[X(t+\tau)-X(t)\right]^2\right]. \quad (2)$$

ASF plots for the walls strains evolution are given in Fig. 6. The period of variations according to plots is $T\approx 1$ year, i.e. variations are of a seasonal nature. Their amplitude is $\pm 15\%$ of the deformation averaged over sensors. Trend is found in ASF plots as the minimal function value for the majority of sensors is non-zero. The mean-square value of non-cyclic temporal deformation variation is by definition:

$$\sigma^2=\frac{S\left(\tau\ =T\right)}{2}. \quad (3)$$

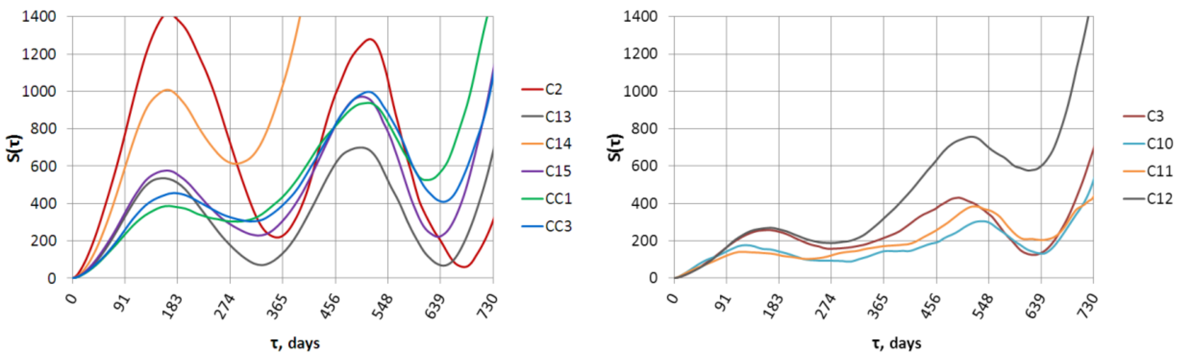

Figure 6: ASF plots for the walls strains

This parameter is useful for estimation of the rate of the process change. The relative speed of the compressive strain growth in walls of the ground floor is 2-15% a year, while the wall average value is 9%.

Additionally, ASF plots allow the classification of walls by the value of the deviation from the trend dependence. Two main groups are identified, the first being the walls close to the building exterior and is characterized by significant seasonal variations (attributed to thermal cycles and soil-construction interaction). The second group are the walls closer to the shear core with lower variations.

CONCLUSION

Long-time monitoring was performed on the load-bearing structure of a high-rise apartment in Moscow including both construction and exploitation time. Monitoring data obtained during the construction can be utilized for the formation and optimization of a computer model of the building. The studied stress-strain dependencies indicate that some factors are not included into simulation, first being the redistribution of stresses in statically indeterminate systems and the second is the rheological characteristic of reinforced concrete. The variations revealed are to be considered in analysis of monitoring data in order to avoid false conclusions and the following unnecessary emergency measures.

Measurements during the exploitation stage allowed us to define the characteristics of strain variations over time. Seasonal drifts are caused by thermal cycles and a complex interaction of the construction with soil base and reach 15% of the average values. Moreover, a stable increase in the contraction deformation of walls was found and it is attributed to changes in wall material properties.

The experimental data provided by the monitoring system allow the theoretical forecasting of the bearing structure stress-strain state evolution thus making the monitoring technique a valuable asset for the estimation of construction reliability and the residual resource of reinforced concrete constructions.

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