MONITORING OF BUILDING COLUMNS DURING CONSTRUCTION

Dr. Branko Glisic [1], Dr. Daniele Inaudi[2], Er. Kee Ching Hoong[3] and Er. Joo Ming Lau[4]

[1]*SMARTEC SA, Via Pobiette 11, 6928 Manno, Switzerland,e-mail: glisic@smartec.ch*
[2]*SMARTEC SA, e-mail: inaudi@smartec.ch*
[3]*Structural Engineering Department, Housing & Development Board (HDB), HDB Hub 480 Lorong 6 Toa Payoh, Singapore 310480, e-mail: hkc1@hdb.gov.sg*
[4]*Structural Engineering Department, Housing & Development Board (HDB), e-mail: ljm1@hdb.gov.sg*

Abstract. *Structural monitoring is more and more accepted in the domain of civil engineering as a proper mean to increase the safety and to better plan the management activities. The employed monitoring strategy depends on several parameters such as the type of structure, its dimensions and construction material, the loads and their combinations, the predicted durability etc. In this paper, a monitoring strategy applicable in case of column-supported structures such as buildings is developed. It has been applied as a pilot monitoring project on a nineteen storeys tall residential building in Singapore. The total strain in the supporting columns is measured using embeddable long-gage fiber optic sensors and data analysis is performed according to available model codes in order to distinguish different types of strain such as shrinkage and creep as well as to evaluate the load in the columns. The monitoring schedule has been planed to cover the whole lifespan of the building, including the construction period. At the time of writing this paper, all nineteen storeys were built, but roof and finishing works were not completed. The available results obtained by the proposed monitoring strategy are analyzed and presented. This analysis includes the local structural behavior of each instrumented column, the global structural behavior of the different dwelling units and the evaluation of the performances of the employed monitoring strategy.*

1. Introduction

Singapore is a cosmopolitan city-state often described as a gateway to Asia with a city landscape of tall buildings. The Housing and Development Board (HDB), as Singapore's public housing authority, has an impressive record of providing a high standard of public housing for Singaporeans through a comprehensive building program. As part of quality assurance of new HDB tall buildings, it was decided to perform long-term structural monitoring of a new building of a project at Punggol East Contract 26. This monitoring project is considered as a pilot project with two aims: to develop a monitoring strategy for column-supported structures such as buildings, and to collect data related to the behavior of this particular building providing rich information concerning their behavior and health conditions. The monitoring is to be performed during whole lifespan of the building, from costruction to the in use. Thus, for the first time the sensors are used in a large scale life cycle monitoring of high-rise buildings.

The Punggol EC26 project consists of six blocks founded on piles, and each block is a nineteen-storeys tall building, consisting of 6 Units and supported on more than 50 columns at ground level. The block called 166A has been selected for monitoring. It's construction started on December 2000 and the end of the works is expected in October 2002. At the moment of writing, the 19th storey was completed. A view of the building under construction is presented in Figure 1.

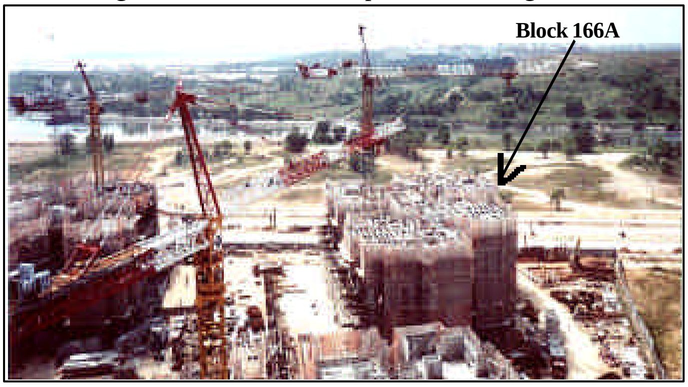

Fig. 1: View to the Block 166A of Punggol EC26 project during construction

2. Design criteria for monitoring

Several monitoring criteria have influenced the development of the monitoring strategy. They are listed below.

i. Monitoring of critical members of the structure has been required. The critical members are structural elements which malfunctioning or failure will generate, partial or even complete, malfunctioning or failure of the structure.

ii. Monitoring has to be performed at local column level and at global structural level. Knowledge concerning the behavior of one or few structural elements (columns) is not sufficient to make conclusions concerning the global structural behavior, therefore representative number of elements has had to be monitored

iii. The monitoring is to be performed over the whole-lifespan of the structure, including the construction phase. The monitoring system selected for this type of monitoring must have appropriate performances, notably high accuracy and long-term stability.

iv. The selected monitoring system has to be designed for structural monitoring; it has not to be influenced by local material defects in concrete, such as cracks or air pockets.
v. The budget accorded to monitoring activities has been limited. Being a pilot project which contains some uncertainties and which is subjected to development and changes it was decided to limit the number of sensors installed in the building, and to concentrate on the results obtained from this limited number of sensors in order to evaluate the method and improve its performance.
vi. For aesthetical reasons it was not permitted for sensors and sensor cables to be visible or to egress directly from the columns.

The presented criteria have called for a particular monitoring strategy including the selection of the monitoring system, the definition of the sensor type and position, the development of the installation procedures, the establishment of measurement schedule and the development of algorithms for data analysis.

3. Monitoring strategy 1: selection of monitoring system and Sensor type

The conditions sine qua non for selection of type of sensor was imposed by criteria 3, 4 and 6: according to criteria 3 the sensor has to survive for long periods with high stability, hence it has to be immune to corrosion, humidity, temperature variations and, electro-magnetic field and interferences; according to criteria 4 the selected sensor has to have a long-gage and according to criteria 6 it has to be embeddable in the concrete. Thus, the SOFO system [1] is evaluated as the most suitable for this application.

The SOFO system (French acronym for Surveillance d'Ouvrages par Fibres Optiques – Structural Monitoring using Optical Fibers) is based on low-coherence interferometry in optical fiber sensors [1]. It consists of long-gage sensors, a reading unit and data acquisition and analysis software. The sensor contains two optical fibers called the measurement fiber and the reference fiber, both placed in the same protection tube (see figure 3). The measurement fiber is coupled with host structure and follows its deformation. In order to measure shortening as well as the elongation, the measurement fiber is prestressed to 0.5%. The reference fiber is loose and therefore independent from the structure's deformations; its purpose is to compensate thermal influences to the sensor.

Typical sensor gage-length ranges from 250 mm to 10 m. The resolution (minimal detectable change of optical signal translated in measured deformation) reaches 2 μm independently form the gage length and accuracy of measurement is 0.2% of the measured value (linear correlation between the optical signal and the deformation). The dynamic range of the sensors is 0.5% in compression and 1.0% in elongation, and single measurement typically takes 6 to 10 seconds.

The SOFO system was developed in early 1990's and since 1995 it was commercialized and applied to the monitoring of a wide range of civil structures, such as geotechnical structures, bridges, dams, residential and industrial buildings, just to name a few [3], [4], [5], [6]. The system is insensitive to temperature changes, EM fields, humidity and corrosion, and immune from drift for at least 6 years, making it ideal for both short- and long-term monitoring. Being designed for direct embedding in concrete [3], the sensors allow an easy and fast installation. The long gage-length makes them more reliable and accurate than traditional strain sensors, averaging the strain over long bases and not being influenced by bcal defects in material (e.g. cracks and air pockets). More information on the SOFO system and its applications can be found in the references [6]. The components of the system are presented in Figure 2.

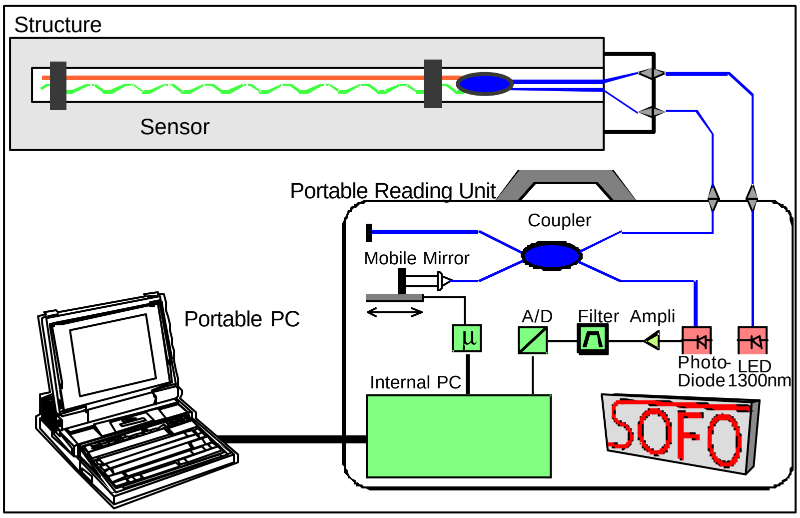

Fig. 2: Schema of functioning and components of the SOFO system

4. Monitoring strategy 2: selection of Sensor topology and network

4.1. Monitoring at local column level

A good compromise with respect to design criteria 1 and 5 has been to equip 10 ground columns (between 1st and 2nd floor) with the sensors. The ground columns have been selected being the most critical elements in the building while the number of sensors was adapted to the available budget.

The dominant load in each column is compressive normal force; therefore it is supposed that influence of bending to deformation can be neglected. Consequently single sensor per column, installed parallel to column axis, and not necessary in the center of gravity of the cross-section is estimated as sufficient for monitoring at local column level. The position of the sensor in column is schematically presented in Figure 3. The length of the sensors is determined with respect to the available height of the column (3.5 m) and on-site conditions, hence two-meters long sensors have been used.

In each column the sensor was attached on rebars before the pouring of concrete as represented in Figure 4. The sensor connector has been protected with a small connection box, which is also embedded in concrete (see Fig. 4). In this way neither the sensor cable nor the connector egresses from the column. The connection box is provided with a small opening allowing access to the sensor connector after the column is poured. Closed opening and connected sensor are presented in Figure 4.

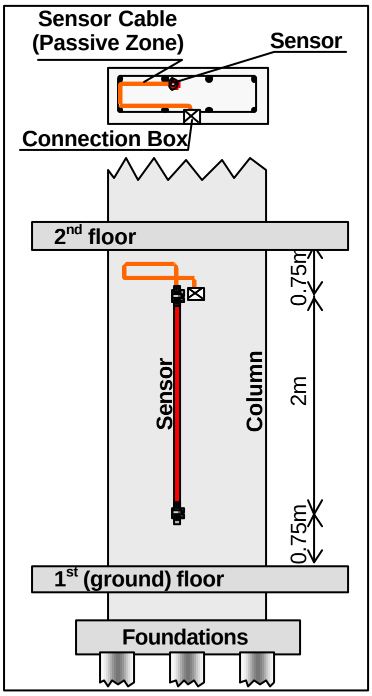

Fig. 3: Sensor position in column

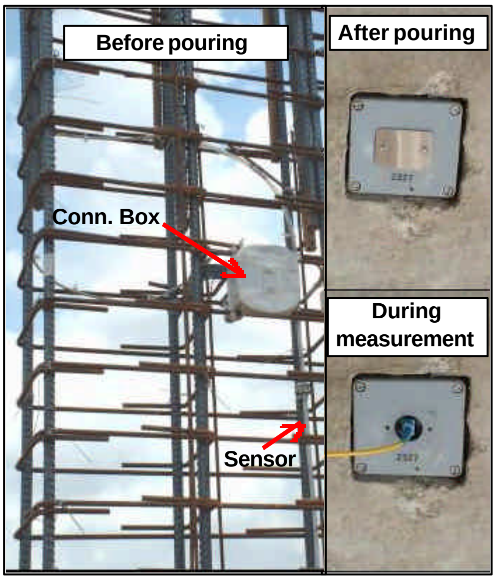

Fig. 4: Sensor and connection box installed on a rebar cage, and connection box after the pouring of columns

4.2. Monitoring at global structural level

Monitoring of building at the global level is based on correlation of the measurements performed on each column. The main expected issues are unequal settlement of foundations that may produce redistribution of strains and stresses in columns and in some cases rotations of the 2nd floor.

Settlement in the foundation of a column can be detected analyzing the strain evolution at the column level and in comparison with other columns belonging to the same Unit. For example if the foundation of a column is subjected to settlement, the strain in this column will decrease since it becomes less loaded, and the strain in the neighboring columns will increase because they take over part of the load released by the settlement of the observed column.

The number of columns to be equipped by sensors has been limited, thus not all parts of the building could be provided with sensors. It was decided to equip two sets of two Units, the first set with three sensors and the second set with only two sensors. The remaining two units were not monitored.

The position of columns equipped with sensors is presented in Figure 5. This configuration of sensors allows, on a local structural level, the monitoring of columns with different cross-sections, and on a global level, the monitoring of the structural behavior of four units and an estimation of the global building behavior.

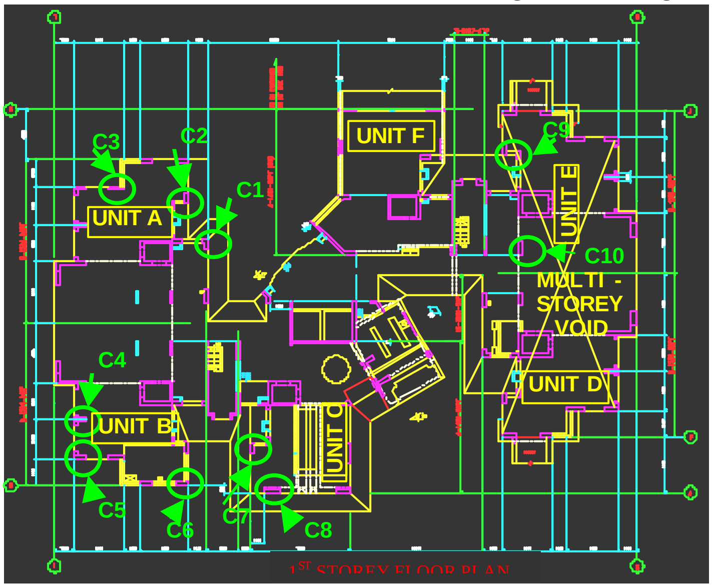

Fig. 5: Position of the columns in ground floor equipped with sensors

5. Monitoring strategy 3: Data assessment

5.1. Average strain in concrete columns

The sensor installed in a vertical column measures average strain in the column over the sensor length and at the position in cross-section where it is installed (see Figure 3). The average strain measured by a sensor is given by the following equation:

$$\varepsilon = m_s / l_s \tag{1}$$

Where ε denotes the average strain over the sensor length (active zone), m_s - deformation measured by the sensor, and l_s - length of sensor.

The following seven forms of the strain can occur during the concrete life [3], [7]: Plastic shrinkage (ε_p), autogenous shrinkage (ε_a), drying shrinkage and swelling (ε_h), carbonatation shrinkage (ε_{car}), thermal strain (ε_T), strain due to load (ε_s) and Creep (ε_j). Thus the total strain at time t after the pouring of concrete can be expressed as:

$$\varepsilon(t) = \varepsilon_s(t) + \varepsilon_j(t) + \varepsilon_T(t) + \varepsilon_p(t) + \varepsilon_a(t) + \varepsilon_h(t) + \varepsilon_{car}(t) \tag{2}$$

Some components of strain occur only during the early age some of them afterwards, but the sensor will always measure their total sum. To evaluate each part of the strain it is necessary to know the concrete composition, and to measure some additional parameters like temperature, humidity, load, etc. Even if all these parameters are monitored, the evaluation remains difficult due to lack of knowledge about the sources of the phenomena and difficulties to mathematically model them.

The creep strongly depends on stress level and the age of concrete (after pouring) when the stress is generated [2]. Younger concretes express bigger values for creep. On the other hand, the total shrinkage depends on the water content in concrete, which depends on environmental humidity, diffusion coefficient of the concrete and geometry of the column cross-section [2], [7]. Temperature strain depends on temperature variations but also on thermal expansion coefficient, which is not constant in time and depends on age and humidity [3], [8]. Finally the strain due to load can be redistributed even if the load is constant since the strain in other parts can vary in time and can provoke a redistribution of strain and stresses in hyper-static structures.

As presented in the previous paragraph, an extremely accurate analysis of strain requires monitoring additional parameters and the use of very sophisticated modeling for calculation. The analysis performed in such a way is expensive and exaggerated with respect to the aim of the monitoring project. This is why a simplified approach is adopted.

5.2. Numerical modeling

The numerical modeling is based on the use of all unknown parameters such as creep coefficient, shrinkage of concrete, etc. from available codes, and in this case the CEB-FIP Model Code 1990 [2] has been used. The mathematical models are simplified and modeling is not time-consuming. The detailed presentation of the model excceds the topic of the paper and therefore only the main features are presented.

The monitoring started when the period of early age of concrete was finished. Thus all the components related to early age deformation in Equation 2 are neglected. Therefore, the total average strain measured by sensor at time *t* after the pouring can be expressed as:

$$\varepsilon_m(t) = \varepsilon_\sigma(t) + \varepsilon_\varphi(t) + \varepsilon_T(t) + \varepsilon_{sh}(t) \qquad (3)$$

Where ε_m denotes average strain measured over the sensor length (active zone), ε_{sh} denotes total shrinkage and other parameters are as in Equation 2.

The values of creep $\varepsilon_\varphi(t)$ and total shrinkage $\varepsilon_{sh}(t)$ were determined using the code and with respect to the corresponding assumptions [2], and the values of thermal strain $\varepsilon_T(t)$ were neglected. The evolution of elastic average strain (strain related to load) $\varepsilon_\sigma(t)$ was then calculated from the Equation 2 and its relation with the stresses and normal forces evolution was established using the following equation:

$$e_s(t) = \frac{s(t)}{E} = \frac{N(t)}{EA} \qquad (4)$$

Where σ denotes stress in column, N – normal force applied to column, E – equivalent Young modulus of columns (concrete, 28GPa + rebars, 200GPa), and A – equivalent area of cross-section (concrete + rebars).

In the Equation 4, the following additional assumptions were adopted:

- The influence of all other loads (e.g. bending moments, torsion and shear forces) to strain can be neglected.
- The Young modulus is constant in time and independent on stress level (behavior of concrete is linear);
- The area of cross-section is constant in time.

6. Results and analysis

6.1. Description of monitoring process and conditions

At the time of writing, measurements recorded during the construction of 19 storeys were performed. To decrease the costs of monitoring in this phase, only periodical readings have been performed, one campaign over all the sensors after a new storey was completed. The early age measurements are estimated as not important in this project and therefore, were not performed. The aim of these measurements has been to increase the knowledge concerning the real behavior of the columns during construction and to control the construction process.

The most important parameters that have influenced performances of monitoring were the schedule of measurements, temperature, loads and numerical model for data analysis.

The initial measurements were performed after the 2nd storey was achieved (remind that the 2nd storey is the first storey built on columns equipped with sensors, see Figure 4). This measurement is a reference for all further measurements. The initial measurements before the 2nd storey was built as well as the measurements after the 3rd storey was built were not registered since the sensors were inaccessible. These missing measurements involved some imperfection in the calculation during data analysis.

The temperature in Singapore is ranged between 20°C and 30°C during the day or night and independently from the season. This fact along with the limited budget for monitoring leaded to decision to not monitor the temperature.

Full data analysis of the recorded results exceeds the topic of this paper. Therefore only themes important to present and highlight the performances of employed monitoring strategy are presented in this section.

Diagram presented in Figure 6 shows the time-dependent evolution of the average strain in columns after each new storey was completed. The average strain is calculated using Equation 1.

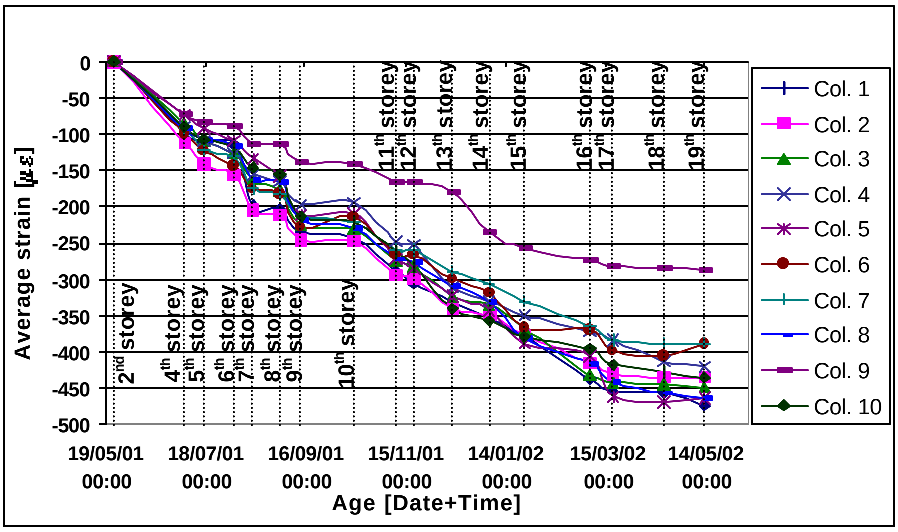

Fig. 6: Evolution of total average strain in columns monitored by SOFO system

6.2. Analysis of measurements at local column level

The different shrinkage and creep components of strain, presented in Equation 3, were calculated for each column using CEB-FIP Model Code 1990 [2] and are presented, for the column C3, in Figure 7.

The elastic strain is obtained from monitoring in an indirect way using the Equation 3 (thermal strain was neglected). The theoretical elastic strain evolution has been calculated using known theoretical values for loads and Equation 4. These two curves are presented and compared for the column C3 in Figure 7.

The qualitative behavior of all the columns was comparable (see Figure 6). The shrinkage component of the strain has participated with 16% to 19% in the total measured strain, with the tendency of slight decrease with time (see Figure 7).

The creep component increases from approximately 30% in beginning to approximately 40% after the 19th storey was completed. During the same period the elastic strain decrease from approximately 50% to 40-42% (see Figure 7).

For all the columns the difference in theoretical elastic strain and elastic strain obtained from monitoring was initially 100% to 200%, and decreased during the construction. After the 19th storey was completed, it has been ranged between –32% and + 27% for all the columns with exception of the column C9, which deformed significantly lower (see Figure 6). This relative difference in theoretical and monitored value is due to several influences. First, the theoretical elastic strain considers only the dead-load of the storeys, while the real on-site state was different since during the construction the scaffoldings and some construction material was present, and they increased the effective load of columns. Second, the influence of temperature variations could not be fully neglected: it is estimated that the change in only 1°C generates the strain approximately equal to the elastic strain generated by one storey. Thus, the temperature variation of 5°C can involve the inaccuracy in determination of elastic strain, which is as big as 25%.

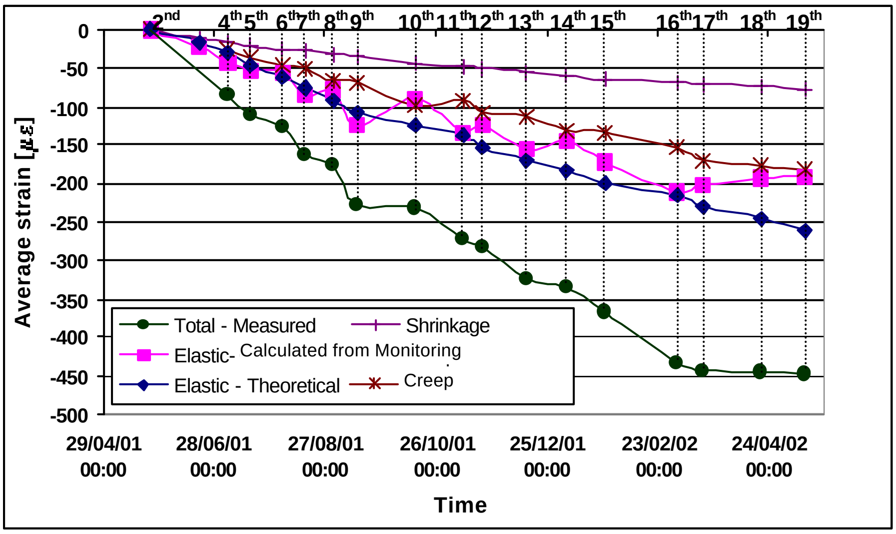

Fig. 7: Evolution of strain components obtained from modeling and monitoring, and evolution of theoretical elastic strain for column C3.

The third source of difference is the imperfection of the model used to calculate shrinkage and creep [2]. This model is general and doesn't take into account real parameters, but only the values found in literature. Fourth possible source of difference is a slight redistribution of load among the columns belonging to the same unit due to stiffness of the 2nd floor 3D structural frame (see also the next subsection). Finally, the lack of measurements before pouring of 2nd storey, and after the construction of 3rd storey, imposed hypothesis that the load increments due to construction of 2nd, 3rd and 4th storey was equal, which is probably not the case.

The presented relative difference is more emphasized in beginning, since the load and corresponding elastic strain are low, and it logically decreases with advancement of construction. Thus, the elastic strain obtained form monitoring is qualitatively comparable to the theoretically predicted elastic strain during the whole monitoring period (see Figure 7 and 8), and quantitatively comparable after the influence of presented sources of difference is minimized, i.e. approximately after the 6th storey was built.

The load evolution in each column has been determined using elastic strain values obtained from monitoring and the Equation 4. The obtained histories of loads fit with the theoretical values of loads as good as the corresponding histories of elastic strain. Thus, only the column C9 was less loaded than expected. The load histories, theoretical and monitored, in case of columns C1 and C8 are presented in Figure 8. In the same figures the load corresponding to the temperature variation of

±5°C is shown in order to highlight the temperature influence to the deformation of columns.

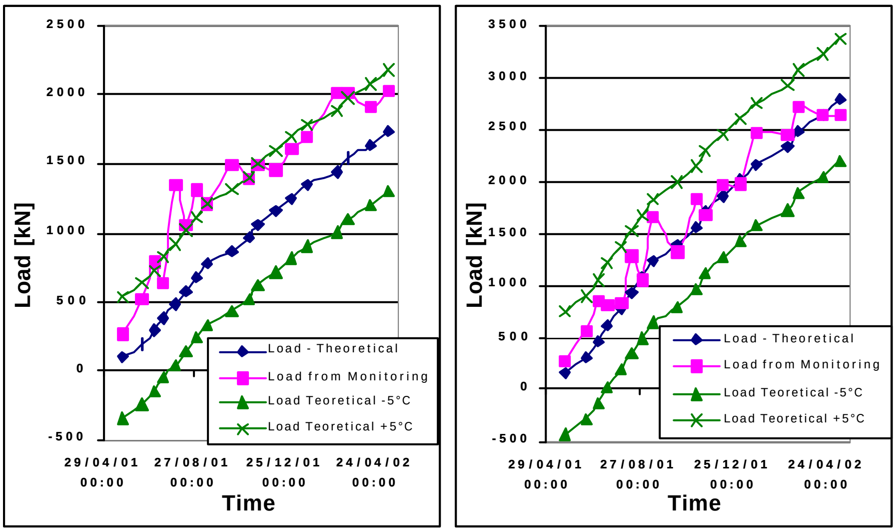

Fig. 8: Evolution of load in columns C1 and C8 – comparison between theoretical values and values obtained from monitoring

6.3. Analysis of measurements at global structural level

Analysis at global level is based on comparison between the strains measured in the columns belonging to the same Unit and globally, between all the instrumented columns.

The columns C1, C2 and C3 are located in Unit A (see Figure 2). The average strain measured in these columns is approximately the same for each column (see Figure 6). This indicates that the 2nd floor slab practically displaced as a rigid body. The fact that the measured strain is approximately equal for each column leads to conclusion that the vertical displacement of the 2nd floor is performed with an inclination, which can practically be neglected.

The estimated strain and the forces in columns C1 and C2 are slightly higher than theatrically predicted (see Figure 8), while in column C3 they are slightly lower (see Figure 7). The observed difference is probably due to redistribution of stresses and strains, which is imposed by the stiffness of the 2nd floor 3D structural frame and interaction with the other columns that have not been equipped with sensors. This statement is supported by the fact that the sum of forces in concerned columns obtained from monitoring is approximately equal to the corresponding sum obtained from the theoretical prediction.

Since the measured strains are in relatively good agreement with theoretical predictions for each column, and since there is no significant difference in their magnitudes, one can conclude that there is no non-uniform settlement of columns foundations (see Figure 6).

The analysis and conclusions concerning the Units B and C are the same as for Unit A (see Figures 7 and 8), with notice that for Unit C the analysis is less complete and less conclusive since only two columns belonging to this Unit have been equipped with the sensors.

Different behavior was noticed in the unit E (see Figure 5). Column C10 has deformed for the same order of the magnitude as the columns C1 to C8, but the measurements results of columns C9 has represented only approximately 0.63 of the strain in column C10, after each new storey was built (see Figure 6). It is important to highlight here that structural conditions of the columns C9 and C10 are different from other columns. In the first six floors of the Unit E there is no dwelling units (see Figure 5). The space above the column C9 is practically empty, while the column C10 additionally supports a bridge for connection to building parking. Therefore, the behavior of 3D structural frame in Unit E is more complex, and its theoretical modeling was difficult and possible only with limited accuracy. The monitoring has helped to understand the real behavior in case of this complex part of the building and to improve theoretical modeling. A third sensor installed in a column belonging to the Unit E could help to explain even better the behavior of the column C9 and the Unit it-self. Thus, due to lack of information, the analysis of the behavior of the Unit E is only partially conclusive.

Figure 6 shows that all the columns have approximately the same strain evolution diagram, with exception of the column C9 whose behavior was proportional to that of column C10. Such a behavior of the columns indicates consistent and expected evolution of the building during the construction. An irregularity was noticed on a global level: the evolution diagrams are not proportional to loads, sometimes they are constant even if the new storey was built (diagrams are constant after 7th, 9th and 17th storey, see Figure 6) and sometimes high jumps are noticed. Consistent behavior of the columns indicated two possible reasons for this irregularity, the first is unknown additional non-permanent load on the floors (scaffoldings, stocks of material, machines etc.) and the second is unknown strain due to temperature variations. Consistency in magnitudes of measured total strains (along with explanation of behavior of the column C9) leads to conclusion that no non-uniform settlement of foundations or Units is observed regarding the building at global structural level.

7. Evaluation of performances of employed monitoring strategy

The presented monitoring strategy has consisted of selection of a suitable monitoring system, the sensor topology and position in column, the position of instrumented columns in the building, and of models used for data analysis. All these parameters were set regarding the rigorous design criteria.

The SOFO monitoring system has been selected. The installation of the system did not influence the construction works (no delay was generated). All the installed sensors survived embedding operation including pouring and vibrating of the concrete. The SOFO sensors, due to their long-gage allowed monitoring at structural level, while high accuracy and stability made possible long-term monitoring with no calibration or other intervention on the system. Measurements have been taken manually due to on-site construction conditions. After the construction of the building will be completed, all the sensors can be connected to single central measurement point allowing automatic and remote monitoring. The SOFO monitoring system fully responded to design criteria, and it performance is estimated as excellent.

At a local level, a single sensor per column was very good choice since the strain is characterized only by uniform compression. This statement is confirmed by quantitatively consistent behavior of columns. If bending of columns is expected, then the following two solutions are proposed: to install sensor in the center of the cross-section (less expensive), or to install pairs of sensors, symmetrically arranged with respect to the center of the cross-section (more expensive, but allows monitoring of curvature of the column).

The limited number of instrumented columns per Unit was good option and it allowed analysis at global level. However, the employed strategy could be improved if some additional columns were monitored. Units D and F were not provided with sensors and therefore no relevant information concerning their behavior was collected. Also, the installation of at least three sensors per Unit will significantly improve the analysis (the best analyzed units are A and B, and they have been equipped with tree sensors).

Due to the limited number of monitored parameters (only total average strain was monitored) data analysis consisted of combination between results of measurement and numerical modeling. Important parameters like creep and shrinkage were modeled numerically using CEB-FIP Model Code. The results have shown qualitative consistency and quantitative agreement with the theoretic predictions in approximate average range of ±25.

More accurate data analysis will require monitoring of additional parameters like shrinkage, creep, temperature, humidity etc. Such complete monitoring can be expensive and is probably not necessary, since the approach presented here provided satisfactory results. However, the data analysis can considerably be improved with reasonable additional investment by involving columns temperature monitoring. Presented experience has confirmed that even small thermal variations can significantly influence the deformations and generate uncertainties in the results interpretation and analysis.

In spite of rigorous design criteria, the results obtained using the described strategy are estimated as very good. Important parameter related to local and global structural behavior were collected and allowed detailed analysis of structural behavior during construction.

8. Conclusions

A pioneer project for the monitoring of residential buildings in Singapore is presented. The monitoring strategy as well as results collected during the construction of nineteen storeys are presented and analyzed. The registered parameter was average strain in columns and it allowed the monitoring of structural behavior at a local column, and a global structural (storey) level.

The use of fiber-optics sensors on such a large scale for monitoring of high-rise buildings is a first in Singapore and is directions that will help designers better understand the behavior of tall buildings during its life cycle from construction to service conditions. Such pioneering effort have already yielded results from the insights gained from enlarged knowledge concerning the real column behavior during construction and including the unexpected behavior of column C9 and Unit E which will help research into the accurate modeling of complex structures.

The employed monitoring strategy and the selected SOFO monitoring system have successfully responded to the design criteria. The monitoring strategy has shown high performance in spite limitations imposed by design criteria (limited number equipped columns, lack of temperature measurement, lack of accurate shrinkage and creep coefficients, uncertainty concerning the real load during campaigns of measurement, etc.).

9. Acknowledgements

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