Long-term monitoring of high-rise buildings using long-gage fiber optic sensors

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ABSTRACT: Recent development of fiber optic sensors and informatics technology, made structural health monitoring of civil structures cost effective. In this paper a large-scale lifetime buildings monitoring program is presented. The program started with a pilot project in 2001 in Singapore and since then an important number of high-rise buildings was monitored. The monitoring aims of this unique program have been to increase safety, verify performance, control quality, increase knowledge, optimize maintenance costs and evaluate condition of the structure after earthquake, impact or terrorist act. The long-gage fiber optic sensors were embedded in the ground-level columns during the construction, thus the monitoring started with the birth of the structure. Based on results it was possible to evaluate and follow the performance of the buildings in long term through every stage of their life including construction, 48-hours live loading and tremor.

1 INTRODUCTION

Civil structures are omnipresent in every society, regardless of culture, religion, geographical location and economical development. It is difficult to imagine a society without buildings, roads, rails, bridges, tunnels, dams and power plants. Structures affect human, social, ecological, economical, cultural and aesthetic aspects of societies and associated activities contribute considerably to the gross internal product. Therefore good design, quality construction as well as durable and safe exploitation of civil structures are goals of structural engineering.

Structural Health Monitoring is becoming recognized in the domain of civil engineering as a proper mean to increase the safety and optimize operational and maintenance costs of the structures. The data resulting from the monitoring program is used to optimize the operation, maintenance, repair and replacing of the structure based on reliable and objective data. Detection of ongoing damage can be used to detect deviations from the design performance. Monitoring data can be integrated in structural management systems and increase the quality of decisions by providing reliable and unbiased information.

In case of residential, high-rise buildings, the malfunctioning can have serious consequences. The most severe is an accident involving human victims. Even when there is no loss of life, populations suffer if infrastructure is partially or completely out of service. The economic impact of structural deficiency is twofold: direct and indirect. The direct impact is reflected by costs of reconstruction while the indirect impact involves losses in the other branches of the economy.

Learning how a residential high-rise building performs in real conditions will help to design better structures for the future. This can lead to cheaper, safer and more durable structures with increased reliability and performance. Structural monitoring represents a good way to enlarge knowledge of structural performance.

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 construction 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. A view of the building under construction is presented in Figure 1.

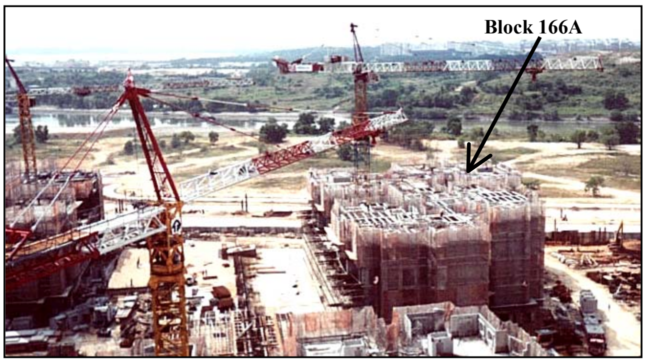

Figure 1. View to the Block 166A of Punggol EC26 project during construction

2 DESIGN CRITERIA FOR MONITORING

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

1. 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
2. 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
3. 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
4. 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
5. 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
6. 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 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 (Inaudi 1997) 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 (Inaudi 1997). 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 (Glisic 2000), (Glisic et al. 2002), (Inaudi et al. 1999), (SMARTEC 2005). 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 (Glisic 2000), 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 local defects in material (e.g. cracks and air pockets). More information on the SOFO system and its applications can be found in the references (SMARTEC 2005). The components of the system are presented in Figure 2.

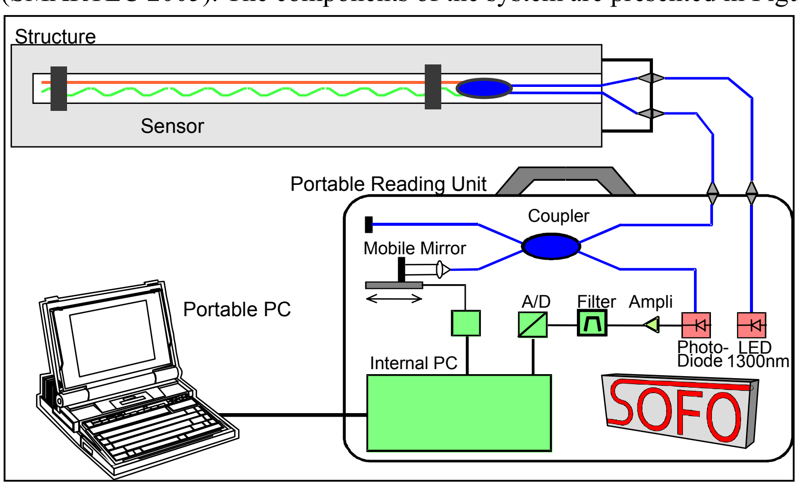

Figure 2. Schema of functioning and components of the SOFO system

4 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 Figure 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.

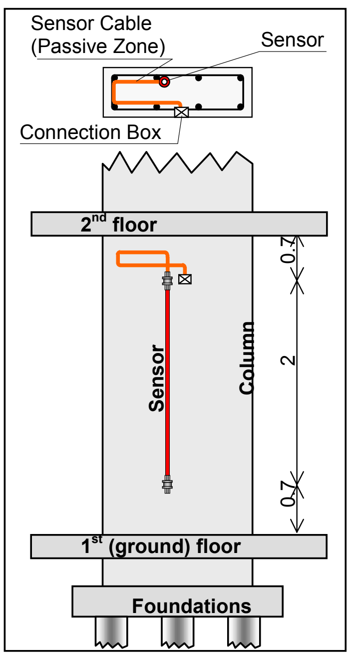

Figure 3. Sensor position in column

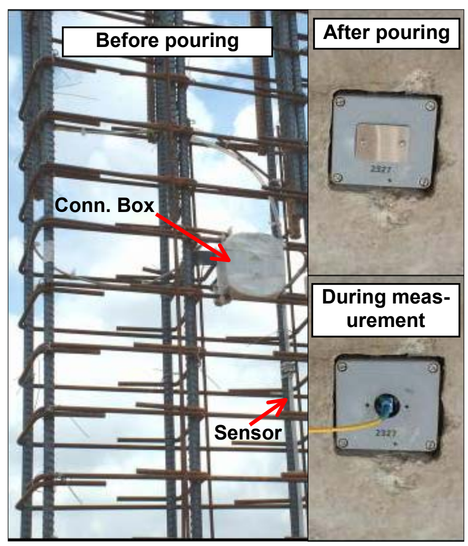

Figure 4. Sensor and connection box installed on a rebar cage, and connection box after the pouring of columns

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.

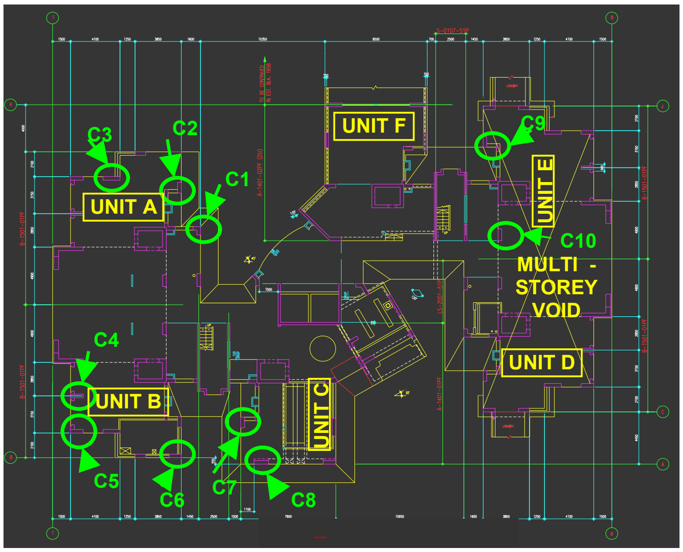

Figure 5. Position of the columns in ground floor equipped with sensors

5 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 (Glisic 2000), (Neville 1975): 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_φ). Thus the total strain at time t after the pouring of concrete can be expressed as:

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

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 (CEB-FIP Model Code 1990). 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 (CEB-FIP Model Code 1990), (Neville 1975). Temperature strain depends on temperature variations but also on thermal expansion coefficient, which is not constant in time and depends on age and humidity (Glisic 2000), (Emanuel & Hulsey 1977). 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 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:

$$\varepsilon_m(t) = \varepsilon_s(t) + \varepsilon_\varphi(t) + \varepsilon_T(t) + \varepsilon_{sh}(t) \tag{3}$$

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 (CEB-FIP Model Code 1990), and the values of thermal strain $\varepsilon_T(t)$ were neglected. The evolution of elastic average strain (strain related to load) $\varepsilon_s(t)$ was then calculated from the Equation 2 and its relation with the stresses and normal forces evolution was established using the following equation:

$$\varepsilon_s(t) = \frac{\sigma(t)}{E} = \frac{N(t)}{EA} \tag{4}$$

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:

1. The influence of all other loads (e.g. bending moments, torsion and shear forces) to strain can be neglected.
2. The Young modulus is constant in time and independent on stress level (behavior of concrete is linear);
3. 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 performed over more than four years were collected. To decrease the costs of monitoring, only periodical readings have been performed, one campaign over all the sensors after a new storey was completed, and later periodically every few months. This periodical manner of collecting data is justified by the fact that no issue was detected during the construction phase or later. The very early age measurements are estimated as not important in this project and therefore, were not performed.

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 monitored during more than four years.

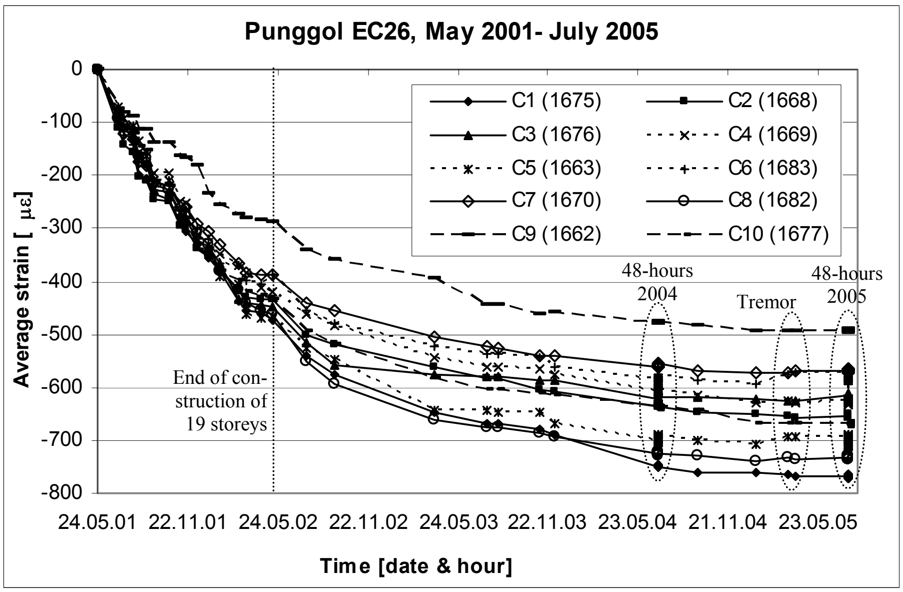

Figure 6. Evolution of total average strain in columns monitored by SOFO system

The average strain values presented in Figure 6 are calculated using Equation 1. The following four particularly important periods are highlighted in Figure 6: (1) end of construction of 19 storeys, (2) the first 48-hours continuous monitoring session performed in July 2004, (3) before and after tremor monitoring and (4) the second 48-hours continuous monitoring session performed in July 2005. All these periods as well as the full four-years monitoring record are analyzed more in details at local and global level in the next subsections.

6.2 *Analysis of measurements at local column level*

6.2.1 *Comparison between designed and monitored total strain during construction and in long-term*

The different shrinkage and creep components of strain, presented in Equation 3, were calculated for each column using for purpose developed software based on CEB-FIP Model Code 1990, and are presented for the columns C3 and C9, in Figures 7 and 8 respectively. The designed elastic strain evolution has been calculated using known theoretical values for loads and Equation 4, and total design strain as a sum of creep, shrinkage and elastic strain. The temperature was not monitored and thermal strain was neglected. The total designed strain is compared with monitored strain in Figures 7 and 8.

The designed total strain in column C3 is practically equal to measured total strain indicating that the performance of the column follows numerical calculus. Contrary, the measured total strain of column C9 is significantly lower than the designed total strain indicating over-dimensioning of the column.

The qualitative behavior of all the columns was comparable (see Figure 6). The shrinkage component of the strain participates with 10% to 15% in the total measured strain, four years after construction. The creep component increases from approximately 30% in beginning to approximately 40% after the 19th storey was completed, and up to 45% after 4 years. During the same period the elastic strain decrease from approximately 50% to 40-42% (see Figure 7).

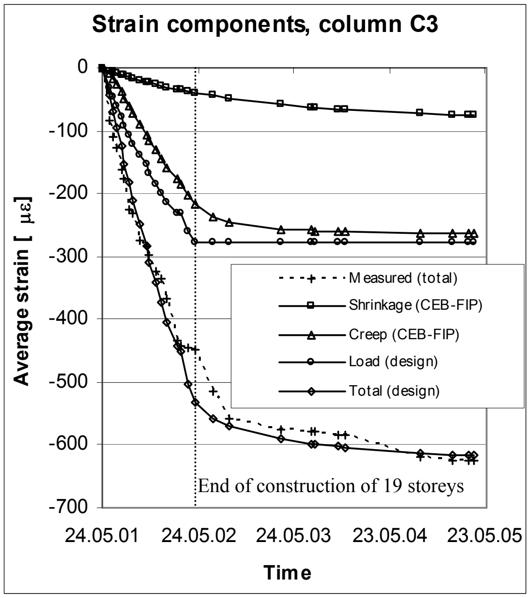

Figure 7. Strain components in column C3

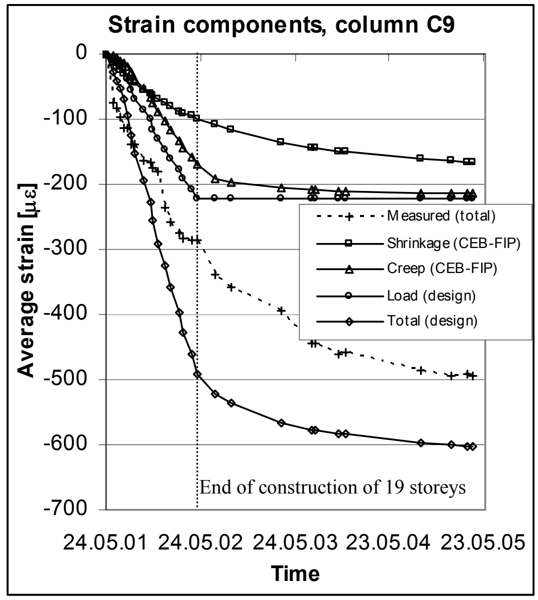

Figure 8. Strain components in column C9

For all the columns the difference in designed total strain and total strain obtained from monitoring was 100% to 200% after first two storeys were built, 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 Figures 6 and 8). 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%. The third source of difference is the imperfection of the model used to calculate shrinkage and creep (CEB-FIP Model Code 1990). 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 design load and corresponding elastic strain are low, and it logically decreases with advancement of construction. Thus, the total strain obtained form monitoring is qualitatively comparable to the theoretically predicted (designed) strain during the construction and the whole monitoring period (see Figures 7 and 8), indicating correct and safe performance of the columns.

6.2.2 *48 hours continuous monitoring sessions, July 2004and July 2005*

The aims of 48-hours monitoring campaign performed in July 2004 were (1) to learn the building behavior caused by daily temperature changes and inhabitant fluctuations and (2) to record the health state of the building as a reference for comparison with the future monitoring results.

It was decided to perform one measurement over all the sensors every hours in order to quasi-continuously monitor the structural behavior of the building. The temperature sensors were not present and therefore, only ambience temperature was monitored along with relative humidity and weather description in order to observe possible correlation.

Since the period of 48 hours is relatively short, the part of strain generated by creep and shrinkage can be neglected. Thus, the two main factors influencing the average strain variations are temperature variations in columns due to weather and day-night heating and cooling, and vertical load changes due to movement of inhabitants that are at work during the day (empty building, lower load) and at home during the night (full building, higher load).

The values of total measured strain are relatively stable during the observed period and show dependence rather on ambient temperature variations, since the load changes were small (not all the apartment are inhabited). This dependence is different for different columns. Some columns experience small dimensional variations while some columns show bigger dependence. The summary of column reaction to change in ambience temperature is presented in Table 1.

Table 1: Column average strain generated by ambience temperature changes

	Ambient temperature	Average strain in columns [με]									
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Average value	28°C	-749	-635	-620	-607	-697	-586	-559	-725	-478	-638
Negative variation	-3°C	-2	-3	+3	-4	-8	-8	-2	+2	-2	-4
Positive variation	+2°C	+2	+3	-3	+5	+8	+11	+4	-2	+2	+2

This different reaction of columns can be explained by different temperatures of the column with respect to the ambience temperature and interaction with other columns and storey slab. Temperature variations in columns are smaller or bigger than ambiance variation due to thermal inertia of concrete and direct exposure to Sun.

Temperatures in columns were not directly measured, consequently it is not possible to make an accurate correlation between the temperature and average strain changes. On the other hand, the columns have different stiffness and therefore the total strain is also consequence of their interaction through the storey slab. This is why some columns have inverse reaction to the temperature variation (shrinkage in case of heating, e.g. columns C3 and C8). As an example, the diagram of total strain change in column C6 registered during 48-hours session in July 2004 is presented in 9.

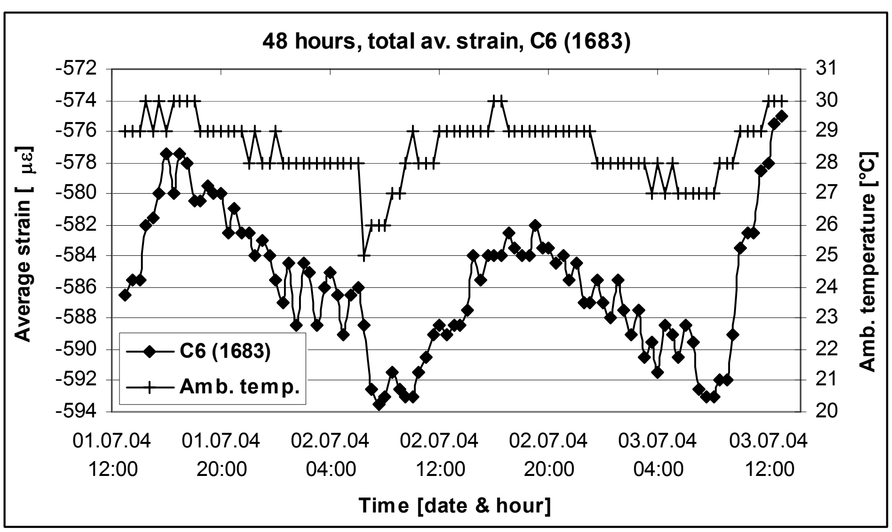

Figure 9. Total average strain and ambient temperature recorded during 48-hours continuous monitoring session performed in July 2004

In the evening hours (18h00 to 22h00) the temperature was relatively constant but inhabitants are expected to come home and load the building. Since no significant compression in columns was recorded during this period it is reasonable to conclude that the in-and-out movement of inhabitants doesn't influence significantly the behavior of the building.

The 48-hours continuous record is used as a reference for the future measurements. An example of comparison between the 48-hours monitoring sessions performed in July 2004 and July 2005 are presented for column C6 in Figure 10.

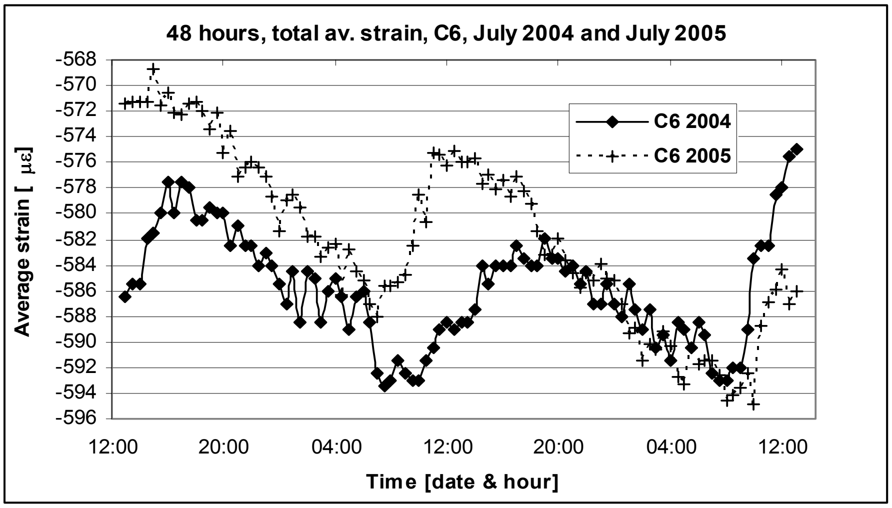

Figure 10. Total average strain in column C6 recorded during 48-hours continuous monitoring sessions performed in July 2004 and July 2005

The values of total average strain recorded in July 2005 are similar to those recorded in July 2004, and small difference is consequence of different temperature conditions. Therefore, no degradation in structural performance of columns is noticed during the one-year period elapsed between two 48-hours sessions.

6.2.3 *Post tremor analysis*

In March 2005 the earthquake in neighboring Indonesia created a tremor in Singapore. In order to evaluate potential degradation in structural performance a single session over all the sensors was performed just after the tremor. Results of this session are presented in Figure 11.

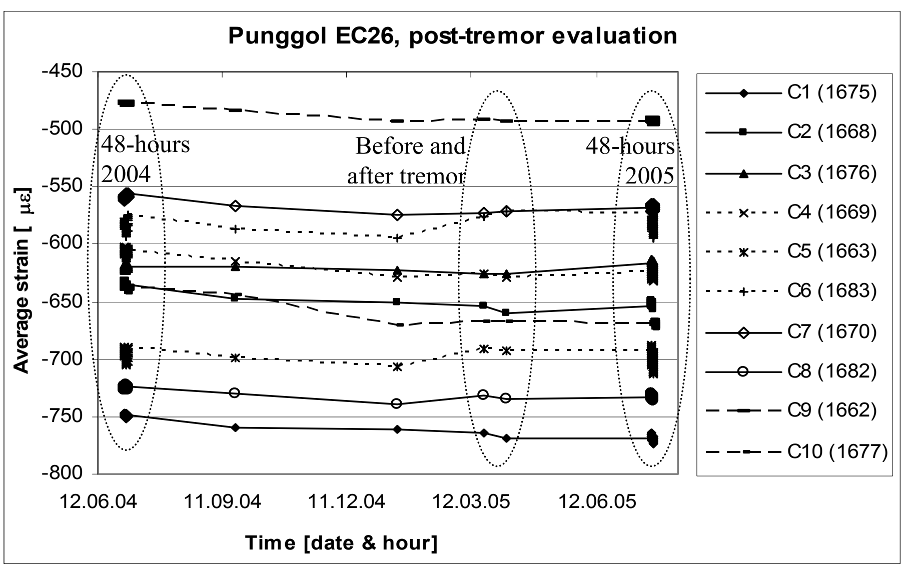

Figure 11: Average strain measurements recorded before and after tremor

The change in strain before and after the tremor varied in different columns from –7 με to +5 με. This variation is considered as regular, and generated by temperature and live load variation rather than tremor, since in range of previously discussed 48 hours variation registered in 2004. Moreover, the range of 48-hours variation of strain registered in 2005, which is similar to that registered in 2004, confirmed that no degradation of performance occurred due to tremor.

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.

6.3.1 *Global analysis during construction*

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 2^{nd} 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 2^{nd} 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, while in column C3 they are slightly lower (Glisic et al. 2003). The observed difference is due to redistribution of stresses and strains, which is imposed by the stiffness of the 2^{nd} 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.

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 7^{th}, 9^{th} and 17^{th} 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.

6.3.2 *Global analysis in long-term*

The global analysis in long-term consists of observation in correlation changes between the columns. If no degradation in performance occur, the correlation between the columns is expected to be linear, since the horizontal elements, beams and slabs, impose linear redistribution of total strain. If malfunction occurs in one column, the correlation between this column and other columns will not be linear any more. The correlation between the column C1 and other columns is presented in Figure 12. For the reasons of clearness, only two correlation lines and their coefficients are presented in the figure.

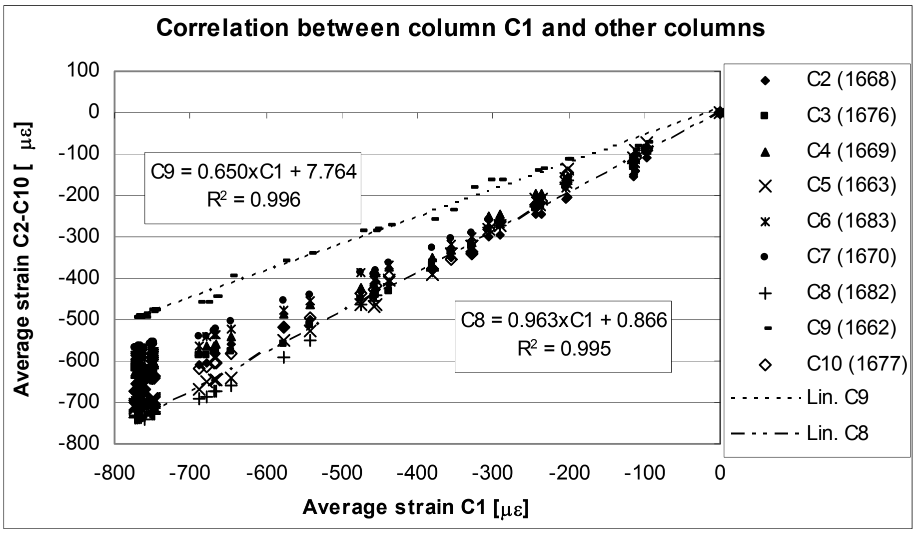

Figure 12. Correlation between column C1 and other columns

The coefficients of correlation R between the column C1 and other columns is better than 0.989 indicating good linear correlation and sound structural performance.

7 CONCLUSIONS

A pioneer project for the monitoring of residential buildings in Singapore is presented. The monitoring strategy as well as results collected during four years on a 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 the first in Singapore and sets 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. Moreover, the 48-hours sessions confirmed sound performance of the building in long-term and made possible post-tremor analysis.

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.).

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