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LARGE SCALE LIFESPAN MONITORING OF HIGH-RISE BUILDINGS USING LONG-GAUGE 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. The results of monitoring were analyzed at local – column, and global – building level and the software developed in order to separate strain components such as elastic strain, creep, and shrinkage. The comparison between the different buildings constructed within the same complex, by the same contractor, and with the same concrete properties allowed quality control and cross-comparison after the tremor provoked by neighboring Indonesian earthquake. The employed monitoring system, method, and the results gathered over more than five years are presented and analyzed in this paper.

INTRODUCTION

Structural Health Monitoring is becoming recognized in the domain of civil engineering as a proper means 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 the whole lifespan of the building, from construction to the in use. Thus, for the first time the optical fiber sensors are used in a large-scale for life cycle monitoring of high-rise buildings.

The Punggol EC26 project consists of six blocks founded on piles, and each block is a nine-teen-storey 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.

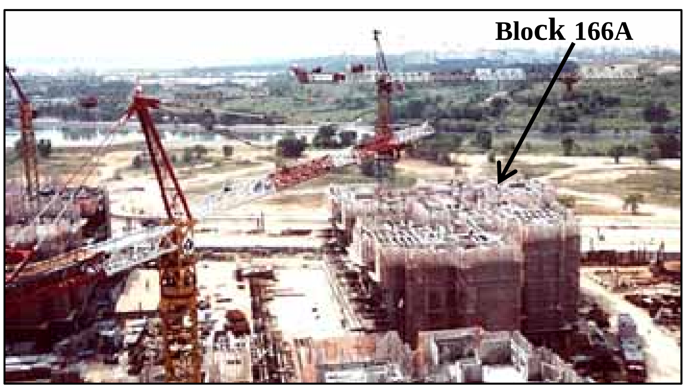

Figure 1. View of Block 166A of Punggol EC26 project during construction

MONITORING SPECIFICATIONS

Several monitoring criteria have influenced the development of the monitoring strategy.

It was required to monitor critical members, which malfunctioning or failure will generate partial, or even complete, malfunctioning or failure of the structure. Monitoring has to be performed at local and at global structural levels. Knowledge concerning the behavior of one or few structural elements (columns) is not sufficient to make conclusions concerning the global structural behavior; therefore a representative number of elements has to be monitored.

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.

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, consequently the sensors must have long gage length.
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.

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 [1]. Consequently, the monitoring system SOFO [2], based on low interference in optical fibers, is evaluated as the most suitable for this application.

SELECTION OF SENSOR TOPOLOGY AND NETWORK

A good compromise with respect to design criteria 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 length of the sensors is determined with respect to the available height of the column (3.5 m) and on-site conditions; hence two-meter long sensors have been used. The position of the sensor in column is schematically presented in Figure 2.

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 in absolute value since it becomes less loaded, and the strain in the neighboring columns will increase in absolute value because they take over part of the load released by the settlement of the observed column, and correlation between these redistributed strains will be changed. The position of columns equipped with sensors is presented in Figure 3.

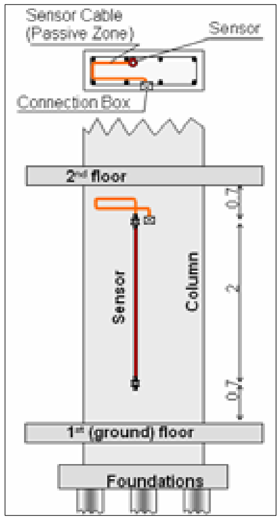

Figure 2. Sensor position in column

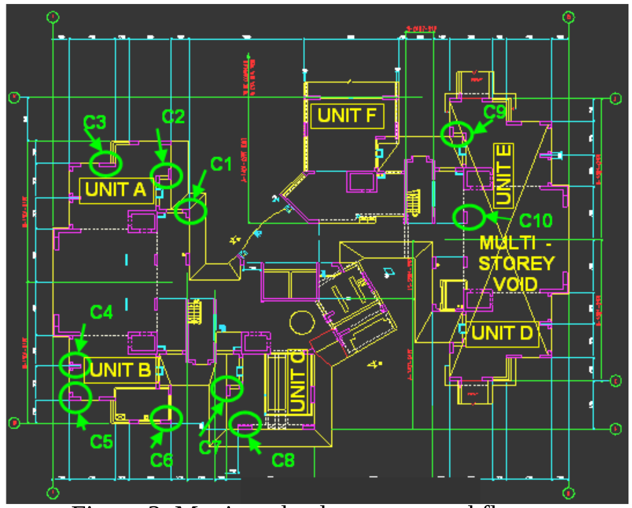

Figure 3. Monitored columns, ground floor

RESULTS AND ANALYSIS

At the time of writing, measurements performed over more than five 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.

In order to (1) learn the building behavior caused by daily temperature changes and inhabitant fluctuations and (2) record the health state of the building as a reference for comparison with the future monitoring results, it was decided to perform 48-hours quasi-continuous campaigns of measurements (one measurement every hour over 48 hours) once a year since July 2004. These measurements were very helpful in evaluating the health condition after the unusual events such as tremor (see further text).

Full data analysis of the recorded results largely exceeds the topic of this paper and can be found in references [1,3,4]. Therefore only themes important to present the most important achievements and highlight the performances of employed monitoring strategy are presented in this section. The diagram presented in Figure 4 shows the time-dependent evolution of the average strain in columns monitored during more than five years.

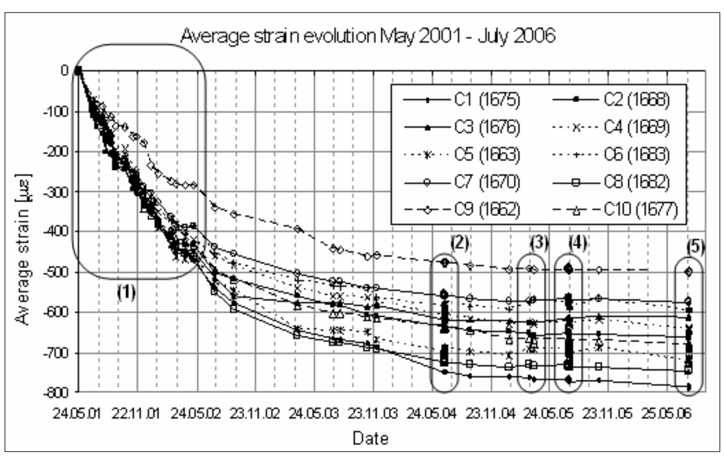

Figure 4. Evolution of total average strain in columns monitored over five years

The following five particularly important periods are highlighted in Figure 4: (1) construction of the 19 storeys, (2) the first 48-hours continuous monitoring session performed in July 2004, (3) before and after tremor monitoring, (4) the second 48-hours continuous monitoring session performed in July 2005 and (5) the third 48-hours continuous monitoring session performed in July 2006.

In order to illustrate the interpretation of the measurement at local column level, the column C1 is presented in more details. The concrete was considered as linear visco-elasto-plastic material. Based on concrete design, the Young modulus was considered to be 28 GPa. The parameters of creep and shrinkage were calculated using models [5], and load time history was determined using the designed values of load for each storey with "as built" schedule. A particular problem in the analysis is the estimation of the errors that have taken into account the different influences such as temperature variations, vertical load, bending, creep, and shrinkage [3].

In order to perform data analysis automatically and in quasi-real-time, the software that takes into account the evolution of all the strain components (elastic, thermal, creep and shrinkage) is created. The monitored total strain, compared with design strain computed using the software is presented in Figure 5. The typical and maximal error limits are also presented in the figure.

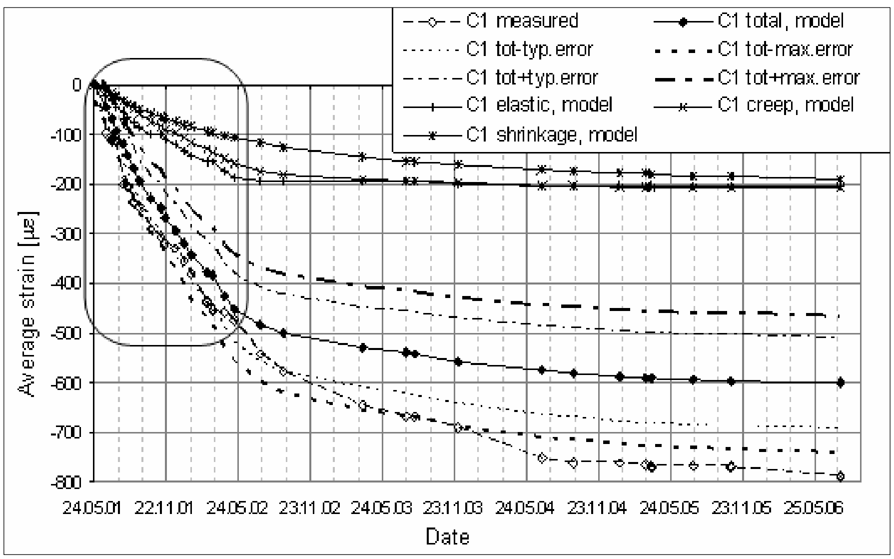

Figure 5. Comparison between the design model and results for column C1

During the construction phase (the first 12 months) the monitored strain is in agreement with the design (encircled area in Figure 5). However, during the moths that follow, the drift from the design is noticed, and this drift exceeded the typical error four months later and maximal error one year and a half later. Certain doubts concerning the determination of the error are present, but the fact that the drift shows clear tendency indicates an unusual structural behavior.

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. Example of analysis is performed on Unit A, containing the columns C1, C2 and C3 equipped with sensors (see Figure 3). The monitored strain evolutions for these columns are presented in Figure 4.

If no degradation in performance occurs, 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 C2 and other two columns is presented in Figure 6.

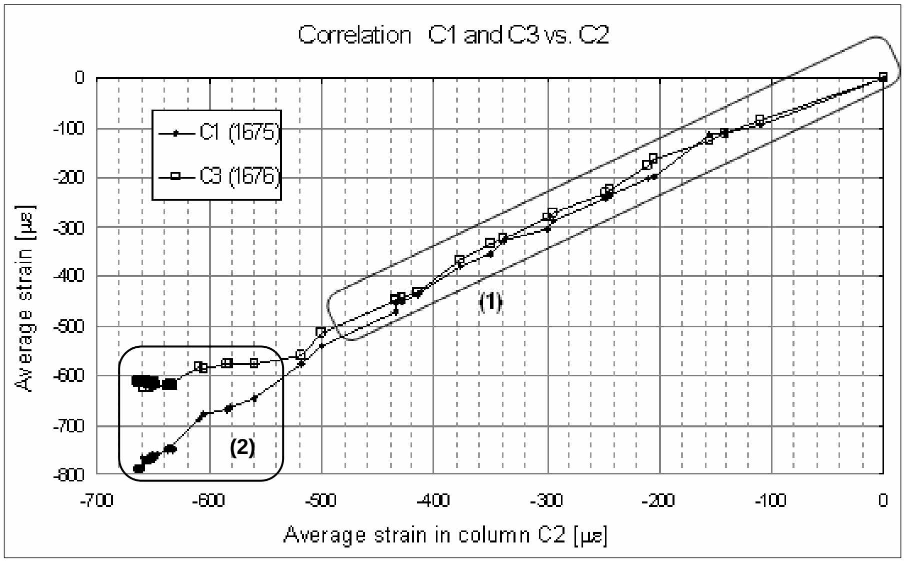

Figure 6. Correlation between column C2 and other columns; highlighted period: (1) construction of 19 storeys; (2) lost of linearity

Loss of linearity is clearly observed in the encircled area (2). The loss of linearity appears at the same time as a discrepancy between the design and measurements presented for column C1 in above text and Figure 5. For both cases, the unusual behavior can be explained by:

1) Overloading of the column (e.g. by an unknown live load)
2) Creep and shrinkage evolution
3) Stiffness of the 2^{nd} storey 3D structural frame and interaction with the other columns that have not been equipped with sensors
4) Unequal settlements of the foundations in columns and neighboring cores
5) Inclination (rotation) of the 2^{nd} storey

Since the shrinkage is similar for all columns, and the creep is proportional to elastic strain, the simple redistribution of stresses and strains will reflect small changes in linearity. Since all the Units in the building are interconnected with structural elements it is not likely to expect an independent rotation of the 2^{nd} storey slab, unless it is damaged. Visual inspection did not confirm the damage, therefore the most probable reason for discrepancy in columns behavior is unequal settlement of the foundations. Actually, no increase and even decrease in absolute strain of column C3 (see Figure 4) confirms the hypothesis of differential settlements: the column C3 settles and unloads, while the column C1 takes the load and deforms more.

The strain in the column is far below serviceability and ultimate strain limits and the drift has a tendency to stabilize. Simplified analysis demonstrated that the order of magnitude of differential settlement is 1 mm approximately, which demonstrates the sensitivity of the monitoring system and efficiency of employed monitoring strategy. Thus, detected anomaly does not present any risk for the residents. However, the strain evolution is to be monitored in the future in order to provide data necessary to trigger an early rehabilitation process.

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 4.

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 it was in range of 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.

CONCLUSIONS

A pioneer project for the monitoring of residential buildings in Singapore is presented in this paper. The monitoring strategy as well as results collected during five years on a nineteen storey building 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.

Such pioneering efforts have already yielded results from the insights gained from enlarged knowledge concerning the real columns behavior during construction. Differential settlement with low magnitude, inoffensive (at present time) to building performance was detected. 48-hours sessions allowed better assessment of the building's performance in the long-term and made post-tremor analysis possible.

The employed monitoring strategy and the selected fiber optic monitoring system have successfully responded to the design criteria. The monitoring strategy has shown high performance (detection of differential settlement of 1 mm, post tremor analysis, etc.) in spite of limitations imposed by design criteria (limited number of equipped columns, lack of temperature measurement, lack of accurate shrinkage and creep coefficients, uncertainty concerning the real load during campaigns of measurement, etc.).

The use of fiber optic sensors on such a large scale for the monitoring of high-rise buildings is the first in Singapore and the world, and sets directions that will help designers to better understand the behavior of tall buildings during its life cycle from construction to service conditions.

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