IMPLEMENTATION OF A HEALTH MONITORING STRATEGY FOR A HIGH RISE BUILDING STRUCTURE

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ABSTRACT

Monitoring the integrity of structures especially tall buildings, under severe loading is an important requirement for the validation of their design and construction, also for conducting maintenance plan. This paper presents implementation of a Structural Health Monitoring System (SHMS) in a high rise building that would be very beneficial in detecting early damage to the structure. The building considered is a 42-story concrete proposed to be at Toronto, Canada. The building is proposed to be monitored using the fiber optic sensors system that will allow monitoring, controlling and addressing any structural deficiencies before significant failure occurs. The monitoring strategy will include sensors to measure shrinkage, strain, deflection and creep. The lateral displacement of high rise building structure is usually considered as one of the major indicators to ensure the structural safety of the building. The building could be monitored for lateral and vertical deformation to ensure that stresses and strains are recorded over the lifespan of the building and the monitoring intervals is to be every 10 year interval in order to get the lateral and vertical deformation. These deformations will be simulated using finite element software program model in order to get the increase of the forces applied on the structure and will be compared to the design forces. The main focus is to ensure that the building remains safe throughout its lifespan and allow owners to feel more assured about the safety of their building.

1 INTRODUCTION

SHMS is an important engineering requirement for majority of civil engineering applications, especially for important complicated structures such as high rise buildings. SHM is a system designed to detect the structure performance overtime to ensure its safety and to extend its lifetime. This system is performed using non-destructive testing techniques for continuous assessment, to identify the structures integrity taking into considerations risk levels. The usual SHM sensors for the strains and deflection will be utilized in determination of damage existence at the structure critical members. SHMS aims to detect the structure overtime and to develop a guideline for evaluating its performance and to predict the maintenance plan of the structure. Health monitoring provides information on the integrity of large-scale structures and development of application techniques for early stage detection of damage that becomes very important for the health monitoring. The advanced sensing techniques can inspect the structure status, evaluate performance, determine the structural management for maintenance, and estimate the cost. SHM is considered as the observation of a system over time. Based on periodically measurements from a sensor network, features sensitive to the damage are extracted in order to define and predict the structural system condition.

SHM strategy begins with the periodic measurements for the critical structure members that are measured through sensing tools like the usage of sensors, by collecting these data for a management system that will be integrated to estimate the structure performance. These data are collected mainly through sensors networks and interrogations systems. These sensors are used to measure features sensitive to the damage in the structure that affects the integrity of the structure performance. These data such as the cracks, strain and stresses can provide a health assessment to the structure, i.e. based on these properties the structure performance can be evaluated accurately. The employment of a finite element model to monitor the structure performance is performed to determine the state of the structure. The forces, stresses and strains are recalculated using the monitored data from deformations and strain measurements in the structure.

In current study, the calculations of live, dead, snow, wind and earthquake load calculations has been evaluated in order to adequately determine the amount of vertical and lateral deformations applied on to the building structure. An analysis using ETABS was performed to adequately determine the amount of lateral deformation applied. A comprehensive analysis on each of the floors has been performed on each of the columns in order to find a precise over all loading of the structure. The footing of the building structure has also been analyzed to determine the adequacy of the applied loads. Sensors will detect any minor and major deflections, stresses and strains that may be affecting structural components of the building and will red flag any abnormal deviations that may take place. Moreover, the loading capacity of the existing footing, columns, shear walls, and beams in the initial design of the building were analyzed. A column schedule was completed and a foundation adequacy check was also performed. The aforementioned steps must be completed to ensure the building is as safe and economically feasible as possible.

2 LOADING CALCULATION

3.1 Dead loading

The specified dead load of the building structure includes the weight of the structure itself, all components of the structure (i.e. beams, columns, foundations, slabs, etc) permanent equipment and partitions. Dead loads remain constant in magnitude and fixed in location for the life of the building structure. The dead load can be accurately predicted from density of the material, dimension of the structure and the design configuration. We used different superimposed dead loads provided in our architectural drawings specific to each of the building floors. Our calculations show the un-factored loading that is being exerted onto the building foundations.

3.2 Live loading

Live loads applied on to floors or roofs of the structure vary depending on the use and occupancy loading requirements. Unlike dead loads, live loads cannot be precisely calculated but estimated using the national building codes. Since live loads are generally expressed as uniform loads over an area or along the length of members, the concept of tributary area is used in order to find the loads that the structural components (i.e. beams, girders and columns) carry.

In the 42 storey building, the tributary area was applied to a typical floor, and then it was extended to the rest of the floors. The national building codes have considered the maximum possible loading conditions. However, in designing high rise buildings, the full live load applied on the floors is excessively restrictive; so these codes have allowed a reduction in the live load factors where this reduction is a function of the number of buildings' floors and the tributary areas. The live load reduction factors have been accounted for as specified in NBC 2010.

a) Where structural members support the tributary area of the floor or a roof that contains the tributary area greater than 80m^2 and either used for design load of 4.8 kPa or used for storage/parking and garages the following formula was used: (A=Tributary Area of structural member)

[1] $0.5 + (20/A) ^ (1/2)$

b) Where structural members supports a tributary area of a floor or a roof that is greater than 20m^2 the following formula was used: (B=Tributary Area of structural member)

[2] $0.3 + (9.8/B) ^ (1/2)$

The live load factor has tremendously reduced the amount of loading applied onto the building foundation to obtain a more accurate result to the amount of additional floors that may be added to the existing building structure.

3.3 Wind loading

Wind loading analysis is a vital component that needs to be considered when designs a building structure. If wind loads are not analyzed precisely, this may impact the structural components of the building which includes columns, shear walls, roofing and slabs. Furthermore, it will also impact various non-structural components which include windows and doors.

Lateral loads such as wind loads usually govern the design of high rise buildings; where structural stability must be considered in order to ensure that the building can withstand wind loads. Wind loads were calculated using the static procedure from NBC 2005 4.1.7.1 as shown below: (Refer to Appendix B)

[3] $P = I_w q C_e C_g C_p$

Importance Factor: Iw = 1. For the building is determined from Table 4.1.7.1 based on the importance category of the structure.

Reference Velocity Pressure: q1/50 = 0.52 kPa. It is obtained from Table C-2 in Appendix C from the NBC.

Exposure Factor: Ce. It is determined from Table 2.3.
Gust Effect Factor: Cg = 2.0. By considering the building is as a whole and main structural member.
Net Pressure Coefficient: Cp is as follows:

- a) The net pressure coefficient Cp for floors 1-10 was assumed to be 1.6
- b) The net pressure coefficient Cp for floors 10-42 was assumed to be 1.8

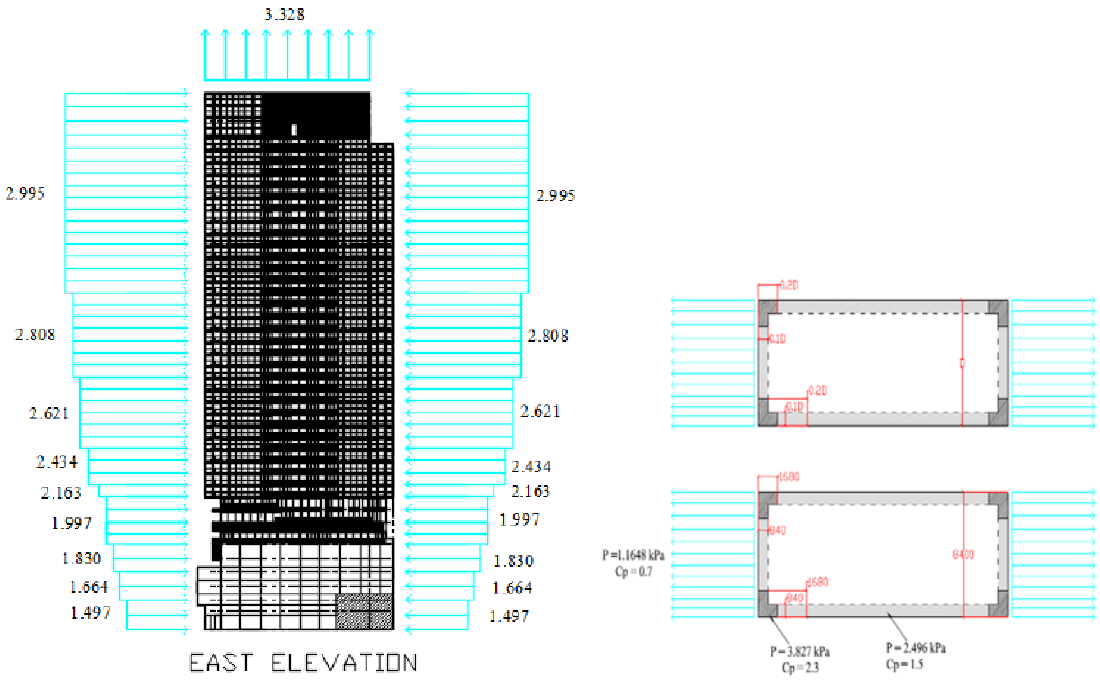

Figure 1: East elevation and roof plan wind loading

3.4 Earthquake loading

In order to develop the building structure that resists the earthquake ground motion, the following information was conducted:

Site Properties (4.1.8.4)

Soil Profile Type: From Table 4.1.8.4.A. pg. Division B 4-22
Site Classification for seismic site response is Class B- Rock
Seismic Response Accelerations: Seismic data were obtained from Table C-2 pg.C-24 Appendix C, Division B of NBC 2005

S(0.2)=0.26
S(0.5)=0.13
S(1.0)=0.055
S(2.0)=0.015
PGA=0.17

Acceleration and velocity based site coefficients: The short period site factor, F_a, is used as an amplification factor for spectral values of 0.2 s and less: $F_a = 0.8$. From Table 4.1.8.4.B. pg. Division B 4-22

The long period site factor, F_v, is used as an amplification factor for spectral values of 1.0 s and above: $F_v = 0.6$. From Table 4.1.8.4.C. pg. Division B 4-23

Structural Configuration (4.1.8.6)

Structural Configuration relates to the overall form and type of lateral resisting system that is being used, according to (4.1.8.6.) our structure is considered to have regular seismic force resisting systems.

Direction of Loading (4.1.8.8)

Earthquake ground motions can be applied onto the structure from any direction. The type of SFRS in our high rise building is a conventional construction moment resisting frames in both directions. Therefore, the seismic effect can be assumed to be the same in all directions

SFRS Ductility-Related Force Modification Factors, Rd, Over strength-Related Force Modification Factors, Ro, and General Restrictions (4.1.8.9)

For concrete structures designed and detailed according to CSA A23.3
Conventional construction, moment-resisting frames

$R_d = 1.5$
$R_o = 1.3$

Restrictions
$I_E.F_a.S_a\ (0.2) = 0.21$
$I_E.F_v.S_a\ (1.0) = 0.03$

3.5 Snow loading

Snow loads are forces that are applied vertically on to the roof or other flat, exposed surfaces such as porches or decks. Recommended ground snow loads are normally specified by the local building code or building official. The weight of snow is added to the building weight when the seismic force is determined. The basic roof snow load for a flat roof is determined from the basic roof snow load equation.

The basic roof snow load equation is:

[4] S=Is * (Ss*(Cb * Cw * Cs * Ca) + Sr)

The ground snow load, Ss, and the associated rain load, Sr, are the snow and rain parameters set by the building authority and under NBCC 2010 are based on a return period of 50 years. In our case we have used the importance factor to be 1.0 because it falls under the normal importance. We have also when looking at Toronto zone we find out that the Ss = 0.9 and Sr = 0.4 in our case.

The basic roof snow load multiplier Cb=0.8 for small roofs.

Cs is the slope factor and is 1 for roof slopes less than 15 degree regardless of the roof being slippery or not. In our case we take Cs to be 1 because we have a flat roof.

Cw is a wind factor. In our case Cw is to be considered as 1.

Ca is the snow accumulation factor. In our case Ca=1 since the snow load does not accumulate significantly.

3 STRUCTURAL HEALTH MONITORING SYSTEM METHODOLOGY

SHMS helps in monitoring deformations in the soil and structural system over its life span in order to ensure safety and high efficiency in the construction process and maintenance. By measuring and obtaining several structural parameters, a vital link between the structure and the central monitoring site. SHMS consists of fiber optic sensors that are located at critical positions throughout the high rise building, equipment for data transmission and servers for data collection, analysis and immediate monitoring and control of the status of the building. Significant structural parameters are identified and also the sensor type and installation locations. The fiber optic sensor will be used for SHM due to several reasons, such as its sensitivity, reliability, durability, multiplexing capability, resistance to hazardous and hostile environments and immunity to electromagnetic induction. The building operators monitor and control the status of the building by monitoring the SHMS online every certain monitoring interval to adequately pinpoint any structural deficiencies that may take place. The vertical and lateral deformations will be analyzed using ETABS. The loads will then be calculated to determine the adequacy of the deformations that will take place, so when the deformations and stresses in the building reach a specific level; the SHM system raises warnings for the owner to take an immediate action.

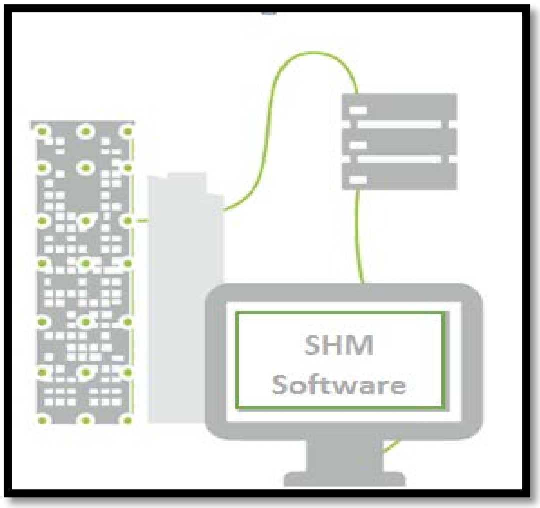

Figure 2: Structural Health Monitoring System

The development process SHM system contains three different stages:

I. **Construction Stage:** Significant structural parameters are identified; computer and mathematical models are run within the server, and also the sensor type and installation locations. The fiber optic sensor will be used for SHM due to several reasons, such as its sensitivity, reliability, durability, multiplexing capability, resistance to hazardous and hostile environments and immunity to electromagnetic induction. Moreover, the fiber optic sensor measures static strains in a large scale and at a low speed for operational load monitoring while measures ultrafast strains in a small scale and at a fast speed for damage monitoring. Thus, an accurate and simple picture of the changing condition of the building structure is conduced.

II. **Design Stage:** Fiber optic sensors are installed strategically into specific structural components of the building and software models are verified and corrected after a period of time of monitoring and evaluating the deformations and stresses where the advanced sensing techniques can inspect the structure status, evaluate performance, determine the structural management for maintenance, and estimate the cost. SHMS is considered as the observation of a system over time. Based on periodically measurements from a sensor network, features sensitive to the damage are extracted in order to define and predict the structural system condition by evaluating the deterioration model for the structure. Including an important measurement of the current design, analysis and maintenance of structures (Miyamoto et al. 2001).

III. **Monitoring Stage:** The building operators monitor and control the status of the building by monitoring the SHMS online every 10 years to adequately pinpoint any structural deficiencies that may take place. The vertical and lateral deformations will be analyzed using finite element model using software ETABS. The forces and strains will be calculated to determine the adequacy of the deformations that will take place in the upcoming 10 years, and the same cycle will be repeated for the following 10 years.

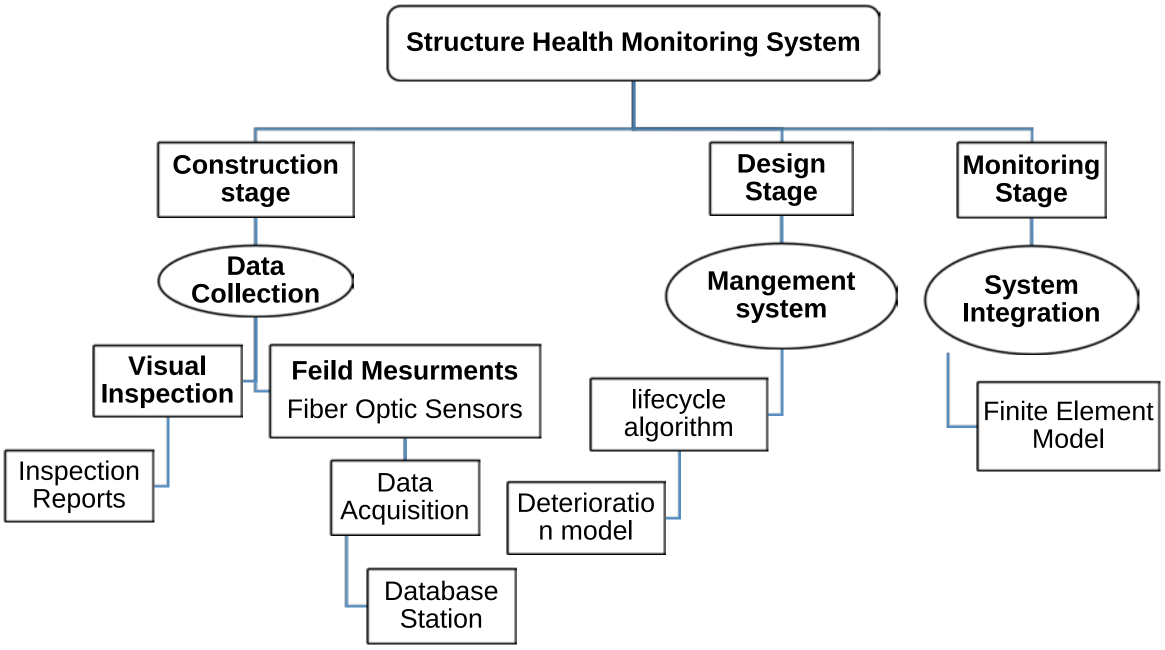

Figure 3: Implementation of structural health monitoring system

4 FIBER OPTIC SENSORS IN STRUCTURAL HEALTH MONITORING

Fiber-optic sensors are the primary candidates for complete sensing sensors and have many advantages over other electrical sensors. Field of fiber optic sensors has grown very rapidly in the past 20 years and attracted an intense worldwide attention for research and development.

Delta Rocket in 1987 invented a closed-up fiber gyro to replace mechanical gyros that were the first fiber optic sensor. Such Fiber Optic Sensor (FOS) s are originated from fiber optic communications (Hong-Nan, et al., 2004).Due to different environmental perturbations while transmitting light from one location to another, optical fiber experiences geometrical and optical changes. Geometrical changes are considered as the size and shape of sensors and optical changes are related to reflective index and mode conversion.

5.1 Fiber-optic Bragg grating (FBG)

Fiber-optic Bragg Grating (FBG) sensors, as shown in figure 4, are the most common types of fiber optic sensors used for structural applications. The sensors have been known as a non-destructive evaluation (NDT) technique for all structural applications. FBG specialty is strain sensing locally with high resolution and accuracy. Also, the physical size of optical fiber is very small compared with other strain measuring components and it qualifies to be fixed into structures for determining the strain distribution without manipulating the mechanical properties of the original materials (Kin-tak, et al., 2001).

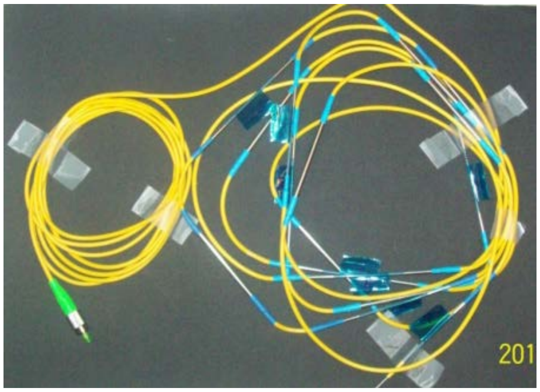

Figure 4: Fiber Bragg Grating sensors array

5.2 Principals of FBG sensors

Strain measurement

In 1987, FBG technology has been discovered by Hill et al. In general, the FBG system includes optical fiber with prewritten grating sensors, a broadband source (light emission device), coupler and optical spectrum analyzers (OSA). For strain measurement in concrete structures, load is transferred directly from host materials to the fiber core of the grating region by the action of shear. This causes the length of the grating area to be changed and reflective result of the core section to be different consequently.

Currently, grating is written with two methods namely: holographic method and phase mask method (Zhi, et al, 2004). Provided grating from Electrical Lab of Ryerson University uses mask method which exposes fiber to a pair of strong Ultra-violet (UV) interference signal. This creates the grating in the core of the optical fiber, those performs fundamentally as a wavelength selective mirror. Figure 5 shows a schematic illustration of FBG system for strain measurement. Measuring the reflected wavelength change from the system would show the mechanical properties of the structure.

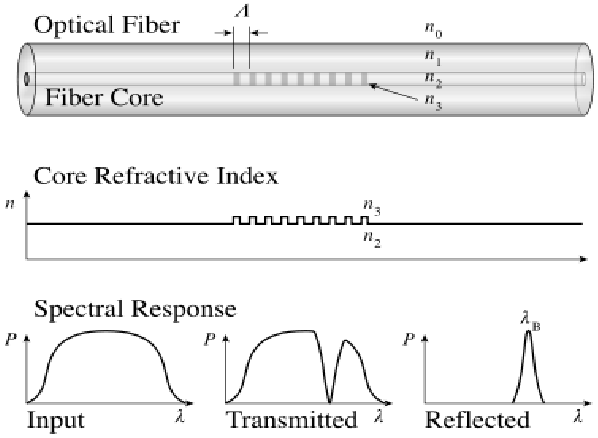

Figure 5 FBG strain measuring system

Light is illuminated from the broadband source via a coupler, and then part of the light is reflected back to the coupler. The part of light which is reflected back to the coupler and the reflected-wavelength are detected by the OSA. The common sensing region or grating length is about 5-20 mm. Therefore, in large-scale structures, the FBG can measure as point sensors similar to electrical strain gauges (Allan, et al., 2006).

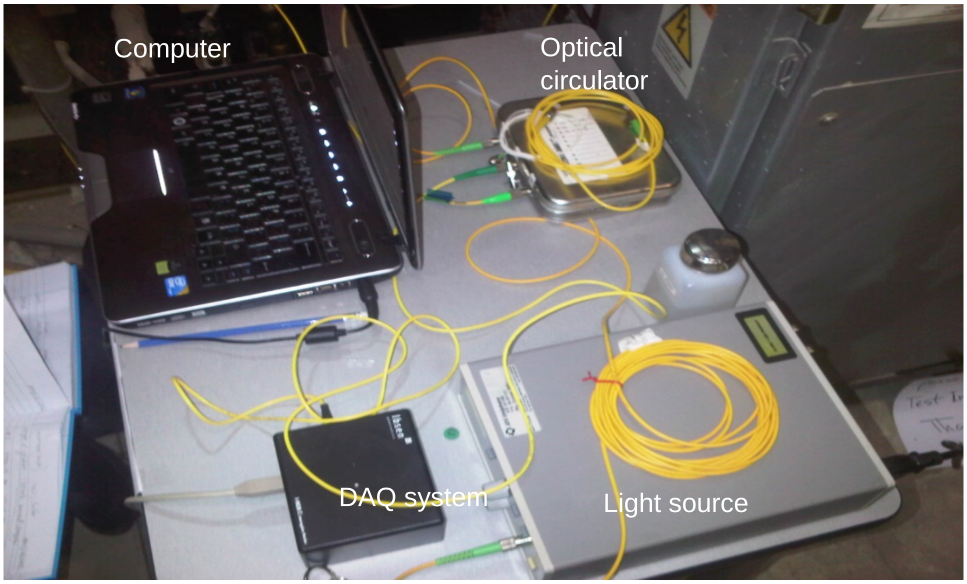

Figure 6: Ryerson University fiber optical sensor interrogation system

The test setup arrangement for fiber optical sensor interrogation system is shown in Figure 7. The system consists of a light source, multi-link, a fiber optical cable especially prepared to measure at different required points, a DAQ system, and a computer with special software installed on it. In the work performed in Ryerson fiber optic laboratory, the IMON E USB 2.0 Interrogation Monitors were used. The IMON E USB 2.0 Interrogation Monitors offer kHz spectrum monitoring of Fiber Bragg Grating (FBG) sensors.

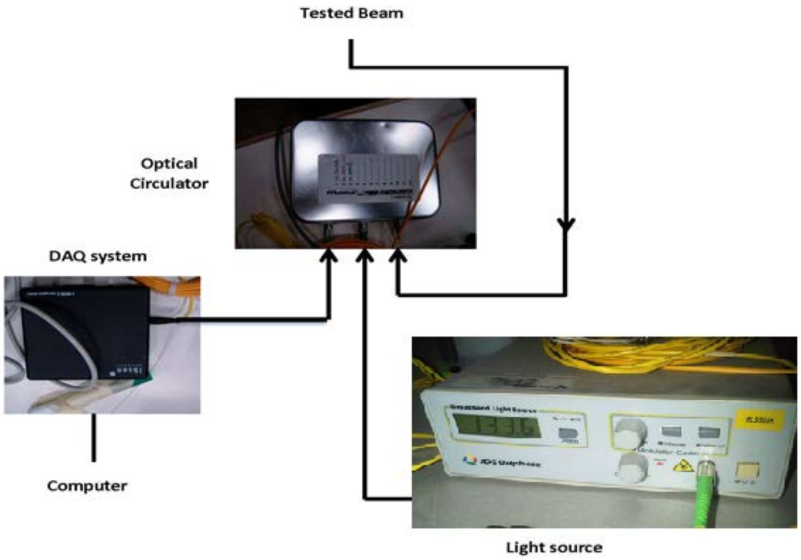

Figure 7: Overview of test setup arrangement for fiber optical interrogation system

5 CONCLUSION

The scope of the study is to achieve a health monitoring strategy for high rise structures using non-destructive techniques. This monitoring enhances the development of a reference data used for detection of changes on the structural behaviour indicating damage, and supporting the maintenance plan. This monitoring strategy has been developed to monitor the health of the building through the use of fiber optic sensors that will put the client as well as the consultant's minds at ease once the building is serviced. Basically, this strategy is based on a long term monitored data, strain and deflection, collected using fiber optic sensors installed at certain points within the structure. Implementing a finite element model for the high rise building is to recalculate the forces, stresses and strains using the monitored data from deformations and strain measurements in the structure and to compare these forces to the design forces in order to determine the state of the structure.

6 REFERENCES

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APPENDIX A: TABLES

Table 1: 11th-38h Typical Floor – Column

COLUMN	AREA (200 SLAB THICKNESS)	SLAB	LL REDUCTION FACTOR	LOAD FACTOR (Resident:SID=1.3,LL= 1.9)	LOAD (KN)
45	15.399	0.2	1	8	123.192
47	5.14501	0.2	1	8	41.160096
37	15.0666	0.2	1	8	120.5328
49	8.37594	0.2	1	8	67.007496
27	17.3028	0.2	1	8	138.4225
50	17.55	0.2	1	8	140.4
52	26.13	0.2	0.912411494	7.8336	204.69149
11	23.3663	0.2	0.947617429	7.9005	184.60443
8	11.6438	0.2	1	8	93.15
59	7.0875	0.2	1	8	56.7
6	12.731	0.2	1	8	101.848

Table 2: 11th-38h Typical Floor – Column

WALL	AREA (200 SLAB THICKNESS)	SLAB	AREA (210 SLAB THICKNESS)	SLAB	REDUCTION FACTOR	LOAD FACTOR (Stairewells:SID=0,LL= 4.8)	LOAD FACTOR (Resident:SID=1.3,LL= 1.9)	LOAD (KN)
13	16.0812	0.2		0.21	1	9.6	8	128.64925
11	54.0675	0.2		0.21	0.7257406	8.28355472	7.479	404.36555
10	65.4742	0.2		0.21	0.6868814	8.09703058	7.405	484.8416
5	119	0.2		0.21	0.586972	7.617465704	7.215	858.61437
4	59.7	0.2	10.36395	0.21	0.7051594	8.184764909	7.44	573.45696
20	18.5987	0.2		0.21	1	9.6	8	148.7895
19	34.7245	0.2		0.21	0.8312449	8.789975305	7.679	266.66249
18	20.8575	0.2		0.21	0.9854597	9.530206448	7.972	166.28378
17	36.6371	0.2		0.21	0.8171927	8.722525095	7.653	280.3716
2	82	0.2		0.21	0.6457054	7.899385722	7.327	600.80089
16	54.3963	0.2		0.21	0.7244517	8.277368069	7.476	406.69185
3	34.16	0.2	12.2	0.21	0.8356167	8.810960145	7.688	408.47611
15	32.6904	0.2		0.21	0.8475237	8.868113867	7.71	252.05261
14	34.5875	0.2		0.21	0.8322962	8.795021933	7.681	265.67921

APPENDIX B: ETAB DRAWINGS

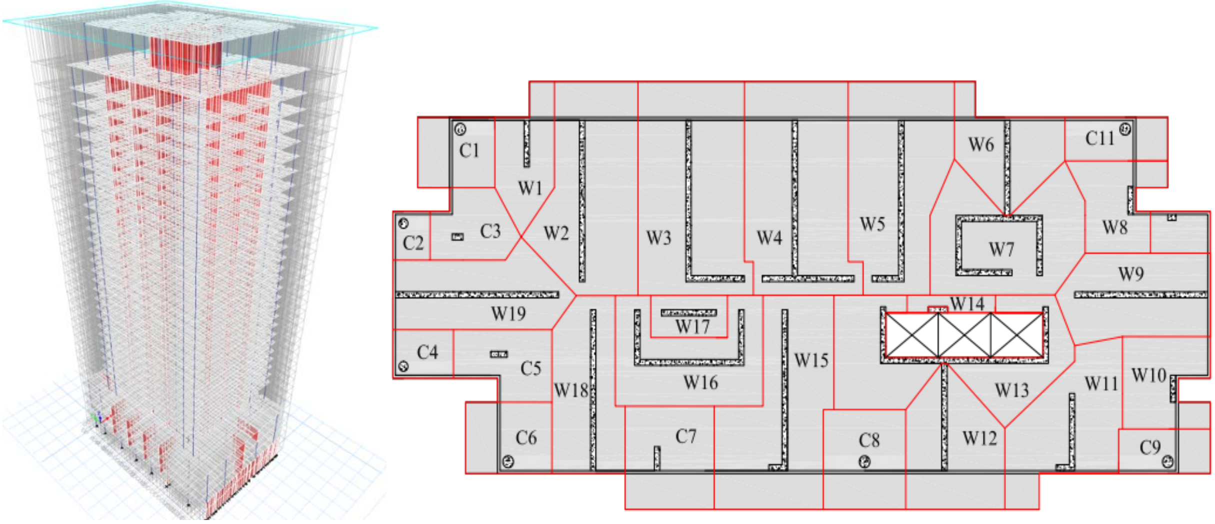

Figure 8: ETABS Elevation Model and the typical floor roof