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Preliminary Design of Structural Health Monitoring for High-Rise Buildings

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Abstract

The purpose of structural health monitoring is to evaluate structural behavior due to various external loads through installation of appropriate measurement. Accordingly, a guideline for monitoring standards is necessary to evaluate the safety and performance of a structure. This paper introduces preliminary design of SHM for high-rise buildings, which is the stage creating a guideline. As for preliminary design of SHM, first step is to calculate the displacement and member force through structural analysis. After that, limitations or qualifications are proposed for management. Secondly, based on the results from first step, issues related monitoring such as monitoring method, measurement type, or installation location are determined. This method leads building managers to reasonably define the structural safety over the whole life cycle. Furthermore, this experience contributes to development of SHM forward and it is expected to be useful for other types of structures as well such as spatial structures or irregular buildings.

Keywords: SHM (Structural Health Monitoring), Measurement, Tall building, Structural behavior, Preliminary design

1. Introduction

The primary purpose of Structural Health Monitoring (SHM) is to monitor and evaluate building performance during the whole building life cycle to provide safe and optimized environment for the building users. The installed measurements in the building and predictable management system will be needed for evaluation of the structure behaviors. When hazardous situation occurs, using simulation of structural behaviors, the state range regarding health or emergency of building can be decided. This contributes to active building management.

SHM has been applied for civil structure such as suspension bridges and power plants, and structural safety has been checked for maintenance through SHM. SHM technique is applied for safety evaluation of structures which can affect public safety such as public facilities, high-rise buildings, structures connecting with urban railway and so on. However, building structures have a large number of structural members comparing with civil structures and the applicable locations to install sensors are limited. Also, it is more complicated to find the relation between loads and member behavior. Therefore, prediction of actual structural behaviors of buildings is more difficult than that of other civil structure.

This paper proposes a basic guideline for SHM based on a preliminary design example of SHM project for a structure currently being built. Because other company will install and operate sensors shortly, the proposed SHM guideline will need to be updated according to the results. The market related to SHM technique is expected to grow up in the future since SHM needs total solution service consisting of various fields of professionals such as measurement, operation system and structural analysis to monitor the structural healthy condition.

For this reason, installing sensors to monitor are used for civil structures (based on sensors for safety monitoring system). On the other hand, for building structures, safety evaluation method is applied based on pattern recognition (statistical pattern recognition techniques). This evaluation method is also expected to be developed because parameters for evaluation of structure behavior are limited.

2. Outline of Structural Health Monitoring

It is important to determine the purpose of monitoring for SHM. Operation and measurement concept can be optimized by client's needs. For this reason, the SHM concept and purpose need to be decided with client.

There are three parts for planning health monitoring. These are structural analysis part for prediction of structure

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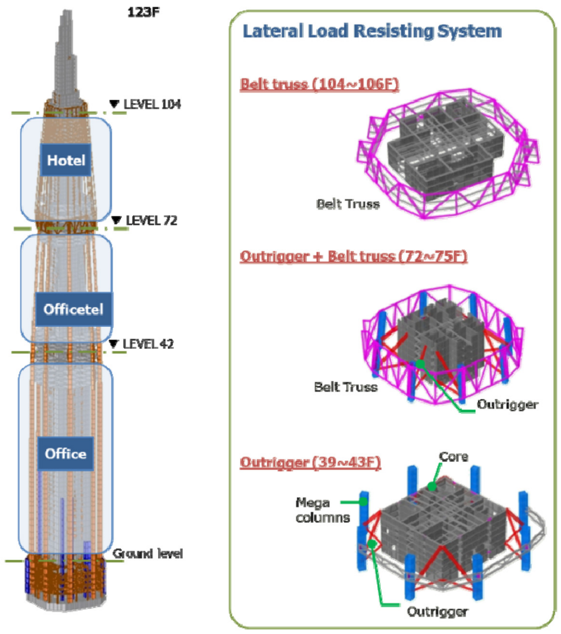

Figure 1. Introduction of study building.

behavior, hardware part for selection of proper measuring instruments, and software part for evaluating based on the measured data. Each part's specialists should have system management ability for understanding other fields' results and sharing input and output one another.

Structural analysis is the most familiar task to structural engineers. At first, understanding the overall structural behaviors is important. Especially as for high-rise buildings, structural characteristics such as participation factors per each member, eigenvalue analysis results or main structural members behavior regarding the lateral force need to be examined. Using this process, it can be determined which members need monitoring. Afterward, the method of connecting main structural members and required measurement data for each member is defined.

Interrelations between various items related to measurement purpose, specification, measuring location, and measuring instruments with member forces expressing structural behavior are required.

3. Reference Building for SHM Study

The studied high-rise building is located in Seoul, Korea and consists of 123 stories. The total height is 555 m (including antenna spire). The lateral load resisting system consists of core wall, mega columns, and outrigger and belt trusses. The structural design has been completed to secure safety, stability and serviceability under the lateral loads as well as gravity load. Since this building's structural behavior is governed by wind load, we conducted this study based on the displacement caused by wind load and checked the change of natural frequency and structural stiffness by construction stages.

SHM has a process different from structural analysis. Structural analysis is conservatively carried out based on displacement and member force associated with the whole structural behavior. However, SHM needs to reflect precise structural stiffness by predicting and measuring structure behavior.

4. Preliminary Design for SHM

For structural review of SHM, the simulation of structural behavior similar to real building is conducted.

This study is conducted to suggest how to make the initial plan regarding SHM and analyze the relationship between structural members and measuring instruments or maintenance system before commencing the SHM for structural engineers.

Chapter 4.1 and 4.2 describe how to make an analysis modeling considering actual structural behaviors. So we can understand why analysis modeling needs to be modified accordance with each construction stage in these chapters.

Chapter 4.3 and 4.4 indicate that the main members are selected by displacement participation rate. And then how to find a proper position for installing measuring instrument is also mentioned.

The contents regarding the assumption of damage scenarios are stated in the chapter 4.5. The assumption of damage scenarios can be made by predicting the displacement and the frequency change rate based on stiffness reduction of the main structural members.

Lastly, chapter 4.6 points out that guideline will be needed to make it easier for building users and maintenance managers to understand the state of the building health. So, the approximate SHM guideline is suggested in this paper but it might be appropriately modified in a case by case.

4.1. Structural Behavior of Building

To understand the building behavior under actual load is necessary so that structural health monitoring proceeds. At the design stage, the structure is assumed to be flexible in order to evaluate conservatively the maximum lateral displacement of the structure. However, the actual structure is different from the assumed modeling due to several factors such as the non-structural elements, actual material strength or design safety coefficient. These factors cause the structure stiffer than the assumed modeling.

Fig. 2 shows the change of the structural dynamic behavior at the construction stage. Reflecting the modulus of elasticity and strength of the concrete applied to the core wall and mega column at the first construction stage, the period was reduced by 7% compared to that of the design stage, and the structure becomes stiffer.

In Fig. 3, additional stiffness that can be generated are listed, and if the model is modified reflecting this and the

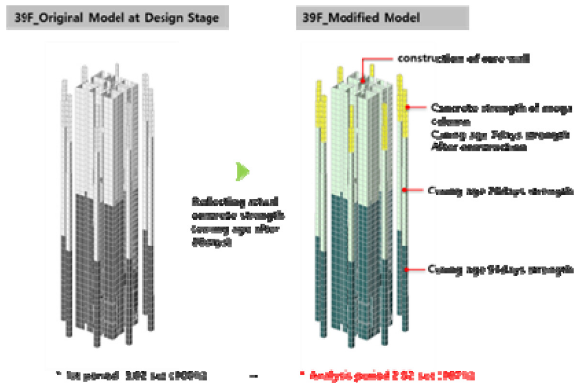

Figure 2. Additional stiffness factor (material strength).

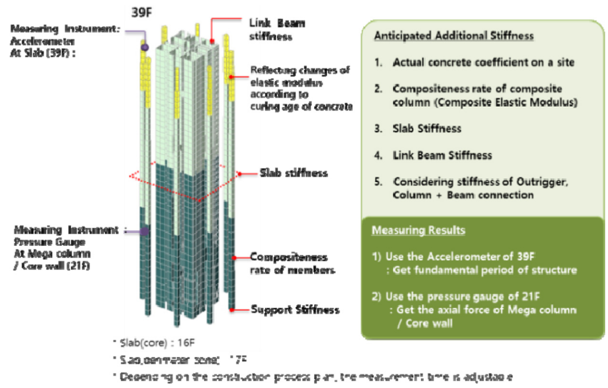

Figure 3. Additional stiffness factors.

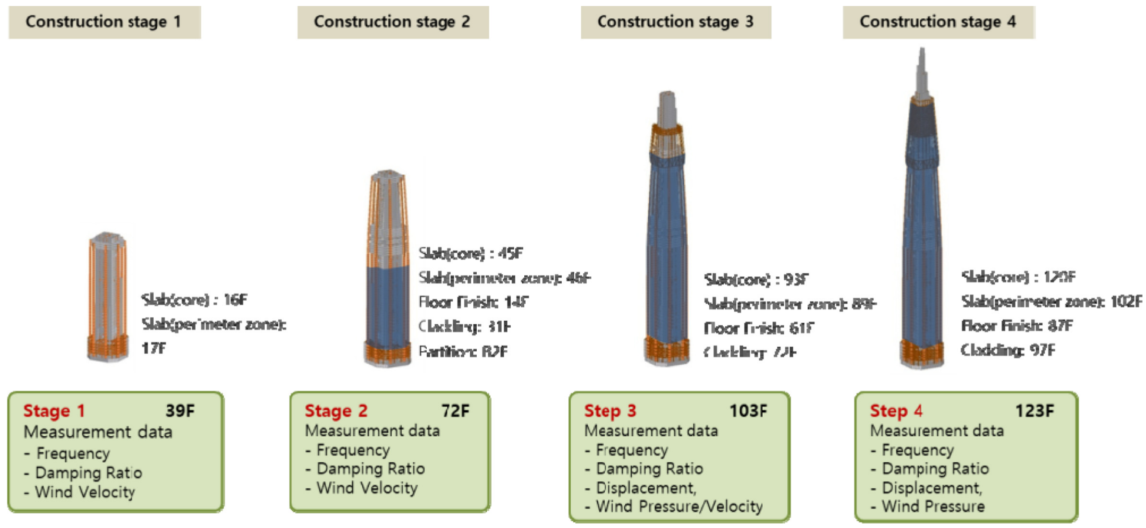

Figure 4. Construction stages.

measuring data, the analysis model will reflect the actual structural behavior.

The final analysis modeling which reflects the actual conditions at the monitoring stage is used for building maintenance. This modeling is important for predicting the real building shape in terms of total displacement and natural frequency.

4.2. Analysis Modeling Performance Using Measurement

An actual building behavior can be predicted from measured data. Based on these expectations of the building behavior, the analysis modeling can be completed. This is the final modeling used for monitoring over the building life cycle. Thus, the building needs to be examined stage by stage for accurate expectation.

In this project, four construction stages are considered as shown in Fig. 4. In each stage, a modeling is performed considering the expected load -self weight or finish load- or other factors which can affect building behaviors. If the analysis results are different from the measurement data, some factors can be modified so that the modeling has similar behaviors with the actual building's behavior. For example, at stage 2, the analysis modeling has 72 stories; however, partition loads are modeled up to the basement 2nd floor and finish load is applied up to the 14th floor. The analysis results are compared with the measurement data such as frequency, damping ratio and wind velocity. And then, the modeling can be modified depending on the measured data. As the construction stages go on, the modified analysis modeling becomes similar to the actual building.

Through measurement, information such as the displacement, straightness or acceleration can be checked in real time. On the other hand, the result from analysis has different types of value with the measured value. Therefore, the additional process is necessary to convert the values for comparison.

4.3. Selection of Main Structural Members

To select the main structural member for SHM is based

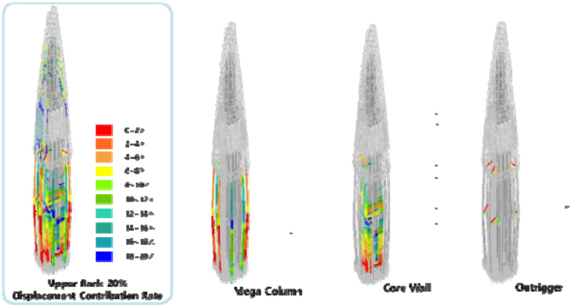

Figure 5. Upper rank 20% displacement contribution rate.

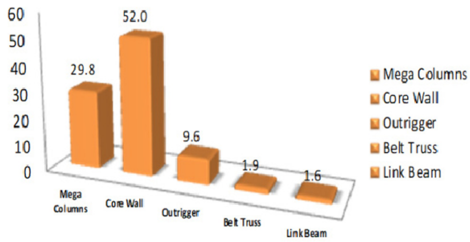

Figure 6. Contribution Rate of Main Members.

on method of displacement participation factor and strain energy density (ref #4).

The main members sorted by displacement contribution rate from upper to lower is as follows: core wall, mega column, outrigger, belt truss, link beam. It's a stress value resulted by random Wind Load (Wx) and Unit Load.

After the structural design is completed, the structural engineers already understand the behaviors of their building and main structural members. However, in order to select reasonable measurement position on structural members, the above two methods were applied. Displacement participation factor of members is accessible to importance concept which is each member's effect related to structure behavior and strain energy density is a value dividing displacement participation factor from member's volume like structural response concepts. In accordance with above procedures, displacement participation factor of the core wall is 52%, mega column 29.8%, and outrigger 9.6%. Fig. 6 shows the structural elements having the top 20% contribution.

4.4. Measuring System

It is necessary to understand how the measured values of installed instruments are related to the structural analysis results. The installed instruments are accelerometers (1-axis, 3-axis), inclinometer, GPS, strain gauges, axial force gauges, and wind pressure gauges. An axial force gauges will be used to check the axial force of the mega column, and strain gauges to be attached to each member can be used to verify the stress of the link beams and outriggers. Accelerometers, GPS, and inclinometers are used

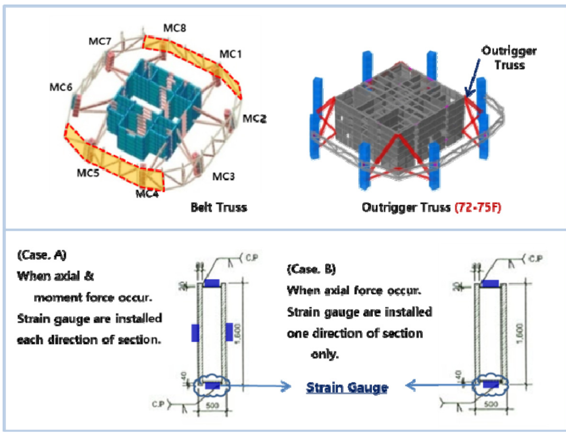

Figure 7. Installed location of strain gauges on Outrigger and Belt truss.

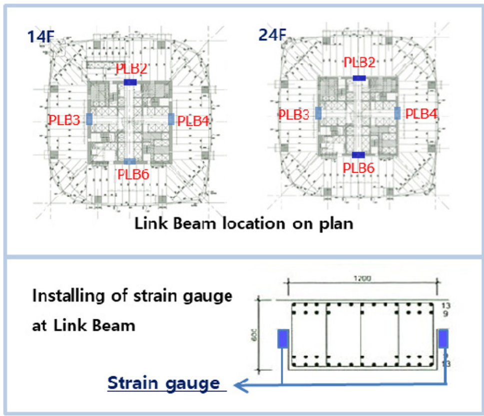

Figure 8. Installed location of stain gauges on Link beam.

to review the dynamic behavior and maximum displacement of buildings. Measuring data mining methods should be classified as static or dynamic depending on the characteristics of the design variables.

In case of predicting building level behavior, an accelerometer is installed at the required position to find fundamental period and mode shape of structure, and dynamic measuring instruments are applied so that real time measurement is available.

To understand member level behavior, the stresses at structural members are predicted after selection of main structural members. For example, mega column, steel belt trusses and outriggers of high-rise buildings have large stresses related to axial force, and some of members are subjected to axial force and moment at the same time.

If the axial force and moment occur at each face of the section, strain gauges should be installed at each side (Case.A). In this case, measuring instruments are arranged like fig.7, static measuring instruments having intermittent time term not real-time dynamic measuring instruments can be applied.

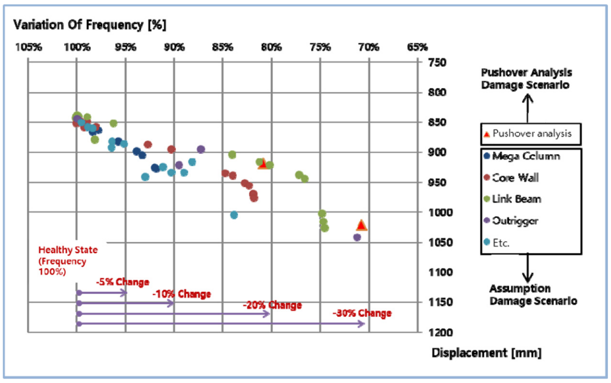

Figure 9. Damage scenarios.

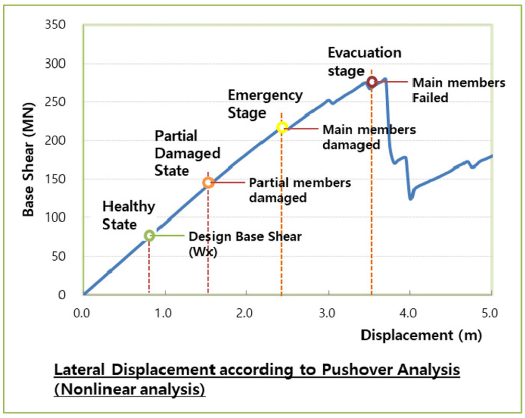

Figure 10. Building state based on structure behavior.

However, when the axial force occurs only at the section, compressive stress can be assumed as being same in all section area, so strain gauges are installed just one direction only (Case.B). Refer to the below Fig.7 for detail.

4.5. Damage Scenarios

After getting information about the contribution rate of the main structural members according to the displacement participation factor method, the members to be measured are selected. However, since the number of the measured members is small in comparison with total number of structural members, it is difficult to evaluate the overall structural behavior.

In order to resolve this problem, we apply the pattern recognition technique to the SHM of the building structures. The damage scenario is based on the concept of pattern recognition technique.

An assumption damage scenario is created by assuming some cases that damages occurred in major structural members. And a simulation is carried out according to the assumption damage scenario. After preceding various cases of damage scenarios, we can get the data related to rate of change for the displacement and frequency. For example, there is a certain condition that stiffness reduction occurred due to partial damage of mega column which has highly displacement participation factors. The rate of change related to the structural displacement and frequency was examined by the simulation in this case. Also mega columns were classified by floor layer, stiffness reduction was applied to each of the grouped mega column. And then we checked the rate of change related to the structural displacement and frequency. Similar to the above method, simulation was conducted for the grouped main members such as outrigger, link beam, and belt truss. When those members were virtually damaged by stiffness reduction, we predicted how the result would affect the structural safety.

According to this assumption of damage scenario, if disaster and evacuation alarm arise, it is possible to know which members have had a major impact on the damage scenario.

This damage scenario technique might need to be developed to consider the actual building behavior. After the analysis of the correlation between the structural behavior and the measurement data, if this result can meet the client's purpose of SHM, it will be a more advanced structure maintenance method.

4.6. Guideline for the Building Maintenance

Since the users using the maintenance program like maintenance manager and client are not supposed to be engineers, the maintenance guideline has to be written to be easily understandable for their building state.

Depending on the state of building, an operating system that can present instructions to the building users is required. For example, it can be used, depending on whether it is in good condition, in some damages, or in a state of evacuation. In case of partial damage, it is suggested to judge whether maintenance or reinforcement measures are necessary or not and if evacuation is needed, or instructing users to evacuate is needed.

Fig. 10 shows the structural behaviors due to material nonlinearity. Based on this analysis, it is possible to check the entire process from when the structure is safe to when it collapses. Based on this graph, it is possible to provide the building users with an information of the building state.

This software might be differently represented depending on the needs of the client and used to express the state of the building based on the measurement data and to detect the risk in the event of disaster.

5. Conclusion

Based on many existing research results, we have described the SHM applied to a practical project. It would be necessary to discuss with other researchers whether this method is suitable for the SHM of specific high-rise structures or not.

As mentioned above, the monitoring of building structures is complicated because of the complex relationship between various loads and structural members. However, if the proposed building monitoring technique is further developed, it will have a positive effect on the maintenance of the structures.

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