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The Structural Health Monitoring System
结构健康监测系统

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A sophisticated and comprehensive structural health monitoring (SHM) system was designed to monitor the Ping An Finance Center (PAFC)'s continuous static and dynamic response to conditions in real time. This chapter outlines all seven subsets of the whole SHM system, including their components, function and the relationships between them. It then offers a perspective on the research and application in other relative fields based on the PAFC SHM system as an international benchmark platform with the use of field measurement data. Finally the chapter illustrates some monitoring results for the under-construction project.

一套复杂全面的健康监测系统用于对平安金融中心塔楼施工阶段和使用阶段的静力和动力响应信息进行连续、实时的监测。本文概述了平安金融中心健康监测系统的子结构系统的构成、功能及各个子结构系统之间的相互关系。然后以平安金融中心健康监测系统为基准试验平台，展望了可在相关领域进行的部分研究与应用。最后介绍了塔楼在施工阶段所取得的部分监测结果。

Introduction

Housner defined a SHM system as "an effective method that obtains the inherent information of the structure under operation from field measurement data to judge and estimate the change of main property index caused by structure damage or material deterioration (Housner et. al., 1997)." Since 1993, John Brown and colleagues created a long-term monitoring system about the change of dynamic responses and structural properties for a 128 meter 65-story office tower (Brown et. al., 1998 and 2007). Later, many investigators carried out high-rise building wind-induced response and seismic vibration monitoring. Li made full-scale measurements on high-rise structures to identify their wind-induced response properties under strong wind conditions (Li et. al., 2000, 2004 and 2007). It is reported that in the USA, Japan, and Taiwan there are more than 150, 100, and 40 buildings (respectively) with strong motion monitoring systems for seismic excitation/response measurement and post-earthquake damage assessment (Ni et. al., 2009).

PAFC is a tube-in-tube super high-rise building. The external tube consists of eight steel-reinforced concrete columns while the internal tube was constituted by reinforced concrete shear wall. There are five outriggers connecting the two tubes acting as a reinforcing band. The total height of this 123-stories (5 floors underground) building is 660 meters and its structural height is 597 meters. The outline of the structure shows a flat curve due to the slight differences of the changing rectangular plane size of different stories. The plane dimensions of the first floor are 56 meters long and 56 meters wide, shrinking to 46 meters long and 46 meters wide up to the 100th floor. But the plane dimensions of the internal tube remain at 36 meters long and 36 meters wide, including all vertical circulation facilities (see Figure 3.10).

Eleven types of equipment, including 428 sensors deployed on the tower, conduct full life-cycle monitoring of the structural static and dynamic performance (see Table 3.2). This chapter describes the constitution, implementation and some applications in the relative research field of SHM.

前言

Housner 等将结构健康监测系统定义为:用现场监测方式从营运状态的结构中获取其内部信息，来判断和评估结构因损伤或退化导致的主要性能指标改变的有效方法[Housner et. al., 1997]。超高层建筑中的监测源于1993年，Brown john等人对一栋65层，高280m的办公塔楼的动力响应和结构性能的变化实施了长期的监测[Brown et. al., 1998 and 2007]。后来，许多研究者开展了对于超高层结构在风荷载作用下的风致响应和地震作用下的动力响应监测。李秋胜和他的研究团队对大量的高层建筑进行了在强风作用下的全尺寸观测，以识别结构的风致响应特性[Li et. al., 2000, 2004 and 2007]。据报道，在美国、日本和中国台湾，分别有超过150栋、100栋和40栋的高层建筑安装了强震仪监测系统，用于测量地震激励和结构地震响应，并进行震后损伤评估[Ni et. al., 2009]。

深圳平安国际金融中心的主体结构由钢筋混凝土核心筒(内含型钢柱)与8根巨型外框架柱组成，并由外伸臂桁架联系核心筒与巨型型钢混凝土柱，地上118层，地下5层，塔尖高度660m，结构高度597m。塔楼外形呈曲线变化，各层轮廓尺寸略有不同。大楼首层平面尺寸约56m×56m，随

Modular Design of SHM System

The SHM system of PAFC use the megatall building as a platform, integrating multidisciplinary research together including the web of sensors, signal transmission and procession, computer calculation and analysis, software development and structure detection and diagnosis. This system consists of seven sub-system modules: sensor measurement system (SMS), data acquisition and transmission system (DATS), data processing and estimation system (DPES), data management system (DMS), support and protection system (SPS), structure health assessment system (SHSS), software system (SS) (see Figure 3.11).

Sensor Measurement System

This sub-system is mainly composed of 11 types of equipment (see Figure 3.12 and 3.13). The monitoring content for in-construction stage including:

1. Climate monitoring: Temperature, humidity, rain, air pressure
2. Load monitoring: Earthquake motion, wind speed and direction, temperature
3. Horizontal displacement of the top of the tower
4. The inclination of the tower
5. Vertical deformation (the shrinkage and creep of the shear wall and column)
6. The stress, strain and pressure of a typical location
7. The settlement of the overall tower

Except the above items, the additional monitoring content for the in-service stage includes:

1. The dynamic property: the modal, mode shape and damping of the structure.
2. The dynamic response, such as wind-induced response.

Figure 3.10. Structure visible during construction.
图 3.10. 深圳平安金融中心：施工图景

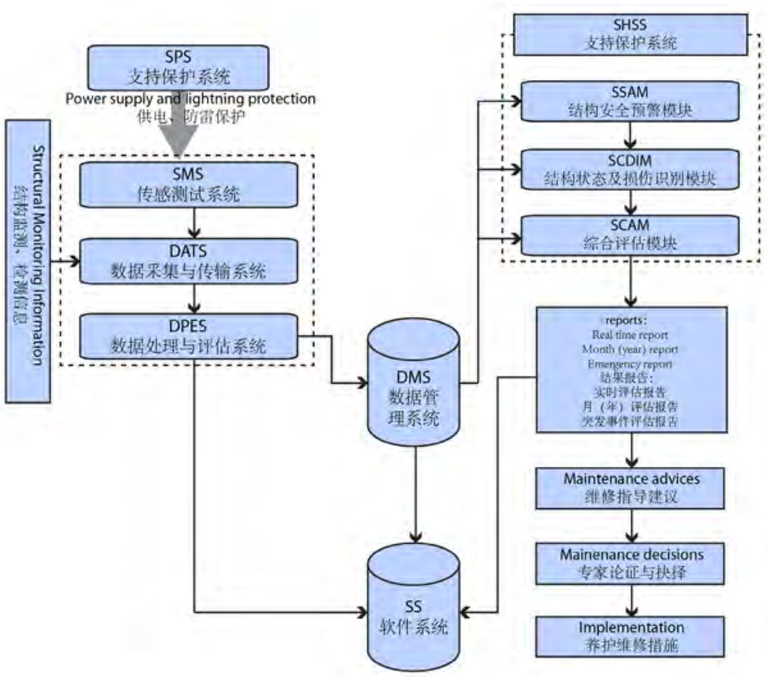


Figure 3.11. Function relation of the sub-systems
图3.11. 健康监测系统功能框图

着塔体向上收细，楼层平面同时从两边向内收缩而成，100层以上的楼面逐渐收进至约46m×46m。中央核心筒平面尺寸约30m×30m的矩形，内含所有垂直交通设备。平安金融中心效果图和结构施工图如图3.10所示。

11种共计428个传感器和监测设备安装于结构上，用于结构全寿命周期内的结构静力及动力响应监测。本文描述了整个健康监测系统的组成、实施以及在相关研究领域的部分应用。在施工阶段及使用阶段安装的传感器数量和类型汇总如表3.2所示。

No. 编号	Sensor type 传感器类型	Monitoring items 监测项目	Number of sensors 传感器数目		Manufacturer/ model 厂家/型号
			In-construction monitoring 施工阶段监测	In-service monitoring 使用阶段监测	
1	Weather station 气象站	Temperature, humidity, rain, air pressure 温度,湿度,雨量,大气压	1	1	GMEC/WP3103
2	Anemometer 风速仪	Wind speed and direction 风速和风向	1	1	GILL/Windmaster pro
3	Wind pressure sensor 风压计	Wind pressure 风压	-	40	Setra/ Setra 268
4	Total station 全站仪	Displacement 位移	1	-	Leica/Leica TS30
5	Optical fiber inclinometer 光纤倾斜仪	Inclination 倾斜	32	32	Fibersensing/ FS6400
6	Digital electronic level 电子水准仪	Whole settlement 整体沉降	1	1	Leica/Leica DNA03
7	GPS	Displacement, inclination 位移，倾斜	2	2	Leica/Leica GMX902 GG
8	FBG strain sensor 光纤光栅应变传感器	Strain, stress 应力、应变	300	300	NSCSMCN/CB-FBG-EGE-100 CB-FBG-GFRP-W01
9	FBG temperature sensor 光纤光栅温度传感器	Temperature 温度	40	40	NSCSMCN/ FBG-T-01
10	Seismograph 强震仪	Earthquake motion 地震	1	1	IEMCEA/GDQJ
11	Accelerometer 加速度计	Acceleration 加速度	-	10	Jewell/LSMP-2
Total 总计			378	428	

Table 3.2. The number and type of sensors deployed for in-construction and in- service monitoring.
表3.2.施工阶段和使用阶段传感器数量和类型汇总

In the light of FEM simulation results, choosing the most adverse position where the stress is maximum under general ambient loading or extreme loading condition, or the weak location where the cross stiffness of structure mutates under external loads. Then install proper sensors at those selected positions to measure the important responses. For example, the distribution of story shearing force between the core tube and external frame under frequent earthquakes could be obtained by establishing the model with ETABS software (see Figure 3.14). It can be seen that the shearing force mutations appear at the floors where there exist the belt truss. So these floors have sensors naturally (Fu et. al., 2012).

It is worth noting that, such equipment as weather stations, anemometers, and global positioning systems (GPS) are fixed to the top of the structure in the construction stage, rising with the building until the end of the construction stage. They will be installed at the top of the tower at the final service stage.

Data Acquisition and Transmission System

This sub-system could be divided into three aspects according the different type of sensor signal, including the fiber Bragg grating sensor, the analog signal sensor, and the digital signal

健康监测系统的模块化设计

深圳平安国际金融中心结构健康监测系统是一个以超高层建筑结构为平台，集传感器网络、信号传输与处理、计算机计算分析、软件开发、结构检测与诊断等为一体的多学科相互交叉的监测系统。本健康监测系统由7大子系统模块组成: 传感测试系统、数据采集和传输系统、数据处理与评估系统、数据管理系统、支持保护系统、结构健康评估系统、软件系统。各个模块之间的功能关系如图3.11所示。

传感测试系统

塔楼的监测系统包括了11种428个传感器设备和监测仪器。传感器空间布设位置如图3.12、3.13所示。在施工阶段，监测的内容主要为7项:

1. 气候环境监测: 气温、湿度、雨量、气压监测;
2. 结构荷载监测: 地震、风速风向、温度;
3. 塔楼水平位移测量;
4. 塔楼倾斜测量;
5. 竖向变形监测(巨柱、混凝土核心筒收缩徐变);
6. 关键部位应变和压力监测。
7. 塔楼整体沉降

在使用阶段，在上述施工阶段监测内容的基础上，增加2项监测内容:

1. 结构动力特性，如结构模态、振型;
2. 结构动力响应，如风致响应。

根据有限元分析结果，选择结构在一般环境荷载或极端荷载作用下应力最大的

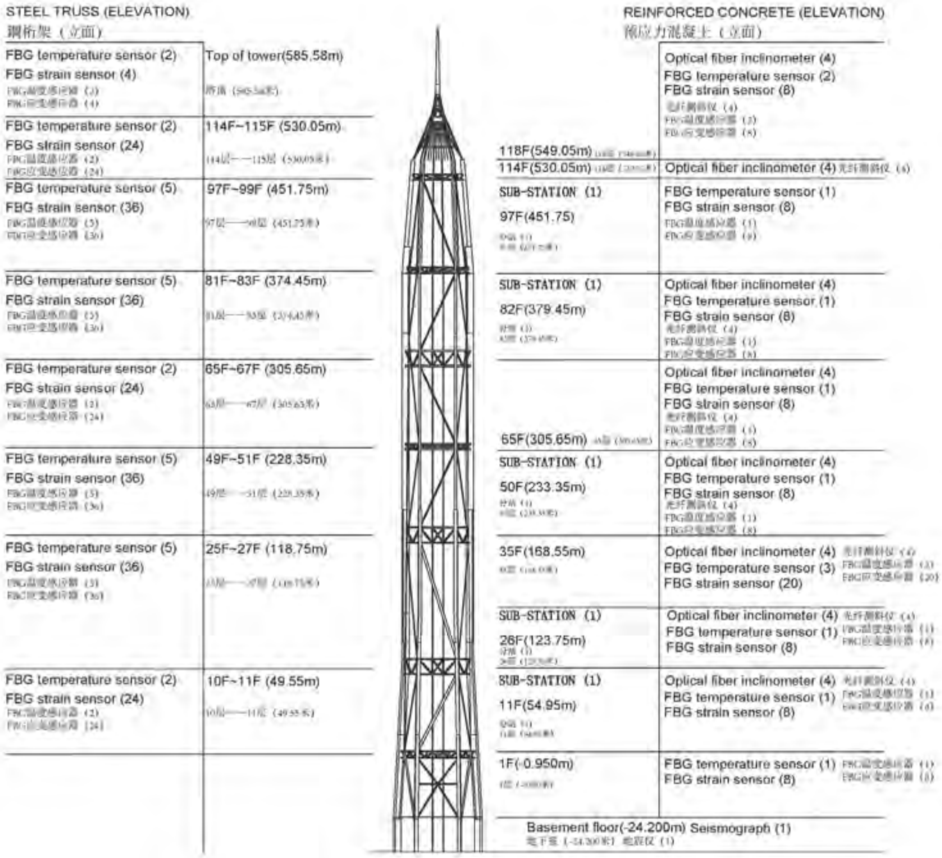


Figure 3.12. (a) Deployment of sensors and sub-stations (data acquisition units) for in-construction monitoring
图 3.12. (a) 施工阶段监控传感器布置图

Figure 3.12. (b) sensor construction
图 3.12. (b) 传感器施工

sensor. Different sensors are processed by corresponding signal processing modules, switched to become a uniform digital signal with data acquisition modules, and finally transferred to the remote control center through the data transmission module.

To ensure the synchronizing of the data analysis, it is required that all measurement begins at the same time. The NTS-71 time server is adopted, the time is calibrated precisely by the built-in GPS, and the network time protocol (NTP) provides the time-synchronization services for other embedded acquisition devices. The return time is the sum of the GPS and LAN (local area network), more than 1ms.

In the construction stage, it is difficult to place and protect the signal transmission cable. To achieve the real-time transfer for the site-measured data, a wireless transmission scheme is determined. Data is transferred through combined wireless LAN and 3G telecommunication networks. Five sub-stations are built on ordinary truss floors and a temporary monitoring center is built at the construction site. The communication between the sub-stations and temporary monitoring center is through wireless

结构受力最不利位置，或者在外力作用下结构横向刚度产生突变的结构薄弱位置以及典型楼层位置，如塔尖，布置相应类型的传感器，以期得到重要的结构响应信息。如运用ETABS软件建立的结构有限元仿真模型，在小震作用下，内筒、外框结构楼层剪力分配如图3.14所示。从图中可以看出，剪力发生突变的地方为带状桁架所在层，所以带状桁架所在楼层均有布置传感器[8]。

值得注意的是，气象站、风速仪、GPS在施工阶段就已经临时安装于塔楼顶部，并随施工进度升高，待结构主体结构施工完成后，再将他们永久固定于塔楼顶部。

数据采集和传输系统

根据传感器信号的不同，相应地分成光纤光栅传感器、模拟信号传感器和数字信号传感器的数据采集与传输三个部分。不同类型的传感器采用不同的信号调理模块，调理后的信号经过数据采集模块的处理与转换，形成统一的数字信号，最后利用数据传输模块将统一的数据信号传输到远程控制中心。

为了保证分析数据的同步性，即要求各种仪器能够在同一时刻开始采集。本系统中采用NTS-71型时间服务器来实现采集时间的同步，先通过系统中的GPS精确校准时间服务器的时间，再通过监测网络时间协议 (NTP) 为其它嵌入式采集设备提供时间同步服务。这样系统总的时间精度能够高于1ms，是GPS时间精度和局域网时间精度之和。

在施工阶段，信号传输线缆的布设和保护有较大的困难，为保障现场采集数据的实时传输，拟采用无线数据传输方案，通过无线局域网和3G电信网络传输数据。选择5个典型桁架楼层建立临时采集站，并在施工现场建立临时监测中心，临时采集站和临时监测中心之间通过无线局域网进行通讯，临时监测中心的数据通过3G电信网络传输到远端监控中心。施工阶段数据采集和传输系统集成图如图3.15所示。

在使用阶段，利用MOXAEDS 308型工业以太网交换机和多芯光缆组成环形光纤网，取代无线局域网，将各个数据采集站将所采集的数据发送到监测中心。使用阶段数据采集和传输系统集成图如图3.16所示。

数据处理与评估系统

数据处理与数据库子系统负责对数据采集与传输模块采集的数据进行处理，并提交给后续各子系统使用，同时对数据采集与传输模块的工作进行操作控制。数据处理分析模块

LAN, while the communication between the temporary monitoring center and the remote control center is through a 3G telecommunication network (see Figure 3.15).

In the service stage, a ring optical fiber web composed of MOXAEDS 308 industrial Ethernet switches and multifiber cable constitutes the wireless LAN, which transmits data between the sub-stations and the monitoring center (see Figure 3.16).

Data Processing and Estimation System
This sub-system is aimed at processing the acquired data for the subsequent use in other sub-systems. It also controls the process in the data acquisition and transmission system in turn. This module consists of pre-processing and post-processing aspects (see Figure 3.17).

Data pre-processing focuses on real-time information extraction. The original data was "cleared up" in the first step to remove the useless data. In the second step, we calculated the targets detection and statistical characteristic parameters based on the "clean" data-processing results.

Data post-processing focuses on long-term information extraction. This involves conducting off-line analysis of the data after pre-processing to obtain the model parameters, implied information and long-term regularities by way of statistical analysis, characteristic extraction and data mining.

Data Management System
This sub-system stores and manages data. Data modification, deletion, query and printout are implemented in this stage.

The PAFC SHM system central database consists of a large-scaled relational database and a geographic information system (GIS) database, including the dynamic database, static database and analysis result database built upon the server. The invariable, or rarely variable static chart information is sent to the static database. The processed original data is developed in the dynamic database. The analysis results are printed out directly, and stored in the analysis result database.

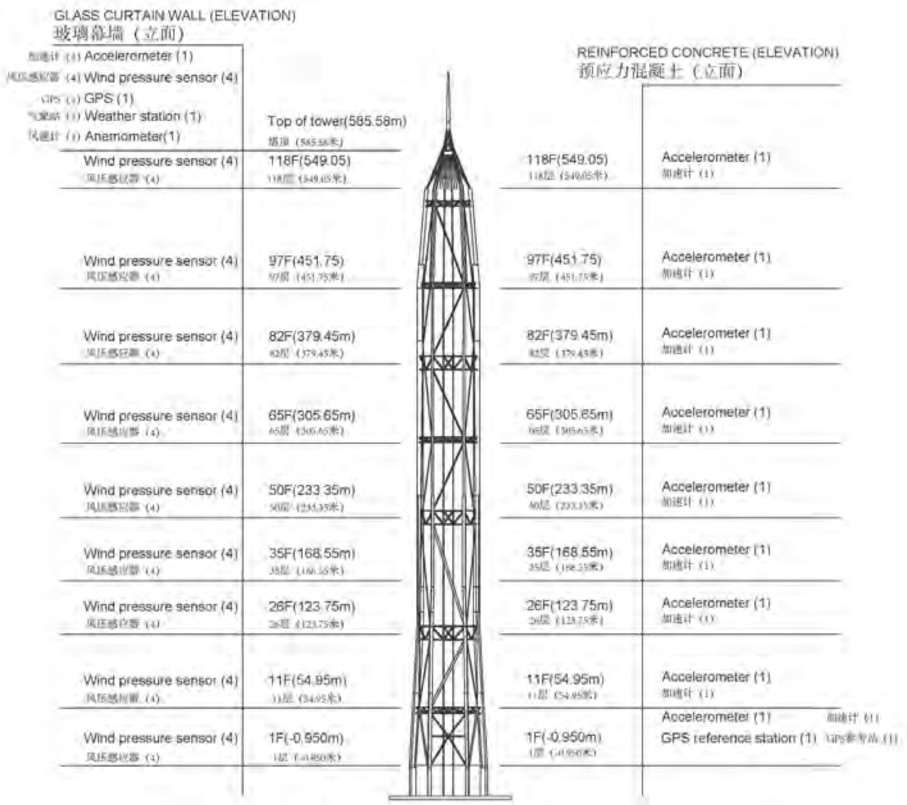


Figure 3.13. Deployment of additional sensors and instruments for in-service monitoring
图 3.13. 使用阶段增加的传感器布置图

由前处理与后处理两部分组成，如图3.17所示。

数据前处理侧重于数据的实时信息提取。数据前处理首先对原始数据进行清洗、整理，去除错误的信息，根据需要对"干净"数据进行预处理，然后计算目标监测量，统计特征参数。

数据后处理侧重于数据的长期信息提取。对经过前处理的数据进行离线分析，通过统计分析、特征提取、数据挖掘的手段来获取模型参数、隐含特征和长期规律。

数据管理系统
数据管理系统的主要功能是实现对结构监测过程中所获取数据的存储和管理，通过该系统可进行数据的修改、删除、查询和打印输出等操作。

平安金融中心健康监测系统中心数据库由大型关系数据库和GIS数据库来建立，它是由动态数据库、静态数据库和分析结果数据库组成的建立在服务器端的数据库。对于那些

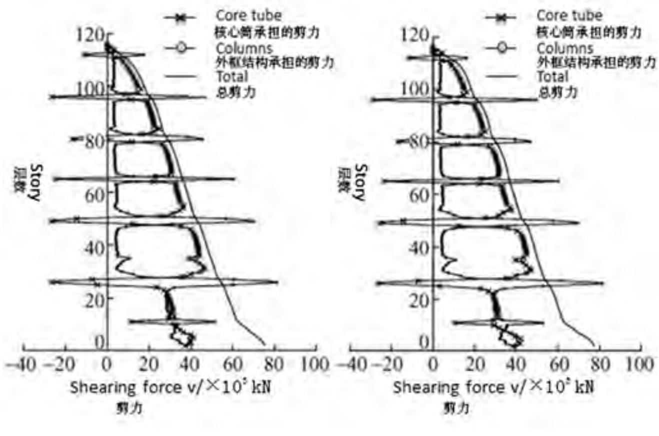


Figure 3.14. The distribution of the shearing force between core tube and columns: (a) X-direction (b)Y-direction
图3.14. 内筒、外框结构楼层剪力分配曲线: (a) X方向 (b)Y方向

Support and Protection System

This sub-system provides stable power supply, suitable construction environment, lightning and protection for the various devices.

The power supply system mainly works for the data acquisition station and sensors. The power supplied for stations is 220V AC; meanwhile the power for sensors is supplied by the station, with an electric pressure converter to ensure uninterrupted power supply for sensors.

This sub-system has lightning protections optimized for different destruction patterns, including direct lightning strikes, lightning surge invasions, lightning electromagnetic pulse jamming and lightning ground potential counterattack.

Structure Health Assessment System

This sub-system is the core of the whole SHM system, containing three modules: structural security alarm module (SSAM), structural condition and damage identification module (SCDIM), and structural comprehensive assessment module (SCAM).

The SSAM adopts the graded warning mechanism. According to the force state, there are three grades: first grade (yellow), second grade (orange) and third grade (red). If the red alarm activates, it indicates that situations in which load effects exceed the ultimate bearing capacity happen frequently.

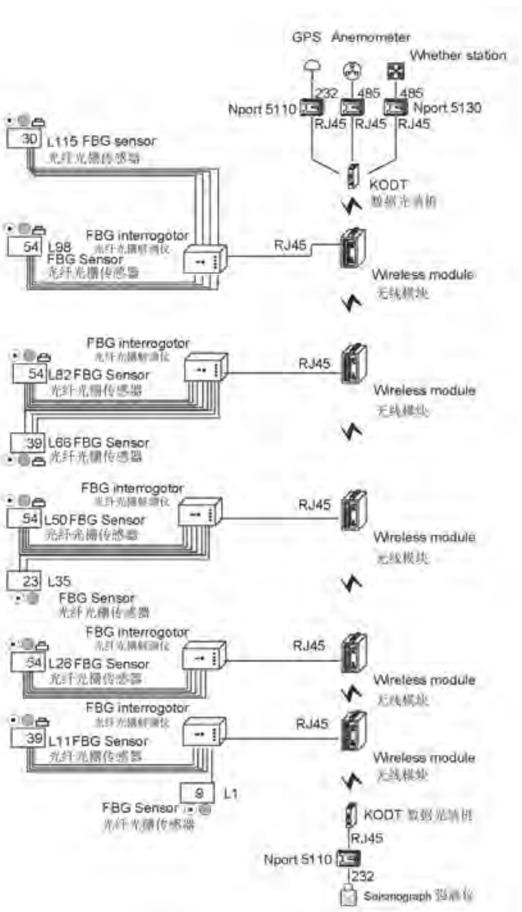


Figure 3.15. Sensor integrated system in construction stage
图 3.15. 施工监控传感器集成图

不变或很少变化的静态图形信息，利用GIS软件建立静态数据库。来自监测系统的原始监测数据，经过预处理后建立动态数据库。对分析结果直接输出，存贮到数据库中，形成分析结果数据库。

支持保护系统

为其他设备提供稳定的电源供应和适宜的工作环境，并提供防雷、防浪涌保护。

供电系统包括数据采集站供电系统和传感器供电系统。数据采集站采用220V交流电压供电，传感器系统由采集站通过电压转换器不间断供电。

本监测系统将针对直接雷击的侵袭、雷电波侵入、雷击电磁脉冲干扰、地电位反击等几个侵害途径分别建立防雷系统。

结构健康评估系统

结构健康评估子系统是深圳平安国际金融中心健康监测系统的核心，由三个子模块构成: 结构安全预警模块、结构状态及损伤识别模块、结构综合评估模块。

结构安全预警模块对结构出现的危险状态进行分级预警。根据结构的受力状态，建筑危险状态通常采用三级预警机制:一级 (黄色) 预警、二级 (橙色) 预警和三级 (红色) 预警。若红色预警启动，说明建筑结构长期出现超过承载力极限状态的情况。

结构状态及损伤识别模块对结构重要构件的状态参数及损伤情况进行识别。首先要建立结构初始健康状态样本集，然后利用监测数据建立使用阶段结构状态样本集，再把这两类样本集的数据作为损伤识别算法的输入，经计算分析得到结构构件的损伤情况。

结构综合评估模块对结构的安全性、耐久性及适用性进行综合评估。深圳平安国际金融中心健康监测评估层次共分为4 层，分别是: 目标层、准则层、大指标层、小指标层。目标层为建筑整体健康状态评估，准则层为各区段建筑性能状态评估，大指标层为每一监测区段的安全性、耐久性及适用性各分项性能评估，小指标层为各检测项目评估指标。

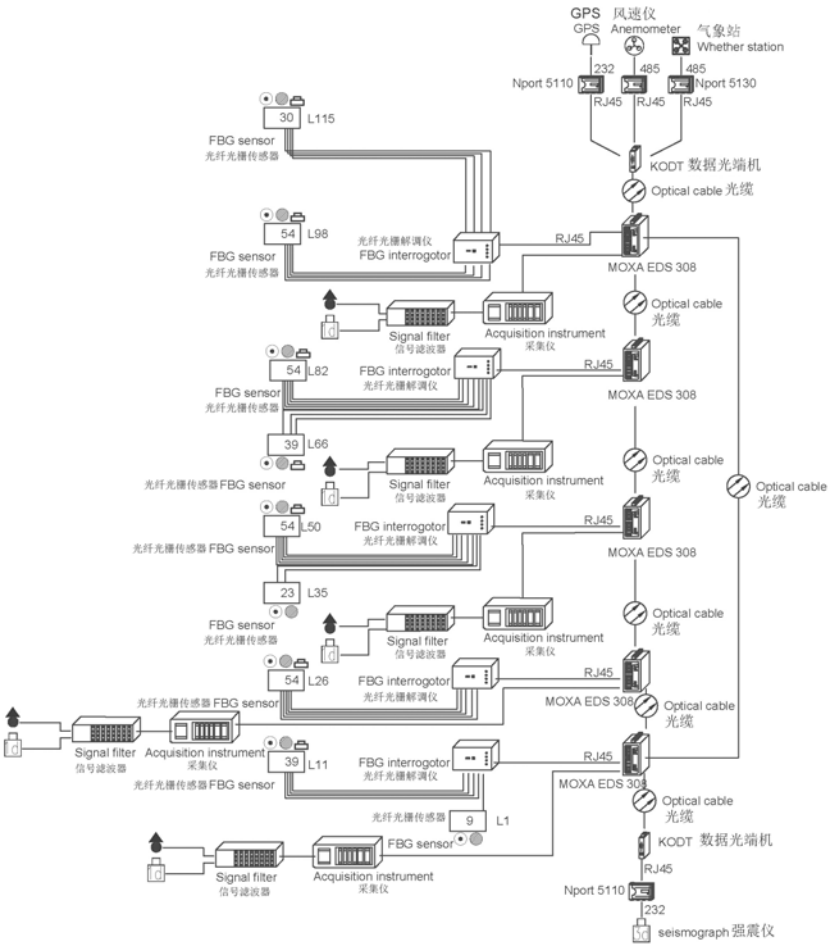


Figure 3.16. Sensor integrated system in service stage
图 3.16. 健康监测传感器集成图

The SCDIM identifies the structural damage and the important component state parameter. It first, sets up the initial undamaged state sample, then builds the samples in different operation stages and makes the conjoined analysis between the two kinds of samples, using the damage identification algorithm to judge the component state.

The structural comprehensive assessment module makes an overall performance assessment for the structure, aiming for structural safety, durability and serviceability. The PAFC SHM system is divided into an object layer, a criterion layer, a big index layer and a small index layer. The four layers correspond to the overall state assessment, the segment state assessment, the itemized index assessment of the safety, durability and serviceability and the monitoring item assessment, respectively.

Software System

This sub-system is made up of data processing software (B/S architecture) and user interface software (C/S architecture). It shows real-time data to the users on demand through the system and accepts control and input from the users. As a design of person-machine mutual system, on the premise of advanced technology, convenient operation and visual understanding, this system should meet the requirements of management interface, data description and reports for the future network office.

Using the PAFC SHM System as a Benchmark

Establishment of the Finite Element Model

Generally, the accurate finite element models are the basis for the structural damage identification. The initial PAFC finite element model has been established by the investigators according to the original design information about the material parameters, load condition and other essential structure data. This would be updated step-by-step with the real-word measurement data in

软件系统

软件系统可划分为2个子系统，即数据处理软件子系统 (B/S架构) 和用户界面软件子系统 (C/S架构)。通过该系统实现将各种数据实时按需求向用户展示，并且接受用户对系统的控制与输入。作为一个完整的系统人机交互子系统进行设计，系统在具有技术先进、操作方便、直观易懂的前提下，具备向用户提供操作及管理界面、数据表示、报告等满足未来网络发展办公的需求。

以平安金融中心健康监测系统为试验基准平台的研究与应用

建立有限元基准模型

许多结构损伤识别的算法，都需要建立较为精准的无损有限元基准模型。研究者们根据结构设计资料建立了初始的有限元分析模型，然后根据结构在多个不同的施工阶段和使用阶段的现场实测静力、动力响应数据，对初始结构模型进行动态的模型修正，建立不同阶段的动态修正基准模型，进行结构受力状态分析并预测结构的未来状态特征信息。使用结构模态特性去诊断大尺度结构的局部损伤是很困难的，于是研究者们提出了一种将整体模态数据和局部应变信息相融合的多层次数据融合结构健康评估方法来进行结构局部损伤的准确诊断。此种方法实际是一种考虑结构长期服役状态中结构的参数和荷载不确定性的结构损伤概率统计识别方法。它已经运用于广州塔的结构单元和截面的局部损伤诊断[Ni et. al., 2006 and 2008]。通过根据实测结构应变数据获得结构局部单元或截面的效应概率密度函数，而相应的结构抗力概率密度函数通过结构设计参数或者材料测试来确定，然后利用一阶可靠度方法来建立结构局部安全指标，进行损伤识别。鉴于平安金融中心整合的施工阶段和使用阶段的传感器系统，能够对结构的静态应变、动态应变和长期累积应变进行监测，便可建立结构动态统计有限元基准模型，进行塔楼整体状态和局部单元、截面的概率损伤识别。

多种基于动力特性的结构损伤识别方法比较分析

基于动力响应的损伤监测已经在国内外得到了广泛的应用，研究学者们提出了大量基于动力特性的损伤监测方法和结构损伤动力检测算法。监测方法包括固有频率的变化、

different construction stages and in the completed stage, so as to obtain the dynamically updated benchmark model in different critical stages. With the model, the estimation of instant structural state analysis, and even the prediction of future service conditions, could be done. However, it could be difficult to diagnose the damage of the local structure member or cross-sections with the intrinsic modal properties only. So a multilevel data fusion SHM assessment method which combines the global modal properties and local strain information was proposed by the interested researchers. In fact, it is a kind of statistical probability method for structural damage identification, which had been pioneered in the Guangzhou New TV Tower SHM system for local detection (Ni et. al., 2006 and 2008). In this method, two types of probability density functions (PDFs) should be determined. The PDF of the load effect in an element or a cross-section is obtained directly from measured strain data, while the PDF of the resistance of the structure or materials is derived from the prescribed structure information or material tests, then employ the first-order reliability method to identify the most vulnerable structural elements and quantify real the safety reserve of each component. The remarkably integrated PAFC SHM system could monitor the static strain, dynamic strain and cumulative strain constantly. This enables engineers to construct the dynamic statistically finite element benchmark model for the probability estimation of the integral structure state, as well as local-element or cross-section performance.

The Comparative Analysis of Multiple Dynamic Characteristics-Based Structural Damage Identification Methods

The dynamic characteristic-based damage identification methods have been applied widely in China and abroad. A large amount of relevant methods and corresponding algorithms have been undertaken by researchers. The monitoring methods mainly cover the change of frequency, the change of mode shape, the change of mode shape curvature, the residual force vector, the stiffness matrix and flexibility matrix, the damage criterion, the change rate of element modal strain energy and the change of frequency-response function. The highly effective intelligent algorithms include the neural network method, genetic algorithm, dynamic

振型的变化、振型曲率的变化、残余力向量、结构刚度矩阵及柔度矩阵、损伤指标法、单元模态应变能变化率、频响函数变化等损伤检测技术。结构损伤动力检测算法包括神经网路法、遗传算法、动力反演法、灰色系统理论等智能算法[Zhu et. al., 2011]。如Salawu 对利用频率的变化进行损伤检测作了全面的综述[Salawu, 1997]。Salawu 对一实际桥梁修复前后进行了修复位置的判别，利用 MAC (modal assurance criteria，模态保证准则) 能够判别出结构修复前后的动态特性发生了变化，利用 CMAC (coordinate modal assurance criteria，坐标模态保证准则)判别了修复位置[Salawu, 1995]。周先雁等运用残余力法对钢筋混凝土试验钢架模型的损伤进行了准确定位[Zhou, 1998]。Pandey 和 Biswas 利用结构损伤前后近似柔度矩阵差的变化规律，研究了悬臂梁、简支梁和自由梁的损伤检测，结果表明柔度矩阵差是良好的损伤检测指标，特别是当损伤位于高应力区域的时候，效果十分明显[Pandey and Biswas, 1994]。特别地，一些学者提出了一些专门针对超高层结构的损伤识别方法。包括Hilbert-Huang变换和异常诊断技术[Zhou, 2002]、小波变换诊断技术[Zhou, 2004]和基于主成分分析的神经网络技术[Ni et. al., 2006]等。

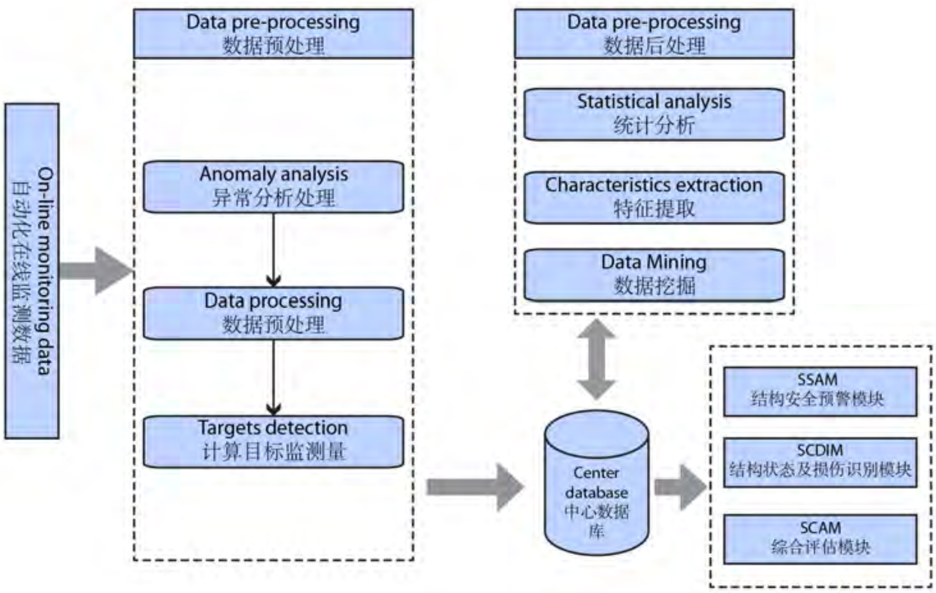


Figure 3.17. The flow chart of the DPES
图 3.17. 数据处理与评估系统工作流程图

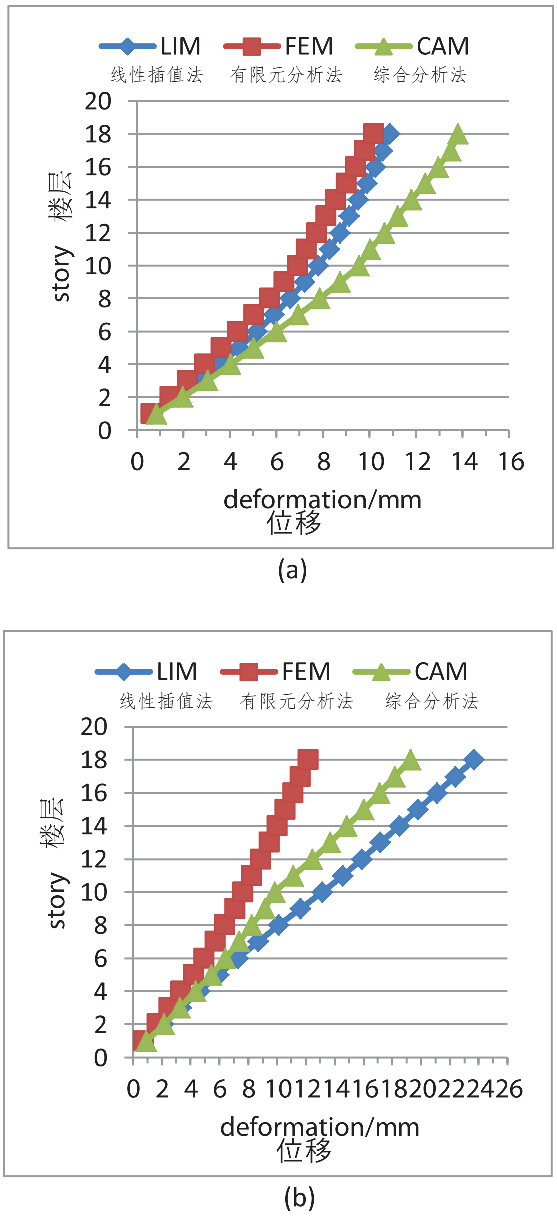


Figure 3.18. Vertical deformation: (a) external columns, (b) core-tube
图 3.18 结构竖向变形：(a) 巨柱 (b) 核心筒

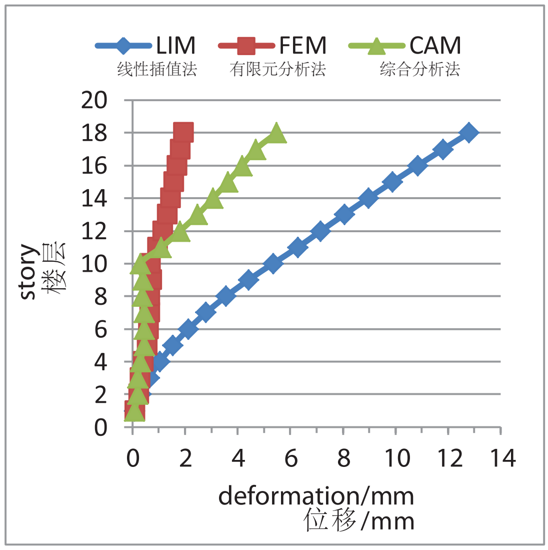


Figure 3.19. Relative vertical deformation between core-tube and external columns
图3.19 塔楼核心筒与巨柱相对竖向变形图

inversion method and grey system theory(Zhu et. al., 2011). For example, Salawu summarized the method based on the change of frequency (Salawu, 1997), Salawu judged the damage location of a practical bridge with MAC (modal assurance criteria) and CMAC (coordinate modal assurance criteria) (Salawu, 1995). Zhou located the damage of a test reinforced concrete frame model accurately using the residual force method (Zhou, 1998). Pandey and Biswas studied the cantilever beam, simply supported beam, and free beam damage identification through the change rules of the appropriate flexibility matrix difference, concluding that the flexibility matrix difference is an effective indicator, especially when the damage is in the high stress region (Pandey and Biswas, 1994). Particularly, some damage identification methods for tall buildings were developed by scholars, like Hilbert-Huang transform and a novelty detection technique (Zhou, 2002), wavelet-based diagnosis technique (Zhou, 2004) and principal component analysis-based neural network technique (Ni et. al., 2006).

Though the aforementioned methods have their inherent advantages respectively, the feasibility in the practical engineering structure, especially for the large-scale structures, had rarely been examined. So it could be a beneficial chance to treat the PAFC as a test platform to estimate the operation state both in construction and service stages. Furthermore, the effectiveness and limitations of the above methods could be cross-verified and calibrated, which could be a valuable reference for the future tall building damage identification.

这些方法都有其相应的优势，但是这些方法在实际结构中应用的可行性，特别是在大尺度结构中运用的可行性很少被验证，所以研究者们将运用这些方法，以平安金融中心为试验基准平台，对结构施工阶段和使用阶段的状态特征进行综合分析评价，并借助结构全面的实测数据，交叉校核验证这些方法在超高层结构运用中的有效性和局限性，可为超高层结构的损伤识别方法研究提供一定的参考。

传感器的优化布置

结构健康监测系统主要通过布置在结构上的多种传感器采集到的数据和信号进行损伤识别和健康状况评估。由于大型复杂结构的节点和构件过多以及自由度数量巨大,必须对传感器进行优化布置，以期用最少的监测传感器数量获得最有效的结构状态信息。对传感器数量及位置进行优化理论研究,不但可以有效地降低监测成本,而且可以提高监测系统处理信息的效率,因而具有重要的研究意义。平安金融中心建立了一套复杂的传感器监测系统，对不同阶段的结构状态进行实时连续测量。根据此传感器系统在实际监测中的应用情况，可为大尺度结构的传感器布置研究提供一定的参考。

验证结构TMD系统的有效性

RWDI风洞试验结果表明,考虑10年重现期台风作用下，结构顶部风振加速度为0.259m/s²，超出舒适度要求，设计拟在塔楼112层内筒两个对角处分别设置一个重400t的TMD 装置来控制和减小塔楼的风振加速度。根据结构典型楼层布设的加速度传感器，可以监测结构在台风作用前后

The Optimized Sensor Placement

The measured data from the sensors deployed on the structure is the basis of the SHM system for the assessment of the health condition. The larger the structure scale is, the more degree of freedom needed, so the placement of sensors must be optimized to get the most serviceable information using the smallest number of sensors. The optimal design of the number and placement of sensors not only could reduce the monitoring cost, but also improve the data processing. The sophisticated sensor placement in the PAFC SHM system could also be a reference for the large-scale structure sensor layout in accordance with the real-time feedback in the practical application.

Verifying the Function of the Tuned Mass Damper (TMD) System

The RWDI wind tunnel test results indicate that the wind-induced acceleration at the top of PAFC is 0.259m/s^2, which exceeds the requirement of the structure serviceability. So two TMDs, weighing 400t each, were deployed at the core tube diagonal in the 112th floor to reduce and control the wind-induced acceleration. Based on the measured response information from the sensors before and after the typhoon excitation, the effectiveness of the TMD system and feedback state of the TMD equipment was verified.

Construction Monitoring Results

Structure Vertical Deformation

From the vertical deformation of the core tube and the external columns and their relative vertical deformation curves when the core tube was constructed to the 59th floor (see Figure 3.18 and 3.19), was found in the analysis results that three kinds of methods yield consistent conclusions, with fine differences for the absolute vertical deformation. But for the relative vertical deformation, the linear interpolation method's (LIM) result is the largest, while the FEM simulative analysis method's result is the smallest, and the comprehensive analysis method (CAM) has the in-between result with more reference.

的结构动力响应信息，然后将二者进行比较分析，判断TMD装置对于结构动力响应的影响，验证TMD系统的有效性并及时为TMD的服役状态提供反馈信息。

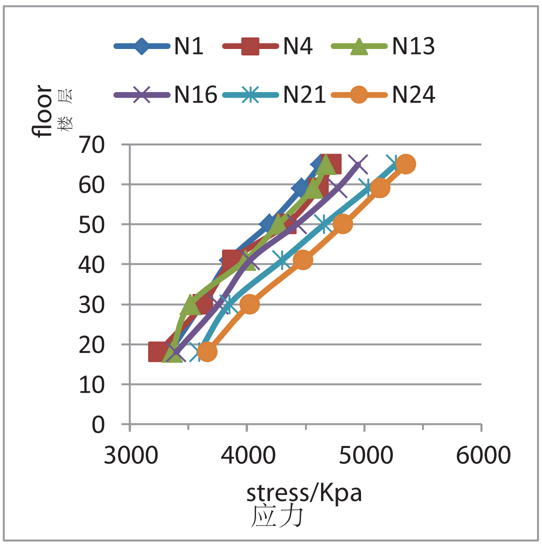
施工阶段监测成果

结构竖向变形

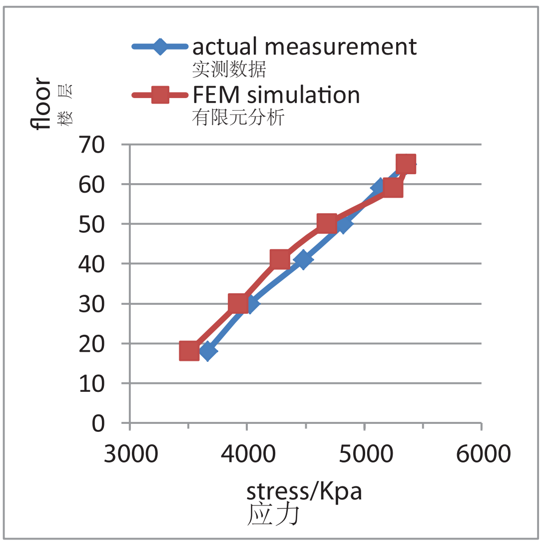
核心筒施工至59层时塔楼巨柱与核心筒竖向变形结果及相对竖向变形如图3.18、3.19所示。从以上分析可以看出，对于绝对竖向变形，三种计算方法计算结构较为接近。对于相对竖向变形，完全基于实测的线性插值法计算的相对变形值偏大，完全基于理论的有限元分析法得到的相对竖向变形值较小，结合实测及理论的综合分析方法得到了较好的结果。

结构应力监测

根据工程施工进展和数据采集条件，共进行了6次数据采集工作，对应于塔楼核心筒施工至18层、30层、41层、50层、59层和65层。桩基础底部和典型上部楼层的应力计算结果如图3.20、3.21所示。现场实测数据较为清楚的描述了桩底和典型上部楼层的应力变化趋势，现场实测数据与有

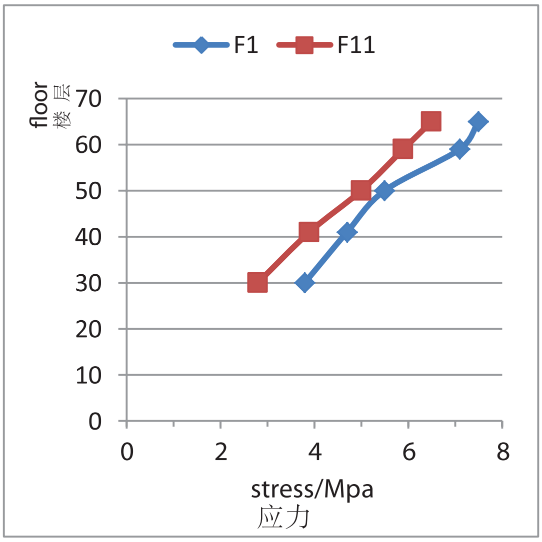


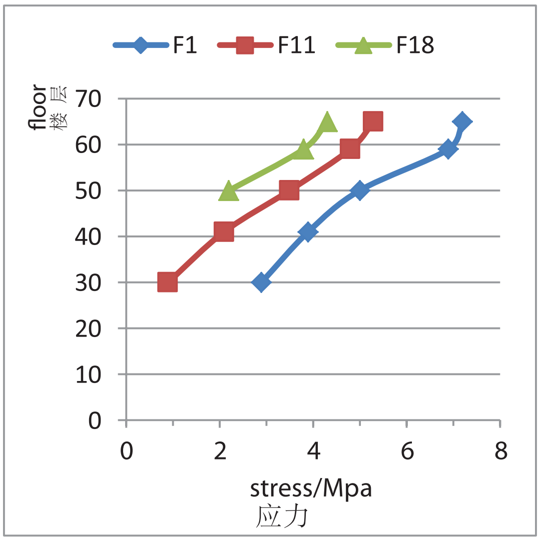
(a)



(b)

Figure 3.20. the stress of the pile bottom: (a)The measured stress of the pile bottom (b) the stress comparison of N24
图 3.20 桩底应力值比较：(a) 桩底应力实测值 (b) N24 桩底应力比较





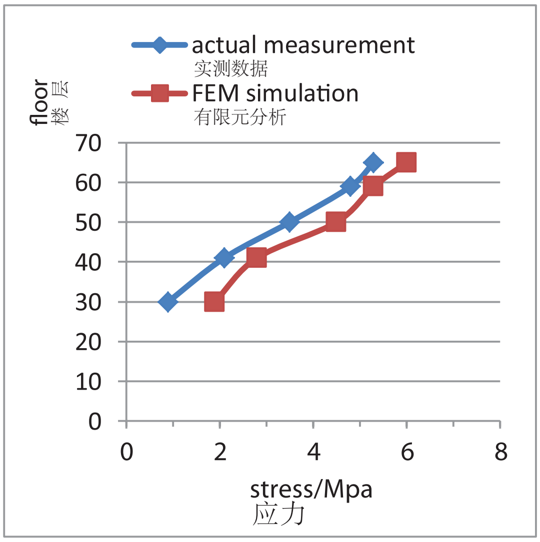


Figure 3.21. The stress of the above-ground floors : (a) core tube (b) external columns (c) the comparison between the measurement and the FEM results of F11.
图 3.21 上部楼层应力值比较: (a) 核心筒 (b) 巨柱 (c) F11层实测与有限元结果比较

The Stress of the Structure

According to the construction progress and actual data acquisition condition, six data measurements were carried out when the core tube was constructed up to the 18th, 30th, 41st, 50th, 59th and 65th floor respectively, calculating the stress analysis results of the pile bottom and representative above-ground floors (see Figure 3.20 and 3.21). The field-measured data describes the changing trend of the stress of the pile bottom and above-ground floors clearly, and the fine distinction between the actual measurement and FEM simulation results indicate the accuracy and reliability of the real-world measured data.

Conclusion

The PAFC SHM system is a breakthrough for the application of health monitoring technology in tall buildings built after the Guangzhou New TV Tower. The integration of in-construction monitoring and in-service monitoring achieved the whole-lifecycle monitoring of the structural state in real time from the beginning of construction to the future service stage. The comprehensive assessment system conducts the construction, detection and maintenance accurately and assures the structural safety operation. The modular design of the system ensures the effective independence of the sub-systems; meanwhile, the cooperative functions link them together as a whole. Eleven types of equipment, including 428 sensors, conduct an all-around monitoring of the structural static and dynamic performance. The complete field-measured data make the PAFC become a full-scale test benchmark platform for the establishment of the dynamic statistical finite element benchmark model, the verification of

限元分析之间的较小的区别说明了实测数据的准确性和可靠性，反映了传感器监测系统的有效性。

总结

平安金融中心健康监测系统，是国内继广州塔之后，健康监测技术在超高层建筑中应用的又一个重大的突破。由结构施工阶段及使用阶段集成而成的健康监测系统，实现了对结构从施工伊始至未来服役阶段的全生命周期内的状态特征信息进行连续、实时的监测，采用全面的结构健康评估系统正确指导结构的施工、检测和维护，确保结构满足预定功能安全运行。结构系统的模块化设计，保证了系统各个子功能之间的高效独立性，同时，各个子系统之间的相互协同工作，形成一个有机结合的整体。安装于结构上的11种总计428个传感器和监测仪器，能够对结构的结构响应信息进行全方位的监测，全面现场实测数据使平安金融中心成为了一个全尺度的基准实验平台，通过现场实测数据建立结构统计动态有限元基准模型，可以用来校核各种结构损伤识别技术和算法的有效性和局限性，为超高层结构监测系统的传感器优化布置提供参考，同时为结构TMD the effectiveness and limitation of various damage identification methods, the reference of the optimized sensor placement in high-rise structures and the assessment of the TMD operation state. In a word, this system is an important exploration for the health monitoring technology application in the tall structures, which promotes the development of health monitoring technology and creates a beneficial condition for technology innovation and perfection. Moreover, the system could monitor the structure information in real time and feed the data back to the engineers in time to take effective maintenance measures, which would enhance the sense of comfort and safety in the building.

系统的运营状态评估提供依据。总之，平安金融中心健康监测系统是超高层建筑健康监测应用的一个重要的有益的探索，推动健康监测技术在工程界的发展，为健康监测技术的革新和完善创造了积极的条件。更重要的是，此套监测系统可以通过实时监测结构服役信息并及时反馈结构服役状况以采取有效的维护措施，这将极大地提高用户的舒适度和安全感。

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