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A Review of the Structural Performance Monitoring Project

工程结构性态监测项目实施综述

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Through a comprehensive discussion of the systematic application of structural performance monitoring in construction, operation and maintenance of the Shanghai Tower, the author illustrates that structural performance monitoring and information processing is critical to the construction and operation of modern large complex buildings. Structural health monitoring offers verification of engineering design, control of risk as well as management of quality, schedule and operations. Moreover, the accumulation of a tremendous amount of structural-performance raw data can inform the improvement of structural engineering techniques.

本文通过结构性态监测在上海中心大厦工程施工和运维期间系统化应用之综合性论述，阐明了结构性态监测与信息化处理是现代大型复杂建筑物施工和运营管理技术的创新型拓展，不仅对工程设计验证和工程风险管理、质量管理、进度管理、运维管理起到了良好的辅助作用，而且，大量结构性态原始数据的获得与积累，从基础工作层面为结构工程技术的进一步发展和超大型建筑相应规范的不断完善提供了有利的条件。

Purpose and Necessity of the Structural Performance Monitoring of the Shanghai Tower

As a landmark of the Far East, the Shanghai Tower (see Figure 3.10) requires high standards because of its tremendous height, importance, social impact, and long service life. Main engineering challenges include the ultra-high tower, ultra-deep foundation, and systems that ensure structural integrity. From a geological perspective, most of the Shanghai region is located in a 200-300 m thick soft alluvial layer with a high level of underground water. Its location also makes it vulnerable to typhoons and earthquakes. Weather extremes appear to be associated with global warming. Objectively, there are little advantages to the construction of supertall buildings in Shanghai. In addition, risks and uncertainty must be taken into consideration, such as long-term excavation at great depths and façade installation. Therefore, the primary task of tracking and monitoring construction and operational phases is to ensure safe construction and a smooth operation for the building.

The Shanghai Tower's structural performance monitoring system helps dynamically observe risks, quality levels, and structural states under typhoon, earthquake, and other disaster loads in both the construction and operation of the Shanghai Tower. The system also provides a safety warning in case of extreme disaster conditions, and provides necessary information for inspections and maintenance. Meanwhile, as an innovation in engineering management, the work helps accumulate basic data for the future development and engineering of super high-rise buildings.

Code Practice, Basic Guidelines and Processes, Scope and Contents, and Components of the Structural Performance Monitoring

Code Practice, Basic Guidelines and Processes of the Structural Performance Monitoring

The code practice of the structural performance monitoring of the Shanghai Tower is as follows: 1)Design standard for structural health monitoring system (CECS333:2012), 2)Technical code for construction process analyzing and engineering monitoring (JGJ/T302-2013); The basic guidelines should include the following aspects: 1) monitoring plan should be systematic and relevant, 2) monitoring the structure in adverse environmental conditions during construction,

上海中心大厦工程结构性态监测实施的目的和必要性

上海中心大厦 (见图3.10) 是远东地区的地标性建筑，其区位和重要性极高，社会影响度大，使用周期长; 工程具有超高、超深、技术复杂且综合程度高等特点。从地理和气象条件来看，上海地区大部分形成于200-300米厚的软弱冲积层，地下水位较高，地理位置易受台风和周边地区地震的影响，加之全球气候变暖，极端气象状况频发，客观上并不具备建设超高层建筑的理想条件。此外，施工过程中也存在诸多风险和不确定因素例如长期的深基坑开挖和外幕墙的安装等等。因此，对其在施工和使用阶段进行跟踪监测之首要任务是确保上海中心大厦项目安全建造和健康营运。

建立上海中心大厦结构性态监测系统，可以动态了解大厦在建造和使用过程中的风险状态、质量水平以及强台风、地震等灾害性荷载作用下的结构性态，进行极端灾害情况下的安全预警，对检查和维护提供必要的信息和依据。同时，该项工作对于工程技术管理而言是一种创新，可以为超高层建筑未来的技术发展与工程建设，做好基础资料的收集与分析工作，因而具有重要的工程价值和社会意义。

temporary and permanent structural integrity, to achieve the classification warning of stress for important components, and construction quality tracking, 3) monitoring the structure to withstand the long-term effect of strong wind, earthquake, and temperature load, to inform and verify the critical reaction of the structure under load in extreme environmental conditions, 4) obtaining first-hand data and technical analysis, so the final form, force, displacement and frequency of the structure can meet the design requirements, 5) establishing a data exchange and sharing platform to provide services for operation management and technique development.

The basic processes of structural performance monitoring are as follows:

1. installation of monitoring devices and equipment in accordance with the project implementation process and conditions
2. field testing data collection
3. data analysis and management
4. risk warning and maintenance tracking
5. data sharing and research

Scope and Contents of the Structural Performance Monitoring

The scope of the Shanghai Tower structural performance monitoring covers the temporary supporting structure for excavation, the permanent steel structure and reinforced concrete structure, the curtain wall structure, ambient temperature, wind environment, wind & seismic -induced vibration and structural response, structural elevation, strain, forces and displacements, damping systems and so on. The specific contents are as follows:

1. Structural seismic response monitoring
2. Structural wind environment (including wind speed, wind loads and direction) monitoring
3. Structural displacement and settlement monitoring for both temporary and permanent structure

Figure 3.10. Shanghai Tower (Source: Shanghai Tower Construction & Development Co., Ltd.)
图3.10. 上海中心大厦 (来源: 上海中心大厦建设发展有限公司)

上海中心大厦工程结构性态监测的基本规程、导则和流程、范围与内容及系统组成

结构性态监测的基本规程、导则和流程

上海中心大厦结构性态监测工作的基本规程: 1) 结构健康检测系统设计标准 (CECS333:2012)，2) 建筑工程施工过程结构分析与监测技术规范 (JGJ/T302-2013); 其导则应包括以下几个方面: 1) 监测工作规划设计应具有系统性和关联性，2) 通过监测结构在施工过程中不利的环境因素、临时和永久结构的安全性及关键质量，实现对重要构件应力应变超界的分级预警和施工质量跟踪，3) 通过监测结构在营运过程中承受强风、地震、温度荷载的长期作用，对结构在极端环境条件载荷作用下的临界反应进行预警和验证，4) 获得第一手数据资料和在此基础上的技术分析，使最终得到的结构形态、内力、位移和频率等符合设计要求，5) 建立数据交互和共享平台，为运营管理和技术开发提供服务。

结构性态监测的基本流程如下:

1. 按照工程实施进程和条件安装监测装置和设备
2. 现场检测数据采集
3. 数据分析和管理
4. 风险预警和维护跟踪
5. 数据共享和研究

结构性态监测的范围和内容

上海中心大厦结构性态监测范围涵盖基坑临时支护结构，永久钢结构和钢筋混凝土结构，幕墙结构，环境温度，风环境，风振与结构响应，地震与结构响应，结构标高、应变、内力和位移，阻尼系统等，具体内容如下:

1. 结构地震响应监测;
2. 结构风环境包括风速、风压和风向的监测
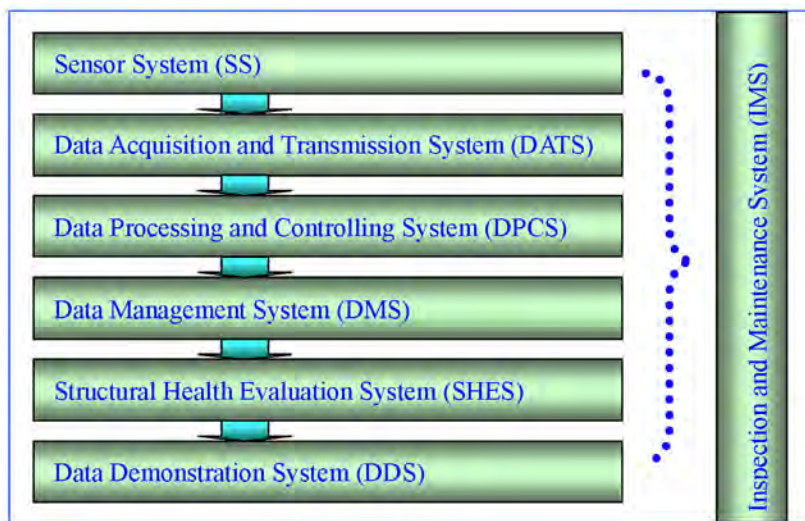3. 对临时结构和永久结构的位移和沉降监测
4. 结构加速度响应监测

Figure 3.11. The organizational structures of each subsystem (Source: Shanghai Tower Construction & Development Co., Ltd.)

图3.11. 各子系统形成的组织架构 (来源: 上海中心大厦建设发展有限公司)

4. Structural acceleration response monitoring
5. Structural temperature monitoring
6. Structural components of stress and strain monitoring
7. Structural elevation monitoring
8. Tower structure inclination monitoring
9. Structural component surface crack monitoring
10. Working condition of panel wall sliding bearing monitoring

Introduction of the Components of the Structural Performance Monitoring for the Shanghai Tower

Monitoring systems in the construction and operation phases essentially consist of five parts: 1) sensor system; 2) data acquisition and transmission system; 3) data processing and analysis system; 4) data management system; 5) structural state assessment system. The organizational structure of each subsystem is shown in Figure 3.11. A diagram of the BIM model and the sensor model is shown in Figure 3.12. The connection architecture diagram between the monitoring subsystem, the corresponding sub-system, and control center is shown in Figure 3.13. The architecture diagram of the structural performance monitoring database is shown in Figure 3.14.

Part Results of the Shanghai Tower Structural Performance Monitoring Project

Podium Basement Construction Monitoring

Engineering Features and Risk Analysis
Shanghai Tower is located in the heart of Lujiazui Finance and Trade Zone, near the Shanghai Jinmao Tower, the World Financial Center and other high-rise buildings. Pipelines around the site are extremely complex. The excavation area of the podium basement is about 23,460 m² with a depth of 26.70 m. The piled rafts as the podium foundation are buried 26.3 m underground. The podium basement is built in a top-down construction sequence with the unity of the two walls underground as a retaining structure. When the podium basement is under construction, the main structure is used as the horizontal support system. Through a detailed analysis, the risks of constructing the podium basement are summarized as follows:

Risk No.1: Geological survey results show that the bottom surface of excavation is placed on layer 6 or layer 7_1. Around the foundation, there are soft clay based layers on layer 3, 4, and 5 with obvious thixotropic and rheological characteristics. Layer 7_1 is the powder (sand) soil layer with good water permeability. Without proper measures to precipitate or seal water, it is easy to bring about sand drifting, piping, and other adverse geological phenomena.

Risk No.2: The pit is excavated at a great depth, with the bottom placed on layer 6 and layer 7_1. In excavation, the soil at the bottom has a certain degree of resilience, which affects the supporting structure of the pit or causes rebounding crack problem of the drilled caisson piles. In addition, as the water level drops in the pit, displacement of the soil around the pit leads to

5. 结构温度监测
6. 结构构件应力应变监测
7. 结构标高监测
8. 塔楼结构倾斜度监测
9. 结构构件表面裂缝监测
10. 幕墙滑移支座工作状态监测

上海中心大厦工程结构性态监测系统组成简介

施工阶段和使用阶段监测系统基本上由5个部分组成: 1) 传感器系统; 2) 数据采集与传输系统; 3) 数据处理与分析系统; 4) 数据管理系统; 5) 结构性态评估系统。各子系统形成的组织架构参见图3.11。上海中心BIM模型+传感器模型示意图参见图3.12，监测分项与相应子系统及总控中心的连接架构示意图参见图3.13，结构性态监测数据库架构示意图参见图3.14。

上海中心大厦工程结构性态监测项目部分成果简介

裙房基坑施工监测
工程特点与风险分析
上海中心大厦位于陆家嘴金融贸易区核心地段，紧邻上海金茂大厦、环球金融中心等多幢超高层建筑，场地四周管线极为复杂。裙房基坑开挖面积约23460 m²，开挖深度26.70m，裙房基础采用桩筏基础，埋深约为26.3m。裙房地下室采用逆作法施工，以两墙合一的地下连续墙作为围护结构，裙房基坑逆作施工时，以主体结构作为水平支撑体系。通过详细分析，发现裙房基坑施工过程中存在以下风险因素。

工程风险1: 地质勘察结果表明，基坑工程底面置于第⑥层或第⑦₁层中，基坑周边以第③、④、⑤₁等软弱粘性土层为主，有较明显触变及流变特性。第⑦₁层为粉(砂)性土，透水性较好。若降水和止水措施不当，极易产生流砂、管涌等不良地质现象。

工程风险2: 基坑开挖深度大，坑底置于第⑥层或第⑦₁层中，开挖时坑底土体会有一定的回弹，对基坑支护结构将产生不利影响，同时可能引起的已施工钻孔灌注桩的回弹拉裂问题。另外，坑内水位下降，基坑周边土体的位移带动相邻既有建筑物、道路和地下管线等发生变形，影响它们的
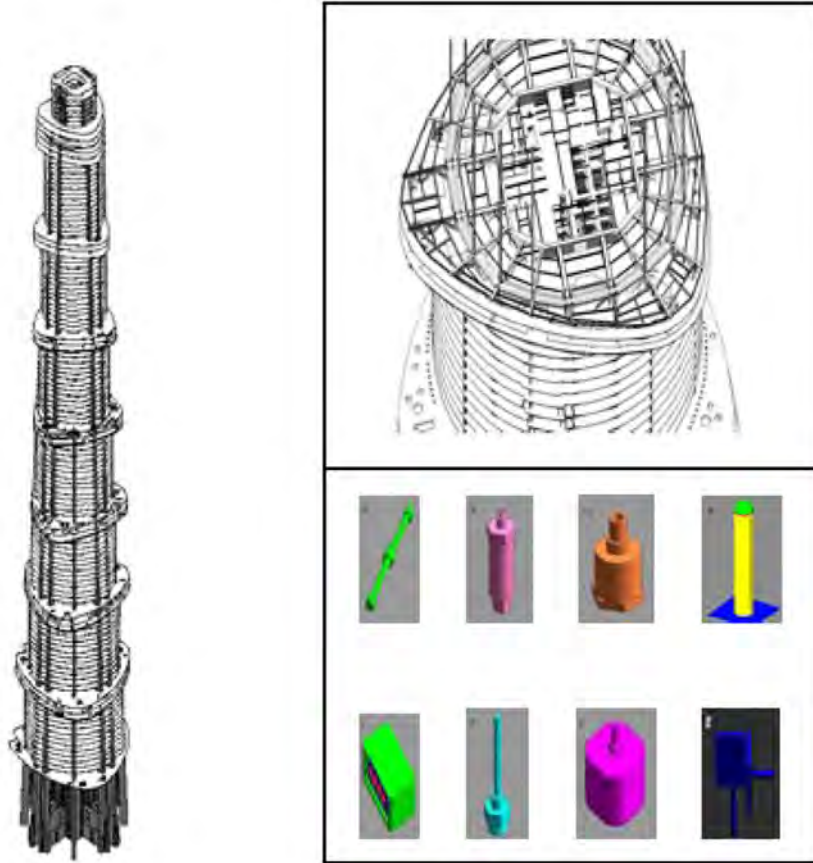
Figure 3.12. BIM Model +Sensor Model of the Shanghai Tower (Source: Shanghai Tower Construction & Development Co., Ltd.)

图3.12.上海中心BIM模型+传感器模型 (来源: 上海中心大厦建设发展有限公司)

the deformation of the existing buildings, roads and underground pipelines, which may affect their operation. The project affects the surrounding environment seriously because of the deep pit excavation and the long cycling period of confined water precipitation.

Risk No.3: Excavation and temperature changes may lead to the internal stress redistribution of the envelop enclosure system, and its operation state also faces high risks.

Monitoring Contents Setting

According to the characteristics of the project – the environment, geology, soil, and water conditions, and risk control requirements – it is determined to set the following independent comprehensive monitoring items:
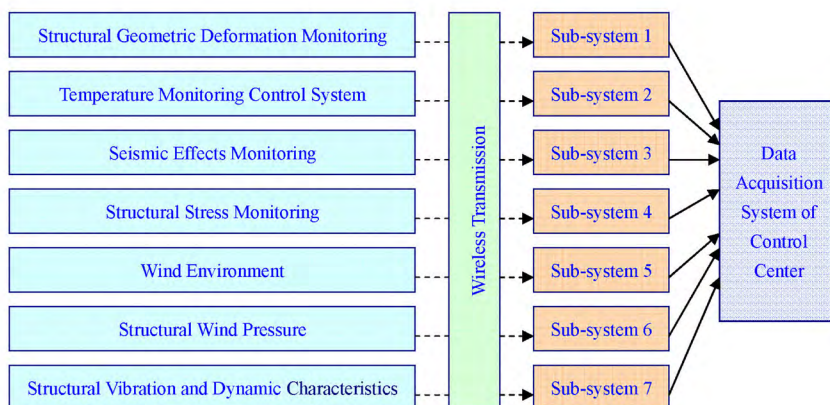

Figure 3.13. The connection architecture diagram between monitoring subsystem and the corresponding sub-system and control center (Source: Shanghai Tower Construction & Development Co., Ltd.)

图3.13. 监测分项与相应子系统及总控中心的连接架构示意图 (来源: 上海中心大厦建设发展有限公司)

正常使用。本工程深基坑开挖和承压水降水周期长，对周边环境影响显著。

工程风险3: 基坑开挖和温度的变化将引起围护结构体系内部应力的重分布，围护结构体系的工作状态同样存在较高的风险。

工程监测内容设定

根据本工程的特点、周围环境、地质和水土条件及风险控制要求，按照安全、经济、合理的原则，决定在施工过程中设置以下独立的综合监测项目:

1. 基坑围护监测
   - 围护顶部变形和围护结构侧向位移监测
   - 立柱桩垂直位移和桩身应力监测
   - 地墙竖向钢筋和混凝土应力监测
   - 裙房基坑B0层—B4支撑结构监测
2. 水工、土工和地表监测
   - 坑外土体侧向位移与分层沉降监测
   - 坑内土体隆沉监测
   - 坑内外潜水水位观测
   - 坑内外承压水位观测
   - 墙侧土压力与孔隙水压力监测
   - 坑外地表沉降监测

实际完成各类监测工作见表3.3。

地下室底板后浇带封闭跟踪监测

监测目的

按照施工图设计要求，地下室后浇带需在主楼结构封顶后实施。由于本工程有五层地下室，基坑维护结构范围大，裙房地下室逆作法施工周期长，仅地下室所有后浇带封闭施工周期就超过半年时间，且此项工作属于关键施工路径。如果等塔楼结构封顶开始后浇带封闭将会严重影响整个工期。因此，施工总包基于施工荷载与塔楼沉降变形的长期跟踪与分析，提出提前进行后浇带封闭的建议。

设计单位认为，后浇带提前封闭会使得地下室底板结构因主楼封顶与后浇带封闭时差内产生的沉降变形转变为结构底板的附加应力，底板应力升高可能产生混凝土细微裂缝的增加，降低结构品质与防水可靠度。显然，理论上工期与结构品质这一矛盾是客观存在的。
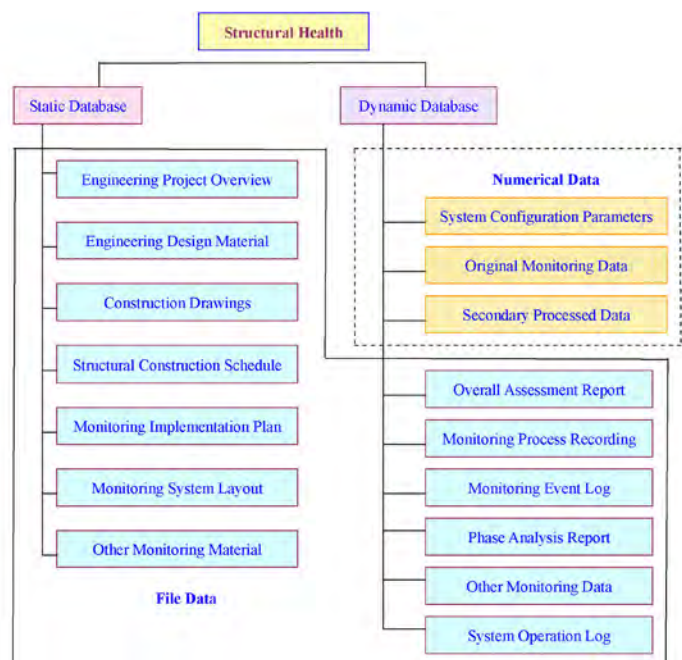
Figure 3.14. The architecture diagram of structural performance monitoring database (Source: Shanghai Tower Construction & Development Co., Ltd.)

图3.14. 结构性态监测数据库架构示意图 (来源: 上海中心大厦建设发展有限公司)

1. Foundation pit enclosure monitoring
   - deformation of the top enclosure and lateral displacement of envelop enclosure monitoring
   - the vertical displacement of the pile and the pile upright stress monitoring
   - vertical reinforcement and concrete of the wall stress monitoring
   - the podium pit layer B0-B4 supporting structure monitoring
2. Hydraulic, geotechnical, and surface monitoring
   - Lateral displacement of the soil outside and layered settlement monitoring
   - upheaval and setting of the soil inside monitoring
   - the diving water level observation inside and outside the pit
   - internal and external confined water level observation
   - the side soil pressure and pore water pressure of the wall monitoring
   - the field subsidence outside monitoring

The actual completion of various monitoring items is shown in Table 3.3.

Post-Poured Belt Sealing of the Basement Floor Tracking Monitoring

Monitoring Purpose

In accordance with the design requirements outlined in construction plans, the post-poured belt in the basement should be implemented after the main building structure is roofed. As the project has five basements with a large range of temporary structures, it takes a long period of top-down construction to accomplish the basements of the podium, with over six months to finish all the post-poured belts in the basements. This work is also a critical construction path. It will postpone the entire construction plan if the closure of post-pored belts start after the tower is roofed. Thus, the engineering contractor suggests starting the closure of the post-poured belts in advance, based on a long period of tracking and analysis on construction stress and settlement deformation.

The designer believes that pre-closure of the post-poured belts can transform the settlement deformation caused by the time difference between roofing the main building and the closing the post-poured belts into additional stress of the structural base floor. Stress increase of the floor may intensify concrete cracks and reduce structural integrity and waterproof quality. Theoretically, the contradiction between project duration and structure quality is an objective reality.

Through comprehensive evaluation and by references similar engineering experiences, the construction party and the project contractor put forward technical solution for the two-phase

建设方、施工总包单位经过综合考量并参照类似工程经验，与设计单位反复研究，在基于大量数据分析的基础上，提出了底板后浇带封闭两阶段实施的技术方案，优化材料使用与止水构造，并基于结构分析，在底板高应力区布置钢筋应力监测计，在底板第二阶段后浇带封闭之前，强化关键部位钢筋应力与沉降的持续监测，与此同时，基坑降水措施同步实施。其中，钢筋应力和沉降监测数据评估作为底板后浇带第二阶段施工与基坑降水实施的重要依据。地下室底板高应力区钢筋应力监测计布置参见图3.15。

数据采集与分析

在底板后浇带第一阶段施工完成7个半月后，通过监测获得的底板关键部位钢筋应力监测数据参见表3.4。

上述监测数据显示: 当塔楼超过自重的3/4后开始封闭底板厚浇带，随着塔楼施工载荷的逐步增加和工程措施的合理运用，各测点应力增量均处在较低的水平。测量与分析结果表明，底板结构处在安全的状态，后浇带提前封闭的技术方案是可行的。

幕墙滑移支座工况监测

滑移支座风险状态评估和监测方法

上海中心外幕墙安全运作的关键装置是数量众多的滑移支座，尤其是每区底环梁上的竖向滑移支座。工程师通过之前大量的分析论证提出，垂直滑移支座最大的风险并不是上下滑动超过限值，而是滑移受阻，甚至不滑动。如何探测密闭的支座装置内部是否卡壳呢？

经分析发现，滑动支座 (特别是向下闭合的滑动支座) 受阻的过程如下:

1. 底部吊杆松弛，耳板与吊杆间的预留槽消失;
2. 底部吊杆松弛后受压变形;
3. 受持续受压的变形影响，幕墙的预留槽消失;
4. 吊杆在压力下屈曲,

幕墙板和配件受挤压损坏。最终，幕墙的滑移支座被卡壳，幕墙板受挤压甚至破碎。显然，在幕墙的支撑系统内，最大的风险存在于滑移支座和吊杆。业主工程师在外幕墙抗震试验刚结束时提出增加一个幕墙吊杆受压变形的额外试验，利用已有

Monitoring Item 监测项目	Number of Monitoring Points 监测点数量	Monitoring Period 监测时间	Testing Frequency 测试频次
Deformation of the top of the enclosure monitoring 围护顶部变形监测	54 points 54 点	Aug. 10, 2010 – Apr. 12, 2013	610 times
Lateral displacement of the envelop enclosure monitoring 围护结构侧向位移监测	25 holes (depth of 45m approximately) 25 孔 (孔深约45m)	Aug. 10, 2010 – Apr. 12, 2013	616 times
Lateral displacement of the soil outside monitoring 坑外土体侧向位移监测	11 holes (depth of 59m approximately) 11 孔 (孔深约59m)	Aug. 10, 2010 – Mar. 24, 2013	563 times
Vertical displacement of column piles monitoring 立柱桩垂直位移监测	362 points 362 点	Dec. 28, 2010 – Jul. 27, 2012	314 times
Body stress of column piles monitoring 立柱桩桩身应力监测	12 groups (48 steel stress gauges) 12 组(48 只钢筋应力计)	Feb. 27, 2011 – Jun. 8, 2011	101 times
Vertical rebar stress of the wall monitoring 地墙竖向钢筋应力监测	8 groups (384 steel stress gauges) 8 组(384 只钢筋应力计)	Dec. 28, 2010 – Apr. 12, 2013	436 times
Vertical concrete stress of the wall monitoring 地墙竖向混凝土应力监测	8 groups (192 concrete strain gages) 8 组(192 只混凝土应变计)	Dec. 28, 2010 – Apr. 12, 2013	436 times
Outside layered settlement monitoring 坑外分层沉降监测	4 holes (44 settlement rings) 4 孔(44 只沉降磁环)	Aug. 10, 2010 – Dec. 10, 2012	554 times
Inside soil resilience monitoring 坑内土体回弹监测	8 holes (48 settlement rings) 8 孔(48 只沉降磁环)	–	–
Outside groundwater level observation 坑外潜水水位观测	21 holes (depth of 24m approximately) 21孔 (孔深约24米)	Aug. 10, 2010 – Mar. 15, 2013	852 times
Inside groundwater level observation 坑内潜水水位观测	6 holes (depth of 24m approximately) 6孔 (孔深约24米)	Aug. 10, 2010 – Apr. 7, 2011	230 times
Outside confined level observation 坑内承压水位观测	4 holes (depth of 45m approximately) 4孔 (孔深约45米)	Aug. 10, 2010 – Mar. 19, 2012	576 times
Inside confined level observation 坑外承压水位观测	8 holes (depth of 45m approximately) 8孔 (孔深约45米)	Aug. 10, 2010 – Mar. 15, 2013	852 times
Lateral soil pressure of the wall monitoring 墙侧土压力监测	8 groups (136 soil pressure meters) 8 组(136 只土压力计)	Dec. 28, 2010 – Apr. 12, 2013	436 times
Side pore water pressure of the wall monitoring 墙侧孔隙水压力监测	8 groups (136 pore water pressure meters) 8 组(136 只孔隙水压力计)	Aug. 10, 2010 – Apr. 12, 2013	436 times
Surrounding surface subsidence profile monitoring 周边地表沉降剖面监测	11 groups (55 points) 11 组 (55 点)	Aug. 10, 2010 – Apr. 12, 2013	610 times
Support axial force of Layer B0 monitoring B0 层支撑轴力监测	18 groups (72 steel stress gauges) 18 组(72 只钢筋应力计)	Dec. 28, 2010 – Mar. 6, 2013	651 times
Structural beam axial force of Layer B0 monitoring B0 层结构梁轴力监测	10 groups (40 steel stress gauges) 10 组(40 只钢筋应力计)	Dec. 28, 2010 – Mar. 6, 2013	651 times
Floor stress of Layer B0 monitoring B0 层楼板应力监测	27 groups (216 steel stress gauges) 27 组(216 只钢筋应力计)	Dec. 28, 2010 – Mar. 6, 2013	651 times
Support axial force of Layer B1 monitoring B1 层支撑轴力监测	24 groups (96 steel stress gauges) 24 组(96 只钢筋应力计)	Feb. 16, 2011 – Mar. 24, 2013	652 times
Structural beam axial force of Layer B1 monitoring B1 层结构梁轴力监测	9 groups (36 steel stress gauges) 9 组(36 只钢筋应力计)	Feb. 16, 2011 – Mar. 24, 2013	652 times
Floor stress of Layer B1 monitoring B1 层楼板应力监测	27 groups (216 steel stress gauges) 27 组(216 只钢筋应力计)	Feb. 16, 2011 – Mar. 24, 2013	652 times
Support axial force of Layer B2 monitoring B2 层支撑轴力监测	12 groups (48 steel stress gauges) 12 组(48 只钢筋应力计)	May 28, 2011 – Mar. 24, 2013	551 times
Structural beam axial force of Layer B2 monitoring B2 层结构梁轴力监测	13 groups (52 steel stress gauges) 13 组(52 只钢筋应力计)	May 28, 2011 – Mar. 24, 2013	551 times
Floor stress of Layer B2 monitoring B2 层楼板应力监测	33 groups (168 steel stress gauges) 33 组(168 只钢筋应力计)	May 28, 2011 – Mar. 24, 2013	551 times
Support axial force of Layer B3 monitoring B3 层支撑轴力监测	13 groups (52 steel stress gauges) 13 组(52 只钢筋应力计)	Jul. 10, 2011 – Mar. 24, 2013	508 times
Structural beam axial force of Layer B3 monitoring B3 层结构梁轴力监测	15 groups (60 steel stress gauges) 15 组(60 只钢筋应力计)	Jul. 10, 2011 – Mar. 24, 2013	508 times
Floor stress of Layer B3 monitoring B3 层楼板应力监测	33 groups (168 steel stress gauges) 33 组(168 只钢筋应力计)	Jul. 10, 2011 – Mar. 24, 2013	508 times
Support axial force of Layer B4 monitoring B4 层支撑轴力监测	16 groups (64 steel stress gauges) 16 组(64 只钢筋应力计)	Sep. 10, 2011 – Apr. 12, 2013	446 times
Structural beam axial force of Layer B4 monitoring B4 层结构梁轴力监测	10 groups (40 steel stress gauges) 10 组(40 只钢筋应力计)	Sep. 10, 2011 – Apr. 12, 2013	446 times
Floor stress of Layer B4 monitoring B4 层楼板应力监测	31 groups (160 steel stress gauges) 31 组(160 只钢筋应力计)	Sep. 10, 2011 – Apr. 12, 2013	446 times

Table 3.3. The summary sheet of actual completion of various monitoring items in podium pit construction (Note-1)
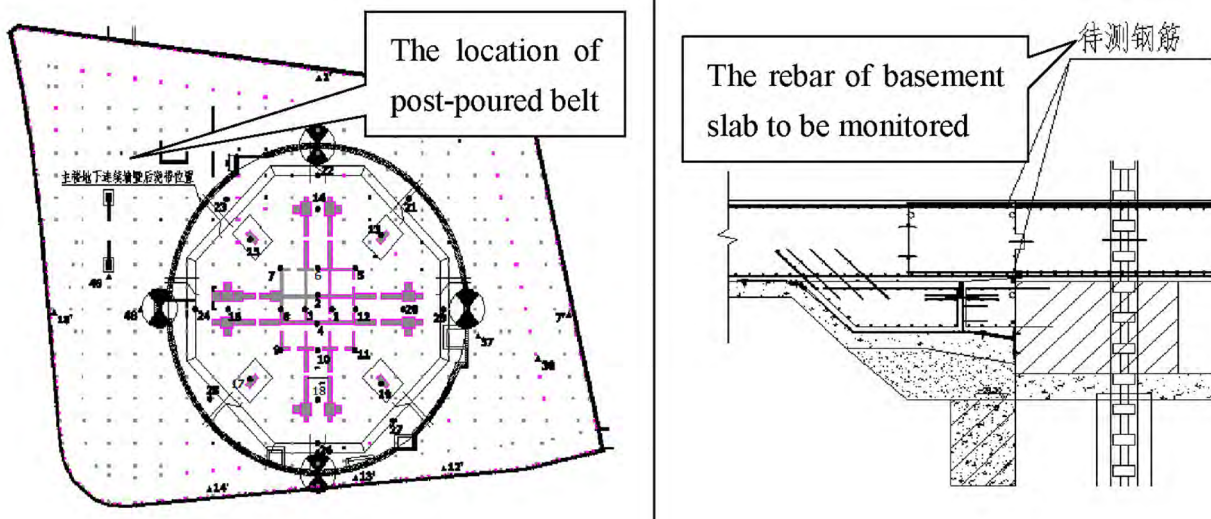表3.3. 裙房基坑施工实际完成各类监测工作汇总表

Figure 3.15. Monitoring point layout diagram (Source: Shanghai Tower Construction & Development Co., Ltd.)
图3.15. 测点布置图 (来源: 上海中心大厦建设发展有限公司)

implementation of post-poured belt closure after repeated discussion with the designer on the basis of enormous data analysis.

1. Optimize material usage and the water sealing structure.

2. Install rebar stress meters in the high stress zone based on structural analyses.

3. In the second phase of construction for the post-poured belts, enhance rebar stress and settlement monitoring of critical portions before closing the post-poured belts.

4. Take effective measure to depress the groundwater level at the same time. Rebar stress and settlement monitoring data evaluation is an important basis for the second-phase of the post-poured belts construction and the precipitation of the pit. The rebar stress monitoring gauges layout is shown in Figure 3.15.

Data Acquisition and Analysis
Seven and a half months after the completion of the first phase of the floor post-poured belt construction, the rebar stress monitoring data of the critical part is shown in the table 3.4.

The monitoring data above shows: the floor post-poured belt closure starts when the tower is constructed over 3/4 of its total self-weight. With the gradual increase of loads in construction and the rational use of construction measures, the stress increment of each monitoring point is at a relatively low level. Monitoring and analysis results indicate that the floor structure is in a safe condition and it is feasible to close the post-poured belts in advance.

Monitoring Point Number 测点编号	Micro-strain Increment 微应变增量	Stress Increment (Mpa) 应力增量
E-1-BM1	-104.134	-20.8268
E-1-BM2	-185.538	-37.1076
E-2-BM1	-92.721	-18.5442
E-2-BM2	-133.588	-26.7176
S-1-BM1	-157.441	-31.4882
S-1-BM2	-18.797	-3.7594
S-2-BM1	-44.109	-8.8218
S-2-BM2	-126.723	-25.3446
W-1-BM1	-168.718	-33.7436
W-1-BM2	-81.777	-16.3554
W-2-BM1	-50.893	-10.1786
W-2-BM2	-176.942	-35.3884
N-1-BM1	-199.008	-39.8016
E-1-RM1	-292.286	-58.4572
S-1-RM1	-104.179	-20.8358
W-1-RM1	-34.292	-6.8584

Table 3.4. Data of the steel stress gauges of the floor post-poured belts(Note-2)
表3.4. 底板后浇带钢筋应力计数据

Construction Monitoring of Slipping Bearing of the Panel Wall

Risk Condition Assessment and Monitoring Methods of the Slipping Bearing
The key device is the large number of slipping bearings to ensure the safe operation of the façade wall in the Shanghai Tower, especially the vertical slipping bearings on the bottom ring beam in each zone. After numerous analyses , the engineers found that the biggest risk of the vertical slipping bearings is not to slip past their limits, but to block slipping or even not slip. What method is there to detect whether it is stuck inside the sealed bearing device?

It was found that blocked slipping especially hindered downward slipping under the following conditions:

1. the bottom tension rod is loosened. The gap between the ear-plate and the tension rod disappears.

2. the bottom tension rod suffers compressive deformation after being loosened.

3. with continuous compressive deformation, the reserved gap in the inserting slot of the panel wall disappears.

4. the rod buckles under pressure and the fittings and glass plates are squeezed and damaged.

Hence, the real risk for the façade is when a sliding bearing is stuck and the panel is squeezed and crushed under pressure. In the façade support system, the greatest risk exists in the vertical slipping bearings and the tension rod. During the façade wall seismic testing, the owner's engineers proposed an additional experiment, a panel and rod compressive deformation test. Under the existing test conditions and with a slightly improved testing device, a gradual compression test began on the panel wall support ring beam, rod, and panel unit, to analyze rod buckling and the critical value of deformation of the panel when its frame is under pressure. The ultimate success of the testing requiress the health monitoring of the bearings with the actual material.

试验条件，对测试装置稍加改造，进行幕墙支撑环梁、吊杆、幕墙单元板块逐级压缩的特殊测试，通过对吊杆的应力应变监测，找到吊杆曲屈，幕墙板块受压的临界变形值。试验最终获得成功，从而为推进支座健康监测获得了第一手资料依据。

在监测对象的选择方面，经与设计组研究分析，每区选择受拉力最小的三根吊杆作为监测对象，通过对钢吊杆应变的间接监测实现对滑移支座是否正常工作的跟踪检测。塔楼吊杆体系与吊杆应力计布置示意图参见图3.16。

监测报警阀值设定与评估
监测对象设置报警阀值条件如下：

1) 吊杆应变ξ: (<-200με) 二级报警;

2) 吊杆应变ξ: (0~-200με) 一级报警;

3) 吊杆受拉: 安全。

从实际监测的数据来看，目前钢吊杆中的应变均处于十分安全的状态，见表3.5。

上海中心大厦结构振动监测
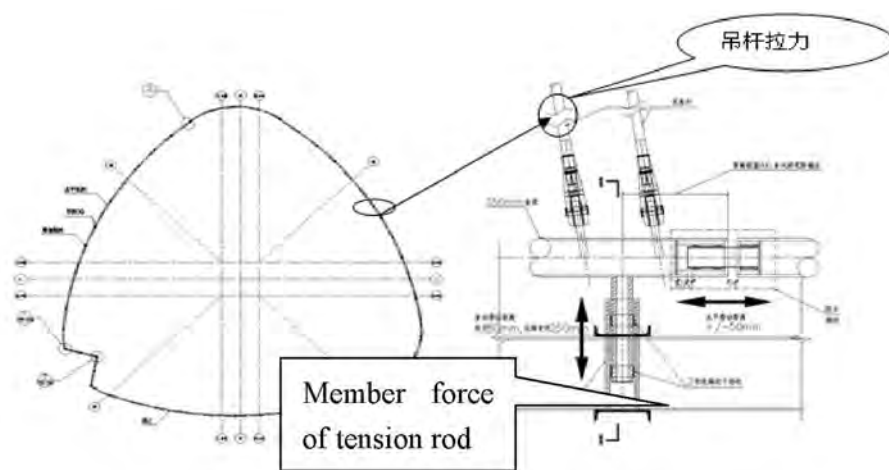为了获取施工中的上海中心大厦的动力特性，对其安全性及结构性态进行评估，同时，对阻尼系统调谐装置的设计给出实测

Figure 3.16. The tower boom system and strain gauge layout diagram (Source: Shanghai Tower Construction & Development Co., Ltd.)
图3.16. 塔楼吊杆体系和吊杆应力计布置示意图 (来源: 上海中心大厦建设发展有限公司)

The diagram of monitoring tension rod at 22nd floor 22层测点示意图	Monitoring Points 测点	Strain Data Time 应变数据及时间			
		2014.1	**2014.2**	**2014.3**	**2014.5**
	22-ST-MQ1	38.58	34.45	38.58	45.95
	22-ST-MQ2	28.65	28.65	31.71	30.06
	22-ST-MQ3	41.52	26.05	46.39	-62.73

Table 3.5. The diagram of monitoring tension rod at 22nd floor and strain data
表3.5. 22层测点位置和应变

After research was performed by the designer group, the three rods under the smallest tension in each zone were chosen as the monitoring objects. The operation states of the slipping bearings are under observation by indirect monitoring of the rod's stress. The façade supporting system and strain gauge layout diagram is shown in Figure 3.16.

Alarm Threshold Settings and Evaluation of Monitoring
The alarm thresholds of monitoring objects are set according to the following standards:

Rod strain ξ: (<-200µξ) Alarm Level II

Rod strain ξ: (0~-200µξ) Alarm Level I

Rod tension: Safe.

The actual monitoring data shows that the current steel rod strain is completely safe (see Table 3.5).

Structural Vibration Monitoring of the Shanghai Tower
In order to obtain the dynamic characteristics of construction for the Shanghai Tower, it is necessary to evaluate its safety and structural performance, providing a measured basis for the design of the damping system tuning device. Besides monitoring the process, the monitoring unit tested the dynamic characteristics of the two major horizontal orientations of the tower on February 23, 2014 and March 25, 2014 respectively after the last two main tower cranes were dismantled. The monitoring points are set on 124 layers of core-wall shaft, as shown in Figure 3.13.

The testing lasted for 1605.45s and 1523.45s, the sampling frequency was 20Hz and the number of sampling points was 32109 and 30469. With preprocessing of the signals, the acceleration time-history curves on the two major orientations of x-y-direction are shown in Figure 3.17.

The test results on the monitoring point identify the natural frequency and the damping ration of the structure in the peak and semi-power point methods, which is shown in Table 3.6. (A dynamic characteristic of the first three orders of structure is listed).

The identifying result proves that the natural frequency and damping ratio of the Shanghai Tower are both within the normal range and the dynamic characteristics on the main major orientations are similar, which is in accordance with the provision 3.5.3 of "Seismic Design Code GB50011-2010". The testing data of the first order of structural natural frequency is closing to 0.1093Hz, which is calculated based on table-10.4.1 in the "Report of Seismic Fortification" special review for Shanghai Tower (done by Thornton Tomasetti). The previous deviation of the frequencies along the two major orientations resulted from the uneven layout of the main tower cranes.

Reflections and Conclusions on the Structural Performance Monitoring

From have seen, the structural performance monitoring of the Shanghai Tower is effective for both temporary and permanent structures.

The systematic structural performance monitoring, including pulsating stress test of the tower, stress, structural deformation and settlement, wind, temperature, water and soil in and outside the pit, and seismic structural response monitoring on critical parts of the structure, offers plenty of basis to control construction risk, improve construction quality, verify design results and apply scientific engineering measures(such as final concretion of the steel truss, foundation pit dewatering regulation, structural temperature stress and deformation control, vertical

依据。除了过程中的监测，2014年2月23日和2014年3月25日，在最后两台主塔吊被拆除后，监测单位分别对塔楼结构的两个水平主轴方向的动力特性进行了测试。测点位于124层核心井筒，两个主轴方向和测点位置参见图3.13，

测试时长分别为1605.45s和1523.45s，采样频率为20Hz，采样点数分别为32109个和30469个。对信号进行预处理后，两主轴x、y方向的加速度时程曲线如图3.17注2所示。对测点测试结果采用峰值法和半功率点法分别识别结构的自振频率及阻尼比，结果见表3.6 (仅列出结构前3阶动力特性)。

从识别结果可见，上海中心大厦塔楼的自振频率及阻尼比均在正常范围内，且两主轴方向动力特性相似，符合《抗震设计规范GB50011-2010》中3.5.3的规定，即结构在两个主轴方向的动力特性宜相近的要求; 其一阶自振频率正在趋近0.1093Hz，此值是根据Thornton Tomasetti公司完成的上海中心大厦抗震设防专项审查报告当中表-10.4.1提供的数据计算得来的。之前出现的两主轴方向频率偏差主要与主塔吊不均匀布置有关。

关于结构性态监测工作的思考与结论

上海中心大厦工程结构性态监测无论是针对临时结构还是永久结构，从目前取得的成果来看，该项带有拓展性的工作是富有成效的。

包括塔楼脉动测试在内的结构关键部位应力、结构变形与沉降、风环境、温度环境、基坑内外水土环境、地震结构响应等系统化的结构性态监测，为控制施工风险、提高施工质量、验证设计结果、科学应用工程措施如钢桁架最终固结、基坑降水调节、控制结构温度应力和变形、竖向结构标高补偿、阻尼系统调谐装置的设定等提供了大量的依据，达到了这一系统性工作的基本目标。另外，上海中心大厦BIM信息模型与结构性态监测软件系统的结合将进一步提升监测工作的信息化水平，同时为大厦的运维管理提供了先进和方便的技术工具。
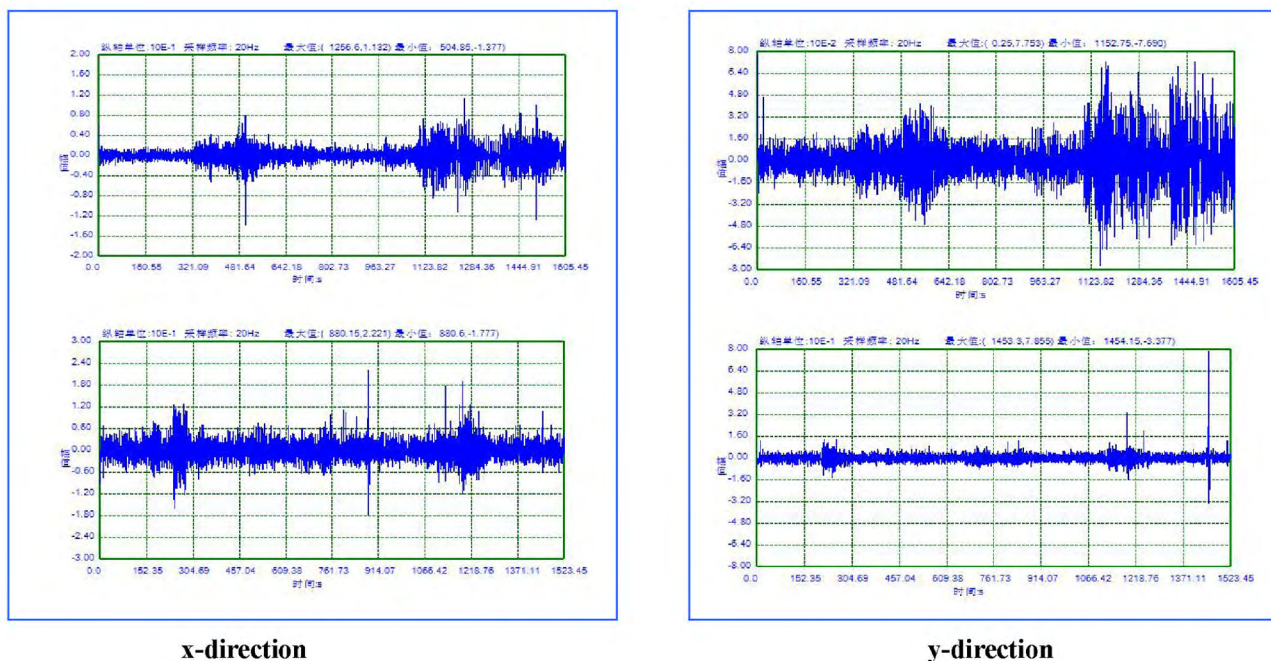
x-direction **y-direction**

Figure 3.17. Accelerarion time-history curves on the two major orientations of 15 monitoring points
图3.17. 测点两主轴方向加速度时程曲线 (15个监测点)

structure elevation compensation and damping system tuning device setting), which meets the basic objectives of this systematic task. In addition, the combination of the Shanghai Tower BIM model and the structural performance monitoring software system will further improve monitoring, and provide advanced technology and convenient tools for the operation and maintenance of the building.

Structural performance monitoring and information processing develop the construction and operation management techniques of modern large complex buildings. Feedback and evaluation obtained by monitoring assists project design verification, engineering risk management, quality management, schedule management, and operation and maintenance management. In the aspect of technological progress, the accumulation of structural performance data creates favorable conditions to improve structural engineering techniques and construction standards of ultra-large and ultra-deep buildings.

结构性态监测与信息化处理是现代大型复杂建筑物施工和运营管理技术的拓展，是从结构响应到结构感知与反馈的技术进化。监测获得的信息反馈与评估对工程设计验证和工程风险管理、质量管理、进度管理、运维管理起到了良好的辅助作用。从技术进步的角度而言，大量结构性态原始数据的获得与积累作为一种基础性工作，为结构工程技术的进一步发展和超高超大超深建筑规范的不断完善，创造了很好的条件，其发展前景令人乐观。

Monitoring points layout 测点位置示意图	Orientation 方向	Mode 模态	Frequency 频率 (Hz)		Damping Ratio-Monitoring Point 1 阻尼比(%) - 测点1	
			Feb.-2014 2014.2	Mar.-2014 2014.3	Feb.-2014 2014.2	Mar.-2014 2014.3
	x	1	0.1196	0.1172	1.70	2.78
		2	0.3613	0.3438	0.85	1.09
		3	0.7300	0.7070	0.52	0.64
	y	1	0.1196	0.1172	2.00	2.72
		2	0.3491	0.3516	0.63	1.17
		3	0.7129	0.7227	0.47	0.77

Table 3.6. Dynamic Characteristic of each order of the Shanghai Tower (Note-2)
表3.6. 上海中心大厦各阶动力特性

References (参考书目):

"**Report on the Information Monitoring of the Podium Pit Engineering of the Shanghai Tower Project, Shanghai, China**" <Note -1>.

"**Report on Pulsating Stress Test of the Shanghai Tower**" and "**Report on the Structural Performance Monitoring of the Shanghai Tower**" <Note -2>.