MASTER

Design of a monitoring system for the Shard London Bridge

Lemmens, B.J.A.

Award date:
2011

Link to publication
THESIS REPORT
Design of a monitoring system for the Shard London Bridge

15 April 2011

Bart Lemmens
Student MSc Construction Technology
Department of Structural Design & Construction Technology
Eindhoven University of Technology
the Netherlands

Host company:

[Signature]
London, 15 April 2011

Dear Sir/Madam

This research is all about making sure that the geometry of the structure of a high-rise building will be at its intended positions. This process is often referred to as “Dimensional Control”. In example, factors associated with dimensional control are the accuracy of construction methodologies, building movement imposed upon the structure by the environment, and movement within the structure itself. This research has resulted in the design of a structural monitoring system.

The Shard project is used as a case study to support an academic exercise with construction experience. The journey involved in this research has been very interesting indeed as it ultimately relates to a wired variety of aspects, such as surveying, structural behaviour of high-rise buildings, architectural details, buildings physics and construction methodologies.

Please note that this research can not relate to the building as a whole as only samples have been used for data collection for the case study. Data collected for this research has been subject to interpretation by the author and the interpretation may be different if conducted by a different person. Conclusions cannot automatically represent the whole building or other projects and the author cannot be held responsible for any interpretation or conclusions derived from this report.

It has been a privilege to be part of the project and I would like to genuinely thank all parties involved for their much appreciated efforts. In particular, I would like to thank Mace for their invitation and my graduation committee for their support and guidance during the process.

Graduation Committee
Prof. Dr. Ir. J.J.N. Lichtenberg (committee chairman), Dr. Ir. P.A.J. van Hoof (lead reviewer), Dr. Ir. E.W. Vastert (lead reviewer), Mr. Adrian Thomson (host company representative)

This report discusses the Master’s thesis research carried out within the program of Architecture, Building and Planning. The report was used to assess the quality of the study undertaken. The conclusions, results, calculations and other data present in this report may require further research for broader application. Therefore, we consider this to be an internal report, which cannot be used for external purposes without express permission.

Construction Technology Specialisation
Faculty of Architecture, Building and Planning
Eindhoven University of Technology
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUMMARY</td>
<td>5</td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>7</td>
</tr>
<tr>
<td>1. Objective of this Document</td>
<td>7</td>
</tr>
<tr>
<td>2. The Shard London Bridge</td>
<td>7</td>
</tr>
<tr>
<td>3. Structure</td>
<td>7</td>
</tr>
<tr>
<td>4. A guide to this document</td>
<td>8</td>
</tr>
<tr>
<td>2. WORK STUDY</td>
<td>9</td>
</tr>
<tr>
<td>2.1. Cause &amp; Motive</td>
<td>9</td>
</tr>
<tr>
<td>2.2. Research Relevance</td>
<td>10</td>
</tr>
<tr>
<td>2.3. Terminology</td>
<td>11</td>
</tr>
<tr>
<td>2.4. Reasons for Monitoring</td>
<td>11</td>
</tr>
<tr>
<td>3. RESEARCH QUERIES</td>
<td>12</td>
</tr>
<tr>
<td>3.1. Research Objective</td>
<td>12</td>
</tr>
<tr>
<td>3.2. Research Queries</td>
<td>13</td>
</tr>
<tr>
<td>4. RESEARCH METHODOLOGY</td>
<td>14</td>
</tr>
<tr>
<td>5. VITAL LOCATIONS</td>
<td>17</td>
</tr>
<tr>
<td>5.1. Requirements</td>
<td>17</td>
</tr>
<tr>
<td>5.2. Construction Sequence</td>
<td>17</td>
</tr>
<tr>
<td>5.3. Consequences of Dimensional Deviations</td>
<td>18</td>
</tr>
<tr>
<td>6. MOVEMENT PREDICTIONS</td>
<td>20</td>
</tr>
<tr>
<td>6.1. Introduction</td>
<td>20</td>
</tr>
<tr>
<td>6.2. Movement Impact in relation to Time</td>
<td>20</td>
</tr>
<tr>
<td>6.3. Most Significant Movement</td>
<td>21</td>
</tr>
<tr>
<td>6.4. Core Shortening &amp; Settlement</td>
<td>22</td>
</tr>
<tr>
<td>6.5. Settlement &amp; Shortening Prediction</td>
<td>23</td>
</tr>
<tr>
<td>7. THEORETICAL LEVEL</td>
<td>24</td>
</tr>
<tr>
<td>7.1. Introduction</td>
<td>24</td>
</tr>
<tr>
<td>7.2. Axial Shortening</td>
<td>24</td>
</tr>
<tr>
<td>7.3. Theoretical Level at time of Erection</td>
<td>25</td>
</tr>
<tr>
<td>7.4. Super Elevations at Time of Frame Erection</td>
<td>27</td>
</tr>
<tr>
<td>7.5. Conclusions</td>
<td>28</td>
</tr>
<tr>
<td>8. SURVEYING METHODOLOGY</td>
<td>29</td>
</tr>
<tr>
<td>8.1. Objective</td>
<td>29</td>
</tr>
<tr>
<td>8.2. Site Setting-Out</td>
<td>29</td>
</tr>
<tr>
<td>8.3. Site Perimeter Vertical Position</td>
<td>30</td>
</tr>
<tr>
<td>8.4. Core Vertical Position</td>
<td>32</td>
</tr>
<tr>
<td>8.5. Core Horizontal Position</td>
<td>33</td>
</tr>
<tr>
<td>8.6. Steelworks Vertical Position</td>
<td>33</td>
</tr>
<tr>
<td>8.7. Slab Vertical Position</td>
<td>33</td>
</tr>
<tr>
<td>8.8. Accuracy of Data Collection</td>
<td>34</td>
</tr>
<tr>
<td>9. Actual Building Movement</td>
<td>35</td>
</tr>
<tr>
<td>9.1. Objective</td>
<td>35</td>
</tr>
<tr>
<td>9.2. Main Findings</td>
<td>35</td>
</tr>
<tr>
<td>9.3. Conclusion</td>
<td>37</td>
</tr>
<tr>
<td>10. Steelworks Analysis</td>
<td>38</td>
</tr>
<tr>
<td>10.1. Objective</td>
<td>38</td>
</tr>
</tbody>
</table>
SUMMARY

Work Study
A Work Study was conducted at the Shard London Bridge from March until the end of May 2010. During the very beginning of construction, dimensional deviations of the steel frame were not being identified relative to its theoretical positions at time of erection. For this research, a dimensional deviation is the difference between the intended position and actual position of a structural member. In terms of fabrication, a dimensional deviation is the difference between intended and actual dimension of a member. At the time of conducting the work study, it was unknown to the author to what extent the intended steelworks positions were achieved at time of erection relative to a fixed point outside the project site.

Secondly, from a research point of view, more building movement monitoring of the structure could be in place to assess its possible impact on the structure. Verification of building movement predictions should take place to ascertain if design predictions are met in practise. An understanding to know where deviations occur and what the causes are allows developing countermeasures, if required. It was concluded that for this research it was worth developing a monitoring system which identifies vertical dimensional deviations of the structure, as well as monitoring of vertical building movement in order to verify design predictions. A monitoring system is a set of processes which consists of surveying of the structure, data analysis and follow-up if required.

Main queries were: “Have the intended positions of the structure at time of erection been met?” and “Has building movement at time of frame erection occurred as predicted?” Required were:
1. On Site Monitoring Regime of Structure Measure
2. A Tool which provides an analysis of data collected Data-Analysis
3. Implementing countermeasures if required Follow-Up

Research Methodology
As a result based upon the work study, the Research Objective was defined as follows:
The development of a monitoring system which provides an analysis of dimensional deviations at vital locations of the structure as well as verification of movement predictions in order to avoid the occurrence of significant dimensional deviations of The Shard.

In order to develop a monitoring system, the main research queries which have been answered are:
1. What are vital locations to be monitored?
2. What are relevant factors to be included in the monitoring system?
3. What are requirements the design should comply with?
4. What is the monitoring strategy to be adopted?
5. What is the monitoring scope (what, when, where, who, how)?
6. How does data-analysis take place?

Vital Locations
A vital location is a location where significant dimensional deviations could result in loss of performance of the building. This can be structural, architectural, operational or related to building physics. For this research, vital locations for this project are for every storey in general: top of steel near perimeter, top of slab near perimeter, core level.

Relevant Factors
Relevant factors are factors which could significantly distort the positions of the geometry. In theory, such relevant factors could be related to installation & manufacturing accuracy and building movement. In order to ascertain which factors are relevant for this research, a sample of the building (level 05-15) has been analysed by collecting surveys results at vital locations. Significant predicted building movement by the Engineer is mainly vertical. Both columns and core are expected to be subject to axial shortening and settlement. Columns are expected to shorten more relative to the core. Thus, if a slab was poured to level, its positions would be distorted after movement occurs.
The intention of the design team is to obtain a floor which is ‘fully’ level at end of construction. In order to achieve this, columns have been super elevated (produced over length and preset) at time of erection. If structural movement occurs as predicted after members have been installed, it would be expected that a floor which is level will be achieved at end of construction. Column super elevations have been specified by the Engineer at time of installation of steelframe at a certain level. Movement predictions are given at time of frame installation of a certain level, as well as at end of construction.

Further to an analysis of a sample of the building, the following factors were considered to be relevant to be included in the scope for the monitoring system:

1. Core Shortening at time of construction of structural frame at a level.
2. Core Settlement at time of construction of structural frame at a level.
3. Top of Steel Level at perimeter at time just after construction of a structural frame at a level.
4. Perimeter Settlement at time of construction of a structural frame at a level.

**Design Requirements**
The monitoring system should show an improvement of the dimensional variability of the structure. It should monitor the dimensional accuracy of the structure and it should monitor building movement relative to design predictions. Ultimately, the monitoring system should be implemented and tested.

**Monitoring Strategy**
Quality management principles (ISO9000:2005) have been applied to the monitoring system:

1. Awareness: Set the quality objective, ie. intended positions and movement predictions.
2. Data Analysis: Measure achievement of theoretical level & verification of movement predictions.
4. Establish Continual Improvement: Revision of procedures if required to reinforce improvement.

A checklist has been created such that the construction team can follow up the outcome of data-analysis tool, if required.

**Monitoring Scope**
Relevant factors have been included in the monitoring scope. These are mainly core movement, perimeter movement at time of frame erection, as well as level of the structure at the perimeter at time just after frame erection. These factors will be surveyed bi-weekly. A surveying methodology has been established to obtain the data required (some alterations to methods that were already in place). Readings from survey reports have been inserted into the data-analysis tool.

**Data Analysis Tool**
The data analysis tool (spreadsheet) compares movement predictions with recorded movement at time of installation of a steelframe at a certain level. Secondly, the tool compares steelframe actual levels with theoretical positions at time of installation. Also, it provides a trend-analysis (graph) to show historical data inserted into the data analysis tool. This allows to spot sudden changes in results.

**Implementation**
Data for level 05 to level 40 have been monitored by the monitoring system. Survey reports was input which has been entered into the data-analysis tool. First main finding from data-analysis was that steelworks showed deviations in certain areas. After use of the checklist, possible causes seemed to be low installed positions and deflection. Improvement has been obtained in example by proactively propping of beams.

Secondly, tool output showed that actual core movement seemed to approach predictions; the core seemed to travel down at a higher rate than predicted. The design team has been contacted as per the checklist. As a result, designed super elevations have been adjusted for level 41 and beyond.

**Evaluation**
The monitoring system has been tested in practise and it meets research requirements. In general, more data and more sophisticated software could further improve the system. In principle, the design strategy for a monitoring system could be useful for assuring buildability of supertall buildings.
1. INTRODUCTION

1.1. Objective of this Document
The objective of this document is to outline the MSc thesis conducted from March 2010-April 2011. A typical graduation process of a student Construction Technology consists of cause & motive for research (problem definition as a result of a work study), a research phase (data collection) and a design phase (solution for the problem). In practise, the data collection and design phase can merge.

1.2. The Shard London Bridge
An opportunity was offered to conduct a work study at The Shard London Bridge Project which is currently being constructed in London. The Shard London Bridge Project will be the tallest building in Western-Europe upon completion in 2012 (310m). The building will consist of apartments, offices, hotel and a public viewing gallery. A work study has been conducted on this project from March-May 2010 in regards to the steelworks erection processes, which resulted in a thesis proposal on the subject of Dimensional Control. The next paragraphs provide a brief overview of the Project.

![The Shard London Bridge - December 2010](image)

1.3. Structure
Architect Renzo Piano compares his architectural design of the building to a "Shard of Glass". The use of glass and transparency are important factors in his design. The pattern of light and deflections on the glass will change during the day because of inclined façade elements and steps in elevations.

The Shard is located in an inner-city location next to London Bridge Railway Station, London Bridge Underground Station, London Bridge Bus Station and Guy's Hospital. Another typical aspect is that an old 24-storey high-rise Building Southwark Towers had to be demolished prior to be able to commence the Works.

The Shard consists of a hybrid structure, which is a steel frame and concrete core structure up to level 40, followed by an all concrete structure up to level 70. The spire of the building is expected to be a steel structure from level 72 and beyond. The substructure of the building was constructed top-down.

(theshard.com, 27-02-2011)
1.4. A guide to this document

1. Introduction
2. Work Study
3. Research Queries
4. Research Methodology
5. Vital Locations
6. Movement Predictions
7. Theoretical Level
8. Surveying Methodology
9. Actual Building Movement
10. Steelworks Analysis
11. Composite slab Analysis
12. Relevant Factors
13. Design Requirements
14. Monitoring Strategy
15. Monitoring Scope
16. Data-Analysis Tool
17. Implementation
18. Evaluation

Figure 1.3.1. Artist’s Impression (shardlondonbridge.com, 06/02/2011).
Figure 1.3.2. Structure green: steel frame, blue: concrete structure (Structural Engineering Report, WSP, 2009)
Figure 1.3.3. Section (building.co.uk, 2007)

Figure 1.4.1. Report Contents
2. WORK STUDY

2.1. Cause & Motive
A work study was conducted at the Shard London Bridge from March until the end of May 2010. The work study investigated product, process and procedures based upon a series of observations in regards to the Steelworks. Main conclusion was that achieving the intended vertical positions of such a tall structure is complicated by building movement as well as the accuracy of installation of the structure. Both factors potentially distort vertical positions of the structure.

During the very beginning of construction, dimensional deviations of the steel frame were not being identified relative to its theoretical positions at time of erection. For this research, a dimensional deviation is the difference between the intended position and actual position of a structural member. At that moment in time, it was unknown for the author to what extent the intended steelworks positions steelworks were achieved at time of erection relative to a fixed point outside the project.

Secondly, from a research point of view, more building movement monitoring of the structure could be in place to assess its impact on the structure. The Structural Engineer has predicted expected building movement. Verification of building movement predictions should take place to ascertain if design predictions are met in practise. If predictions would be exceeded this results in dimensional deviations. In order to avoid significant dimensional deviations exceeding project specifications or expectations, it should be known to what extent intended positions are achieved in practise and what could be the cause for such deviations. An understanding to know where deviations occur and the causes are allows to develop countermeasures and obtain quality improvement.

It was concluded that for this research it would be worth developing a monitoring system which identifies vertical dimensional deviations of the structure, as well as monitoring of vertical building movement in order to verify design predictions. An analysis of deviations is not sufficient; it should be followed up by actions to avoid the occurrence of deviations. Monitoring in this context is defined as conducting surveys of a structure in order to be able to make decisions in regards to the construction phase and life-span of a structure. A monitoring system is a set of processes which consists of surveying of the structure, data analysis and follow-up. Follow-up could consist of countermeasures if significant deviations are being recorded. (Stufib, 2003, Geode/ft 2001)

Main questions:
1. Have the intended positions of the structure at time of erection been met?
2. Has building movement at time of frame erection occurred as predicted?

Required are:
1. On Site Monitoring Regime of Structure Measure
2. A Tool which provides an analysis of data collected Data-Analysis
3. Follow-up: implementing countermeasures if required Follow-Up

Figure 2.1.1. Monitoring System (derived from Geode/ft 2001, Stufib, 2003)
2.2. Research Relevance

A direct cause for this thesis is the importance of Dimensional Control in order to achieve the complex geometry of the Shard. It is fair to say that it is a complicated building with different shards, a complex structure and building movement to be expected during construction. By nature, the Shard has several steps in its perimeter and there are special structural members such as kinked columns, cantilevers, partly suspended floors and Vierendeel trusses.

In general for any building, dimensional deviations could have consequences from an architectural, structural, operations and building physics perspective. Furthermore, dimensional deviations could complicate the construction process. Dimensional Control could result in a more efficient and accurate construction process whilst obtaining a building which meets its intended coordinates and the specifications. Therefore, from a research point of view, significant dimensional deviations should be further investigated in order to develop countermeasures, if necessary, and the effects structural movements may have should be assessed and possibly taken into account during construction. In order to assess the research relevance the possible consequences of dimensional deviations should be identified. Focus of the research should only be on vital locations where significant dimensional deviations would result in loss of performance.

The Technical Information Service (1989) categorises these possible consequences as follows:

![Possible Consequences of Dimensional Deviations](Technical Information Service, 1989)

Dimensional variability can be considered acceptable as long as loss of performance can be avoided. The consequences of dimensional deviations as identified by the Technical Information Service will be addressed as follows:

**Architectural Quality**

Achieving the desired coordinates and sizes of the building contributes to the architecture of the building. Correct fitting and alignment of any visible building component will contribute to the achievement of the intended geometry. In regards to the perception of dimensional deviations, a distinction can be made between visibility, conspicuousness and annoyance. (Vastert, 1992)

**Structural Quality**

If there would be major dimensional deviations the structural integrity and the joints could theoretically be affected. Another aspect is that a high-rise building should be able to accommodate significant movement in the overall structure and the joints. Movement can be categorised into the aspects “position”, “dimension” and “shape”. Free Body Movement introduces a change of position; a possible consequence could be falling. (Technical Information Service, 1989)
A change with regards to dimension would be lengthening or shortening. Snapping or crushing could be possible consequences. Regarding the aspect of shape, bending or torsion could occur which might result in breaking or shearing. (Technical Information Service, 1989)

**Building Physics**
Dimensional Deviations could result in a loss of weather tightness and damage to services.

**Operation Functions**
Loss of Operation Functions could be a result of dimensional deviations which may obstruct proper use of the building. (Technical Information Service, 1989)

### 2.3. Terminology

The British Standard “A Guide to Accuracy in Building” (BS 5606:1990) specifies the terminology with regards to Dimensional Control. In this regard the most important terminology applicable to this thesis proposal should be identified as follows:

- **Target Size**: reference size from which deviations would ideally be zero
- **Reference Size**: size specified in the design to which deviations are related
- **Deviation**: the difference between the Target Size and the Actual Size
- **Tolerance**: agreement made on the allowable variation to the Target Size

The British Standards Institute categorises dimensional deviations into an induced deviation (1) and an inherent deviation (2). These deviations can be specified as follows:

- **Induced Deviation**: inevitable departure from target size due to the building process
- **Inherent Deviation**: inevitable departure from target size due to the physical properties of building materials and soils

Induced Deviations are a result of human activities. These are a result of the setting-out process, manufacturing and the construction methodology used. On the other hand, inherent deviations are caused by material properties and environmental conditions. Both induced deviations and inherent deviations result in dimensional deviations. Some of the inherent deviations may be reversible (elastic) whereas others are irreversible (inelastic). For cause & effect of deviations please refer to Appendix A. (BS 5606:1990)

### 2.4. Reasons for Monitoring

Monitoring of a building or an environment can be conducted for different reasons:

1. **Risk Management**
   Monitoring of a structure could take place to manage risks; in example damage to adjacent buildings. This is applicable in particular to civil structures such as tunnelling under a city.

2. **Structural**
   Monitoring could take place to ensure the structural integrity is achieved as intended.

3. **Scientific**
   Monitoring could take place to learn more about structures, material and the environment.

4. **Legal requirement**
   Monitoring could be compulsory as per a legal requirement. (Stufib, 2003)

Jardine (2001) describes the need for structural monitoring of civil structures as follows:

“*In most cases measurements are made during construction to provide assurance that movements do not exceed expectations. They should be continually reviewed throughout construction and it may be that economies in terms of cost or programme can be made by changing the method of construction or the temporary works requirements.*” (Jardine, 2001)

This research focuses on the building itself; not the environment or surrounding buildings. A full monitoring system for the environment and adjacent structures is in place. Only vital locations of the building will be monitored as not every single point of the building can be monitored. The top of the building will not be considered (level 70 and beyond). Reason for monitoring in regards to this thesis is mainly a scientific as well as structural; to **learn about buildability aspects of high-rise buildings.**
3. RESEARCH QUERIES

3.1. Research Objective
As a result based upon the work study, the Research Objective was defined as follows:

The development of a monitoring system which provides an analysis of dimensional deviations at vital locations of the structure as well as verification of movement predictions in order to avoid the occurrence of significant dimensional deviations of The Shard.

A monitoring system is a set of processes which consists of surveying of the structure, data analysis and follow-up, with the objective of identifying dimensional deviations of the structure. In terms of plan position, a dimensional deviation is the difference between intended and actual position.

Significant deviations are those deviations which exceed tolerances. A monitoring system could give cause for countermeasures to be undertaken to avoid the occurrence of significant dimensional deviations. In example, a countermeasure could be an improvement of the installation accuracy or building design adjustment.

![Monitoring System](image)

In order to develop a monitoring system, the main questions which have been answered are:

1. What are **vital locations** to be monitored?
   - This research focuses on locations where significant dimensional deviations would result in loss of performance. Such locations are called "vital locations" (1\textsuperscript{st} demarcation).

2. What are **relevant factors** to be included in the monitoring system?
   - The monitoring system monitors relevant factors which could have a significant influence on the positions of the structure achieved at vital locations at time of erection (2\textsuperscript{nd} demarcation). Such factors could be related to the installation accuracy, manufacturing accuracy and building movement. Relevant factors have been identified by conducting an analysis of a sample of the building to (level 05-15).

3. What are **requirements** the design should comply with?

4. What is the **movement strategy** to be adopted?
   - Requirements have specified the desired output of the monitoring system as well as how the monitoring system will be followed-up with actions if the geometry has not achieved intended positions at time of frame erection or if design predictions have not been met.
5. What is the **monitoring scope** (what, when, where, who, how)?
   Following from the identification of relevant factors the scope has been further detailed.

6. How does **data-analysis** take place?
   Transformation from input (survey results) results into output which consists of:
   a) List of deviations of the structure (have intended positions been achieved?)
   b) Comparison of predicted and actual movement (has building movement occurred as predicted?).
   A data-analysis tool (spreadsheet) has been developed which transforms input into output. The spreadsheet should compare actual and intended positions of the structure at time of erection and present this in an understandable manner.

### 3.2. Research Queries

The following Research Queries have been answered:

#### Research Query 1
What are vital locations of the building to be monitored?

a) What is a requirement for a location to be considered vital for the building?

b) What specifications apply to vital locations with regards to allowable dimensional deviations?

#### Research Query 2
What are relevant factors to be included in the monitoring system?

a) What is the most significant predicted building movement during construction of the Shard?

b) What is the theoretical level to which the structural frame needs to be set at time of erection?

c) Where are significant dimensional deviations identified at the vital locations at time directly after erection in regards to level 05-15?

d) What is actual vertical movement which has occurred during construction of level 05-15?

e) What are the reasons which have most likely caused the listed dimensional deviations?

f) Which aspects of building movement should be monitored?

As a result of the data collection, an understanding of relevant factors to be monitored has been obtained which allowed the design of the monitoring system to take place:

#### Research Query 3
What are requirements the design should comply with?

#### Research Query 4
What is the movement strategy to be adopted by the design?

#### Research Query 5
What is the monitoring scope for the design?

#### Research Query 6
How does data-analysis take place?

#### Research Query 7
Does the design meet the specified requirements and has the overall research objective been achieved?
4. RESEARCH METHODOLOGY

This section outlines the methodology involved in answering the research queries and it identifies what data has been collected. Finally, a graph summarises the major steps undertaken.

In principle, the "rational design method for a monitoring system" as developed by GeoDelft/TNO (2001) has been adopted. Notwithstanding the fact that such monitoring systems are mainly focussed on civil structures such as tunnelling projects, the design methodology is relevant and was used to a large extent. The major steps involved in the methodology can be visualised in the following map:

![Design of a Monitoring System](image-url)

Figure 4.1. Design of a Monitoring System (derived from Stufib, 2003 and Geodelft, 2001)

**Research Query 1: Vital Locations**
A "vital location" is a location where dimensional deviations are expected to exceed specifications which could potentially result in loss of performance. Project specifications were found in the Movement & Tolerances Report, specifications and drawings. Vital locations have been listed on the basis of the effects these deviations potentially have resulting in loss of performance.

**Research Query 2: Relevant Factors**
Relevant factors are factors which could significantly distort the positions of the geometry. In theory, relevant factors could be related to the accuracy of installation, manufacturing accuracy and building movement. In order to ascertain which factors are relevant in practise, a sample of the building (level 05-15) has been analysed by taking samples of the accuracy of the structure at vital locations.

The following steps have been conducted in order to determine relevant factors:

1. **What is significant building movement which has been predicted?**
   Significant movement have been derived from the Movement & Tolerances Report and the Axial Shortening Report. A demarcation has been made as not all aspects can be monitored.

2. **What is the theoretical position to which the frame needs to be set at time of erection?**
   Theoretical positions have been derived from the Axial Shortening Report.
3. Where have significant dimensional deviations occurred at vital locations?

Actual positions of the structure have been surveyed on site and compared with theoretical or "intended" positions. An analysis of survey data allowed identifying deviations. The data collection was based upon samples taken from monitoring reports, referred to as the "population". The samples are as follows for level 05-15:

<table>
<thead>
<tr>
<th>Source</th>
<th>Observed Deviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steelworks As-Built Reports</td>
<td>Column &amp; Beam positions, level and alignment</td>
</tr>
<tr>
<td>Concrete Core As-Built Reports</td>
<td>Core positions, level and alignment</td>
</tr>
<tr>
<td>Concrete Slab As-Built Reports</td>
<td>Concrete Level</td>
</tr>
</tbody>
</table>

4. What actual building movement has occurred at time of frame erection?

Building movement has been compared with movement predictions to ascertain which aspect of building movement has had significant impact in practise and therefore needs to be monitored for the remainder of the project. In order to find out what relevant movement has occurred, a site monitoring regime has been established. This included the following:

<table>
<thead>
<tr>
<th>Type of Movement</th>
<th>Observed Datum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Settlement</td>
<td>Movement monitoring of a core datum</td>
</tr>
<tr>
<td>Site Movement</td>
<td>Movement monitoring of site perimeter</td>
</tr>
<tr>
<td>Ground Floor Column Movement</td>
<td>Movement monitoring of perimeter base plates</td>
</tr>
</tbody>
</table>

5. What are causes for recorded deviations and which factors are therefore relevant?

On the basis of data collected and observations, causes for recorded deviations have been ascertained. Such comprehensive analysis provided an understanding of what factors are relevant to be included in the design of the monitoring system.

Research Query 3: Design Requirements

Following from previous research question, a focus has been established for the monitoring scope of the monitoring system. Prior to developing the monitoring system, requirements have been listed on the basis of data collected, on site discussions and by analysing relevant literature.

Research Query 4: Monitoring Strategy

The monitoring system has identified if the intended positions of the structure has been achieved at time of erection at vital locations. Also, movement predictions have been verified at time of frame erection. Significant deviations should be followed up with actions to avoid loss of performance of the structure. Based upon literature analysis it was identified how the tool can give cause for quality improvement and how it fits into the project quality management system.

Research Query 5: Monitoring Scope

The data collected has provided insight as to what factors are relevant to be monitored during construction. The monitoring scope specifies what, where, who, when and how should be monitored.

Research Query 6: Data-Analysis

Survey results of positions of the structure at vital locations have been analysed and presented in a summary. A data-analysis tool (spreadsheet) has been developed which calculates the difference between actual positions and intended positions. Also, the tool compares predicted movement and actual movement.

Research Query 7: Evaluation

After implementation of the monitoring system, it was ascertained that the established monitoring system has contributed to avoiding the occurrence of significant dimensional deviations which exceed project specifications.
The development of a monitoring system which provides an analysis of dimensional deviations of the structure at vital locations as well as verification of movement predictions in order to avoid the occurrence of significant dimensional deviations of The Shard.

Figure 4.2. Research Methodology
5. **VITAL LOCATIONS**

5.1. **Requirements**

A monitoring system cannot possibly monitor all locations of the geometry of the building, considering the limited scope of this research. Therefore, this chapter determines which locations in the building are considered to be “vital” for this research (1st research demarcation).

A **vital location** is a location where significant dimensional deviations could potentially result in loss of performance of the building. This can be structural, architectural, operational or related to building physics. In order to assess where the vital locations are, the theoretical impact of most significant deviations should be assessed. This means that it should be ascertained in a hypothetical exercise what possible consequences of deviations are in terms of loss of performance, whether being architectural, structural, loss of operations or related to building physics.

5.2. **Construction Sequence**

Prior to identifying vital locations the general construction sequence should be understood and considered. In general, the construction of a typical level involves the following steps:

- Pouring the slip form
- Erecting the steel frame (up to level 40, beyond: an all-concrete frame)
- Installing the steel deck (up to level 40, beyond: a post-tensioned concrete slab)
- Installing rebar and pouring the concrete slab
- Placing brackets
- Installing cladding
- Installing MEP (Mechanical, Electrical and Plumbing) and applying finishes

A stream chart is shown below identifying the main construction sequences:

![Construction Process of a Storey](image)

*Figure 5.2.1. Simple Stream Chart of the Construction Process up to level 40*
5.3. Consequences of Dimensional Deviations

As discussed in section 2.2, dimensional deviations could potentially result in loss of performance from an architectural, structural, operational and building physics perspective. On the basis of the aforementioned categories, the major trades of the Shard will be analysed to identify locations which can be considered vital for this research.

- **Core**
  Core verticality exceeding tolerances could result in additional forces and moment imposed on the building. Steelworks connected to the core could not be level which in effect would be reflected in the vertical positions of the slabs. If the core settles beyond expectations the building will deviate from the intended coordinates of the geometry. Also, points are set out in relation to the primary core datum which is the vertical axis of the building. If the core exceeds horizontal specifications it might cause a problem for the lift shaft and the elevator landings. For this reason it is important that the core plan positions and core level achieve the intended positions.

![Steel structure and core (Observation 16/09/2010)](image1)

- **Steel Structure**
  Deviations from intended positions could affect the column verticality column. This could have the consequence that similar columns may not look aligned which could be identified as an architectural loss of performance. Secondly, structural behaviour could be affected and might result in a moment which is structural loss of performance. Transfer structures have to deal with significant loads considering the weight of the multiple levels positioned on top of the structure. Significant deviations from the designed positions could therefore potentially affect the structural integrity.

![Example of erection of transfer structure (Observation 06/07/2010)](image2)

- **Composite slab**
  General steelwork, such as beams and columns should comply with project specifications in terms of level. If beams are lower than intended in terms of level, automatically the slab level will be lower as well for the reason is that the slabs are poured to thickness. Theoretically, if slabs are lower than intended finished floor and ceiling zones potentially may be affected as well as floor to ceiling height.
A typical floor sandwich up to level 40 will be as follows: (WSP, Structural Engineering Stage E Report)

![Floor Sandwich Diagram]

**Cladding**

This research focuses on the structural geometry of the building. The cladding follows the structure and is designed to accommodate predicted movement of the structure. This is on the premise that it has been installed to its intended coordinates and that the structural building movement is in line with predictions. Misalignment or significant deviations could hypothetically lead to loss of performance in terms of building physics. From an architectural point of view, significant misalignment of cladding panels might introduce loss of performance from an appearance point of view.

In effect, the following locations of the geometry are considered to be vital locations for this research:

<table>
<thead>
<tr>
<th>Location – superstructure</th>
<th>Aspect</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core walls</td>
<td>Level</td>
<td>Lift shaft, steelworks interface</td>
</tr>
<tr>
<td>Top of beams</td>
<td>Level</td>
<td>Slab level, volumetric space</td>
</tr>
<tr>
<td>Bottom of beams</td>
<td>Level</td>
<td>Slab level, volumetric space</td>
</tr>
<tr>
<td>Top of slab, Slab Thickness</td>
<td>Level</td>
<td>Volumetric space, cladding</td>
</tr>
</tbody>
</table>

*Table 5.3.5. Summary of Vital Locations*

Thus, vital locations are related to the vertical position of members with the exception of the core.

![Vital Locations Diagram]
6. MOVEMENT PREDICTIONS

6.1. Introduction

In order to determine which factors are relevant to be included in the monitoring system, actual movement should be compared with predicted building movement.

This chapter provides an answer to the following research query:

What is the most significant predicted building movement during construction of the Shard?

In principle, design for movement is necessary in order to avoid loss of performance from an architectural, structural design, operational and building physical perspective. (CIRIA, 1989)

Building movement can consist of the following aspects:

![Figure 6.1.1. Inherent Deviations (CIRIA, 1989)]

6.2. Movement Impact in relation to Time

The design of the building should be able to resist building movement and should comply with project specifications. In other words, installed components should be within the allowable range of coordinates at the time of completion of the building. Building movement can occur prior to an object being erected, during the erection of an object and finally after an object has been erected.

At the time of erection of the building, the installed components should comply with project specification, i.e. they should be manufactured and installed within the allowable range of dimensions and coordinates (tolerances).

A supertall high rise building is significantly different than a small building as far more loads are imposed and the environment is expected to have an increased impact on the positions of the building. The environment is likely to cause thermal movement and sway. Loads may cause members to shorten and deflect.

The impact of these factors is likely to increase when the structure gets taller during the construction process. Furthermore, a large concentration of load on the substructure and soil could result in settlement and/or site movement. (CIRIA, 1989)
In general, significant movement in relation to high-rise buildings can be visualised as follows:

![Image of movement affecting the geometry](image)

**Figure 6.2.1. Visualisation of movement affecting the geometry**

The green colour shows range which defines the range of allowable coordinates an object should be positioned in. Black shows the actual positions of installed objects.

1. Structure complying with tolerances
2. Settlement
3. Axial shortening of members
4. Thermal movement
5. Sway
6. Sway

The impact of these different types of movement varies; this is further explained in Appendix A.

### 6.3. Most Significant Movement

The structure of The Shard has been modelled and building movement has been analysed by the Structural Engineer which is summarised in the Movement & Tolerances Report and the Axial Shortening Report.

Categories of building movement identified by the Design Team are:

- **Permanent Movement (Vertical):**
  - Axial Shortening of Core & Columns (Shrinkage, Elastic Shortening, Creep)
  - Core Settlement
  - Site & Foundation Settlement
  - Deflection of Slabs & Beams

- **Temporary or Dynamic Movement:**
  - Sway (Horizontal)
  - Thermal Movement (Vertical & Horizontal)
  - Site & Foundation Settlement (Vertical)

(Movement & Tolerances Report, WSP)

In the structural design of the Shard, temporary movement should be allowed for the structure. This could be sway and thermal movement in example. The impact can be different from day to day depending on environmental conditions. Joints should allow this movement to take place. For more information please refer to Appendix A and C. (Movement & Tolerances Report, 2009)

**Permanent vertical movement** is the most significant movement for the geometry as it permanently changes positions of members. This movement occurs during construction and would affect the intended coordinates of the geometry of the building. Without countermeasures the vertical positions of the geometry would have been affected. This vertical movement consists of axial shortening (Core & Columns) and settlement (Core & Perimeter). The main countermeasures are explained in the next chapter which have resulted in the theoretical level to which members should be set.
6.4. **Core Shortening & Settlement**

Automatically associated with concrete specifications is the fact that concrete will shrink when being poured. Upon introduction of a load the concrete will shorten and after a certain amount of time creep will occur. The combination of shrinkage, shortening because of loads (elastic movement) and creep is referred to as **Axial Shortening**. (Alexander, 2001)

Stuart Alexander (2001) defines the sources of axial shortening as follows:

1. **Axial Strain**
   
   Load accumulated whilst constructing the tall building are subject to initial elastic strain which increases gradually due to the phenomenon of creep. Creep is the tendency of a solid material to slowly move or deform permanently under the influence of stresses.

2. **Shrinkage**

   After concluding thermal contraction of concrete shrinkage occurs which effect will be decreasing with time.

3. **Construction Sequence**

   The sequence determines what shortening has already occurred.

4. **Loading Sequence**

   The time and magnitude of the addition of remaining loads will have an effect upon the structure.

5. **Time-dependent effects**

   Both creep and shrinkage are dependant of when the concrete was cast. (Alexander, 2001)

Core shortening impact is most significant at mid-height of the building, as shown in the theoretical graph on the right.

Pile shortening and pile settlement is likely to occur because of loads being imposed upon them. The higher the building will be built, the more loads will be imposed.

**Core settlement** is the sinking of the core and is dependent on the overall loading and the compressibility of the soil. Partly settlement occurs instantly on application of the load. The remainder occurs gradually while the soil adjusts to new loads. (CIRIA, 1983)

If no countermeasure would be undertaken, core settlement could have an impact on the building and its levels; they would be lower than intended. At the start of slip form construction, the core was super elevated by 8mm in order to counteract the predicted core settlement. During core construction, the top of the core is supposed to be cast to “00” relative to external, which means that settlement and shortening which occur at time of casting need to be counteracted.

---

**Figure 6.4.1. Core Wall Section (not to scale)**

*Explaining theoretical core shortening pattern*
The top is supposed to be cast at its intended level 00 which is illustrated by the following sketch:

**Slip Form Construction**

Top of Core cast to level “00” relative to external

![Theoretical Gridlines](image)

Core Topped Out

Top of the core was super elevated by 8mm and the top needs to be cast at “00” relative to external datum

**6.5. Settlement & Shortening Prediction**

When starting erection at level 11 (steelframe), 9mm of core shortening is predicted up to level 11. When erecting level 19, 14mm core shortening is predicted. For level 31 and 39, 18mm shortening is predicted. The author’s interpretation of the report is such that 8mm settlement was expected at time of completion, as the core was super elevated by 8mm. No specific statements about predicted settlement when erecting a certain frame of a level have been specified. *(Axial Shortening Report, WSP)*

**Core Shortening Predictions - At time of frame erection of a certain level**

Top of Core cast to level “00” relative to external

![Theoretical Gridlines](image)

L72 Core Topped Out

L31

L39

L11

L19

L00

-18 shortening

-14 shortening

-9 shortening

-18 shortening

Predicted Settlement

Figure 6.5.1. Vertical Core section: Predicted column shortening at a certain level at time of completion

Figure 6.4.2. Vertical Core section (not to scale)
7. THEORETICAL LEVEL

7.1. Introduction
This chapter provides an answer to the following query:
What is the theoretical level to which the structural frame needs to be set at time of erection?

7.2. Axial Shortening
"Axial shortening of columns due to long term creep and shrinkage is inevitable in tall reinforced concrete buildings. However, calculation of exact values of axial shortening is not a straightforward task since it depends on a number of parameters such as the type of concrete, reinforcement ratio, and the rate and sequence of construction" (Huag, Stewart et al, 2007)
Core shortening can be visualised as follows:

![Figure 7.2.1. Core Axial Shortening (not to scale)](image)

Identified in the drawing above is core shortening and the impact it would have on the level if the columns would not shorten. Equally, column shortening can be visualised as follows:

![Figure 7.2.2. Column Shortening (not to scale)](image)

In general, steel columns (up to level 41) and concrete columns (level 41 and beyond) will shorten more than the core. The difference between column shortening and core shortening is called differential shortening. Reasons for differential shortening are explained in appendix B. Suppose a steel frame would be installed to designed level, differential shortening would distort these positions and the floor would not be level. This distortion is visualised in the following sketches.
If the steel frame would be installed to "Final Level" at time of Erection (green), the landscape at end of construction (blue) would be as follows after distortion by differential shortening (red):

![Figure 7.2.3-7.2.4. Example: Visualisation of Shortening impact in red (not to scale)](image)
7.3. Theoretical Level at time of Erection

In order to achieve a floor in a levelled plane at time of completion, differential shortening will be counteracted during construction. At time of frame erection columns will be super elevated which involves constructing over length (taller) members and installing them at a super elevated level. This means that at certain levels column splices will be packed so the column super elevated level is achieved. The theoretical landscape of level 28 at time of erection at that level is as follows:

\[\text{Figure 7.3.1. Theoretical level: orange and values shown - Final level: green plane - Shortening indicated in red}\]

\[\text{Columns super elevated} \quad \quad \quad \quad \text{Columns super elevated}\]

\[\text{Figure 7.3.2. Core & Column Theoretical Positions - Super Elevated: Red (not to scale)}\]

The red colour in figure 7.3.1 shows the amount of column shortening which will occur from Ground Floor to level 28. In the corners of the building there will be little column shortening in comparison with the columns in the middle of the building which have more loads imposed upon them. In order to compensate such shortening, columns which will shorten more than the columns at the corner will be super elevated (produced over length). The different super elevations results in a changing landscape (orange colour). At end of construction the "red" parts of the columns are expected to disappear because of shortening, and in effect a levelled floor in one plane will appear. Ultimately, all beams are predicted to arrive at the same level (green plane).
After core settlement, core shortening and column shortening, the final coordinates (designed level) are predicted to be achieved at the time of completion of the building.

This can be visualised as follows:

Figure 7.3.3. Final Level at date of completion = Designed Level

Figure 7.3.4. Final Level at date of completion = Designed Level (not to scale)

Figure 7.3.5. Example of steel structure (up to L40) (WSP Brochure, 2010)

Figure 7.3.6. Concrete structure (L40 and beyond) (WSP Brochure, 2010)
7.4. Super Elevations at Time of Frame Erection

The Structural Engineer has specified column super elevations at time of frame erection for every level. In example, Column 524/24B at level 44 is supposed to be super elevated by 13mm at time of level 44 frame erection. At time of level 44 frame erection, the core is predicted to have shortened 5mm. Note that this prediction is only valid at time of frame erection as afterwards more movement will occur. In effect, level 44 columns will be super elevated at time of erection which is visualised by the “orange landscape” shown below. After movement has occurred at the end of construction, level 44 is expected to be in one plane at a certain level as illustrated by the “green plane” in the 3D sketch shown below. (Axial Shortening Report, WSP, 2009)

To conclude, members are set to a super elevated level and are expected to travel down to a predicted position. For these reasons it is important to verify core shortening and settlement predictions because the super elevations are specified relative to the core. Furthermore, perimeter movement should be recorded as this could also distort the surveyed actual positions.
The columns itself will be made over length in order to achieve the super elevated landscape as shown in figure 7.4.1. Packs will be added to steel columns will compensate for production deviations in order to achieve the super elevated level of the column splices. Concrete columns will also be made over length in order to comply with the specified super elevated levels.

![Figure 7.4.4.-7.4.7. Steel Column Super Elevations; over length fabrication and addition of packs to the column splice (Left: Column Detail, Mace 2010 – Right: Observations, April 2010)](image)

7.5. Conclusions
The supertall building has a complex structural behaviour. As the building is expected to be subject to significant vertical movement, the building has to be set to “higher” vertical positions at time of frame erection relative to intended vertical positions at end of construction.

**Design for Movement**
1. The building is subject to differential shortening. This means that adjacent columns are expected to shorten by different rates. Furthermore, perimeter columns are predicted to shorten more relative to the core.
2. At time of frame erection, the Structural Engineer has specified column super elevations. This means that columns are set out higher than its designed position (produced over length) such that the steel frame will meet designed position after shortening has occurred.
3. Column super elevations are listed for every four levels in the Axial Shortening Report.

**Movement Predictions at time of Frame Erection & End of Construction**
4. Predictions have been made for the amount of core shortening which has occurred at time of frame erection of a certain level.
5. Predictions have been made for the amount of column and core shortening which is expected to have occurred at end of construction.

**Final Positions at End of Construction**
6. Designed “final” positions can only be achieved if members are installed to the intended levels and produced to intended length. Therefore, the achieved positions on site should be compared with super elevated column positions at time just after frame erection.
7. Designed “final” positions can only be achieved core and columns move exactly as predicted. Relevant movement is axial shortening (core & columns) and settlement (perimeter & core). Therefore, movement predictions should be verified by comparing actual movement with movement predictions at time just after of frame erection.
8. SURVEYING METHODOLOGY

8.1. Objective
This section details how data of the positions of erected members at vital locations is collected for a sample of the building. This data is needed to establish relevant factors for this research in order to specify the monitoring scope. In order to be able to find out what the dimensional variability is at vital locations at time just after erection, the difference between actual position and theoretical should be identified. The actual position can be measured on site whereas the theoretical position at time of erection is to be derived from calculations by the Structural Engineer. (Axial Shortening Report, WSP)

The actual position is the position of an installed member within the site in relation to a fixed point of reference on the core. If the site would settle relative to the external, in consequence the position of an object on site will travel down. The position of an installed member on site relative to the external control outside the Site is defined as the Relative Position.

Actual Level = Level of Object Relative to Reference on the Core

8.2. Site Setting-Out
The current site setting-out benchmarks have been observed on site. With the intention to survey the as-built position of a certain point at a member erected on site, there should be a permanent independent reference point for the duration of the works. This is referred to as the “Primary External Datum” which involves survey stations at three locations outside the site. The actual level of an erected member on site can be obtained by relating it to the external.

The Primary External Datum will be transferred to a centre punched steel bolt fixed into the concrete wall which will be known as the “Primary Core Datum” (S115). This Primary Core Datum will be transferred vertically in order to be used as a reference point for all levels. The core datum is the main vertical axis of the building to which all the levels will be set. (1432-G-GA-1900, Mace)

Figure 8.2.1.
Upon completion of the substructure the gridline was transferred to the superstructure. Plumb holes were set out and casted. With lasers the grid is transferred vertically (indicated in blue in the graph below). In order to transfer the grid to the higher levels, plumb holes will be casted in all floors. The gridlines can be established for the upper floor by using the reference from the plumb holes and the primary core datum. Any objects surveyed after installation can be related to the core datum.

8.3. Site Perimeter Vertical Position
As noted, in order to ascertain actual positions the site perimeter should be monitored. Points surveyed within the site perimeter are as follows, as observed:
- Level of points at a few places within the site perimeter (114, 113, 116)
- Primary external datum (110, 111, 112)

The points are recorded on a monthly basis and show the deviation in vertical position of the site perimeter and the external datum.

A change in recorded values would indicate vertical movement of the secant wall or the core. It should be noted that the accuracy of the surveying equipment should be considered when comparing surveys reports which were conducted at different moments in time.
Other than movement in the secant wall, steel columns could be subject to movement. This should be taken into account in order to make a fair judgement of the dimensional accuracy of the built geometry. It would be unfair in example to state that a column has been installed at a "too low level" if the base plate of the column was subject to settlement after installation. For this reason, base plate levels will be monitored for this research. Perimeter column base plate levels at ground floor will be monitored in order to ascertain difference in level. Again, the level of the base plates will be related to the external datum such that the actual levels of the base plates will be obtained (figure 8.3.3.-8.3.4).
8.4. Core Vertical Position
As identified in the previous chapter, core movement should be recorded. Monitoring the vertical position regularly allows identifying vertical movement of the cores. The objective is to record deviations in vertical positions of the entire core of the Shard which can be achieved by monitoring vertical movement of the primary core datum. In addition, possible differential movement between the core of the Shard and the 20-storey backpack core can be monitored.

As observed, core shortening is measured by using a tape of 30 meters. Fixed points are located on core walls which can be used for installing the tape. The purpose of measuring shortening is to compare the distance between established datums at different floors in order to show if between floors compression in terms of vertical position has occurred.

Based upon the length used (every 7 floors when possible) a certain force has to be imposed upon the tape to obtain proper tensioning of the tape which gives accurate readings (as observed approximately 5kg for 30m). A spring balance is used to impose such load as specified on the tape.
(Observations, 13-10-2010)
8.5. Core Horizontal Position

According to the Concrete Society, frequent slip form checks should be made for level, elevation, rotation and plumb, diameter and wall thickness. *(Concrete Society, 2008)*

The core setting-out takes place in relation to plumb holes (blue) and a GPS system which is installed on top of the slip form. Real time data is generated on a computer which can establish the current positions and level of the slip form.

Measuring the plan position shows the horizontal deviation from the intended positions of the core walls. Such information is required to ascertain the core verticality and plumbness.

Frequent monitoring is required for the slip form driver to be able to counteract apparent deviations. For this reason, monitoring takes place frequently; approximately once every meter.

*Figure 8.5.1. Core Movement Monitoring: a combination of GPS and Optical Plumbing*

8.6. Steelworks Vertical Position

For this research, the vertical position of the steelwork is surveyed in relation to the following points:

- **Top of beams near perimeter columns**
  Steel beams will be monitored at top of steel near perimeter columns.

- **Top of fin plates which connect steel beams to the core**
  Steel Fin Plates monitored at the top relative to the core.

- **Top of column splices (columns are two storeys tall)**
  The level of steel column splices (connection between two columns) will be monitored. An example of a steelworks survey report can be found in appendix G.

*Figure 8.6.1. Surveying of Steelwork Positions – Steel Beams: level (z-axis) – Columns: level & alignment (x, y, z)*

8.7. Slab Vertical Position

Slabs are poured to thickness on top of the built steel structure. The slab will not be poured to a certain level as a reference; rather, it will be poured with a consistent thickness of the slab. The level of the top of the concrete slab therefore is dependent of the level of the top of the steel structure.

After the concrete has been cured an as-built survey report will be issued which shows the top of the slab in relation to the core datum at the level reviewed. Please note that these values do not show the deviation from the theoretical level. For this reason the recorded values (actual level) need to be converted to the difference with the theoretical level. In order to assess the slab thickness, strictly speaking the bottom of the slab should be surveyed at consistent points at similar moment in time.
Notwithstanding allowable steelwork deviations, steelworks could have deflected as a result of self-weight as well as the weight of the concrete applied on top of it. Obviously the concrete would incorporate any steelwork deviations as it has been poured directly on top. For this reason, slab surveys should be related to steelwork surveys and theoretical levels in order to make a fair judgement. An example of slab levels and slab thickness surveys please refer to appendix G.

### 8.8. Accuracy of Data Collection

Survey reports conducted on Site are subject to factors which could distort the accuracy of the readings. In order to make fair judgements, the following factors should be considered when ascertaining the dimensional variability of the built geometry:

In general, surveying errors can consist of **gross errors** ("blunders"), **systematic errors** (result of natural conditions), and **random errors** (unpredictable human inability to measure). (Schofield, Breach, 2007)

#### Equipment

Setting-up of total station introduces a small deviation; secondly there could be a small inaccuracy as to the readings between different points dependent upon the accuracy of the instrument. The equipment used by independent site surveyors who conduct the setting-out is as follows:

- **LEICA TCR1201 Total Station**
  - Angular Standard Deviation +/- 1.0",
  - Distance Standard Deviation +/- 1.0mm + 1ppm
- **LEICA ZL Automatic Zenith Plummet**
  - Accuracy: 1 mm over 200 meters
- **LEICA DL3 Diode Laser Eyepiece**
  - Beam diameter is 4mm at 100m
- **LEICA NA24 Automatic Level**
  - Accuracy for 1km Double Run +/- 1.5mm

(1432-MS-0002 rev. D, SES, Mace, 2010 - Please note: equipment used could vary amongst different trades)

#### Building Movement

The establishment of gridlines generally occurs in midrange temperature conditions such that the impact of environmental conditions is limited. If required adjustments for temperature will be taken into account by adjusting the equipment. Plumb hole markings will be favourably be established after the concrete slabs have achieve its seven day strength such that the effect of horizontal shrinkage will be limited. (1432-MS-0002, Mace)

Sway does potentially have an influence upon the establishment of plumbing control markings which will increase when the building increases in height. The plumbing control markings will be transferred vertically from the storey below such that verticality tolerances of 2mm can be achieved between each storey plumb hole. Considering such verticality tolerances, the effect of building drift is not considered significant for a single storey. In order to minimize sway effect, checks will favourably be carried out whilst cranes are not active and when wind impact is insignificant. (1432-MS-0002, Mace)

#### Time the survey was conducted

The time factor can have impact on the values recorded in any survey on site. As a tall building is expected to involve building movement, in example more shortening could have occurred when surveys have been undertaken some months later than planned. Furthermore the point of reference, the primary core datum, could have travelled down as a result of core shortening and settlement as explained in section 6.5. (1432-MS-0002, Mace, 2010)
9. Actual Building Movement

9.1. Objective
The objective of monitoring building movement is to assess its actual impact and to ascertain which aspects of building movement should be included in the monitoring system for this research.

9.2. Main Findings
Core settlement and core verticality have been monitored since March 2010 until early November 2010 on a bi-weekly basis for core levels 05-59. The results are as follows:

1. Core Settlement
The core was super elevated by “+8mm” and therefore it was expected to settle by this amount to travel down to “0mm” vertical position after plunge column shortening and settlement. The core has however travelled down to “-17mm” (17/10/2010).

Figure 9.2.1. Core Settlement
Figure 9.2.2. Core Shortening
Figure 9.2.3. Core Construction (26/11/2010)
2. **Core Shortening**
The core has shortened from the basement up to level 35 by 14mm. (1432-G-GA-1901 rev.P, Mace, 15/10/2010). For level 35, 18mm shortening has been predicted at time of completion. (Axial Shortening Report, WSP). It would seem that the recorded shortening pattern approaches predictions for time of completion. For this reason, it will be useful to keep recording core shortening to verify design predictions validity.

3. **Core Verticality**
The core horizontal positions have shown only minor deviations up to level 56 (196m). Core plan positions have been measured by both GPS and EDM. The difference in readings has been within the range of 02-05mm. Please refer to Appendix H to see the full data collection for a series of levels. The largest horizontal deviation to be recorded is a “+32mm” deviation whereas a “+25mm” has been allowed.

4. **Perimeter Settlement**
The site perimeter has experienced settlement and heave which fluctuate between +01mm and -10mm. Please refer to appendix I.

![Figure 8.2.4. Perimeter Datum](image1)

![Figure 8.2.5. Perimeter Datum Movement: Settlement/Heave (mm)](image2)

5. **Column Shortening**
Measuring column shortening is complicated by column base plate movement on one hand and differential shortening between core and columns on the other hand.

Furthermore, columns and core could theoretically be subject to thermal movement. In theory, concrete and steel have a similar thermal expansion coefficient of $10^{-6}$/K at 20°C. (Wikipedia.com, 30/01/2011)

One can wonder is thermal movement should be considered when columns splice are resurveyed on site. Again, this can not be proved; however, an assumption can be made on the basis of surveys.

![Figure 14.6.1. Core Datum Monitoring](image3)
At similar locations at different moments in time a survey will be carried-out in order to ascertain the impact of thermal movement.

- At 07 October 2010 (15°C) a survey has been carried out at 106.450mm (level 29). A specific column splice has been surveyed in terms of level.

- At 26 November 2010 (04°C) another survey has been carried out in regards to the exact same column splice.

The column splice has been surveyed relative to a reference point on the core (primary core datum). In order to make a fair comparison of the data collected, movement of the reference point should be taken into account in the time between the two surveys.

The core has travelled down more (-9mm) relative to perimeter column settlement (-3mm) which is a 6mm difference. One would therefore expect the same column splice to read “+6mm” relative to the core in the second survey. In practise, the second survey conducted at 26 November 2010 shows the splice being “-3mm” in terms of its vertical position (level).

This is 9mm lower than the expected “+6mm”. This 9mm difference could either point towards:
1. Thermal Contraction
2. Column Axial Shortening   Expected column shortening at time of completion is 40mm.
3. Surveying Tolerance                Estimated maximum of ±2-3mm.

Considering the loads which have already been imposed upon the structure, it could be likely that some column axial shortening has been recorded.

To summarize, it will be very difficult to determine the exact impact of shortening and thermal influence which has occurred in practise. As column shortening can be predicted relatively accurately by design and seems to be difficult to measure in practise, this factor will not be integrated in the monitoring scope for this research.

9.3. Conclusion
Both findings involve vertical movement of the core levels. Settlement is related to the entire building being lower as all members are set out in relation to the core. Shortening is related to the storey-to-storey heights.

As noted in section 7.4, super elevations are based upon a predicted shortening pattern. For level 35, 18mm shortening was expected at time of completion of the building (Axial Shortening Report, WSP) whereas currently already 14mm has occurred. This value already approaches the final predicted values up to 4mm, even though more loads are expected to be imposed upon the core. Thus, it will be useful to keep recording core shortening to verify design predictions validity.

The recorded perimeter settlement values could have influence upon the column base plate levels near the perimeter. The ground floor column base plate movement should therefore be considered when analysing data of the actual levels of the erected steel members. Core settlement which may exceed predictions should be counteracted to avoid that the building will have lower positions than intended. Again, more data needs to be collected during course of construction.
10. Steelworks Analysis

10.1. Objective
The objective of the data collection is to ascertain where the most significant dimensional deviations are occurring. This section concentrates on steelworks dimensional deviations for levels 5-15, based upon a series of samples taken from survey reports.

10.2. Methodology
As explained previously, ascertaining the location of the most significant deviations at time of erection involves comparing the "actual" position with the "theoretical" position. The difference is referred to as the "dimensional deviation" in terms of plan position. An example is offered below:

\[
\text{Dimensional Deviation} = \text{Actual Position} - \text{Theoretical Position}
\]

\[-10\text{mm} = +12\text{mm} - 22\text{mm}\]

The dimensional deviation should be compared with project specifications to ascertain if the beam in particular is out of tolerance. For applicable tolerances please refer to Appendix E.

10.3. Data Collection (Level 05-15)
Actual vertical positions of the erected steelworks have been monitored on site. Data-analysis shows where large deviations are occurring of beam end levels near control points (perimeter columns). Furthermore, fin plate levels have been included in the statistical analysis. The analysis is shown for the entire floor as well as zones. There have been four zones indentified which divide the floor into North-West, North-East, South-West and South-East.

When comparing the intended positions as per the specification with as-built drawings, the largest deviations and their locations can be identified. In addition to that, analysis of as-built survey drawings allows identifying deviations in specific locations.
From the data collection, the main findings are the following:

1. **Fin plates showed a trend of increasing deviations for levels 05-15**
   Fin plates are connected directly to the core; in this way the steel frame is tied into the core. If the actual fin plate positions deviate, one can expect the beams which are connected to the fin plates to deviate in position as well. Data analysis shows this is the case in some instances.

   If the vertical position of a single fin plate relative to an adjacent fin plate B, deviates in excess of 5mm it can be assumed that the beams are likely to deviate as well by the same amount which increases the difficulty to achieve the “adjacent beam tolerance clause” (NSSS 9.6.11).

2. **Beam levels showed deviations at lower levels**
   Beam levels show deviations in certain areas. Both “high values” (higher vertical position than the intended position) and “low values” have been recorded. Especially cantilevers, which are tied into the structure on one end only, often have “low” values relative to the theoretical level.

3. **Beam levels showed deviations in North-West Corner**
   Beam levels show deviations in certain areas. Both “high values” (higher vertical position than the intended position) and “low values” have been recorded.

*Figure 10.3.3-10.3.7. Examples of steel beams, steel columns, connections and fin plate to core (Observations, 25/03/2010)*

*Figure 10.3.8. Beam Levels in the North West-Corner*
10.4. Examples

Some examples are offered which show deviations from the final steelworks level at time just after erection relative to the primary core datum on the core.

- **Example: Fin Plates (level 9)**

  This is an example of the recorded fin plate variability, which ultimately reflects upon the top of beam levels which are connected to the fin plates.

![Figure 10.4.1-10.4.3. Fin Plates connected to the core (2800-SRS-SK-C342-AB-022, Mace 2010)](image)

- **Example: Cantilevers (level 8)**

  Cantilevers are beams which are supported on one end only. The beam carries the load to the support where it is resisted by moment and shear stress. Recorded “low” levels in some areas are expected to travel down after dead loads of the slab are imposed. The deviation from the theoretical position could therefore be expected to increase.

![Figure 10.4.4-10.4.5. Cantilevers, South-West corner level 9](image)

![Figure 10.4.6. Cantilevers top of beam levels prior to pour (2800-SRS-SK-C342-AB-020, Mace 2010)](image)
Example: Mid-Span Beam positions (level 9)
In some instances, mid-span beam positions are low, especially where beams are not directly connected to columns or fin plates.

Figure 10.4.7-10.4.8. Mid-span beam levels prior to pour (2800-SRS-SK-C342-AB-025, Mace 2010)

10.5. Conclusion
As the conclusions are based upon a series of samples taken from survey reports for level 5-15, it should be noted that these findings cannot represent the floors or the building as a whole.

For this research it was decided to be worth avoiding the occurrence of these deviations in order to improve the dimensional variability of the steelworks. In chapter 12, causes for deviations for the samples taken, will be ascertained in order to provide necessary input for the design phase.
11. Composite Slab Analysis

11.1. Objective
The objective of this chapter is to ascertain the dimensional accuracy of the installed slabs for levels 05 to 15. The allowable deviation for a 130mm composite slab is ±6mm which is governed by the National Structural Concrete Specification (NSCS) as identified in Appendix F. (NSCS, 2004)

11.2. Slab Level Deviations
Slabs are being poured to thickness on top of the steelwork. Generally, these are two possible reasons for deviations to slab levels, which are:
1. Actual slab thickness deviates from the theoretical slab thickness.
2. Actual thickness matches the theoretical thickness; however, the level of the steelworks on to which the slab was poured deviates from the theoretical level.

Reasons for steelworks level deviations recorded at time after concrete pour in the same area could be related to the following aspects:
1. Combination of self-weight deflection and deflection as a result of the concrete pour.
2. Deviations because of cambers have not dropped out.
3. Deviations because of the inaccuracy of the erection process.
4. Deviations because of the deviations as to steel section size.
To conclude, the slab levels are dependent of the thickness that has been achieved and the levels of the steel structure located directly underneath.

11.3. Main Findings

Slab Thickness
The most practical method to survey the slab thickness is to take samples of the slab thickness by surveyors on site. Measuring the actual slab thickness disregards many variables noted above and only leaves the slab erection accuracy, i.e. slab thickness, into the equation. Slab thickness has been surveyed at levels in several areas at level 06, 08, 09 and 12. In 98% of samples taken slab thickness complied with specifications (±6mm allowable thickness deviation, please refer to Appendix F).

Slab Levels
Slab levels have been recorded for the entire floor up to level 25. In general, slabs levels are found to be “low” in terms of level in several zones of the poured levels. In north-west corners from level 9-12, slab levels are found to be “high” (>±15mm).
In the same areas slab thickness has been surveyed and as noted in the majority of the cases (98%) there are only minor deviations to the slab thickness (<-6mm). Thus, in most cases the slab level deviations seem to directly relate to the steelworks vertical positions which support the slab.

**Cantilever**

A cantilever can be visualised as follows if there is an equally distribution of dead load. A deviation from position on the beginning or end of the cantilever can contribute to a further deviation to its intended position, especially when a concentrated load is imposed upon the cantilever end.

![Cantilever Diagram](commons.wikimedia.org, 31/01/2011)

**Beam Cambers**

The largest deviations can be noticed at mid-span of beams which are not directly connected to columns, i.e. a beam-to-beam connection. Beams are assumed to deflect once concrete has been applied. In order to counteract deflections, in general large steel beams over 8m in length have been designed with cambers. Cambers are expected to drop after "final" loads have been imposed.

![Camber Principle](commons.wikimedia.org, 31/01/2011)

In some relatively "high" top of slab levels have been recorded, in some cases up to a "+30mm" deviation to the slab level. However, after investigation it appeared that in several cases the camber does not seem to have dropped, which has resulted in the slab level to be "high". This seems to be the case in example for several north-west corner areas at different levels (07, 08, 11, 12, 14).
The investigation for levels 05-15 consisted of the following surveys:

1. Top of Slab Level - after pour
2. Top of Steel Level - prior to pour
3. Top of Steel Level - after pour
4. Bottom Beam Level - after pour
5. Slab thickness - after pour

Figure 11.3.5. As Designed Floor Sandwich (right)

Figure 11.3.6. (below) Section showing beam 3C from gridline S3 to J at level 12 Survey data used in the analysis:
- Steelworks: 2800-SRS-SK-C342-AB-037
- Concrete Slab: 2400-ASB-SL-1012
- FFL/FCL/Beam Depth: 1432-G-GA-2412 (Mace, 2010)

Example: Level 12 Camber has not entirely dropped yet

[30mm] camber

The example shown above shows that a beam which was supposed to have a 30mm camber was installed. In practise, the produced camber was 36mm (complies with tolerances) and mid-span beam level was +48mm. Current surveys show that the camber has dropped by only a small amount from +36mm to approximately +25mm relative to its beam end positions. As a result, the slab poured on top shows a +41mm top of slab level. Thus, it would seem that the camber has not entirely dropped which causes high slab levels. Both beam depth and slab thickness comply with tolerances.

In the area where slab levels are low indeed steel levels are low as well and probably deflection has resulted in further downward movement of the level. Another example can be found in Appendix K.

11.4. Conclusion
To conclude, based upon the samples taken on site for levels 05-15, the 98% of slab thickness seem to show only minor deviations (<6mm). As the slabs have been poured to thickness, in general slab levels are a direct result of the steelwork beam levels. Thus, the main focus for this research should be on the steel frame as this informs upon the slab levels.
12. RELEVANT FACTORS

12.1. Objective
The objective of this chapter is to answer the 4th Design Query regarding the sample taken (L05-15): 
What are the reasons which have most likely caused the listed dimensional deviations?

Deviations from theoretical position of erected steel members for samples taken (levels 05-15) could potentially be caused by production methodology, erection methodology and building movement. If one wants to get to the stage of avoiding the occurrence of significant deviations, cause and effect of these deviations should be understood.

![Diagram of Causes for deviations (CIRIA, 1989)](image)

12.2. Manufacturing
Any dimensional deviations could potentially have been caused by the Production Accuracy, Erection Accuracy and Building Movement. As informed, steelworks production accuracy is measured on site and there are no members transported to site which do not confirm with dimensional specifications.

Based upon a series of checks conducted on site, production of steelwork members complies with the dimensional specifications. Samples involved measuring section sizes of several beams at level 07, 09, 12 and 19. Each beam was measured at beam ends, mid-span and many other instances. Notwithstanding minor exceptions, the vast majority of beam section sizes and produced cambers comply with tolerances.
12.3. Building Movement Influence
There is a need to find out to what extent building movement has had an influence in regards to the vertical position (level) of steelwork members. Thermal movement and wind movement are predicted to have only minor influence on the steelworks levels, with the exception of the spire of the building. Two factors which can influence steelwork levels are foundation movement (movement of columns to which the beams are connected) and initial beam deflection at mid-span locations prior to concrete has been poured upon the beam. These two factors will be investigated in the next two sections.

12.3.1. Column Base Plate Movement
A perimeter movement pattern has been recorded in chapter 8. Perimeter steel columns are located near the perimeter and may have been subject to similar movement. If the majority of the steelworks deviations is caused by perimeter movement, this would be important to take into account in the design phase of the monitoring system in order to avoid the occurrence of such deviations.

The question whether perimeter foundation movement (column base plate movement) has affected vertical positions of erected members at higher levels is complicated to answer. The reason is that there are several variables which affect the vertical position of a member, such as: accuracy of production of a member, accuracy of the erection of a member, shortening of columns which are connected to a member and finally possible ground movement.

The only decent way to ascertain a correlation between Ground Floor perimeter settlement and the vertical position of members erected at levels above the perimeter would seem to periodically monitor movement on one hand, and vertical positions of members erected on levels above the perimeter above on the other hand. In other words: movement which occurs underneath this member at ground level after the erection of a member.

The data gathered can then be analysed by carrying out the statistical method of “covariance” or “correlation”. The statistical covariance method ascertains if a movement pattern at ground floor level which occurred at a certain period in time is significantly reflected in the pattern of vertical positions of members recorded in the same period.

Hypothesis: The recorded Ground Floor Column movement significantly correlates with beams levels at the levels above
In simple terms: Beam levels at a certain level in the superstructure are “low” or “high” as a direct result of movement at the base of perimeter columns at Ground Floor level
Data series 1: Movement of perimeter columns at ground floor level – surveyed every month
Data series 2: Beam levels at consistent locations above the ground floor columns at a similar moment in time

Figure 12.3.1. Hypothesis: Has Ground Floor Column Base Plate Movement had any impact on levels 05-15 of the steel frame structure?
Ground floor base plates have been monitored, please refer to section 7.3.

The standard deviation ranges from 3 to 4.4mm. The mean deviates from “-2mm” to “-4mm”. The survey margins to survey two different points are estimated to be 1-2mm. Secondly, establishing the survey equipment at a position could involve a deviation of 1-2mm. In effect, it would appear that the range of data collected does not significantly exceed the accuracy of the equipment as no major deviations have been recorded.

A similar analysis has also been carried out for every zone of a level (North-West, South-West, North-East, and South-East). Again, no significant correlation can be established on the basis of the data collection. For that reason it can be concluded that Ground Floor (column base plate) movement has not had a significantly influence on the position of members erected above ground floor within a similar time period. An example of the survey reports of Ground Floor Column Base Plate Movement can be found in Appendix J.

![Base Plate Surveys - Standard Deviation - Change in Level](image)

**Figure 12.3.2. Ground Floor Base Plate Change in Level - Dimensional Variability (April – October 2010)**

However, it could be that in the future the influence of base plate might become more significant as more loads will be imposed upon the perimeter columns. For this reason, base plate movement is an important factor to remain subject to frequent monitoring.

For levels 05-15, analysis has shown that base plate movement did not have a significant impact upon levels of the steelworks erected above. However, more loads will be imposed while the structure progresses so therefore a trend analysis is needed to be carried out. In case the base plates will show an increase in settlement the affect upon the structure should be ascertained.

Favourable monitoring frequency: bi-weekly / every two storeys. For the duration of the job this should provide enough data to generate a trend-analysis, more surveys will involve more costs. Other movement surveys will be carried out simultaneously (ambient temperature). Output: trend analysis

### 12.3.2. Core Settlement

Core settlement can be measured relatively accurately relative to an external reference point. Settlement is expected to decrease the more the building will reach structural topping out. Core settlement has increased gradually. More loads will be imposed upon the core so this has to be ascertained and monitored to verify design predictions.

Favourable monitoring frequency: bi-weekly / every two storeys

Output: comparison with design predictions
12.3.3. Core Shortening

Core shortening can be measured relatively accurately. As detailed in section 7.4, a balanced tape measure is used. The core has a total length of 244m above ground and 13m substructure. A temperature change of 20 degrees would theoretically impose 62mm compression upon the core over its total length. This is 0.9mm compression per level. (Wikipedia.com, 30/01/2011)

The ambient temperature of the environment is not necessarily the temperature of the material. The core acts as a buffer relative to the ground and its thermal response includes a delay as a result of the thermal mass of concrete. Temperature difference between equipment and reference could result in a surveying deviation:

“Variations in the ambient conditions from the specified reference values can give rise to errors in the measured size of a dimension. Temperature, especially direct sunshine, is normally the most significant of these ambient conditions. The actual temperature of either the object to be measured or the measuring equipment may be difficult to determine in practice since it is unlikely that either will be at uniform temperature and because temperature differentials within the object to be measured or in the equipment will exist.” (BS 7307-1:1990)

During construction, only part of the core is subject to direct sunlight. Adjustments for temperature have been conducted by surveyors in accordance with the manufacturer’s specifications for the spring balance tape. The coefficient for thermal expansion is almost the same for a steel tape and steel reinforced concrete, so any adjustment will be minor. (1432-MS-0002, SES/Mace, 2010)

Does thermal movement of the core significantly distort core axial shortening measurements?

- This query cannot be answered with unambiguous proof; however, based upon data collected an assumption can be made. In July 2010, 13mm of shortening was measured up to level 35. This amount of shortening has remained the same until mid-October 2010.
- From mid-October it has gradually increased up to 20mm. In this period of time, the core has risen from level 38 to level 71 so a considerable amount of loads have been imposed which is likely to have caused the recorded amount of shortening. After topping out of the core, the amount of shortening has remained consistent, with 19mm shortening recorded up to level 25 at 05/01/2011.

On this basis, the assumption is made that thermal movement does not have a significant input upon the core shortening surveys. Thus, continuing of core shortening monitoring is required to verify design predictions and possible thermal influence upon readings is disregarded for this research.

Favourable monitoring frequency: bi-weekly / every two storeys
Output: comparison with design predictions
12.4. Erection Methodology Accuracy & Deflection

In the previous section, it was shown that ground floor perimeter column movement did not have a statistical influence upon the position of the steel members erected up to level 15. Consequently, this leaves the erection methodology and possible deflection into the equation.

The erection methodology consists of the setting out methodology and the actual installation of members on site, an example is shown on the next page. Observations were conducted in order to get an understanding where further improvement is necessary. More examples of a breakdown for the erection methodology are shown in Appendix L. Whilst observing the erection processes related to the major deviations (fin plate levels and beam levels), the following observations have been made on site at start of construction (samples taken):

1. Temporary storage was placed in some areas which might have caused “low” beam level values after conducting a survey.
2. There was little surveying guidance on site to check positions of erected members during the installation process, at time observations were conducted.
3. Cantilevers are expected to be subject to deflection. Once installed at a “lower” level than intended, once poured the level will travel down more.
4. Double-storey Column splices are adjusted every four levels. In general, a column splice is located between two storeys as by design columns are double-storey height.

12.5. Main findings from Observations

Notwithstanding the erection process, the main observations in regards to Quality Management are listed below, mainly on the basis of observations made at start of construction concerning levels 5-10:

1. The theoretical level to which members should be set was not indicated in as-built drawings.
2. Dimensional deviations are not listed in as-built drawings.
3. Attention for Dimensional Control needs to be reinforced within Quality Plans & Procedures to allow for specific monitoring and quality assessment to take place.

12.6. Summary for Areas of Improvement

To summarise the findings as a result of observations and data-analysis for a sample of levels 05-15, the following areas for improvement can be identified:

Figure 12.6.1. Areas for Improvement based upon analysis of samples for level 05-15
12.7. Conclusion

It can be confirmed that a monitoring system is needed which offers an analysis of the dimensional deviations of the structure as well as a trend analysis of relevant building movement. In simple terms, it should identify areas where the structure will have significant deviations which need to be counteracted. Furthermore, it should show a trend analysis of relevant building movement, such that the impact and design predictions can be verified.

Further to a detailed analysis of a sample of the building, relevant factors to be monitored for this research are the following:

1. Core Shortening at time of construction of a level  
   - to be compared with predictions
2. Core Settlement at time of construction of a level  
   - to be compared with predictions
3. Top of steel Level at perimeter at time just after construction of a level  
   - to be compared with intended positions
4. Perimeter Ground Floor Column Settlement at time of construction of a level  
   - to be compared with predictions

For movement predictions please refer to section 6.5.
For the theoretical level of the structural frame please refer to chapter 7.

The demarcation for this research can be illustrated as follows:

![Diagram of relevant factors](image)

*Figure 12.7.1. Summary of Relevant Factors to be Monitored by the Monitoring System*
13. Design Requirements

The overall goal of the monitoring system is to avoid the occurrence of significant dimensional deviations of the building. The construction team needs to know during construction:

1. Where are **dimensional deviations of the structure** occurring?
2. Does the recorded **building movement** meet design predictions?
3. What are the **causes** which have most likely caused recorded dimensional deviations?

Such understanding of where something is expected to exceed specifications and what the cause is, allows the construction team to improve the accuracy of the structure (proactive approach). Designing solutions for improvement may not necessarily guarantee that the solutions will be implemented on site if they are not reinforced by a system which strives to achievement of continuous improvement. In this regard ISO9000:2005 explains the following relevant terminology:

**Quality Management**  Coordinated activities to direct and control an organisation with regards to quality

**Quality Improvement**  Part of quality management focussed on increasing the ability to fulfil quality requirements

**Continual Improvement**  Recurring activity to increase the ability to fulfil requirements

![Figure 13.1. Cycle of Quality Improvement (ISO9000:2005)](image)

Derived from theory and data analysis, more specific requirements can be specified:

1. The monitoring system should show an **improvement of the dimensional variability of the structure** by avoiding significant dimensional deviations.
   a) The monitoring system should monitor the **dimensional accuracy of the structure**
   b) The monitoring system should monitor **building movement relative to design predictions**.

2. The monitoring system should be **implemented and tested**.
14. Monitoring Strategy

14.1. Introduction
Designing a tool which analyses dimensional deviations of the structure and conducts a trend analysis of building movement might not have the desired effect if its output is not followed up by any actions. Actions could be construction solutions, design adjustment and revision of procedures in example. For this reason, the tool is not a stand-alone object; it has to be part of a quality improvement cycle.

![Monitoring System](image)

*Figure 14.1.1. Monitoring Strategy*

14.2. Quality Management System
ISO stipulates a methodology for continuous improvement, which consists of determining the requirements for a process, measure the extent to which they are achieved, and ultimately preventing loss of quality by establishing improvement. These are the following basic steps:
1. Determine the needs and quality objectives.
2. Establish methods to measure the effectiveness and efficiency of each process.
3. Determining means of preventing nonconformities and eliminating their causes.
4. Establishing a process of continual improvement. (ISO9000:2005)

14.3. Quality Improvement Cycle
If the aforementioned main findings and observations are included into the equation this results into the following input for the design of the monitoring system within a quality management system. The quality management principles are applied to the dimensional accuracy of the steelworks structure:

1. **Awareness** *(quality objective)*
   - Identification of theoretical level to be achieved in survey drawing
2. **Data Analysis** *(measure and analyse process achievement)*
   - Measure compliance with theoretical level and analysis of building movement
3. **Process Improvement** *(preventing nonconformities)*
   - Erection methodology improvements to achieve theoretical level
4. **Establish Continual Improvement**
   - Revision of procedures which implements continual process improvement

The understanding of the place of the data-analysis tool within the quality management cycle provides useful input for the design process. Derived from the ISO9000:2005, a cycle of continuous improvement can be composed for the monitoring system.
For the structure as a whole, a similar cycle can be developed. The position the data-analysis tool has within the cycle is vital; it measures the achievements of a process. This can give cause for improvements of the dimensional accuracy on one hand, and possible adjustment of design predictions on the other hand.

Now the position of the data-analysis tool within the project quality management system is clear, the monitoring strategy can be specified. There are three types of action following from data-analysis:

1. **No Action**
   - Accuracy of the structure meets specifications and building movement is well within design predictions. Other than continued monitoring no action needs to be undertaken.

2. **Improve Accuracy Structure**
   - It should be ascertained what the most likely causes are for recorded deviations, if significant deviations have been recorded. In terms of relevant factors, reasons could be the accuracy of the installation process and building movement.

3. **Design Adjustment by the Design Team**
   - If building movement exceeds design predictions this could give cause for an adjustment to the model prepared by the Structural Engineer. This could result into different setting-out values for the structure in example or adjustments to joints between components.

### 14.4. Definition of Follow-Up Process

The definition of the follow-up process flows from the aforementioned quality management principles. Thus, in order to improve a cause for a deviation needs to be ascertained. In most cases, such significant deviations, if any recorded, could be related to relevant factors (section 12.7).
Essentially, the data-analysis could result in two categories of output which needs to be followed-up: (1) deviations of the structure and (2) building movement exceeding predictions.

1. **Deviations of the Structure at the Perimeter**
   It should be assessed if the cause for deviations exceeding tolerances is related to the installation accuracy or building movement, both identified as relevant factors (section 12.7).
   - If major *construction loads* were in place at the very same area where the beam level deviation is recorded there could be a correlation with the recorded deviation of the structure. Reviewing future loadings and their impact could be a remedy.
   - If ground floor *column base plate movement* has exceeded predictions, in example the columns settle more than predicted, there could be a correlation with the recorded deviation of the structure. It is advisable that correlation can be ascertained provided more than a month’s worth of data has been collected to limit the influence of surveying error in the trend analysis. In case of correlation the design team should be contacted.
   - If after analysis the factors above do not seem to be applicable, by method of deduction it would seem that the beam may have been *installed inaccurately*. Observations on site could possibly localise areas for improvement and the methodology could be revised.
   - Even though *manufacturing tolerances* and *surveying tolerances* are not expected to be relevant factors, it could be useful to verify them in case no explanation for the recorded deviation can be found. In such instances, beams can be measured and the calibration of the surveying equipment as well as methodology can be reviewed. It is expected that after a few random checks confidence can be obtained and these checks can be carried out once every month. Obviously, investigating these aspects in every single instance of a significant deviation might be a costly exercise.

Conclusive evidence may not be found as it is not an exact science; by deduction of factors an impression may be obtained in regards to the likely cause for the significant deviation.

![Follow-Up Process - Deviation of Structure](image)

**Figure 14.4.1.**
Follow-Up Process- In case of a significant deviation of the structure

*Note: Steps in red may be skipped if confidence has been achieved*

2. **Predicting actual movement with predictions is straightforward in the sense that two values are being compared. If movement exceeds predictions the design team should be contacted.**

The follow-up process, if required, can consist of preventing significant deviations and reinforcing procedures to ensure continual improvement as per the quality improvement principles. The follow-up process is detailed in a flow chart on the next page summarising the above.
Follow-Up Flow Chart

**REVIEW PROCESS**

1) **STRUCTURE**
   - Have significant deviations been recorded at level X? **NO**
     - **YES** (a series of deviations exceeds ± 10mm)
       - Does Ground Floor Base Plate Movement Exceed Design Predictions? **NO**
         - **YES**
           - Has there been a reason for deflection such as temporary loads? **NO**
             - **YES** (constructions loads in the very same area)
               - Has the beam depth exceeded tolerances? **NO**
                 - **YES**
                   - Does an independent resurvey show very different readings? **NO**
                     - **YES**
                       - Assume cause is an installation issue
         - **NO**
           - Does the recorded settlement at ground floor exceed design predictions? **NO**
             - **YES**
               - Do Nothing Conduct Next Review in two weeks time
             - **YES**
               - Contact DESIGN TEAM
     - **NO**
       - Does the recorded shortening measured up to level X exceed design predictions? **NO**
         - **YES**
           - Contact DESIGN TEAM
         - **NO**
           - Does the recorded settlement at ground floor exceed design predictions? **NO**
             - **YES**
               - Contact DESIGN TEAM
         - **YES**
           - Does the recorded ground floor column base plate movement exceed design predictions? **NO**
             - **YES**
               - Do Nothing Conduct Next Review in two weeks time
             - **NO**
               - Contact DESIGN TEAM

2) **CORE MOVEMENT**
   - **ACTION**
     - Do Nothing Conduct Next Review in two weeks time

3) **COLUMN MOVEMENT**
   - **ACTION**
     - Do Nothing Conduct Next Review in two weeks time

**ACTION**

1. Contact DESIGN TEAM
   - **ACTION**
     - Conduct Site Audit
     - Reduce loads if required
     - Support temporary loads if required

2. Conduct SITE AUDIT
   - **ACTION**
     - Contact SUPPLIER
     - Conduct random SITE CHECKS
     - Conduct FACTORY AUDIT
     - Revise INSPECTION & TEST PLAN (ITP) if required

3. Reduce loads if required
   - **ACTION**
     - Contact DESIGN TEAM
     - ConductNext Review in two weeks time

4. Support temporary loads if required
   - **ACTION**
     - Contact DESIGN TEAM
     - ConductNext Review in two weeks time

5. Contact DESIGN TEAM
   - **ACTION**
     - Conduct SITE AUDIT
     - Check MONITORING REGIME
     - Verify SETTING-OUT on site
     - Review SURVEYING RESOURCES
     - Revise INSPECTION & TEST PLAN (ITP) if required

Figure 14.4.2: Follow-Up Process for a certain Level X
Note: Steps in red may be skipped if Confidence has been achieved
15. Monitoring Scope

15.1. Introduction
After having obtained an understanding of position of the tool within the Quality Management System, the design scope for this research can be further specified. A technique often used to ascertain the scope of a design or a process relative to its requirements is the "SWH technique". This technique enables to specify what the basic actions are the design should fulfil as it is an acronym for What, Why, Where, When, Who, and How. (acronyms.thefreedictionary.com, 30/01/2011)

15.2. Basic Scope

**What**
Offering an analysis of dimensional deviations of the structure as well as monitoring core and perimeter movement

**Why**
An understanding of the accuracy of the structure and building movement could give cause to improve construction methodologies and/or to adjust the design if design predictions have been exceeded in reality.

**Where**
The data-analysis tool should include data collected from surveys at vital locations.

**When**
During construction of the structure of the Project.

**Who**
The Main Contractor and information to be shared with the Design Team if required.

**How**
By providing an overview of data collected during several months which can be interpreted by the Main Contractor to see whether or not the required accuracy of the structure has been obtained and if any further action is required.

This broad scope now needs to be narrowed for which the following questions need to be answered:

1. Which structural members should be monitored?
2. Where are such structural members located?
3. When should structural members be monitored?
4. Who should undertake monitoring?
5. How should monitoring take place and what equipment should be used?
15.3. Structural Frame at Perimeter
The structural frame will be monitored at top of steel beams near perimeter columns, as indicated in the following plan:

![Figure 15.3.1. Example of Points at the perimeter to be surveyed](image)

15.4. Core Movement Monitoring
Core Shortening and Core Settlement results have been recorded since this was physically possible.

![Figure 15.4.1. Core Settlement](image) ![Figure 15.4.2. Core Shortening](image)

**Surveying Method & Equipment**
Core Shortening is being measured with a spring balance tape (2x 50m) which allows adjustment for ambient temperature of the concrete relative to the tape measure itself (section 8.4). This is considered the most accurate method. Monitoring different datums at top and bottom of the core could involve too large surveying errors considering the height of the building.

Settlement monitoring takes place by surveying a fixed point on the core relative to external datum with a total station (section 8.4). Precise levelling could provide more accurate readings with a smaller surveying, however, many readings taken for the duration of the project is expected to provide sufficient understanding of settlement beyond 5mm.

To conclude, the initial methodology has been revised during construction. More aspects have been surveyed and the reporting has improved, also the monitoring frequency has been increased.
Survey Reports
The manner in which the data was collected and presented in a report has been subject to improvement construction of the building. These monitoring reports will be input for the data-analysis tool. Please refer to the last three pages of Appendix Q.

15.5. Perimeter Movement Monitoring
Perimeter Movement monitoring consists of measuring consistent fixed points of ground floor column base plates near the perimeter. Surveys will be conducted bi-weekly and the readings could show vertical movement of ground floor column base plates.

Monitoring of fixed points at perimeter ground floor base plates

Figure 15.5.1. Perimeter Movement

Surveying Method & Equipment
Precise levelling could provide readings which are more accurate relative to external control. As the surveying error is expected to be reduced, a better understanding of vertical movement can be obtained. However, as many reports are generated (every few weeks) for the duration of the project, the view was developed that significant trends such as settlement beyond 5mm would be picked up by the current methodology.

It was advised to increase the number of surveys to a frequency of every two weeks / every two levels. Ground floor perimeter column surveys have been taken at the same day as the core movement surveys in order to get consistent results. Thus, current methodology can remain in place but the frequency is increased. Please refer to Appendix M for a simple comparison of surveying equipment relative to the monitoring scope.
### 15.6. Detailed Monitoring Scope

<table>
<thead>
<tr>
<th>Visualisation</th>
<th>What</th>
<th>Where</th>
<th>When</th>
<th>How</th>
<th>Who</th>
<th>Why</th>
<th>Follow-up</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I. Perimeter</strong></td>
<td>Ground Floor Perimeter Movement - Level; vertical position</td>
<td>Perimeter Column Base Plates at Ground floor</td>
<td>Bi-weekly, at time just after construction of level X.</td>
<td>Survey the vertical position of a consistent fixed point at every base plate relative to external datum.</td>
<td>2 Surveyors + Total Station</td>
<td>Verification of Movement Prediction (Perimeter Movement Predictions are listed in the Movement &amp; Tolerances Report)</td>
<td>Contact Design Team if Predictions are exceeded.</td>
</tr>
<tr>
<td></td>
<td>Structure - Level; vertical position</td>
<td>Top-of-Steel at perimeter at a certain level X just after construction of level X.</td>
<td>Bi-weekly (when a certain level X has been finished)</td>
<td>Survey top of steel near perimeter columns at a certain level X relative to the primary core datum of level X.</td>
<td>2 Surveyors + Total Station</td>
<td>Verification of Compliance with Level Tolerances (Tolerances are listed in the Movement &amp; Tolerances Report)</td>
<td>Investigate causes if deviations exceeding tolerances have been recorded. Use checklist.</td>
</tr>
<tr>
<td><strong>II. Core</strong></td>
<td>Core Settlement - Level; vertical position</td>
<td>Settlement of the Core at time just after construction of level X.</td>
<td>Bi-weekly, at time just after construction of level X.</td>
<td>Survey the vertical position of a consistent fixed point at ground floor of the core (ground floor primary core datum) relative to a fixed external datum.</td>
<td>2 Surveyors + Total Station</td>
<td>Verification of Movement Prediction at level X (Predictions are listed in the Axial Shortening Report)</td>
<td>Contact Design Team if Predictions are exceeded.</td>
</tr>
<tr>
<td></td>
<td>Core Shortening</td>
<td>Shortening of the Core from the Basement up to a certain level X considered.</td>
<td>Bi-weekly, at time just after construction of level X.</td>
<td>Survey the distance between consistent established core datums (lines on the core walls) from the Basement up to level X considered.</td>
<td>2 Surveyors + Spring Balanced Tape</td>
<td>Verification of Movement Prediction at level X (Predictions are listed in the Axial Shortening Report)</td>
<td>Contact Design Team if Predictions are exceeded.</td>
</tr>
</tbody>
</table>

*Table 15.6.1. Monitoring Scope*
16. Data-Analysis Tool

16.1. Objective
The major ingredients for the tool have been identified; the monitoring scope has been specified as well as the monitoring strategy. The next step in the design process has been the development of the data-analysis tool.

Objective
The objective of the data-analysis tool is to:
1. Identify dimensional deviations of the structure at time of erection.
2. Verify building movement predictions during course of construction.

As a lot of data will be generated, a data-analysis tool will be needed (spreadsheet) to record information and calculate the difference between intended positions and actual positions of the structure. The data-analysis tool basically transforms input (survey values & design predictions) into output (analysis).

16.2. Black Box
The flow below outlines the flow of sub processes which result in obtaining output.
**Input**

Input consists of survey results and theoretical positions of the structure. The latter are derived from the Axial Shortening Report.

**Transformation**

The transformation process involves calculating the difference between actual values measured and theoretical positions. Also, it calculates a trend analysis of the accuracy and recorded building movement. This transformation will be explained in a value stream map.

**Output**

After analysis of the input the tool generates a report. The interface will be shown in paragraph 16.4. A report will be generated on a bi-weekly basis. Historical reports will be useful to show the accuracy and movement of the structure over time.

**Follow-up**

The interpretation phase is the responsibility of the user, in this case the construction team. By doing so, ongoing monitoring and analysis could give cause for improving the accuracy of the installation process or to make design adjustments to the building if design predictions are exceeded in practise. The follow-up process has been defined in section 14.3 and 14.4.

**16.3. Data-Analysis Process**

The transformation of input into output will now be explained in more detail.

**INPUT** *(Bi-weekly at a certain Level X, at time just after erection of Level X)*

As explained, input will be as follows:

1. Survey of Level X at top of steel near perimeter columns, directly after its erection.
2. Survey of Building Movement which has occurred at time directly after erection of Level X. [Included are Core Shortening, Core Settlement, Perimeter Column Settlement]

![Figure 16.3.1 Example: Input for Level 20 Survey](image-url)
1) Calculate Steelworks Deviation (= difference between intended positions and actual positions). Intended positions or theoretical levels are derived from the Axial Shortening report from the Structural Engineer.

**Dimensional Deviation = Actual Position – Theoretical Position**

*Figure 16.3.2. Example: Calculation of deviation at time of erection*

Green: Predicted Final Level – Red: Predicted Shortening – Orange: Super Elevated Level at time of Erection

*Figure 16.3.3. Example: Calculation of deviations (values shown are an example)*
2) Calculate Difference between Predicted Movement and Actual Movement.
Core Shortening and Core Settlement predictions when installing a certain level are listed in section 6.5.

**Predicted Movement Verification = Actual Movement – Predicted Movement**

The tool identifies the difference between actual measure movement and prediction for a certain level. In example, for level 31 a total of 01mm core shortening was predicted at time of installing the steel structure of level 31. 

Suppose in practise 12mm would be measured, predictions would be exceeded by 11mm. At end of construction, 18mm core shortening has been predicted up to level 31. Current measured 12mm shortening at time of level 31 frame erection equals 67% of total shortening prediction (18mm).

![Figure 16.3.4. Example of Shortening Prediction Verification (values shown are an example)](image)

Equally, the amount of recorded settlement will be compared with predictions:

![Figure 16.3.5. Example of Settlement Prediction Verification (values shown are an example)](image)
3) Calculate Normal Distribution of Survey Readings.
Graphs can be created based on a statistical analysis. Research by the British Standards Institute showed that for each construction task, or each manufacturing process, normal methods of working resulted in a consistent pattern of dimensional variability even if the best efforts have been made. (BS 5606:1990)

- Collection information ("dataset") needed for the normal distribution in a spreadsheet:
  a) Calculate the standard deviation ($\sigma$)
  b) Calculate the mean ($\mu$)
  c) Calculate the mean–standard deviation and mean – 2 * standard deviation ($\mu - \sigma$)
  d) Calculate the mean + standard deviation and mean + 2 * standard deviation ($\mu + \sigma$)

“The standard deviation (SD) is a measure of the extent of this spread about the mean value (see BS 6100-1.5.1 for a full definition of SD). In some processes, the mean value differs from the target value and this difference is termed the systematic deviation. Characteristic accuracy is expressed in terms of the SD and the systematic deviation.” (BS 5606:1990)

- Compose a normal distribution chart which consists of the above four data sets

![Normal distribution chart](image)

Figure 16.3.6. Normal distribution graph – number of time a value occurs (BS 5606:1990)

“The shape of the normal distribution curve is such that a range of ± 1 SD about the mean value will include 68.27 % of sizes, ± 2 SD will include 95.45 % of sizes, ± 2.5 SD will include 98.75 % of sizes and ± 3 SD will include 99.73 % of sizes.” (BS 5606:1990)

**OUTPUT** *(Bi-weekly, include readings from previous levels)*
1. List of Steelwork Deviations & Trend Analysis Graph for recorded levels up to level X.
2. Graph of Core Settlement and Perimeter Column Settlement recorded up to level X.
3. Summary of Actual Recorded Movement at level X in comparison with Predictions for Level

Examples of the output will be shown in section 16.6.
Firstly, a detailed process chart will be shown on the next page to explain the steps involved in the transformation carried out by the data analysis tool.
Figure 16.3.7. Process Dimensional Control Tool
16.4. Data-Analysis Tool Demo

The tool needs to have a clear interface which combines the major components being:

1. **Structure Deviations**
   - Perimeter top of steel level.

2. **Ground Floor Perimeter Column Base Plate Movement**
   - Perimeter ground floor column base plate level.

3. **Core Movement**
   - Core shortening & settlement.

Basically, the tool is divided into these three parts. The first page consists of a menu which allows selecting in which phase the project is in (start-up, up to level 40, or level 40 and beyond). Secondly, a new report can be made or historical reports can be viewed.

**Start-up Phase - Interface**

The start-up phase consists of a Dimensional Control Strategy Document, especially written for the project, as well as a checklist for relevant method statements. Such information will be useful when carrying out audits during the installation process.

![Image of Data-Analysis Tool Interface](background photo: skyscrapercity.com, 08/01/11)

**Input**

Bi-weekly, a new report will be generated in the tool. Monitoring results from surveyors will be inserted into the tool. Taking level 20 as an example, this will include the following three steps:

**Step 1. Input Structure Deviations**

The user inserts survey values for the steel structure (in general approximately 30 readings). These are top of steel levels near the perimeter. Such readings will be taken directly after erection of the steel structure as per section 8.6 relative to the primary core datum at the level considered.

![Figure 16.4.2. Tool: Steelwork Deviations Overview for a certain level](image)
**STEP 1: Structure Level Survey**

![Diagram of structure levels](image)

**Figure 16.4.3. Input screen example: Beam Levels at perimeter of level 20 – Also refer to Appendix O.**

**Step 2. Input Column Base Plate Movement**

The readings of column base plates at ground level at time of installation of the steelframe at level 20 will be inserted into the tool. Please refer to section 8.3 and 15.6 for the surveying methodology.

**Figure 16.4.4. Right: Example of base plate readings**

**Figure 16.4.5. Below: Input screen for base plate movement**

**STEP 2: Ground Floor Column Base Plate Movement**
Step 3. Input Core Movement

The amount of core settlement which could have occurred at time of level 20 frame erection will be inserted, in example 7mm. Please refer to section 8.4 and 15.6 for the surveying methodology. The amount of core shortening up to the upper level which has been constructed will be inserted, in example 14mm. Please refer to section 8.4 and 15.6 for the surveying methodology.

Figure 16.4.6. Right: Example of Core Movement

STEP 3: Core Movement Monitoring

Figure 16.4.7. Input Screen: Example of Core Movement
Figure 16.4.8. Below: Output Screen, example steelframe deviations -- Also refer to Appendix O.

Output 1: Structure Deviations

The tool calculates dimensional deviations at time as per section 16.3, and shows them in a summary per floor (figure 16.4.8). Any significant deviations which exceed tolerances will be highlighted.
Also, a trend analysis is offered to ascertain if there is a drop in the recorded accuracy of the structure. Data collected to date for other floors up to level 20 will be shown (figure 16.4.9).

**RESULTS [1/3] Trend Analysis Perimeter Structure**

1) Deviations from Theoretical - Structure [perimeter]

![Diagram of Beam Level Deviation Near Perimeter Columns from Theoretical Level]

*Figure 16.4.9. Tool Output Example: Structure Trend Analysis for several months – Also refer to Appendix O. The green lines indicated in the legend show the trend of outer and middle values (i.e. Mean, M-2*SD, M+2*SD). A narrower spread means fewer deviations - Please refer to section 16.3.*

Output 2: **Ground Floor Column Base Plates**

A trend analysis of Base Plate Movement to date is offered. This shows either a trend in heave or settlement of column base plates (figure 16.4.10). Correlation with the steel structure deviations can be ascertained by comparing two graphs of trend analysis for base plate movement and the structure.

![Diagram of Base Plate Surveys - Dimensional Variability of Change in Level since 1st Survey]

*Figure 16.4.10. Ground Floor Base Plate Movement – Refer to Appendix P*
Output 3. Core Movement

The tool shows the amount of recorded core settlement relative to design predictions (figure 16.4.11).

RESULTS [3/3] Core Movement

The summary below provides an overview of core movement relative to design predictions at the time of erection of the steel frame at a certain level. More examples of output can be found in Appendix Q.

Figure 16.4.11. Tool Output: Core Settlement Overview for several months

Figure 16.4.12. Tool Output: Core Movement recorded at time of erection of the steelframe at certain levels
17. Implementation

17.1. Introduction
The monitoring system which has been developed is not a stand-alone item; it clearly is part of a Quality Improvement Cycle. In order to show the implementation which has taken place in practise, examples will be offered as to how it has contributed to the quality improvement of the steelworks accuracy. The Quality Improvement Cycle will be explained as it has taken place in practise.

17.2. Awareness
The quality objective is to achieve the theoretical level at time of erection within the allowable range of deviations. The level to which the structure is set at time of erection is now being highlighted on the drawings, as indicated on picture shown below in green colour.

At column splice level this is the prescribed super elevation (=theoretical level) derived from the Axial Shortening Report. Indicated in blue are the measured actual levels relative to the primary core datum.
Cambers
In general beams longer than 9m have a camber which explains the relatively large recorded level values at mid-span of the beam recorded directly after installation. The designed cambers are indicated in the following manner: "<IC>". A survey conducted at mid span after erection will show to what extent the camber has been achieved.

![Figure 17.2.2. Indication of < Camber > (SRS, Mace)](image)

![Figure 17.2.3. Location of Cambers](image)

17.3. Data-Analysis Tool Output
The data-analysis tool has been used throughout the construction of the project. Main findings in regards to the output of the tool are as follows:

1. Increasing trend of steelworks deviations from level 5 to level 15
   An increasing trend of steelworks deviations gave cause for improvement. For levels 5-15 there was no clear correlation with perimeter columns base plate movement. Specific deviations per levels in particular areas have been identified. Several deviations have been recorded in areas where there are cantilevers and at some mid-span conditions.

   ![Beam Level Deviation from Theoretical Level near Perimeter Columns](image)

   Figure 17.3.1. Tool output: Perimeter Steel Beam Level Trend Analysis – Level 5-15

2. Increasing Trend of Core Settlement & Core Shortening.
   After 20/05/2010, an increase in core settlement has been identified. As the core was super elevated when cast by 8mm, it would be at level “00” when 8mm settlement would have. At 03/12/2010 21mm of settlement was recorded. After 29/07/2010, a core shortening increase has been recorded.

   Up to level 39, 17mm core shortening was recorded at 04/12/2010. At end of construction 18mm shortening was predicted up to level 39. Thus, movement seemed to approach predictions (94%).

### Core Shortening Predictions - At time of completion of the steel frame at a certain level

<table>
<thead>
<tr>
<th>Erection of Structure At level</th>
<th>Datum Survey</th>
<th>Amount of Shortening</th>
<th>Recorded Settlement</th>
<th>Shortening %</th>
<th>Predicted Shortening at Completion</th>
<th>Predicted Shortening at Erection</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>4-12-2010</td>
<td>-17</td>
<td>-21</td>
<td>94%</td>
<td>-18</td>
<td>-2</td>
</tr>
</tbody>
</table>

**Figure 17.3.2.** Tool Output 04-12-2010

### Core Datums - Actual position during construction of the steel frame at a certain level

**Figure 17.3.3.** Vertical Core section: Predicted column shortening at a certain level at time of completion

**Figure 17.3.4.** Vertical Core section: Actual movement during construction of the structure at a certain level

Example level 31: 13mm of shortening was recorded up to level 31, actual level of L31 datum is “-11mm”. A total of 14mm adjusted were made up to that date for core datums up to level 31.
These two main findings were flagged up during course of construction. Follow-up actions in regards to the steelworks will be discussed in paragraph 17.4 and core movement in paragraph 17.5.

17.4. Steelframe Deviations Follow-Up

Listing of identified dimensional deviations has taken place (refer to the “cloud” in as-built drawings). Listed are dimensional deviations which exceed specifications.

![Figure 17.4.1. Identification of deviations](image)

The Data-Analysis Tool has shown deviations in certain areas. The follow-up process (section 14.4) has resulted in insight as to possible causes combined with observations on site at certain lower levels. Areas for improvement in terms of the erection process have been identified as follows:

1. Low Beam levels because of installation
2. Low Beam levels because of deflection
3. Fin Plates

1. Low Beam Levels as a result of the installation process

Some beams have been installed at relatively low levels, which is not expected to be caused by perimeter movement or beam manufacturing exceeding tolerances (confirmed by samples on site). After concrete pour, these levels might travel down more. Therefore, favourably, at time of erection this phenomenon should be avoided. Adjustments of positions of installed members can occur prior to installation (connection/position redesign), during installation and after installation.

**Beam and Column Connection Design**

The geometry of the Shard consists of several cantilevers and the structure is all tied into each other. Furthermore, two storey columns provide the constraint that if misalignment does occur one has to live with it for two storeys. Vertical level deviations of columns to which beams are tied has been reduced by recording deviations and packing them accordingly.

**Adjustments during installation**

Steel members which deviate in position can be adjusted in terms of position during the installation process. Adjustment might increase time of the erection but it avoids loss of performance and the possibility of remedial works which could involve difficulty. Positions can be adjusted by the means of moving beams and columns by adjustment in bolted connection (movement in both directions), jacking (horizontal movement) or propping/pulling (vertical position). Essential to be able to avoid significant deviations from position of members is to survey positions during or directly after the installation process and compare them with the intended positions. Surveying guidance during erection has been increased to avoid low beam positions as much as possible.

**Adjustments after installation**

For a construction project, conducting remedial works would typically involve removal and refitting, or adjusting the positions by the means of propping (vertical position adjustment).

Proactive propping has taken place on site to improve recorded low beam level positions. These props will remain in place until such time the slab has been poured, to avoid an increase in level deviations.
2. Beam Levels and Deflection
As shown in the previous section, when low beam levels have been identified in a provisional survey drawing directly after erected, possibilities should be ascertained to adjust levels.

*Propping beams near storage areas*
As identified, in order to avoid deflection because of temporary storage, props will be installed to counteract such deflection. Temporary storage has to be coordinated and counteracted if necessary.

*Figure 17.4.2. Example – area level 27*

Before propping:

*Figure 17.4.3-17.4.4. Propping of Beams – Level 27 (20-09-2010) (2800-SRS-SK-C342-AB-067, Mace)*

After propping:

*Figure 17.4.5. Results in second survey of Beams – Level 27 (12-10-2010) (2800-SRS-SK-C342-AB-067, Mace)*

*Propping of Cantilevers End*
Cantilevers are beams which are fixed to the geometry at only one end. Consequently, these beams are more likely to deflect at the beam end where they are not supported. If an as-built value would read "low", it is expected that this value will go down more because of future deflection. Future deflection could occur as a result of dead loads, i.e. concrete pour and cladding panels, and live loads. For these reasons propping of "low level" cantilevers is necessary to avoid deviations.
As the survey results show, significant improvements have been made to both the mid span beam levels and the top of cantilever levels. Propping remains in place until the concrete slab has been poured and fully cured.

3. Fin Plate Installation

Fin plate installation should favourably take place within 5mm deviation from position. Extra checks and survey of the holes within the plate prior to pour should be ascertained. Surveying guidance and an increase of resource provides extra checks which assure that the dimensional accuracy is monitored and ultimately improved. Surveying guidance on site has been increased and additional checks are conducted in regards to setting-out of the steelworks.

4. Process for Continual Improvement

A process for continual improvement consists of measuring the efficiency and effectiveness of a process. Whilst measuring the process it can be identified if improvement is required. Procedures, i.e. a predefined way to carry out a process, can reinforce the need to verify and improve a process. Documenting achievement of quality improvement is an aspect of the audit trail which is required as per ISO requirements to which major contractors endeavour to comply with. (ISO9000:2005)
The aforementioned solutions have been implemented in the Method Statement, which stipulates that these improvements of both process and procedures should be carried out on site. Revised documents and procedures are:

<table>
<thead>
<tr>
<th>Name</th>
<th>Content</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steelworks Erection Method Statement</td>
<td>Erection Engineering Strategy</td>
<td>Procedure, Document</td>
</tr>
<tr>
<td>Dimensional Non Conformance Procedure</td>
<td>DNCR Procedure</td>
<td>Procedure, Document</td>
</tr>
<tr>
<td>Inspection and Test Plan (ITP)</td>
<td>Guidelines for inspections &amp; tests</td>
<td>Procedure, Document</td>
</tr>
</tbody>
</table>

Dimensional non-conformances will be identified in drawings. Not only does this increase the awareness of the achieved dimensional quality; it also enables to conduct a trend analysis. By listing non-conformances, actual improvement can be measured and remedial works can be agreed – if any. The Engineering Strategy and Inspection and Test Plan reinforce quality improvement. All the above procedures have been incorporated in the works.

17.5. Core Movement Follow-Up
The second finding from the data collection is core movement which seems to approach design predictions. Core settlement and shortening have been partially counteracted by adding length to the core when cast, as per section 6.4. As a result of the data collected the view was developed that at time of completion there may have occurred more shortening and settlement than predicted. During construction surveys seem to indicate that core movement approaches expectations at an early stage.

Level 05-40
When the first shortening and settlement was recorded, countermeasures were necessary to avoid that the top of core and core datums would be lower than the intended vertical positions at time of completion of the building. During course construction the part of the core which hasn’t been cast yet was set out taller than its designed length. Length was added to the tape during setting out such that top of core would be cast to “00” relative to external datum. Length added to the tape should equal recorded core movement at that moment in time. Datums established on the core have also been adjusted; length was added during datum setting-out in between storeys as shown in figure 17.5.1.

![Figure 17.5.1. Vertical Core section (not to scale):](image)

1. The top of the core was cast to “00” relative to external at time of casting.
2. Datum establishment on the core was adjusted: length added in between two storeys (indicated in red in the sketch above) – up to January 2011.

![Figure 17.5.2. Example of core datum (shown in the 16.5.1 as a horizontal blue line)](image)
Length was added to the fixed distances between storeys on the setting-out tapes by small amounts, in example 1mm per level, such that significant steps in the structure will be avoided. Significant steps in the structure would be unfavourable as it might affect finished floor and ceiling interfaces with the structure, cladding and lift openings.

After future shortening and settlement the intention would be that the datum and top of the core would match final positions at time of completion, as per the Axial Shortening model by the Structural Engineer.

![Figure 17.5.3. Vertical Core section: Theoretical / final conditions (not to scale)](image)

Achieving intended final positions of datums is on the premise that shortening and settlement occur in accordance with design predictions. However, if further shortening and settlement occurs which exceed expectations this is expected to distort final positions of the core and installed core datums.

**Level 40 and beyond**

In December 2010, the core was topped out. Up to level 39, a total of 17mm shortening was recorded (18mm expected at end of construction) and 21mm settlement.

From these results, it would seem that more shortening and settlement is expected to occur than predicted as more loads will be imposed upon the structure when construction progresses. This could theoretically result in floors not being level as the core travels down more relative to the perimeter.

The following might occur at time of completion if was continued from level 41 and beyond with the prescribed super elevations:

![Figure 17.5.5. Final positions of the structure if the core travels down more than expected (floor not level)](image)

The picture shown above shows that theoretically the floor would not be level if the core travels down more than predicted. This condition should favourably be avoided.

In consequence, for levels 41 and beyond the prescribed super elevations of the columns might be "too high" relative to the core datum, as the position of the core seems to be lower than intended. In order to obtain a plane which is level at time of completion between the core and the perimeter, the view was developed that column super elevations needed to be reduced for floors to be constructed beyond level 41. As per the follow-up checklist, the design team was contacted.

Indeed, after analysis by the design team and Structural Engineer, the column setting-out values have been adjusted, which means that theoretical vertical column positions were lowered relative to the core datum.

Thus, columns will be set to lower levels than intended because the core has travelled down more than initially expected.
In example, column S24/24F was to be set to “+22mm” relative to the core datum. After adjustment, it will now be set to “+5mm” relative to the core datum. For the remainder of the construction of the project it is recommended to keep monitoring core movement.

The reduction of concrete column super elevations beyond level 41 is illustrated as follows:

![Graph showing steel superelvated levels and reduced levels with +22mm and +05mm labels.]

Figure 17.5.6-17.5.7. Reduction of Column Super Elevations at time of erection - beyond level 41

A Dimensional Control Strategy Document has been prepared for the project to outline what movement monitoring needs to be in place for the structure and how it is supposed to be recorded and documented. This document is part of the audit trail for dimensional control on the Shard.

17.6. Conclusion
To conclude, the monitoring system gave cause for improvement. First topic is avoiding dimensional deviations of the steel structure. In example, temporary propping of beams and cantilevers as well as revised procedures has avoided dimensional deviations exceeding specifications.

Secondly, recorded building movement (settlement & shortening) was perceived to approach design predictions. Column setting-out beyond level 41 has been adjusted to avoid dimensional deviations at time of completion.
18. Evaluation

18.1. Criteria
Gradually, from level 15 and onwards several solutions have been implemented step by step based upon use of an analysis supported by the monitoring system. The design requirements can now be evaluated:

- The monitoring system should avoid the occurrence of significant dimensional deviations and should therefore show an improvement of the dimensional variability of the structure (avoiding significant dimensional deviations). This improvement should be measured to ascertain whether it has actually taken place.
  
  An answer to this last question will be provided in detail in the next paragraph.

- The monitoring system should monitor the dimensional accuracy of the structure (dimensional deviations at time just after erection).
  ✓ Indeed, the data analysis tool calculated the dimensional deviations at time just after erection by calculating the difference between theoretical and actual positions of the structure.

- The monitoring system should monitor building movement relative to design predictions.
  ✓ Indeed, the monitoring system monitors building movement relative to design predictions.

- The monitoring system should be implemented and tested.
  ✓ The monitoring system has been implemented and tested; its output has supported the construction team.

18.2. Quality Improvement
It can be appreciated that the monitoring system has been implemented but more importantly the following question arises: Has the above actually resulted in an improvement of the steelworks dimensional accuracy? In other words: Have significant dimensional deviations been counteracted?

Certainly, cause & effect can not be scientifically proven; the likelihood of having been of influence to a process can only be made credible in this regard based upon a selection of samples taken. The three major factors related to dimensional deviations are as follows: production accuracy, erection accuracy and building movement. The production accuracy has not changed significantly and the influence of building movement can not be proven for lower steelwerk levels. Thus, if any improvement would be recorded it is likely to relate to a large extent to the erection methodology and quality improvement.

Dimensional Accuracy of the Structure — Level 05 to Level 40
From the samples taken, the dimensional variability of the steelworks has gradually improved:

- The mean (µ) has moved from “+5mm” to “0mm”.
- The standard deviation (σ) has been reduced gradually from “8mm” to “5mm”.
- The range of “µ ± 2σ” has narrowed down from “-10mm/+22mm” to “-10mm/+10mm”.

The dimensional variability of fin plates has decreased within the quality objective of ±5mm (level). Beam level tolerance is ±10mm. Level 28 and beyond is statistically 95.5% within beam level tolerance in regards to samples of beam levels taken near the perimeter. Considering that the fin plate positions have improved as well and that all beams are connected to perimeter columns and fin plates, it is likely that the majority of the beams levels has improved. Furthermore, major improvements have been recorded by proactive temporary propping of beams and cantilevers (section 16.4).
The graph above shows that a narrower normal distribution chart means that smaller deviations to the theoretical level have been recorded. The standard deviation has decreased.

**Dimensional Accuracy of the Structure – Beyond Level 40**

If column super elevations would not have been reduced for level 41 and beyond, hypothetically slabs may not have been entirely level in one plane at time of completion of the building. For this reason, it seems reasonable to assume that dimensional deviations may have (partly) been avoided as a result of a proactive approach of the construction and the design team.

**Research Objective**

In conclusion, it seems to be fair to say that dimensional deviations at time of erection have been identified by the monitoring system. During the construction process, countermeasures have been developed to avoid the occurrence of significant dimensional deviations. The overall objective of this research has been achieved to develop a monitoring system. Obviously, it needs to be noted that the analysis and data collection within this research only relate to samples of the building and cannot possibly represent the building as a whole as samples have been taken at a certain moment in time.
18.3. Relevance for the Shard Project
The levels covered by this research include samples of level 5-40 which consist of a steelframe structure. Beyond level 40 up to level 70, the structure will consist of concrete columns and a post-tensioned slab. In effect, the tool could work exactly the same. The need for analysis of the accuracy of the structure as well as monitoring movement will remain in place. Data generated can be inserted within the data-analysis tool in a similar manner as for levels up to 40. Lessons learnt have been used for the benefit of the project, especially those in regards to deflection and setting-out of the perimeter.

18.4. Relevance for Future Projects
Notwithstanding the fact that this thesis and tool are strongly related to a particular construction project, this research provides interesting aspects for high-rise projects for the following reasons:

Design Stage
1. In the design stage of a supertall building, design for movement should be considered to avoid distortion of the geometry after erection because of permanent building movement. This is not only valid for high-rise buildings but also buildings which are expected to be subject to significant deflection or significant differential shortening of the structure.

2. Building Movement predictions could be optimised as a result of actual data collected from projects. Structural members and joints can be designed accordingly.

Construction Stage
1. In principle, the monitoring system could be used for other projects if time is invested to adapt it to the projects storey heights and floor plans.

2. Verification of design assumptions, such as the amount of shortening and settlement which is expected to occur, is important to make sure that the building meets its intended positions.

3. Important aspects to be monitored for super tall high rise buildings are: perimeter settlement, core shortening & settlement and column shortening & settlement. Also, it should be ascertained what the impact of thermal movement and sway is impact the structure. If this impact is predicted to be significant, this should also be monitored during construction. For every tall building specific monitoring requirements may be different.
CONCLUSIONS

Objective
As a result based upon the work study, the Research Objective was defined as follows:

The development of a monitoring system which provides an analysis of dimensional deviations at vital locations of the structure as well as verification of movement predictions in order to avoid the occurrence of significant dimensional deviations of The Shard

Relevant Factors
Vital locations for this project are for every storey: top of steel near perimeter, top of slab near perimeter, core level. Relevant factors are factors which could significantly distort the positions of the geometry. In theory, such factors could be related to installation & manufacturing accuracy and building movement.

Significant predicted building movement by the Engineer is mainly vertical. In particular core movement and perimeter movement. Movement predictions are given at time of frame installation of a certain level, as well as a prediction at time of end of construction. A sample of the building (level 05-15) has been analysed by taking samples of surveys results at vital locations.

Further to an analysis of a sample of the building, the following factors are relevant to be included in the scope for the monitoring system which will be monitored every two weeks or every two levels.

1. Core Shortening at time of construction of structural frame at a level.
2. Core Settlement at time of construction of structural frame at a level.
3. Top of Steel Level at perimeter at time just after construction of a structural frame at a level.
4. Perimeter Settlement at time of construction of a structural frame at a level.

Monitoring System
As per its design requirements, the monitoring system should show an improvement of the dimensional variability of the structure. The monitoring system monitors the dimensional accuracy of the structure and it monitors building movement relative to design predictions. The data analysis tool (spreadsheet) compares movement predictions with recorded movement at time of installation of a steelframe at a certain level. Secondly, the data analysis tool compares steelframe actual levels with theoretical positions at time of installation. Also, it provides a trend-analysis (graph) to show historical data inserted into the data analysis tool. This allows to spot sudden changes in results. A checklist has been created such that the construction team can follow up the outcome of data-analysis tool, if required. The installation methodology could be improved or the design could be adjusted.

Implementation
Data for level 05 to level 40 have been monitored by the monitoring system. Survey reports was input which has been entered into the data-analysis tool. First main finding was that the steelworks showed deviations in particular areas.

After analysis, possible causes seemed to be relatively low installed positions and deflection due to temporary loads. Improvement has been obtained by proactively conducting beam propping to counteract relatively low beam levels. Procedures have been revised to reflect this proactive regime.

Furthermore, tool output showed that actual core movement seemed to approach movement predictions. From the data collected the core seemed to travel down at a higher rate than predicted. As per the follow-up checklist, the design team has been contacted for their interpretation. As a result, designed super elevations have been adjusted for level 41 and beyond.

Evaluation
The monitoring system has been tested in practise and it meets research requirements. In general, more data and more sophisticated software could further improve the system. In principle, the design strategy for a monitoring system could be useful for assuring buildability of supertall buildings.
RECOMMENDATIONS

1. The data-analysis tool which has been developed within this research could have been extended and improved if more advanced software methodologies were applied. Favourably, a more integrated interface using different software should have been used for easier usage and maintenance of the data-analysis tool.

2. Live strain measurements, precise levelling and an increase of the accuracy of GPS systems could give cause for the development of live and more accurate monitoring systems. Live monitoring could identify in more detail the impact of temporary building movement as well as permanent building movement.

3. An online integrated interface could be visited by parties of the project which would allow a real-time understanding of the structural performance of the building. Possibly, a monitoring system described above could be linked to BIM-systems (Building Information Modelling) and visualised in 3D in the near future. If such a program would be able to show deviations and consequence in 3D that would be very helpful for the design and construction team.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temperature</td>
<td>temperature of the surroundings [30]</td>
</tr>
<tr>
<td>Arithmetic Mean</td>
<td>a method to derive the central tendency of a sample space, often referred to as the mean or average when the context is clear [30]</td>
</tr>
<tr>
<td>Axial Shortening</td>
<td>combination of shrinkage, shortening because of loads (elastic movement) and creep [2]</td>
</tr>
<tr>
<td>Characteristic Accuracy</td>
<td>accuracy, expressed in terms of systematic deviation or standard deviation or both, found by measurement of a representative sample and assumed to be characteristic of the whole [3]</td>
</tr>
<tr>
<td>Completion Date</td>
<td>date when the building will be handed over to the Client</td>
</tr>
<tr>
<td>Construction solutions</td>
<td>practical solutions which could potentially be implemented during course of construction [10]</td>
</tr>
<tr>
<td>Continual Improvement</td>
<td>recurring activity to increase the ability to fulfil requirements [9]</td>
</tr>
<tr>
<td>Camber</td>
<td>an arching curve of a beam or girder provided to lessen deflection and improve appearance [28]</td>
</tr>
<tr>
<td>Creep</td>
<td>tendency of a solid material to slowly move or deform permanently under the influence of stresses [11]</td>
</tr>
<tr>
<td>Deflection</td>
<td>degree to which a structural element is displaced under a load [11]</td>
</tr>
<tr>
<td>Deformation</td>
<td>change of shape of an object [11]</td>
</tr>
<tr>
<td>Dimensional Control</td>
<td>management of dimensional quality [15]</td>
</tr>
<tr>
<td>Dimensional Deviation</td>
<td>difference between actual and intended position (used within this report)</td>
</tr>
<tr>
<td></td>
<td>difference between the actual size and target size [3] (general definition)</td>
</tr>
<tr>
<td>Elastic Movement</td>
<td>movement on a structure which will returns to its initial state after removal of the main factor of influence causing movement [11]</td>
</tr>
<tr>
<td>FCL</td>
<td>finished ceiling level</td>
</tr>
<tr>
<td>FFL</td>
<td>finished floor level</td>
</tr>
<tr>
<td>Foundation Movement</td>
<td>movement of foundation induced by load application on the structure or arriving from some action of the ground itself [11]</td>
</tr>
<tr>
<td>Gross Error</td>
<td>surveying mistakes, i.e. blunders often resulting from fatigue or the inexperience of the surveyor [13]</td>
</tr>
</tbody>
</table>
Induced Deviation
inevitable departure from target size due to building process [3]

Inherent Deviation
inevitable departure from target size due to the physical properties of building materials and soils [3]

Location
series of specific position in physical space which is subject to boundaries [10]

Location Grid
a grid to assist planning authorities and designers in plotting the location of boundaries, buildings, roads, underground utilities or other features. On plans or drawings, a location grid may be presented either by continuous lines or by the points of intersection of these lines (grid intersections) [5]

Mean
arithmetic mean

MEP
mechanical, electrical and plumbing

Moisture Movement
movement caused by changes in the relative humidity [11]

Monitoring
safeguarding that a process works properly [16]

Monitoring System
set of processes which safeguard a process by measuring a process, analysis of data collected and follow-up if required [16]

Procedure
specified way to carry out an activity for a process [9]

Process
interrelated or interacting activities which transform inputs into outputs [9]

Product
result of a process [9]

QA
quality assurance [9]

Quality Assurance
part of quality management focussed on providing confidence that quality requirements will be fulfilled [9]

Quality Control
part of quality management focussed on fulfilling quality requirements [9]

Quality Improvement
part of quality management focussed on increasing the ability to fulfil quality requirements [9]

Quality Management
coordinated activities to direct and control an organisation with regards to quality [9]

Random Error
surveying error which are beyond the control of the observer and result from the human inability of the observer to make exact measurements [13]

Reference Size
size specified in the design to which deviations are related [3]

Shortening
reduction in length of an object as a result of a load [2]

Shrinkage
amount by which anything decreases in size as a result of material properties [2]
Shrinkage Movement: movement due to material section and reinforcement ratio [11]

Significant Deviation: a dimensional deviation which exceeds tolerances

Site Grid: transfer of the location grid from the plan or drawing to the site by setting-out. [5]

Site Surveyor: person entrusted with the carrying-out of one or more of the different measuring operations in the building process [5]

Soil Movement: movement of the soil caused by loads imposed by the structure, the ability of the foundations to deal with these loads and finally the influence of the water level [11]

SSL: structural slab level

Standard Deviation: measure of the extent of this spread about the mean value [3]

Structural Grid: grid to define the position of structural elements which can also be projected up and along the building as the construction proceeds [5]

Strain: dimensional change in the shape or volume of a body as a result of an applied stress or stresses [2]

Subsidence: motion of a surface as it shifts downward relative to a datum such as sea-level [30]

Systematic Deviation: difference between the mean value and the target value [3]

Systematic Error: surveying error which can be constant or variable throughout an operation and are generally attributable to known circumstances such as natural conditions [13]

Target Size: reference size from which deviations would ideally be zero [3]

Temporary Movement: movement which does not have a permanent impact

Thermal Movement: movement due to changes in temperature and radiation [11]

Tolerance: permissible variation of the specified value of a quantity [3]

Tolerance: agreement on the allowable dimensional deviation [15]

TOS: top of steel

Uniform movement: movement with same form, manner, or degree; not varying or variable [11]

Uplift: opposite of subsidence, which results in an increase in elevation of a surface [30]
The following references used in this document are listed in alphabetical order by title:

<table>
<thead>
<tr>
<th>Nr</th>
<th>Title</th>
<th>Pages</th>
<th>Author/Publisher</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td>Axial Shortening of Concrete Columns and Walls</td>
<td>p.36-38</td>
<td>Alexander, Stuart, published in Concrete</td>
<td>March 2001</td>
</tr>
<tr>
<td>4.</td>
<td>BS 5964-1:1990 Building setting out and measurement</td>
<td>p.1</td>
<td>British Standards Institution</td>
<td>September 1990</td>
</tr>
<tr>
<td>13.</td>
<td>’Imagine that you are on level 80 and you want a sandwich. How long will that take you?’</td>
<td>p.1</td>
<td>Building.co.uk, Thomas Lane</td>
<td>2007 – Issue 36</td>
</tr>
</tbody>
</table>
16. Monitoren van Betonconstructies p.4-13 Stufib, Rapport Nr.7, Stufib studiefiel 154 2003
26. Slipforming of vertical structures – Good Concrete Guide 6 p.20 Concrete Society June 2008 CS 162
28. Thefreedictionary.com n/a Thefreedictionary.com 06 March 2011
30. Wikipedia.org n/a Wikipedia.org 06 March 2011