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Deformation of multi-storey flat slabs, a site investigation

Shivan Tovi[1a], Charles Goodchild[2b] and Ali B-Jahromi[*3]

[1]School of Computing and Engineering, University of West London, W5 5RF, London, UK
[2]The Concrete Centre, SW1V 1HU, London, UK
[3]Department of Civil Engineering, School of Computing and Engineering, University of West London, W5 5RF, London, UK

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Abstract. Traditional reinforced concrete slabs and beams are widely used for building. The use of flat slab structures gives advantages over traditional reinforced concrete building in terms of design flexibility, easier formwork and use of space and shorter building time. Deflection of the slab plays a critical role on the design and service life of building components; however, there is no recent research to explore actual deformation of concrete slab despite various advancements within the design codes and construction technology. This experimental study adopts the Hydrostatic Levelling Cells method for monitoring the deformation of a multi-storey building with flat slabs. In addition, this research presents and discusses the experimental results for the vertical deformation.

Keywords: deformation; flat slab; reinforced concrete; multi-storey

1. Introduction

Concrete deflections can be controlled if the service load behaviour has been studied carefully. The behaviour of the service load initially depends on the material properties of the concrete but, at the early stage of design, these factors are largely unknown. Using nonlinear and inelastic behaviour of concrete at the service load to design for the Serviceability Limit state (SLS) is complicated, due to shrinkage, creep and other elements such as humidity and temperature. Standard codes for (SLS) design are comparatively modest and, in some cases uncertain; indeed, even inaccurate in modelling structures' behaviour Tovi *et al.* (2016) indicates. In short, there has been a widespread failure to calculate the effect of shrinkage and creep on concrete structures (Tovi *et al.* 2016).

Deflection in respect to pre-stressed and reinforced slab structures may be calculated by several techniques, using either simple, or more advanced and refined methods, for instance Precise Levelling, Getec Hydrostatic levelling, SAA (Shape Access Array), and Optical fibre. Beside elastic deformation it is important to include the effect of shrinkage and creep. A clearer

∗Corresponding author, Associate Professor, E-mail: Ali.Jahromi@uwl.ac.uk
[a]Ph.D. Candidate
[b]Principal Structural Engineer, E-mail: cgoodchild@concretecentre.com

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understanding of concrete slab behaviour may be obtained from advanced analytical methods.

One of the key issues in designing for deflection using typical classic techniques is the lack of a valid provision. Hence, the high costs involved in curing, casting and testing procedures of structural elements requires finding for inexpensive new effective tools for designing of reinforced concrete slab behaviours such as deflection, crack width, etc. This involves use of classical and /or modern designs for prediction of concrete slab deflection with assurance on attitude and non-linear strain distribution (Mohammadhassani *et al.* 2013).

The reasons for controlling deflection are: (Technical report no. 58 by The Concrete Society 2005).

- To use as a measurement tool to understand the vibration in a slab structure
- To avoid alteration, because achieving deflection limit in concrete slab structures requires sufficient stiffness
- To alleviate safety concerns, since deflection in flat slabs must be unnoticeable by residents

Current design limits on deformation such as Eurocode 2 are based on limits set four decades ago as presented ISO 4356 (1977), when the forms of construction, partitions, finishes, cladding, and services were very different to what they are now. It is possible, therefore, that the current limits are too conservative, and more research is thus needed to understand current performance in order to enable more sustainable and economic designs.

Serviceability and strength are two main criteria to consider when designing concrete structures. There has been limited recent research into deflection limits for concrete slabs and this emphasises how significant and important this study will be for understanding the behaviour of the deflection of concrete slabs (Tovi *et al.* 2016).

In many cases, appropriate control of deflections may be achieved by complying with detailed span/depth ratios. There are some cases, however, where they should be determined to conform to tolerances concerning partitions and cladding, such as the case in St George's Wharf, London, UK (Vollum 2004). Conventional analysis designs for reinforced concrete slab structures are acceptable and the attitude of structural elements can be effectively determined by solving various numerical relationships (Razavi *et al.* 2016).

Reinforced concrete is a popular and durable structural material, and a very economical material to design sustainable suspended floors as indicated by Taylor (1977). The deflection of concrete slabs, depends on many variables such as loading, strength and cracking, among others, and the estimation of this deflection is critical in the sizing and reinforcement of slabs. The current design limits appear to be traditional, perhaps inappropriate to today's forms of structural design and material reduction in the name of sustainability. The International Federation for Structural Concrete (fib) encourages more research on the behaviour of reinforced concrete slabs by applying both experimental and observation programme and this research is taking up the challenge (fib 2014).

The design of reinforced concrete structures is usually based on small deformation theories. The different design methods aim at keeping deflections and crack widths within adequate serviceability limits (Gouverneur *et al.* 2015).

This study aims to develop a methodology for obtaining and monitoring accurate deflection data from a multi storey concrete structure.

2. Deflection check methods

Eurocode 2 is considered to be one of the most advanced design codes available. It allows deformation to be checked by using calculation, suggesting a method using a cracking distribution coefficient gives an adequate prediction. Eurocode 2 also allows the use of deemed-to-satisfy span to-effective-depth ratios. These methods are compatible and economic for use with mega constructions (Moss and Brooker 2006).

Numerous optimum or minimum load designed structural components are under intense work conditions. More often, the small deflection linear theory is no longer applicable. It is very important to apply and understand crack and fracture attitude with non-linear analysis (Akbas 2015).

Some conditions where direct deflection computation is required, are listed below:

• If an assumption of deflection is needed

• If the deflection limits are not adequate for the span/250 for quasi-perpetual behaviours, or span/500 for partition members and/or cladding load

• Direct examination of deflection proposes an economic solution, when the design demands a specific shallow section

• To define the impact on deflection of premature striking of formwork or of interim load construction periods on the structure

The Concrete Society (2005) indicated in its technical report no. 58 that finite element methods are generally considered as the functional methods to obtain actual values of deflections. Limiting quasi-permanent, long-term, and deflection to span/250 is normal as Beeby (1971) states. However, unless a specific demand is required, and if cladding or brittle partitions have been supported, to control the movement deflection limit should be reduced to span/500 (Tovi *et al.* 2016).

The deflection of slab structures subjected to various loads increases as a result of shrinkage from losing moisture and creep due to the applied load. In addition, a magnification of the initial deflection occurs due to time dependent elements of shrinkage and creep.

Time has a significant impact in terms of changing the rate of deformation in concrete structures. It was argued by Heiman and Taylor (1977) that five years is a crucial time for the displacement to reach peak value, and although time dependent deflection can be computed at any time period, the prevalent procedure for design purposes is to assess the ultimate value at five years.

The deformation of large slabs may cause cracking in finishes and partitions, damaged windows and doors, inadmissible flooring slopes and roof ponds. Heiman and Taylor (1977) stated that deflection increases due to loading slabs throughout the construction period and during supporting procedures. Loading normally occurs at early stages, resulting in extreme cracking and slabs losing stiffness.

The best methods for calculating deflection are recommended by The Concrete Society (2005) technical report no. 58. This is presented in section 2.1 under the Rigorous Method.

2.1 The rigorous method

The rigorous method is the most useful method for calculating deflection; it is an appropriate technique to define an actual assumption of deflection but this method normally requires computational simulation. However, The Concrete Centre has presented number of spreadsheets using the rigorous method to define the deflection calculation for various types of slabs and beams, as indicated by Goodchild and Webster (2006). The rigorous method is a cost-effective guide to

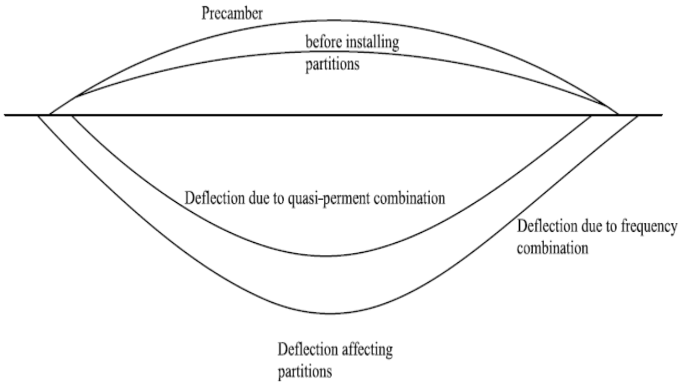

Fig. 1 Slabs precambering, reproduced (Mosley 2007)

execute particular deflection computations, in addition, it contains the capacity to recommend the effect of early stage loading on the slab structure. Commonly, ‘The Rigorous Method’ refers to the distribution coefficient method of Exp (7.19) in Eurocode 2 (2008). There are other rigorous methods but, in light of the variability of concrete strengths, loadings over time, etc., their validity is questionable.

2.2 Simplified method

A simplified method is practical for computing deflection by hand calculation, and is also useful for estimating and verifying deflection value results from computer programs and/or where the program or computer are not available. Essential simplification of this method is that the impacts of loading at the early stage are not accounted specifically. In fact, when computing the cracking moment, an allowance is produced for the impacts.

The self-weight of newly casted slab concrete cannot be supported by itself and should be diverted either entirely or partially to lower levels through props, since unhardened slab concrete cannot appropriately develop its stiffness and strength until it is hardened completely (Kang *et al*. 2013).

During construction, reinforced concrete slabs that have been placed at different times develop a gravity load resisting system, where adjacent slabs are connected by props. Actions (Loads) applied into the system are self-weights of joined concrete slabs and construction live actions. These actions (Loads) are transferred according to the proportional stiffness ratio of concrete slabs and applied to each slab as a construction action. According to a level construction cycle or the number of propped levels, the construction action applied to the reinforced concrete slab is specified through the relative stiffness ratio with the age of each reinforced concrete slab (Kang *et al.* 2013).

3. Precamber

Effect of horizontal deflection in the slab can be reduced when the slab is precambered. In practice, however, excess precamber causes the slab to remain constantly cambered due to the difficulty of calculating the deflection. The Concrete Society (2005) indicates the use of a

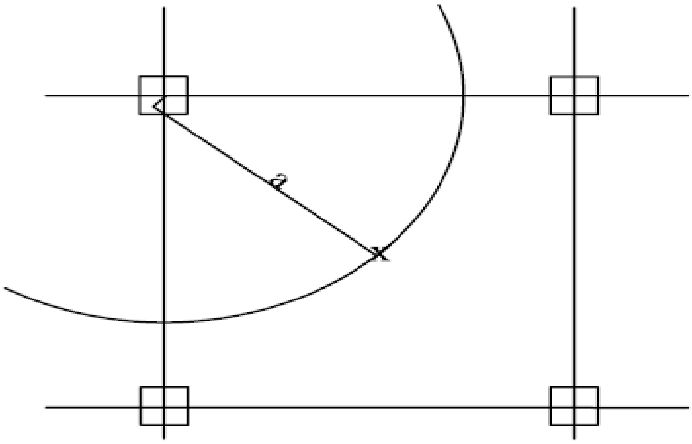

Fig. 2 Stimulated flat slab satisfied criteria

precamber of up to half the quasi-permanent deflection, however, a lower value is recommended. In conclusion, deflections affecting cladding or partitions cannot be deducted using precambering.

4. Flat slab

Flat slabs are efficient and popular method for constructing floor system structures, due to their bi-directional behaviour. However, calculating their deflection is not an easy process as The Concrete Society (2005) in technical report no. 58 presented a number of methods for estimating flat slab deflection. The most suitable and popular method is to calculate the average deflection for two parallel column strips, adding the deflection of the middle strip orthogonally to obtain the maximum deflection of the slab in the central region. Simulated flat slab satisfied criteria are detailed in (Fig. 2) as recommended by The Concrete Society, Technical Report no. 58 (2005).

When maximum allowance $\delta = \frac{L}{n}$

And X is the position of maximum δ deflection

Where

L=Span of the slab

n=Limiting span-to-depth ration

Hence,

The deflection at $X < \frac{2a}{n}$, (the deflection could be more critical on the gridline)

When=a is radius from corner of the slab

X is the distance from centre to the curvature

5. Site investigation

Elephant and Castle location in London has been selected for slab deflection investigation by

Table 1 Comparison of various methods for measuring deflection on slabs (Getec 2016) and (Atkins *et al*. 2016)

Technic	Advantage	Disadvantage
Precise levelling	Inexpensive, costing £4000 (costing £4000 for the whole site including 8 storeys	Additional operation for site staff Not reliable/imprecise Subject to obstruction by false work/formwork, following trades, services, ceilings, occupation (Getec 2016)
Getec Hydrostatic levelling	Accurate Remote data collection Small boxes (say 100×120×120 on u/s slab)	Costly, £1950/station i.e., £4000 per bay of 7×12 m Specialist installation PC and internet connection required on site. Tubes for water and signals Robustness during construction Desirability post construction (Getec 2016)
SAA (Shape Access Array)	Accurate Remote data collection Non-specialist installation	Array cast in, ('Joined sticks') Costly, £450/m i.e., probably approx. £16,000 for two bays (Getec 2016)
Optical fibre	Inexpensive	Unproven technology which could be the subject of a research itself (computers and optical fibre rather than concrete and deflection) (Atkins *et al*. 2016)

using Hydrostatic Cell Levelling system (HCL) for a period of six months. This site was identified after considering site access, timeframe for loading of the floor above, largest span and largest deflection. The HCL installation was completed on 16th September 2015 and the PC was set to record readings throughout the night so as to collect the measurements needed to check the data quality. A water test was completed on 17th September 2015 and the reading data results were checked for accuracy. Following the water test, the data was exported to the website. Data was collected every 15 minutes and was available for viewing shortly after being recorded. Fig. 10 illustrates the HCL system in action observing the deflection and the transfer of data back to the Getec website. Values shown in blue are the settlements in mm, while values shown in orange are the temperatures for that cell. Two cells that do not have temperatures are in close proximity to cells that do.

This site investigation has the following characteristics:

- A six-month timeframe, started on mid-September 2015 to early February 2016.
- Specialisation-specialists are part of the team for the input of their specialist advice, Getec Company (Keller Group plc represented by Keller UK) involved in installing HCL on the site to observe the deflection.
- Installation core team of 1-3 members, including the researcher and two engineering technicians from Getec.

5.1 Various methods for measuring deflection

Several methods were considered for monitoring the slab deflection as summarised in Table 1 and Getec Hydrostatic was selected after considering advantages and disadvantages of each method.

5.2 Hydrostatic levelling cells method

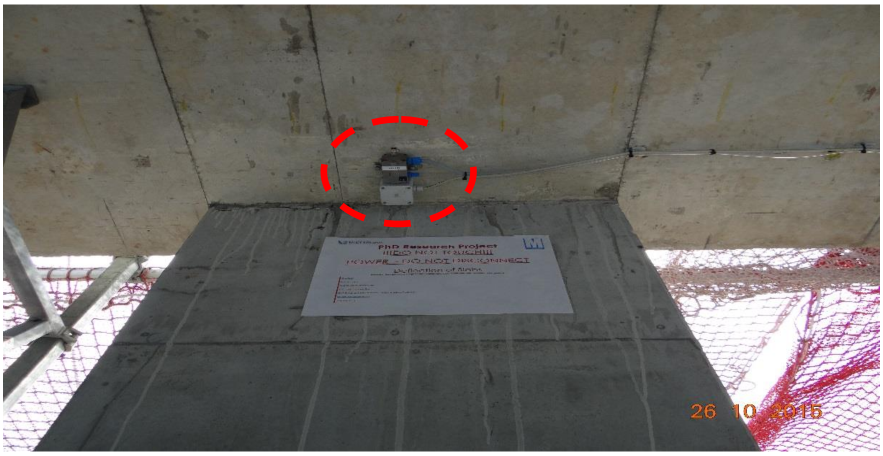

Fig. 3 Hydraulic cell level

In the Hydrostatic Cells levelling method (HCL) the data is expressed in numeric terms, such as temperature, location, dimensions and percentages. Since the research needs to be both replicable and valid, care is required in all aspects of data acquisition and analysis. Allocating the correct position for the cell is essential in order to obtain the most accurate data deflection, as illustrated in (Fig. 3) shows the location of the Hydrostatic Cell Level position on the column.

The Hydrostatic Cells Levelling method provides:

• Highly precise measurements of 0.025 mm
• Long life, low maintenance
• Continuous monitoring every 5 seconds if required

The method requires:

• One fixed reference point outside the zone of influence
• Power supply, site PC and internet connection

In the method, water from a water reservoir installed higher than the cells and kept at a constant pressure in the system. The water line is a completely sealed circuit passing through each monitoring cell and the reference cell. The reference cell is situated outside the settlement zone so that it does not move. All movements from cells within the circuit being referenced to this cell and these are reflected as a change in height.

The airline also passes through the cells in a circuit but, unlike the water line, is left open in the environment; this is stable so all the cells have the same air pressure. If a cell location moves, the capacitive pressure transducer situated between the water and air chambers in the cell records the difference in pressure. The electrical signal from the cell, which varies from 4 mA to 20 mA, is sent to a data box, which then transmits to a site logger that converts the signal to useable units (mm).

Once the circuit is complete, the system is set to zero through the software. Any subsequent change in water pressure is recorded from each cell in the chain and compared with the reference cell. If settlement occurs in one cell location, as the structure moves downwards the water pressure will increase in that cell showing a negative value. If the cell is raised due to heave, the pressure decreases showing a positive value.

Fig. 4 illustrates the water pressure reservoir connected to tubes transferring water pressure to the cells.

Fig. 4 Hydraulic cell level water pressure reservoir

Fig. 5 Hydrostatic cells levelling connected to data box

5.3 Principle of hydrostatic multi-point cell levelling (HCL)

Stationary hydrostatic multipoint levelling systems have been installed successfully for a long time for the continuous monitoring of building deformation and other structures. The observation technique essentially consists of various monitoring points, which are connected by water and air pipes and tubes as illustrated in Fig. 5.

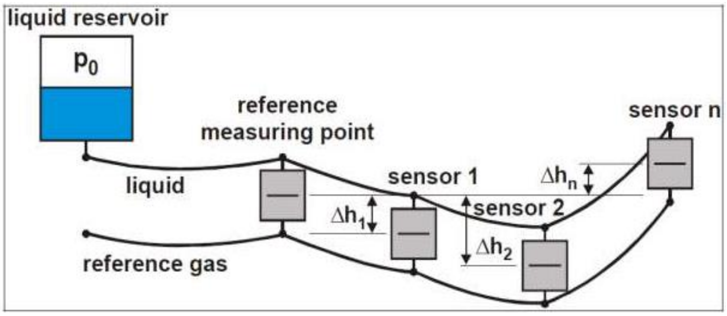

Fig. 6 Principle of operation

The HSL measures pressure differences versus a reference measuring point. These changes of pressure are converted to a height difference. The reference level is defined by the liquid horizon in a header tank. A water tube connects all the measuring points to the header tank and therefore, with the reference level, because the header tank is not linked to the measuring circuit, the level changes experienced by the liquid (e.g., through liquid losses, equal heating) have no influence on the measurement results.

The sensor is energised and the output measured in milliampere (mA). This analogue value is converted to a height difference in engineering units using a unique linear factor generated during cell calibration and supplied by the manufacturer. The reference level is defined by the liquid horizon in a header tank. All the measuring points are connected to the header tank via a tube and therefore to the reference level. Because the header tank is not linked to the measuring circuit, changes in the level of the liquid (liquid losses, changes in barometric pressure and temperature) have no influence on the measurement results.

The pressure transmitters were available in different measuring ranges from 10 cm up to 10 m and different sensors can be combined in one system. Eight sensors were used in the investigation. Sets of cells were been linked to each other via a small hole drilled through the party wall. The movement monitored by the cells was relative only, absolute values were derived by monitoring externally.

The analogue signals from the pressure devices were captured and converted into measuring values during the use of the measuring system in a free time range, with the mean value and standard deviation being calculated at the end of each time range. The standard deviation of the mean value is normally an amount between 0.02 mm and 0.05 mm. An integrated mathematical temperature model corrects the influences of temperature.

5.4 Accuracy

The heart of the hydrostatic levelling system are capacitive pressure devices, which are characterised by their stability and reliability. The technical specifications are as follows (Getec 2016)

- Operation Temperature: 20 to+80℃
- Stability (being reliable and requiring little maintenance) 0.2 mm
- Linearity (The cells are fitted with a water and air line) 0.2 mm
- Resolution: 0.01 mm
- Measuring range: 200 mm

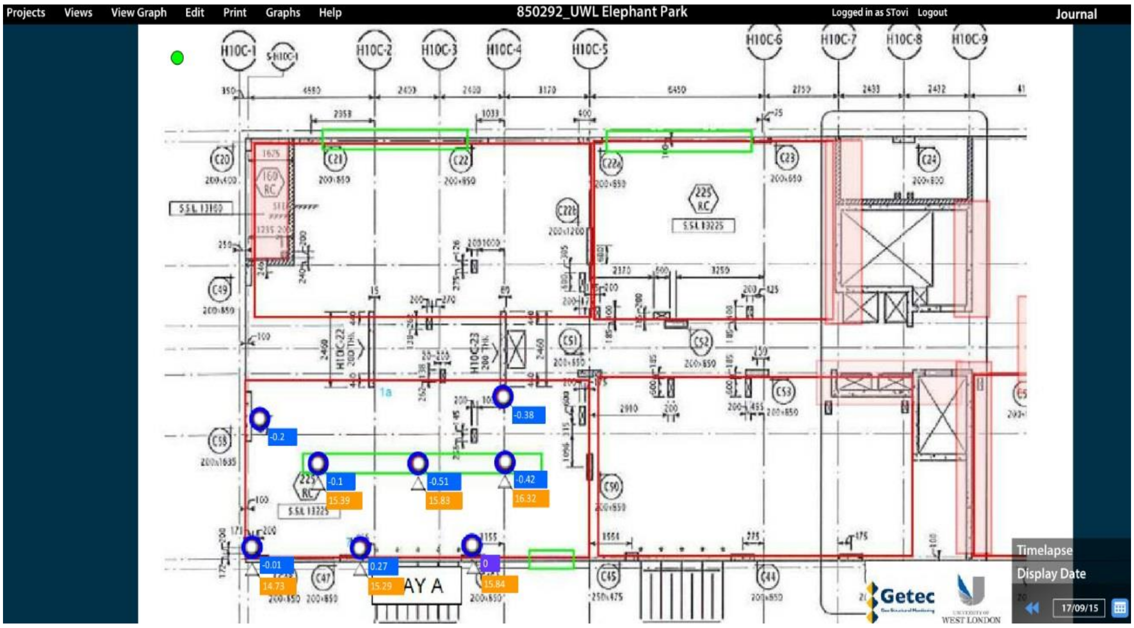

Fig. 7 HCL system in action observing deflection and transferring data

Fig. 8 Location of site investigation, elephant & castle-London

5.5 Monitoring software

Getec Software was used to visualise the data and saves them in an archive. The functionality of the visualisation software is as follows:

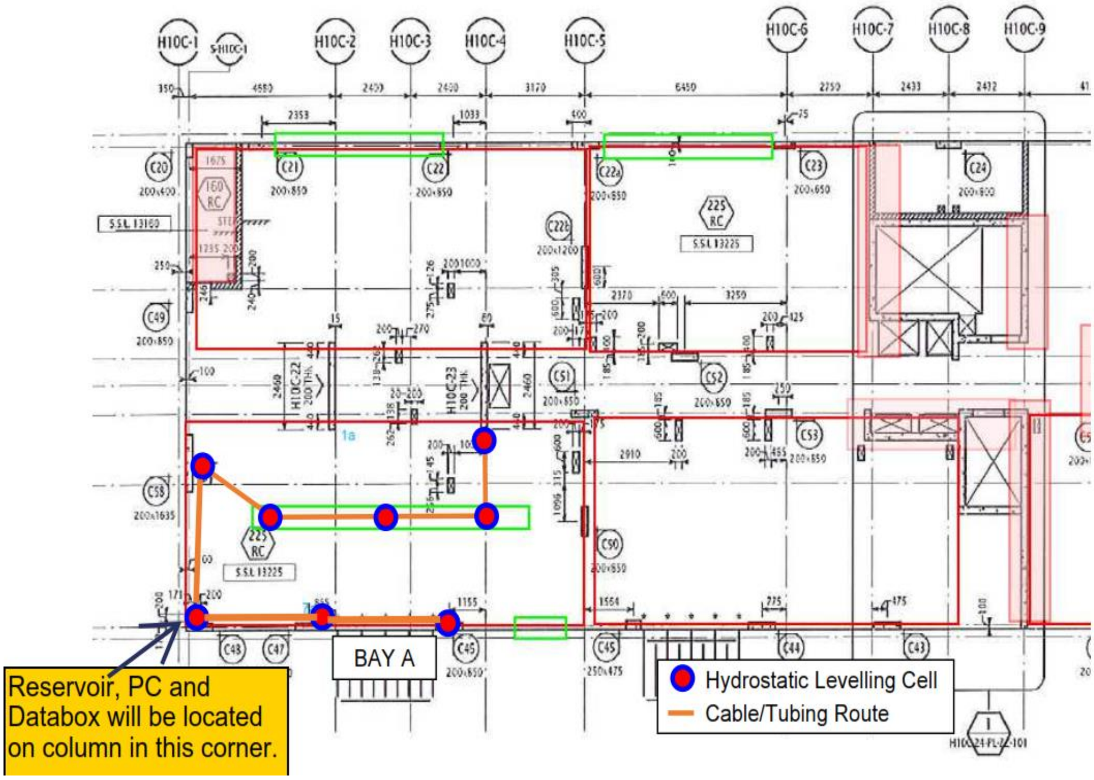

Fig. 9 HCL attached to the underside of the concrete slab

- Time Series
- Alarm functions
- Solines and Sections
- Process visualisation-Panel control
- Various software interface
- Archive for measuring value-ODBC Databases MS Access
- Data capture using a RS-485 bus line

6. Hydrostatic cell level site installation

The graphical data were reviewed by selecting a certain point or all points together. It is also possible to plot settlement and temperature side-by-side to see any variation effects between the two. When viewing a chart, it is possible to change the scales and the date ranges that are plotted. If any events occurred on site, or there are any comments in general within the system, these can be logged by expanding the journal option in the top right of the window, and typing a log entry for the time shown below in the bottom right. Hence, if an historical observation or comment needs to be made this can be done by first changing the “Display Date” to the time of the event.

Getec UK were tasked with the supply and installation of eight Getec 500 HCL onto the underside of a third floor reinforced concrete flat slab at a new development, Elephant Gardens located in Elephant & Castle-London, along with the real-time presentation of the data obtained from the monitoring system using the specialist web-based monitoring software from Getec Quick View.

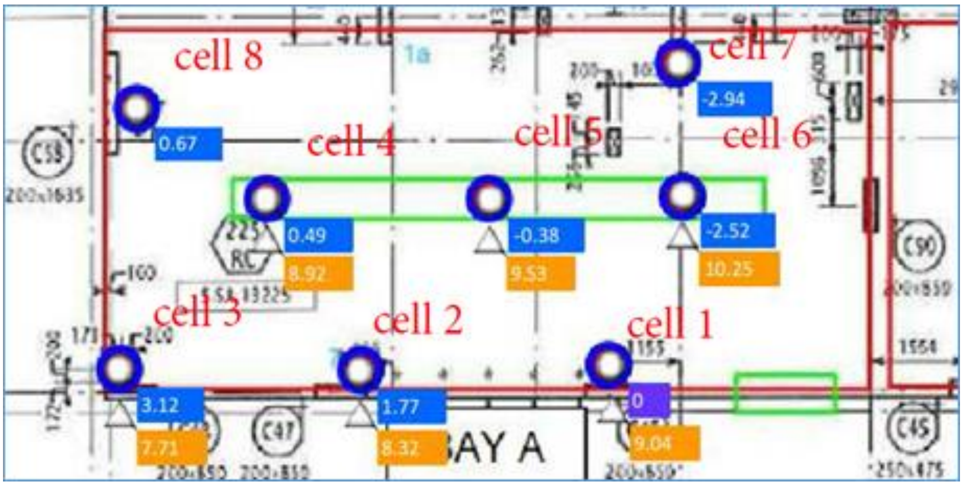

Fig. 10 Deflection of reinforced concrete slab, site investigation

The formwork and falsework were left in an inordinately long time; approximately one month instead of typical two weeks turnover. This practice may have contributed to reduction of overall deflection and as indicated in the result certainly minimised the deflection during the first month. Further study is required to investigate and quantify positive impact of the long term propping.

The HCLs were attached to the underside of the concrete slab with two 6 mm diameter, 50 mm long stainless steel masonry screws into 8 mm diameter RAWL plugs. These required 8 mm holes to be drilled into the concrete slab to a depth of approximately 50 mm. Access was by means of a small scaffold tower.

The data logger PC and the liquid reservoir were mounted with four and two of the same screws, respectively, at locations deemed most suitable when on site.

The cabling and tubing was run between the HLCs around the edge of the concrete slab and secured with cable ties to cable tie bases and nailed to the concrete approximately every 0.5 m using a gas actuated fastening tool.

Due to the location of the bleed valves on the HLCs a different method needed to be adopted to fill the system. To achieve this each HLC was removed from the slab and tilted to an upright position, thus allowing the air to be bled from the HLC as it usually would be. Once all the air had been bled from the HLC it was then re-attached to the underside of the slab. To facilitate the filling of the system the header tank was placed as high up as possible as recommended. Fig. 9 shows the approximate location of the HLCs.

7. Deflection results from site investigation

The Hydraulic Cell Levelling System monitoring vertical movement and temperature at the Elephant and Castle site were removed from the block HC10 third floor slab on 5th of January 2016 after 142 days of observing deflection on the slab using eight cells, as described earlier.

From Fig. 10, the location of cells can be clearly identified, the numbers in the top boxes above are vertical movement in mm after 142 days of monitoring, and the numbers in bottom boxes show the temperatures of each Hydraulic Cell Level.

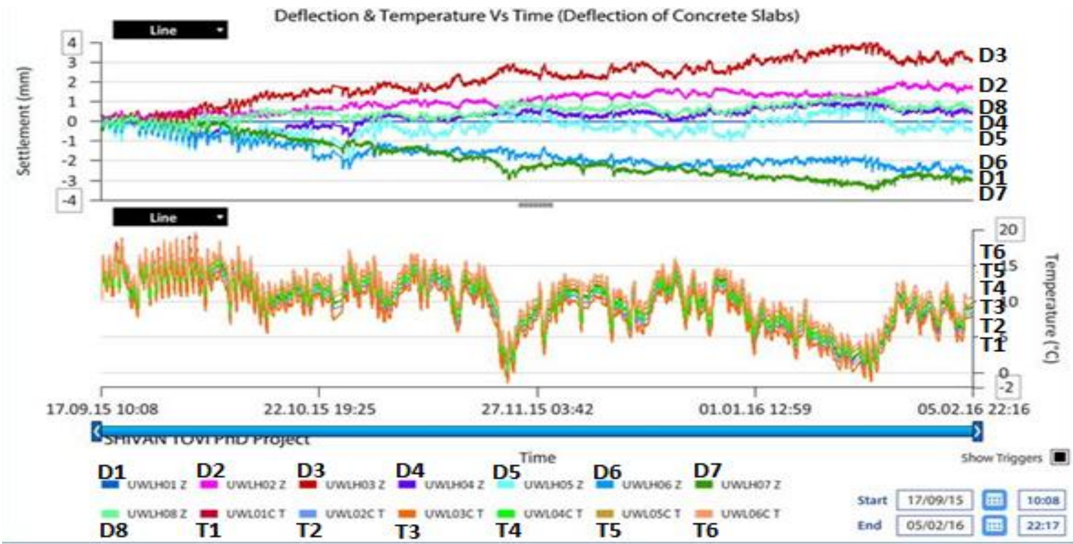

Fig. 11 Deflection and temperature vs. time (Deflection of concrete slab)

Table 2 Numbered and colour coded guide for HCLs

Deflection (Cell ID)	Location (Fig. 13)	Colour code (Graph 2)	Maximum value (mm)
UWL01Z (D1)	Cell 1		0 (Benchmark)
UWL02Z (D2)	Cell 2		1.77
UWL03Z (D3)	Cell 3		3.12
UWL04Z (D4)	Cell 4		0.49
UWL05Z (D5)	Cell 5		-0.38
UWL06Z (D6)	Cell 6		-2.52
UWL07Z (D7)	Cell 7		-2.94
UWL08Z (D8)	Cell 8		0.67
Temperature (Cell ID)	**Location (Fig. 13)**	**Colour code (Graph 2)**	**Temperature value (℃)**
UWL01CT (T1)	Cell 1		9.04
UWL02CT (T2)	Cell 2		8.32
UWL03CT (T3)	Cell 3		7.71
UWL04CT (T4)	Cell 4		8.92
UWL05CT (T5)	Cell 5		9.53
UWL06CT (T6)	Cell 6		10.25

Fig. 11 demonstrates deflections and temperatures results. The upper part of the figure shows the deflections results while the lower part shows the temperature results. Deflection and temperature results are numbered and colour coded in Fig. 11 according to the template shown in Table 2.

The data indicates that the slab has not sagged much at all due to the back propping for 30 days. It does seem, however, that the slab was sloping down from the corner by 6 mm diagonally across the 12 m bay.

A margin of deflection around 2 mm occurred, especially in the mid-span of the slab 12×7 m corner bay in block H10C, particularly on cell no. 6 and cell no. 7, the 2 mm deflection occurred at the beginning of the investigation after back propping the reinforced concrete corner bay slab. The back propping was applied seven days after pouring the slab.

When the slab was still wet HCLs were positioned under the slab while the workers were pouring the rest of the 3rd floor on the top. The slab monitoring started 17 hours after the casting. Fig. 11 illustrates that the slab has been deformed by 2 mm and it can be seen that the deflection started developing very slowly. Starting from 0 mm to 0.51 mm, and then by day 142 ending up with 2 mm.

7.1 Negative deformation

Table 2 shows negative deformation for Cell 5, 6 and 7. This can be explained by column shortening. Technical Report no. 67 (2008) recommends the shortening of a panel of columns (various concrete strengths and restraint percentages) and concludes that an ultimate shortening of 1.4 mm/m is possible, for instance 4-5 mm in a typical structure height. The report indicates that it is hard to reduce the shortening considerably. A better technique is to limit the differential shortening by calculating all reinforced concrete columns to the same standard, and by conserving long obvious spans between various structural shapes, for instance between interior reinforced concrete columns and shear walls and cores on the one side and perimeter concrete columns on the other.

8. Conclusions

The behaviour of the service load depends on the material properties of the concrete however, at the early stage of design, these factors are largely unknown. And using the nonlinear and inelastic behaviour of concrete at the service load to design for serviceability limitation is complicated. Codes for serviceability limitation design are comparatively modest and, in some cases uncertain; indeed, even inaccurate in modelling structures' behaviour. There has been a widespread failure to calculate the effect of shrinkage and creep on concrete structures.

In this research Hydrostatic Cell Levelling system were identified as a practical system for monitoring slab deflection. Slab monitoring started from a very early stage in the casting when the slab was still wet. The Hydraulic Levelling Cells were positioned under the slab while the workers were pouring the rest of the 3rd floor on the top. This study shows that the slab has been deformed by 2 mm, and it can be seen that the deflection started developing very slowly. Starting from 0 mm to 0.51 mm, and then by day 142 ending up with 2 mm.

The formwork and falsework were left in an inordinately long time-approximately one month instead of typical two weeks turnover. This practice may have contributed to reduction of overall deflection and as indicated in the result certainly minimised the deflection during the first month. Further study is required to investigate and quantify positive impact of long term propping.

The shortening of 1.4 mm/m is allowable. A better technique is to limit the differential shortening by calculating all reinforced concrete columns to the same standard, and by conserving long obvious spans between various structural shapes.

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