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Deformation of multi-storey flat slabs, a site investigation

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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

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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

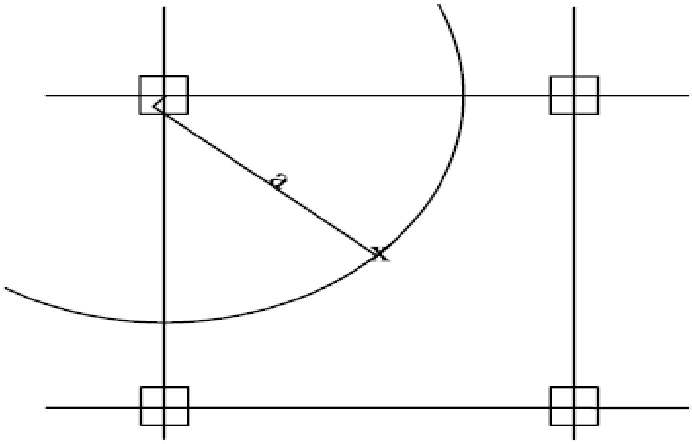

Fig. 2 Stimulated flat slab satisfied criteria

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

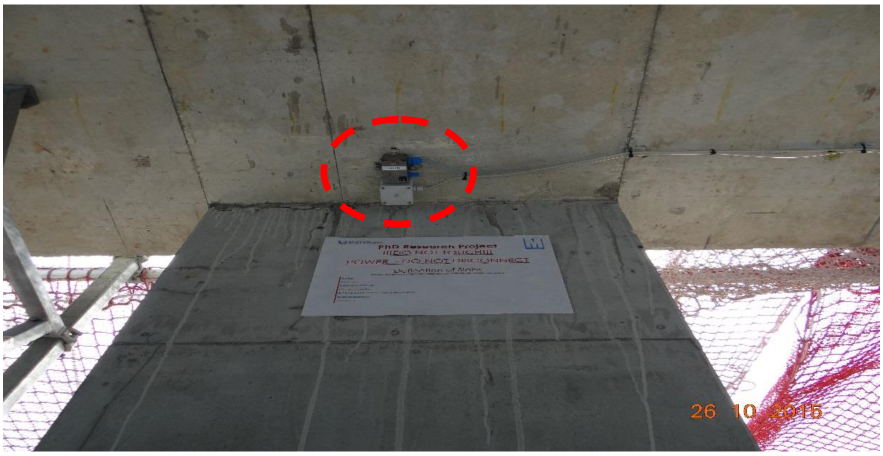

Fig. 3 Hydraulic cell level

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.

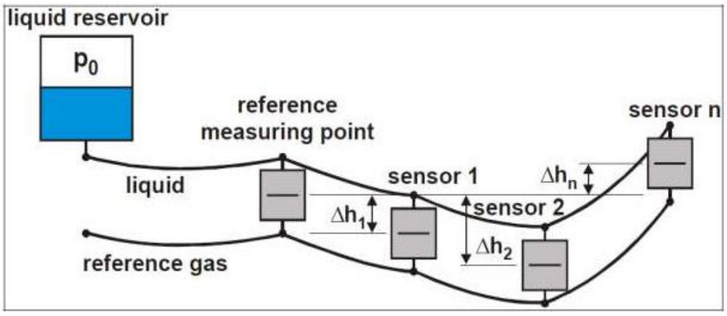

Fig. 6 Principle of operation

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

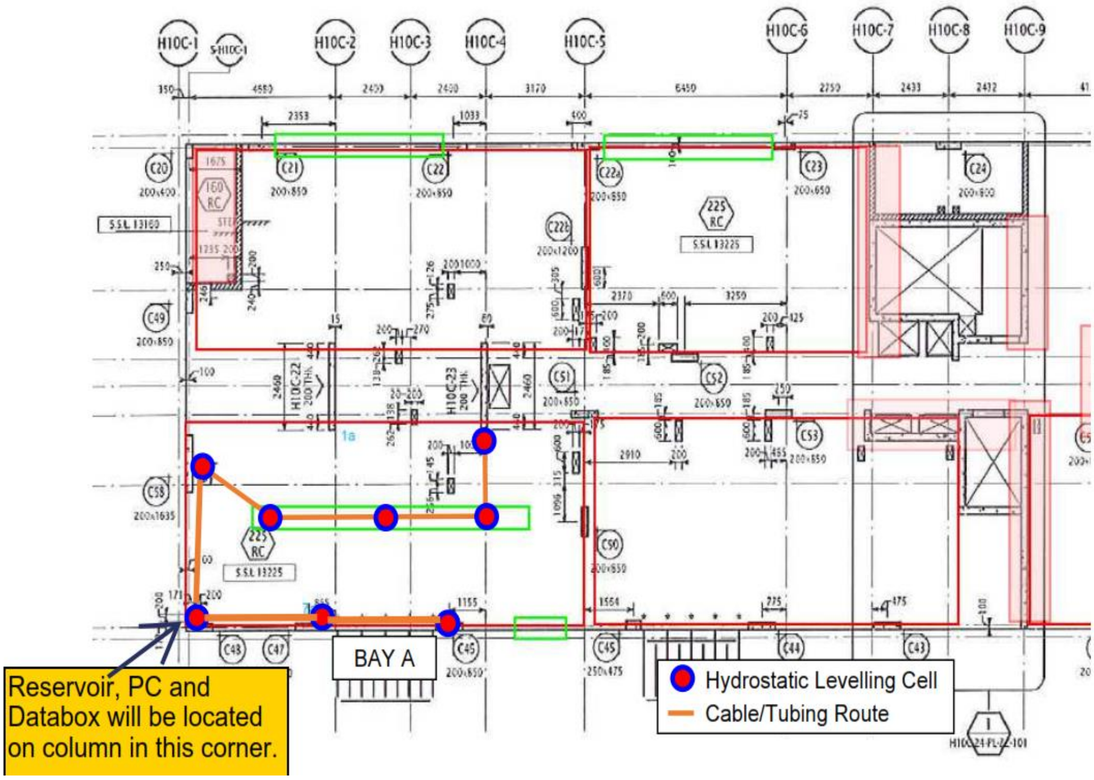

Fig. 9 HCL attached to the underside of the concrete slab

- 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.

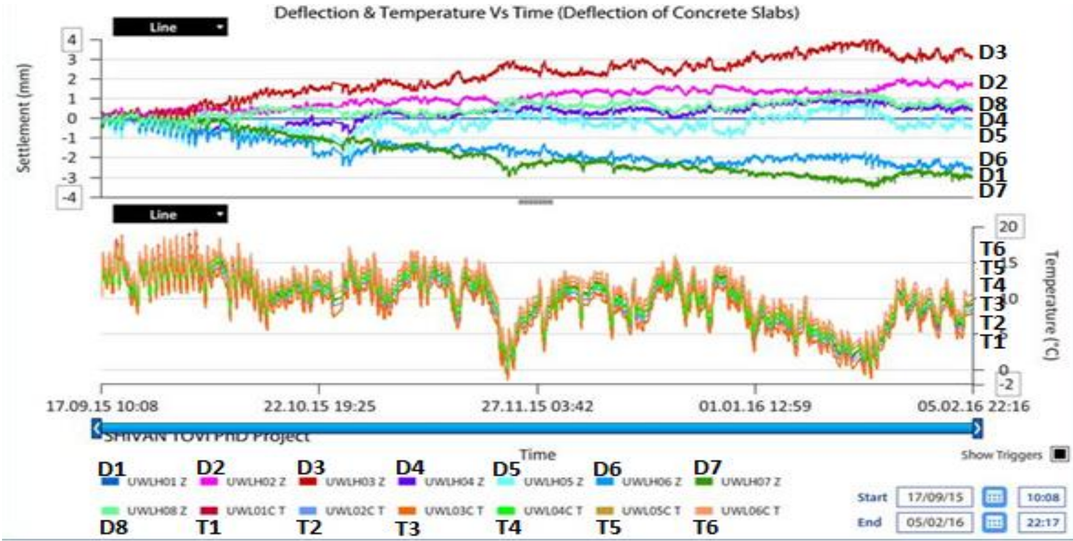

Fig. 11 Deflection and temperature vs. time (Deflection of concrete slab)

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 (°C)**
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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