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# Monitoring the axial displacement of a high-rise building under construction using embedded distributed fibre optic sensors

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## Abstract

The floor-to-floor axial shortening of vertical load-bearing elements is an important factor in the design and construction of high-rise buildings. Contractors need to allow for the expected final compression of columns and walls due to superimposed load, concrete creep and shrinkage, particularly when installing finishes and partitions in lower floors, while the building has not yet been completed. An added complication arises from the differential shortening between elements of different stiffness.

This axial shortening is predicted by designers using empirical models, in advance of construction. However, in practice, the shortening at every level cannot be measured continuously using traditional surveying measurement techniques during construction. Therefore, a monitoring system using distributed fibre optic sensors (DFOS) measuring strain and temperature, is being installed during the construction of Principal Tower, a 50-storey reinforced concrete building in London. DFOS sensors are being embedded inside two columns and two walls as the construction progresses. Using the strain and temperature data acquired from this system, the axial deformation relative to the ground level can be calculated along the whole height of the completed elements, at any time during the construction. Thus, the engineers and contractors are able to verify their predictions and adjust their assumptions if necessary.

A selection of the data acquired during the construction of the first 17 levels of the building is presented. These data have shown that the amount of shortening experienced by a member is influenced by the member's stiffness and size. The monitoring data have also revealed that thermal movement has a significant effect on the overall axial displacement of the building.

## 1. Introduction

The topic of axial deformation of tall buildings has been investigated for several decades. It is well known that, as a building is being constructed, the additional dead load from a newly constructed level, results in elastic shortening of the vertical load-bearing elements beneath it. In addition, these elements also deform axially due to thermal expansion and contraction, material creep and, in the case of concrete structures, shrinkage.

The net effect is time-variable and difficult to predict, as it depends on the interaction of several parameters related to the structural design, member geometry, material properties and environmental factors. Thus each individual load-bearing element will deform differently, leading to differential shortening between adjacent columns, and between columns and core walls. This can give rise to additional forces in the connecting floor slabs and beams (Pan et al. 1993), which need to be accounted for in the structural design. Differential shortening can also damage non-structural elements such as finishes, external cladding, mechanical services and partition walls, if these are not installed with sufficient tolerance and inbuilt flexibility (Fintel et al. 1986).

The shortening of each vertical load-bearing element is estimated in advance of construction, in order to guide the pre-setting of the column and wall heights at each level. This ensures that, upon completion of the construction, the building's floors are as close as possible to the intended levels. Several methods have been proposed to assist engineers in predicting the elastic and inelastic shortening of individual structural members (Pan et al. 1993; Fintel et al. 1986; Fintel & Khan 1969), and to compensate for the expected differential shortening (Park 2003; Park et al. 2013). However, there is a great degree of uncertainty in these calculations. In addition, these predictions only account for the permanent shortening of the members and do not take into account transient thermal effects.

In order to verify the shortening predictions during construction, it is common for contractors to use surveying techniques to measure the actual shortening of individual members at a selection of levels. This usually consists of manual measurements using laser-based instruments, typically carried out once every few weeks or even months. Being one-off measurements, there can be little control, if any, over the time of day and the environmental conditions under which these measurements are taken. Therefore the transient thermal effects cannot be accounted for, making it difficult to do a meaningful comparison between the measurements and the predicted deformation: essentially one is comparing the predicted shortening due to load, creep and shrinkage, with the actual shortening due to all actions including thermal expansion or contraction at the time of measurement.

An alternative, or addition, to manual measurements is to have an embedded displacement monitoring system, such as the ones described by Kim & Cho (2005) using vibrating wire strain gauges (VWSGs), by Choi et al. (2013) using VWSG-based wireless sensor nodes, and by Glisic et al. (2013) using fibre optic long-gauge strain sensors (SOFO). Such embedded systems have thus far used point sensors, and therefore were limited to measuring displacement at just one or a few levels. This limits their usefulness as they cannot provide a measure of the local member shortening at un-instrumented levels, or of the global shortening of the whole building.

The limitations of current techniques for measuring the actual shortening of tall buildings motivated the development of a monitoring system using distributed fibre optic sensors (DFOS). The fibre optic sensing cables are embedded in reinforced concrete elements during construction, while, at the same time, a fibre optic analyser takes automated measurements of temperature and strain from the embedded cables. This system is being deployed for the first time at Principal Tower, a 50-storey building currently under construction in central London. This paper describes the monitoring system and reports on a selection of the data acquired from the first 17 levels of the building.

## 2. Principal Tower

Principal Tower (Figure 2.1 left) is a residential building currently under construction in central London. It is designed by world-renowned architectural firm Foster + Partners, and is scheduled for completion in mid-2018. The overall project contractor is Multiplex and the tower is being constructed by Careys. When complete, the 163 m-tall building will consist of 50 storeys above ground, overlying two basement storeys. Construction of the tower started in July 2016 and, at the time of writing (May 2017), the first 25 levels had been built, with the facade installation and internal fit-out ongoing in the lower seven levels (Figure 2.1 right).

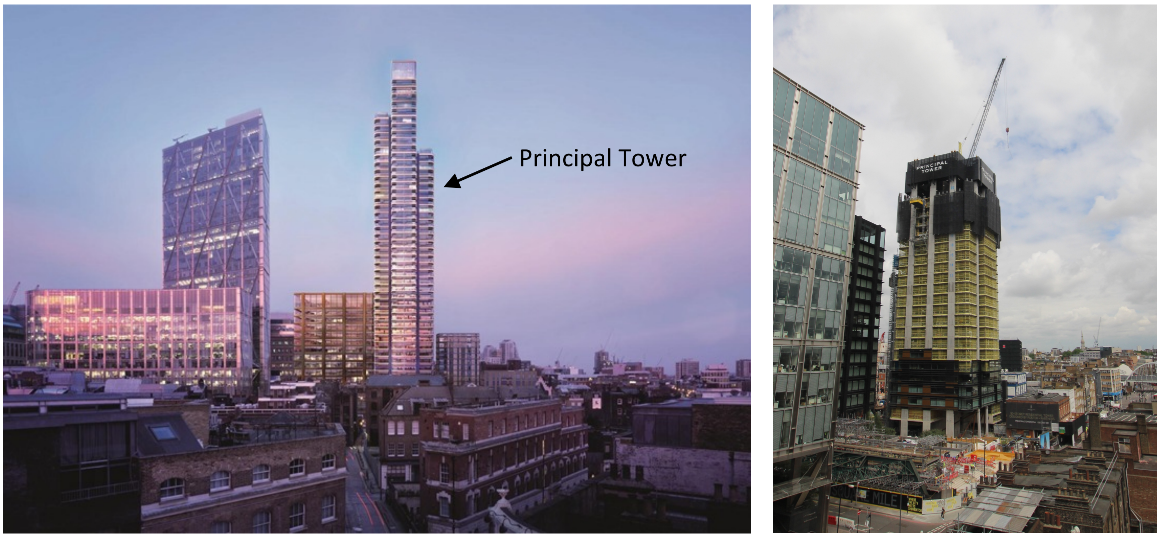

**Figure 2.1. Principal Tower: illustration showing the design of the tower (left), and the tower currently under construction (right).**

## 2.1 Structural system and prediction of axial shortening

The structural system, designed by WSP, consists of a central reinforced concrete core, 200-225 mm-thick post-tensioned concrete floor slabs and 12 columns around the buildings' square floor plan perimeter. The ground level (level 0) has a 5 m-high foyer and the rest of the floors have a clear height of approximately 2.9 m. A section of the tower footprint, including four columns and part of the core, spans over a new railway tunnel excavated directly beneath the ground floor. This required a complex load transfer structure to be incorporated into the ground floor slab. The columns that are supported directly by this structure, rest on vibration-isolating rubber bearings.

During the design stage, WSP undertook a construction stage analysis in order to predict the axial shortening of the core walls and each individual column. The calculations account for the geometry and reinforcement area of the elements, as well as the time-dependent concrete properties and superimposed load as the building is being constructed. These predictions are being used during the construction of the tower to pre-set the concrete casting levels of the columns and walls.

## 2.2 Construction of Principal Tower

The basement levels were constructed using a top-down method, allowing the tower to be constructed simultaneously. The tower structure is being built using an automated jumpform, which uses an array of 20 tonne-capacity jacks to lift the rig up off the cast concrete, typically 2 days after it has been poured.

For the first nine levels, only the core was erected using the jumpform, while the columns were cast using traditional falsework and shuttering. At the tenth level (level 9), the rig was adapted and enlarged to encompass the whole floor footprint, such that the core and all the columns then started being constructed using the jumpform system. The slab construction follows a maximum of three floors lower. This was the first building in the UK to use such a technique, allowing the construction to proceed at a rate of one floor per week.

## 3. Distributed fibre optic monitoring system for measuring axial displacement

The monitoring system developed for measuring axial displacement is based on long-distance distributed fibre optic sensing (DFOS) using the Brillouin scattering technique. This technique is explained in detail by Kechavarzi et al. (2016) and by Motil et al. (2016). In a nutshell, a fibre optic spectrum analyser launches light pulses into a single-mode optical fibre and measures the peak Brillouin frequency of the backscattered light signal, $\nu_B$, coming from everywhere along the fibre. The signal is discretised at regular distance intervals along the fibre, which is calculated from the return time of the light. $\nu_B$ is directly related to the strain and temperature of the optical fibre at the location where the backscatter occurred. Therefore, by comparing $\nu_B$ to the peak Brillouin frequency of an earlier baseline measurement, $\nu_{B0}$, one can derive the change in strain and / or temperature that occurred at each measurement point along the fibre.

### 3.1 Fibre optic sensor system

At Principal Place, two adjacent columns (referred to as C8 and C9) and two locations in the core walls (referred to as W1 and W2) were chosen to be monitored (Figure 2.1 left). All four elements are supported directly by the basement foundations and not by the load transfer structure.

Column C8 has a rectangular profile of 2.1 x 0.35 m and terminates at level 42. Column C9 has a rectangular profile of 1.25 x 1.25 m at levels 0 and 1, an L-shaped profile of 1.95 x 0.36 m and 1.265 x 0.47 m from levels 2 to 23, a rectangular profile varying between 1.27 x 0.61 m and 2.09 x 0.56 m from levels 24 to 42 and a circular profile of 0.525 m diameter from levels 43 to 49. Walls W1 and W2 start as 0.6 m thick at level 0, changing to 0.5 m thick at level 19 and 0.4 m thick at level 36. W1 terminates at level 42 while W2 extends all the way to level 49.

Each location is being instrumented with a pair of fibre optic cables: a 4-core single-mode fibre cable with a tightly bonded nylon outer jacket and a cross-section of 5.2 × 1.3 mm, which measures strain and temperature (Fujikura JBT-03813, referred to as the strain cable), and a 4-core single-mode fibre loose-tube cable with a thermoplastic outer jacket and a 6 mm diameter, which measures only temperature (Excel 205-300, referred to as the temperature cable). The cables are cable-tied to the reinforcement of the instrumented elements during steel fixing, and subsequently embedded in the concrete (Figure 2.1 right). The sensor cables start from level 0 (ground floor) in the case of C8, W1 and W2, and from level 1 in the case of C9. The cables were prepared with sufficient length to extend all the way up to the top of the elements and wound on cable reels that are housed in the jumpform rig. This enables the rig operatives to un-reel the cables as the construction progresses upwards.

Before the columns and walls started being concreted at the ground floor, the sensing fibres in the cables were connected together with a combination of fusion splices and mechanical optical fibre connectors to form two closed-loop circuits, one for columns C8 and C9 and another for walls W1

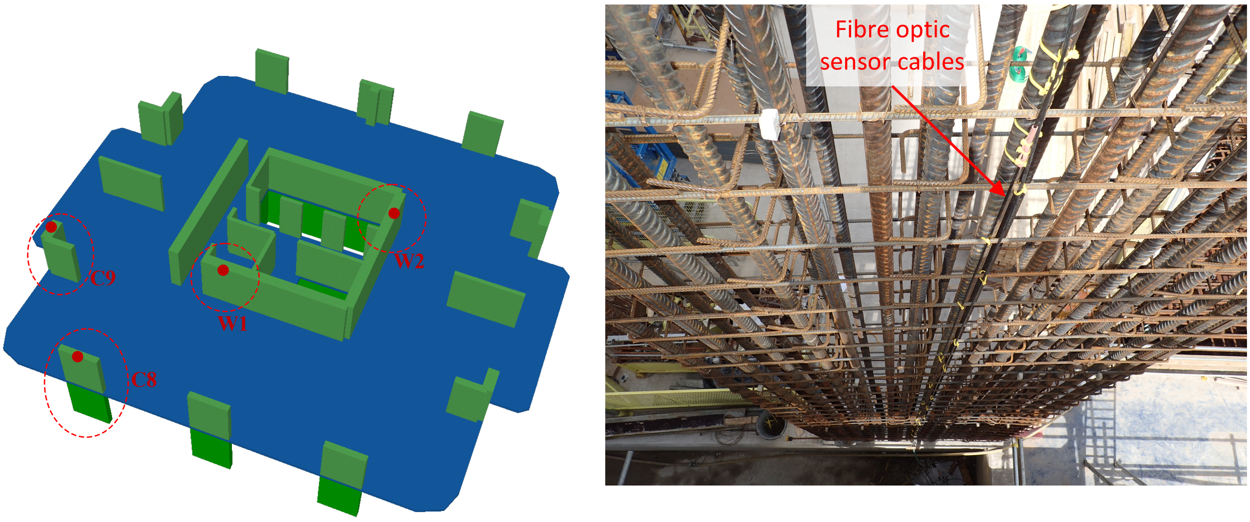

**Figure 2.1. Location of the instrumented columns and walls (left), and the fibre optic cables tied to the reinforcement prior to concreting (right).**

and W2. Each circuit was plugged into a channel of a two-channel Brillouin optical time domain analysis (BOTDA) spectrum analyser (Omnisens DITEST STA-R), which is housed permanently in a secure monitoring room inside a building close to the tower. Having the columns and walls monitored from separate optical fibre circuits meant that, if the instrumentation in one of the elements developed a fault or was damaged, monitoring on its respective circuit could be stopped while it was being repaired, without affecting the monitoring of the other circuit. More details about the sensor system are provided by de Battista et al. (2017).

## 3.2 Monitoring

Automated monitoring started on 3rd September 2016, nine days before the lowest part of the core was concreted. Since then, measurements from each optical fibre circuit have been taken at least twice every hour. The monitoring was stopped temporarily on a number of occasions, either to carry out repairs on the sensing cables following accidental damage, or due to unexpected software problems which were resolved in the early months of the monitoring.

The measurements provide the peak Brillouin frequency at 0.2 m intervals along the embedded sensing fibres, with a spatial resolution of 1 m. Thus the sensor system provides around 3000 measurements points along the four instrumented locations. Each measurement is the averaged result of 3000 individual readings and takes about 8 minutes per channel to complete. The data files are then stored in the analyser's internal memory and transferred automatically to an off-site secure server over an Internet connection.

## 3.3 Data processing

The Brillouin frequency data from the individual measurement files are post-processed to derive the change in temperature and total strain at 0.2 m intervals along the constructed levels of the concrete elements, with respect to a baseline measurement. Each level has its own baseline measurement, which, by default, is taken as the first measurement recorded just after midnight immediately following the concreting of the element. When data are not available at the time of concreting, the baseline is taken as the first available measurement recorded just after midnight.

The thermal strain of the concrete is then estimated from the temperature data, using a thermal expansion coefficient of 10 με/°C. It is assumed that the measured temperature is representative of the whole cross-section, and that the columns / walls are free to move unrestrained. By removing the estimated thermal strain from the total strain, a measure of "mechanical strain" is also obtained.

Finally, the total and mechanical axial displacement at each measurement point along the elements are estimated by integrating the total and mechanical strain, respectively. The displacement is calculated for each level individually, relative to the bottom of that level. The levels are then combined to obtain the cumulative displacement along the whole height of the instrumented elements, relative to a datum at the lowermost measurement points: the bottom of level 0 for C8, W1 and W2, and the bottom of level 1 for C9.

## 4. Results and discussion

The total axial displacement derived from the monitoring system during the construction of the first 17 levels of the building, are shown in Figure 4.1 for columns C8 and C9, and in Figure 4.2 for walls W1 and W2. These plots show the displacement averaged over a 1 m section (5 measurement points) at mid-height of each level. There are a number of periods with missing data when the monitoring was stopped temporarily for various reasons, as explained in Section 3.2. Since each level has its own initial baseline measurement, the displacement data following the resumption of monitoring were unaffected by the period of missing data.

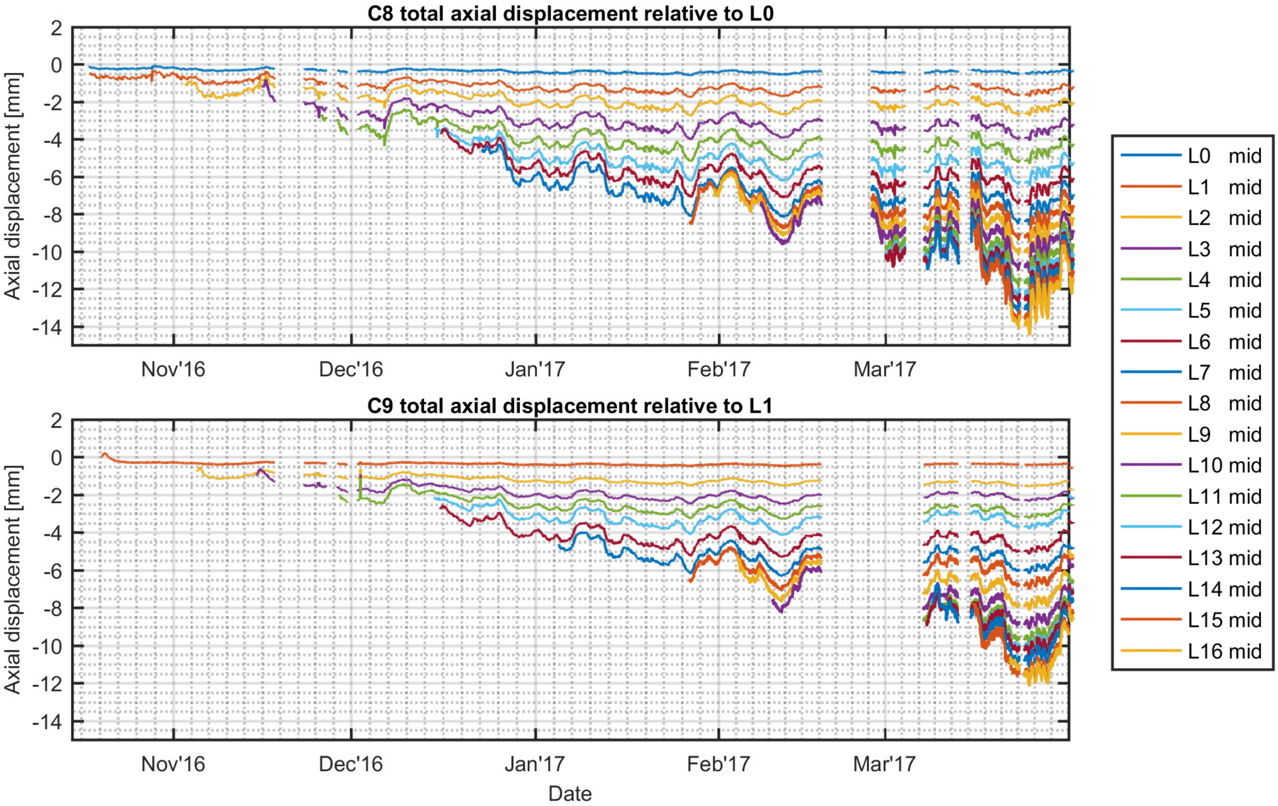

Figure 4.1. Axial displacement of columns C8 (top) and C9 (bottom) estimated from strain measurements taken between mid-October 2016 and end of March 2017. Negative displacement indicates shortening.

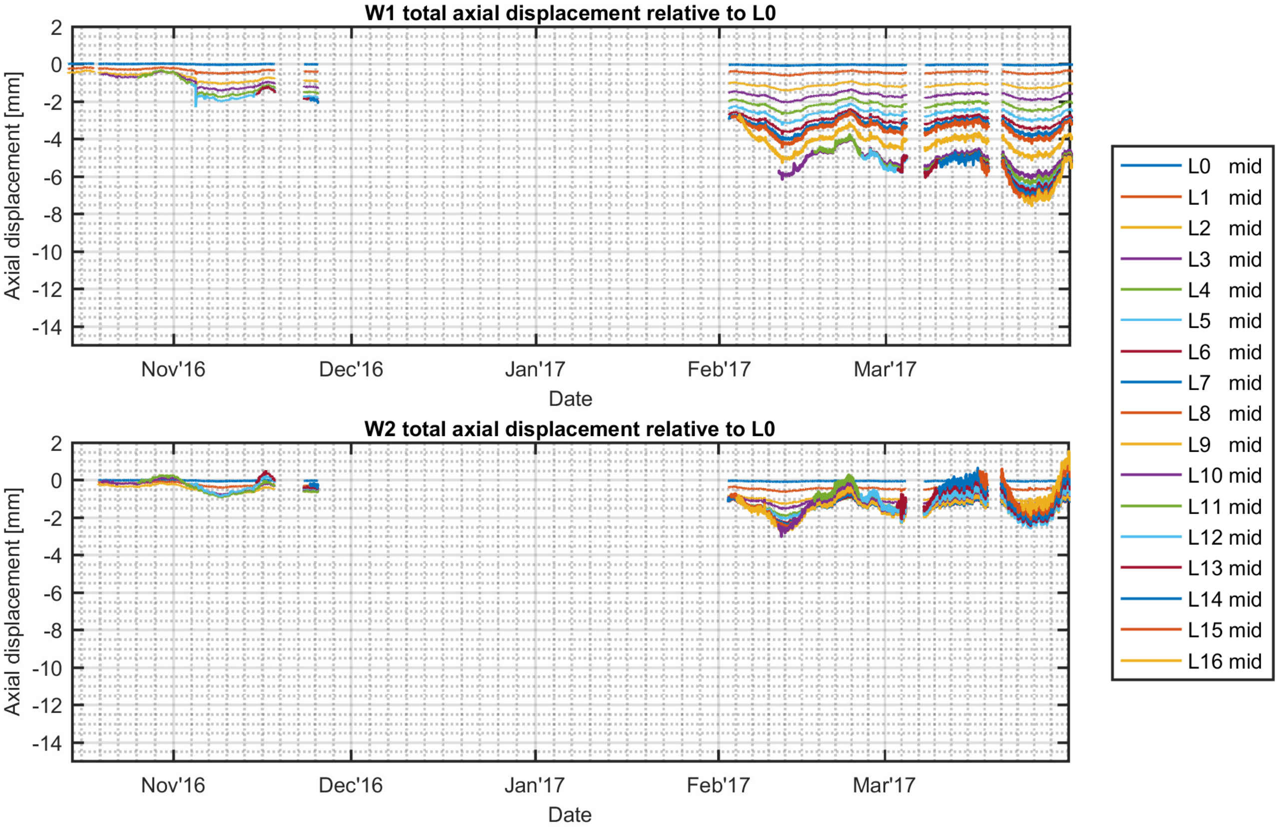

Figure 4.2. Axial displacement of columns W1 (top) and W2 (bottom) estimated from strain measurements taken between mid-October 2016 and end of March 2017. Negative displacement indicates shortening.

In the case of the walls, there was a long break in the monitoring from 24th November 2016 to 3rd February 2017. This was due to accidental damage sustained in one of the sensing cables when the core was up to level 7. The damage could not be repaired before early February 2017, since the jumpform rig was being adapted to incorporate the whole building perimeter, from December 2016 to January 2017. During this period, only one additional level was constructed on the core (level 8), for which the baseline was taken 58 days after concreting, when the monitoring was resumed.

*Differential shortening*

As expected, the four instrumented elements have deformed at different rates. Column C8, which has approximately half the cross-sectional area and a similar amount of steel reinforcement to C9, has shortened around 15 – 25% more than C9 (Figure 4.1), despite supporting approximately 12% less dead load. Similarly, both columns are shortening significantly more than the core walls (Figure 4.2), as the walls have a larger cross-sectional area and are stiffer.
While the displacement data of the two columns and wall W1 indicate a general shortening trend over time, the deformation pattern of wall W2 (Figure 4.2 bottom) is rather unexpected. W2 has shortened much less than W1, despite having the same thickness and a similar amount of reinforcement. The data show that, at times, W2 has even elongated, particularly during warmer periods. It is possible that this section of the wall, which is only 3.6 m long and bounded by perpendicular walls at each end, is more restrained. This requires further investigation.

*Thermal effects*

The data show that the axial shortening of all four elements did not increase uniformly with time, contrary to what is assumed in the prediction calculations. There is a strong thermal effect that gives rise to occasional fluctuations in displacement. One example is the decrease in shortening that happened during a warmer period in the second week of January 2016, when uncharacteristically high daytime maximum temperatures of around 10°C were recorded around London. Conversely, there was an increase in shortening during a particularly cold period in mid-February 2017, when the maximum recorded temperature was around 2°C.
An inspection of the mechanical axial displacement estimated from the data, shows that thermal effects can account for around half of the total deformation during temperature extremes. An example of this is shown in Figure 4.3 for column C9. This can have unexpected consequences

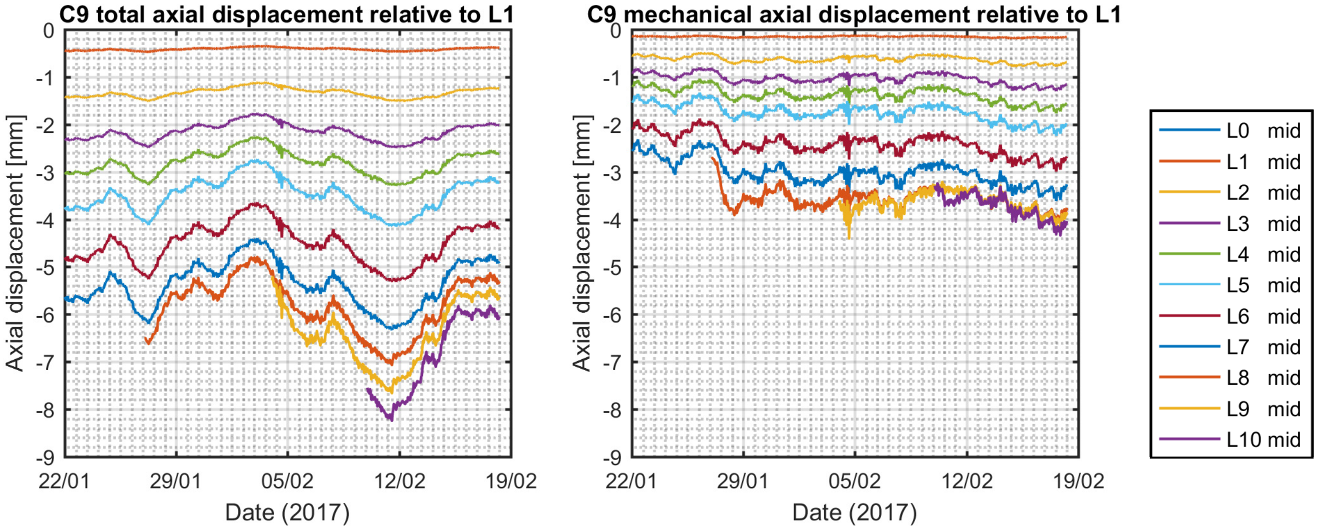

**Figure 4.3. Data extract from a four week period during January and February 2017, showing the total axial displacement (left) and the mechanical axial displacement, i.e., excluding thermal effects (right), of column C9.**

when using shortening estimates to pre-set column heights, particularly when concreting during hot or cold periods, since these estimates do not normally account for such transient thermal effects.

*Effect of abrupt loading*

Since the monitoring system is recording data continuously, it is possibly to capture events which cannot be observed with periodic or occasional measurements. Figure 4.4 shows one such example, where, at around 6pm on 4th November 2016, the cumulative shortening over six levels at wall W1 more than doubled suddenly, going from -1.1 mm to -2.3 mm between one reading and the next. Upon inspection of the construction logs, it became apparent that this one-off event happened when the jumpform rig was locked onto the core, after it had been raised from level 5 to level 6. At this point, the core concrete at level 5 was only one day old. It is likely that the transfer of the load from the jacks onto the locking pins was unusually abrupt close to W1, thus causing the sudden local shortening. Although the shortening started decreasing immediately after this event, about 0.5 mm cumulative residual deformation remained in the wall over the six levels.

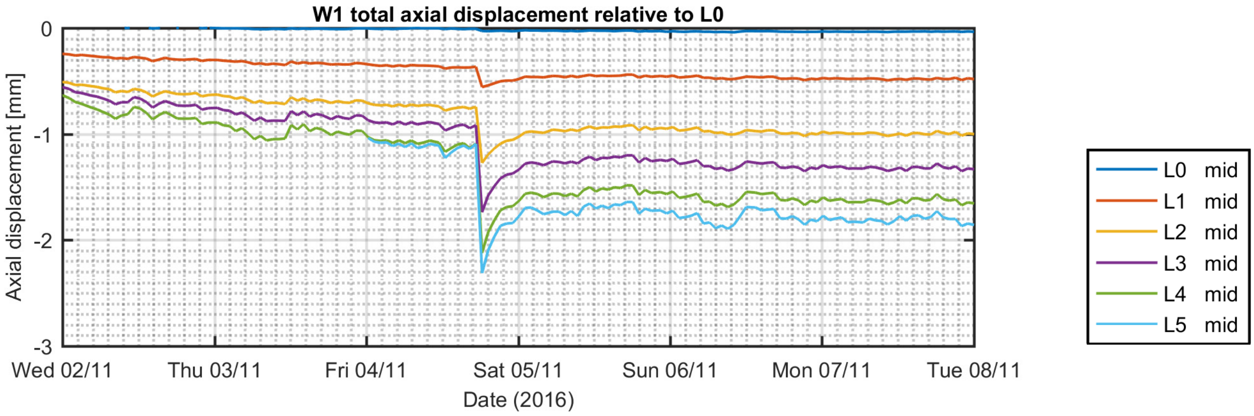

**Figure 4.4. Data extract from six days in November 2016, showing a sudden increase in the shortening (negative displacement) of wall W1.**

## 5. Conclusion

Axial shortening is an important aspect of the design and construction of tall buildings. The combined effect of elastic and inelastic shortening of individual load-bearing columns and walls needs to be accounted for in advance, during construction. However, predictions of the time-dependent shortening of concrete elements are notoriously inaccurate as they try to account for the interaction between several parameters; it is not uncommon for these predictions to be quoted with a margin of error in the region of 60%.

Therefore, it is imperative that construction does not rely on shortening predictions alone, but that contractors also measure the actual shortening as construction progresses, so that the predictions can be adjusted accordingly if necessary. This is commonly done by means of manual measurements using surveying techniques, which are typically taken once every few weeks or months, and only at a small selection of levels. These measurements are therefore of limited use.

In this paper, a novel monitoring system for continuously monitoring the axial displacement along the whole height of a reinforced concrete tall building, as it is being constructed, has been presented. The system uses distributed fibre optic sensor (DFOS) cables, which are embedded in the concrete at selected columns and walls, as the construction progresses. At the same time, a fibre optic Brillouin spectrum analyser measures the strain and temperature along the DFOS cables. The data are post-processed to obtain the axial displacement profile along the whole height of the instrumented elements, at any point in time.

This system is being installed at Principal Tower to monitor two columns and two core walls. The data that have been acquired so far, provided the displacement time histories of the instrumented elements with unprecedented detail. These have shown how an element's shortening is affected by its profile and stiffness, with smaller and less stiff elements shortening more.

The continuous data have also shown that transient thermal effects can play a significant role in axial shortening, at times accounting for as much as 50% of the total deformation. This is a particularly important observation, in light of the fact that shortening predictions prior to construction do not take into account such thermal effects. Another advantage of having a continuous monitoring system is that it is possible to observe occasional and unexpected events. This has been illustrated with an example where the monitoring system picked up a sudden increase in shortening in one of the walls, most likely arising from an abrupt load transfer of the jumpform rig from the jacks onto the locking pins.

Even from the small selection of data that has been presented in this paper, it can be seen that a DFOS-based continuous axial shortening monitoring system can be very beneficial to contractors and design engineers during the construction of tall buildings. It is envisaged that systems similar to the one deployed at Principal Tower will be used in other tall buildings in the near future.

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The data presented in this paper can be obtained from https://doi.org/10.17863/CAM.10423

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