Slab deflections

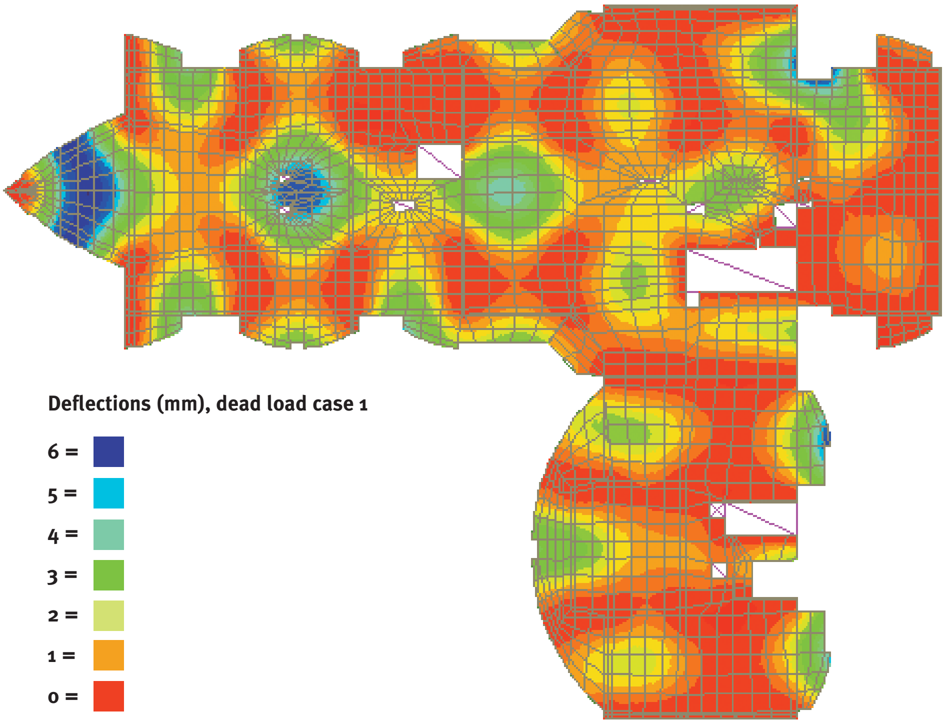


Figure 1: Lusas deflection prediction output for a prow end of St George Wharf

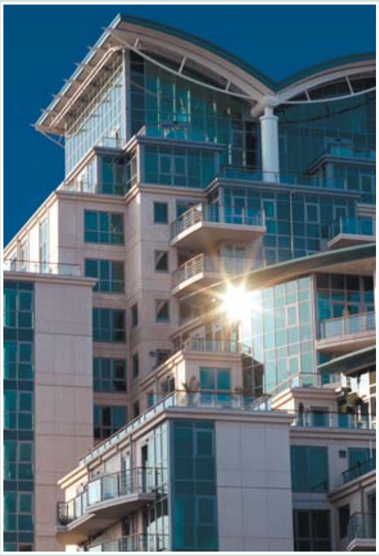
In most cases adequate control of deflections may be achieved by complying with specified span/depth ratios. However there are some situations where they should be calculated in order to comply with tolerances concerning cladding and partitions.

Key Points

This Case Study discusses experiences of predicting and measuring actual deflections in reinforced concrete flat slabs.

- Prediction of deflections in two-way spanning systems is not straightforward and deflections may not be easy to calculate without computer aided analysis.
- Deflections and the times at which they occur should be considered in conjunction with the limits associated with them. In general, deflections need to be considered both before and after installation of cladding and partitions.
- Early age construction loading can have a significant impact on deflections as a result of induced cracking. Appropriate modelling of cracking behaviour is therefore essential if realistic deflections are to be predicted.
- The sensitivity of the predicted deflections to the assumptions made, particularly the tensile strength of the concrete, should be assessed and the likely error bounds determined. Past experience suggests typical error bounds for deflection calculated to be +0/–30% arising from conservative assumptions about material properties.

St George Wharf Case Study



Introduction

The European Concrete Building Project at Cardington was a joint initiative aimed at improving the performance of the concrete frame industry. It led to the preparation of a series of Best Practice Guides, giving recommendations for improving the process of constructing in-situ concrete frame buildings.

As part of a programme to disseminate and apply what has been learnt from Cardington, BRE has subsequently worked directly with those involved in St George Wharf, a high-profile, 100,000 m^2 mixed-use phased development on the River Thames.

BRE worked jointly with the developers, St George (South London), their engineers, White Young Green, and specialist concrete contractors, Stephenson, to develop and implement process improvements tailored to the St George Wharf site.

This work has led to a series of innovations being trialled, the results of which are summarised in this series of Best Practice Case Studies.

Introduction

Adequate control of deflections can usually be achieved for in-situ reinforced concrete beams and slabs by compliance with specified span/depth ratios. However, as flat slab structures become more slender, serviceability is increasingly governing their design. This publication is concerned with situations where prediction of deflections is considered desirable or is a specific requirement.

As for many similar developments, the specific issues in relation to deflections for the St George Wharf development were:

- The influence of deflections on internal partitions and the required allowance for these.
- The tolerances on the precast cladding fixed around the perimeter of the structure.

A further issue, which is becoming increasingly important, is the influence of early age loading, as there is a desire to speed up the floor cycle. In-situ reinforced concrete structures can be subject to significant loads during construction. This results from the need to support freshly cast slabs above those already constructed, and for the construction to support its self-weight when struck. In many cases, construction loads from casting the slab above will be greater than service loads and will govern long-term slab deflections.

Since precast cladding is normally manufactured to fixed dimensions, it is generally the deflection of the slab relative to the supports around the perimeter, both before and after installation, that is of particular interest.

In contrast, with internal partitions, it is generally the deflections subsequent to their installation which are of most interest because the internal partitions can be adjusted to fit the dimensions at the time of installation. Since partitions can in theory be installed in any location at any stage after construction it is prudent to calculate deflections for this purpose at the positions where maximum deflections are likely to occur (i.e. at the centre of a bay). A worst-case load history should be assumed, which could involve less early age loading so that greater deflection occurs at a later stage.

The load history of the slab cannot be predicted precisely but, in practice, reasonable assumptions may be made, based on likely construction sequence and accepted values for additional construction loads. The magnitude of deflections depends on both the level and duration of loading and concrete strength at the time of loading. Ideally, designers need to consider both the influence of the likely tensile strength of the concrete at key stages in the construction process and the influence of the load history on creep.

Curvature in reinforced concrete flat slabs in flexure lies between that of an uncracked and a fully cracked section. In practice some cracking will be anticipated in flat slabs and this will vary, depending on the location and load history. For this reason the most thorough approaches involve integrating curvatures at different positions in different directions across the slab, based on predicted levels of cracking. In practice an iterative process may be required to arrive at the extent of cracking at a particular location.

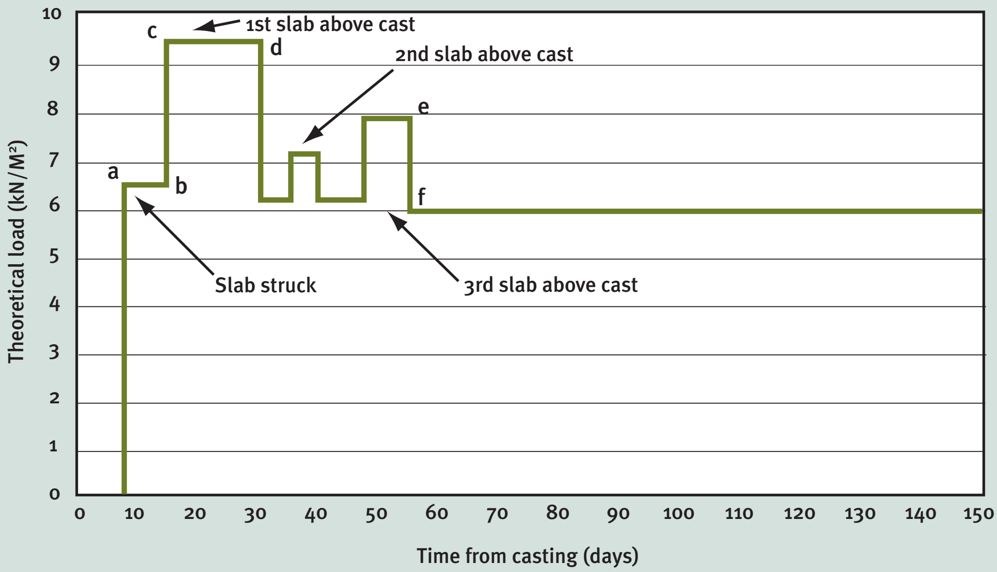


Figure 2: Typical load history for slabs at St George Wharf

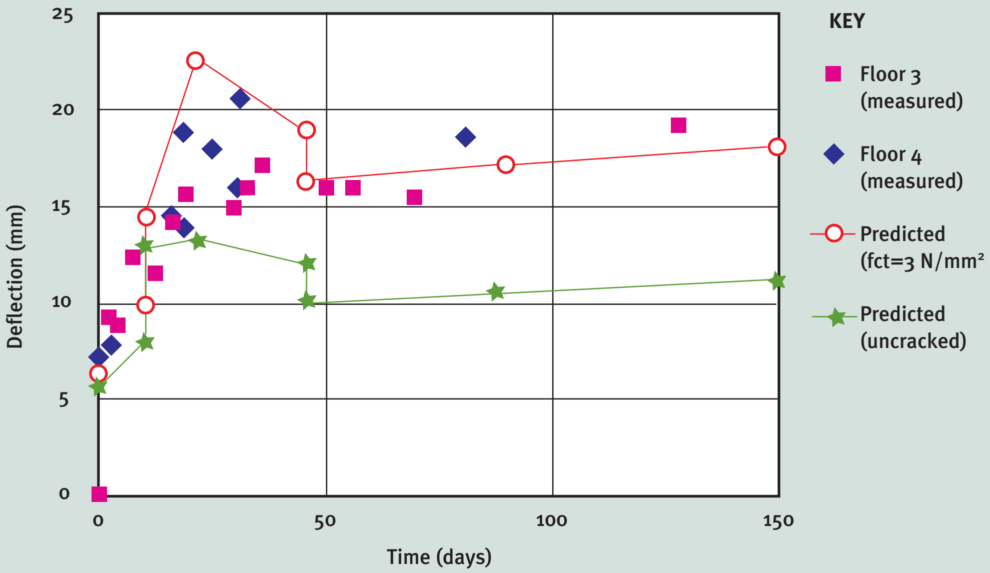


Figure 3: Maximum deflections at St George Wharf

Construction loading

Figure 2 shows a typical load history for the slabs at St George Wharf. Here the forces in the two levels of backprops used were measured. It can be seen that the slab carried its self-weight when struck and the peak load occurred when the slab above was cast. For load histories similar to that in Figure 2, the theoretical peak construction load is given by:

$$w_{peak} = w_{self} + w_{form} + c(w_{self} + w_{con}) \quad .\ .\ .\ .\ 1$$

Where

w_{peak} = peak construction load

w_{self} = self weight of slab e.g. 6 kN/m² for a 250 mm thick slab

w_{form} = weight of formwork (a value of 0.5 kN/m2 is normally taken).

c is a carry through factor of at least 1/(number of supporting floors)

w_{con} is a construction load comprising formwork etc. (a value between 0.75 and 1.5 kN/m^2 is reasonable)

This applies to situations where:

- The most recently cast slab carries its self-weight after striking;
- Flying form systems are used so that the formwork load is applied before any backpropping is installed; but,
- Backpropping is installed prior to any other significant construction loads.

Based on measurements in prop forces at Cardington and assuming little significant pre-load, Beeby [1] showed that the peak construction load occurred in the top slab of the supporting assembly when the slab above was cast. Beeby's work shows that it is conservative to take c as 0.7 provided there is at least one level of backpropping. The value of c will be lower if the backprops are preloaded but it is difficult to be sure of the amount of preload achieved in practice.

There are some other interesting points to note in Figure 2. The first is the duration for which the peak loads have been sustained. The second is the effect of preload in the backprops. Preloading has reduced the initial peak construction load when constructing the slab directly above, and because two levels of backpropping were used, the theoretical peak load when constructing the third slab above was actually higher than when constructing the second.

Methods of deflection prediction

Current advice for predicting deflections is given in References 2 and 3.

Deflections can be estimated in flat slabs by the judicious adding of deflections in beam strips spanning in orthogonal directions.
The main limitations of this approach are:

- The method may be applicable only to structures with rectangular grids.
- Deflections are sensitive to column moments that are not accurately predicted by equivalent frame analysis.
- It is not possible to model the effect of variation in moment across the width of beam strips.

For this reason the best method for predicting slab deflections in two way spanning systems may be finite element analysis. The simplest approach is to carry out an elastic analysis in which the elastic modulus is reduced to account for the effects of cracking, creep and shrinkage. The effect of creep can be taken into account in deflection calculations using
a method known as the effective modulus method: an effective concrete elastic modulus $E_{composite}$ can be used to account for the different ages at which loads are applied and their duration.

$$E_{composite} = \Sigma w_i / \Sigma(w_i / E_{ceffi}) \quad \ldots\ldots\ldots 2$$

Where

$$E_{ceffi} = E_c / (1+\phi_i)$$

i denotes the load increment.

For flat slabs subjected to a construction load history similar to that in Figure 2, Vollum [4] has shown that the combined effect of cracking and shrinkage increases deflections in flat slabs by a factor of around 2.

The superposition of creep coefficients to obtain overall creep effects can become quite complicated. For load histories similar to those shown in Figure 2, a conservative approach is to use a reduced elastic modulus to account for the effects of creep, shrinkage and cracking combined. The corresponding reduced elastic moduli are virtually independent of slab thickness. For a typical 250 mm slab the reduced elastic moduli are:

4.1 kN/mm^2 for a concrete cylinder/cube strength of C30/37

5.1 kN/mm^2 for a strength of C40/50

6.0 kN/mm^2 for a strength of C50/60

These values should be used in conjunction with a maximum loading of w_{perm} as defined below to arrive at total deflections.

There are various components of load that generate long-term deflection. The influence of short-term construction load on long-term deflection may be assumed to be adequately covered using the methods above. In practice most structures only ever experience a proportion of the imposed load. For this reason the total deflection in the context of, for example, assessing precast cladding fit is probably best estimated as a_{perm}. This is the deflection calculated under the influence of the total dead load plus a proportion of the imposed load (typically 30%). This combined load can be defined as w_{perm}.

For the purposes of assessing deflections of partitions, which can be cut to fit on installation, it is the subsequent deflections that are of primary interest. Based on research at Cardington, Vollum recommends that this deflection δ_a can be estimated from:

$$\delta_a = a_{perm}(1 - 0.55 w_{self} / w_{perm}) \quad \ldots\ldots\ldots 3$$

Where w_{self} is the self-weight of the slab only. More accurate estimates of deflection can be obtained using cracked section analysis, which can be carried out on a number of commercially available finite element packages.

Prediction of deflections at St George Wharf

Deflections were predicted initially at St George Wharf using various methods based on finite element analysis [4]. The designer, White Young Green, used Lusas Finite Element software to carry out an elastic analysis to estimate slab deflections (an example is illustrated in Figure 1). The elastic modulus was reduced to account for creep but no reduction was made for cracking. Consequently, the predicted deflections were significantly less than those measured in the structure.

Deflections were also predicted at stages a to f in Figure 2 using a non-linear finite element programme developed at Imperial College. This is shown in Figure 3. The effect of construction loading was included in the analysis.

Measurements of construction loading and deflection

An extensive programme of deflection measurements was undertaken. The deflections were measured using simple levelling equipment, which worked well within the limits of accuracy obtainable using such techniques (typically +/–1 mm). Deflections were typically measured before and after striking and before and after application of peak construction loads. Tests were carried out to establish the creep and shrinkage characteristics of the concrete.

Findings

A set of measurements taken at the prow end of the St George Wharf development has provided the following insights.

1. The predicted deflections from the Imperial College non-linear finite element analysis compared well with the measured deflections as shown in Figure 3 and were significantly greater than those originally predicted, which neglected cracking. Figure 3 also shows that predictions based on an uncracked section can significantly underestimate self-weight deflections.
2. Care should be taken to ensure that boundary constraints are accurately modelled in deflection calculations. Columns are best modelled with three-dimensional 'brick' elements in finite element analyses.

3. Cracking was observed at soffit locations and in the tops of the slabs over columns.
4. The cracking observed appears to be more extensive than at Cardington. This may be due to the actual concrete strengths achieved on this project being closer to the nominal design strength, resulting in the cracking moment being exceeded by a greater margin and at more locations. The cracks may also be more visible due to the reduced floor to ceiling heights.
5. Despite deflections having been larger than originally predicted, this is not believed to have caused problems.
6. Based on the information collected the developer intends to review the need for complicated deflection head details on future phases of the project.

Conclusions

1. Serviceability issues, particularly deflections and vibrations, are becoming increasingly important with the move towards longer span, more slender, reinforced concrete flat slab structures.
2. Reliance on span/depth ratios may be insufficient, particularly if deflection limits are specified for particular items such as cladding and partitions. Furthermore, better knowledge of deflections on site has the potential to provide economy in specifying items such as deflection head details and the movements that they must accommodate.
3. Prediction of deflections in two-way spanning systems is not straightforward and may require finite element analysis.
4. The limitations of standard finite element software based on linear elastic analysis for predicting deflections should be recognised, particularly its sensitivity to the assumed material properties and the difficulty in accurately representing the effects of cracking.

Recommendations

1. In general span/depth ratios may continue to be used as a satisfactory method of controlling deflections.
2. If deflections are to be predicted then, as found at Cardington, the designer should be aware that slab deflections can be increased significantly by cracking induced by construction loading. If the deflections are not to be underestimated, such cracking must be allowed for when predicting deflections.
3. The effect of peak construction loads should ideally be considered at the design stage when considering both the serviceability and ultimate limit states. This is because slabs are subject to peak construction loads, which tend to govern long-term deflections and can theoretically be close to the design ultimate load of slabs designed for domestic loading.
4. Where deflections are likely to be an issue and reliance on span/depth ratios is not deemed sufficient, the modelling employed should ideally be sophisticated enough to allow the sensitivity of predicted deflections to the age, magnitude and duration of the construction loads to be assessed.

The work undertaken and the conclusions reached in relation to the innovations described above should be viewed in the context of the particular project on which the innovations have been trialled.

This Case Study is underpinned by a full report [4] giving the background and further information on the work undertaken.

References

1. *Early striking of formwork and forces in backprops* by A. W. Beeby, BRE Report 394. Published by Construction Research Communications, London, 2000.
2. *Deflections in concrete slabs and beams.* The Concrete Society. A joint report from BCA, The Concrete Society and RCC, 2003.
3. *Approaches to the design of reinforced concrete flat slabs* by R. Moss. BRE Report 422. Published by Construction Research Communications, London, 2001.
4. *Backprop forces and deflections in flat slabs: construction at St George Wharf* by R. Vollum. BRE Report BR463, 2004.

Acknowledgements

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The Best Practice Guide, *Flat slabs for efficient concrete construction,* summarises work carried out on these topics during the construction of the in-situ concrete building at Cardington. This can be downloaded free from the Downloads section of The Concrete Centre's website at **www.concretecentre.com** and at **http://projects.bre.co.uk/ConDiv/concrete%20frame/default.htm**

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