Slab deflections

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 by hand.
- 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 error bounds typically +0/-30% in the calculated deflection resulting from conservative assumptions about material properties.
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 governed by their deflection. 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 weight of 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 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 importance 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 skipping over the backprops 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 influence 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. For practice an iterative process may be required to arrive at the extent of cracking at a particular location.

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 which 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 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 

\[ E_{\text{composite}} \] can be used to account for the different ages at which loads are applied and their duration. 

\[ E_{\text{composite}} = \frac{2E_0}{E_0 + E_0'} \] 

Where 

\[ E_0 = E_c (1+\alpha) \] 

\[ \alpha \] denotes the load increment.

For flat slabs subjected to a construction load history similar to that in Figure 2, Vollem [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 complex. 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 modulus are virtually independent of slab thickness for a typical 250 mm slab, the reduced elastic moduli are:

• 4.1 kN/mm² for a concrete cylinder/cube strength of C30/37
• 5.1 kN/mm² for a strength of C40/50
• 6.0 kN/mm² for a strength of C50/60

These values should be used in conjunction with a maximum loading of \[ w_{\text{perm}} \] 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 perim This is the deflection calculated under the influence of the total dead load plus a proportion of the imposed load (typically 95%). This combined load can be defined as \[ w_{\text{perm}} \].

For the purposes of assessing deflections of precast elements which can be cut to fit on installation, it is the subsequent deflections that are of primary interest. Based on research up to its following, this paper recommends that this deflection \( d_{\text{t}} \) can be estimated from:

\[ d_{\text{t}} = \frac{w_{\text{perm}} - 0.55w_{\text{f}}}{E_{\text{composite}}} \] 

Where \( w_{\text{f}} \) 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 (a typical slab is illustrated in Figure 2). 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. 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 \( w_{\text{f}} \)). 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 development have 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 lower than those originally predicted, which neglected cracking. Figure 3 also shows that predictions based on an uncropped 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 often modelled with three-dimensional ‘brick’ elements in finite element analyses.
6. Based on the information collected the deflections observed appear to be more extensive than at Cardington. This may be due to the more typical concrete strengths achieved on this project 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.

4. The cracking observed appears to be more widespread than at Cardington. The reduced floor to ceiling heights may have increased the sensitivity of predicted deflections to the age, magnitude and duration of the construction loads to be assessed.

3. Cracking was observed at soffit locations and on the tops of the slabs over columns. This may be due to the more typical concrete strengths achieved on this project 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. Furthermore, better knowledge of deflections on site has the potential to provide economy in specifying items such as cladding and partitions. Furthermore, it is hoped that these studies will continue to be used as a satisfactory method of controlling deflections.

2. If deflections are to be predicted, then the deflections observed at Cardington should be used as a satisfactory method of controlling deflections. The limitations of standard finite element analysis as the only viable option.

1. In general 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. Furthermore, better knowledge of deflections on site has the potential to provide economy in specifying items such as cladding and partitions. In addition, it is hoped that these studies will continue to be used as a satisfactory method of controlling deflections. 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. Furthermore, better knowledge of deflections on site has the potential to provide economy in specifying items such as cladding and partitions. In addition, it is hoped that these studies will continue to be used as a satisfactory method of controlling deflections.

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, it is hoped that these studies will continue to be used as a satisfactory method of controlling deflections.

3. Prediction of deflections in two-way spanning systems is not straightforward and may not be easy to calculate by hand, leaving finite element analysis as the only viable option.

4. The limitations of standard finite element analysis 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 noted 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 with 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.

Acknowledgements

The support of the DTI for this project under the Partners in Innovation scheme is gratefully acknowledged.

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

References


Case Studies in this series of applying best practice:

• St George Wharf project overview
• Early age concrete strength assessment
• Early age construction loading
• Reinforcement rationalisation and supply
• Slab deflections
• Special concretes

Ref TCC/03/06
First published 2004
Price group A
ISBN 1-904818-06-4
© The Concrete Centre 2004
Published by The Concrete Centre on behalf of the project partners.
www.concretecentre.com,
For further copies of these Best Practice Case Studies contact
www.concretebookshop.com

All advice or information from The Concrete Centre is intended for those who will evaluate the significance and limitations of its contents and take responsibility for its use and application. No liability (including that for negligence) for any loss resulting from such advice or information is accepted. Readers should note that all Centre publications are subject to revision from time to time and should therefore ensure that they are in possession of the latest version.