The results from both Leeds and Durham showed that tension stress in the concrete in the tension specimens reached a roughly constant level in a period ranging from about 6 hours to 30 days. In the slab specimens the time period was about 10 to 30 days which fitted well with the tension test results since, on average for all the specimens, the steady state level was reached after about 20 days. Thus, the most immediate practical result from the test programme was that it was found that, unlike creep and shrinkage which develop slowly over a period of years, tension stiffening reduces from its instantaneous value to a steady state long term value in a much shorter period. This is illustrated in Figure 5 for a tension specimen with a 16 mm diameter (No. 5) rebar which had three increments of loading giving *nominal* stresses of 237, 314 and 381 MPa (approx. 34400, 45600 and 55300 psi) in the steel and 3, 4, 5 MPa (approx 435, 580, 725 psi) in the concrete for load stages of 43.9, 58.0 and 70.6 kN (approx 9.9, 13.0 and 15.8 kip) respectively. This Figure also indicates that loss of tension stiffening was largely independent of the load level applied to the specimen.

The initial decay of tension stiffening could be very rapid indeed as indicated in Figure 6 for a similar tension specimen but this time with a 20 mm diameter (No. 6) rebar. It was also shown that there is no recovery of tension stiffening when load is removed. Consequently, repeated short term loads (i.e. less than a day) will lead to a reduction similar to that for a longer term load and overloading during the life of a structure (e.g. during construction) will leave a member with only the long term tension stiffening effects.

A practical significance of rapid tension stiffening loss arises from the requirement that the long term increment in deflection occurring after installation of finishes and partitions should be limited, typically, to span/500. This criterion is often the critical one in slab design rather than the limitation on the total deflection. The current calculation procedure is to assume that the short term value of tension stiffening applies at the time of installation of finishes and partitions and that this reduces to the long term value over the lifetime of the structure. The research findings summarised above suggest that, assuming the slab has been supporting its dead weight and construction loads for some weeks, or possibly months, before the finishes and partitions are finally installed, the long term values of tension stiffening will have already become established. This will result in a significantly smaller calculated increment in deflection after installation. The total deflection will not be significantly changed; the calculated short term deflection will simply be rather larger and the long term deflection smaller than in current calculations. The result may, however, result in significant economies in some cases.

POSSIBLE MODIFICATIONS TO DESIGN CODES AND FURTHER WORK

Since it was shown that loss of tension stiffening occurs over a period which is short term in contrast to creep, there is scope for possible modifications to the design codes. With BS8110 this is straightforward at it is only necessary to use $f^* = 0.55$ MPa (80 psi) (see Figure 2) for both short and long term loadings. Eurocode 2 could be modified by using $\beta = 0.5$ for both loading situations. ACI 318 would be more difficult to modify since long term deflection is calculated by multiplying the short term value by the factor λ (see Equation 3) and the tests showed that it can be difficult to differentiate between short and long term deformations. In addition, λ combines the effects of creep, shrinkage and tension stiffening thus considerable redrafting may be required if the ACI 318 provisions are to reflect tension stiffening explicitly. There is scope for further work to fully validate these recommendations.

Interest in tension stiffening is still high. Of particular interest are the effects of shrinkage and research in this area is on-going. An additional area of research is the effects of bar diameter. Most tests to date, including those of the authors, have been confined to bars with a maximum diameter of 20 or 25 mm (No. 6 or No. 8 rebars) and little work has been done with bar diameters in excess of these. This problem is currently being addressed at Durham where a test programme using tension specimens containing rebars up to 50 mm diameter (No. 16), the largest available in the UK, is currently in progress. *Preliminary* indications from this work are that tension stiffening reduces even more quickly when these large diameter bars are used, as summarised in Figure 7. It is hoped that further results will be presented at the convention.

CONCLUSIONS

Much work has been undertaken over very many years to investigate and quantify tension stiffening and this is reflected in the relatively sophisticated approaches for the calculation of deflections currently proposed by the major design codes. Recent research has suggested some updating of these approaches may be appropriate and further research is in progress which hopefully, in due course, will lead to further refinements.

The treatment of tension stiffening is still very much a live issue and is likely to remain so for the foreseeable future in view of its fundamental influence on the service load performance of reinforced concrete beams and slabs.

ACKNOWLEDGEMENTS

The experimental described in this paper was funded by the Engineering and Physical Sciences Research Council (EPSRC) in the UK. The assistance of Mr Ian Wenkenbach with the large diameter rebar tests is gratefully acknowledged.

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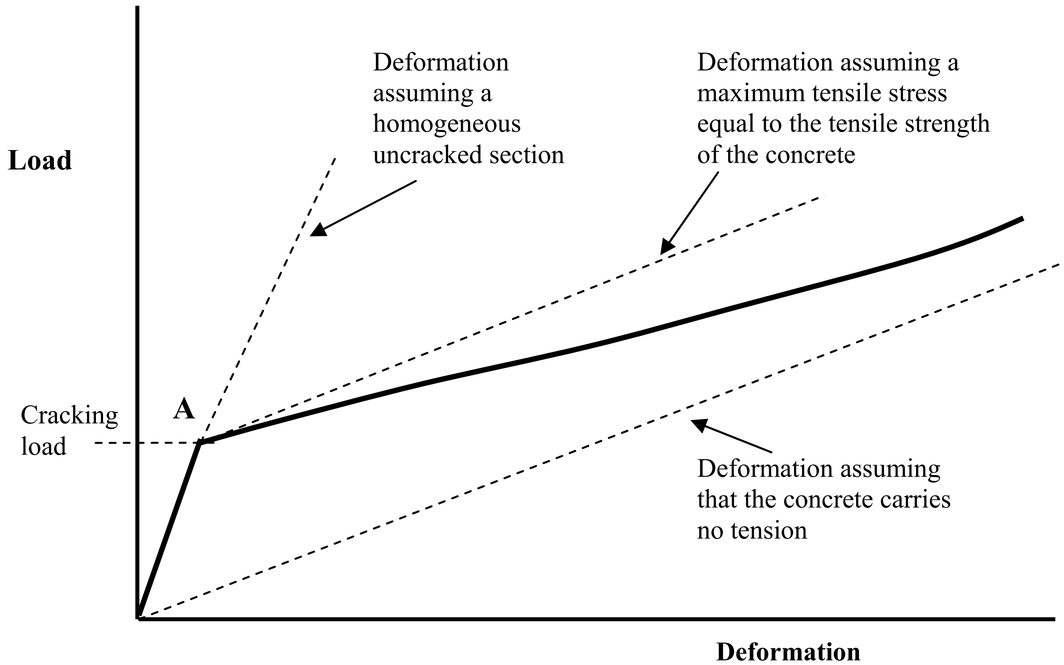

Fig.1 – Schematic Load-Deformation Response

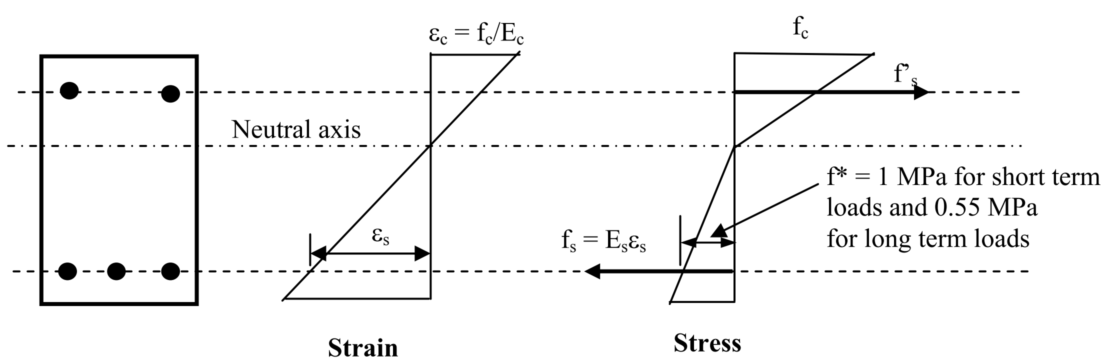

Fig.2 – Assumptions in BS8110 for the Stresses and Strains in Cracked Sections

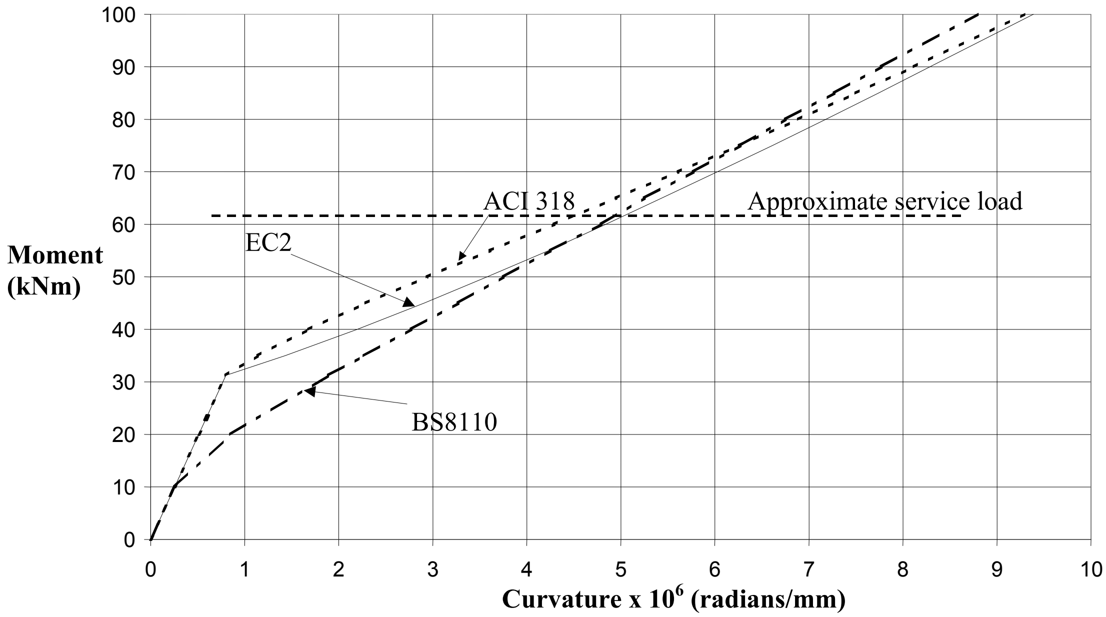

Fig. 3 – Comparison of Code Methods for a Slab with 0.5% Reinforcement

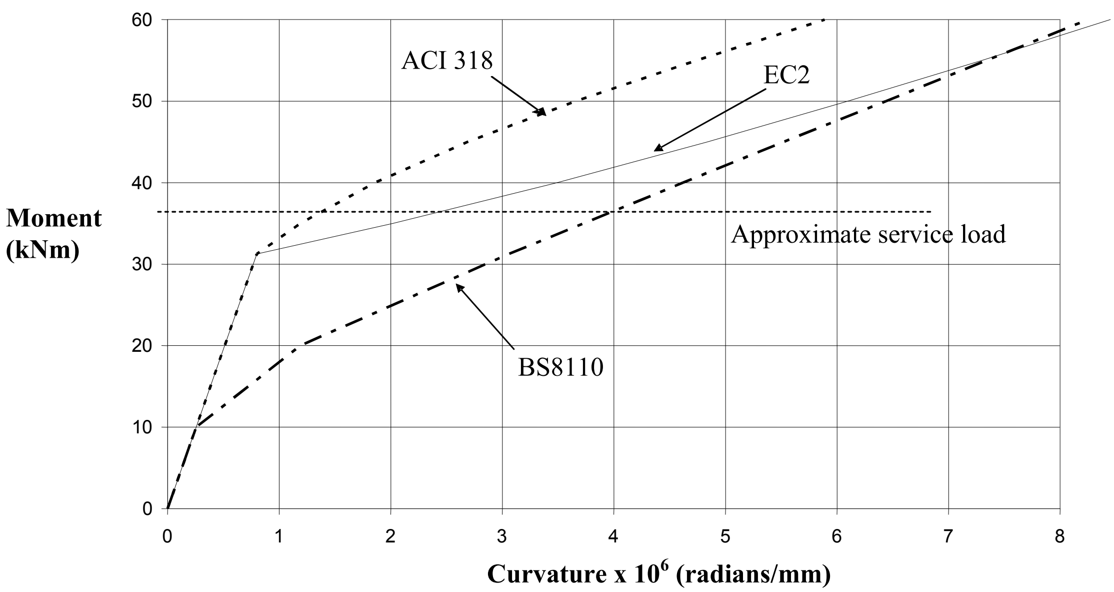

Fig. 4 – Comparison of Code Methods for a Slab with 0.25% Reinforcement

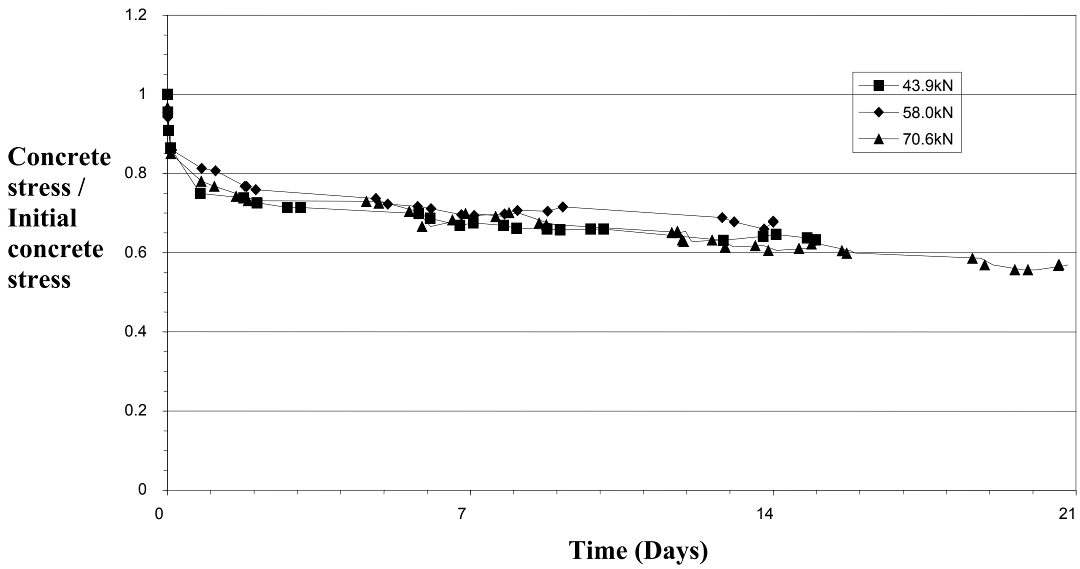

Fig. 5 – Comparison of Decay rates of Concrete Tensile Stress (16 mm Rebar in 120x120 mm Section)

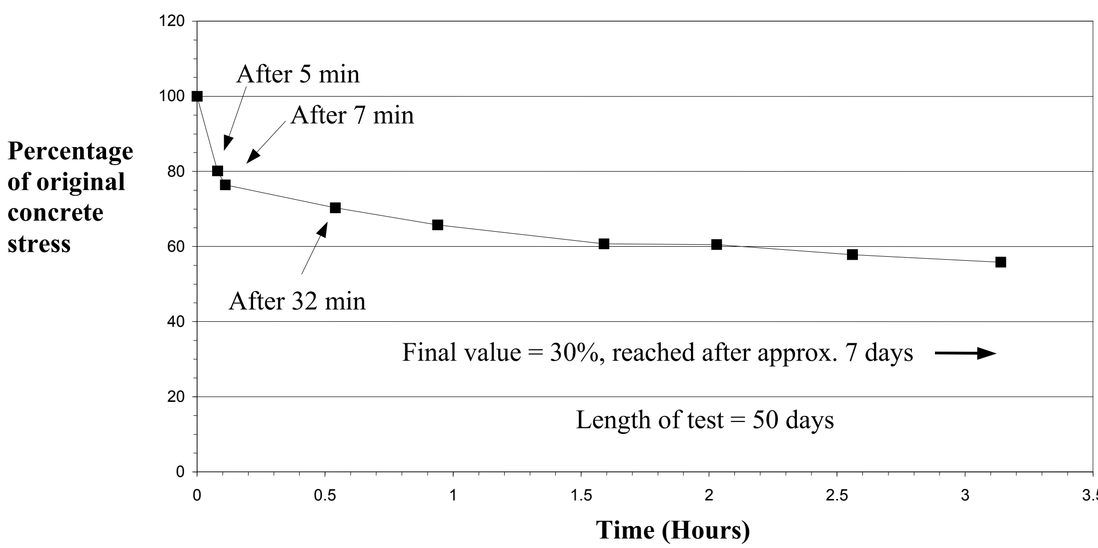

Fig. 6 – Initial Decay of Concrete Stress (20 mm Rebar in 120x120 mm Section)

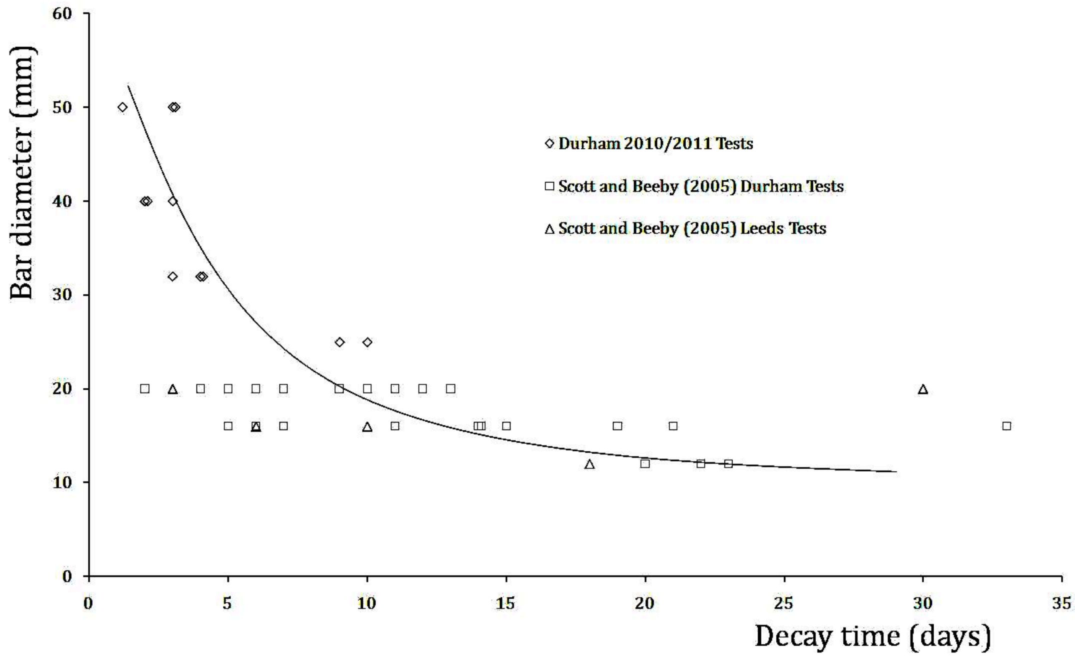

Fig. 7 – Influence of Bar Diameter on Decay of Tension Stiffening

Creep and Shrinkage Induced Deflections in RC Beams and Slabs

R. I. Gilbert

Synopsis: The effects of creep and shrinkage on the time-dependent behavior of reinforced concrete flexural members are discussed and a procedure for the prediction of the long-term deflection of reinforced concrete beams and slabs is presented. The time-dependent deformations caused by creep and shrinkage are modeled using tractable formulations developed using the age-adjusted effective modulus method of analysis. The procedure includes the time varying nature of tension stiffening and the effects of time-dependent shrinkage-induce cracking. Sample calculations are provided. The method is validated against a wide range of test data and is shown to provide reliable estimates of in-service deformations.

Keywords: cracking; creep; curvature; deflection; serviceability; shrinkage; tension stiffening; time-dependent

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INTRODUCTION

The broad design objective for a concrete structure is that it should satisfy the needs for which it was contrived. In doing so, the structural designer must ensure that it is both safe and serviceable, so that the chances of it failing during its design lifetime are sufficiently small. The two primary structural design objectives are therefore *strength* and *serviceability*.

Modern design codes for structures have adopted the *limit states method* of design, whereby a structure must be designed to simultaneously satisfy a number of different *limit states* or design requirements, including adequate strength and serviceability. Minimum performance limits are specified for each of these limit states and any one may become critical and govern the design of a particular member. For each limit state, codes of practice specify both load combinations and methods of predicting the actual structural performance that together ensure an acceptably low probability of failure.

In order to satisfy the serviceability limit states, a concrete structure must be serviceable and perform its intended function throughout its working life. Excessive deflection should not impair the function of the structure or be aesthetically unacceptable. Cracks should not be unsightly or wide enough to lead to durability problems and vibration should not cause distress to the structure or discomfort to its occupants.

In this paper, the effects of creep and shrinkage on the deflection and cracking of reinforced concrete beams and slabs are discussed and quantified. A procedure for the prediction of the long-term deflection of reinforced concrete beams and slabs is presented. The time-dependent deformations caused by creep and shrinkage are modelled using tractable formulations developed using the age-adjusted effective modulus method of analysis. The procedure includes the time varying nature of tension stiffening and the effects of time-dependent shrinkage-induce cracking. Sample calculations are provided. The method is validated against a wide range of test data and is shown to provide reliable estimates of in-service deformations.

EFFECTS OF CRACKING ON CROSS-SECTIONAL RESPONSE

Consider a reinforced concrete element subjected to uniform bending. The average instantaneous moment-curvature response is shown as curve OAB in Fig. 1. At moments less than the cracking moment, M_{cr}, the element is uncracked and the moment-curvature relationship is essentially linear (OA in Fig. 1) with a slope equal to the flexural rigidity of the uncracked transformed section, $E_c I_{uncr}$. When the moment reaches the cracking moment M_{cr} (i.e. when the extreme fiber tensile stress caused by bending and restraint to shrinkage reaches the flexural tensile strength, $f_{ct.f}$), primary cracks form at reasonably regular centres and the average moment curvature relationship becomes non-linear. When a primary crack develops, there is a sudden change in the local stiffness at and immediately adjacent to each crack. At a section containing a crack, the tensile concrete carries little or no stress, the flexural stiffness drops significantly and the local moment-curvature relationship on a cracked cross-section follows the dashed lines AA′C (when $M \geq M_{cr}$) in Fig. 1. The slope of line A′C is equal to the flexural rigidity of the cracked transformed cross-section, $E_c I_{cr}$.