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Some remarks on the interaction of long-term effects in deflections of RC members

Carlos Zanuy *

Department of Continuum Mechanics and Structures, E.T.S. Ingenieros de Caminos, Canales y Puertos, Universidad Politécnica de Madrid, Madrid, Spain

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ABSTRACT

Serviceability requirements of concrete structures establish the limitation of deflections. Even though the exact prediction of deflections is a difficult task that is neither necessary nor possible, the assumptions of codes of practice to consider time- and cycle-dependent effects of reinforced concrete are conceptually questionable. A common rule is that both sustained and repeated loading result in a reduction of the tension stiffening contribution. Nevertheless, the cyclic behaviour of reinforced concrete is nonlinear and non-symmetrical during unloading and reloading, leading to deformations larger than those corresponding to the fully cracked member during unloading stages. In this paper, an approach is presented to distinguish between time- and cycle-dependent effects. A curvature component is added to the estimation of curvatures so that the cyclic effect can be understood as a different contribution to deflections with respect to creep and shrinkage. The comparison with experimental results indicates that the cyclic component of deformations cannot be neglected.

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1. Introduction

Serviceability criteria for reinforced concrete structures are based on limitations for deflections, crack widths, stresses or strains. Prediction of deflections in real structures is a complex task due to the uncertainties of relevant parameters (shrinkage, creep, temperature), but also to the real load history of the structure. Besides dead loads, civil engineering structures are commonly subjected to cyclic loads due to traffic, wind or waves. Even though the influence of time-dependent effects (creep and shrinkage) or thermal variations has been usually considered at the design stage, the effect of cyclic loads has often been neglected or considered in an oversimplified way. A typical assumption consists of taking linear unloading-reloading behaviour, but reinforced concrete actually behaves nonlinearly and non-symmetrically in unloading-reloading cycles, leading to significant residual deformations. After a load-unload cycle, reinforced concrete hardly returns to the previous situation. Therefore, the permanent state of real structures differs from that obtained in a sustained load test and is a result of previous occurrence of cycles with higher peak loads that can play a significant role in deflections. Even though an exact calculation of deflections is neither necessary nor even possible, it is convenient to put into evidence some incorrect assumptions that may lead to significant mistakes and confusing concepts among practice engineers. Gilbert [1], in a paper with an insightful title, already suggested that oversimplified approaches may lead to non-negligible deviations from actual deflections.

Many works have dealt with the time-dependent behaviour of reinforced concrete [2–8] and some others have focused on cyclic loads [9–11], but the interaction between both effects has not usually been studied, in spite of the fact that it is a relatively common situation of real structures. Moreover, codes of practice do not help practice engineers in understanding such interactions. The Eurocode 2 [12], as many other codes, assumes that the in-service response of reinforced concrete lies somewhere between that given by the uncracked member (state I) and the fully cracked member (state II). Due to the concrete capacity of carrying tensile stresses between cracks (tension stiffening), deformations are considered to be smaller than those given by the state II. Such a behaviour is considered by the Eurocode 2 by means of the following interpolation between states I and II (refer to Fig. 1):

$$\alpha = (1 - \xi)\alpha_I + \xi\alpha_{II} \quad (1)$$

where α is a deformation parameter (deflection, curvature, strain, etc.) and ξ is the following distribution coefficient:

$$\xi = 1 - \beta\left(\frac{M_{cr}}{M}\right)^2 \quad (2)$$

* Address: c/ Profesor Aranguren 3, 28040 Madrid, Spain.
E-mail address: czs@caminos.upm.es

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Nomenclature

A_c	concrete area
A_s	steel area
E_s	steel modulus of elasticity
I	moment of inertia
M	bending moment
M_{cr}	cracking moment
P	load
d	effective depth
$h_{c,eff}$	depth of effective area of concrete in tension
s_r	crack spacing
t	time
t_0	loading time
t_s	curing time
x	compression zone depth
k_{cs}, k_φ	curvature correction coefficients
$\Delta\kappa$	increase of curvature
Φ	diameter of steel reinforcement
α	deformation parameter
ε	strain
ε_{cs}	shrinkage strain
ε_{sm}	mean steel strain
φ	creep coefficient
ξ	distribution coefficient
κ	curvature
ρ	steel reinforcement ratio
σ	stress
$\sigma_{s,II}$	steel stress at the crack
τ	bond stress
τ_f	negative frictional bond stress

Subscripts

$_0$	initial
$_{I,II}$	state I or II
Neg.TS	negative tension stiffening
$_c$	concrete
$_{cs}$	shrinkage
$_m$	mean
$_s$	steel
$_\varphi$	creep

The influence of load history is introduced by parameter β (= 1 for short-term loading, or = 0.5 for sustained or repeated loading). The previous model is based on the monotonic response of reinforced concrete (Fig. 1) and it assumes that tension stiffening reduces due to time- or cycle-dependent effects. The previous assumption may fail in the sense that non-monotonic loads result in the development of deformations larger than those corresponding to the state II (referred to as negative tension stiffening contribution in terms of [13,14]). It seems necessary a review of existing methods to estimate deflections for structures subjected to cyclic loads. In this paper, the component of deformations due to cyclic effects is included separately from time-dependent effects. Even though discussions of this paper are referred to the formulation of the Eurocode 2, a similar development could be made in terms of other formulations.

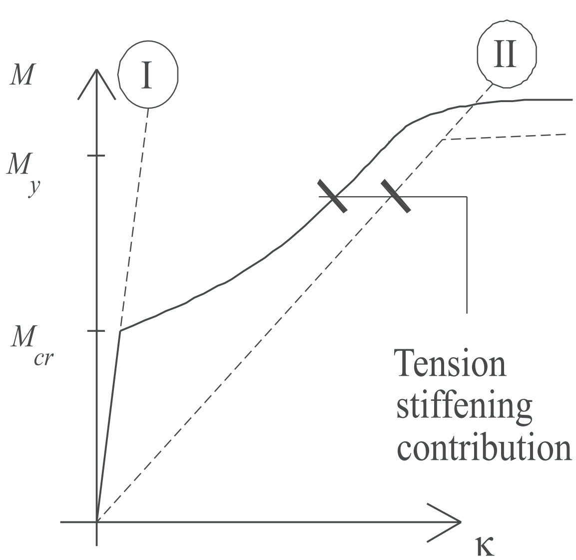

Fig. 1. Moment-curvature diagram of a RC section.

2. In-service behaviour of reinforced concrete

2.1. Time-dependent behaviour

Concrete creep and shrinkage result in increasing deformations of reinforced concrete members. A significant number of variables are involved in the creep coefficient (φ) and the free shrinkage strain (ε_{cs}), and different models have been adopted by codes of practice [12,15,16]. At section level, shrinkage results in the progressive development of a residual curvature, and creep leads to a stiffness reduction. Creep and shrinkage effects can be studied at both states I and II. Deflections can then be obtained by integrating mean curvatures, which in turn are a result of some interpolation between curvatures of states I and II (e.g. according to Eq. (1)). The reduction of the cracking moment due to accumulation of tensile stresses in the concrete, in cases where shrinkage prior to loading has occurred, should also be considered in the interpolation and the distribution coefficient of Eq. (2).

The long-term response of the state I is mainly governed by creep, which can be considered to reduce the concrete modulus of elasticity. Shrinkage can also lead to increasing curvature as a result of the different position of the centroids of the net concrete area and the gross section. In contrast, the long-term behaviour of the state II is governed by both creep and shrinkage, leading to a reduced stiffness of the cracked section and a significant residual curvature. Many models have been published for the last decades to analyze the long-term response of reinforced concrete sections [17,18] and a good way to summarize them can be established by the long-term multipliers of the states I and II [19]. Accordingly, the time-dependent increase of curvature due to shrinkage and creep can be expressed as follows, respectively:

$$\Delta\kappa_{cs} = -\varepsilon_{cs}\frac{k_{cs}}{d} \tag{3}$$

$$\Delta\kappa_{\varphi} = \varphi k_{\varphi}\kappa_0 \tag{4}$$

where κ_0 is the short-term curvature, d is the effective depth, and k_{cs} and k_φ are curvature correction coefficients, which depend on the section dimensions, amount of reinforcement, creep coefficient and free shrinkage strain. The curvature correction coefficients can

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