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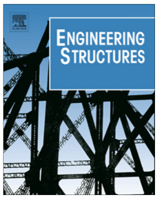

Simplified serviceability design of jointless structures. Experimental verification and application to typical bridge and building structures

Giancarlo Groli [a,c,*], Alejandro Pérez Caldentey [a,b], Alejandro Giraldo Soto [a,b], Francesco Marchetto [a], Javier Ezeberry Parrotta [a]

[a] Polytechnic University of Madrid, Profesor Aranguren, s/n., 28040 Madrid, Spain
[b] FHECOR Consulting Engineers, Barquillo, 23, 2°, 28004 Madrid, Spain
[c] Ferrovial-Agromán, Ribera del Loira, 42, 28042 Madrid, Spain

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ABSTRACT

In this article an experimental campaign aimed at validating a previously published simplified serviceability design method of the columns of long jointless structures is presented. The proposed method is also extended to include tension stiffening effects which proved to be significant in structures with small amount of reinforcement subjected to small axial loading. This extension allows significant improvement of predictions for this type of element. The campaign involved columns with different reinforcement and squashing load ratios, given that these parameters had been identified as crucial when designing columns subjected to imposed displacements. Experimental results are presented and discussed, with particular regard to cracking behaviour and structural stiffness. Considerations on tension stiffening effects are also made. Finally, the application of the method to typical bridge and building cases is presented, showing the feasibility of jointless construction, and the limits which should be respected.

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1. Introduction

When dealing with sustainability in construction, great stress has to be put on the durability of structures. In fact, many RC structures built during the XXth century have failed to show sufficient serviceability standards after few years of construction. One of the reasons for this lack of durability can be found in the use of elastomeric bearings and expansion joints. As already pointed out in [1], their wide use has been based on the idea that it is better to let the structures expand than to resist the forces produced by imposed deformations (temperature, shrinkage, etc.). However, experience has shown that these elements are main culprits in cases of durability problems. Additionally, their cost is often a not negligible part of the cost of the structure.

The growing use of jointless structures has therefore been motivated by the growing concern for durability. Integral structures have been satisfactorily used since the mid XXth century in the US, both for reinforced concrete and composite structures, first in short bridges, and lately reaching remarkable lengths (up to 100 m, as reported in [2]). More recently, the British Department of Transport has published *Design for durability* documents [3], encouraging the use of jointless structures, and even forbidding midspan joints.

The problem of imposed deformations on concrete structures has been studied by many researchers from the experimental [4,5] and from the theoretical [6–11] points of view. However none of these references include a method which can be easily applied in everyday engineering practice. As a contribution to overcome the difficulties involved in designing the columns of long jointless structures taking into account the non-linearity provided by cracking of RC, a simplified method has been proposed by Pérez et al. [1] and Ezeberry [10].

In order to validate this method and explore other aspects concerning design (such as cracking), a specific experimental campaign has been undertaken. The experimental program involved four columns made of conventional concrete ($f_{cm} \approx 38$ MPa), conventional reinforcement (B-500 steel), with different levels of axial force (30% and 80% of the squashing load) and reinforcing bar diameters (Ø12 mm and Ø25 mm. These columns were designed to represent a part of a jointless building. The columns were subjected to contemporised action of horizontal and vertical forces from the fictitious structure. The horizontal force was applied by hydraulic jack, whereas the vertical action was simulated by prestress of internal rebars.

After validation through experimentation, the simplified method mentioned above is used to compile an application guide aimed at providing designers with an order of magnitude of the jointless

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[*] Corresponding author at: Polytechnic University of Madrid, Profesor Aranguren, s/n., 28040 Madrid, Spain. Tel.: +34 654 28 90 18.
E-mail address: ggr@he-upm.com (G. Groli).

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Nomenclature

ε_s	tensile strain of steel
ε_{sh}	shrinkage strain
ε_{sr}	state II analysis strain in steel for the cracking moment
Ø	bar diameter
Λ	normalized displacement
υ	squashing load ratio
χ	curvature
ρ_s	reinforcement ratio
$\rho_{s,eff}$	effective reinforcement ratio
σ_s	stress in the reinforcement at the crack
σ_{sr}	state II analysis stress in steel for the cracking moment
b	width of the section
c	clear cover of longitudinal reinforcement
d	effective depth of reinforcement
E_s	modulus of elasticity of steel
E_c	instantaneous modulus of elasticity of concrete
$E_{c,\infty}$	long-term modulus of elasticity of concrete
f_{cd}	design compressive strength of concrete
f_{ct}	tensile strength of concrete
h	height of the cross section
l	length used for strain measurement ($l = 20$ cm)
L	height of the support
k	embedment coefficient (ranging from 3 to 6)
$s_{r,m}$	mean crack spacing
$s_{r,max}$	maximum crack spacing
TS	factor, smaller than 1, accounting for tension stiffening
w	crack opening
x	depth of the neutral axis assuming a fully cracked section

lengths which can be achieved for typical applications. The objective of these further investigations is to promote the use of integral structures (buildings or bridges) by removing technical difficulties, and eventually lead to a wider use of this technique, with benefits from the point of view of durability and sustainability of concrete construction.

2. Simplified method for serviceability design of columns of long jointless structures

Long-term displacements in RC members may cause delayed damage to the structure itself and other elements. Therefore, they must be accurately estimated at the design stage. The magnitude of the forces acting on the section is significantly affected by the reinforcement ratio and the process can be assessed using a non-linear time-dependent analysis, although this type of analysis requires the selection of a number of parameters, and is computationally demanding.

An easy tool for the approximate evaluation of the reinforcement requirements needed for serviceability conditions in the supports of integral structures has been proposed by Pérez et al. [1]. The method is based on the integration of the moment/curvature law along the support, taking into account the non-linearity generated by the presence of cracked (less stiff) and uncracked (stiffer) regions. By following an iterative procedure, for a given imposed displacement at the support head, the forces acting at the column base are found, and therefore the tension in the reinforcement. As a result a number of curves are obtained, in which the stress in the reinforcement is plotted as a function of a parameter $\Lambda = k\delta d/L^2$ (which can be understood as a *normalised displacement*, since the only variable is imposed displacement δ), the reinforcement ratio $\rho = A_s/dh$ and the squashing load ratio $\upsilon = N/(0.85 \cdot b \cdot d \cdot f_{cd})$. In the definition of Λ, parameter k is the embedment coefficient ranging from 3 (for a cantilever) to 6 (for a doubly embedded column), d is the effective depth of the section and L is the height of the support.

It is worthy to point out that in order to solve in a closed form for rectangular cross-sections the equations governing the moment/curvature relationship (sectional analysis), linear-elastic constitutive laws are used for concrete in compression (neglecting tensile strength) and for steel in both tension and compression. This is justified by considering that, for the force ranges common in the serviceability phase, the concrete behaviour can be regarded as elastic, and Tension Stiffening effects are of limited importance, especially for flexure with significant axial force or high reinforcement ratios. In any case it is shown in this study that these effects are favourable and therefore neglecting them is an approximation to the problem from the safe side.

With this method, which can be applied using charts to simplify the design process, it is possible to operate a non-linear superposition of instantaneous and time-dependent imposed deformations. Long-term effects are taken into account by modifying the Young modulus of concrete and repeating the analysis. This method is known as the effective modulus method (i.e. $E_{c,\infty} = E_c/1 + \varphi$, where φ is the creep coefficient). Then, instantaneous (e.g. temperature) and long-term effects (e.g. shrinkage) are summed up by the procedure explained in Fig. 1.

The procedure involves the following steps:

- Using a short term curve, determine the stress ratio σ_s/f_y from the instantaneous Λ parameter.
- Using the long term curve, determine the equivalent long term value of Λ, Λ_∞ which would provide the same stress level. Add to this value the increment due to long term strains (shrinkage), $\Delta\Lambda_\infty$.
- Determine the stress level corresponding to $\Lambda_\infty + \Delta\Lambda_\infty$. This stress corresponds to the sum of short and long term effects.[1]

3. Experimental program

3.1. Test design

The tests have been designed to fulfil the following criteria and technical limitations:

- The specimens should be representative of real structures.
- The load capacity is limited by the hydraulic jack available which has a maximum capacity of 200 kN, and a maximum displacement range of 100 mm. Therefore, the specimens should be designed to develop their full capacity within that range.
- The axial force is be introduced by means of internal prestressed bars, due to the difficulties of keeping a centred vertical force and, at the same time, imposing a displacement at that point using jacks in two directions.

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[1] Displacement reversals can happen when temperature expansion exceeds shrinkage and creep. Nevertheless, one of the assumptions of the simplified method is that columns are reinforced symmetrically, and the case of displacements reversals is implicitly taken into account. Such effects will therefore have no influence on the analysis when the tensile resistance of concrete is neglected. Displacement reversals, will at most reduce tension stiffening effects, but this can be taken into account in the Tension Stiffening model used to correct the model, if desired.

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