Crack Control for Imposed Deformations

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Summary

The effects of imposed deformations on structures and the criteria to guarantee the level of performance (durability and serviceability) required for different types of use has been a matter of research and discussion in the last 20 years. Eurocode 2 recommendations on this subject and of BS 8007 on liquid retaining and containment structures were taken as code references.

The behaviour of structures to imposed deformations are analysed including the differences between external imposed deformations, as temperature variations, or internal, as concrete shrinkage. The differences between the cases where restrictions are at the extremities or laterally, as in walls, and its implications on design are discussed. It is concluded that in walls the stress resultants are smaller, and this should be considered in design. Recommendations are proposed to evaluated minimal amounts of reinforcement and crack widths in these cases.

KEYWORDS
Imposed deformations; minimal reinforcement, crack control; non-linear analysis.

1. Introduction

Serviceability and durability are important engineering challenges of our days, as they are associated to quality, claimed by society at different levels. In construction this is certainly the case and, as well, for structural concrete. Serviceability criteria is aimed at insuring structural performance as vibration and deformations control and, in particular for concrete structures, at limiting cracking.

The influence of cracking on durability has been discussed for many years and if at first was thought to be a crucial parameter, presently there is a big consensus that, in general, it is not the case. Although, this is only true within certain circumstances, that will be referred to on this paper.

This contribution discusses the criteria to control the effects of imposed deformations on structural concrete on a reliable and economic basis. Those effects are mainly cracking that, as we know, is nearly inevitable in structural concrete, even when prestressed. In consequence, it is important to have efficient and economic ways to control it. Non-linear analysis of structural elements submitted to imposed deformation due to thermal cooling of immature concrete or, later, due to concrete shrinkage or temperature variations are presented.

Research studies of the last 20 years have dealt thoroughly with this theme in the basis of experimental [1, 2] and analytical [3, 4] works. The codes, in particular Eurocode 2 [5], have clearly considered the topic, and engineers have now a good orientation concerning how to deal with the situation. It is very important that EC2 [5] clearly points out that these actions are to be considered only on serviceability analyses, of course, if ductility is guaranteed and if there are no second order effects. However, there are still some aspects needing clarification, and it should not be forgotten that the amount of reinforcement has, in these cases, important economic impact. In fact, for the general situations, in slab buildings, in walls or in tanks this reinforcement is not to be applied locally, but along all, or an important part of the structure.

In this paper the general concept for evaluating the amount of reinforcement to insure a certain maximum crack width for the effects of imposed deformations are referred to and the EC2 [5] indications in this matter are taken as reference. This procedure gives reasonable and feasible results but is based on the behaviour of a reinforced concrete tension tie submitted to an isolated axial imposed deformation. In practical situations other cases can occur that change the behaviour. It is the case where the structure restriction has border conditions different from the simple tension tie or when an axial effect due to an imposed deformation acts simultaneously with a load flexion effect. The first aspect is discussed in this paper and the relevant points concerning design highlighted while the superposition of imposed deformation/load effects has been recently discussed [6, 7].

2. Influence of Cracking in Durability and Design Criteria

In the seventies there was a certain consensus that there was a close relation between crack opening and risk of corrosion as pointed out by MC-78 recommendations and the great majority of nations codes at that time. Since then and as a result of tests performed at some laboratories during the eighties there was evidence showing that this relation was, at least, not clear. As Favre [1] says and EC2 [5] design recommendations point out, transverse cracks of the order of magnitude of 0.3 to 0.5mm shouldn’t be considered as adverse for long term durability, even in aggressive ambient. This type of cracks could be responsible to shorten the beginning of the first corrosion stage but would have no influence on the process onwards. Nevertheless, it was recognised that if cracks followed the line of the reinforcement, the so called coincident crack, there could be a rise on corrosion risk. Of course, in the cases of a slab or wall there is always the possibility that a transverse crack is a coincident crack, for a steel bar in the perpendicular direction. And that is expectable as transversal reinforcement can influence where the element cracks.

Some more recent experimental studies on this matter tend to confirm what has been referred before and bring some further elements. Arya and Darko [8] pointed out that increasing crack frequency (smaller crack distances but keeping the same crack opening sum) increases the amount of corrosion. François and Arlinguis [9] confirmed that the crack itself, if not over 0.5mm, is not responsible for more corrosion, but tension cracked concrete in general, encourages its development, if in presence of chlorides. This is due to paste-aggregate interface damage. The influence of cracks, on the corrosion process, still needs more detailed research but the present knowledge should be considered as the framework for defining design criteria.

Concerning design and detailing of slab or wall elements submitted to imposed deformations, it is known that cracks are well spaced and cracked concrete in tension is still in the formation phase (see §3.1). So, when there are restrictions to free deformations the major criteria for durability has to be to avoid steel yielding (limits in general crack widths to 0.4 to 0.6mm) and then, if functionally and economically reasonable, to insure a more strict limit. Limiting crack widths decreases the risk of an unfavourable influence on corrosion of a coincident crack.

The final design decision on the admissible crack width should consider other parameters of major importance such as reinforcement cover and concrete compacity and functional restrictions as appearance [5] or, for special cases as tanks, the impermeability exigencies [1, 9, 10] or the deformability limits of concrete epoxy based surface protections.

3. Isolated Axial Imposed Deformations

Firstly the main behaviour characteristics of a simple tie response to an imposed deformation are presented. The nature of the action can be of two types, external, as a temperature variation, or internal, as concrete shrinkage. In the first situation the imposed deformation is applied to all the section (concrete and reinforcement) and, in the second case, only to concrete. These differences are not usually pointed out, and have been shown recently by Alvarez [3] and Luis [6].

As illustrated in fig. 1, for the situation of an axial global imposed deformation (fig. 1.a), each crack is formed for an axial cracking value of approximately, N_{cr}. After each crack, the loss of rigidity is responsible for the axial stress resultant decrease, and, as the action increases, the process is repeated until a stabilized crack pattern is obtained. That situation happens for a value of $\varepsilon_{ff} \approx 1.0$ to 1.5‰, after which the axial effect increases with a state II rigidity, until yielding is reached. Nevertheless, in practice, axial imposed deformations don’t normal exceed a value of the order of 0.5 to 0.7‰ so the process ends at the crack formation phase, with well spaced cracks.

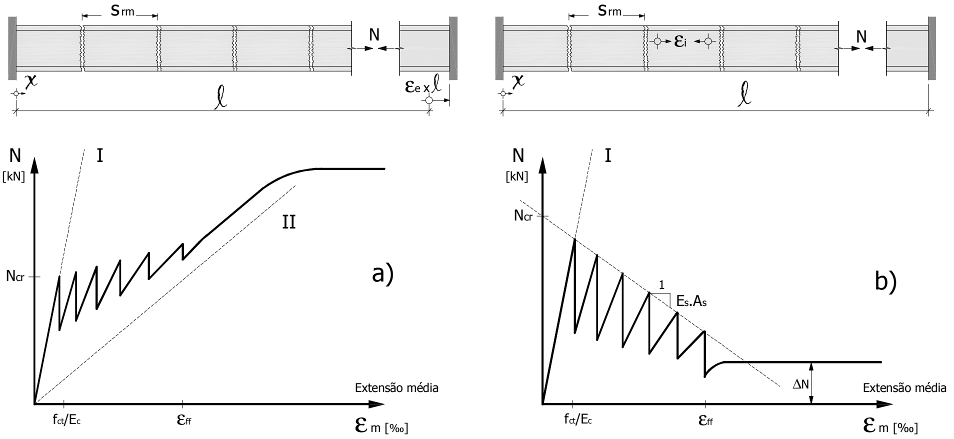
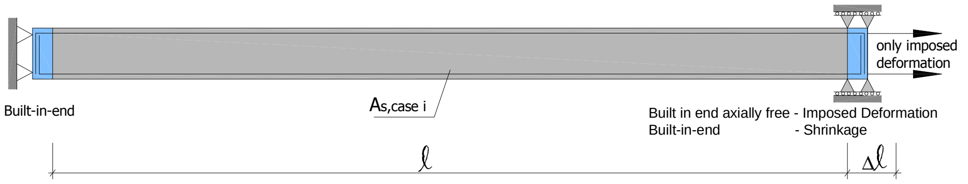


Fig.1 Behaviour (N – ε_{id}) for an external imposed deformation (a) or for concrete shrinkage (b)

Fig. 1.b shows the typical response for concrete shrinkage. In this situation, the axial cracking resultant at the formation of each crack decreases as the process of crack formation goes on. This is due to the self equilibrated state of stresses generated in the section (tension in concrete and compression in steel). This decrease of the peak values is proportional to the reinforcement rigidity.

To analyse the non-linear response of a concrete element to an axial imposed deformation, the ATENA programme [12], has been used. The study has been based on a fixed-end beam as presented in fig. 2 for different cases of reinforcement quantities (case 1 refers to the minimal reinforcement $\rho_{min} = A_s/A_{ct} = f_{ct}/f_{syk} = 0.5\%$).



Different Cases	**$A_{s,\ adopted}$**	**Reinforcement percentage**[%]
1	8ϕ10 (6,28 cm2)	0,52
2	7ϕ12 (7,92 cm2)	0,66
3	9ϕ12 (10,18 cm2)	0,85
4	11ϕ12 (12,44 cm2)	1,04

C25/30:
E_c=30.5 MPa
f_{ct}=2.5 MPa

S500:
E_s=200 MPa
f_{yk}=500 MPa

Fig. 2 Beam model geometry, materials and reinforcement distributions used on the analysis

The axial forces variations, for internal and external imposed deformations, are presented in fig. 3. The main behaviour characteristics can be confirmed and show, that if the steel amount is bigger than ρ_{min}, various cracks can be formed. For concrete shrinkage, this non-yielding criteria could be achieved for a slightly smaller axial force, the N_{cr} value at the formation of the 2^{nd} crack ($\approx 0.8N_{cr}$).

Fig. 4 presents the steel stresses and crack widths evolution for case 2 (ρ=0.66%). It is interesting to notice that crack widths have a small increase with the imposed deformation and areof the same order of magnitude for the cases of internal and external imposed deformation, although the steel stresses are bigger for the external type of action. This aspect should be taken into account for calculating crack widths (see §5).

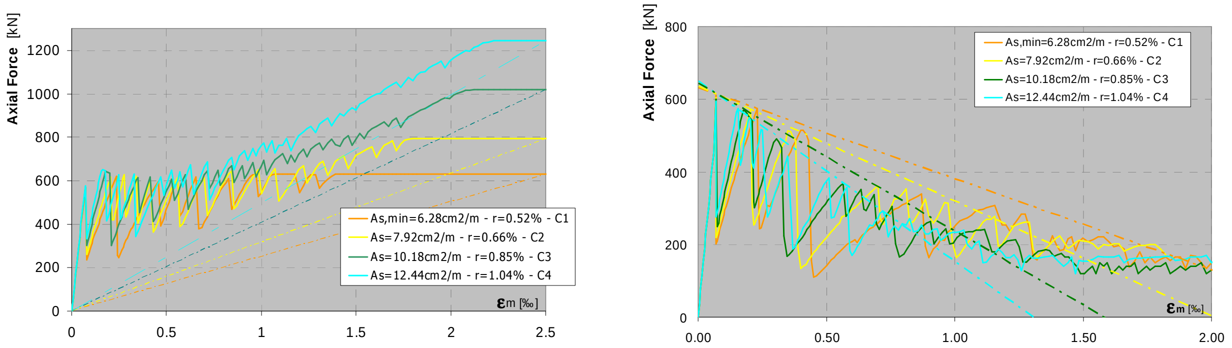


Fig. 3 Non linear responses to external and internal imposed deformations, for case 1 to 4

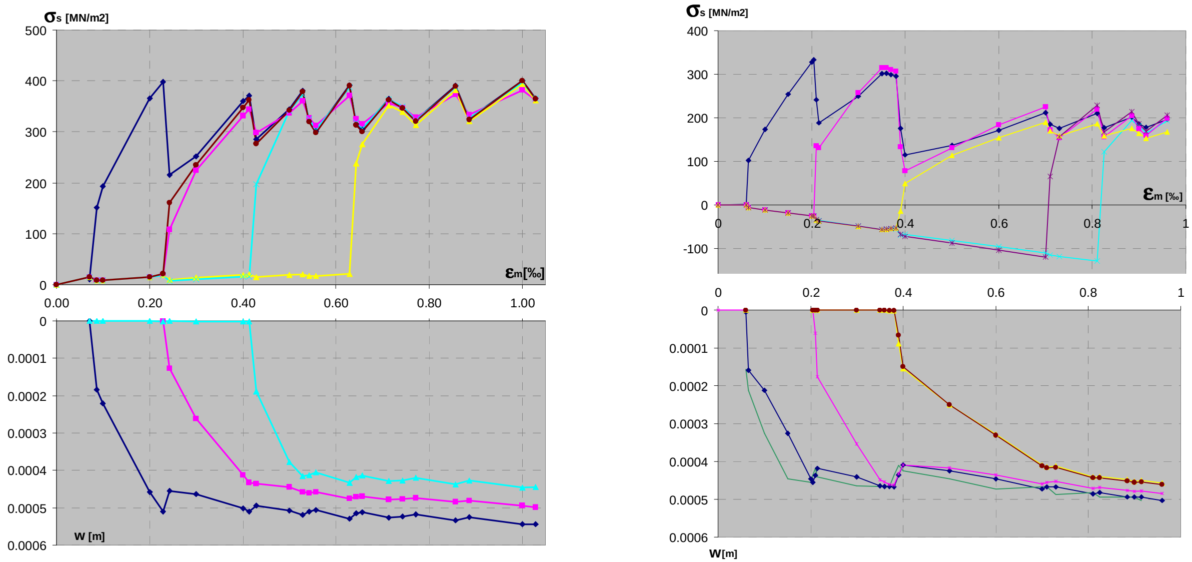
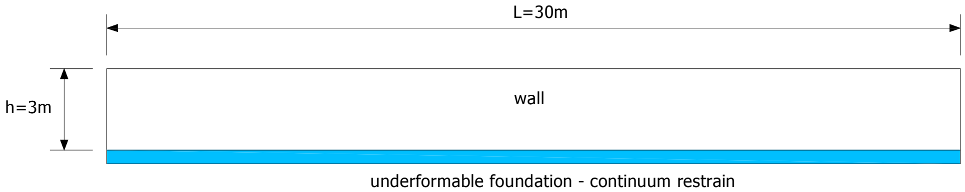


Fig. 4 Non linear evolution of stresses and crack widths for case 2 (ρ =0.66%) for external and internal imposed deformation respectively.

4. Imposed Deformation Effects on Walls

In practical design of walls it is usual important to evaluate the effects of a differential shortening (temperature decreases or concrete shrinkage) of the wall in relation to its foundation. For a situation of an isolated wall the border conditions are different from the basic tension tie. If the longitudinal dimension is approximately six to eight times differential its height the elastic stress distribution in the middle wall zone is similar to the case of an axial imposed deformation. Nevertheless, nonlinear behaviour shows that there are some clear differences and, more relevant, they can influence the design calculation of the minimal reinforcement and crack width. To illustrate this behaviour non linear analysis were done to evaluate the response to that differential deformation, considering different amounts of reinforcement as shown in fig. 5.



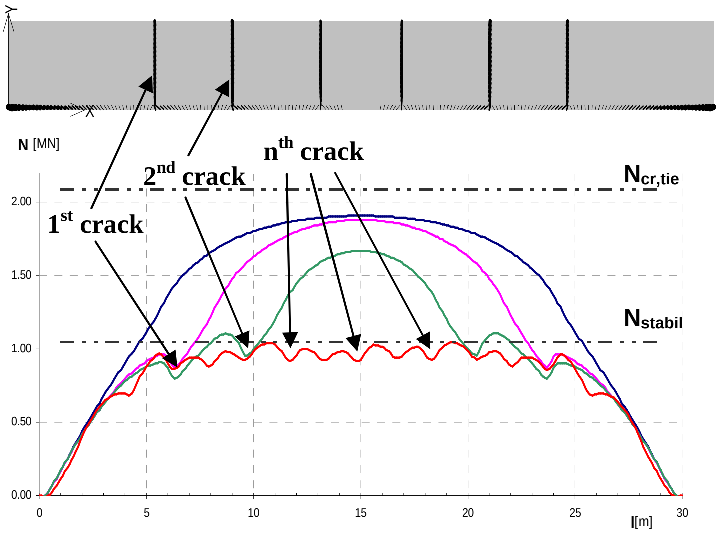
Different Cases	$A_{s,\ adopted}$	Reinforcement percentage[%]
1	ϕ8//0.15 (2x3.35 cm^2)	0.22
2	ϕ10//0.15 (2x5.14 cm^2)	0.35
3	ϕ12//0.15 (2x7.54 cm^2)	0.50
4	ϕ16//0.15 (2x13.41 cm^2)	0.89

E_c=30.5 MPa
f_{ct}=2.35 MPa

S500:
E_s=200 MPa
f_{yk}=500 MPa

Fig. 5 Wall model geometry materials and reinforcement distributions used in the analysis

In fig. 6 the variations of the longitudinal stress resultants along the wall axis is exemplified for case 3, as the cracking process develops. It can be noticed that as cracks are formed, there is an important variation of the axial resultant along the axis, which is different from the behaviour of the simple tie situation. In this case the axial resultant is necessarily the same at all sections by equilibrium, which is not the case for the wall, due to a different distribution of shear and normal vertical stresses along the wall/foundation connection. For bigger deformations the axial tension resultant converges to a nearly uniform value dependant on the amount of reinforcement, given in the table, for the cases of external or internal imposed deformations. It can be noticed that the main cracks were formed from the extremities to the middle zone due to some tension stress concentrations near the base and that at sections already cracked the stress resultants were kept always under the N value, referred above on the table.



ρ [%]	External deformation $\varepsilon_{\Delta T}$		Internal deformation ε_{cs}	
	N_{stabil} [kN]	N/N_{cr}	N_{stabil} [kN]	N/N_{cr}
0.22	620	0.30	600	0.28
0.35	850	0.40	720	0.34
0.50	**1000**	**0.47**	**850**	**0.40**
0.89	1250	0.60	1020	0.48

Fig. 6 Stress resultants variations for the case 3 (ρ=0.5%) and values of N stabilized for all the cases analysed

In fig. 7 the evolution of the steel stresses and crack widths at sections where a transversal crack has been formed are presented. For these diagrams the values considered are averaged along the wall height. The results presented show that the steel stresses are smaller than in the equivalent tension tie case and smaller than yielding value, even when $\rho<\rho_{min}$.

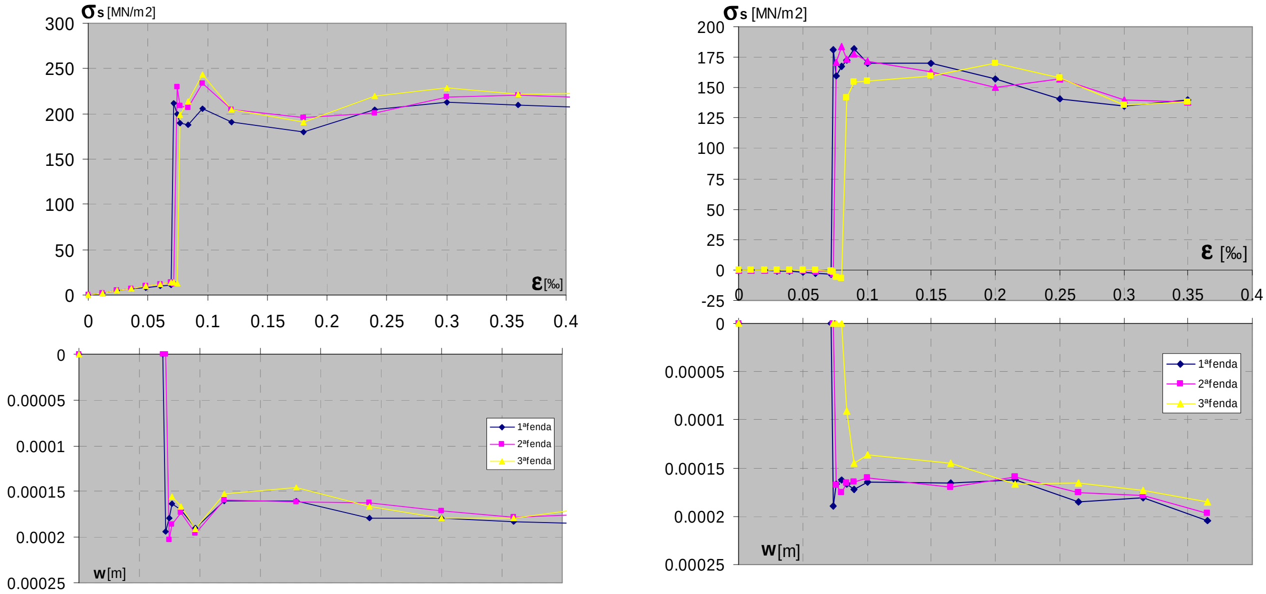


Fig. 7 Non linear evolution of average stresses and crack widths along the wall for case 3 (ρ = 0.5%), for external and internal imposed deformation respectively.

5. Design Comments and Final Recommendations

It must be emphasized that for imposed deformation crack control non-yielding of steel is essential. EC2 part 1 [3] states it clearly and so does in general EC2 part 3 [12], although this document proposes an extension to §7.3.4 (Annexe M) that seems to suggest, that for long walls, crack widths are independent of reinforcement, what can't be correct. This is somehow in line with BS8007 [11] but here the minimal reinforcement is determined for the cooling of immature concrete, and of course taking a smaller f_{ct}, then EC2 gives less minimal reinforcement.

This study shows that, although more research is needed, for imposed deformations crack control and crack width calculations, if the basis of EC2 are taken, the following should be considered:

1. For tension tie type cases, minimal reinforcement, calculation of crack widths and/or indirect control indications are correct, specially for external imposed deformations;
2. For internal deformations it is suggested to adopt conservatively the same amount of minimal reinforcement and evaluate the crack width considering as a case of an external action or, alternatively, taking a smaller value for $N = 0.8\ N_{cr}$, and calculate the crack width for $\varepsilon_{srm} = \varepsilon_{sm} - \varepsilon_{cm} + |\varepsilon_{cs}|$;
3. For walls it is clear that, to guarantee the non-yielding of steel, less reinforcement, than that obtained by expression (7.1) of EC2, is needed. Following the results of this study we suggest for the stress resultant, N, values based on the table presented in fig.6 or, conservatively, $2/3\ f_{ct,eff}\ A_{ct}$ and $1/2\ f_{ct,eff}\ A_{ct}$, respectively, for external and internal imposed deformation. For crack width calculation in the case of internal imposed deformation the expression of ε_{srm} suggested at point 2 should be used.

6. References

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