



State-of-Art about crack control due to imposed deformation

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ABSTRACT

Imposed deformation in structures such as temperature variation, concrete shrinkage and differential settlement of supports are responsible for its lower performance. Therefore, if there are restrictions to the free development of such deformation, tension is generated in the concrete and when it reaches the tension resistance of concrete, it generates cracks. One way to control these crack widths is the adoption of minimal quantities of reinforcement.

This work aims to summarize much of what has been done over the past forty years on the topic of cracking control due to imposed deformations; for this purpose a reasonable bibliographical research has been performed, based on the studies that took place at I.S.T. This document presents and analyzes the results obtained by many researches in this field intending to help to clarify the effects due to imposed deformations in the reinforced concrete structures. These actions must be thoroughly considered in regards of the structure service's condition (Serviceability Limit States). Design for Ultimate Limit States must be considered only in case of eventual second order effects and for the analysis of available ductility verification. It also illustrates the most recent codes indications in such cases and some proposed criteria for structural design for the situations in which structure's imposed deformation are important.

Keywords: imposed deformation, serviceability behavior, minimal reinforcement, crack width

1. INTRODUCTION

Cracking of concrete structures is “almost” inevitable, due to low tensile strength of concrete, but can and must be controlled. It appears that the cracks in reinforced concrete structures, with levels of crack widths unacceptable are due, in general, to imposed deformations. It is therefore of great interest to understand how to limit the level of cracking caused by imposed deformation as a way to reduce their potential effects (reinforcement corrosion and degradation of the appearance of the structure).

In the past, these actions were often less well appreciated, but from the 1970/80 it became clear that a considerable amount of damage, disability and poor performance in service resulted not from the action of the loads, but the effect of imposed deformations. Thus, in recent years, there has been several research works in order to clarify the behavior of these structures in service. Also, the Instituto Superior Técnico (IST), were developed some work on the effects of imposed

deformations and this paper summarizes existing information on the matter from the research work that has been developed at the IST.

A first aspect to highlight is that the imposed deformations may not cause the collapse of the structure (unless they manage any second order effects) but are often responsible for poor performance in service. As the adverse effects of these actions are felt mainly in the behavior in service, they should be considered in the verification to the Serviceability Limit States (SLS). This verification is essentially in crack control, so it is assumed the structure has cracks and therefore it makes sense to consider the reduction of stiffness and efforts generated for elastic. For SLS, crack control due to imposed deformation, is necessary to consider, according to EC2 [6], two design criteria: non yielding of steel, that leads to the minimum of reinforcement and a direct or indirect control of crack opening, usually more demanding.

2. ISOLATED IMPOSED DEFORMATION

For a situation of isolated axial imposed deformation, in general, can be considered that the axial force generated is always less than or equal to the axial cracking value, ie:

$$N_{id} \leq N_{cr} \quad (2.1)$$

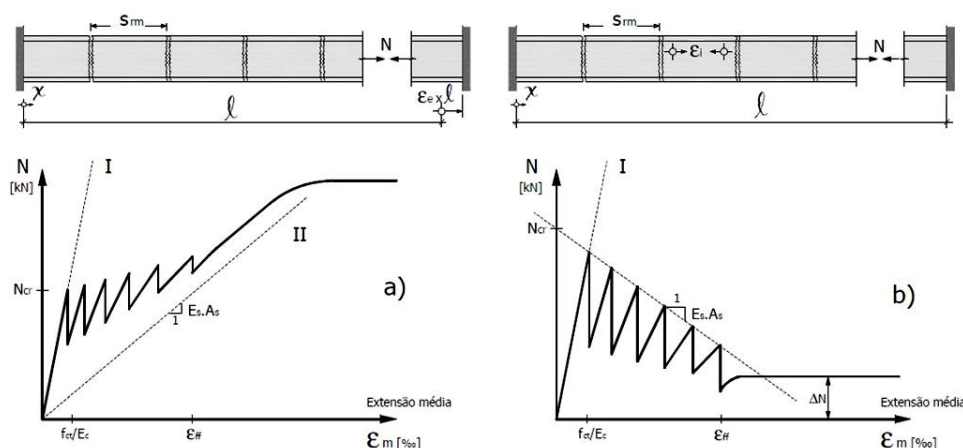


Fig. 2. 1 – General behavior ($N - \epsilon_{id}$) for a global imposed deformation (a) or for a concrete shrinkage effect (b) [13]

Therefore, since the beginning of the crack occurs with a extension of 0.1‰ and, given that the imposed deformation normally does not exceed the value of the order 0.5 to 0.7‰, the structural elements are usually at the crack formation phase. So, as in general the isolated imposed deformation does not reach the stabilized crack phase, the maximum axial generated by this action corresponds to what is necessary for the formation of a new crack and is much lower than that obtained from an elastic analysis. For values of imposed deformation of the order of 0.1‰ to 1.0‰, the axial force due to the isolated imposed deformation corresponds to N_{cr} , to be applied in assessing the behavior in service. [1, 13]

In the case of shrinkage of the concrete, internal imposed deformation (see Fig. 2. 1), in order to ensure non yielding of steel it could use a lower value for the axial force of the order of 0.80 to 0.90 N_{cr} .

It follows then that the situation of isolated imposed deformation, the type of design criteria to use is, first, the definition of a quantity of reinforcement ensures that no yielding of the steel (minimum) under the effect of stress corresponding to level at which there is a crack phase.

3. IMPOSED DEFORMATION EFFECTS ON WALLS

For the walls if the aim is to ensure the non yielding of steel, studies [14, 16] indicate possible to use lower amounts of reinforcement to those obtained by regulating expression EC 2 [6].

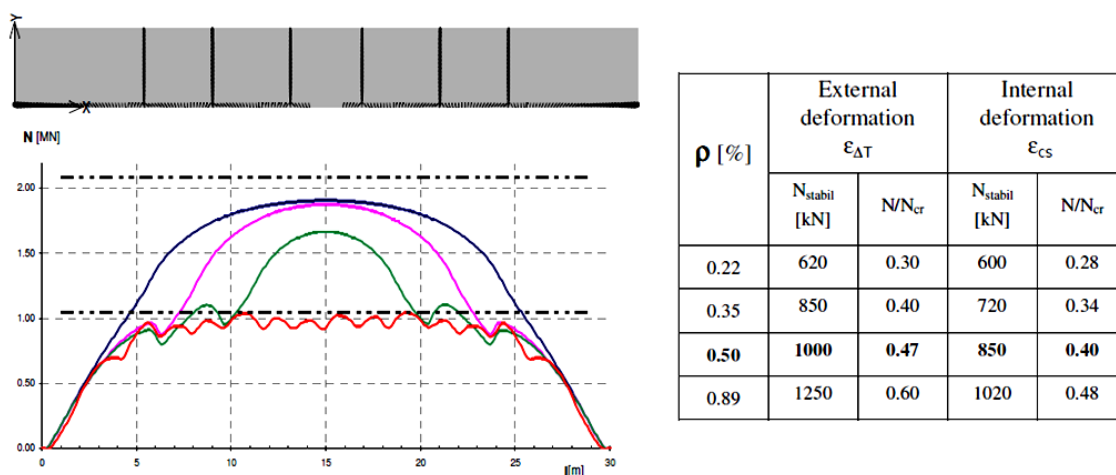


Fig. 3. 1 – Stress resultants variations for the case 3 ($\rho=0.5\%$) and values of N stabilized for all the cases analyzed [14]

Luis [14] suggested that if the objective is to limit the crack opening to a certain value, for the axial force may be used the values presented in table, or, in alternative, may be used, conservatively, $2/3f_{ct,eff}A_{ct}$ and $1/2f_{ct,eff}A_{ct}$, respectively, for external and internal imposed deformation. For crack width calculation in the case of internal imposed deformation the expression 3.1 of ϵ_{srm} should be used.

$$\epsilon_{srm} = \epsilon_{sm} - \epsilon_{cm} + |\epsilon_{cs}| \quad (3.1)$$

4. SUPERPOSITION OF IMPOSED DEFORMATIONS TO VERTICAL LOADS EFFECTS

A basic principle of serviceability design, for this situation, is that stress resultants due to imposed deformations should be obtained as percentage of the elastic value, such that,

$$a) N_{id} = \xi N_{id}^{elast} \quad b) M_{id} = \xi M_{id}^{elast} \quad \text{with } \xi < 1.0 \quad (4.1)$$

Camara [5] pointed the need to account for this aspect in quantifying the effects of the **superposition of imposed deformation due to flexion effects to vertical loads**. Based on nonlinear analysis developed, Camara [4, 5] exhibited an approximate method for evaluating the moments due to an imposed deformation, defining that ξ (which is a coefficient of reduction of elastic stress) could take the values shown in Table 1, depending on the situation of the crack element, the level of distributed vertical load, the percentage of reinforcement and time which the imposed deformation is applied.

$\rho_{flexion}$	ξ					
	$\varphi = 0$			$\varphi = 2.5$		
	r			r		
	≤ 1	1.5	2	≤ 1	1.5	2
0.3	1	0.35	0.2	0.35	0.25	0.15
0.6	1	0.5	0.35	0.35	0.3	0.25
1.2	1	0.7	0.5	0.4	0.35	0.3

$$\rho_{flexion} = \frac{A_s}{bd}$$

$$r = \frac{M_g + \psi_{2q} \times M_q + M_{id}^{elast}}{M_{cr}}$$

$$M_{id} = \xi \times M_{id}^{elast}$$

Table 1 – Approximate values of ξ to evaluate the moments due to imposed deformations as a percentage of elastic values [3]

Looking at the previous table, it appears that the real moment resulting from imposed deformation is, since there is some cracking, always less than 70% of that obtained by a linear elastic analysis. Over time its effects will decrease to values of the order of 20 to 30% of elastic. Therefore, the damage caused by the imposed deformation due to flexion on the structures when superimposed to loads is not as relevant as an elastic analysis might suggest.

As presented by Camara [4, 5] the key is to guarantee that the reserve to the non-yielding reinforcement in a state of bending is sufficient to accommodate the effect of the imposed deformation, ie, it must comply with the following condition:

$$\Delta M = M_y - M_{loads} < M_{id} \quad (4.2)$$

So, the imposed deformation flexion effects are more sensible at sections where the moments due to loads are smaller and consequently have less reinforcement so that the reserve, ΔM , to take into account imposed deformation effects without steel yielding is smaller.

On the topic of **superposition of an axial imposed deformation to vertical loads effects** the main variable set to evaluate the service behavior is the value of axial force to combine with the bending moment due to permanent or quasi-permanent loads.

Fig. 4.1 presents the situation of superposition, study of Luís [13], of an axial imposed deformation to the flexion effects of a vertical load: global imposed deformation and concrete shrinkage effect.

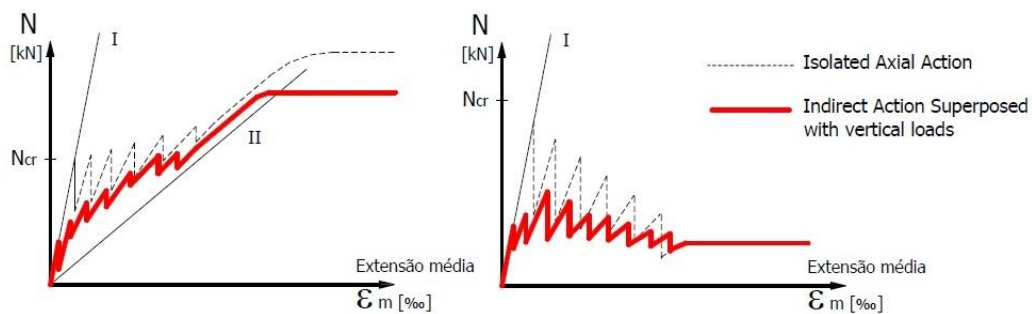


Fig 4. 1 – General behaviour ($N - \epsilon_{id}$) for a situation of superposition of an axial imposed deformation to the flexion effects of a vertical load: global imposed deformation; concrete shrinkage effect [13]

In this situation the loss of axial rigidity is anticipated due to flexion/tension cracks and the maximum value of the axial resultant is clearly smaller than the reference value of N_{cr} . In the case of shrinkage, as the imposed deformation increases, its values tend to decrease (see Fig 4. 1). This behavior aspect is clearly different from the case of a global imposed deformation.

Luis [13] proposed to obtain the resultant axial force due to the imposed deformation by the following expressions:

$$N_{\Delta T} = \xi_{\Delta T} \times N_{cr}; \quad N_{cs} = \xi_{cs} \times N_{cr} \quad (4.3)$$

Although the study of Luis [13] was limited to a certain geometry and parameter variations, it has been possible to clarify some important aspects of structural behavior in cases of superposition of loads and imposed deformations.

Luís [3, 13] estimated the coefficients $\xi_{\Delta T}$ and ξ_{cs} that are defined according to percentage of reinforcement and the level of imposed deformation. The proposed values are:

ρ (%)	Global imposed deformation			Shrinkage imposed deformation		
	0.20‰	0.30‰	0.50‰	0.20‰	0.30‰	0.50‰
0.50	0.40	0.55	0.65	0.40	0.45	0.50
0.80	0.50	0.60	0.70	0.40	0.40	0.45
1.00	0.55	0.60	0.80	0.35	0.35	0.40

Table 2 – Reduction coefficients for evaluation of axial imposed deformation effects [3]

Luís [13] suggested a simplified design reference to take the bold values on the table independently of the steel reinforcement percentage.

As mentioned previously for SLS, crack control due to imposed deformation, is necessary to consider, according to EC2 [6], two design criteria: non yielding of steel, that leads to the minimum of reinforcement and a direct or indirect control of crack opening, usually more demanding. For the criteria of non yielding Luís [13] suggested that the value of N should be evaluated by expression 4.3. For the direct control he suggested a simplified form to estimate the crack opening considering shrinkage as an equivalent temperature variation,

$$w_m = S_r \times \left(\varepsilon_{s2}^{load + \Delta T_{eq}} \right) \quad (4.4)$$

$$\Delta T_{eq} = \Delta T + \frac{\xi_{cs}}{\alpha} \quad \text{with } \alpha = 1 \times 10^{-5} \quad (4.5)$$

Luís [13] suggested a method of structural design for this situation based on elastic analysis. The proposed methodology is summarized in the following steps:

1. Design for Ultimate Limit States (ULS) without consideration of the imposed deformations, ensuring a minimal axial tension reinforcement;

Defined a distribution of reinforcement, should then perform the stress analysis, taking into account the superposition effect. For this should consider the following aspects:

2. For vertical loads is considered, in principle, the quasi-permanent combination;
3. To assess the level of axial force generated by the restriction of free shortening should be applied, first, the imposed deformations, ie, shrinkage and/or temperature variation in the structural model, with a adjust modulus of elasticity;
4. Set the level of reduction of axial force to consider. In areas of the structure where the axial force previously estimated is greater than N_{cr} that should be evaluated by applying the reduction factor, ξ to the value of N_{cr} . In areas where the axial force estimated at 3 is less than N_{cr} , then it will apply this reduction coefficient to that axial;
5. Evaluation the level of tensions in reinforcement, for the pair of efforts (N, M) in section with cracks, defining the suitability of the percentage of reinforcement placed in accordance with the regulatory criteria stipulated;

5. APPLICATION EXAMPLES

In the next subchapters are two case studies: analysis of the wall subject to the restriction imposed deformation and a tank with superposition effects.

5.1. WALL SUBJECT TO THE RESTRICTION IMPOSED DEFORMATIONS

The wall, without structural joints, has the geometry and materials presented in Fig. 5. 1. The longitudinal reinforcement of the wall was designed to the action of the imposed deformations and should be armed so that the crack width is lower than a certain value in order to prevent leakage of liquid.

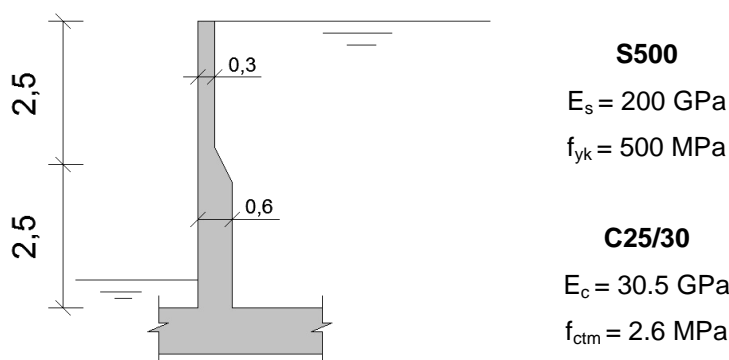


Fig. 5. 1 – Wall geometry and materials

The minimal axial reinforcement was calculated by the expression of EC2 [6] for values of wall thickness of 0.3m and 0.6m. To guarantee non yielding of the steel, could be considered amounts of reinforcement less than minimal, as mentioned in 3, because the axial force after the section crack is less than N_{cr} . The cracks widths where estimated for the minimal reinforcement, in order to verify that the values are acceptable. The estimate was made for two axial: N_{cr} and $N_{id}=0.7N_{cr}$ (axial after crack for internal imposed deformation as explained in 3). The following table presents the results obtained.

h (m)	$A_{s,min}$ (cm ² /m)	ρ_{ef} (%)	$S_{r,max}$ (cm)	Axial Force	σ_s (MPa)	$\epsilon_{sm}-\epsilon_{cm}$	W_m (mm)	W_{max} (mm)
0.30	Ø10//0.10	0.63	66.0	$N_{cr}=780\text{kN/m}$	496.8	0.00162	0.63	1.07
				$N_{dim}=546\text{kN/m}$	347.8	0.00104	0.41	0.69
0.60	Ø16//0.15	1.01	65.9	$N_{cr}=1232.4\text{kN/m}$	461.8	0.00176	0.68	1.16
				$N_{dim}=862.7\text{kN/m}$	323.1	0.00107	0.41	0.70

Table 3 – Average and maximum crack width for the minimal reinforcement adopted

Looking at the results it appears that for minimal reinforcement the maximum crack widths are pretty high compared to the code limits [6]. So, in order to obtain smaller cracks openings, is presented below the reinforcement needed to limit the crack width with and without direct calculation.

For **control of cracking without direct calculation** is considered two limits for crack width: 0.3mm, current code value in terms of durability, and 0.175mm, for reasons of leakage as presented in EC2-part3 [7]. The results obtained are below.

h (m)	w _k (mm)	σ _s (MPa)	ϕ _s [*] (mm)	ϕ _s (mm)	Axial Force	A _s (cm ² /m)	A _s
0.30	0.30	250.0	20	13.4	N _{cr} =780kN/m	31.2	Ø16//0.20 + Ø12//0.20
					N _{dim} =546kN/m	21.8	Ø12//0.10
	0.175	180.0	20	13.4	N _{cr} =780kN/m	43.3	Ø16//0.20 + Ø12//0.10
					N _{dim} =546kN/m	30.3	Ø16//0.20 + Ø12//0.20
0.60	0.30	250.0	20	23.9	N _{cr} =1232.4kN/m	49.3	Ø20//0.125
					N _{dim} =862.7kN/m	34.5	Ø20//0.30 + Ø16//0.25
	0.175	220.0	16	19.2	N _{cr} =1232.4kN/m	56.0	Ø20//0.10
					N _{dim} =862.7kN/m	39.2	Ø16//0.10

Table 4 – Results obtained from the control of cracking without direct calculation

For **control of cracking with direct calculation** in limiting the crack width to 0.175mm, for reasons of leakage, for average diameter of 16mm, the results are below.

w _k (mm)	h (mm)	N (kN/m)	S _{r,max}	ε _{sm} -ε _{cm}	A _s (cm ² /m)	σ _s (MPa)
0.175	0.30	780.0	0.119 + $\frac{0.001442}{A_s (m^2/m)}$	$\frac{2.522 \times 10^{-6}}{A_s (m^2/m)} - 3.41 \times 10^{-5} > \frac{2.34 \times 10^{-6}}{A_s (m^2/m)}$	52.6	148.3
		546.0		$\frac{1.352 \times 10^{-6}}{A_s (m^2/m)} - 3.41 \times 10^{-5} < \frac{1.64 \times 10^{-6}}{A_s (m^2/m)}$	42.7	127.8
	0.60	1232.4	0.119 + $\frac{0.001442}{A_s (m^2/m)}$	$\frac{4.784 \times 10^{-6}}{A_s (m^2/m)} - 3.41 \times 10^{-5} > \frac{3.70 \times 10^{-6}}{A_s (m^2/m)}$	78.3	157.5
		862.7		$\frac{2.936 \times 10^{-6}}{A_s (m^2/m)} - 3.41 \times 10^{-5} > \frac{2.59 \times 10^{-6}}{A_s (m^2/m)}$	57.7	149.5

Table 5 – Results obtained from the control of cracking with direct calculation

It appears that, by direct calculation, the amount of reinforcement needed for a given level of demand are higher than those obtained for the indirect control, it was found, in this example, a difference with a factor of about 1.4, the which justifies that this be in the future clarified. The results show that the ensure lower leakage by limiting the opening of the cracks tight limits leads to values very significant amounts of reinforcement, even taking to the design axial force of 0.7N_{cr}.

5.2. TANK: SUPERPOSITION OF AXIAL IMPOSED DEFORMATION TO ACTION OF WATER

The tank has the following dimensions: in plan, 10m by 15m, the wall thickness of 0.30m and height of 5m. The tank is not buried and inside will contain water. The characteristics of the materials are identical to those for the previous case.

In this situation occurs a superposition of effects, the action of the water on the walls with the effect of axial imposed deformation on them, as can be seen in the next figure.

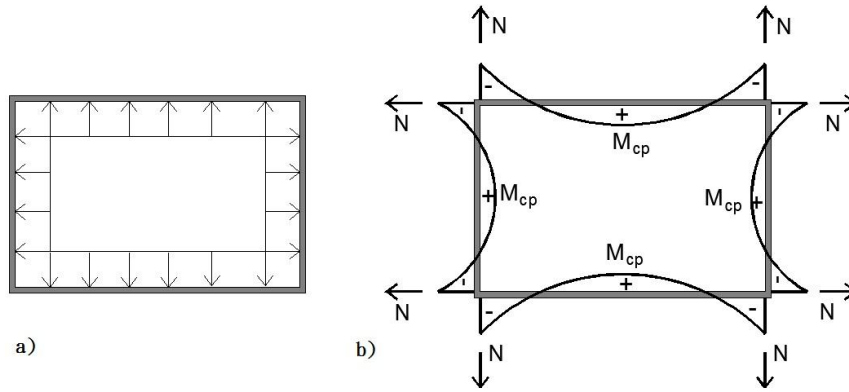


Fig. 5. 2 – Representation, on the plane, the superposition effect in the tank: a) action of water on the walls b) N , axial force due to imposed deformations and action of water, and M_{cp} moments due to the action of water

Taking an adjusted modulus of elasticity $E_{c,28}/3$ and using the expression 4.5 for the calculation of an equivalent temperature variation equal to 45°C, considering shrinkage as an equivalent temperature effect (differential shrinkage of 0,30‰), the distribution of axial resultants are presented in fig.5.3.

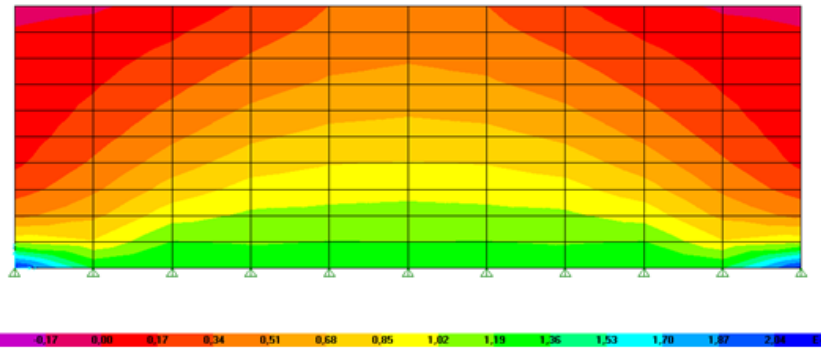


Fig. 5. 3 – Distribution of axial force due to imposed deformation on the wall of 15m length

Applying the methodology proposed by Luís [25] and presented in 4.3, in fig 5.4 the distribution of axial resultants for the serviceability verifications are presented such that:

$$N_{id} = \xi \times N_{cr} = 0.6N_{cr} \text{ if } N_{id} > N_{cr} \quad (5.1)$$

$$N_{id} = \xi \times N_{cr} = 0.6N_{id} \text{ if } N_{id} < N_{cr} \quad (5.2)$$

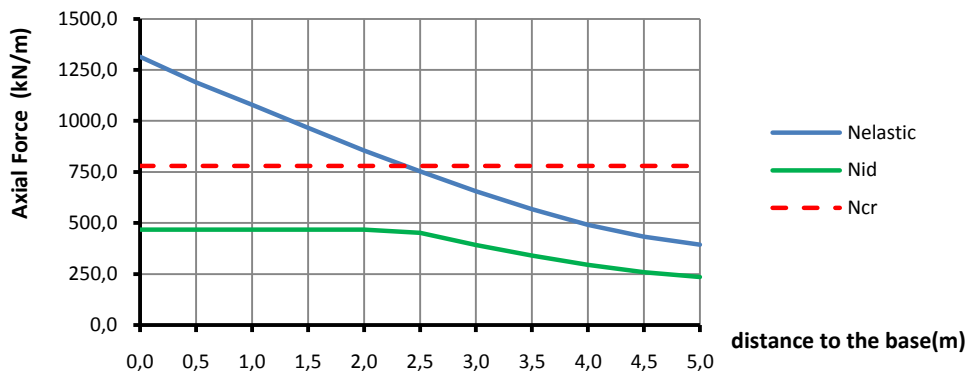
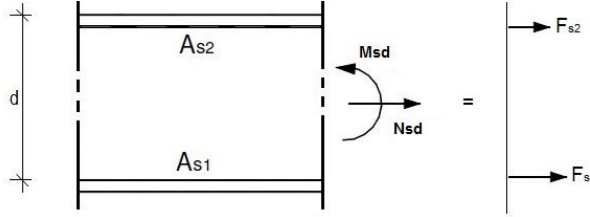


Fig. 5. 4 – Distribution of axial force due to imposed deformation central zone of the wall of 15m length

To analysis the forces, the wall was divided into two equal zones, the upper and lower, in the central area of that wall, and their midpoints are 1.25m from the base (region B) and the 3.75m

(region B). For each region the amount of longitudinal reinforcement to the ULS, on the wall with 15m length, are:

- Region A:



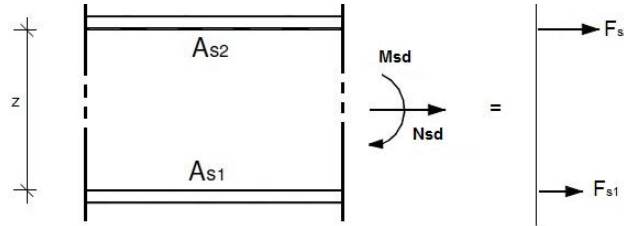
$$N_{sd} = 1.5 \times 41.9 = 62.9 \text{ kN/m}; M_{sd} = 1.5 \times 33.3 = 50.0 \text{ kNm/m} \quad (5.3)$$

$$A_{s1}: F_{s1} = \frac{M}{0.9d} + \frac{N}{2} = \frac{50}{0.9 \times 0.265} + \frac{62.9}{2} = 240.9 \text{ kN/m} \quad (5.4)$$

$$A_{s1} = \frac{F_{s1}}{f_{yd}} = \frac{240.9}{435 \times 10^3} \times 10^{-4} = 5.54 \text{ cm}^2/\text{m} \quad (5.5)$$

Has been adopted the minimal reinforcement calculated in the previous example (subchapter 5.1), $\emptyset 10//0.10$ ($2 \times 7.85 \text{ cm}^2/\text{m}$).

- Region B:



$$M_{sd} = 1.5 \times (-27.1) = -40.7 \text{ kNm/m} \quad (5.6)$$

$$A_{s2}: F_{s2} = \frac{M}{0.9d} = \frac{40.7}{0.9 \times 0.265} = 169.5 \text{ kN/m} \quad (5.7)$$

$$A_{s2} = \frac{F_{s2}}{f_{yd}} = \frac{169.5}{435 \times 10^3} \times 10^{-4} = 3.89 \text{ cm}^2/\text{m} \quad (5.8)$$

Has been adopted the minimal reinforcement calculated in the previous example (subchapter 5.1)), but in this case $\emptyset 16//0.20$ ($A_{s2}=10.05 \text{ cm}^2/\text{m}$) as reinforcement in the inside of the wall section and $\emptyset 12//0.20$ ($5.65 \text{ cm}^2/\text{m}$) as reinforcement on the outside of the wall section.

The analysis of the behavior in service was achieved by taking the most unfavorable combination of actions. The following are the tensions in reinforcement in both regions:

- Region A:

$$N_{cqp} = N_{di} + N_{cp} = 451.8 + 26 = 477.8 \text{ kN/m}; M_{cqp} = M_{cp} = 18.9 \text{ kNm/m} \quad (5.9)$$

$$F_{s1} = \frac{M_{cqp}}{z} + \frac{N_{cqp}}{2} = \frac{18.9}{0.23} + \frac{477.8}{2} = 321.1 \text{ kN/m} \quad (5.10)$$

$$F_{s2} = -\frac{M_{cqp}}{z} + \frac{N_{cqp}}{2} = -\frac{18.9}{0.23} + \frac{477.8}{2} = 156.7 \text{ kN/m} \quad (5.11)$$

$$\sigma_{s1} = \frac{321.1 \times 10^{-3}}{7.85 \times 10^{-4}} = 409.0 \text{ MPa}; \sigma_{s2} = \frac{156.7 \times 10^{-3}}{7.85 \times 10^{-4}} = 199.6 \text{ MPa} \quad (5.12)$$

- Region B:

$$N_{cqp} = N_{di} + N_{cp} = 468 - 6.4 = 461.6 \text{ kN/m}; M_{cqp} = M_{cp} = 45.2 \text{ kNm/m} \quad (5.13)$$

$$F_{s1} = -\frac{M_{cqp}}{z} + \frac{N_{cqp}}{2} = -\frac{45.2}{0.23} + \frac{461.6}{2} = 34.28 \text{ kN/m} \quad (5.14)$$

$$F_{s2} = \frac{M_{cqp}}{z} + \frac{N_{cqp}}{2} = \frac{45.2}{0.23} + \frac{461.6}{2} = 427.3 \text{ kN/m} \quad (5.15)$$

$$\sigma_{s1} = \frac{34.28 \times 10^{-3}}{5.65 \times 10^{-4}} = 60.7 \text{ MPa}; \sigma_{s2} = \frac{427.3 \times 10^{-3}}{10.05 \times 10^{-4}} = 425.2 \text{ MPa} \quad (5.16)$$

In Table 6 is presented the tensions in reinforcement and average and maximum crack width.

	$A_{s, \text{adopted}}$ (cm^2/m)	ρ_{ef} (%)	$S_{r, \text{max}}$ (cm)	Efforts	σ_s (MPa)	$\epsilon_{sm} - \epsilon_{cm}$	W_m (mm)	W_{max} (mm)
Region A	7.85 ($\emptyset 10//0.10$) Outside reinforcement	0.63	49.8	N=477.8kN/m M=18.9kNm/m	409.0	0.00123	0.36	0.61
Region B	10.05 ($\emptyset 16//0.20$) Inside reinforcement	0.76	62.1	N=461.6kN/m M=-45.2kNm/m	425.2	0.00141	0.51	0.87

Table 6 -- Average and maximum crack width for the reinforcement adopted

Analysing the table it appears that the openings of cracks in this case are not in any way acceptable. So to get a better behavior to the SLS is necessary to have higher amounts of reinforcement, to ensure handling characteristics appropriate to its functionality. In the Table 7 is presented the reinforcement quantities to obtain a better service behavior (in region A the outside reinforcement is $\emptyset 16//0.15$ and in region B the inside reinforcement is $\emptyset 16//0.15$).

	$A_{s, \text{adopted}}$ (cm^2/m)	ρ_{ef} (%)	$S_{r, \text{max}}$ (cm)	Efforts	σ_s (MPa)	$\epsilon_{sm} - \epsilon_{cm}$	W_m (mm)	W_{max} (mm)
Region A	20.11 ($\emptyset 16//0.10$) Outside reinforcement	1.52	37.0	N=477.8kN/m M=18.9kNm/m	159.66	0.00048	0.10	0.18
Region B	20.11 ($\emptyset 16//0.10$) Inside reinforcement	1.52	37.0	N=461.6kN/m M=-45.2kNm/m	212.49	0.00069	0.15	0.25

Table 7 – Average and maximum crack width for the new reinforcement adopted

With this reinforcement we have a better behavior, but to ensure that there is no leakage, as can be seen in EC2 [7], its need higher reinforcement.

6. CONCLUSION

The objective of this work consisted in summarizes existing information on the effects of imposed deformations on the concrete structures, from the research work that has been developed at the Instituto Superior Técnico.

In the application examples was interesting to note, in the first example, **wall subject to the restriction imposed deformations**, that with minimal reinforcement the estimates of the maximum crack width are high in comparison to the different code requirements and limiting the

opening of the cracks to tight limits to ensure no leakage leads to very significant amounts of reinforcement. In the second example, **tank with superposition effects**, designing the longitudinal reinforcement to the ULS, get a bad service behavior, so its need to dispose quantities of reinforcement greater than the minimum to have crack width acceptable.

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