Evaluation of the indirect control method of cracking

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Extended Abstract

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October 2016

Abstract

The phenomenon of crack is present ever since reinforced concrete was first used in civil engineering. Nowadays, this issue was gaining relevance, not only for aesthetic reasons, but also because of structures' own safety and durability.

Cracking may either be a consequence of the applied loads or of the imposed deformations in the structure due to temperature variations and shrinkage of the concrete components.

Nowadays, European Standard (Eurocode 2 – "Design of concrete structures") is used, which allows for a more accurate calculation using numerical expressions and another one, less demanding, with the use of tables, in which maximum bar diameters and maximum bar spacing to adopt are indicated, depending on the working stress present on steel.

The aim of this thesis focuses mainly on the analysis and verification of indirect control of cracking and realizes in which situations these data should be applied. In this way, multiple analysis scenarios are conducted to understand the accuracy of the indirect control data for the case of imposed deformations and applied loads, making the differentiation between bending stress and traction.

By analyzing the frames of the indirect control of cracking it is concluded that "the only variable of interest for choosing a particular detail is the working stress on the steel". Through the analysis in this thesis, it is clear that this statement is not entirely correct. The results in the tables of indirect control were done for a reinforcement area similar to the minimum one. This fact is more evident for structures subjected to bending stress than to axial forces.

A reference to some peculiarities is also presented, related to cracking in reinforced concrete elements that are often not taken into account and that result in functional problems in service.

Keywords: Cracking; Crack width; Applied loads; Imposed deformations; Eurocode 2; Minimum reinforcement area

1. Introduction

The phenomenon of cracking is present since reinforced concrete started being used in structures. This phenomenon has not only aesthetic consequences, but can also induce problems in the durability and security of the structure itself. Due to those consequences it is important to control and minimize the cracking in reinforced concrete structures.

The opening of cracks can result from forces directly applied on the structures or from imposed deformations such as shrinkage and temperature variations. The imposed deformations did not always have the importance that they do today. However, not taking these actions into account could lead to large cracks that violate the imposed limits by EC2 which could provoke a deficient behavior in service.

2. The phenomenon of cracking

The crack appears when the section reaches the maximum tensile stress in concrete. When that happens, the tensile stress in this material is transfer to the reinforced area to avoid a fragile break. In Figure 1 we can see the stress diagrams in the structure due to the phenomenon of cracking.

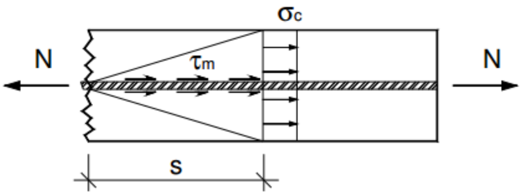

Figure 1 – Schematic model of the transmission of tensions when a crack appears.

To prevent a fragile break it is necessary to adopt a minimum reinforcement area. This concept has an equation for two different goals.

On the one hand, the minimum reinforcement area is associated to the ultimate limit states (ULS) and is adopted only to avoid a fragile break. On the other hand, this reinforcement area is calculated to assure the minimum control of the crack width. This equation of minimum reinforcement area is described in page 120 of Eurocode 2: "Design of concrete structures – Parte 1-1: General rules and rules of buildings”, as shown below:

$$A_{s,min} = k_c k A_{ct} \frac{f_{ct,eff}}{\sigma_s}$$

A_{ct} – is the area of concrete within tensile zone. The tensile zone is that part of the section which is calculated to be in tension just before formation of the first crack;

σ_s – is the absolute value of the maximum stress permitted in the reinforcement immediately after formation of the crack;

$f_{ct,eff}$ – is the mean value of the tensile strength of the concrete effective at the time when the cracks may first be expected to occur ($f_{ct,eff} = f_{ctm}$);

w_k – crack width;

k – is the coefficient which allows for the effect of non-uniform self-equilibrating stresses, which lead to a reduction of restraint forces;

k_c – is a coefficient which takes account of the stress distribution within the section immediately prior to cracking and of the change of the lever arm. In short, it takes the value 1.0 for structures subjected to pure tension and 0.4 for bending stress;

Beyond the minimum reinforcement area there are other aspects that have to be taken into account to have a good behavior in serviceability limit states (SLS). It is necessary to adopt an efficient cover rebar which varies with the structure exposure to aggressive agents, a concrete with good characteristics of porosity and bars with good grip conditions.

It is important to refer that there are studies which show that crack widths below 0.2 can allow at first some permeability, but quickly seal themselves to assure the tightness of the structure. This fact is relevant for special structures like liquid retaining and containment structures.

3. Control of cracking – Eurocode 2

The EC2 has two different methods to calculate the crack width. The first one is an indirect method based in two tables and another one with direct calculation. The maximum limit of the cracks can be between 0.2-0.4 mm, that can vary with the exposition to the environment, the proposed function and nature of the structure.

The indirect method provides the maximum bar diameters or the maximum bar spacing, according to the service stress in the reinforcement steel, while assuming a cracked section.

Table 1 – Maximum bar diameters for crack control.

Steel stress [MPa]	Maximum bar size [mm]		
	w_k $\mathbf{0.4\ mm}$	w_k $\mathbf{0.3\ mm}$	w_k $\mathbf{0.2\ mm}$
160	40	32	25
200	32	25	16
240	20	16	12
280	16	12	8
320	12	10	6
360	10	8	5
400	8	6	4
450	6	5	-

Table 2 – Maximum bar spacing for crack control.

Steel stress [MPa]	Maximum bar spacing [mm]		
	w_k $\mathbf{0.4\ mm}$	w_k $\mathbf{0.3\ mm}$	w_k $\mathbf{0.2\ mm}$
160	300	300	200
200	300	250	150
240	250	200	100
280	200	150	50
320	150	100	-
360	100	50	-

The Eurocode has the particularity, to indirect control, that, to structures subjected to tension, the bars diameter are effected to the factor 1.25. This fact is related with the necessity of a much higher concentration of reinforcement area than bending stress. Afterwards it will be seen that this factor is a good calibration to the bar diameter.

$$\emptyset_s = \emptyset_s^* \frac{f_{ct,eff}}{2.9} \frac{h_{cr}}{8(h-d)} = \emptyset_s^* \frac{2.9}{2.9} \times \frac{h}{8 \times 0.1h} = \mathbf{1.25}\emptyset_s^*$$

h_{cr} – is the depth of the tensile zone immediately prior to cracking, considering the characteristic values of prestress and axial forces under the quasi-permanent combination of actions;

d – is the effective depth to the centroid of the outer layer or reinforcement;

According to Tables 1 and 2, it can be assumed that the crack width only depends on the service stress in steel. There is no distinction between beams and shells or even the reinforcement area needed for the ultimate limit states. The only difference is that for applied forces we can use both tables and for imposed deformations we can only use the table with maximum bar diameter.

Numerical calculation was used to assess the veracity of the tables of indirect control according to the expressions in Eurocode 2 (page 124 and 125 of EC2 – Part 1-1):

$$\boldsymbol{w_k} = s_{r,\text{máx}}(\varepsilon_{sm} - \varepsilon_{cm})$$

$$(\boldsymbol{\varepsilon_{sm}} - \boldsymbol{\varepsilon_{cm}}) = \frac{\sigma_s - k_t \dfrac{f_{ct,eff}}{\rho_{p,eff}}\left(1 + \alpha_e \rho_{p,eff}\right)}{E_s} \geq 0.6\frac{\sigma_s}{E_s}$$

$$\boldsymbol{s_{r,\text{máx}}} = k_3 c + k_1 k_2 k_4 \frac{\emptyset}{\rho_{p,eff}}$$

w_k – crack width;

ε_{sm} – mean strain in the reinforcement under the relevant combination loads, including the effect of imposed deformations and taking into account the effects of tension stiffening;

ε_{cm} – is the mean strain in the concrete between cracks;

$s_{r,\text{máx}}$ – is the maximum crack spacing;

σ_s – is the stress in the tension reinforcement assuming a cracked section;

α_e – is the ratio E_s/E_{cm};

$\rho_{p,eff}$ – is the ratio $A_s/A_{c,eff}$;

$\emptyset$ – is the bar diameter;

k_t – is a factor depending on the duration of the load. For short term loading it takes the value of 0.6 and for long term loadings the value of 0.4;

k_1 – is a coefficient which takes account of the bond properties of the bonded reinforcement. For high bond bars it assumes the value of 0.8 and for bars with an effectively plain surface the value of 1.6;

k_2 – is a coefficient which takes into account of the distribution of strain. For bending stress takes the value of 0.5 and for pure tension the value of 1.0 $\left(k_2 = \frac{\varepsilon_1 + \varepsilon_2}{2\varepsilon_1}\right)$;

k_3, k_4 – these parameters are constant defined for each country (k_3=3.4 and k_4=0.425 for Portugal);

4. Evaluation of the indirect control of cracking

4.1. Influence of the parameters in the equation for crack width

By performing several different analyses we assess the true influence of each variable in the equation of the crack width.

It came to light that the cracking control on beams is often irrelevant, due to the fact that the beams are usually strongly reinforced structures and the verification of the serviceability limit state is normally guaranteed with the verification of the security failure. The fact the maximum bar diameter is used on the indirect control frames can originate the use of too small diameter bars, which sometimes makes the beam detailing unfeasible.

The results for a beam subjected to bending stress with only 2Ø25 of reinforcement area are displayed in Table 3.

Table 3 – Calculation of the crack width to a beam.

Steel stress [MPa]	Crack width – Beam		
	$A_{s,adopted}$ [cm²/m]	w_k [mm]	$\emptyset_{EC2-1}$ [mm]
160	2Ø25 (9.82)	0.13	32
200	2Ø25 (9.82)	0.18	25
240	2Ø25 (9.82)	0.22	16
280	2Ø25 (9.82)	0.27	12
320	2Ø25 (9.82)	0.31	10
360	2Ø25 (9.82)	0.36	8
400	2Ø25 (9.82)	0.41	6
450	2Ø25 (9.82)	0.46	5

This small example shows that the tables of indirect control are not manufactured having into account structures like beams that are conditioned by the ultimate limit states, with a large amount of reinforcement area. For this simple case, the crack width is only out of limits for steel stress above 360MPa. However, these steel stresses are rarely achieved.

Indirect control could lead to adopting very low bar diameters and, consequently, impossible detailing, because of the reinforcement area needed for the ULS.

Still in this aim, is important to point out that these methods only calculate the cracks that are on the area influenced by the reinforced bars. When a high beam, over 0.8 or 0.9m, is submitted to bending stress, the problem is closer to a tension case. This happens due to parameter $k_{2,}$ referring to the distribution of strain along the section. This factor takes the value of 1.0 for sections subjected to pure tension and 0.5 to the bending stress case. In this case the ε_1 is similar to ε_2 which takes in this particular case a value closer to 1.0 (figure 2).

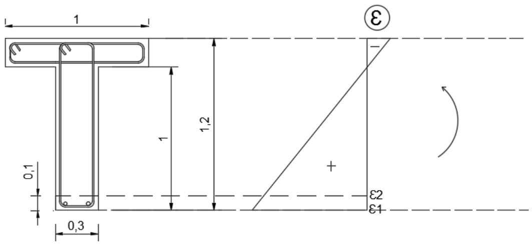

Figure 2 – High section subjected to bending stress.

If a value of 0.5 is adopted for $k_{2,}$ crack widths may fall out off limits.

It is also necessary to calculate the minimum reinforcement area in the web for this type of problem. The beam web is subjected to pure tension due to the high level of the beam neutral axis. The lack of distributed reinforcement area in the web could originate bigger cracks, (out of admissible limits), and a bigger space between them. This phenomenon situates the area analyzed by the calculations, closer to a tension action than a bending stress action.

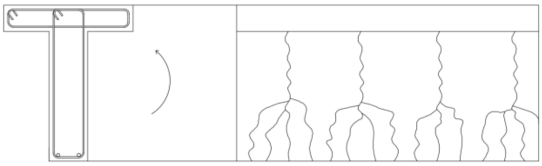

Figure 3 – Propagation of cracks in a high beam without reinforcement area in the web.

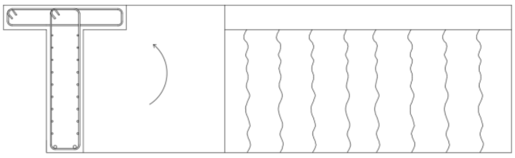

Figure 4 – Propagation of cracks in a high beam with reinforcement area in the web.

The difference in the propagation of the cracks in a high beam with and without the reinforcement area in the web is seen clearly in Figures 3 and 4.

The pure tension stress is much more restricting than the bending stress regarding the control of cracking, as the entire section is under the tension effort in the first case and in the second case only half of the section is under the tension effort. The parameter that has this constraint into account is the previously referred $k_{2.}$ Another relevant parameter is $\rho_{p,eff}$ which in the bending stress case it is slightly bigger due to the effective high of the concrete subjected to tension $h_{c,eff}$. In the bending stress case, this parameter depends on the neutral axis position $\left(\frac{h-x^{II}}{3}\right)$, showing a smaller value, comparing to tension (2.5c). However, to structures with a high thickness, this parameter becomes equal to 2.5c and constant in both cases.

The shells height is another parameter analyzed that proved to be a non-relevant factor due to the fact that these methods calculate only the cracks on the concrete situated on the steel bar's influence area, as seen in Figure 5.

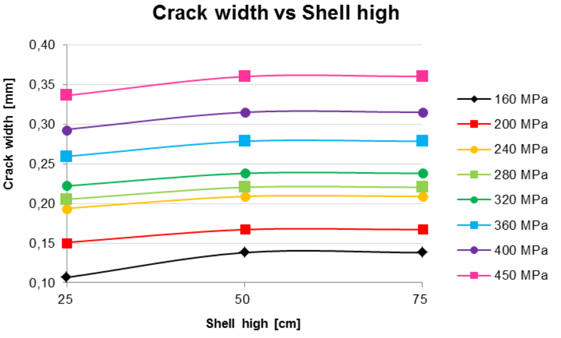

Figure 5 – Crack width vs shell high.

The reinforcement area, or percentage of reinforcement area, is an influenced parameter on cracks calculation. Through the analysis of the indirect calculation tables, it can be concluded that the only fundamental parameter to choose a determination detailing is the service tension on the steel. However, a bigger or smaller steel bar size shall be adopted, proportionally to the reinforcement area. With this example it can be concluded that the inputs on the indirect control frames are not sufficient for a correct dimensioning of the structures.

Finally, the influence of the steel bar diameters on the choice of a particular detailing was analyzed. For a constant reinforcement area, adopting bigger steel bar diameters produces bigger cracks. This happens due to the fact that the number of steel bars is smaller and the spacing between them is bigger, resulting in a reduced surface area of contact between the two materials, concrete and steel. For bigger tensions a bigger sensibility is necessary requested when choosing the correct steel bar diameter as the crack dimension can vary up to 0.5mm.

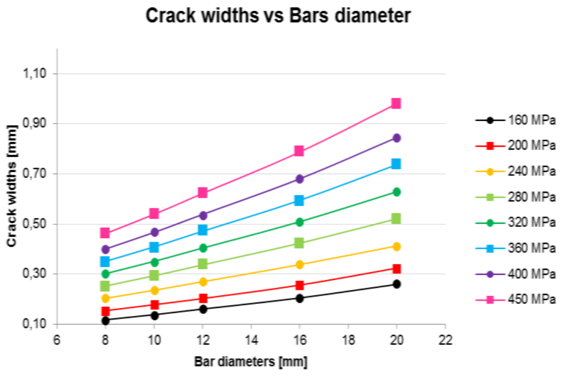

Figure 6 – Crack widths vs bar diameter.

It should be noted that the spacing between bars is another parameter with importance. With this method it only can be calculated the crack width under the influence of the bar diameters. If the bar spacing is too expressive above 5(c+Ø/2), about 250/300 mm, it can cause large out of limits cracks. When detailing a section it is crucial to have this idea in mind to prevent any problems that can lead to large widths.

After the analysis of the different parameters used on the direct calculation, the equations are used to compare the results for tension and bending stress. The indirect method only depends of the service tension in the steel, but it is concluded that the phenomenon of cracking should depend of the reinforcement area for the ultimate limit states.

4.2. Calculation of crack widths for structures subjected to applied forces and imposed deformations

After analyzing the different parameters present in the calculation of the cracking phenomenon, examples were made to verify its applicability to applied forces and imposed deformations for the bending and pure tension stresses.

The tables show good results for imposed deformations, where the reinforcement area is the minimum necessary to control cracking, and conservative results to applied loads, where the reinforcement area is more significant than the first case. These results are more relevant regarding bending stress than axial forces. The fact that the results for applied loads are conservative can lead to small bar diameters, which sometimes can cause the unfeasibility of the section's detailing.

Table 4 shows the results of crack widths for imposed deformations and applied forces subjected to bending stress, when adopting the bar diameters in the indirect control.

Table 4 – Crack widths to imposed deformations and applied forces, submitted to bending stress.

Steel stress [MPa]	Imposed Deformations		Applied Forces	
	$A_{s,adopted}$ [cm^2/m]	w_k [mm]	$A_{s,adopted}$ [cm^2/m]	w_k [mm]
160	9.09	0.16	20.04	0.13
200	7.31	0.22	20.04	0.17
240	6.16	0.27	20.11	0.17
280	5.39	0.32	20.20	0.19
320	4.62	0.36	20.14	0.20
360	4.19	0.37	-	-
400	3.77	0.36	-	-
450	3.57	0.37	-	-

The results in Table 4 were obtained for a shell with 0.25 m of thickness and a bar cover of 0.03 m. The bar diameters used in this example were the ones described in the tables for indirect control.

This example was done for structures submitted to tension too. However, the results in this case are more reasonable than the first case. The shells' detailing was done considering the maximum bar diameter of the tables of indirect control.

This example was done for the same thickness and bar cover.

Results in Table 5 are more similar comparing the obtained crack width with imposed deformations and applied forces.

Table 5 – Crack widths to imposed deformations and applied forces, submitted to tension.

Steel stress [MPa]	Imposed Deformations		Applied Forces	
	$A_{s,adopted}$ [cm^2/m]	w_k [mm]	$A_{s,adopted}$ [cm^2/m]	w_k [mm]
160	22.77	0.19	25.17	0.23
200	18.18	0.27	25.17	0.31
240	15.39	0.30	25.13	0.33
280	13.09	0.31	25.66	0.30
320	11.42	0.33	25.13	0.32
360	10.13	0.36	-	-
400	-	-	-	-
450	-	-	-	-

In imposed deformations subjected to pure tension the minimum reinforcement area is 2.5 times higher than bending stress.

$$\frac{A_{s,min}{}^{t}}{A_{s,min}{}^{b}} = \frac{k_c \times k \times A_{ct} \times \frac{f_{ct,eff}}{\sigma_s}}{k_c \times k \times A_{ct} \times \frac{f_{ct,eff}}{\sigma_s}} = \frac{1.0 \times \frac{h}{2}}{0.4 \times \frac{h}{2}} = 2.5$$

However, later it is concluded that the quotient between the reinforcement area, to have the same crack width, can be bigger than three, according to the service stress steel and the reinforcement area needed for the ultimate limit states.

4.3. Calculation of crack widths according to Eurocode 2 – Part 3

In order to complement the analysis of the control of cracking, the veracity of the control present in Eurocode 2: "Design of concrete structures – Parte 3 Liquid retaining and containment structures", was studied. This part of the EC2 has two figures that provide the maximum bar diameters and maximum spacing bar according to the service stress in the reinforcement (page 13 of EC2-3), similarly to the indirect control in EC2 – Part 1-1.

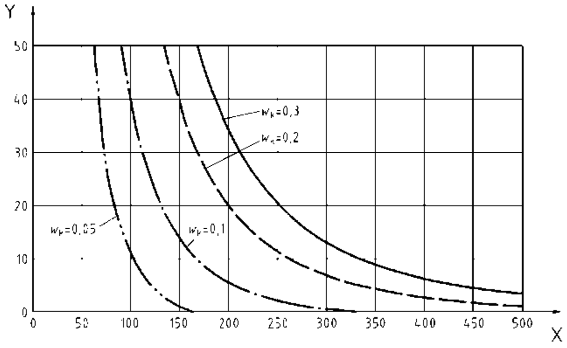

Figure 7 – Maximum bar diameters for crack control in members subjected to axial tension.

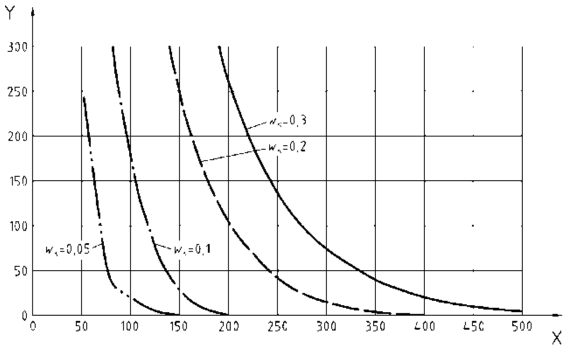

Figure 8 - Maximum bar spacing for crack control in members subjected to axial control.

The two graphs in Table 7 and 8 are used for structures submitted to tension provoked by imposed deformations.

To verify the applicability of these graphs an example was done for a shell with 0.25m of high subjected to axial tension induce by imposed deformations.

Tables 6, 7 and 8 show very good results when adopting the maximum bar diameters in Figure 7 and the maximum bar spacing in Figure 8.

Table 6 – Crack width calculation to a limit of 0.3 mm.

Steel stress [MPa]	Maximum bar spacing		Maximum bar diameter	
	$A_{s,adopted}$ [cm^2/m]	w_k [mm]	$A_{s,adopted}$ [cm^2/m]	w_k [mm]
160	-	-	22.78	0.12
200	-	-	18.46	0.16
240	15.21	0.20	15.13	0.18
280	12.97	0.23	13.00	0.20
320	11.31	0.25	11.57	0.22
360	10.05	0.25	10.13	0.24

Table 7 – Crack width calculation to a limit of 0.2 mm.

Steel stress [MPa]	Maximum bar spacing		Maximum bar diameter	
	$A_{s,adopted}$ [cm^2/m]	w_k [mm]	$A_{s,adopted}$ [cm^2/m]	w_k [mm]
160	-	-	22.83	0.11
200	18.48	0.15	18.60	0.13
240	15.28	0.16	15.15	0.15
280	13.23	0.18	16.76	0.17

Table 8 – Crack width calculation to a limit of 0.1 mm.

Steel stress [MPa]	Maximum bar spacing		Maximum bar diameter	
	$A_{s,adopted}$ [cm^2/m]	w_k [mm]	$A_{s,adopted}$ [cm^2/m]	w_k [mm]
160	22.62	0.09	22.44	0.09

Some results are more conservative for lower steel stress in service. However, the limit of the crack width defined in the first place is never exceeded.

4.4. Alternative graphs

In order to rectify the faults found by the analysis in indirect control of cracking, several graphs are elaborated to match the correct diameter and bar spacing with a determinate service tension and reinforcement area. Those graphs yield good results for different thickness of shells.

This graphs were based in a shell with 0.3 m of thickness and a bar cover of 0.03 m. There are six figures considering structures submitted to bending stress and tension, to the crack widths of 0.2, 0.3 and 0.4mm. Figures 9 and 10 show the different combinations of bar diameter and bar spacing that can be used for a maximum crack width of 0.3 mm subjected to bending stress and pure tension stress.

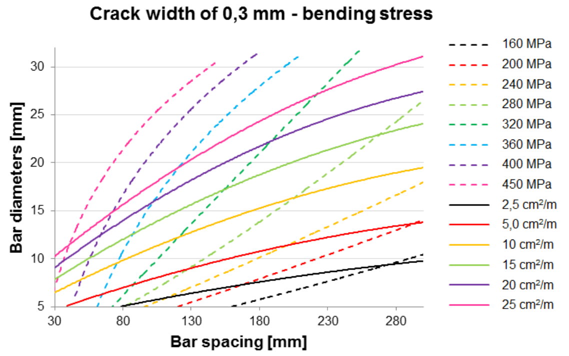

Figure 9 – Diameter bar vs bar spacing, for structures subjected bending stress.

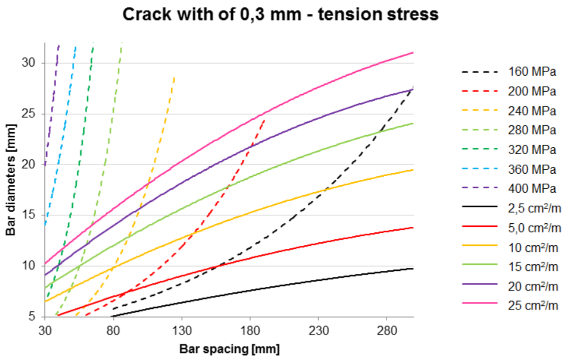

Figure 10 – Bar diameter vs bar spacing, for structures subjected to tension stress.

Through these two figures it can be concluded that there are a lot of choices for detailing a shell with a specific steel stress in service and a reinforcement area for the ultimate limit states (ULS).

In order to simplify the reading of these graphs, an example of a shell subjected to bending stress with a reinforcement area of $15cm^2/m$ and a steel stress in service of 320MPa, is followed.

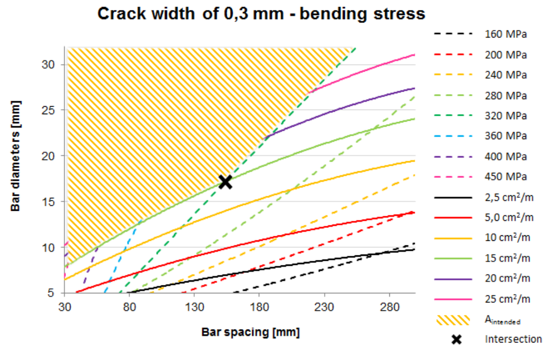

Figure 11 – Graph determination of the pairs bar diameter and bar spacing for a determined steel stress and reinforcement area to the ULS.

First of all, it is necessary to find the intersection point – marked as "X" – between the curve related to the considered steel stress in service and the curve related to the reinforcement area to guarantee the ULS.
Secondly, the area of possible choices of detailing matches to the yellow region marked in the graph.

To prove the efficiency of the new alternative graphs, an example was done comparing the new figures and the indirect method of Eurocode 2 – Part 1. The results are shown in Table 9.

Table 9 – Comparison of the alternative graphs and the indirect control of the Eurocode 2 – Part 1.

Steel stress [MPa]	Alternative graphs		Eurocode 2 – Part 1	
	$A_{s,adopted}$ [cm^2/m]	w_k [mm]	$A_{s,adopted}$ [cm^2/m]	w_k [mm]
160	-	-	-	-
200	-	-	16.36	0.17
240	-	-	15.47	0.18
280	15.98	0.25	15.08	0.19
320	15.13	0.26	15.71	0.20
360	14.75	0.27	15.23	0.22
400	15.71	0.26	-	-
450	15.23	0.28	-	-

It can be seen that the results for EC2-1 are conservative comparing with the alternative graphs. That can be a problem when aiming for more demanding crack widths and higher steel stress in service. In this example, by using indirect control, it could be concluded that there would not be any detailing for steel stress in service above 400MPa. However, with the alternative graphs, there is bar diameter and bar spacing that can be used to stress up to 450MPa.

Figures 12 and 13 show the reinforcement area considered in tables of indirect control of cracking by using the values of maximum bar diameters.

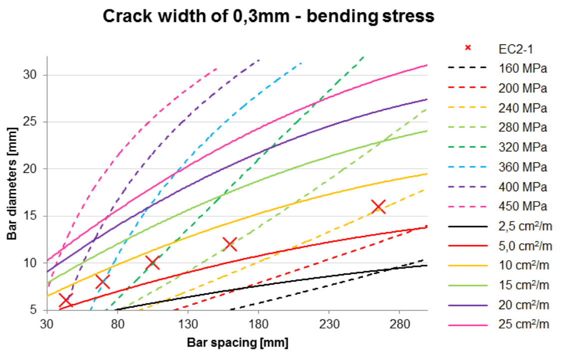

Figure 12 – Bar diameter vs bar spacing with the (dados) of the indirect control of the EC2-1.

It can be concluded that the area taken into account in the tables of indirect control is the minimum reinforcement area for the bending stress. If not considering the reinforcement area to the ultimate limit states, a detailing with reduce bar diameters can be adopted, which, sometimes, leads to a bar spacing so small that it cannot be produced.

The last graph was done for crack widths of 0.2, 0.3 and 0.4 mm to the bending stress and pure tension stress.

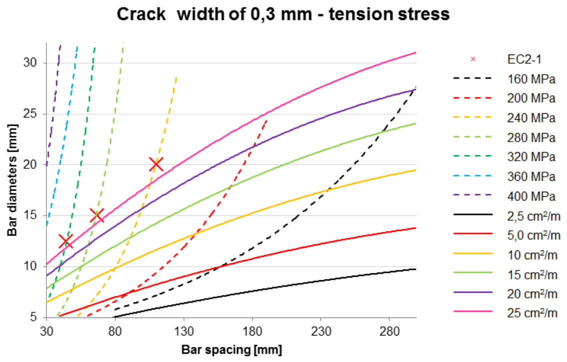

Figure 13 – Bar diameter vs bar spacing with the data of the indirect method control in the EC2-1.

By looking at these two graphs it can be seen that the quotient between the reinforcement area in tension stress and bending stress is near 3.3. For pure tension it is necessary more than three times the reinforcement area used in structures subjected to bending stress.

As these graphs cannot be applied to beams due to the many varieties associated with the detailing section it was necessary to create different graphs that correlate the bar diameters and the effective percentage of reinforcement area needed for ULS.

Six different graphs were produced, for crack widths of 0.2, 0.3 and 0.4 mm, subjected to bending and tension stresses. Figures 14 and 15 display graphs with a crack width of 0.3 mm for bending stress and pure tension.

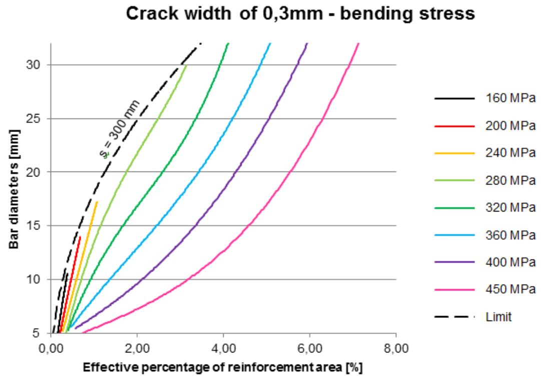

Figure 14 – Diameter bars vs effective percentage of reinforcement area.

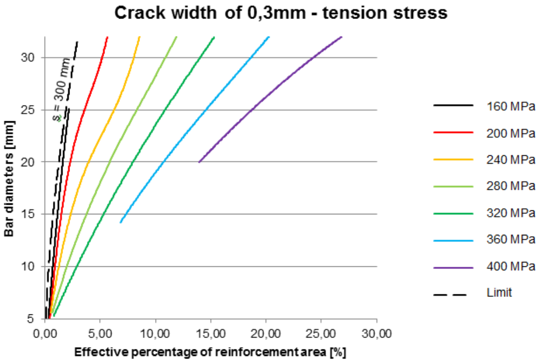

Figure 15 – Bar diameter vs effective percentage of reinforcement area.

Therefore, these graphs can be used with any structure because the effective percentage of reinforcement area is a dimensionless value.

These graphs are limited to a bar spacing of 300 mm such that the user will not choose a detailing that provokes cracks between bars that are not controlled.

5. Conclusions

Finally, with the development of these different cases, it can be concluded what is the influence of the parameters in the equations of the Eurocode 2 and understand the flops in the indirect method.

To bridge these faults and clarify the method that does not involve calculations, one suggests that the assumptions take into account should be clarified, such as:

- Structures like beams should not be detailed based in the indirect method;
- The data in the tables is calibrated for structures subjected to imposed deformations, so it is necessary to pay attention when using this method to structures subjected, mainly, to applied loads;
- These two tables are redundant, so one should consider just one of them.

6. References

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