Proposal of new crack width formulas in the Eurocode 2, background, experiments, etc.

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ABSTRACT
The Eurocodes are being revised in a significant effort undertaken by the Civil Engineering community with partial funding from the European Union. The new version was initially due to be published in 2020, but a more realistic date is 2023. For this revision, the guidelines call to improve ease-of-use, reduce nationally determined parameters and incorporate new, mature, knowledge. On the other hand, changes are to be kept to a minimum since changes imply significant costs in education and updating of existing software.

Within this context, this paper focuses on the updating of Chapter 7 and more specifically on cracking.

Key words: Cracking, stabilized cracking, flexure vs. tension, restraint, Eurocode 2, ease-of-use

1. INTRODUCTION

The responsibility for the review of EN 1992 falls to CEN-TC-250/SC2. In view of the importance of this task, SC2 created, ahead of time, in 2012, before any funding was approved by the European Commission, Working Group1 (WG1) with the task of preparing the new draft of EN 1992-1-1. One of the first decisions of WG1 was to avoid an object-oriented approach and to try to merge part 1-1 with part 1-2 and part 1-3 of EN 1992-1-1. WG1 created several task groups (TGs) do deal with new topics or topics requiring special attention. These topics were: Fibre reinforced concrete, Fibre reinforced Polymers, Existing Structures, Shear and torsion, Fire, Analysis, Time-dependent behaviour of concrete, Fatigue, Bridges and Durability. In 2015, when funding became available, the first project team, (SC2.PT1) was established with the task of writing the first draft of EN 1992-1-1:2020, excluding new topics, and of course fire, which are to be handled by two further project teams. The task of the PT is to take material from the TGs and the existing text from the Eurocode and achieve a new text which should be easier to use and with a significant reduction in nationally determined parameters and with due account for new, mature knowledge.

The current proposal for EN 1992-1-1:2020, which is still evolving, is the result of a gradual process which has involved discussions among the members of Project Team, together with the Convenors of SC2 and WG1, and, also, within WG1 itself. It has also been influenced by the comments received by the National Mirror Groups during the systematic review in 2012 and by comments to subsequent drafts from the PT.

For the topic of cracking the current text is the result of discussions within the PT and WG1 since no TG was tasked with this topic.

2 ADOPTING THE MC 2010 MODEL

The initial draft respected the current EN 1992-1-1 model because, even though, there is evidence that the MC2010 model provides better predictions of experimental data [1], it was not initially deemed to be a sufficient reason for change, given the large scatter of experimental data. However, when consideration was given to defining how time effects are to be considered, the fact that MC2010 considered also the effect of shrinkage was enough to justify the change.

Besides calibration and the consideration of the addition of the shrinkage strain to the strain due to loads for stabilized cracking, shifting to MC2010 involved another big difference: whether crack spacing is different for bending and for pure tensile stresses. EN 1992-1-1:2004 includes factor k_2 which halves the contribution of the bond term to crack spacing when the section is subjected to bending. The argument is that, in bending, due to the triangular distribution of stresses, it is necessary to transmit to concrete half of the tensile force to produce a new crack that it would be necessary for a uniform distribution of stresses (see Figure 1).

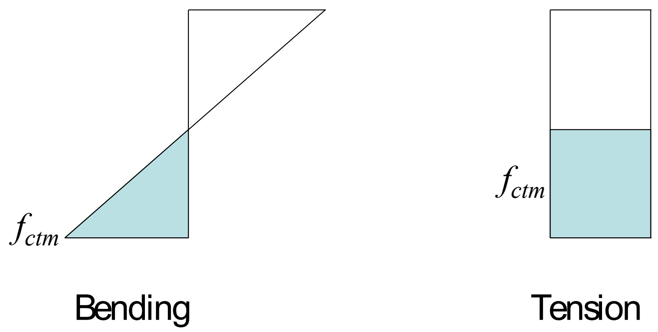

Figure 1 – Tension stress block in bending and tension. According to EN 1992-1-1:2004, the force to be transmitted to concrete through bond in order to produce a new crack would be half for bending than for tension (hence, $k_{2,bending}$=0.5).

MC2010, on the other hand, considers that, in bending, an effective concrete area forms around the bar and that, within this area, the stress variation is minimal (see Figure 2), and therefore there is no k_2 factor. Experimental evidence shows that the situation may be more similar to Figure 1 for small elements [2] and more similar to Figure 2 for larger elements [3] with some type of transition in between.

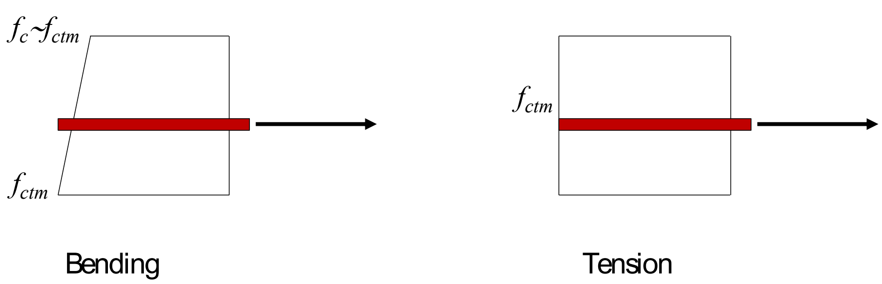

Figure 2 – Tension stress block in bending and tension. According to MC2010, the force to be transmitted to concrete through bond in order to produce a new crack would be more or less the same for bending than for tension (no k_2 factor).

This dual vision of the same problem is further complicated by another effect related to curvature which favours tension over bending and would tend to offset the favourable effect of a smaller crack spacing for bending. This effect shows that the crack width grows proportionately with the curvature as it is measured farther away from the bar.

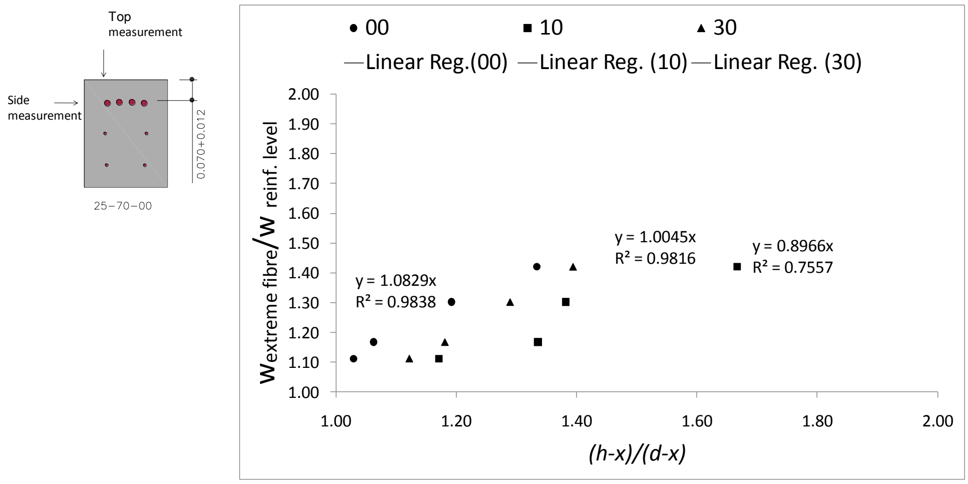

Figure 3 – Experimental evidence showing that the crack width grows proportionally with the curvature as it is measured farther away from the bar [4].

Adopting the MC2010 model was made difficult by the fact that considering the shrinkage strain made the model much more conservative for long term stabilized cracking. This problem was solved thanks to a comment by the French Mirror group, pointing out that adding the shrinkage strain directly implied full restraint. In fact, in most practical cases, the restraint is close to zero since the axial stiffness of a slab is much larger than the flexural stiffness of its supports, so that the slab can move freely. Therefore, the MC2010 equation was modified accordingly, where R_{ax} is the restraint factor:

$$w_{k,cal} = s_{r,\max,cal}\left(\varepsilon_{sm} - \varepsilon_{cm} - R_{ax}\eta_r\varepsilon_{cs}\right) \quad (1)$$

3 INTEGRATING EN 1992-1-3 INTO EN 1992-1-1:2020

As stated above it was one of the early decisions to avoid an object-oriented approach in EN 1992-1-1:2020 so that the clauses should be applicable to all concrete structures. For cracking, this meant integrating the content of EN 1992-1-3 into the Part 1-1. In particular, EN 1992-1-3 deals with cracking due to imposed deformations and the differences in behaviour when an element is restricted at the ends with respect to an element that is restricted at the edges. In the first case which is the typical example of a tie, cracking affects the distribution of forces along the whole tie, so that the formation of a new crack implies a drop in the axial force. In this way, while cracks are forming (crack formation stage), the axial force is never higher than the cracking force and is independent of the applied imposed strain. In the case of an element restrained at the edges, such as a wall restrained by a previously cast foundation or a slab supported by longitudinal walls on the sides, cracking only affects forces locally and the crack width is a function of the imposed strain. This dichotomy has been integrated into the proposal for the EN 1992-1-1 :2002 text as follows:

For elements subject to direct loads (stabilized cracking) or restrained at the ends and subject to imposed strains (crack formation phase), $\varepsilon_{sm} - \varepsilon_{cm}$ may be calculated from:

$$\varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s - k_t \dfrac{f_{ct,ef}}{\rho_{p,ef}}\left(1 + \alpha_e \rho_{p,ef}\right)}{E_s} \geq 0{,}6 \frac{\sigma_s}{E_s} \tag{2}$$

For elements subjected predominantly to restrained imposed strains (crack formation phase) and restrained at the edges, $\varepsilon_{sm}-\varepsilon_{cm}-\eta_r\varepsilon_{cs}$ may be calculated from:

$$\varepsilon_{sm} - \varepsilon_{cm} - R_{ax}\eta_r\varepsilon_{cs} = R_{ax}\varepsilon_{free} - k_t \frac{f_{ct,ef}}{E_{cm}} \tag{3}$$

4 EASE-OF-USE

Among other things, in the PT's vision, ease of use means consistent methods, presenting, easier to use, particular formulations first and afterwards more general equations for more complex problems and using tables to group concepts so that they are easier to grasp, altogether avoiding a list of different but related conditions, lost within the text.

For the case of cracking, the second principle is illustrated by the removal of section 7.3 *Verification of cracking without calculation*, which currently consists of a couple limited tables valid for very particular situations with a series of correction factors to account for other situations by a single formula consistent with the general method which allows the determination of the stress compatible with a given crack width opening, based on the safe-sided assumption that the provided reinforcement is equal to the minimum required reinforcement, according to equation (4):

$$\sigma_s = \frac{3{,}6 f_{ct,ef}}{\phi}\left[\sqrt{c^2 + 0{,}5 w_{k,cal}\phi_s \frac{E_s}{f_{ct,ef}}} - c\right] \tag{4}$$

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