RESIDUAL CRACK WIDTHS OF RC&PC STRUCTURES UNDER CYCLIC ACTIONS

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SUMMARY

This paper discusses the influence of minimum reinforcement on the cracking behaviour of prestressed concrete structures. It deals with the observation and modelling of the reclosing of cracks induced by a permanent compressive stress due to prestressing. A computerised proposed model allows to determine steel-to-concrete slip, bond stress, concrete stress and steel stress along the transmission length (between the cracked section and the homogeneous section (state I)). Good agreement was observed between the analytical model and the results of 11 large scale tests of RC & PC tie elements performed at EPFL. This paper also presents some applications and conclusions of a large parametric study performed using the analytical model.

Keywords: imposed loads or deformations, bond (concrete to reinforcement), unloading, cyclic effects, prestressed concrete, minimum reinforcement, cracking, residual crack widths

1. INTRODUCTION

This contribution skims through one part of a whole research project about *cracking behaviour and requirement on minimum reinforcement for prestressed concrete bridges or structures under cyclic actions*. This research included a series of tests on large reinforced and prestressed concrete tie-elements with different prestressing normal forces and various reinforcement ratios.

It is obvious that the whole problem is extremely complex. The real cracking behaviour of a prestressed concrete bridge is probably governed by two kinds of conditions: Firstly, by bond relationships between concrete and steel reinforcement. Secondly, by geometrical conditions like size or height of structural element and the real normal compressive permanent stresses distribution within concrete sections (induced by prestressing and taking into account the construction history or phases). It is foreseen to deal with this entire problematic at the end of this research project by writing a PhD Thesis and a synthetic report with practical recommendations. The purpose of this paper

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is limited to the prediction of cracking under cyclic loading, confining to bond and cracked concrete behaviour and neglecting for the moment the second aspect.

The behaviour of a large element subjected to a constant growing central traction causing cracking is quite well known. In contrast there is little information available in case of unloading, that is to say inversion of stresses (for example, prestressed elements). Based on our laboratory experiments on 11 large blocks, we aim at proposing a formula for the prediction of the opening of the cracks under various conditions over time (reclosing of cracks, cyclic changes,...).

2. EXPERIMENTAL PHASE

The tests were performed on large post-tensioned tie-elements, with the post-tensioning level (inducing a *permanent state of compression* s_{perm}) and the reinforcement ratio (ρ) varying from one element to another. The tie-elements were 4.50 m long, 0.80 m high and 0.25 m deep (Fig. 1 and Fig. 2).

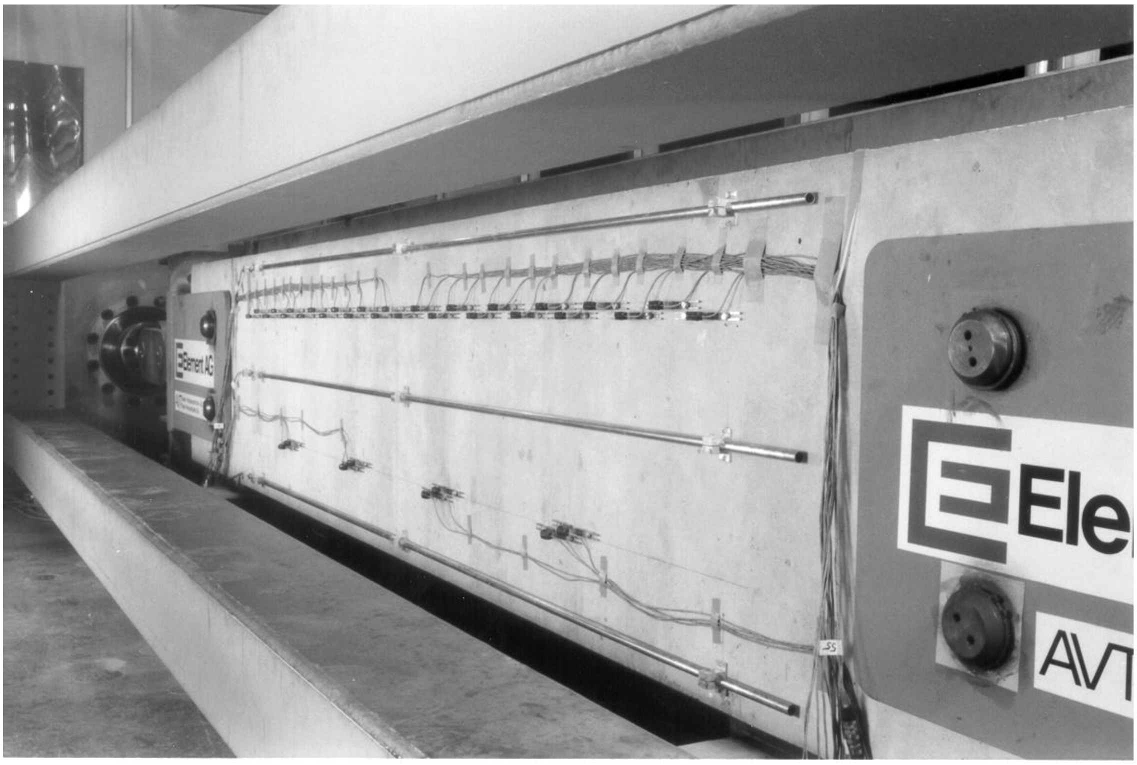


Fig. 1 Tie-element during a test

The tests consisted essentially to axially impose cyclic deformations (9'000 cycles which are representative of actual effects of temperature gradients and/or traffic loads in a real bridge) and to observe cracking formation and crack widths (measured by 70 strain Ω gauges) under maximal loading as well as by unloading under quasi-permanent concrete stresses due to prestressing (σ_{perm}). Results of these tests are reported in reference Laurencet and al. (1997).

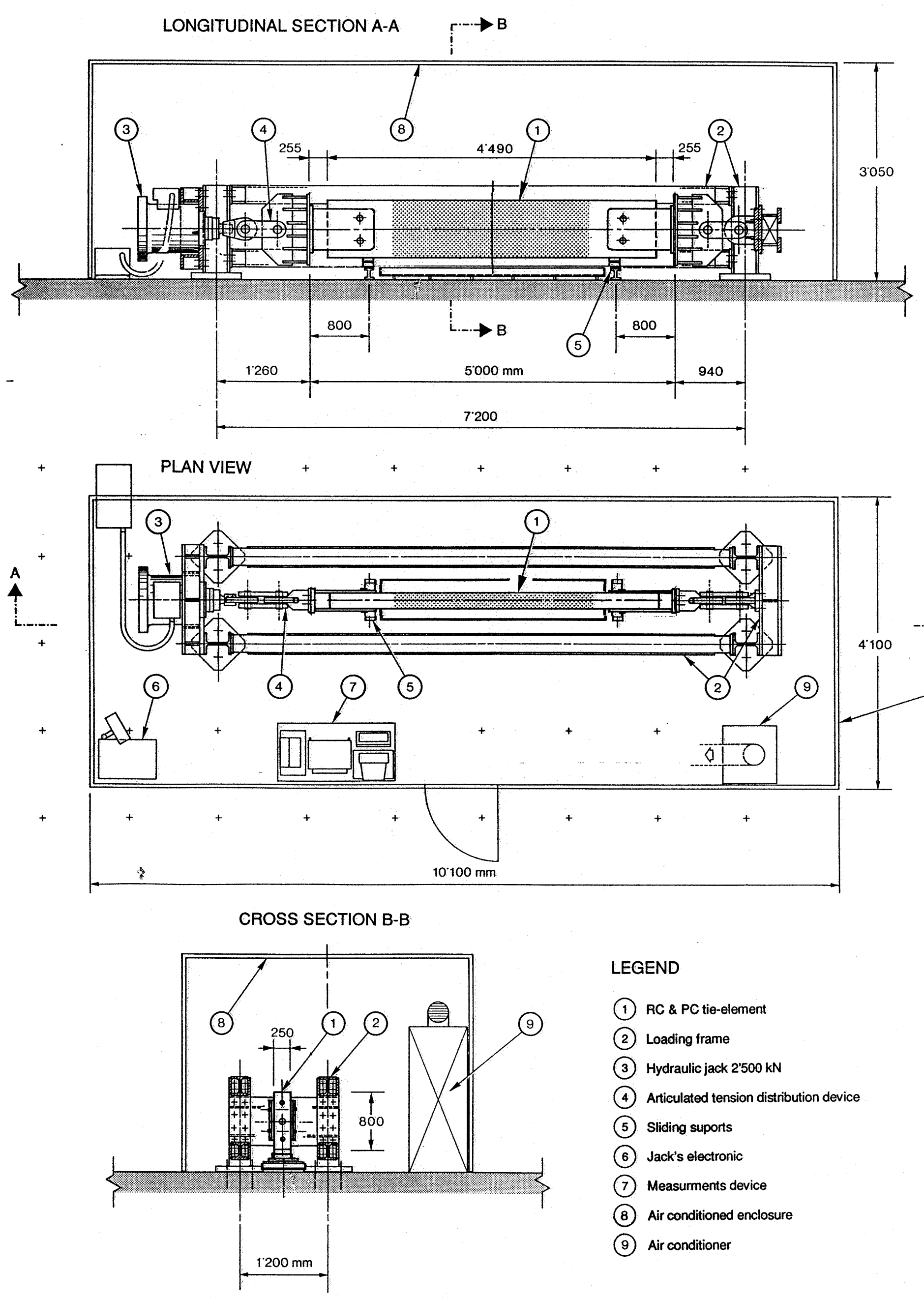
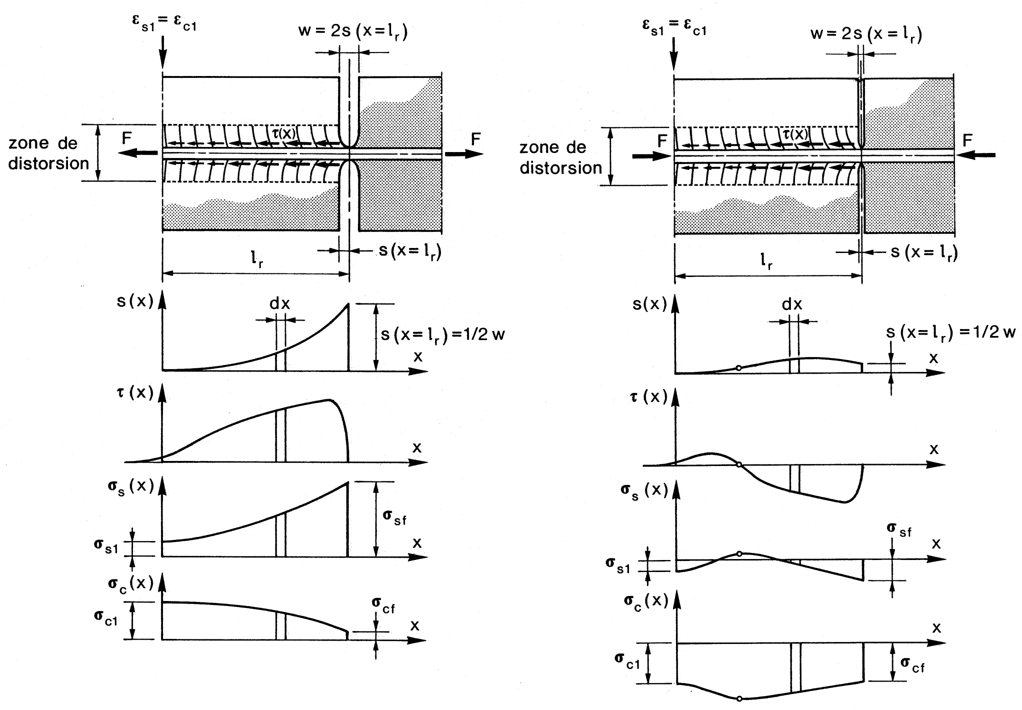


Fig. 2 Test set-up

3. MODELLING

3.1 Introduction

In the following, we propose a local model allowing us to predict the reclosure of cracks under a given compressive force (prestressing), knowing the maximum opening of cracks, geometrical and mechanical characteristics of the section and its diverse components as well as their interaction. The Fig. 3 represents the interplay between steel stresses (σ_s), concrete stresses (σ_c), local bond-stress (τ) and local slip (s) along a cracked element, during loading and unloading. In order to faithfully reproduce those observations, we have to choose adequate laws that represent the actual materials behaviours (§ 3.2). Then, we have to find a way to solve the differential equations (equilibrium) along the transmission length.



a) b)

Fig. 3 Schematic distributions of stresses and local slip along a cracked element
a) loading
b) unloading

3.2 Materials laws in the model

To clearly define the behaviour of *concrete*, it is necessary to make the distinction between homogeneous concrete (uncracked concrete) considered here as an elastic linear material and cracked concrete (localised around the cracks) considered as general softening. For the cracked concrete, Hordijk (1991) proposed continuous functions for loading and unloading, based on laboratory experiments. According to our tests results, it was observed that the first loading (to an imposed deformation of 0.4 ‰) leads to a crack opening larger than 0.25 mm (w_c, end of the softening). As a consequence, it seems reasonable to admit that the initiation's cracking phase is over[4].

[4] The majority of the formulas for modelling the reclosure of cracks seem to have been developed for the case where (w_{max}) < (w_c). As a general rule, no comment is made concerning their validity in the case of more significant cracks, exceeding (w_c).

Reinforced Steel is characterised by an elasto-plastic behaviour. Below, the yielding of the reinforcements marks the upper limit beyond which our model is no longer applicable.

The *bond-stress relationship* is the major factor influencing the opening and the reclosure of the cracks. The bond behaviour between the reinforcing bars and the surrounding concrete is very complex and is influenced by a great number of factors.

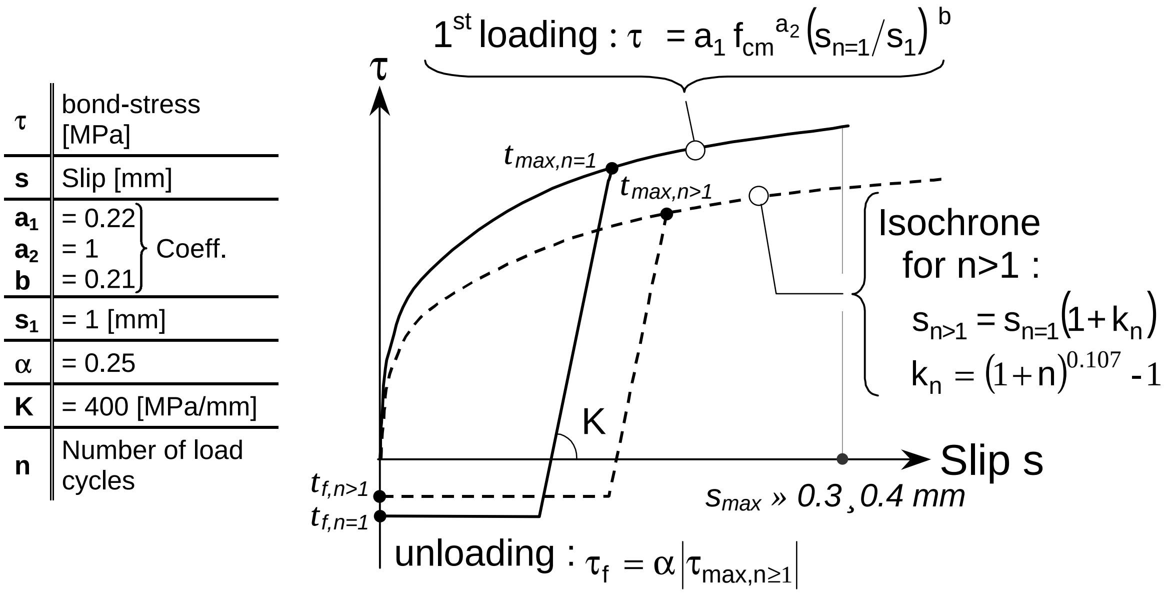


Fig. 4 Bond-stress slip relationship
- according to CEB (1990/1995) for the loading and cyclic effects
- proposed by the authors for the unloading

There are numerous models (sometimes extremely complicated) which seek to reproduce what happens between the surfaces of the steel and of the concrete under loading and unloading. In the framework of this study, we opt, during loading, for the bond relationship proposed by the CEB (1995). Under cyclic tensile loading with constant load level, the increase of the slip due to creep is calculated according to the CEB (MC 1990). For the unloading (under monotonic or cyclic loading) we propose a simplified model taking into account, as far as possible, the results of researches completed these last years dealing with the unloading of bounding.

3.3 Basic relationships

Our model is very close to a model developed by Tassios and al. (1981). Tassios was the first to study the behaviour of the transmission length (l_r) of a cracked element by dividing it into a number of parts of sufficiently small length Δx defined by the sections *i* and *i+1*. Knowing the crack spacing or the anchorage length (pull out tests) his model is able to calculate the full distribution of the slip (s) between the reinforcing bar and the surrounding concrete and of the stresses between the crack and the homogeneous state (state I, where $\varepsilon_c = \varepsilon_s$). He also simply derived deformations of flexural members thanks to his computerised model.

To the best of our knowledge, our model is the first able to calculate the transmission length (l_r), (without knowing the cracks spacing or the anchorage length), knowing only the boundary conditions at the cracked section (for the loading and the unloading).

4. EXAMPLES OF MODEL'S RESULTS

4.1 Calibration

The tests carried out at the EPFL (Laurencet and al. (1997)) allow us to confirm the good performances of the model (Fig. 5).

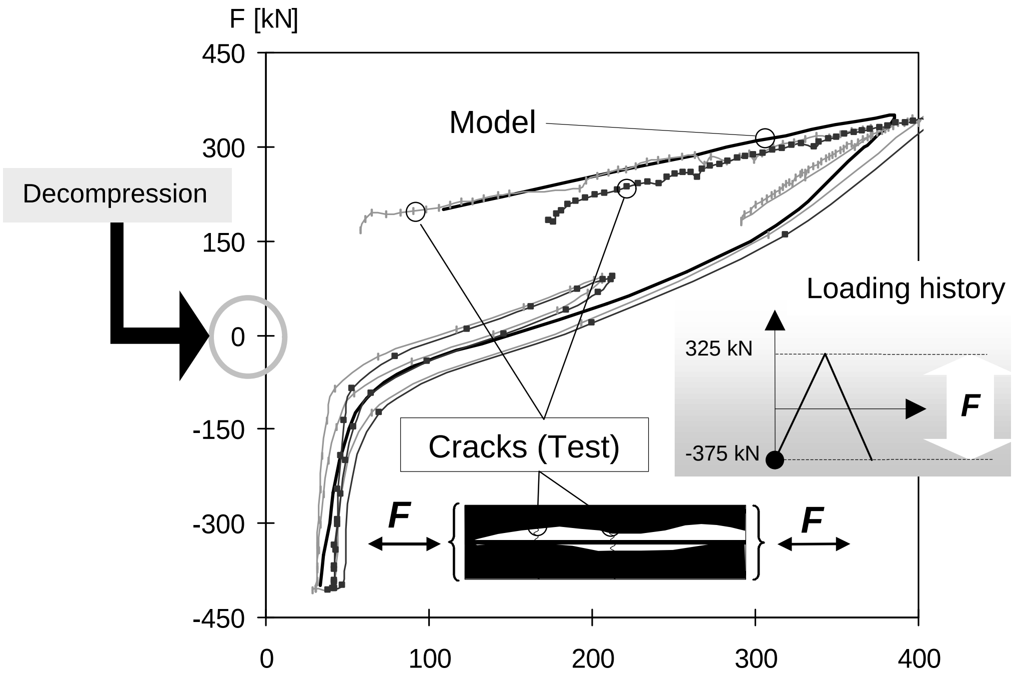


Fig. 5 Comparison between a test (P22) and the model's results

4.2 Parametrical study

A parametrical study performed with the model (Laurencet (1999)), allows us to highlight the influence of reinforcement steel's ratio, post-tensioning level (permanent state of compression) and concrete strength on the *reclosure of the cracks*. This model is able to take into account an imposed load difference ($\Delta\sigma$ [MPa], Rotilio (1998)) or an imposed strain difference ($\Delta\varepsilon$ [‰]). We don't want to linger on the results of the parametrical study in this paper. We just want to have a quick look at the results we have obtained to show the performances of the model for the prediction of the reclosure of the crack widths under cyclic actions (Fig.6 and Fig. 7).

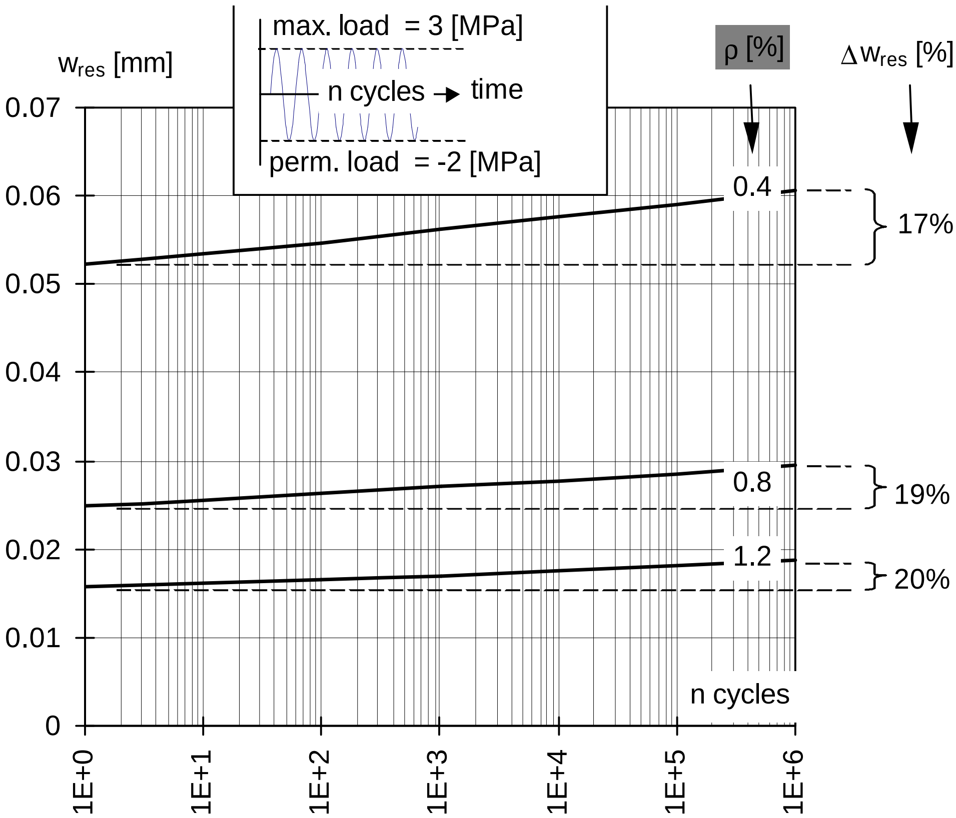


Fig. 6 Influence of the cycles (n) and of r on the evolution of the residual crack width

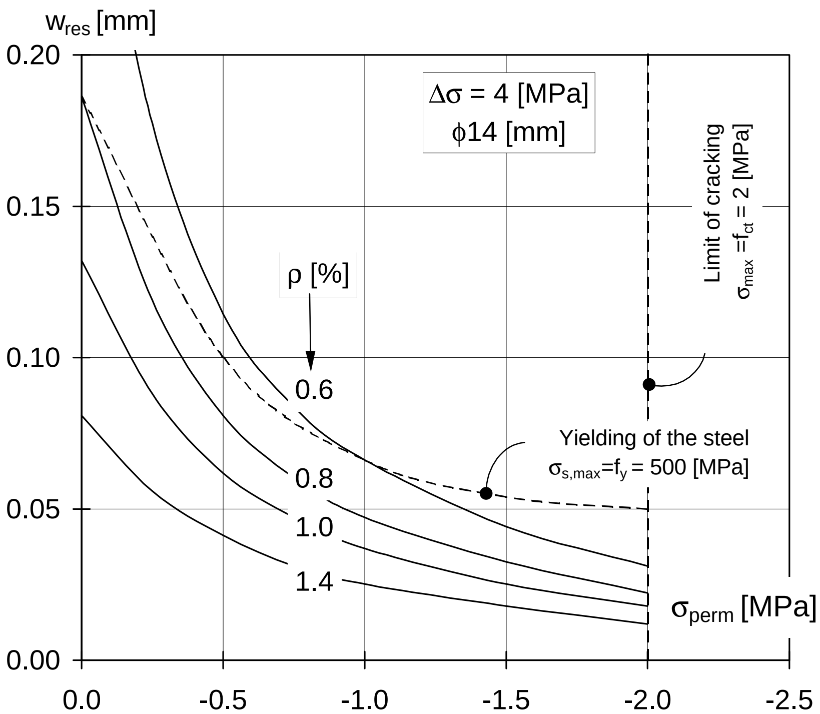


Fig. 7 Influence of s_{perm} and of r on the residual crack width (w_{res}) for Ds = 4 MPa

5. FINAL REMARKS

Tests on large tie-elements were shortly presented. A model was proposed to predict bond and cracking behaviour of reinforced and prestressed concrete structures under cyclic loading (due to imposed variable loads or deformations). A relative good agreement was observed between numerical predictions using this model and experimental results from tests made at EPFL on large specimens.

The tests results as well as a parametrical study made with the proposed model indicate that:

- Residual cracks widths under unloading (that means under quasi-permanent loading level taking into account prestressing) are largely influenced by the concrete permanent stresses (σ_{perm}) and are all the more closed as these stresses are high;
- Reinforced steel ratio (ρ) and, consequently, the minimum reinforcement quantity seems to be of much less important for cracking behaviour and for quality of prestressed concrete structures as observed for reinforced concrete structures;
- For usual quantities of prestressing and of steel reinforcement ratio, the increase in residual crack widths under cyclic actions does not exceed 20 % after 10'000 cycles.
- Minimum quasi-permanent compressive stresses of about 1 ÷ 2 MPa seem to be necessary in order to ensure satisfactory cracking behaviour, durability and quality of prestressed concrete structures (assuming that residual or permanent crack widths of about 50 µm may be considered as acceptable).

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