INVESTIGATION OF THE LONG TERM BEHAVIOUR OF HYBRID CONCRETE STRUCTURES

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SUMMARY

Structural elements consisting of new and old concrete may exhibit durability problems. The younger concrete is often cracked and debonds from the supporting older concrete. This paper presents the results of a parametric study based on a numerical model. The study shows the influence of differences between the shrinkage of new and old concrete, the creep, the thickness of the new layer and the amount of reinforcement. Experiments on slab specimens are briefly presented. The results of these tests will be used to validate the numerical results.

Keywords: concrete of different ages, durability, delamination, fracture mechanics, drying shrinkage, tensile creep, influence of reinforcement.

1. INTRODUCTION

During bridge maintenance, layers of new concrete are often applied to an old structure in order to repair and/or strengthen structural elements. This new thickness improves the protection of rebars against corrosion and the appearance of the structure. In certain cases, it also increases the carrying capacity of slabs, beams or columns. However, it often appears (Krauss, 96), after a few years, that the new concrete layer debonds. The shrinkage difference between the two layers and the difficulty in ensuring a good adherence between the two concretes are the major causes. This poses serious problems of durability to such modifications of structures. The study of the long term behaviour of structural elements is delicate. The time factor is an important influencing parameter. It generally takes a few years to observe the first signs of degradation of such systems. The experimental approach to the problem is thus difficult. The test duration limits the number of parameters which can thus be studied. For this reason, MCS tackled the subject by means of numerical simulation in order to analyze the influence of a broad range of parameters. Simulation is not only used to reproduce an observed behaviour or to design a structure. The aim of this numerical tool is to assist in the understanding of the phenomena. The parameters of the models implemented in the software are determined by means of standardised tests on samples. They are thus reproducible. The article presents the results of a parametric study using the numerical model. The degradation process of the hybrid concrete elements is studied as a function of the thickness of the new concrete, the ratio between creep and shrinkage, the adherence between the old and the new concrete, as well as of the internal stresses generated at early age. The relevance of the choice of the parameters studied and the results of numerical simulations were verified by carrying out a restricted number of experimental tests on slab elements 5.4 m long, 0.5 m wide and between 0.22 and 0.32 m thick.

2. DESCRIPTION AND MODELLING

2.1 Actions

2.1.1 Drying shrinkage

The main action responsible for the cracking of hybrid elements is the drying of concrete. Fig.1 illustrates the cracking mechanism of hybrid slab.

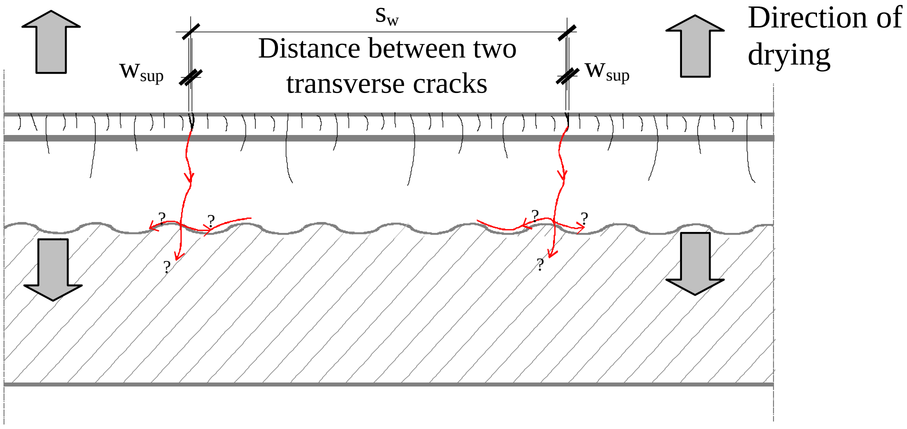


Fig.1 Cracking mechanism of hybrid slab due to drying

Before casting the new concrete, the upper surface of the support is wetted. This wetting increases the bonding between the two concretes and decreases the humidity gradient at the interface. The drying acts on the two faces of the new concrete, but the major effect is on the surface in contact with the environment. When the drying front begins to penetrate into the new layer, the resulting tensile stresses lead to a uniform cracking distributed over all the surface. When the drying front penetrates further, some cracks localise and others close. After a certain time, some cracks reach the interface and propagate in a direction which depends on the stresses in the new and old concrete. If the adherence strength is low, the crack propagates horizontally and the two concretes delaminate. If the adherence is strong enough, the crack continues to propagate vertically in the old concrete.

The model of Bazant (Bazant, 86) was used in order to reproduce the drying shrinkage of concrete. This model is based on a linear relation between the moisture potential (h) and the evaporated moisture content (w). The model is also based on the non linear diffusion equation, where $D(h)$ is the diffusion coefficient as a function of h:

$$\frac{\partial h}{\partial t} = \mathrm{div}\left(D(h)\,\mathrm{grad}\,h\right) \qquad \text{with } D(h) = D_0\left[\mathrm{a} + \frac{1-\mathrm{a}}{1+\left(\frac{1-h}{1-h_c}\right)^4}\right]$$

where D_0 is the diffusion coefficient for $h = 1$, a and h_c are parameters.

This modification of moisture conditions generates strains in the concrete elements. For each time interval, a linear relation between the strains and the change of moisture potential h is assumed :

$$\Delta\varepsilon_{cs} = \alpha_h \, \Delta h$$

where α_h is the constant shrinkage coefficient. All parameters of this model are calibrated by means of standardised shrinkage tests on cylinders (Ø 160 mm, L = 320 mm).

2.1.2 Other effects

The appearance of vertical cracks in the new layer is not only due to the concrete drying. Tensile stresses can also be due to thermal effects at early age, to the endogenous shrinkage or to external loads (traffic, dead load, temperature). The endogenous shrinkage is important for concrete with low water/cement ratio. This parametric study is based on our experimental research for which the concrete has a water/cement ratio of 0,5. In this case, the effect of endogenous shrinkage is neglected. The thermal effect due to the new concrete hydration is described and modelled in (Bernard, 97). In this study, the hydration process of the new concrete is not directly modelled. It is taken into account with a initial stresses state σ_{init} introduced at the beginning of the simulation. Different levels of σ_{init} are assumed with the goal of also representing the influence of an external load. Only static loading is considered. The cyclic loading effect for concrete bridge decks is discussed in (Schläfli, 97).

2.2 Concrete response

2.2.1 Tensile behaviour

The tensile behaviour of concrete is considered to be linear elastic until the principal stresses reach the tensile strength f_{ct}. The elastic modulus E is identical in compression and tension and is time dependant.
When the principal stresses reach f_{ct}, the cracking behaviour of concrete is represented by the fictitious crack model (Hillerborg, 89).
The fracture properties of concrete include the specific fracture energy G_F, the tensile strength f_{ct} and the softening law. This law defines the stress transfer across the fictitious crack when the crack opening displacement COD is lower than a critical value w_c. In this study, the softening law is assumed bi-linear where the breaking point is defined at the following values: $s_1 < f_{ct}$ and $w_1 < w_c$ (Fig.2). Fracture of concrete can be expressed by a unique material property, the characteristic length $l_{ch} = E\, G_F / f_{ct}^2$.

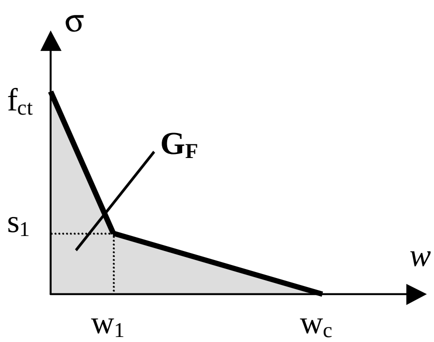


Fig.2 Softening law of concrete

2.2.2 Time influence

The strain compatibility of the new concrete cast on an old concrete support depends on the time factor. Concrete is a viscoelastic material and creep must be taken into account in a study of the long term behaviour of hybrid elements. The tensile creep of concrete

was identified as a major parameter influencing the cracking of hybrid elements (Bissonnette, 96). In his work, Bissonnette has determined the ratio between specific tensile creep and drying shrinkage of concrete $\varepsilon_{\varphi}(t,t_0)/\varepsilon_{cs}(t,t_0)$ on samples (70x70x400 mm). This ratio becomes constant after approximately 15 days and means that the physical phenomenon responsible for drying shrinkage and creep of concrete are at this stage correlated.
We apply the Maxwell Chain Model to describe the viscoelastic behaviour of concrete. In this model, the tensile behaviour is the same as in compression. All parameters of the Maxwell Chain Model are calibrated by means of drying shrinkage test results for different values of the ratio $\varepsilon_{\varphi}(t,t_0)/\varepsilon_{cs}(t,t_0)$. The calibrated model tests agreed well with the experimental results of Bissonnette.

3. PARAMETRIC STUDY

3.1 Parameters

This parametric study was carried out with the FE software MES/2.5D from the Femmasse company. The details of the model are given in (Roelfstra, 94).
Crack propagation in slab elements consisting of new and existing concrete was studied by considering the variation of the following parameters:

- the thickness of the new concrete (h_{new} = 70, 120 and 170 mm)
- the tensile strength of the new concrete ($f_{ct,new}$ = 1.0 and 2.5 N/mm^2)
- the ratio between specific tensile creep and drying shrinkage ($\varepsilon_{\varphi}(t,t_0)/\varepsilon_{cs}(t,t_0)$ = 0.0, 0.1, 0.125, 0.15, 0.2)
- the adherence between the two materials (30, 60 and 90% of $f_{ct,new}$)
- the initial stresses (σ_{init} = 0, 20, 40, 80% of $f_{ct,new}$)
- the presence of reinforcement in the new layer (with or without).

The mechanical properties of the old concrete were:
age τ at time t_0 = 3650 days, $f_{ct,old}$ = 3.5 N/mm^2, E_{old} = 40'600 N/mm^2, $l_{ch,old}$ = 456 mm, $G_{F,old}$ = 137.5 N/m and ($\varepsilon_{\varphi}(t,t_0)/\varepsilon_{cs}(t,t_0)$) = 0.10.
For the new concrete:
age τ at time t_0 = 7 days, E_{new} = 34'400 N/mm^2, $l_{ch,new}$ = 757 mm and $G_{F,new}$ = 22 N/m for $f_{ct,new}$ = 1.0 N/mm^2 and 137.5 for $f_{ct,new}$ = 2.5 N/mm^2.

For this parametric study, the shrinkage coefficient α_h was assumed to be 0.0018 for the two concretes. This value corresponds to a final shrinkage of 0.63‰ at a relative humidity of 65%. For the new and old concretes, the parameters D_0, a and h_c were assumed to be 51.8 mm^2/day, 0.05 and 0.9 respectively.
For the calculations, the environmental conditions were kept constant and with T_{amb} = 20°C and H_R = 70 %.
The element modelled had a length of 1m, was fixed at one end and was supported continuously over the old concrete. The thickness of the layer of old concrete was kept constant during the study at 150 mm. No dead load effect was taken into account. Numerical calculations were carried out for a period of 10 years.

3.2 Results and discussions

The discussion of the results that follows refers to the *reference* calculation carried out with the following parameters: h_{new} = 120 mm, $f_{ct,new}$ = 2.5 N/mm^2, σ_{init} = 20% of $f_{ct,new}$, adherence = 60% of $f_{ct,new}$, $\varepsilon_\varphi(t,t_0)/\varepsilon_{cs}(t,t_0)$ = 0.1 and without reinforcement. Fig. 3 presents the influence of $f_{ct,new}$ and the adherence between the two materials on the mode of cracking of the hybrid element.

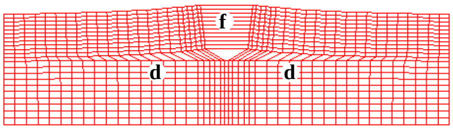
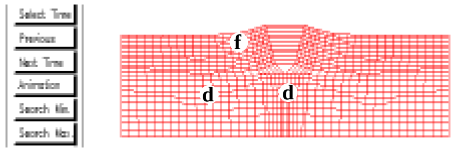
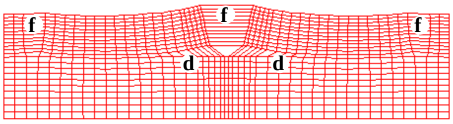
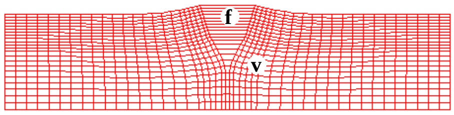
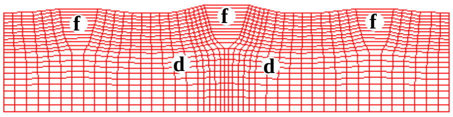
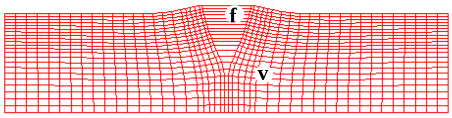
Adherence	$f_{ct,new}$ = 1.0 N/mm^2	$f_{ct,new}$ = 2.5 N/mm^2
30% of $f_{ct,new}$		
60%		(reference) 
90%		

Fig. 3 – Influence of $f_{ct,new}$ and the adherence on the mode of cracking

The cracking of these elements begins with the localization of a vertical crack (f). When this crack reaches the interface, either it is propagated horizontally creating a delamination (d) of the two materials, or it continues to propagate vertically in the old concrete (v). The delamination is directly proportional to the difference between resistance of adherence and the tensile strength of the old concrete. In addition, these results demonstrate the important role played by the support by distributing cracks in the new concrete. Indeed, for a tensile strength of 1 N/mm^2, the spacing of the vertical cracks is inversely proportional to the adherence. To emphasise this effect, Fig. 4 presents the evolution of the crack width at the surface w_{sup}.

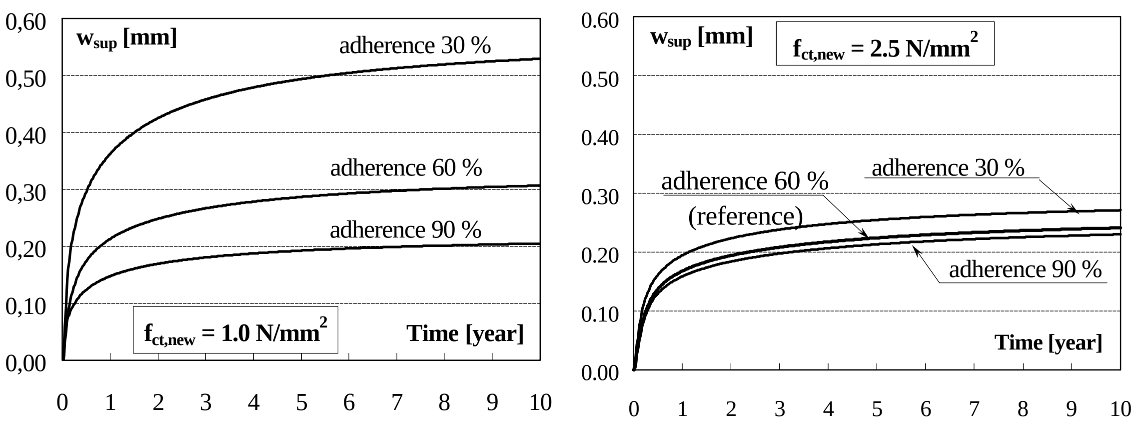


Fig. 4 – Influence of $f_{ct,new}$ and the adherence on w_{sup}

Crack width decreases with an increase in adherence. This decrease is greater in the case of a material whose tensile strength is lower.

For the reference case, the vertical crack propagates up to the old concrete for all values of h_{new}. As the old concrete absorbs the water contained in the new layer, the appearance of a transverse crack is difficult to avoid. The influence of h_{new} on the crack width at the surface is weak. However, the results illustrate in Fig. 5 that the time for the crack to reach the interface (c/h_{new} = 1, with c: depth of the vertical crack) increases with h_{new}.

The same representation is used in Fig. 6 to illustrate the influence of the ratio between specific tensile creep and drying shrinkage on the crack propagation in the new concrete. In this case, for high creep the vertical crack does not reach the interface (c/h_{new} = 1) and thus delamination between the two materials does not occur.

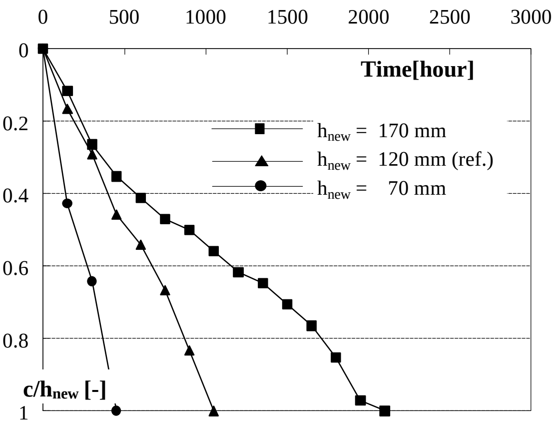


Fig. 5 - Influence of h_{new} on crack propagation

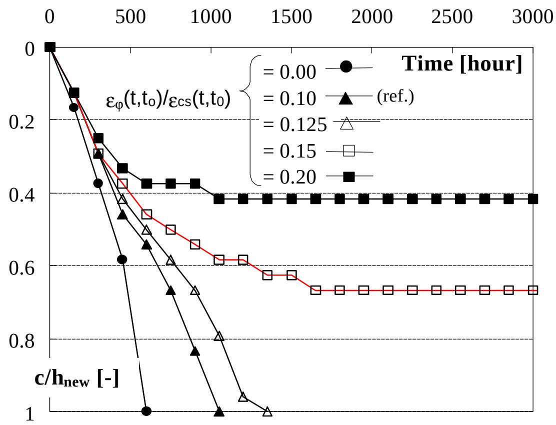


Fig. 6 - Influence of creep crack propagation

Fig. 7 presents the influence of $\varepsilon_\varphi(t,t_0)/\varepsilon_{cs}(t,t_0)$ on the crack width at the surface w_{sup}. The crack width decreases strongly when the tensile creep increases. These results illustrate the important influence of tensile creep on the cracking of the concrete elements subjected to restrained deformations. Practical values of $\varepsilon_\varphi(t,t_0)/\varepsilon_{cs}(t,t_0)$ vary between 0.10 and 0.15.

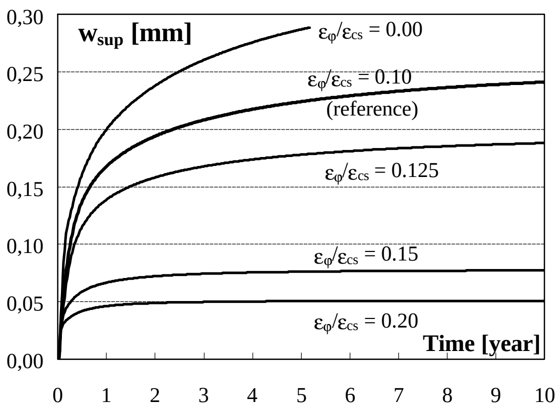


Fig. 7 - Influence of creep on w_{sup}

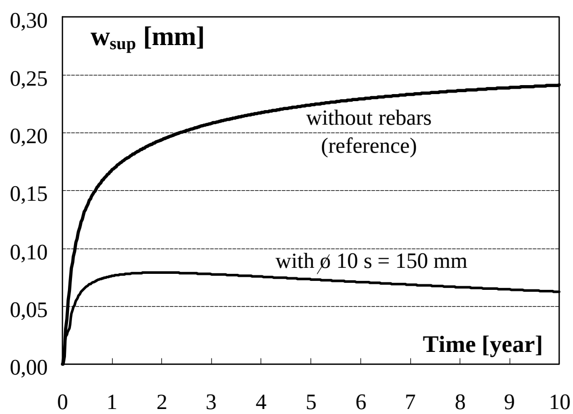


Fig. 8 - Influence of the rebars on w_{sup}

The initial stresses σ_{init} influence mainly the kinetics of the cracking of the hybrid system. For high initial stresses, crack propagation to the interface and the subsequent delamination are quicker. For the cases where the increase in tensile creep makes it possible to avoid the propagation of the crack until the interface (curve with $\varepsilon_{\varphi}(t,t_0)/\varepsilon_{cs}(t,t_0) = 0.15$ in Fig. 6), high initial stresses can be enough to cancel this benefit.

The model used to represent the tensile creep is independent of the applied stress level. Other researchers (Al-Kubaisy, 75) have shown that for a stress level higher than approximately 60% of the tensile strength, the mechanism of creep rupture becomes non linear. Consequently, in this study, the influence of the initial stresses can be somewhat under evaluated.

Fig. 8 presents the influence on the crack width at the surface w_{sup} of reinforcement in the upper part of the new layer. In this case, 10 mm diameter rebar at 150 mm centres are considered ($\rho = A_s/A_{c,new} = 0.43$ %). The results show that the presence of the reinforcement does not prevent the crack propagation through the old concrete. On the other hand, it makes it possible to limit w_{sup} significantly. According to the swiss code SIA standard 162, the percentage of minimum reinforcement in the new layer would be 0.66% in the case of severe requirements. However the results show that the serviceability requirements are also satisfied with less reinforcement. This is explained by the contribution of the support concrete that acts as extra reinforcement in distributing the cracking in the new layer. Consequently, a reduction in the currently recommended rates of minimum reinforcement is possible in the case of hybrid elements. Moreover, this reduction will be greater if h_{new} is low and if tensile creep of the new concrete is high. Indeed, when tensile creep increases (for example $\varepsilon_{\varphi}(t,t_0)/\varepsilon_{cs}(t,t_0) = 0.15$), w_{sup} is small and reinforcement is not activated. In this case, the effect of the reinforcement on limiting crack width due to drying shrinkage is negligible.

4. EXPERIMENTS IN PROGRESS

A series of laboratory measurements on 14 structural elements consisting of concretes of different age is in progress at MCS. Tests are carried out in three different stages. Firstly, during casting of the new concrete, the rise in temperature due to the hydration process was measured using thermocouples. Furthermore, the use of optical fibres allowed the evolution of the cross section strains to be measured. Then, bending creep tests are carried out on each element inside an air-conditioned room to study the long term behaviour of the hybrid structures, ($T_{amb} = 20 \pm 2$°C and $H_R = 30 \pm 5$%). These environmental conditions accelerate the drying shrinkage of each beam over 6 months. The variable parameters of these creep tests are: the thickness of the new concrete (h_{new} = 70, 120 and 170 mm), ratio of reinforcement in the new layer ($\rho = 0.37 \div 2.64$ %), the stress level ($\sigma_{ser}/f_{ct,new}$ = 0.35, 0.77 and 0.90) and the use of metal fibre concrete. During tests, deformation of the two layers is followed using optical fibres and displacements under the loads are measured using sensors. Crack width and delamination are also measured. Finally, a failure test will be carried out on each beam after the creep test in order to determine the damage caused by the various load cases. It will also determine the carrying capacity of the hybrid elements.

5. CONCLUSIONS

The following conclusions concerning the long term behaviour of structural elements consisting of concretes of different age are based on the numerical results presented in this paper:

1. Delamination depends directly on the adherence and the tensile strength ratio between the new and the old concrete.
2. The layer of old concrete distributes the cracking of the new concrete. Crack spacing decreases when the thickness of the new layer and the tensile strength of the new concrete decrease. Moreover, an increase in adherence between the two concretes reduces the crack spacing and limits their widths at the surface.
3. Cracks do not reach the interface if the tensile creep of the new concrete is high. Consequently, the delamination can be avoided by a judicious choice of the new concrete.
4. The ratio between specific tensile creep and the drying shrinkage of new material is identified as a major parameter influencing the cracking of the structural elements subjected to restrained deformations.
5. The use of reinforcement does not prevent crack propagation to the interface. On the other hand, when tensile creep of the concrete is low, crack widths at the surface are significantly limited by reinforcement.
6. Minimum reinforcement as required by current standards can be reduced in the case of hybrid elements.

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