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Modelling Thermal and Hygrometric Effects in Concrete

Modélisation des effets thermiques et hydriques dans les bétons

Modellierung der Wärme- und Feuchtwirkungen in Beton

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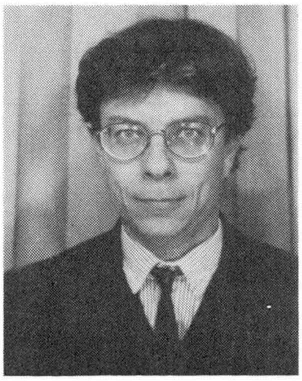
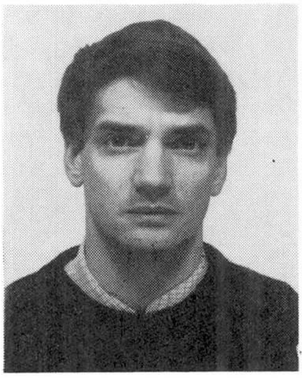




SUMMARY

The development of programs that are increasingly simple to handle and make possible numerical simulation of the phenomena of heat and moisture diffusion in concretes, together with an evaluation of the resulting mechanical effects, which are often large, provides a powerful tool for designers, in optimizing their choices, for those responsible for regulations, in improving standard practice, and for experts, in their diagnostic work. The experience acquired in these three areas is illustrated by examples of recent investigations and appraisals.

RÉSUMÉ

Le développement de logiciels, de plus en plus simples à manipuler, permettant la simulation numérique des phénomènes de diffusion de la chaleur et de l'humidité dans les bétons, ainsi que l'évaluation des effets mécaniques, souvent intenses, qui en résultent, constituent un outil puissant tant pour l'ingénieur concepteur dans l'optimisation de ses choix, que pour le responsable de la réglementation, dans l'amélioration des règles de l'art, et pour l'expert, dans sa démarche diagnostique. L'expérience acquise dans ces trois domaines est illustrée par divers exemples d'études et d'expertises récentes.

ZUSAMMENFASSUNG

Die Entwicklung von immer einfacher zu handhabenden Programmen zur numerischen Simuliering von Wärme- und Wasserverteilungsphänomenen in Beton und zur Ermittlung der daraus entstehenden, oft erheblichen mechanischen Auswirkungen liefert ein leistungsfähiges Hilfsmittel sowohl für den Planungsingenieur bei der Suche nach der optimalen Lösung, als auch für den Verfasser von Bestimmungen bei der Verbesserung von Bauregeln, sowie für den Experten bei der Erstellung seines Gutachtens. Die auf diesen drei Gebieten gesammelten Erfahrungen werden anhand verschiedener Beispiele von jüngeren Untersuchungen und Gutachten veranschaulicht.

1. THE IMPORTANCE OF THERMAL AND HYGROMETRIC EFFECTS IN CONCRETES

In analyzing the performance of concrete structures, three factors are generally considered separately :
- the material, defined by its mechanical properties (modulus, Poisson's ratio, creep law) ;
- the system of mechanical actions (dead load, distributed or concentrated live loads, imposed displacements, etc.) ;
- the ambient medium (climatic conditions, any corrosive agents).

In design rules, the ambient medium is taken into account either by parametering the laws of behaviour (hygrometry in the creep coefficient, for example) or by parametering the values of certain criteria (crack opening, for example).

While this approach is singularly effective in structural design (and can be used to develop satisfactory regulations), it has, nevertheless, two significant limitations. The first arises from the mechanical effects induced by temperature variations (whether during construction [1] or in service [2]) and/or by the natural drying of the concrete [3]. These effects are very large, and often lead to stresses substantially greater than those resulting from the the mechanical actions themselves. The second limitation arises because the mechanical properties of concrete evolve, and this evolution may be significantly altered by local temperature and humidity values [1][4]. The mechanical properties of the concrete are therefore not always uniform throughout the structure.

2. MODELLING OF THEIR MECHANICAL EFFECTS

As in the case of mechanical loads, temperature fields and humidity fields have both structural effects and local mechanical effects.

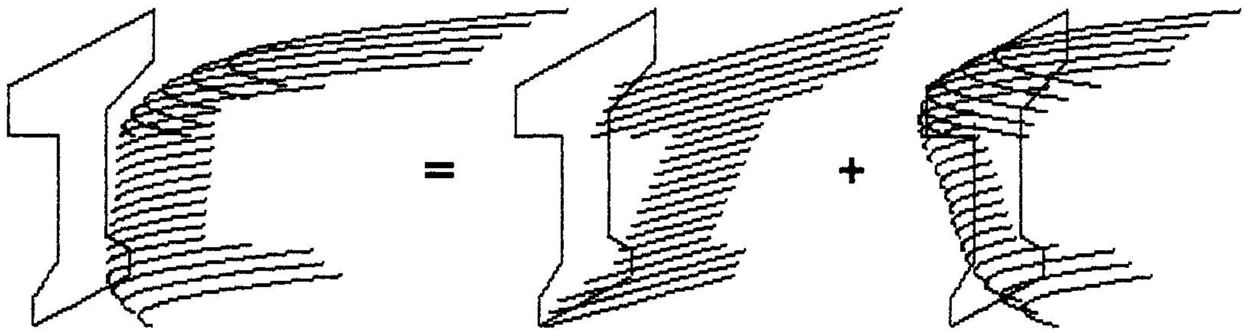


Fig.1 Breakdown of an imposed strain field (in beam theory)

Longitudinal total deformation imposed by a temperature or a moisture field T:	Equivalent plane field (= mean deformation + "effective gradient") defined by :	Self-balanced field in the section ("self-stresses") defined by :
$\varepsilon_z = \alpha.[T-T_0](x,y)$	$\varepsilon_\ell = A.x + B.y + C$	$\varepsilon_p = \varepsilon_z - \varepsilon_\ell$

Constants A, B, and C are obtained from :

$$\int_S \varepsilon_p.ds = 0 \quad ; \quad \int_S \varepsilon_p.x.ds = 0 \quad ; \quad \int_S \varepsilon_p.y.ds = 0$$

In this way, it can be shown [2] that, where beam theory applies, a given

imposed strain field can be regarded as the sum of two fields : a linear field and a self-balanced field. The former is, in each cross section S, a linear function of transverse coordinates x and y. It is obtained by equating its reduction elements (mean over the section and moments about the axes of inertia) with the true field. Its first component appears in form of a longitudinal deformation, generally free (expansion or contraction), the second component, called the "effective gradient", involves an imposed bending deformation, free only in an isostatic beam, where this first field produces no longitudinal stress. The difference between the first plane field and the true field, called the "self-stress" field, has only local effects (longitudinal stresses of which the integral over the section is null). Finally, the resultant longitudinal stresses are reduced by the free bending displacement. This does not hold of the transverse stresses, which result from the true field. This is one of the reasons why, depending on the static diagram of the structure, cracking of thermal origin may be strongly oriented in one direction or the other. This effect can also be quantified by a two-dimensional finite-element calculation (in addition to the plane strain and plane stress cases, the case of free bending must be allow for).
Obviously, this approach can be applied in a similar manner to the effects of drying, and casts new light on the delayed behaviour of concrete structures : shrinkage, as defined by regulations (i.e. as a uniform deformation) is only one of the three components that result from the dessiccation of concrete ; depending on the distribution of the water content in the cross section, there may also be (if the section is asymmetrical and/or dries asymmetrically) an imposed bending strain, free or restrained, and self-balanced stresses.

3. AID TO DIAGNOSTICS

For a certain number of problems (research on laws of behaviour, optimization of certain constructive arrangements, and especially the expert appraisal of pathological structures), it is essential to bear the following two remarks in mind :

1. — the mechanical properties of the material concrete are sometimes far from uniform, and a local value depends on the entire thermo-hygrometric history of the point in question and, to some extent (fatigue, creep recovery), on the entire history of mechanical stresses of the point.

2. — the stress condition at a point (and any cracking) may result not only from the usual mechanical actions (distributed and concentrated loads, imposed displacements) but also from stresses of thermal and/or hygrometric origin, in the form of imposed strain fields.

Such an approach is fully operational for surveys and analyses of the behaviour of structures in service. Its apparent complexity is no reason to take alarm, since, in such applications :

1. — the mechanical and physical properties of the concrete can be determined in situ by various experimental methods, mastered even more completely to the extent that the various causes of heterogeneity are known (elimination of the zones having a high hygrometric gradient, the depth of which can be estimated from the age of the structure, in the samples taken from the structure, for example).
2. — in view of the factors of safety applied to our engineering structures, the probability that damage results from the combined action of two independent causes is rather small : in most of the cases we have dealt with at the LCPC in recent years (about ten a year), the behaviour is or becomes pathological because a parameter, or an elementary mechanism, has not been taken into account

in the design, either through oversight, or because of a gap in the regulations, or because of incorrect prediction of or a change in the actual conditions of service of the structure.

This being the case, the analysis of thermal and hygrometric effects in concrete structures is in the context of the following approach :

1. — recording and examination of the apparent damage, in particular of its topological, geometrical (position, orientation, and spacing), and kinetic characteristics (age at onset, rate of evolution, any cycles), which is full of information ; as a general rule, this examination makes it possible to distinguish clearly between local effects and those related to the overall mechanical behaviour of the structure ; it also makes it possible to distinguish instantaneous and delayed causes, monotonic and cyclic causes ;

2. — analysis of the information to determine, exhaustively, the possible cause(s) ; this stage often yields feedback to point 1 ;

3. — quantitative analysis of each of the causes ; this analysis makes extensive use of numerical models, which make it possible, using the finite element method, to simulate both the processes of thermal or hygrometric diffusion and the resulting mechanical effects ; it then becomes acceptable, and sometimes even preferable, to ignore, idealize, or simplify all the other components, since the aim is to compare the order of magnitude of the calculated effect with that of the observed effects.

The aim of the examples given below is to show the effectiveness of this approach.

4. EXAMPLES OF EFFECTS OF THERMAL ORIGIN

The mechanical effects that result from the temperature fields that develop in a concrete part in the course of its manufacture, with or without accelerated curing, and numerical tools that may be used to deal with these problems have been described extensively elsewhere, with many examples of industrial applications [1][5].
These examples of applications clearly show that, except in the case of design problems, even a rough estimate of the physical and mechanical parameters of the material is more than adequate for dealing with such problems as :
- the choice of the best accelerated curing ;
- a search for and economic comparison of technical solutions to the problem of the cracking that appears during manufacture in parts that undergo accelerated curing or in massive parts ;
- optimization of the staging of concreting in large monolithic structures.

These technological problems of manufacture can generally be simulated by two-dimensional calculations (BITEX program). Thermal phenomena may also have consequences in the longer term, consequences that can be quantified using the same numerical tools, but which in some cases require three-dimensional calculation. This is why we have incorporated the computing module specific to the heat of hydration in the large modular code developed at the LCPC (CESAR system [8]), making it possible to go from the thermal calculations to calculations of their mechanical effects (directly, if the evolution of the mechanical properties of the material is neglected, as is acceptable for the technological objectives mentioned above).

5. EFFECTS OF HYGROMETRIC ORIGIN

The mechanical effects resulting from the natural drying of concrete may be regarded as resulting from imposed strain fields, just as is routinely done, as we have seen, in thermo-elasticity. Such an approach has been fully described elsewhere and has proven its utility in interpreting the behaviour both of the material [3][6] and of structures [7].

5.1. Law of behaviour of material

By calculating the mechanical effects resulting from the true water-content fields in concrete parts, it has been shown that, in small parts, in spite of the surface cracking that always occurs, an apparent shrinkage is in fact found, as the result, after cracking, of residual stresses in the concrete. The scale effect, which is quite marked, can be explained very well thanks to numerical methods. Even drying creep, or at least most of it, is explained [3][6]. The numerical simulation of drying [9] and the calculation of the imposed strains pose no special problem ; the cracking behaviour of the concrete can be taken into account in a satisfactory manner by damage models [10] or, more recently, by a stochastic model [11]. Here, the contribution of numerical models will be to check out the laws of macroscopic behaviour (i.e. of the regulation type), which are difficult to validate experimentally (today, to predict the delayed behaviour of structures of which the running thickness is between 25 and 120-cm, creep laws obtained on specimens that are rarely more than 15-cm thick, in which the mechanisms are significantly different, are used !).

5.2. Behaviour of structures

With few exceptions, it is only in thin parts that dry symmetrically that the effects of drying can be reduced to only "shrinkage" as defined in regulations (i.e. in the form of a uniform deformation). When the thickness of concrete exceeds 80-cm (or 40-cm with a waterproofed side), there is practically no shrinkage, but only restrained deformations. In common structures, the effect of drying is reflected, depending on the thickness of the part, by a mean deformation (the "shrinkage" of the regulations), surface cracking, and, what is most often overlooked, an imposed moment. This imposed moment results from two effects :
- the first is due to the asymmetry of the part and of the boundary conditions (an effect of pavement surfacings on bridges has been observed) ; this is the "moment" component of the imposed field (cf. fig. 1) ;
- the second is due to the asymmetry of the cracking - on the compressed side, the concrete cracks less or not at all ; this effect has been observed in prestressed concrete parts [7], in zones where the stress of one of the two extreme fibres is close to zero ; it can be shown that this effect is large and is capable of explaining the variations in support reaction in redundant prestressed-concrete structures [7].

Here the solution is far less simple, since <u>the nonlinearity introduced by the cracking makes it impossible to superimpose the various effects</u>, or to quantify them separately : as soon as there is bending, cracking is asymmetrical and drying creep becomes meaningless. This is a structural effect, and it can be combined with the law of behaviour of the material only under certain highly restrictive conditions.

5.3 Example of survey

The most important consequence for the engineer is that, in thick parts (i.e., in the case of compact "bridge grade" concretes, over 50-cm thick), shrinkage, considered as overall deformation, is negligible, since drying affects only a very small depth of concrete. Under these conditions of hindered deformations, designing the reinforcements is no longer a question of size (a tendon that is not stretched does no work) but of positioning (the closer together the cracks, the smaller they will be) ; here, the constructive arrangements can be optimized

only by modelling the anchorage of a tendon in a concrete subjected to an imposed strain field.
We were recently led to deal with a problem of this type in order to understand (an essential preliminary to choosing the type of repair) the cracking of a series of motorway bridges. These reinforced-concrete bridges, with solid slabs (fig. 2) had parallel longitudinal cracks, quite open (1 to 2-mm), extending practically their full length. Because their positions were unrelated to those of the supports, we ruled out, from the start, any cause having to do with the mechanical functioning of the structure as a whole.

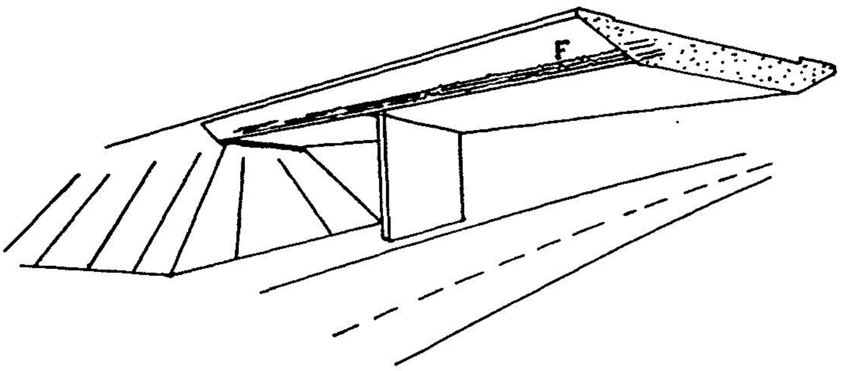


Fig.2 : Schematic drawing of half of one of the motorway bridges having, among other things, longitudinal cracks (F) parallel to 32-mm-dia. reinforcements not included in the working plans and not joined by a transverse tier. The thickness of concrete in the centre portion is 90-cm.

The cracks found were localized in the cantilever arms near each of the large reinforcements (dia. 32-mm) constituting the longitudinal reinforcement of this part of the deck. These reinforcements, not included in the working plans, were added at the last minute, but without the transverse reinforcements standard practice calls for. This body of information led us to hypothesize cracking caused by drying shrinkage. Numerical modelling of the finite-element type was used to quantify this hypothesis.

5.3.1. Hygrometric simulation

Cores taken from the structure were used to determine the distribution of water content versus depth. The water loss was about 5 % at the skin and less than 1 % at a depth of 8-cm. A numerical simulation of drying in the form of an exponential function of depth was judged to be an altogether satisfactory idealization of the phenomenon (fig.3).

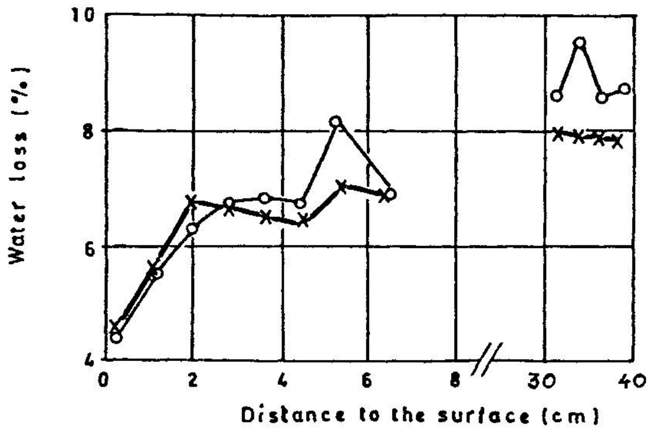


Fig.3 : Distribution of residual water content near the skin of the concrete, obtained by drying discs 6-mm thick taken from the structure, at 105°C. It can be seen that the depth of drying did not exceed 50-mm in spite of the age of the structure (11 years).

5.3.2. Description of computing model

Numerical modelling was carried out using the CESAR finite element computing

program [8]. We carried out a two-dimensional calculation in plane strain, for obvious reasons, and in linear elasticity, assuming, a priori, that the crack was open as far as the reinforcement. Given the symmetries of the structure and cracking pattern, the dimensions of the model used were considerably reduced (fig.4). In addition, we limited the depth of the model to 15-cm, since it seems reasonable to suppose that surface drying no longer affects the concrete at this depth.
Only the concrete portion was taken into account in the calculation. The concrete was here regarded as an isotropic material having a Young's modulus of 40,000 MPa and a Poisson's ratio of 0.17.
We used six-node triangles for the mesh, made denser in the zone around the reinforcement. The boundary conditions pose no special problem (cf.fig.4).
The only loading taken into account in this calculation was loading of the hygrometric type. We estimated the hygrometric contraction coefficient of this concrete at 10^{-3} per point of water loss as a percentage of total weight [12].

5.3.3. Calculation results

Figures 4 and 5 show, respectively, the deformation of the structure and the principal stresses.

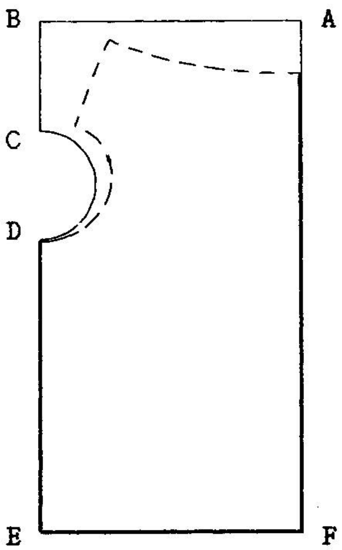
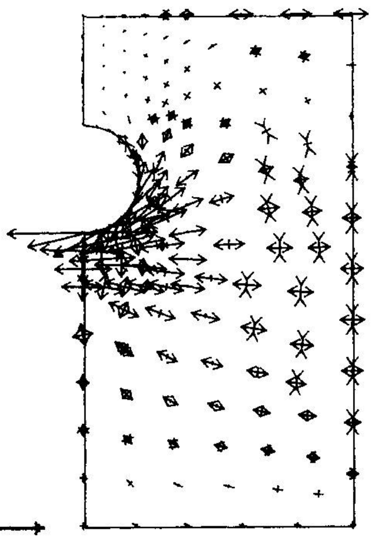


Fig.4 : Model used and its deformation, under an imposed strain field, determined from the measured water contents.
The boundary conditions are :
AB = 75-mm (half of distance between reinforcements : edge free
BC = 32-mm (coating) : edge free (crack)
CD = 32-mm (reinforcements) : circular edge free
DE = 86-mm : U = 0 (no crack)
EF = 75-mm : U = V = 0
FA = 150-mm : U = 0

Fig.5 : Principal stresses →



Three remarks may be made in the light of the calculation results :

1. Because of the symmetries, the values of the horizontal displacements of the nodes on the edge of the crack are half the crack opening values. We accordingly obtained a crack opening of 0.75-mm at the surface and about 0.40-mm at the reinforcement.

2. The values of the principal tensile stresses at the nodes just below the reinforcement remain of the order of 100 MPa. We may conclude that the crack depth does extend beyond the reinforcement. Two other calculations were carried out, with the nodes free over an additional depth of 16 and 60-mm, respectively. The crack opening at the surface changed little, but substantial tensile stresses persisted in the vicinity of the interface with the reinforcement, suggesting the existence of radial cracks.

3. A first calculation carried out with friction-separation contact elements between the steel and the concrete showed that all of the nodes of these

elements separated when the same loading was applied. This justifies our decision not to model the steel or its action on the concrete in our linear calculation.

5.4 Discussion

From the water contents measured in situ, we were able to quantify the opening of the cracks at the 32-mm-dia. reinforcements at 0.75-mm. This agrees with the order of magnitude of the cracks found in the structures, and it may therefore be concluded that the cracks along these reinforcements are indeed caused essentially by drying shrinkage. If such cracks are not found elsewhere in the structure, it is doubtless because the longitudinal and transverse reinforcements are sufficient to ensure cracking that is more closely spaced and hence less marked.
After this validation, two other calculations was made, (i) with an other width of the mesh, in order to confirm that the cracks are more open at the extreme steels of this tier, and (ii) with an other hygral strain distribution, in order to explain why the cracks were not observed previously.
Finally, it was concluded that a passive (so cheeper) repairing will be sufficient to prevent an aggravation of the disorders.
It would be pointless to seek greater precision in the evaluation of the crack openings. However, the existence of very strong tensile stresses tangent to the steel-concrete interface shows that the use of radial contact elements in the vicinity of this interface would doubtless have allowed for a finer-scale analysis of the cracking mechanisms. However, this approach calls for a number of successive calculations simulating the course of the drying process.

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