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Direct Measurement of Stresses in Concrete Structures

Mesure directe de contraintes dans des structures en béton

Direkte Messung der Spannungen in Betonbauwerken

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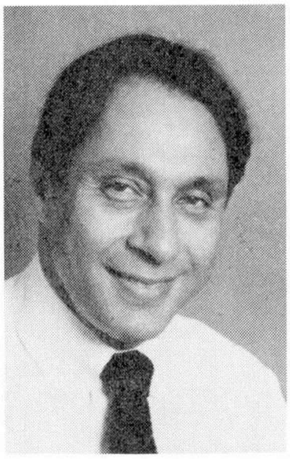


Charles Abdunur got his civil engineering degree, worked for five years on the design and supervision of several big projects, then prepared and obtained his doctorate in 1974. Since then, Charles Abdunur directs several research programs at a civil and structural engineering laboratory.

SUMMARY
To evaluate the absolute stresses in concrete structures, a direct method by partial stress release has been developed. It consists of cutting a slot in the concrete, restoring the initial strain field with an ultra-fine flat jack and measuring the pressure. The method has been thoroughly examined from its theoretical, technological and metrological aspects. It is now operational with an error margin of 0,3 MPa for both compression and tension. Following a thorough study of the shrinkage stress distribution, it is now possible to separate the two components of the measured absolute stress: applied and residual.

RESUME
Afin d'évaluer les contraintes absolues dans des structures en béton, une méthode directe par libération partielle a été adoptée. Elle consiste à pratiquer une entaille dans le béton, puis à rétablir, avec un vérin ultra-plat, le champ de déformations initial et à mesurer la pression. Cette méthode a été minutieusement examinée sur le plan théorique, technologique et métrologique. Elle est désormais opérationnelle avec une marge d'erreur de 0,3 MPa, qu'il s'agisse d'une compression ou d'une traction. Après une étude poussée sur la répartition des contraintes de retrait, il est possible de séparer les contraintes appliquées et les contraintes résiduelles qui forment ensemble la contrainte absolue mesurée.

ZUSAMMENFASSUNG
Eine Methode zur Bestimmung der absoluten Betonspannungen in Bauteilen mit Hilfe von Druckmessdosen wurde entwickelt. Bei dieser Methode wird ein Schlitz in den Beton geschnitten und das ursprüngliche Dehnungsfeld mit Hilfe einer flachen Druckmessdose wieder hergestellt und der Druck gemessen. Das Verfahren wurde vom theoretischen, technologischen und messtechnischen Standpunkt her gründlich untersucht. Es ist jetzt mit einer Fehlergenauigkeit von 0,3 MPa sowohl für Druck- als auch für Zugspannungen einsatzfähig. Eine umfassende Untersuchung über die Schwindspannungsabteilung hat es ermöglicht, die gemessene absolute Spannung in die Komponenten aufgebrachte Spannung und Schwindspannung aufzuteilen.

1. INTRODUCTION

In a concrete structure, showing signs of damage, the determination of the state of absolute stress is an essential element for diagnosis and for the evaluation of its residual strength. However, as these absolute stresses cannot possibly be determined through mere strain measurements, a direct method by partial stress release was considered. It consists in a local elimination of stresses, by cutting a slot, followed by a controlled stress compensation (fig. 1). In practice, the displacement reference field is first determined; a slot is then cut in a plane normal to the desired direction of stress determination; finally, a very thin flat jack is introduced into the slot and used to restore the initial displacement field. The amount of compensating pressure is an indication of the compressive stress in the direction normal to the slot.

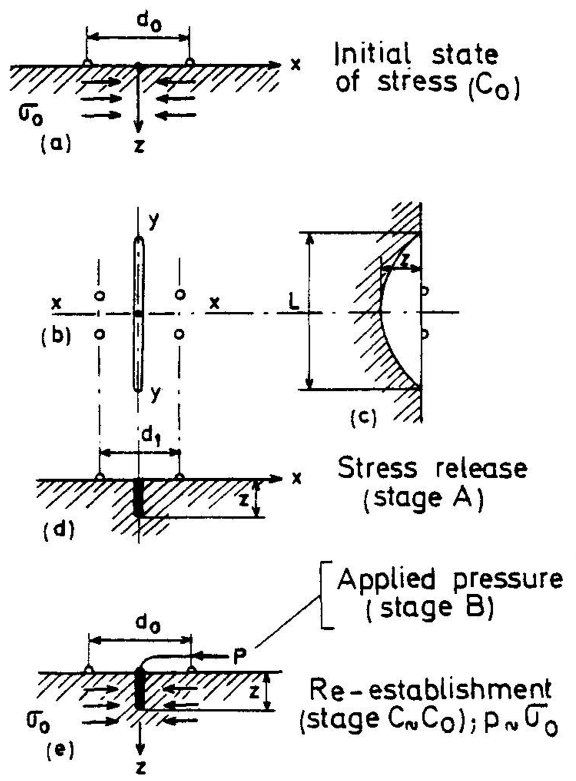


Fig. 1
Different stages of stress measurement by partial release

2. APPLICATION TO CONCRETE

Although this principle was easily applied in rock mechanics, its mere transfer to concrete has been repeatedly disappointing for two main reasons:

- The difficult nature of concrete as a material.
- The complications arising from the absolute need for the miniaturisation of this destructive operation.

To overcome these difficulties, the method was thoroughly re-examined from all its basic aspects that led to several imperatives:

- Behaviour analysis of the slot vicinity from a purely mechanics viewpoint.
- Dry cutting and simultaneous thermal stability to avoid the complete distorsion of measurements.
- Miniaturisation, considered absolutely imperative, but resulting in measurements increasingly sensitive to heterogeneity, hair-cracking, cut clearness and, above all, to the quality of the jack.
- Evaluation of tensile stresses occuring in zones where the applied compression is sufficiently low to allow the prevailance of internal stresses.
- Break down of the measured absolute stress to its two main components: applied and internal.
- Correction for cutting through reinforcement during stress release.

3. ORIENTATION OF THE RESEARCH

Three following basic objectives were fixed:

- To analyse the disturbance in the displacement, strain and stress fields induced by the presence of a slot in a medium subject to known stresses.
- To evaluate the restoration of these fields, using an ultra-fine jack.
- To establish a correlation between the cancelling pressures in the jack and the initial stresses.

The governing parameter is the depth of the slot.

4. EXPERIMENTAL PROGRAM

It followed three lines of attack where different tests often had to overlap:

- Development of specific instruments and procedures.
- Tests on plexiglass, using photo-elasticity and the Moiré-technique, to study the effect of the slot in a homogeneous and isotropic material.
- Identical tests on concrete models, using mechanical and electric gauges, to simulate actual cases and to study local effects.

5. DEVELOPMENT OF THE EQUIPMENT

The equipment included the release and cooling apparatus, the flat jack and the measurement apparatus.

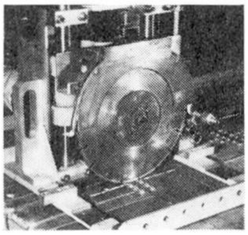


Fig. 2
Cutting machine

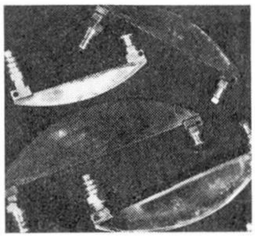


Fig. 3
Flatjacks

Cutting is carried out by successive passes which alternate with measurements. This involves the lifting of the cutting wheel and its reposition with great accuracy (0.1 mm); a special apparatus was constructed for this purpose (fig. 2). A very sharp and clear cut, with a uniform thickness, was thus obtained. Furthermore, a special cooling system was developed to favour dry cutting. The thermal stability thus achieved was excellent. The flat jack had to reconcile miniaturisation with strength and flexibility. A prototype 4 mm-thick jack (fig. 3) was designed by the author, constructed by a craftsman and successfully tested in the laboratory. In the measurement apparatus, the displacement field is materialized by a set of mechanical gauge bases. It is complemented by strain gauges forming the strain field for instantaneous measurements. Immediately prior to cutting, the readings taken of these two sets constitute their respective initial or reference fields.

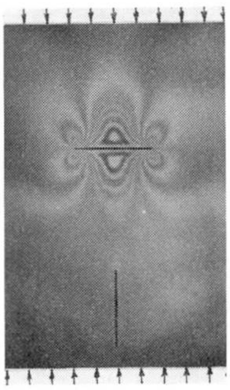
6. THE IDEALIZED MODEL

The surface behaviour of a three-dimensional model was analysed on a series of plexiglass blocks by two complementary optical methods.

6.1 Qualitative analysis

On a plexiglass block, provided with photo-elastic coating, a first slot was cut parallel to the intended direction of loading. Under a uni-axial uniform compressive stress, hardly any disturbance was noticed (fig. 4 a). A second slot, perpendicular to the first one, produced a very clear disturbance in the stress field (fig. 4 b). The observations would favour the measuring of absolute bi-axial stresses.

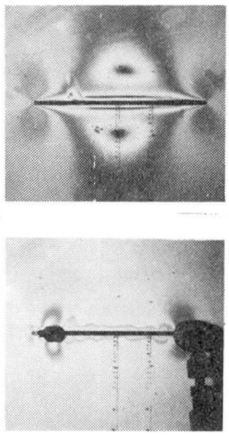
(b)



(a)

Fig. 4
No disturbance in slot (a)

(a)



(b)

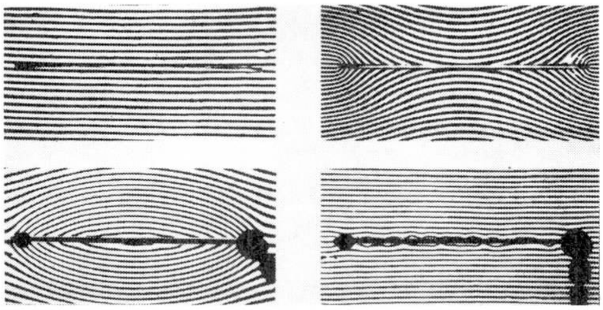
Fig. 5
- Disturbance
- Restoration

Another similar block, containing a slot, was also subjected to pure compression in successive stages. Fig. 5 a again reflects the extent of the disturbance in the stress field. Fig. 5 b, on the other hand, shows the high degree of its re-establishment, using a prototype flat jack. At each stage of loading, the cancelling pressure proved to be exactly equal to the corresponding applied stress.

6.2 Quantitative analysis

A third block, containing a slot, was equipped with a double Moiré-grating (fig. 6 a). It was then subjected to three phases of loading (fig. 6 b, c, d): Pure compression, a uniform pressure with a jack in the slot, finally a combination of the foregoing two. Fig. 8 a, b, c show the results obtained and efficacy of the flat jack in restoring the field. These results also confirm and complement those of the calculation carried out previously by finite elements.

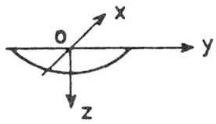
(a) (b)

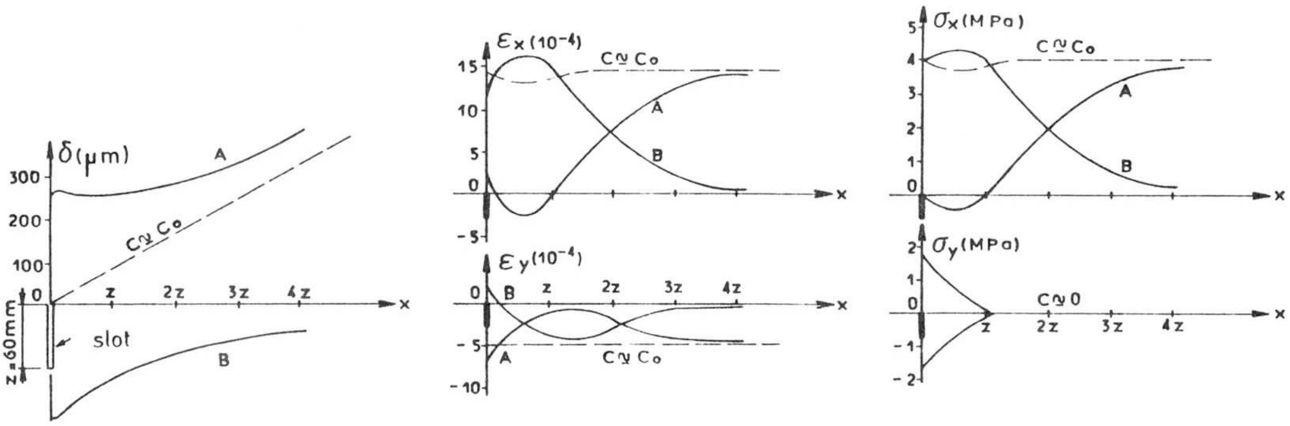


(c) (d)

Fig. 6
Disturbance and restoration of the displacement field
(a) unloaded (b) external loading
(c) pressure in slot (d) combination of b and c

Fig. 7
Co-ordinate axes





a) Displacements; assumed positive towards the slot

b) Strain; contraction assumed positive

c) Stresses; compression assumed positive

Fig. 8 - Displacement, strain and stress distribution along an axis normal to the plane of the slot; obtained on a plexiglass model by the Moiré-technique. Cases of loading: A - Pure compression (σ_x = 4MPa); B - Pressure (4MPa) in the slot; C - Combination of A and B; C_o - Pure compression in a model without a slot. The slight distortion in the results is due to the delicate treatment of data and not to a supposed rigidity of the jack.

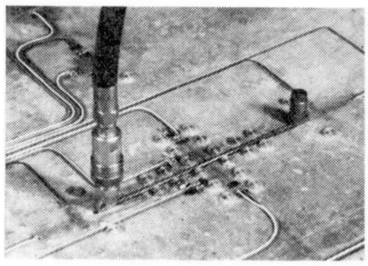


Fig. 9
Measurement apparatus on concrete

7. CONCRETE MODELS SIMULATING THE ACTUAL CASE ACCURACY OBTAINED

Now that the theoretical, technological and metrological problems are resolved, the way is paved for the application of the release method on concrete.

7.1 Compressive stresses

The tests undertaken on plexiglass by optical methods, were repeated on uncracked concrete models by extensometry (fig. 9). They were carried out within the elastic limit and at different slot depths. The results were in close agreement with those already obtained on the idealised models. Fig. 10 shows the essentials of this study, i.e. for a model subjected to pure compression, a maximum error margin of 0.3 MPa was found between the cancelling pressures and the actual applied stresses.

7.2 Tensile stresses

The principle of estimating compression by measuring the cancelling pressure could have the following corollary: Tension can be estimated through measuring a subsequent forced extension and the pressure that caused it, then by extrapolating down to zero displacement (fig. 11).

7.3 The stress gradient

Other tests were carried out on models subjected to flexure. At each slot depth, the measured stresses agreed fully with the theoretical ones, acting at the centre of gravity of the jack. Hence, by measuring the stresses at closely successive depths of the same slot, the gradient can be determined with a good approximation.

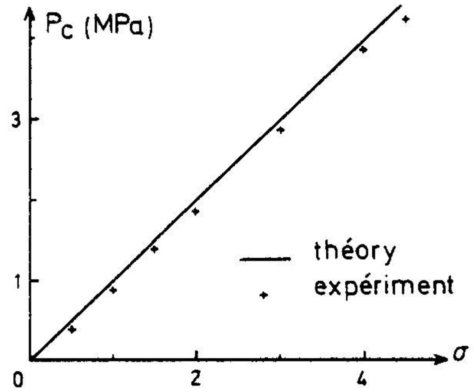


Fig. 10
Comparison between the cancelling pressure and the actual applied stresses.

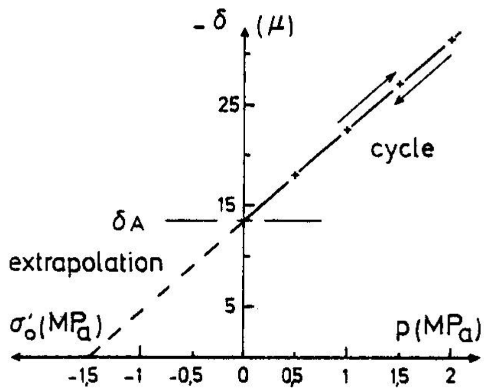


Fig. 11
Evaluation of tensile stresses, σ', by means of a pressure cycle p and corresponding displacement measurements, δ (δ_A: extension on stress release)

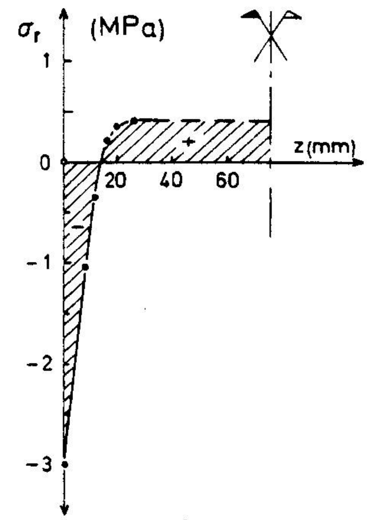


Fig. 12
Distribution of shrinkage stresses

8. THE ACTUAL CASE ON SITE

In all tests carried out so far, the cutting of the slot has been taking place before the application of external loading to eliminate internal stresses and offer a straightforward test of the release method. Now that the accuracy of this method is established, the more complex actual case on site can be tackled. It involves two supplementary problems: the internal residual stresses and the eventual cutting through a reinforcement bar.

8.1 Internal stresses; separation of stress components

The progress achieved in measuring a tensile stress and its gradient paved the way to the comprehension of internal residual stresses in concrete. A series of tests were carried out to analyse the effects of shrinkage. Fig. 12 shows an example of the stress distribution obtained. Shrinkage, as any other internal stress, obeys the law of the equilibrium of forces. When shrinkage and applied external stresses were both involved, the superposition principle proved to be valid. The absolute stress, measured on site, can thus be broken down to its components: the applied and the internal.

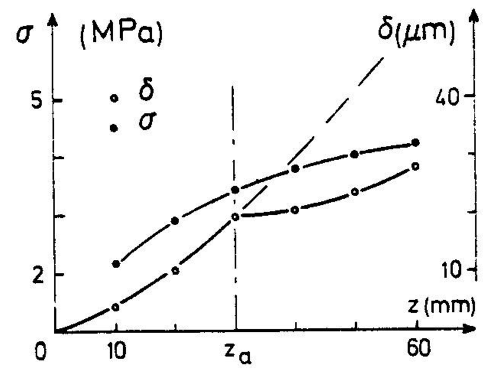


Fig. 13 - Cutting through a reinforcement bar at a depth z_a during stress release: an immediate effect on the displacement field, but not on the measured stress profile.

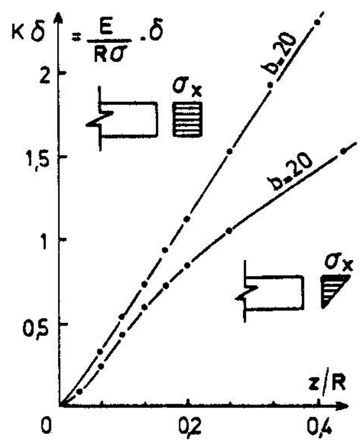


Fig. 14 - Dimensionless reference curves for evaluating the relative state of an unknown medium. The release criteria are expressed as a function of the depth z, for a slot of radius R.

8.2 Presence of reinforcement

All possible steps were taken to avoid cutting through reinforcement during the stress release operation. However, as exceptionally unfavourable cases may arise, tests were carried out to study the effect of such cutting. Fig. 13 summarizes the results. It shows a clear and immediate discontinuity in the evolution of the displacement field, but hardly any effect on the continuity and accuracy of the measured stress profile. It goes on as if the cutting through reinforcement had furnished the given medium with a higher rigidity facing the same stress field.

9. STATE INVESTIGATION OF A MEDIUM

After adequate development, the partial release method can now not only dispense with the constitutive law, but would even help to find it. Through a further analysis of the experimental data, the state of a given medium may be situated with respect to a linearly elastic, isotropic and homogeneous continuum. For this purpose, reference curves were established to define, with dimensionless criteria, a linearly elastic behaviour in the vicinity of a slot, whatever the modulus or the slot radius may be. For two types of stress distribution, fig. 14 shows the release characteristics as a function of a slot depth z and radius R; E is the modulus obtained from fig. 15 and σ the stress assumed equal to the cancelling pressure p_c. For the same slot of different depths, fig. 16 shows, as a function of position x, the response of the displacement field to a unit pressure of the jack. The actual curves can thus be traced and compared with their references. If a serious disagreement is observed, the medium may be cracked or plastified, depending on the direction and sense of deviation.

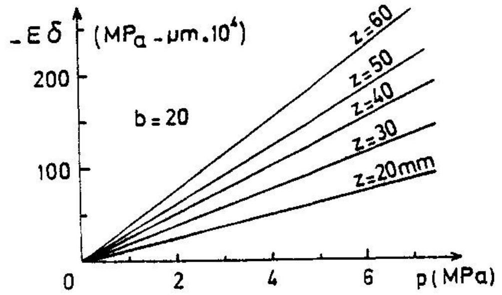


Fig. 15

Graphical estimation of the modulus E. Displacements δ, measured on a base b20, are induced by a pressure p, applied in a slot of different depths z and of a radius R.

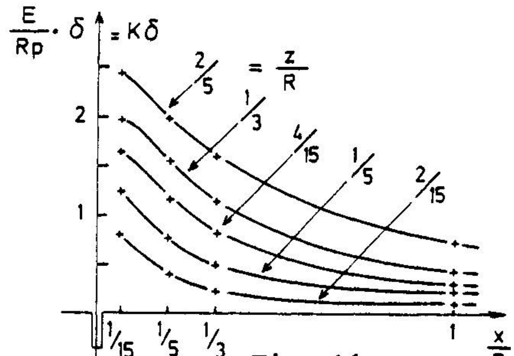


Fig. 16

Dimensionless reference curves for exploring a medium through a unit pressure in the slot (p = 1).

10. CONCLUSION

Progress has been achieved in the evaluation of actual stresses in concrete structures. A method by partial stress release was adopted. As far as instantaneous measurements are concerned, it is now operational.

For conciseness, the discussion was limited to the case of uni-axial stresses, where only one slot is usually necessary and sufficient. Other states of stress, much more complex, are equally accessible to measurement and with the same accuracy. Such cases, however, may require two or three slots in different direction to provide the number of points needed to construct the Mohr circle and determine the complete state of stress.

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