Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 46 (1983)

Artikel: Stress and deformability in concrete and masonry

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DOI: https://doi.org/10.5169/seals-35842

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Stress and Deformability in Concrete and Masonry

Contrainte et déformabilité dans le béton et la maçonnerie

Spannungszustand und Verformungsfähigkeit von Beton- und Backsteinbauwerken

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SUMMARY

In the assessment of concrete or masonry structures, it is essential to determine their absolute stresses and deformability. A method by partial stress release and compensating flat jack pressure was developed. After miniaturisation and improvement, this method is now accurate and operational. It can directly measure the actual absolute stress, separate its components, situate the general state of the assessed medium and estimate its elastic properties and bearing capacity.

RESUME

Dans l'auscultation des ouvrages, en béton ou en maçonnerie, il est essentiel de déterminer leurs contraintes absolues et leur déformabilité. Une méthode par libération partielle et compensation par vérin plat a été développée. Après miniaturisation et amélioration, cette méthode est désormais précise et opérationnelle. Elle peut mesurer directement la contrainte absolue réelle, séparer ses composantes, situer l'état général du milieu ausculté et estimer ses caractéristiques élastiques et sa portance.

ZUSAMMENFASSUNG

In der Beurteilung von Beton- oder Backsteinbauwerken ist es wesentlich, ihre absoluten Spannungen und die Verformungsfähigkeit zu bestimmen. Eine Methode mit flachen Druckmessdosen wurde entwickelt. Nach Miniaturisierung und Verbesserung ist diese Methode jetzt genau und einsatzfähig. Hierdurch ist es möglich, die wirkliche absolute Spannung direkt zu messen und in ihre Komponenten aufzuteilen, den allgemeinen Zustand des untersuchten Bereichs zu beurteilen und seine elastischen Eigenschaften und Tragfähigkeit zu bewerten.

1. INTRODUCTION

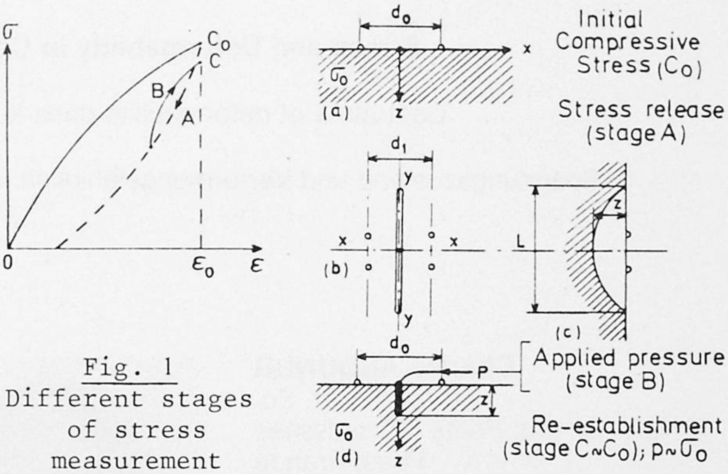


Fig. 1
Different stages of stress measurement

Engineers often encounter concrete and masonry structures showing signs of damage or, in any event, requiring strengthening. In such cases, the determination of the actual state of absolute stress is essential for diagnosis, for the evaluation of the residual strength and for stress control during an eventual repair operation. 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, 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 cancelling pressure is an indication of the compressive stress in the direction normal to the slot.

2. APPLICATION TO CONCRETE; EXTENSION TO MASONRY

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 and the complications arising from the absolute need for the miniaturisation of this somewhat destructive operation.

The extension to masonry has raised specific problems. In such a composite material, with fragile bond and complex stress distribution, the main concern is the stress representativeness at the point of measurement and the reversibility of the stress - strain relationship under the cancelling pressure.

3. ORIENTATION OF THE RESEARCH

To overcome these difficulties, the method was thoroughly re-examined from all its basic aspects. This led to several general and specific imperatives.

For both materials:

- Behaviour analysis of the slot vicinity from a purely mechanics viewpoint.
- Dry cutting and simultaneous thermal stability to avoid distorted results.

For concrete:

- 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 (mainly tensile).
- Break down of the measured absolute stress to its two main components: applied and internal, the latter being rather complex.
- Correction for cutting through reinforcement during stress release.

For masonry:

- Location of points, on the stone-joint assemblage, where measurement may best reflect the actual average stress.
- Keeping the stone-joint disturbance to a minimum.

4. BASIC OBJECTIVES

- 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.

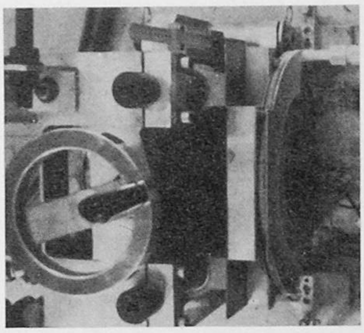


Fig. 2
Cutting machine

5. 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 Moiré, to study the effect of the slot in a homogeneous and isotropic material.
- Tests on concrete and masonry models, using mechanical and electric gauges, to simulate actual cases and study local effects.

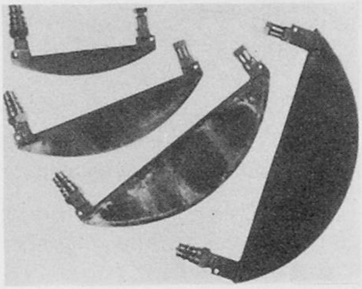


Fig. 3
Flat jacks

6. DEVELOPMENT OF THE EQUIPMENT

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

Cutting is carried out by successive passes which alternate with measurements. A special apparatus was constructed for this purpose (fig. 2). A clear cut, with a very uniform thickness, was thus obtained. Furthermore, a special cooling system was developed to favour dry cutting; a good thermal stability was achieved. The flat jacks had to reconcile miniaturisation with strength and flexibility. Prototype jacks (fig. 3) were designed by the author and successfully tested in the laboratory. They are 4 mm thick and have a maximum depth of 60 mm. In the measurement apparatus (fig. 8), the displacement field is materialised 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 reference fields.

7. THE IDEALIZED MODEL

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

7.1 Qualitative analysis

A plexiglass block, containing a slot and provided with photo-elastic coating, was subjected to pure compression in successive stages. Fig. 4 a reflects the extent of the disturbance in the stress field. Fig. 4 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. Other tests on similar models have shown the possibility of measuring absolute bi-axial stresses.

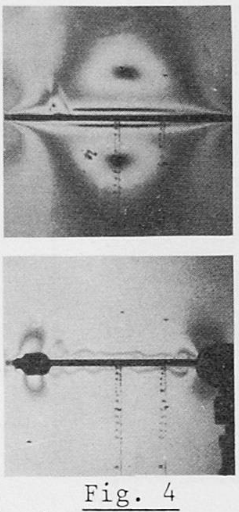
a)
c)


Fig. 4
a) Disturbance
b) Restoration

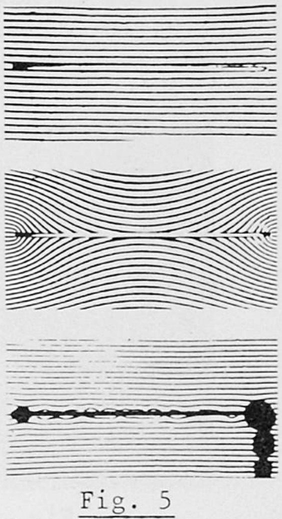
a)
b)
c)


Fig. 5
a) Unloaded
b) External stresses
c) Superposed equivalent jack pressure

7.2 Quantitative analysis

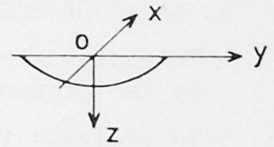
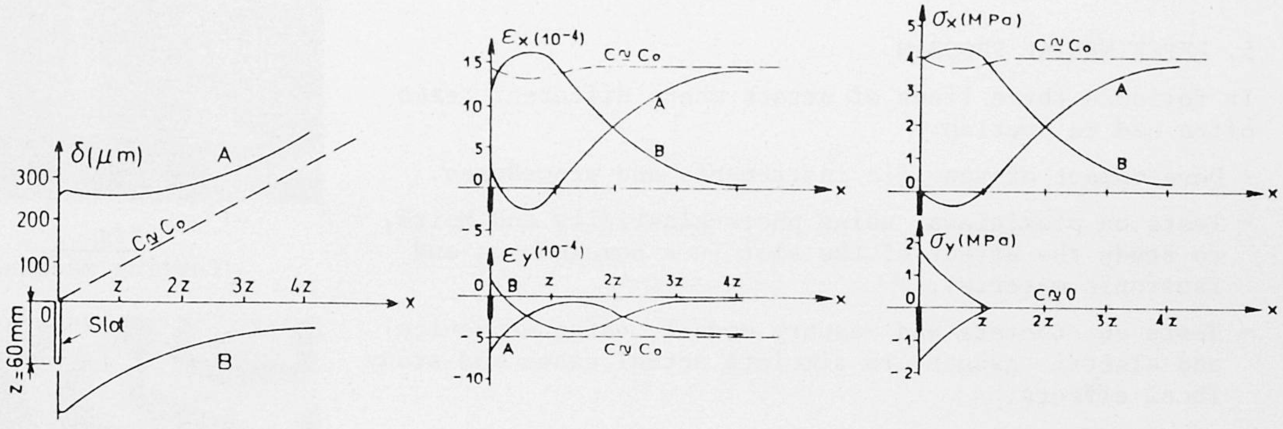


Fig. 6
Co-ordinate axes

Another block, containing a slot, was equipped with a double Moiré-grating (fig. 5 a). It was subjected to pure compression, then a uniform jack pressure was superposed in the slot. Fig. 7 a, b, c show the results obtained and the efficacy of the flat jack in restoring the field. These results also confirm and complement those of a calculation carried out previously by finite elements.



a) Displacements; assumed positive towards the slot

b) Strain; contraction assumed positive

c) Stresses; compression assumed positive

Fig. 7 - 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.

8. TESTS ON CONCRETE MODELS AND ACCURACY OBTAINED

Now that the theoretical, technological and metrological problems are resolved, the way is paved for application.

8.1 Compressive stresses

The tests undertaken on plexiglass by optical methods, were repeated on uncracked concrete models by extensometry (fig. 8). 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. 9 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.

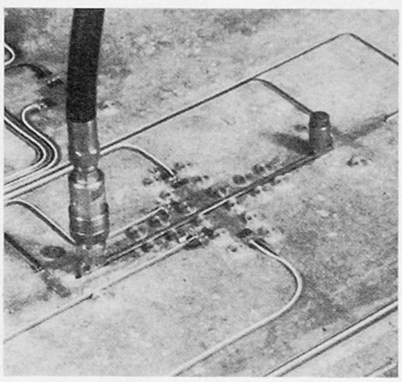


Fig. 8
Measurement apparatus on concrete

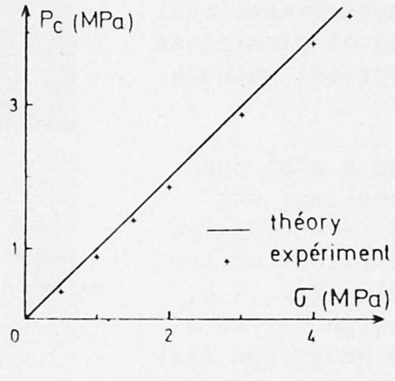


Fig. 9
Cancelling pressure compared with actual applied stresses

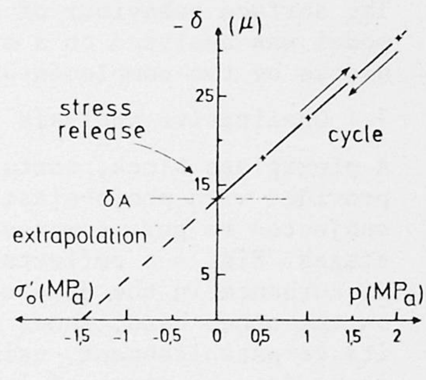


Fig. 10
Tensile stress deduction from a pressure cycle p and corresponding displacements δ

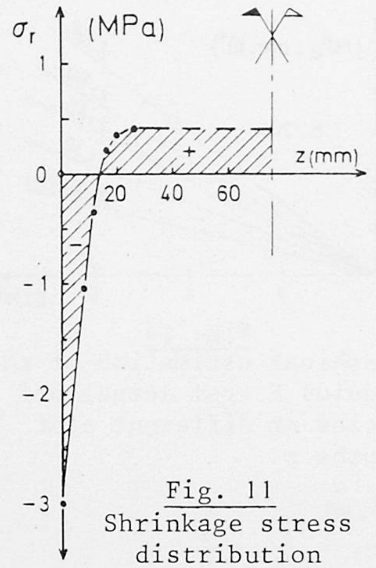


Fig. 11
Shrinkage stress distribution

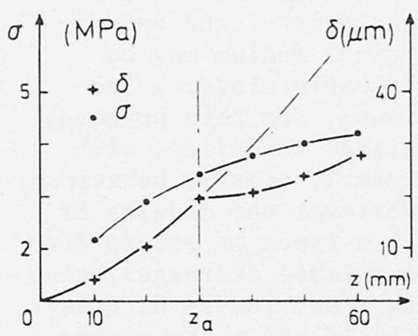


Fig. 12
Cutting through reinforcement (depth z_a): immediate effect on displacement field, none on measured stress profile

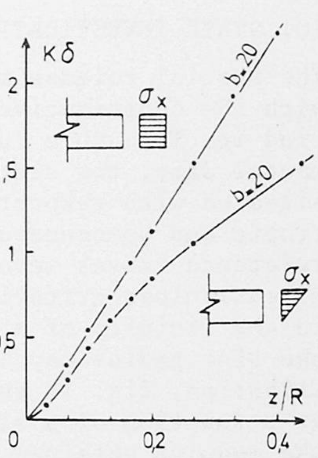


Fig. 13
Dimensionless reference curves evaluating the relative state of a medium through release criteria

8.2 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. 10).

8.3 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.

9. THE ACTUAL CASE ON SITE

In all tests carried out so far, cutting has been taking place before applying external loads 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 reinforcement.

9.1 Internal stresses; separation of stress components

The progress achieved in measuring a tensile stress and its gradient paved the way for the comprehension of internal residual stresses in concrete. A series of tests were carried out to analyse the effects of shrinkage. Fig. 11 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.

9.2 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. 12 summarises 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.

10. STATE INVESTIGATION OF A MEDIUM

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. 13 shows the release characteristics as a function of a slot depth z and radius R; E is the modulus obtained from fig. 14 and σ the stress assumed equal to the cancelling pressure p_c. For the same slot of different depths, fig. 15 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.

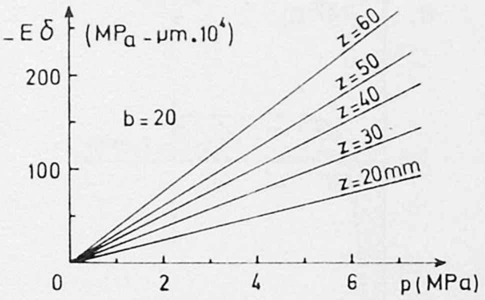


Fig. 14
Graphical estimation of the modulus E from actual p-δ cycles at different slot depths z

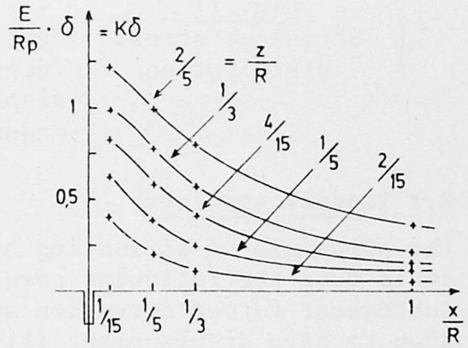


Fig. 15
Dimensionless reference curves for exploring a medium through a unit pressure in the slot (p = 1)

11. LOAD BEARING CAPACITY

In a sound medium, the ultimate load can be estimated through an imposed deviation (from the curves of figs. 14 and 15) under excessive pressures of the jack. In a damaged medium, a divergence from fig. 13 already occurs on stress release; the jack can then be used to confirm the damage and supply the information leading to the ultimate load estimation.
Where the compressive stress is not sufficiently high, excessive jack pressures may cause two successive deviations from the curves of figs. 14 and 15: The first, a sharp one, marks a tension failure of the slot extremities; the second, much more gradual, reflects the approach of ultimate compressive strength.

12. EXTENSION TO MASONRY

Having obtained positive results with concrete, the release method is now being extended to composite materials. No technological changes were necessary and the same procedures, already put forward, were retained.

At an early stage, it was observed that, unlike concrete, masonry units originally have very low internal stresses, which facilitates access to stress components. However, this considerable advantage is annulled by the fact that, in such a composite medium, the mortar joint is very flexible and fragile. The resulting distribution of axial and lateral stresses is a complex function of position.
Hence, the specific questions facing stress measurement in masonry concern the choice of the appropriate slot positions, where:

- stress is most representative of the actual average value in the structure,
- the stress-strain relationship is adequately reversible under the jack pressure,
- the bearing capacity may be estimated.

These problems can mainly be handled through experiment. Even in the case of the first question, where attempts by finite elements are underway, a correct theoretical stress analysis is subject to assumptions on boundary conditions, which only experiment can confirm.

13. MASONRY MODELS; LOCATION OF MEASUREMENT POINTS

Testing involved two full-scale models, a column and a wall. Stones with high elasticity modulus were chosen for better comparison with concrete. In each model, three slot positions were considered (fig. 16):

S1: entirely in the mortar joint
S2: entirely in the stone
S3: partially in two adjacent stones and cutting their common joint at right angles.

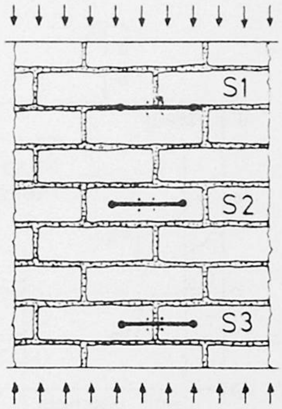


Fig. 16
Proposed location of stress measurement in masonry

14. TESTS, RESULTS AND COMMENTS

An axial load was applied to the column. The wall was subjected firstly to axial, then to accentric loading. The deformability was estimated by extensometry and the actual stresses by the release method.

14.1 General and local deformability

Prior to stress release, each model was loaded in successive stages to examine its general behaviour and establish the various stress-strain relationships.

As expected, plane cross sections do not remain plane even under a well distributed load; the joint cannot prevent normal and tangential relative displacements of stone units. Fig. 17 compares the overall stress-strain relationship to that of each constituent. For stresses higher than 0.6 MPa, the stone and overall moduli are respectively five and four times that of the mortar.

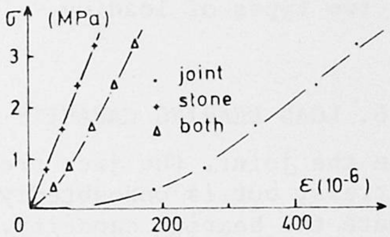


Fig. 17
Stress-strain diagram for a masonry model and its constituents

On site, the deformability is estimated by inserting, in the joints, two jacks facing each other at an easily calculable distance.

14.2 Stress determination. Accuracy obtained

Under constant loading, this operation was carried out by alternating cut and measurement. Fig. 19 summarises the results obtained under two stress profiles: σ_a, pure compression and σ_b, compression and flexure. It shows a high accuracy for slots S2 and S3 (entirely or partially in the stones), but reveals approximate and even singular values for slots S1 (entirely in the joints). The error in S1 is always in excess. In fact, the accuracy of the release method depends on the degree of cohesiveness of the slot's immediate vicinity facing, after release, a high stress concentration on the borders. The mortar being too fragile to meet this condition, a possible though invisible crushing, with uncontrolled disturbance, can lead to an erroneous interpretation of the measured cancelling pressure. Consistent results might be obtained and lead to an empirical calibration formula, but only for a well prepared model and not on site where the mortar has deteriorated. Hence, wherever a relatively high accuracy is required, it is advisable to measure the stress in position S2 or preferably in S3.

Finally, with regard to the curved stress gradients observed, they are probably caused by the confinement of the mortar joint and its resulting lateral stresses.

15. STATE OF A MASONRY MEDIUM

Figs. 13 and 15 have already set standards for situating the state of a monolithic cohesive material. However, their application is rather delicate in a composite medium, where the modulus varies with position and stress (fig. 17). Pending further research, the actual field reactions, to release and pressure, are compared for S1, S2, S3 and with reference to concrete (figs. 19 and 20). These curves confirm the different behaviour of the joints.

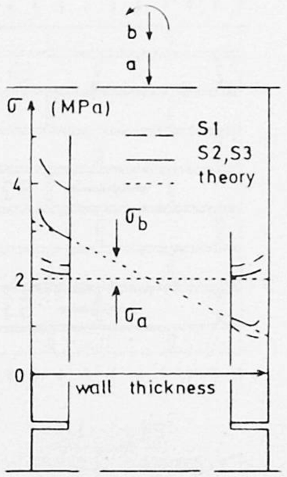


Fig. 18
Stress measurement under two types of loading

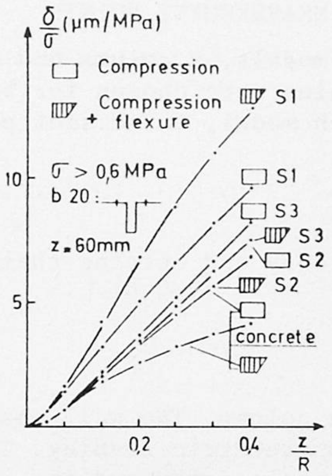


Fig. 19
Relative field disturbances per unit stress release

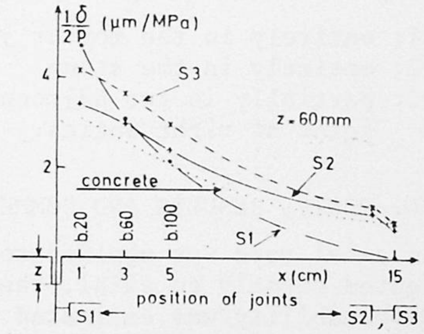


Fig. 20
Relative response to a unit pressure in the slot

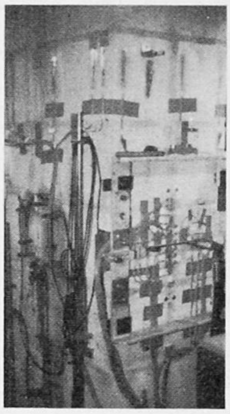


Fig. 21
Masonry model and test set-up

16. LOAD BEARING CAPACITY

In the joint, the jack pressure may lack accuracy in measuring the stress, but is undoubtedly in the only position where it can estimate the bearing capacity. This is carried out by following the same procedure used to determine the deformability on site (§ 14.1) and then by spotting the excessive pressure causing a clear deviation in the strain growth.

17. IN BRIEF

Successful applications on site have been made of the release method.

Automatic stress measurements are being introduced to study the time-dependent behaviour of a structure or to monitor its evolution during eventual repair.

Although miniaturisation has sharply reduced the method's destructive character, post-operational repair techniques, to statical and esthetic ends, are being developed.

18. CONCLUSION

Substantial progress has been achieved in the direct evaluation of the actual stresses in concrete and masonry structures. After miniaturisation and development, the partial stress release method is now operational for instantaneous and, possibly, long-term measurements. This method can also situate the general state of the assessed medium and estimate its elastic properties and load bearing capacity.

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