AN EXPERIMENTAL PROCEDURE TO DELOCALIZE TENSILE FAILURE AND TO IDENTIFY THE UNILATERAL EFFECT OF DISTRIBUTED DAMAGE

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ABSTRACT

To show the effect of the sign of stress on the behaviour of the material, a new procedure is proposed . First it consists in creating distributed damage by a tensile loading, and subsequently applying a compressive loading on the same specimen. Distributed damage is obtained through aluminum bars glued on the lateral surfaces of the concrete specimen, the load is applied on the bars which impose an uniform strain state to the concrete, so that no localization appears in spite of large strain values. The results obtained show that a strain-softening behaviour in the context of continuum media is possible for concrete. The subsequent compressive loading shows that the behaviour is not considerably modified by tensile damage (stiffness and ultimate stress values), that exhibits the unilateral character of concrete behaviour.

INTRODUCTION

Concrete enters the class of strain softening materials. This particularity is due to internal microcracks evolution with loading. That kind of behaviour favours localized failure which is the consequence of an instable configuration linked simultaneously with the specimen geometry, with the existence of defects inside the material and with the boundary conditions due to the loading procedure. The direct tensile test is particularly sensitive to this phenomenon,therefore there is localization when the load reaches the maximum, and after we have a cracking structure behaviour .
Yet, if localization is a common phenomenon in concrete structures, it is not systematic. For example, in reinforced concrete, damage around a bar is distributed . However, modelling the non linear response of the structures requires the knowledge of the behaviour of the damaged material, and its localization properties.

With this aim in view, we present an experimental procedure which permits :

- to generate a distributed damage,
- to study the tensile-compressive behaviour of the damaged material and then to exhibit its behaviour when the applied stress does not have same sign as the one which has created the damage.

PRINCIPLE OF THE TEST

Analysis of a classical tensile test performed with imposed displacement

The tensile test, usually performed on cylindrical or prismatical specimens, leads, when the experiment is made with imposed displacement, to the following behaviour (figure 1) :

$\sigma < \sigma_e$	: no damage	==> linear elastic behaviour
$\sigma < \sigma_e < f_t$	: a few degradations distributed inside the whole volume	==> the curve is lightly inflected
beyond f_t	: localized failure	==> instable state

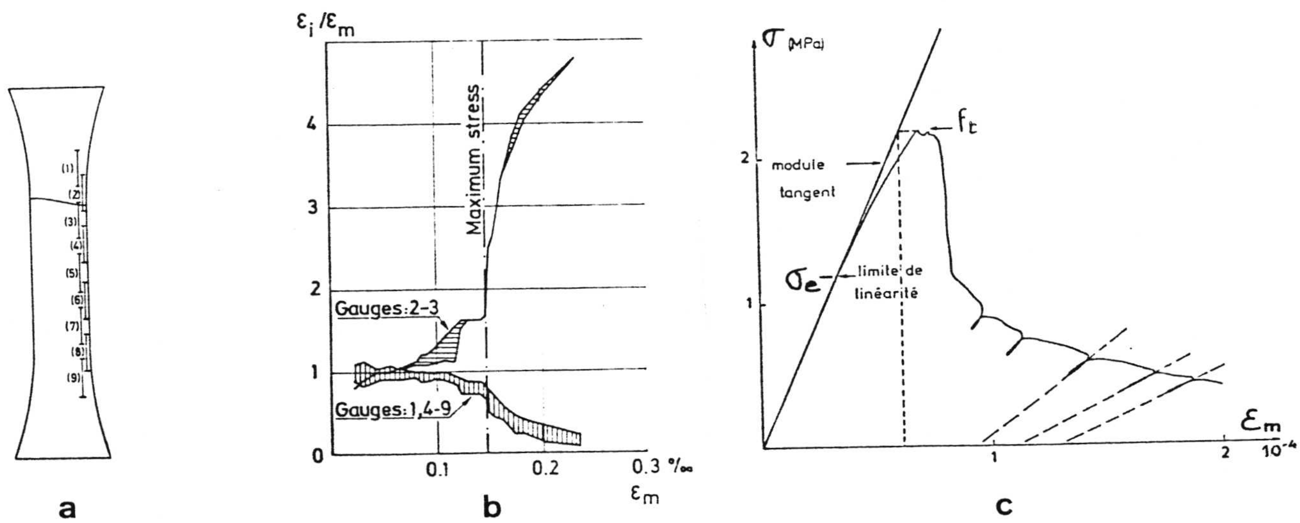

Figure 1 : Localization in a direct tensile test [1] [2]

a - specimen and location of the failure.

b - strains for the gauges crossing the fracture zone (2-3) and for those outside the zone (1,4-9) . ε_i = strain for gauge number i, ε_i = mean strain for the specimen .

c - an example of the global behaviour of the tensile specimen.

The evolution of the strains along the specimen shows that localization seems to appear before the peak and that, in a well-marked way, there is shrinkage of the material outside the fracture zone after the peak .Those internal transfers show that imposed displacements can only control the mean stress in each section of the specimen but absolutly not the strains along it .

Experimental procedure to delocalize the strains

The delocalization can be achieved only by a control of the strains evolution along all the specimen . An external system using adhesion is then necessary . L' HERMITE was the first in 1960 [3] to use such a process which consists in moulding concrete inside a metallic pipe with an internal thread in it for adhesion . The load was applied on the pipe and the strains transfered to the concrete by the thread. But the difference between the two material Poisson ratios introduced a confinement effect and the concrete was in triaxial stress state which was not desired.

BAZANT and PIJAUDIER-CABOT (1987) [4] improved the process and used series of metallic bars distributed and glued on the lateral faces of a prismatic specimen. The transmission of the load in ensured by grips linked by lockings screws and glued on the bars at the ends of the specimen. Then, the disadvantages of the L' HERMITE' s process are suppressed. Yet the disturbance in the stress field deriving from the hooking of the grips has not been studied.

Here, we have chosen the glued bars principle and modified the technique of transmission of the load in order to enable the application of tensile and compressive loading.

DESCRIPTION OF THE TEST

Specimen and loading system specifications

The specimen, shown in figure 2, is a 40 x 80 x 160 cm prism with six bars on each large lateral face. The material tested is a micro-concrete with the following weight mixture : cement 1, water 0.6, sand (0-4mm) 4.5 . The bars are in aluminum alloy (2024), have a square cross section (8 x 8 mm) and are glued to concrete with an epoxy adhesive .

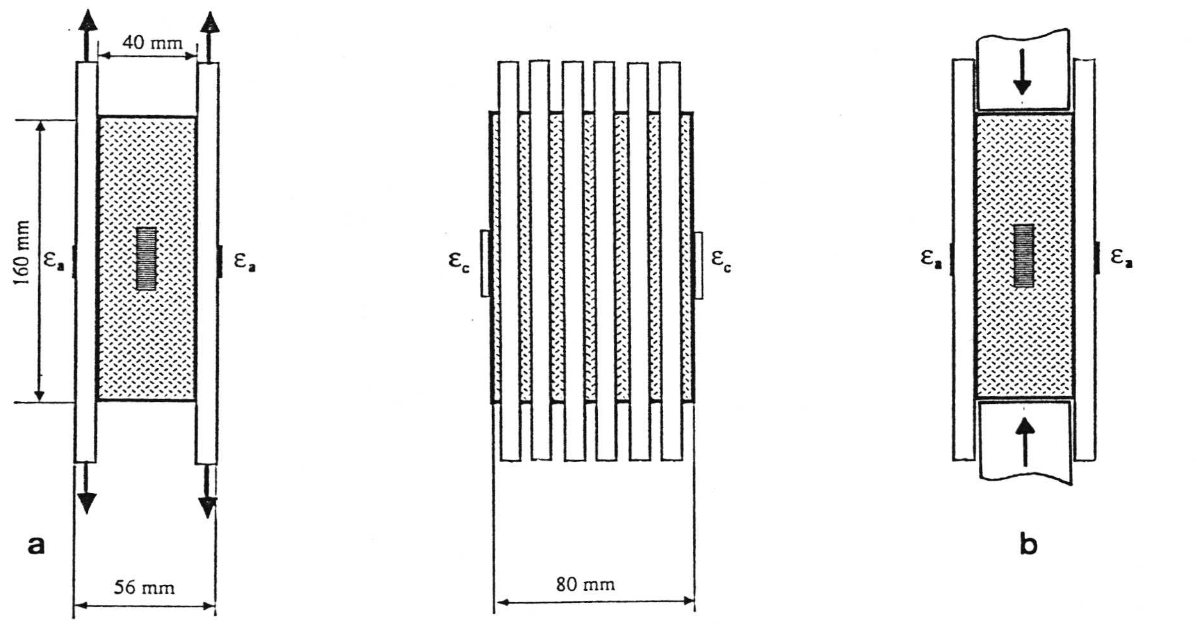

Figure 2 : Specimen equipments .

a - tensile loading
b - compressive loading

The applied load is either tension or compression :

- the tensile loading is ensured by the action of the bars which are separately fixed by locking screws on the grips of the testing machine.

- the compressive loading is directly applied on the ends of the concrete prism ; at that time, the bars are not fixed to the grips.

Analysis of the strain field inside the specimen

A finite elements elastic plane calculation has first been made to ensure that the central zone of the specimen was in an homogeneous state of strain. Figure 3 gives the results of that analysis and we see :

- that the transmission of the tensile loading is progressively achieved along the specimen and is regularized only in the central part of the system, including concrete and bars, on a height of about 60mm,

- that the homogenity on the compressive state is quasi perfect, except at the end of the specimen in a zone near the interface between concrete and bars .

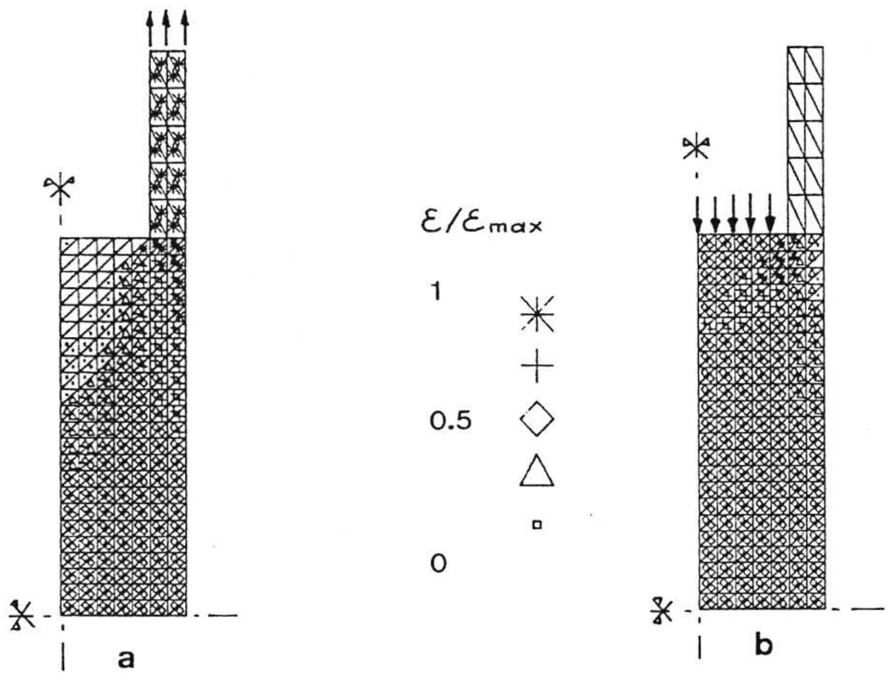

Figure 3 : Strain field analysis .

a - tensile loading
b - compressive loading

This calculation confirms that the measures carried out in the central part are representative of an homogeneous strain field. This measurements are made by strain gauges sticked on the free lateral surfaces of concrete (gauge length : 60mm) and on two opposite aluminum bars (gauge length : 5mm). These two values of the strain must be equal , $\varepsilon_a = \varepsilon_b$ (results confirmed by tests) .

EXPERIMENTAL STUDY

As we said before, two objectives are considered in this study :

- first, to create a distributed damage in the central part of the specimen under a tensile loading,

- second, to study the behaviour of the damaged material under tensile and compressive loadings.

The specimen is tested in a closed loop 100 kN MTS testing machine, controlled by a Motorola 68k computer with a CAMAC analogical digital interface for data acquisition and signal processing .The imposed rate of displacement was $\varepsilon = 10^{-7}\ s^{-1}$ in the central part of the specimen at the beginning of the test. The data acquisition concerns both, the global load F applied on the system, and the axial strains measured on the lateral surfaces of the specimen and on the aluminum bars (see figure 2). The mean values, ε_c for concrete and ε_a for aluminum are used for the presentation of the results. Several tests have been performed and we have chosen to present below the detailed results from the whole analysis of one of them.

Creation phase of tensile distributed damage

In this phase, the global behaviour of the system (ε_c versus F) is given by the curve shown on figure 4. The axial strain ε_a is nearly the same, with a difference always less then five percent as respect as those ε_c measured on the concrete .

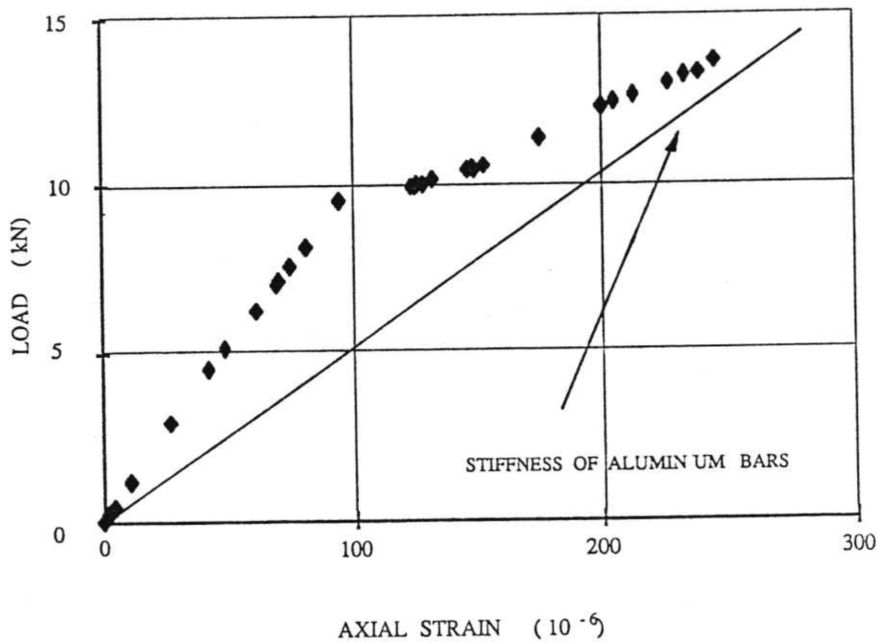

Figure 4 : Global behaviour under the tensile damage procedure .

Two different stages appear during the loading :

- an elastic one, the stiffness of which corresponds to both concrete and bars ;

- a non-linear one, in which the global stiffness decreases due to damage in concrete and eventually the stiffness of the aluminum bars alone is retrieved.

From the global response, and assuming (which was verified) that aluminum behaviour is linear elastic for all the test, by writing the equilibrium of the central section of the system, we can deduce the behaviour of the concrete :

$$F = F_a + F_c \quad ====> \quad \sigma_c = \frac{F - E_a \times \varepsilon_a \times S}{S_c} \qquad (1)$$

$E_a = 72000$ MPa ; $S_a = 768$ mm^2 ; $S_c = 3200$ mm^2 ; F, ε_a and ε_c are measured .

The relation $\sigma_c = f(\varepsilon_c)$ is then obtained from (1) and shown on figure 5 .

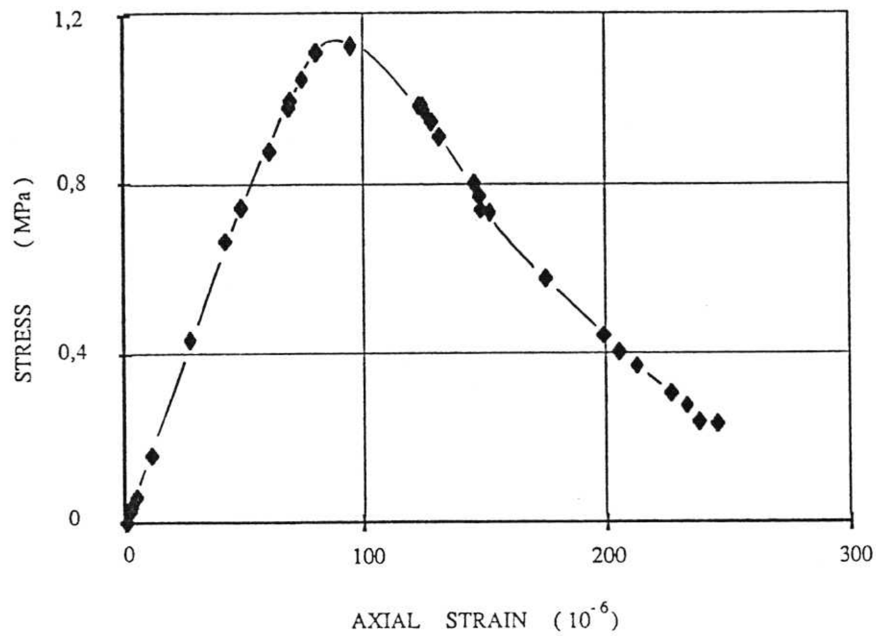

Figure 5 : Behaviour of concrete under tensile distributed damage process .

This curve exhibits :

- a quasi-linear elastic behaviour to the peak;
- a strain softening part after the peak, but with a more progressive evolution than in a classical test (figure 1c) .

Different analyses (visual, by damping...) have not allowed to reveal a localized fracture of the specimen, which enables us to say that the behaviour we have obtained is characteristic of the tensile distributed damage of the tested concrete .

Behaviour of damaged concrete
For two tensile damaged states we have made unloadings down to a zero global stress, for the second one this unloading has been followed by a compressive loading .

Behaviour under unloading process (shown on figure 6) .

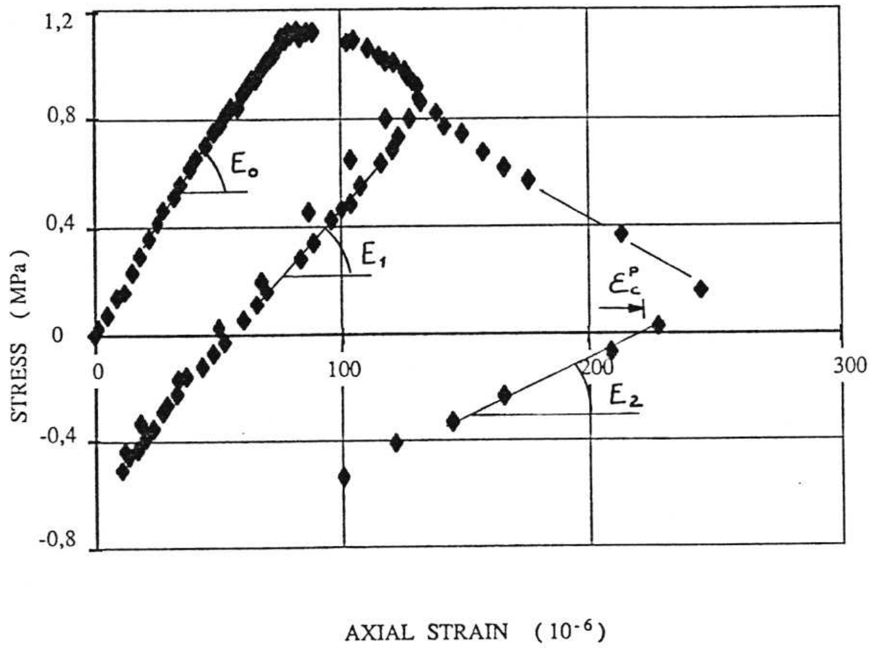

Figure 6 : Behaviour of damaged concrete under unloading-reloading process .

We note that the behaviour is quasi-elastic and linear (a small hysteresis appears during the unloading-reloading process), with an important decrease of the Young 's modulus with damage :

- initial state, $E_0 = 16500$ MPa
- intermediate state ($\varepsilon_c = 1{,}3\ 10^{-4}$) $E_1 = 10700$ MPa
- final state ($\varepsilon_c = 2{,}5\ 10^{-4}$) $E_2 = 4700$ MPa

Besides, the existence of permanent strains induces that :

- when, inside the concrete specimen $\sigma_c = 0$ ($\varepsilon = \varepsilon_c{}^p$) , the load applied to the whole system F° is only supported by the aluminum bars ; then

$$F^\circ = \varepsilon_c{}^p \times E_a \times S_a \qquad (2)$$

- when the global load F = 0, the concrete is in a compressive state due to a prestressed effect of the bars . The strain imposed to the material between these two stages is then :

$$\Delta\varepsilon = - \frac{F^\circ}{E_a \times S_a + E_c \times S_c} \qquad (3)$$

where E_c is the actual Young' s modulus of concrete.

For the damage states considered in the experiment, we find :

- intermediate state : $\varepsilon_c{}^p = 0{,}5\ 10^{-4}$, (2) and (3) give respectively F° = 276 daN and $\Delta\varepsilon = -\ 0{,}4\ \ 10^{-4}$, value confirmed by the experiment ;

- final state : $\varepsilon_c{}^p = 2{,}2\ 10^{-4}$, (2) and (3) give respectively F° =1200daN and $\Delta\varepsilon = -\ 1{,}6\ 10^{-4}$ the experiment giving $\Delta\varepsilon = -\ 1{,}3\ \ 10^{-4}$.

Apart from the fact that these results confirm the validity of the method used to analyse the experiment, they show that the stiffness of damaged material does not change at the same time than the sign of the stress .

Behaviour under compression .

The compressive loading procedure presented before has been applied to the damaged material (final state above-mentioned). The behaviour of concrete in deduced from the global behaviour as in tension loading .

Figure 7-a shows this behaviour at the beginning at the loading until $\sigma_c = -\ 6$ MPa . We find that the Young 's modulus increases quickly to reach $E_0 = 162000$ MPa , a value very close to that of the virgin material ($E_0 = 165000$ MPa) . This phenomenon is linked to the closure of microcracks and expresses the "unilateral" character of the damaged material . Already observed in the case of localized fracture [5] [6] , we confirm here its existence in the case of distributed damage .

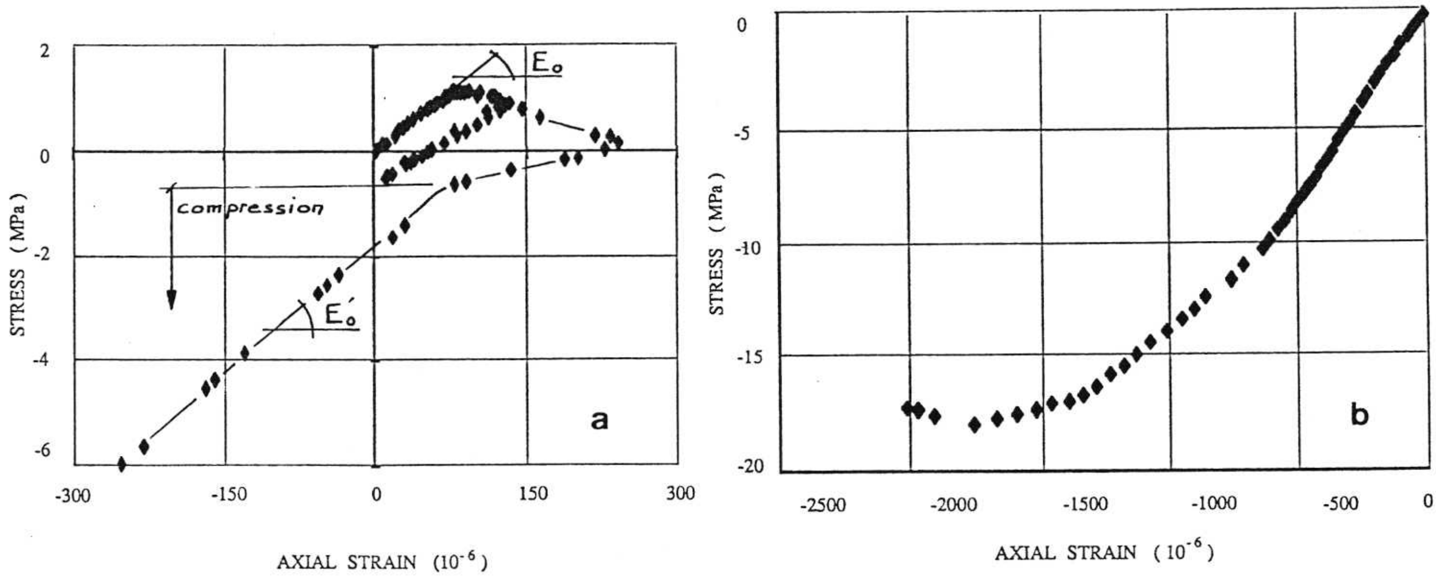

Figure 7 : Compressive behaviour of the distributed damage concrete .
a - unilateral character
b - behaviour until rupture .

This curve shows that the behaviour of the material, first damaged in tension, is quite similar to that of the of the same but undamaged material (initial stiffness, ultimate stress and strain, shape of curve ...) .

CONCLUSIONS AND PROSPECTS

We have presented an experimental procedure allowing both the creation of tensile distributed damage in a concrete specimen and the characterization of the damaged material behaviour under tensile and compressive loadings . From the results analysis we can point out the following :

1. The tensile behaviour of concrete is quasi-linear elastic before the stress peak of the curve and progressively softening beyond .

2. Distributed damage can be controlled until a very small strength of the material, and this damage induces an important decrease of the Young' s modulus and the creation of permanent strains .

3. A compressive loading applied to the damaged material induces a recovering of the the stiffness (unilateral character) .

4. The compressive behaviour is not much changed by a previous tensile damage .

From these different points we can deduce basic concepts for modelling, particularly :

- the interest of using damage variables, in the framework of the thermodynamics of irreversible processes, acting on the mechanical characteristics of the material (Young's modulus, permanent strains ...) .

- the interest to connect the action of these variables to the loading state to which the damaged material is submitted ("tension" or "compression") .

Some models exist in this framework, see e.g. refs [7] [8] , but as far as we know, any have combined all these aspects, of course because other experimental results of the same kind are necessary, in particular under triaxial loadings . As a matter of fact we think we have shown that discussions such as " is strain softening characteristic of the behaviour of the material ? " have no purpose if experiments do not support those assertions.

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