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DYNAMIC UNIAXIAL AND BIAXIAL STRESS-STRAIN RELATIONSHIPS FOR AUSTENITIC STAINLESS STEELS

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Summary

Fast breeder containment structures could be subjected to explosive accidents and impact of missiles, which give rise to propagation and successive reflections of tension waves which deform the material at constant or changing strain rate, with load release and reloading eventually in compression, along multiaxial directions.

Constitutive equations, required for calculation codes, should be able to describe the behaviour of the material under these different dynamic loading conditions. In order to provide an experimental basis to the formulation of the constitutive equations, we have developed a hydropneumatic machine and a Hopkinson bar with which we determined the stress-strain curves for austenitic stainless steels (AISI 304L, AISI 316L) at constant strain rates ranging from $10^{-2}s^{-1}$ to $10^{3}s^{-1}$, in uniaxial tension. From these tests we observed that the main effects of strain rate on the dynamic flow curves of these steels at room temperature are the substantial increase of the flow stress and the marked reduction of ductility with increasing strain rate.

In order to take into account the effects of biaxial loading, we have constructed two machines, which operate on cruciform specimens of small dimensions, of up to 20 mm^2 cross section:

- the first (strain rates 10^{-4} to $10^{-1}s^{-1}$) consists of an electric motor which moves a plate simultaneously acting on four equal arms;
- the second (strain rates 10^{-1} to 10^{2} s^{-1}) is a hydropneumatic machine which may operate along two or three axes. On each axis two gas pistons exert the loading in tension or compression at constant strain rate or with rapidly changing strain rate, with loading release and reloading.

Further severe difficulties will be encountered in the formulation of constitutive equations in dynamics regarding steels subjected to damaging processes such as welding, irradiation, creep, thermal and mechanical fatigue. In fact, testing both AISI 316L welded and AISI 316L irradiated up to 2.2 dpa, we have observed that at 550°C the flow stress at a given strain and the ductility suffer a marked decrease with increasing strain rate, whereas under the same test conditions the flow stress and the ductility of virgin material remain nearly constant with increasing strain rate.

We intend to perform tests on larger specimens (4000 mm^2 cross section) of the steels subjected to the above mentioned damaging processes, radiation excluded, and on welded plates having a thickness near to that needed for the construction of the vessel. For the performance of such tests a high-load biaxial machine is in an advanced phase of design. It is based on the loading principle of the Hopkinson bar with a prestressed bar loading device, characterized by four arms at 90° in which each arm has a length of 100 m. It is intended that this machine will allow impulsive loads to be obtained in tension or compression with a maximum force of 5 MN and a duration of 0.04 s, rise time of about $100 \cdot 10^{-6}$s, producing strain rates depending on the specimen's size, of up to 10^{3} s^{-1}.

1. Introduction

Fast breeder containment structures could be subjected to very different dynamic loading conditions in the case of an accident. Explosive accidents, asymmetric with respect to the centre of the containment vessel, and impact of missiles on the vessel's wall, give rise to propagation and successive reflections of tension waves along the vessel's walls [1] which deform the material at constant or changing strain rate, with load release and reloading eventually in compression, along multiaxial directions.

Constitutive equations, required for calculation codes, should be able to describe the behaviour of the material under these different dynamic loading conditions, taking also into account particular phenomena such as yielding instabilities, Bauschinger effect, softening, anisotropy induced by deformation, effects of damaging processes such as welding, irradiation, creep, thermal and mechanical fatigue.

In order to provide an experimental basis for the formulation of constitutive equations for metals, we have developed a hydropneumatic machine and some techniques based on the principle of the split Hopkinson-Davies bar with which a short specimen of the material can be deformed at high strain rate in uniaxial state of stress [2, 3]. Considering all these requirements, we are able, with the techniques developed, to determine experimentally the response of the material subjected to the following loading conditions:

- tests at constant strain rate,
- tests at constant stress with rapidly changing strain rate,
- loading-unloading tests (interrupted loading),
- stepwise strain rate history.

To cope with the situation of multiaxial state of stress in the structures, the above mentioned devices have been further developed in order to carry out dynamic biaxial tensile tests on cruciform specimens, where the previously mentioned test conditions can be independently realized along the two loading directions of the biaxial testing devices, and the nature of loading can be independently chosen to be tensile or compressive.

2. Uniaxial Dynamic Tensile Tests

In recent years we have determined the dynamic mechanical properties of some austenitic stainless steels, such as AISI 304L, AISI 316L, AISI 321, in virgin, welded and irradiated conditions, under a uniaxial state of stress, using the following devices [4, 5]:

- a hydropneumatic machine for tensile tests at constant strain rate ranging from 10^{-1} to 10^{2} s^{-1},
- a modified Hopkinson bar for tensile tests at constant strain rate ranging from 10^{2} to 10^{3} s^{-1}.

The main effects of strain rates on virgin, welded and irradiated materials (up to a damage of 2.2 dpa), shown in Figs. 1-10, for AISI 316L and AISI 304L can be summarized as follows:

- at ambient temperature the flow stress at a given strain increases sharply and the fracture strain decreases as the strain rate increases (Figs. 1 and 6);
- at high temperatures (400 and 550°C) the flow stress at a given strain and the fracture strains of the virgin material are nearly constant as functions of the strain rate (Figs. 2 and 7). The dynamic flow curves of welded and irradiated materials mainly lie below the static curve (Figs. 3, 4, 8 and 9);
- at both temperatures the high deformation rate induces significant instabilities in the flow curves of welded and heat-affected zone materials as compared to the virgin material and with the "static" flow curve of the same materials;
- at high temperatures both the welded and the heat-affected zone materials show strain rate sensitivities of opposite sign with respect to the virgin material. In fact, it is possible to observe that the strength of specimens cut from welded material decreases and that of the virgin material increases or remains constant as the strain rate increases. Similar behaviour is shown by the fracture strain of the welded and heat-affected zone materials;
- high strain rate, welding and irradiation produce a marked reduction of ductility as compared to the virgin material tested at low rates of strain. For example, as shown in Fig. 5, uniform elongation of virgin AISI 316L, tested at strain rate 10^{-2} s^{-1} and 550°C, is about 33%, which is reduced for the welded material, and, at medium strain rate, it is about 15%. The uniform elongation of AISI 316L irradiated at 2.2 dpa, tested at a strain rate of 10^{-2} s^{-1} at 550°C, is about 21%, which is reduced at medium strain rate to about 13%. Corresponding effects on uniform elongation of AISI 304L are reported in Fig. 10.

The typical differences in dynamic mechanical properties shown by virgin materials when compared to defect materials under a uniaxial state of stress should also be investigated in a multiaxial state of stress because these differences of mechanical properties of virgin with respect to defect material, will be enhanced by the accentuation of the anisotropic behaviour due to defects and to the deformation mode. In fact, once assumed one of the usual yielding criteria, such as Von Mise´s, and a fracture criterion, such as Mohr´s theory, it is worthwhile to recall that:
- the yielding criteria, up to now, have proved efficient in static conditions, for very small deformations and for virgin materials;
- the Mohr envelopes, corresponding to the Mohr circles at which fracture takes place, as shown in Fig. 11, are very different for brittle and ductile materials.

These considerations lead to two main questions:
1) How are these results transferable to dynamic biaxial loading conditions? Are the current yield and fracture criteria sufficient for this, especially for defect materials?
2) How are the results obtained on the small specimens used for dynamic testing transferable to large structures of materials damaged by fatigue, creep and irradiation?

In order to provide an experimental basis for answering these questions, we have prepared some devices with which dynamic biaxial loading conditions can be realized for:

- small specimens having a cross section of up to 20 mm^2;
- large steel specimens having cross sections of up to 5000 mm^2 or structures of any shape.

3. Dynamic Biaxial Tests on Small Specimens

3.1 Choice of Specimens and Stress Field

Bearing in mind that an explosive accident in a reactor vessel produces multiaxial stresses, it was decided to create a biaxial uniform state of stress in the central part of a cruciform plate specimen (Fig. 12) subjected to independent loads on two orthogonal axes.

In fact, considering the principal stress diagram of this system (Fig. 13) and having, as reported here later, the possibility of loading independently and simultaneously in tension and/or compression along the two principal directions, it will be possible to produce the intersection of the yielding surfaces with the plane $\sigma_3 = 0$ (Fig. 13) in all the four quadrants of the principal stress space. Furthermore, being able to reach fracture of the specimen, also the Mohr envelope (Fig. 11) can be determined, e.g. by three circles which touch the envelope, those of centres T, S and C (Fig. 11), corresponding to tension, simple shear, and compression, respectively.

It has been shown [6] by photoelastic techniques that a cruciform plate specimen of uniform thickness, subjected to biaxial tensile loading, gave a uniformly stressed area approximately equal to 2/3 of the test plate area but with more high-stressed regions around the connection points.

At Leicester University, Hayhurst [7], the problem of the higher stresses, relative to the uniformly stressed central region, was overcome by uniformly thinning the central region to such an extent that the uniform central stress exceeds the largest stress at the loading points. It is required that if the plate specimen is deformed in two directions, then the points of load application along the edge of the plate must also be displaced.

Taking into account all these experiences and considerations, we designed the specimen shown in Fig. 12 characterized by a flat thin central part (of up to 20 mm^2 cross section) surrounded by a frame connected to relatively long flexible multiple loading arms.

These specimens were subjected to equal biaxial tensile loading reaching a deformation of about 35% uniformly distributed over the whole surface, as shown in Fig. 14. Thereafter one observes an incorrect action at the corner of the specimen which must be further improved at this point. The specimen should also be modified in order to apply a compressive load along one and/or both orthogonal directions, so that it will be possible to investigate the effects of a dynamic stress field in the whole space of the two principal stresses.

In addition to the dynamic mechanical properties of materials in uniform biaxial stress fields this specimen configuration allows the investigation of the effects on material behaviour of artificial defects, such as holes, slits and notches, introduced in the central flat part, permitting the simulation of stress concentrations which may arise around holes and nozzle intersections in pressure vessels or other reactor structures.

We are simultaneously performing a stress analysis of the specimen by the finite element method in order to verify the uniform distribution of stresses and the correlation between the load borne by the specimen and the effective stress in the central part of the specimen.

The specimen is instrumented with a strain gauge rosette on one face of the central part whereas on the other face a grid is photo-etched. Small strains are measured by the strain gauges, while large strains are measured by recording the deformation of the grid with a fast camera.

3.2 Biaxial Testing Device for Strain Rate Range $10^{-4} - 10^{-1}$ s^{-1}

This device is shown in Fig. 15. It consists of an electric motor with a rotation velocity which can be varied between 3 and 700 revolutions per minute, which moves a plate pushing simultaneously on four equal arms connected to the specimen. The load sustained by the specimen is measured by strain gauges attached to the elastic bars connected to the specimen.

3.3 Biaxial Testing Device for Strain Rate Range $10^{-1} - 10^{2}$ s^{-1}

This device (Fig. 16) consists of four hydropneumatic elements, aligned two by two, along two axes at 90^{o}. The main components of each element are the cylinder, the piston, the gas and water chambers, the discharge orifice and the membrane.

After having loaded both the gas and water chambers at equal pressure, four membranes are broken simultaneously by firing four exploding wire detonators having an operation time of 2 microseconds, thus obtaining the synchronous action of the four pistons connected to the cruciform specimen.

After the four membranes have been broken, water flows out through the four calibrated orifices at a constant rate, thus imposing a strain on the specimen with a constant strain rate. In fact, the pressure acting on the pistons governs the displacement velocity, because the load resulting from it is much larger than the force needed to break the specimen. The load sustained by the specimen along the two directions is measured by strain gauges attached to the elastic piston's bars. Strains are measured directly on the specimen as mentioned previously.

The action of the pistons can be set up in tension or compression by a simple 180^{o} rotation of the cylinders. Strain rate can be independently controlled along the two axes by changing the diameter of the orifices. The synchronism of the action of the four pistons is shown in Fig. 17, where the loads on the four bars connected to the specimens are recorded versus time.

With this machine tests can also be carried out at a constant stress, where strain rate changes rapidly. In this case, the water chambers are provided with much larger orifices, allowing the pressure above the pistons to drop very rapidly. This causes the specimen to be loaded by the constant force due to the gas pressure below the pistons and thereby to undergo strains at a constant stress. In fact during a test the gas volume increase, the pressure of which moves the pistons, is negligible in comparison with the total volume of the chamber so that the gas pressure can be maintained constant.

In the case that the strain rates along the two axes are to be set equal, synchronisation has also been obtained by leading the water discharge to a single membrane, all the discharge circuits having the same length. Two further hydropneumatic elements, mounted on a third axis orthogonal to the other two, makes this machine suitable for triaxial testing, for the determination of not only the intersections but the whole surfaces of yielding and fracture, as shown in Fig. 13. This is particularly important for defected or anisotropic materials such as concrete.

4. Dynamic Biaxial Tests on Large Specimens

In order to answer the second question mentioned at the end of chapt. 2, relative to the importance of transferring the results to real size structures, we now have under construction a high-load dynamic biaxial machine (Fig. 18) based on the loading principle of the modified Hopkinson bar, which will be operational by the end of this year.

This machine consists of four arms, each arm has a length of 100 m and is made of a parallel-wire steel cable connected at one end to a hydraulic piston with gas accumulator capable of generating 5 MN loads and at the other end to the specimen, similar to that shown in Fig.12, which may have a cross section of up to 5000 mm^2. Any other structure shape, reproducing a real one, may be loaded by this device.

At the beginning of the test the pre-stress imposed by the piston goes through two exploding bolts on the concrete structure of the central bunker. The simultaneous explosion of the bolts ignited by exploding wire detonators, transfers the dynamic load simultaneously to the specimen and/or structure under testing.

Each of the four generated tension pulses has a rectangular shape with an amplitude of up to 5 MN, a calculated rise time of about 100 microseconds and a duration of 40 milliseconds, due to the length of the arms, which can be prolonged indefinitely for medium strain rates by the action of the gas accumulator associated to the hydraulic piston. By all these means strain rates ranging from 10^{-4} to 10^{3} s^{-1}, depending on the specimen shape and strength, can be achieved.

The highest pre-stress in the steel cable could be about 150 kg/mm^2 resulting in a displacement velocity of the free end of the cable of about 40 m/s. Each arm of the machine is provided with brakes which, for safety reasons, arrest the displacement of the end of the cable connected to the specimen before the cable passes from tension to compression. A mechanism is foreseen which transforms the pulses to be applied to the specimen from tension to compression (see Fig. 19).

A test programme on real thickness steel plates, damaged by welding, fatigue, creep and/or artificial defects, has been prepared.

Tests are also planned on composite materials, such as plane, reinforced and prestressed concrete.

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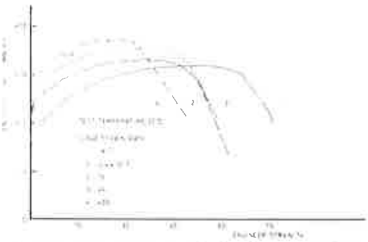

Fig 1 STRESS STRAIN CURVES FOR AISI 316 L STAINLESS STEEL VIRGIN
COLLABORATION EURATOM-C N E N

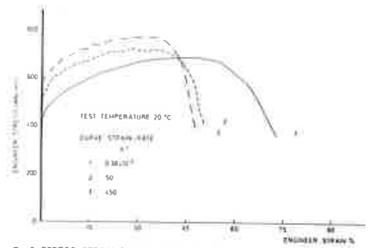

Fig 6 STRESS-STRAIN CURVES FOR AISI 304 L VIRGIN
COLLABORATION EURATOM-CEA

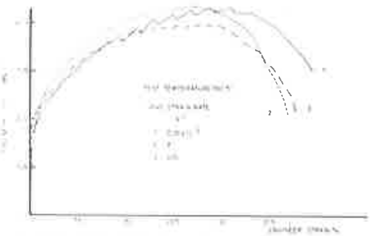

Fig 2 STRESS-STRAIN CURVES FOR AISI 316L STAINLESS STEEL VIRGIN
COLLABORATION EURATOM-C N E N

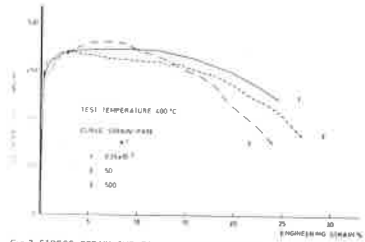

Fig 7 STRESS-STRAIN CURVES FOR AISI 304 L VIRGIN
COLLABORATION EURATOM-CEA

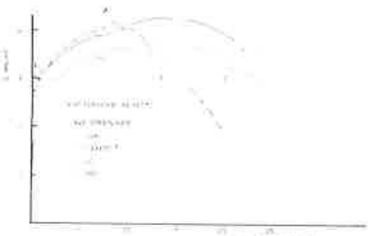

Fig 3 STRESS-STRAIN CURVES FOR AISI 316 L S S WELD
COLLABORATION EURATOM-C N E N

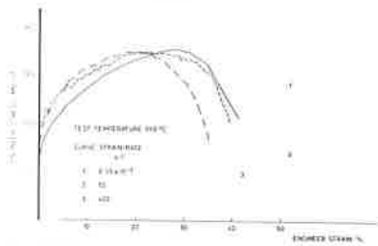

Fig 8 STRESS-STRAIN CURVES FOR AISI 304 L STAINLESS STEEL WELD
COLLABORATION EURATOM-C N E N

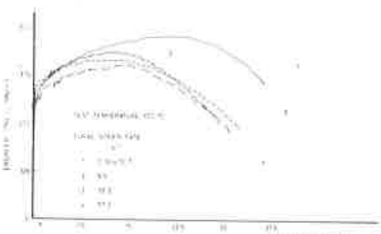

Fig 4 STRESS-STRAIN CURVES FOR AISI 316 L STAINLESS STEEL IRRADIATED
TO 2.2 DPA COLLABORATION EURATOM-CEA

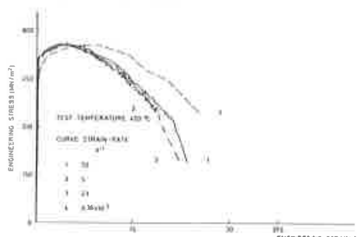

Fig 9 STRESS-STRAIN CURVES FOR AISI 304L S S IRRADIATED TO 2 2 DPA
COLLABORATION EURATOM-CEA

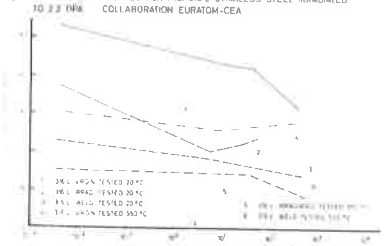

Fig 5 EFFECT OF STRAIN-RATE ON THE UNIFORM ELONGATION OF AISI 316 L S S VIRGIN,
WELD, IRRADIATED TO 2,2 DPA AT 400 °C
COLLABORATION EURATOM-CEA
EURATOM-C N E N

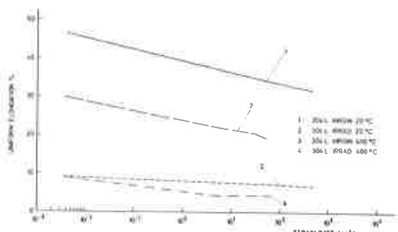

Fig 10 EFFECT OF STRAIN RATE ON THE UNIFORM ELONGATION OF AISI 304 L S.S. VIRGIN
AND IRRADIATED TO 2 2 DPA AT 400 °C
COLLABORATION EURATOM-CEA

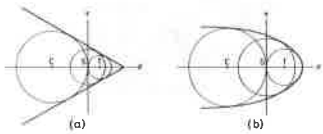

Fig 11 MOHR ENVELOPES FOR BRITTLE (a) AND DUCTILE (b) MATERIALS

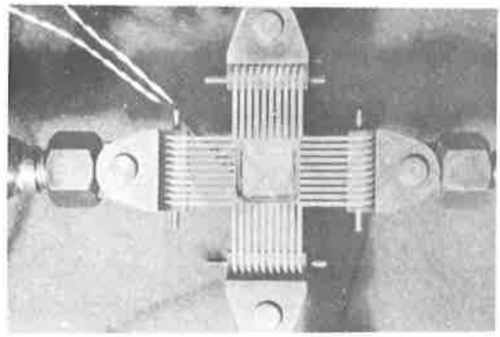

Fig.12

Biaxial specimen for dynamic tensile tests

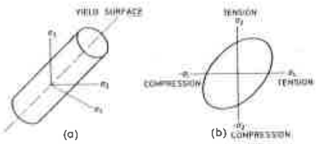

Fig 13 a) STRESS SPACE
b) INTERSECTION OF STRESS SPACE WITH PLANE $\sigma_3 = 0$

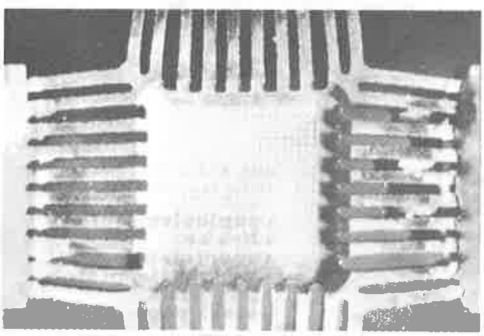

Fig.14

Biaxial specimen deformed up to 35 %

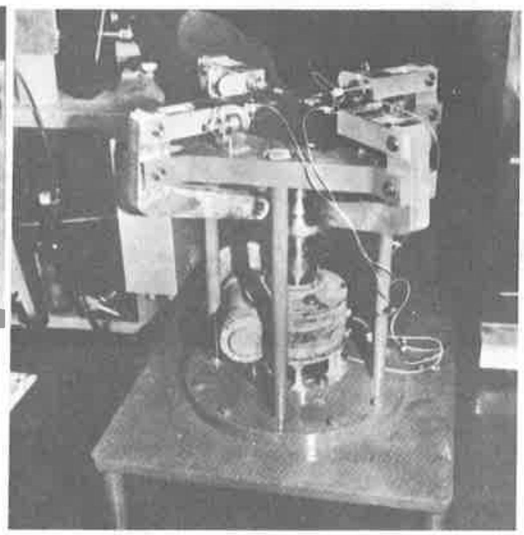

Fig.15 Biaxial testing machine. Strain rate range 10^{-4} TO 10^{-1} s^{-1}

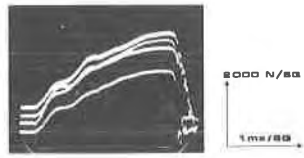

Fig.17

Hydropneumatic dynamic biaxial machine. Record of load versus time.

BIAXIAL DYNAMIC TESTING APPARATUS

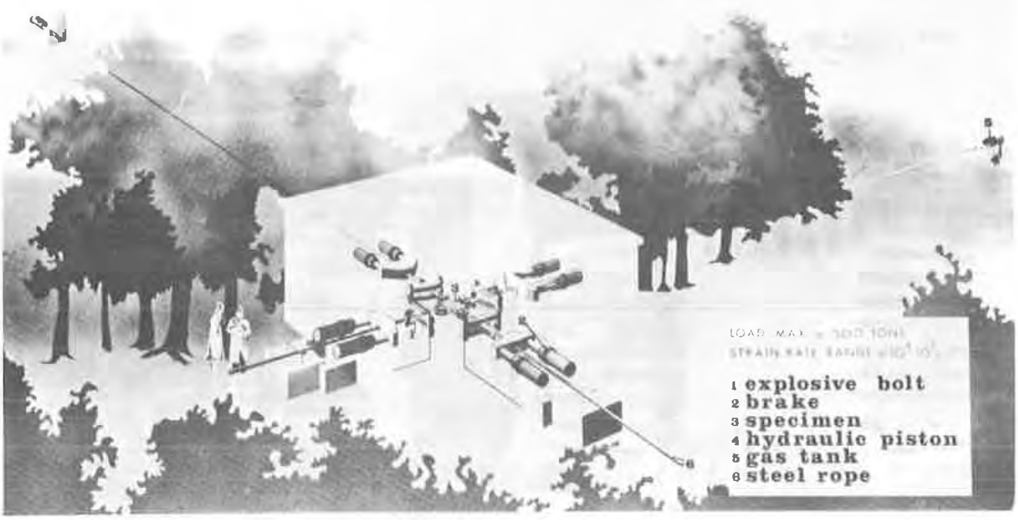

Fig.18

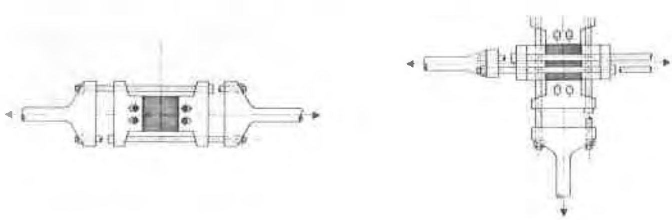

Fig 19 DEVICE FOR BIAXIAL TESTS IN COMPRESSION