The split Hopkinson bar, a versatile tool for the impact testing of concrete

H. W. Reinhardt

Prof., Dr.-Ing., Stevin Laboratory, Department of Civil Engineering, Delft University of Technology, The Netherlands.

H. A. Körmeling

Ir., Research Engineer, NBM, The Hague, The Netherlands.

A. J. Zielinski

Dr.-Ir., Dywidag Systems, Zaltbommel, The Netherlands.

Material properties under impact loading were studied by means of the split Hopkinson bar method. The paper describes the basic features of the equipment and gives the technical specifications of the materials and components used. The equipment, which had been designed for uniaxial tensile loading, was adapted for pull-out bond testing, for cryogenic testing, and for biaxial compression/tension testing. The various requirements and adjustments are dealt with and the principal results illustrating the various applications are reported. It is explained that testing equipment suited for strain rates between 0.05 *and* 25/*sec. has been developed at fairly low cost.*

1. INTRODUCTION

A few years ago, the safe design of concrete foundation piles in regard to brittle failure during driving was discussed in the Netherlands. Since cracking of concrete is governed by the tensile strength and brittle failure can occur when the reinforcement is less than a minimum value, the question arose whether high stress rates during pile driving may influence the value of tensile strength, and therefore the minimum reinforcement ratio as well. Accordingly, a testing program was set up for the investigation of the impact tensile strength of concrete. It soon became apparent that the hydraulic equipment available in the Stevin Laboratory was not fast enough for the loading rates required. Other methods were therefore considered which would be suited for uniaxial testing and would allow stress rates between 2,000 and about 100,000 N/mm^2 sec., besides being comparatively inexpensive.

It was decided to adopt an idea from Kolsky [1], who had suggested modifying Hopkinson compressive bar to operate with tensile pulses. Because some preliminary tests on a rather simple prototype satisfied the expectations, a more professional apparatus was built. After the first test series on plain concrete the equipment was further developed for bond testing, repeated loading, biaxial testing, testing at cryogenic temperatures and for the testing of steel fibre reinforced concrete.

This paper describes the basic idea of the equipment, the adjustments for various purposes and the general experience. Some experimental results will be given which illustrate the capability of the testing method. The equipment is confined to tensile loading, while other researchers have used the method for rock and concrete compressive loading ([13], [14], [15]).

2. PRINCIPLE OF THE SPLIT HOPKINSON BAR

Hopkinson [2], a British physicist, carried out impact tests on various materials. He generated a compressive

* Extended version of a contribution to the RILEM International Conference on Destructive Testing Equipment, Dübendorf, Switzerland, April 18/19 1985.

pulse in a bar by an explosive charge or an impacting bullet. The compressive pulse reflected at the opposite end of the bar as a tensile pulse and caused fracture of the brittle material such as rock or mortar. Kolsky [1] used the idea of wave propagation in a bar and made the method operational for wide application. This method is now known as split Hopkinson (pressure) bar. Figure 1 shows the schematic of a split Hopkinson bar for compressive testing. The striker bar approaches from the left and impacts the incident bar. The compressive pulse travels through the incident bar and reaches the specimen. At this interface, a part of the incident pulse is reflected due to the mismatch of the mechanical impedances of bar and specimen. Another part is transmitted into the specimen. If the wave-transit time in the short specimen is small compared with the duration of the loading pulse, many wave reflections can take place in the specimen. Hence the stress and strain along the specimen can be assumed to be uniform. Equilibrium at the interface between specimen and transmitter bar means that the force in the specimen and the force in the transmitter bar are equal. Strain measurement on the elastic transmitter bar by strain gauges gives the force acting on the specimen with a

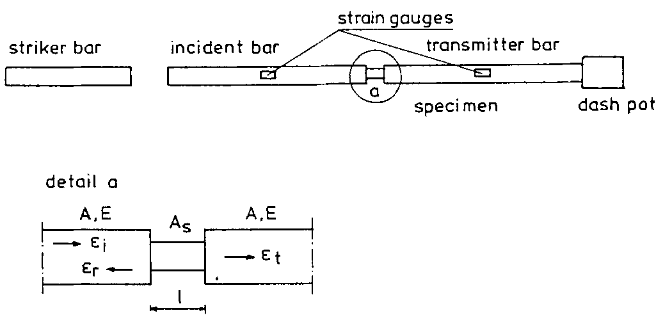

Fig. 1. —Schematic of the split Hopkinson bar.

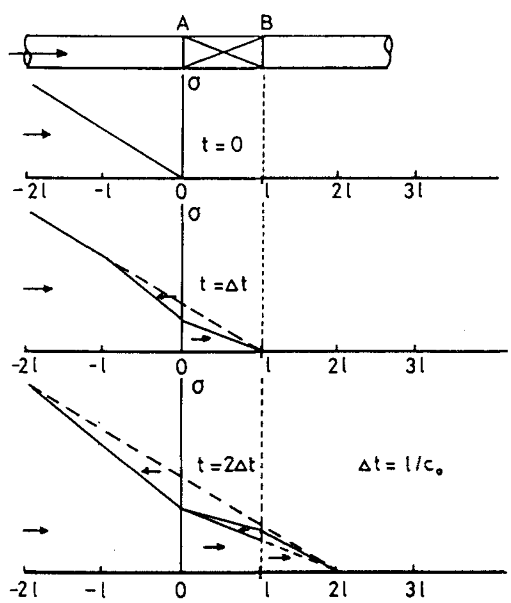

Fig. 2. —Wave travelling through the specimen.

time shift equal to the distance divided by the wave propagation velocity.

The average strain ε_s in the specimen can be calculated from the displacements at the end of the specimen. The theory, which is well documented [3], leads to the expressions:

$$\varepsilon_s = -2\, c_0/l \int_0^t \varepsilon_r \, dt$$

and:

$$\dot{\varepsilon}_s = -2\, c_0\, \varepsilon_r / l, \qquad (1)$$

where c_0 is the wave propagation velocity, ε_r the reflected pulse in the incident bar and l the specimen length. The stress in the specimen is:

$$\sigma_s = E\, \varepsilon_t\, A/A_s, \qquad (2)$$

where E, A and ε_t are Young's modulus, cross-sectional area and transmitted pulse in the transmitter bar and A_s is the cross-sectional area of the specimen. From equation (1) it follows that a high strain rate is achieved if ε_r is large. For a given pulse, ε_r is large if the mismatch between the impedances is large. This can be achieved by using a specimen diameter which is small in comparison with the incident bar or a bar material which is stiff in comparison with the specimen material.

Equation (1) shows that the average strain in the specimen can be determined by measuring the reflected pulse in the incident bar. To make this possible the incident pulse and the reflected pulse have to appear separately in succession, which means that the length of the striker bar and the distance of the strain gauge to the specimen are correlated. Within limits it may be possible to separate two crossing waves by two-point strain measurements and an electronic analyser [4].

The requirements of our concrete testing program differed at least in two main points from the usual split Hopkinson bar test: the stress (or strain) rate is comparatively low, which means a long pulse (of the order of a few meters), and the material is concrete, which means that the specimen width should be at least four times the maximum aggregate size. According to equation (1) a constant strain rate can be obtained by a uniform reflecting pulse and therefore a uniform incident wave. We were not able to achieve this. Therefore another procedure was adopted.

It was endeavoured to match the incident and the transmitter bar as closely as possible to the impedance of the specimen and to generate a pulse with a constant *stress (strain) rate* instead of a uniform stress (strain). If a linearly increasing pulse is divided into step pulses and the repeated reflexion and transmission are superposed, subsequent situations are obtained according to figure 2. It turns out that the stress rate in the specimen is the same as the stress rate of the incident pulse.

In this arrangement the stress is determined from strain measurements on the transmitter bar, and the strain is measured directly on the specimen. The reflected pulse in the incident bar is no longer important.

The length of the incident bar and the transmitter bar should be such that the pulses reflected from the ends of the bars do not interfere with the incident pulse. If T is the loading time until fracture and f_t the tensile strength, the length of the bars should be:

$$L \geqq 1/2\, T c_0 \qquad \text{and} \qquad L \geqq 1/2\, f_t c_0/\dot{\sigma}, \tag{3}$$

where c_0 is the wave propagation velocity and $\dot{\sigma}$ the envisaged stress rate. The diameter of the bars should be less than 20 times the length, otherwise dispersion effects may make the application of the one-dimensional wave theory doubtful [1].

3. APPLICATION OF THE SPLIT HOPKINSON BAR TO CONCRETE TESTING

3.1. Basic equipment

The incident and transmitter bars consist of an elastic material. To match the impedance of the bars with the concrete specimen, structural aluminium was chosen instead of steel, which would have been cheaper (table I).

Table I shows that high-strength concrete comes closest to aluminium.

The diameter of the bar was adjusted to an available 74 mm core drill by means of which the concrete specimens were drilled from concrete blocks. The length of the incident bar is 3.50 m, of the transmitter bar 6.65 m, the specimen is 100 mm long. Figure 3 gives an impression of the main dimensions of the vertical arrangement. The bar is supported at the upper end by a buffer which should minimize the reflexion of waves. As buffer material rubber pads and steel springs have been used; however with unsufficient result. It appeared that fix clamping to the steel frame was best.

The bar is guided through four teflon (PTFE) bushings and horizontally supported. The deadweight of the lower bar is compensated by counterweight. The stress pulse is generated by a drop weight which slides along the lower bar and hits the anvil at the lower end.

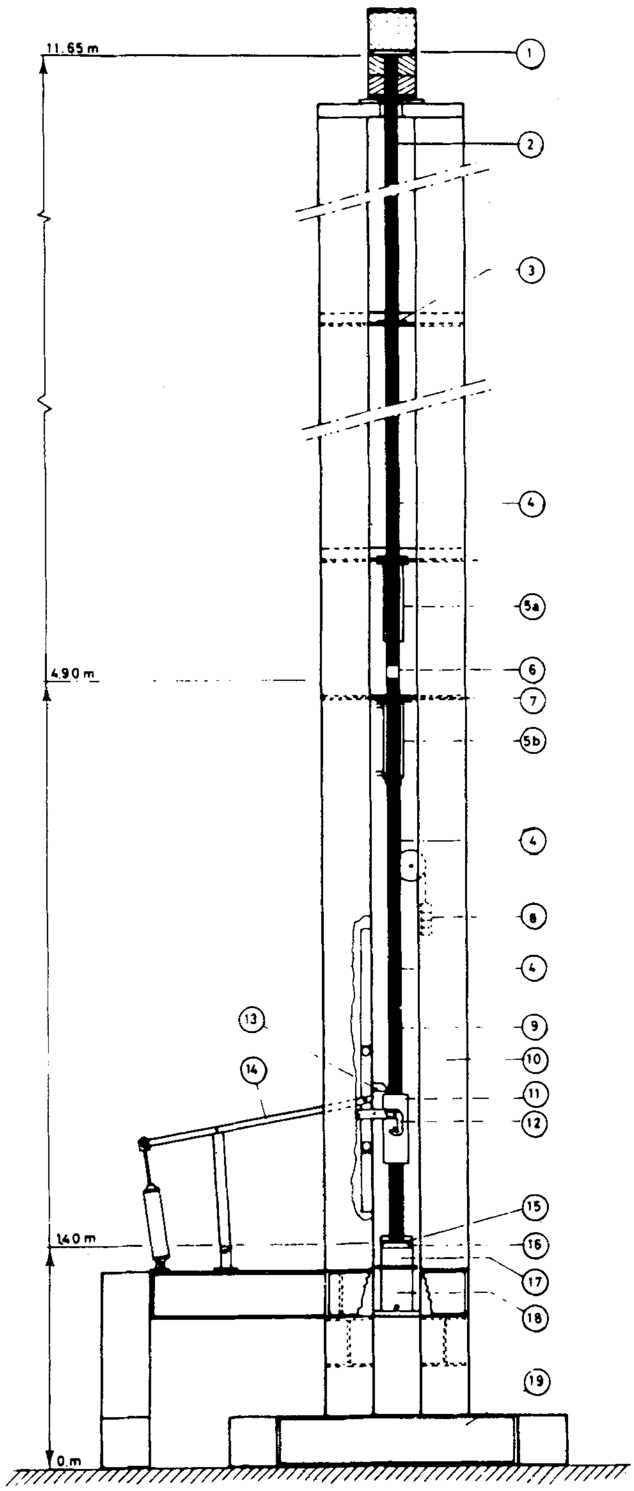

Fig. 3. —Split Hopkinson bar equipment, schematically.
1, buffer; 2, upper bar; 3, guide; 4, strain gauge; 5*a*, upper cooling jacket; 5*b*, lower cooling jacket; 6, concrete test specimen Ø 74 × 100 mm; 7, working platform; 8, counterweight; 9, lower bar; 10, frame; 11, drop weight; 12, coupling; 13, uncoupling; 14, lifting device; 15, damping material; 16, anvil; 17, guide tube; 18, pneumatic jack; 19, frame base.

TABLE I

MECHANICAL IMPEDANCE OF SOME MATERIALS $I = c_0\rho = \sqrt{E.\rho}$.

Material	E (GN/m²)	ρ (kg/m³)	I (MNs/m³)	c_0 (m/s)
Aluminium	68	2,730	13.6	4,990
Steel	210	7,800	39.9	5,110
Concrete:				
low strength	7	2,400	4.1	1,700
high strength	40	2,400	9.8	4,100

The drop weight consists of a steel mass which is guided by three nylon guides. The drop weight mass can be changed from 5 to 40 kg. The loading pulse depends on drop weight mass and velocity (drop height) and the contact between drop weight and anvil. Figure 4 shows several stress-time relations for a few combinations of the parameters mentioned. It can be seen that fast and high amplitude pulses are the result of maximum drop weight and as few rubber layers as possible (rubber of 80 shore). Instead of rubber, cardboard or multi-plywood have been used successfully. The linearity of the pulses is excellent for high loading rates, but is less for the lowest rates [5].

The loading is determined from strain measurements on the upper bar. Four strain gauges (Hottinger 3/120 Ly63) are fixed at a distance of 1 m from the specimen. The strain of the concrete specimen which is glued to the aluminium bars is measured by 60 mm strain gauges or by proximity transducers, type Hottinger TR10, fixed to the aluminium bars (*fig.* 5).

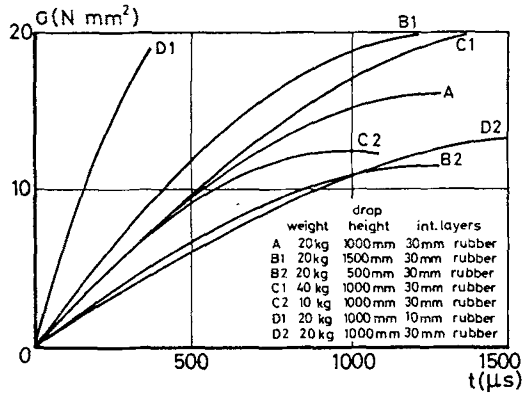

Fig. 4. — Stress-time relation for various combinations of drop height and interlayer.

The measuring signals are amplified by a Tektronix AM 502 amplifier and fed to four or five channels of a modified two-channel transient recorder (Nicolet Explorer II) which has a maximum measuring frequency of 2 MHz and a 4 *k* core. The results are plotted on a *x-y*-recorder or stored on a floppy disk which could be processed by the laboratory computer HP 21 MX. Synchronizing the stress-time and strain-time relations results in stress-strain curves.

This basic equipment was installed in the basement of the Stevin Laboratory. Because of its height, it extends through the demountable groundfloor, just under the crane of the testing hall. Except the Hopkinson bar itself, nearly all parts of the equipment belong to the exchangeable testing modules of the laboratory. The working level is the ground floor where the specimen is inserted. From there the drop weight can be raised by remote control and released.

3.2. Plain concrete under single uniaxial tensile pulse

The investigation of the uniaxial impact tensile strength was the first test series with the split Hopkinson bar. Specimens ∅ 74 mm were drilled from a concrete block. They were cut to about 100 mm length and the ends were ground plane-parallel. The cylinders were glued between the upper and the lower bar with the filled acrylic-based fast glue F88 from Tridox Products, Philadelphia. During glueing the lower bar was lifted by an air pressure jack which subjected the specimen and joints to a pressure of 0.1 N/mm². To ensure proper adhesion the ground concrete faces were impregnated with a polyester resin.

In this series, the basic equipment was used without alterations. About 150 tests were performed with stress rates between 2 and 62 kN/mm²s, which yielded a relation between tensile strength and stress rate of the following form:

$$f/f_0 = (\dot{\sigma}/\dot{\sigma}_0)^{\alpha}, \quad (4)$$

where f is the impact strength and f_0 the static tensile strength, while $\dot{\sigma}$ and $\dot{\sigma}_0$ are the stress rates in impact and static testing, respectively. The power α depends on the concrete mix, temperature and humidity. The order of magnitude is 0.05.

3.3. Plain concrete under repeated uniaxial tensile pulses

The experimental program had its origin in pile driving. Therefore the influence of repeated impacts on the tensile strength was as relevant as the influence of the loading rate itself. To facilitate impact fatigue loading, an automatic lifting mechanism operated with compressed air was added to the split Hopkinson bar. It lifted the drop weight and released it at a preset level. The frequency of impact was approximately 16 loading cycles per minute. The number of cycles ranged between 500 and 6,000 cycles to fracture, corresponding to a total test duration of about 30 minutes to 7 hours.

The maximum upper stress was controlled by the appropriate drop height and number of layers on the anvil. A typical loading pulse shows a short transient time whereafter a constant stress rate appears till just under the maximum stress. Then the stress drops to a low value and is reversed due to reflection at the upper end of the transmitter bar.

The reflexion is greatly attenuated by the buffer, and the remaining compressive stress is thought to be too low to affect the tensile strength of the concrete. During the tuning of the system it was found that a low peak stress was associated with a low stress rate of 2 to 6 kN/mm²s. During the test the number of cycles to failure was counted and the peak stress checked by the transient recorder.

The results of 89 repeated loading tests were analysed with the relation:

$$\sigma_{max}/f_0 = A - B \log N, \quad (5)$$

where f_0 is the single loading static strength and N the number of cycles to failure. A and B are coefficients depending on concrete mix, temperature and humidity. In this investigation [6] A had an average value of 1.43 and B was 0.104.

3.4. Pull-out test on reinforcing steel in concrete

Bond between reinforcing steel and concrete is usually investigated by pull-out tests in which an embedded bar is pulled out of the concrete. The embedment length should be small in order to make the bond stress along the embedment length as uniform as possible. Whereas numerous results from static testing were available there was hardly any information on bond under impact loading. It was decided to use the split Hopkinson bar and to adjust it to new testing requirements.

The pull-out specimens consist of reinforcing steel Ø 10 which is embedded in a concrete cylinder of 102 mm diameter drilled from a large concrete block. The embedment length is 3 times the steel diameter. The concrete is glued to an aluminium adapter which reduces the diameter from 102 to 74 mm, which is the diameter of the basic split Hopkinson equipment [7]. A hole is machined in the adapter where the proximity transducer is mounted which measures the relative displacement of the upper end of the reinforcing steel to the aluminium bar. This displacement is called slip. The lower end of the steel bar is welded to a steel plate which is glued to the incident aluminium bar. When prestressing strands were tested, some modifications were necessary. The pull-out force was measured by the strain of the reinforcing bar or by the strain of the transmitter bar in the case of strands.

Since reinforcing bar and strand have a much smaller impedance than the incident bar a great part of the incident pulse is reflected. This leads to the fact that the transmitted pulse is shifted in time and has a lower loading rate than the incident pulse. But the pull-out force is still high enough to complete the experiment.

It appears that the stress rate is almost constant over a large range of the experiment. By synchronizing the stress-time and slip-time relations and eliminating time, bond stress-slip relations were obtained. 25 impact tests on deformed reinforcing bars yielded the following relation:

$$\tau/\tau_0 = (\dot{\tau}/\dot{\tau}_0)^\eta, \qquad (6)$$

where τ and τ_0 are the impact stress and static bond stress, $\dot{\tau}$ and $\dot{\tau}_0$ the bond stress rates and η a coefficient which depends on the slip δ and the static cube compressive strength f_c of the concrete according to:

$$\eta = (0.7 - 1.75\,\delta)/f_c^{0.8}, \qquad (7)$$

where δ is in millimeters and f_c in N/mm^2. The bond stress rates tested were between 20 and 160 kN/mm^2s. The loading rates were varied by the number of interlayers between drop weight and anvil, as has been described in Section 3.1. Data acquisition and processing were also the same as previously written.

3.5. Fibre concrete under single uniaxial tensile pulse at ambient temperature

After the test series on plain concrete, it was attempted to test steel fibre concrete with the same basic split Hopkinson bar. It soon became apparent that the energy of the drop weight was only sufficient to crack the specimen but not to pull out the fibres completely. Another aspect was the maximum attainable strain rate which had so far been 1.5/sec., but which had to reach 20/s according to a new program requirement. In order to increase the energy and the strain rate, an idea of Albertini and Montagnani [8] was adopted, i. e. to prestress the incident bar and to release the prestressing force in a very short time.

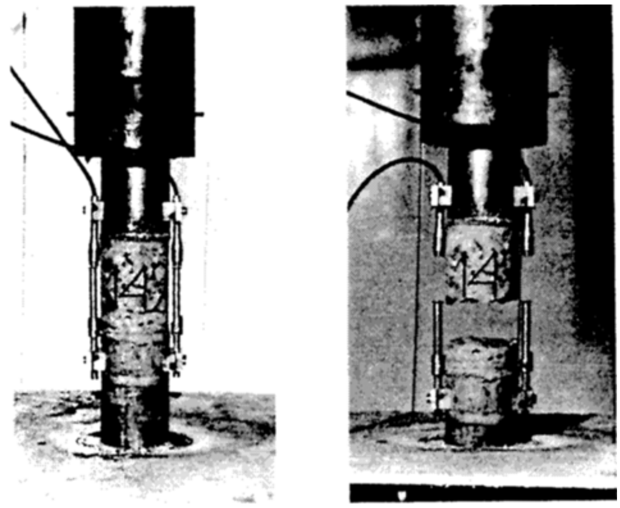

Fig. 5. — **Concrete specimen with contactless LVDTs before and after failure.**

Figure 6 illustrates the realization of that idea. The incident bar and the transmitter bar are connected by

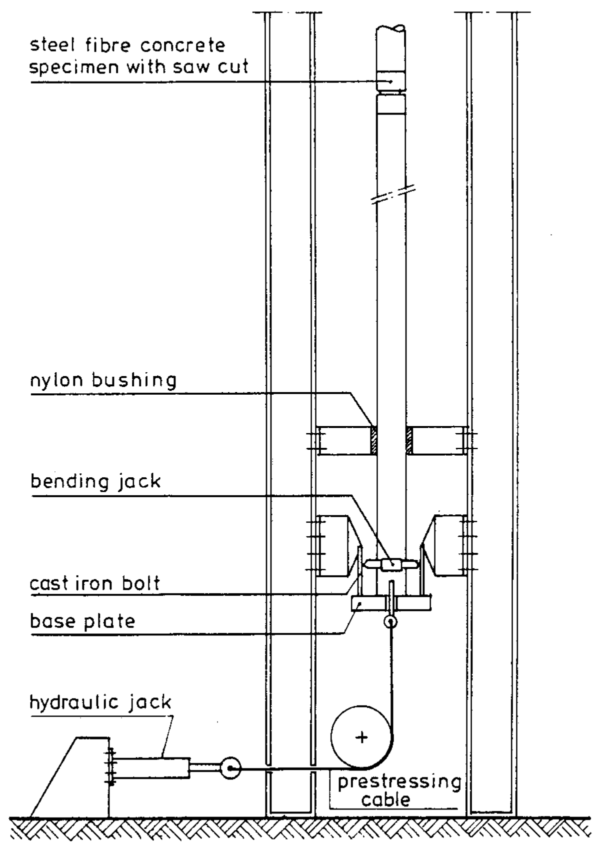

Fig. 6. — **Prestressed Hopkinson bar.**

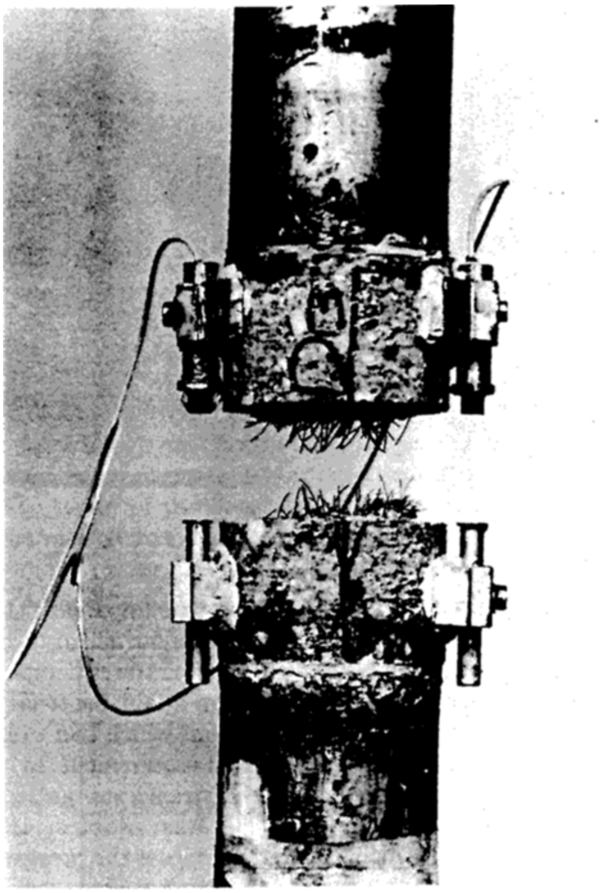

Fig. 7. — Steel fibre concrete specimen after failure.

the specimen. The incident bar rests on a base plate which is held by two cast iron bolts fixed to two supports. A 1.5 m long prestressing cable is fixed to the lower end of the incident bar by a bolt in a blind hole. The prestressing cable goes via a wheel to the hydraulic jack mounted on a stiff support. After the cable is prestressed to the appropriate force (maximum 100 kN) the cast iron bolts are fractured simultaneously in bending by a small separate hydraulic jack. Within 20 μs the prestressing force is transmitted to the incident bar. The tensile pulse travels to the specimen, fractures it and pulls the fibres completely out of the concrete. Figure 7 shows a specimen after fracture. It turned out that the best material for the prestressing cable was aramide, which has about the same strength as prestressing steel but a 40% lower modulus of elasticity. This means more strain energy stored at the same prestressing force. An improvement to the arrangement as shown in figure 6 could be achieved by prestressing a lower part of the incident bar. The frictional collar with the iron bolts is raised to a higher position on the incident bar. By this means the pulse was introduced into the bar without delay.

A theoretical treatment [11] revealed a linear relationship between the prestressing force and the strain rate. On the other hand, the experiments clearly showed that the strain rate during a test was not constant. As could be expected from equation (1), the strain rate increases when the reflected pulse increases. This happens when the impedance of the specimen decreases during the test, which is the case as soon as cracks occur. Most of the tests started with $\dot{\varepsilon} = 1.5$/sec., switched to $\dot{\varepsilon} = 10$/sec. after cracking and increased to $\dot{\varepsilon} = 23$/sec. during fibre pull-out.

Strain and force measurements were performed as already described in Section 3.1. Figure 8 gives a comparison of the stress-elongation relation of steel fibre concrete under static and under impact loading with the corresponding relations for plain concrete up to 0.2 mm elongation. The influence of impact loading is quite evident for both concretes. The measurements were taken until 1.7 mm elongation. Beyond this displacement the contactless LVDTs were not sensitive enough.

3.6. Fibre concrete under single uniaxial tensile pulse at −170°C

When natural gas is to be stored at atmospheric pressure in the liquefied state it is cooled to —165°C. Safety walls made of fibre reinforced concrete can protect LNG storage facilities against catastrophic events. For judging the effectiveness of fibre concrete the cryogenic properties should be known, including the tensile impact strength. For this reason, the split Hopkinson bar as described in Section 3.5 was provided with a cooling chamber around the specimen [12].

The chamber is a flat-ended cylinder of 210 mm height and 270 mm outside diameter. It consists of two halves united by a joint sealed with silicon mastic. The 22.5 mm thick walls of the chamber are composed of an inner and an outer layer of 5 mm thick glass fibre reinforced epoxy resin with insulating foam sandwiched between. The thermal resistance of this sandwich wall, which has been developed by the Engineering Physics Department of the Delft University of Technology, is extremely high (1.12 Km^2/W). The free inner space of the chamber is large enough to allow uniform circulation of nitrogen vapour which is sprayed against the blades of a fan (*fig.* 9).

The extremely low temperature caused a few problems in regard to the mounting of the specimen on the Hopkinson bars. Since the coefficient of thermal expansion of aluminium is about twice that of concrete, thermal stresses develop in the joint between the concrete and the aluminium. They were large enough to cause failure, always in the joint, already during cooling. 30 mm thick steel plates were therefore glued to the ends of the specimen and to the aluminium bars. Stycast 5850 FT filled epoxy (Emerson and Cuming) with catalyst 9 was used as bonded material. Hardening lasted overnight at 20°C to achieve a tensile bond strength of 58 N/mm^2. The following day the displacement transducers were attached by means of F88 acrylic-based fast glue (Tridox Products).

Then cooling with liquid nitrogen started at a rate of 2 K/min. Through bore holes in the Hopkinson bars close to the specimen the ends of the specimen were

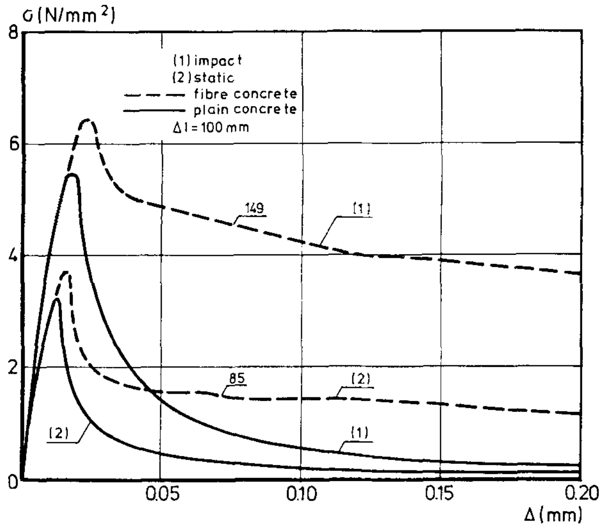

Fig. 8. — Stress-elongation relation for steel fibre concrete and plain concrete at static and impact loading.

cooled and nitrogen was sprayed into the cooling chamber. A uniform temperature distribution in the specimen was thus achieved. The temperature in the specimen was monitored with copper/constantan thermocouples. The cooling rate in the chamber was controlled by a micro-computer (Commodore 64) and a platinum resistor whose change in resistance was measured and converted to a digital signal. The signal was compared with the calibration curve which is not necessarily linear. The difference between the measured signal and the prescribed chamber temperature is used as the steering signal for the nitrogen flow.

Displacement was measured by two HBM TR10 proximity transducers specified for temperatures between —160 and +120°C. However, no problems were encountered down to —196°C (liquid nitrogen), except that the sensitivity was reduced by about 5%. The most vulnerable parts were the lead wires which

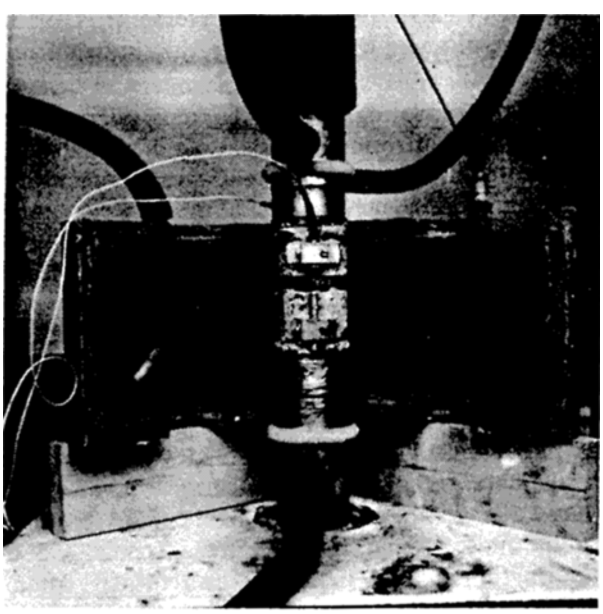

Fig. 9. — Cooling chamber for cryogenic testing.

had to be handled carefully. The force was measured via the strain of the transmitter bar. The data were amplified in Tektronix AM 502 amplifiers and fed into a Nicolet Explorer II transient recorder. With the aid of the HP 21 MX laboratorium computer stress-elongation curves were generated and the fracture energy was calculated by integrating the area under the curves.

An example of the results (*fig.* 10) shows that cryogenic temperature has only a rather small effect on plain concrete and a negligible effect on steel fibre concrete under impact loading. This is contrary to what is found in measurements at slow loading rates.

3.7. Plain concrete in biaxial impact loading: static compression-impact tension

The one-dimensional case of loading is rather the exception than the rule in real structures. Combinations of compressive/compressive and tensile/compressive stresses are quite usual. A question which arises when

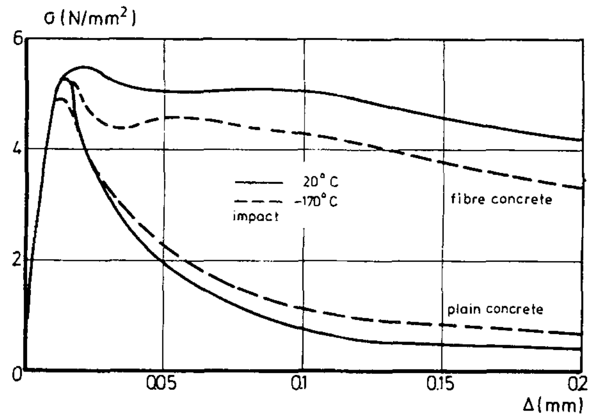

Fig. 10. — Stress-elongation relation for fibre concrete and plain concrete at 20 and —170°C during impact.

judging the impact behaviour of beams is: what is the shear load capacity of a prestressed beam? In this case a sustained compressive stress acts in the longitudinal direction of the beam, whereas inclined impact tensile stresses are superposed. This situation was translated to a test program in which transversely precompressed specimens were subjected to impact tensile loading.

For this reason the basic split Hopkinson bar was extended by a horizontal prestressing device. Figure 11 shows the arrangement. It consists of four steel platens (40 x 550 x 750 mm) mounted on steel bars of 20 mm diameter. The two outer platens are fixed, the two inner ones slide along the steel bars. Between the right-hand pair of platens a flat jack (capacity 400 kN) is placed, whereas a load cell is placed between the other pair. The prestressing force is transmitted to the concrete prism via brush platens. Each brush consists of 1,260 individual rods (4 x 4 x 100 mm) spaced with 0.2 mm clear distance. These brushes were available in the laboratory from a former investigation [9]. Although the face area of the brushes (180 x 130 mm) was larger than the loading face of the concrete prism (50 x 100 mm), they could successfully be used.

Figure 11 shows also that the cylindrical bars of the Hopkinson equipment were adjusted to the rectangular cross-section of the concrete prism by means of two aluminium adapters. They were glued to the bars with F88 fast acrylic glue. Four pairs of measurements were made: prestressing force with the load cell, transverse strain by means of 30 mm strain gauges on the concrete, longitudinal force by means of strain gauges on the transmitter bar. The pairs of measurements were averaged, amplified and fed into two transient recorders (Nicolet Explorer II). The data were treated in the same way as described in Section 3.1.

Figure 11 gives also a view of a fractured specimen which had been prestressed up to 0.7 times the cylinder compressive strength. If the prestress was less than 0.5 f_{cyl} a single fracture plane occurred. The usual result was that the failure envelope for biaxial loading under impact was similar to the one obtained in static loading, while the absolute impact strength was about twice that in static loading [10].

4. GENERAL ASSESSMENT OF THE SPLIT HOPKINSON BAR EQUIPMENT

Impact testing of concrete is not as usual as impact testing on metals, for which standard tests have been developed (Charpy test, Robertson test). Impact strength of concrete does not belong to the properties necessary for characterization or acceptance of this material. Therefore it is justified to develop specific testing equipment. If this is agreed, a method should be applied which allows the determination of physical properties which can be used in the analysis of structures. This means that the boundary conditions of the test must be clearly defined and that the method should give reproducible results. Besides scientific or technical requirements, there are economic aspects. Equipment which is to be developed for special tests should not be too expensive.

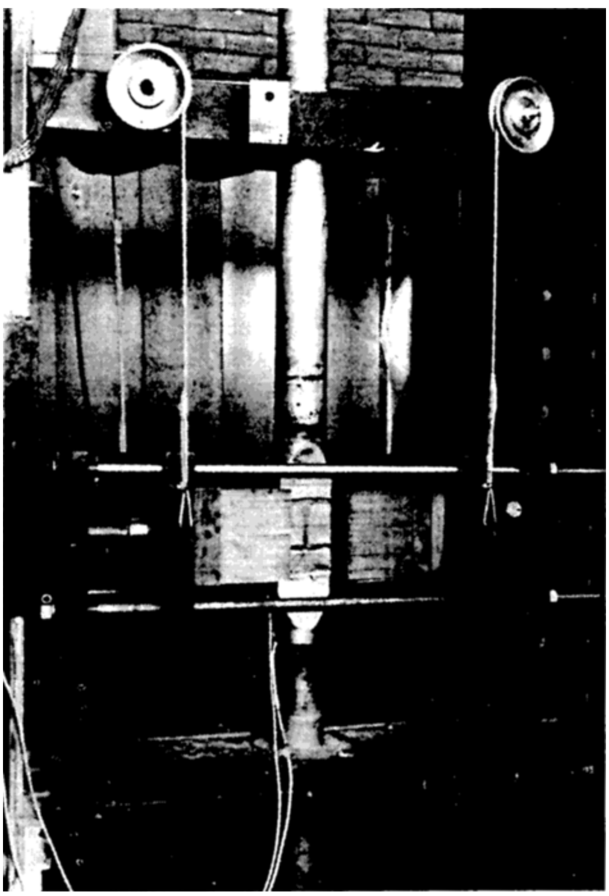

Fig. 11. —Transverse prestressing with brush platens.

We believe that the split Hopkinson bar satisfies the requirements stated. So far as the boundary conditions of the test are concerned they are clearly defined. It is a uniaxial tensile test with almost rigid clamping. The rotation of the ends of the specimen is negligible when a crack occurs. Eccentricity is obviated by glueing the specimen directly to the aluminium bars which are carefully aligned. Hence the stress state is uniform and the stress (strain) rate is also uniform over the cross-section of the specimen. The strain rate is almost constant till the onset of failure. As soon as cracks appear, the impedance of the specimen changes and the strain rate increases. If the descending branch of a stress-strain curve is determined, it must be realized, that the ascending and the descending branch may have strain rates differing by a factor of 10 to 100.

The physical meaning of the tensile strength should be considered. Tensile strength is a necessary property in a "strength-of-materials" approach. It is also a parameter in nonlinear fracture mechanics since it determines the maximum stress near a crack tip. If Young's modulus and the fracture energy, i. e. the area under the complete stress-strain curve, are measured, all the requisite quantities are established for a nonlinear fracture mechanics analysis of a strain softening material.

Another point is the reproducibility of the results. After preliminary difficulties with proper fixing of the specimen and with synchronizing the stress-time and displacement-time outputs had been overcome, the scatter in the results was comparable to that known from static testing of concrete.

Some points relating to the economic aspect also call for mention: investment costs, operating costs and labour costs. The investment costs were rather low because standard elements of the laboratory were used for the support frame, and electronic equipment was also available. If new equipment had been purchased an amount totalling US \$ 25,000 would have been needed. The operating costs comprise strain gauges, fast glue, wires, etc. For the cryogenic tests about 50 l of liquid nitrogen is consumed in each test. The labour costs vary from test to test. A strength test without strain measurements can be performed by two persons in half an hour. This includes glueing the specimen, loading and recording the force in the time, plotting the result and removing the fractured specimen with a gas burner and chisel. Strain measurements require another half hour. Cryogenic tests require glueing with overnight hardening, slow automatic cooling for two hours and testing in the morning. Preparing the cooling equipment, applying the LVDTs, glueing and removing the specimen, and plotting the results take about half a day. Of course all these labour costs relate to the current state of the equipment. The development of the method required an input of effort of about one year from an engineer and two years from a laboratory assistant, spread over six years. As has been described, this time involved several adjustments and extensions which made the system versatile for various applications.

5. CONCLUSIONS

Impact testing of concrete is not as usual as impact testing of metals. Therefore a specific method has been developed which satisfies scientific and economic requirements. The split Hopkinson bar method seems appropriate for this task.

The following capabilities of the equipment should be mentioned:

— strain rates of 0.05 to 25/sec. were achieved in uniaxial tensile tests;

— stress rates of 2 to 100 kN/mm^2 sec. (before cracking) were achieved in uniaxial tensile tests;

— bond stress rates between 20 and 160 kN/mm^{2}s were achieved in pull-out tests on reinforcing bars;

— repeated impact tensile loading was performed with automatic loading control;

— cryogenic temperatures (—170°C) were generated for tensile impact testing of plain and steel fibre reinforced concrete;

— impact tensile testing with simultaneous static transverse compression was a first attempt at biaxial loading.

In general it can be concluded that the split Hopkinson bar has been developed with low investment costs since most of the mechanical and electronic equipment came from available general purpose laboratory equipment. Labour costs depend on the type of test. The equipment has grown from a very special device to a versatile instrument for the impact testing of concrete.

REFERENCES

[1] Kolsky H. — *Stress waves in solids.* Clarendon Press, Oxford, 1953.

[2] Hopkinson B. — *A method of measuring the pressure produced in the detonation of high explosives or by the impact of bullets.* Phil. Trans. Roy. Soc. London, Series A, Vol. 213, No. 10, 1914, pp. 437-456.

[3] Zukas J. A. *et al.* — Impact dynamics. John Wiley κ Sons, New York, 1962.

[4] Lundberg S., Henchoz A. — *Analysis of elastic waves from two-point strain measurement.* Experimental Mechanics, Vol. 17, No. 6, 1977, pp. 213-216.

[5] Körmeling H. A., Zielinski A. J., Reinhardt H. W. — *Experiments on concrete under single and repeated uniaxial impact tensile loading.* Stevin Laboratory Report 5-80-3, Delft University of Technology, Delft, 1980.

[6] Zielinski A. J., Reinhardt H. W., Körmeling H. A. — *Experiments on concrete under repeated uniaxial impact tensile loading.* RILEM Materials and Structures, Vol. 14, No. 81, 1981, pp. 163-169.

[7] Vos E., Reinhardt H. W. — *Influence of loading rate on bond behaviour of reinforcing steel and prestressing strands. RILEM Materials and Structures, Vol.* 15, *No.* 85, 1982, *pp.* 3-10.

[8] Albertini C., Montagnani M. — *Dynamic uniaxial and biaxial stress-strain relationship for austenitic stainless steel.* Nuclear Energy and Design, Vol. 57, 1980, pp. 107-123.

[9] Nelissen L. J. M. — *Biaxial testing of normal concrete.* Heron, Vol. 18, No. 1, 1972.

[10] Zielinski A. J. — *Concrete under biaxial loading: static compression-impact tension.* Stevin Laboratory Report 5-85-1, Delft University of Technology, Delft, 1985.

[11] Körmeling H. A. — *Impact tensile strength of steel fibre concrete.* Stevin Laboratory Report 5-84-8, Delft University of Technology, Delft, 1984.

[12] Körmeling H. A. — *The uniaxial impact tensile behaviour of plain and steel fibre reinforced concrete at —170°C.* Stevin Laboratory Report 5-84-13, Delft University of Technology, Delft, 1984.

[13] Hokaletho K. O. — *Brittle fracture of rocks under impulsive loads.* Int. J. Fracture Mechanics, Vol. 6, 1970, pp. 249-256.

[14] Lindholm U. S., Yeakley L. M., Nagy A. — *The dynamic strength and fracture properties of Dresser basalt.* Int. J. Rock Mechanics and Mining Sc. & Geomech. Abstr. 11, 1974, pp. 181-191.

[15] Aronsson R., Fagerlund G., Larsson B. — *Betongs slagseghet i palar.* Cement- och Betonginstitutet, CBI No. 7676, Stockholm, 1976.

RÉSUMÉ

Le « split Hopkinson bar », un instrument universel pour l'essai au choc du béton. — *Les caractéristiques des matériaux sous des charges dynamiques sont étudiés par la méthode « split Hopkinson bar ». La publication décrit les possibilités de base de l'équipement et donne les spécifications techniques des matériaux et des composants utilisés.*

L'équipement, qui a été conçu pour des chargements uniaxials en traction, convient très bien pour des essais de détermination de la traction d'adhérence par arrachement, pour des essais cryogéniques et pour des essais de compression/traction biaxials. On décrit les exigences et les différents réglages nécessaires et on donne les résultats principaux qui illustrent les différentes applications. On explique que l'équipement d'essai est adapté pour des vitesses de déformation entre 0,05 et 25/s, qui ont été réalisées pour un coût relativement bas.