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

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/mm² 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
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 time shift equal to the distance divided by the wave propagation velocity.

The average strain $\varepsilon$ 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:

$$\varepsilon = -2 \frac{c_0}{l} \int_0^t \varepsilon_r \, dt$$

and:

$$\delta = -2 \frac{c_0}{l} \varepsilon_r$$

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

$$\sigma = \frac{E \varepsilon_r A_s}{A}$$

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 reflection 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.