H10/4

Mechanical Properties in Tension and Compression of Plain Concrete at a High Strain Rate

C. ALBERTINI, E. BLERY, M. MONTAGNANI, E. V. PIZZINATO
Commission of the European Communities, Joint Research Centre-Ispra Site, Ispra, Italy

ABSTRACT

Modified Hopkinson bars of large dimensions have been developed for high strain rate tension and compression testing of plain concrete. The strength and deformation ability of plain concrete show a marked increase with increasing strain rate. Therefore, in dynamics, the ability of plain concrete to absorb energy increases largely as compared to the case of slow loading rates.

1 INTRODUCTION

The stress-strain and fracture characteristics at a high loading rate are important elements to be implemented in the constitutive equation of plain concrete because they may significantly contribute to the precise prediction of the consequences of catastrophic events, such as earthquakes and explosions, on civil engineering structures. An experimental study of the mechanical properties of steels has been performed in the last decades using a Hopkinson apparatus (Davies, 1948) consisting of two long bars between which a short specimen is sandwiched. A mechanical pulse is launched in this bar system by a projectile which impacts on one of the bar ends. The mechanical pulse propagates along the bars, which remain elastic, and acts on the specimen, deforming it up to fracture.

The physical principles on which this methodology is based are mainly two:

- the bars must be long enough to perform the test before the pulse reflections from the bar ends return to the specimen;
- the specimen must be short enough to have a negligible stress and strain gradient along its length due to the pulse propagation.

Normally, Hopkinson bars for steel have a diameter of 10-20 mm, which is sufficient to load small specimens representative of fine-grained material like steel.

In the last decade, two research groups (Kormeling et al., 1980; Malvern et al., 1986) increased the bar diameter to 60 and 75 mm, respectively, in order to load representative plain concrete specimens having an aggregate of 8-10 mm size. It has been demonstrated by Malvern et al. that a lateral inertia confinement cannot influence the stress measurements because this phenomenon is delayed with respect to fracturing of the specimen.

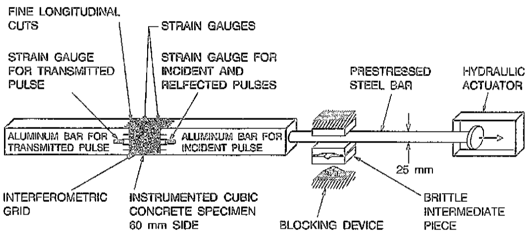
SMiRT 11 Transactions Vol. H (August 1991) Tokyo, Japan, © 1991

The Hopkinson bar system developed in our research differs from the two systems mentioned above by two peculiarities:

- the mechanical pulse is generated by the elastic energy stored in a prestressed bar (not by an impacting projectile) (Albertini et al., 1974);
- the bar shape is a square of 6x6 cm instead of being round.

2 EXPERIMENTAL EQUIPMENT

The Hopkinson bar developed in our laboratory for tensile tests of plain concrete is sketched in Figure 1. As a first operation, a hydraulic actuator prestresses only the steel bar up to its elastic limit because of the frictional action of a blocking device. The successive operation is the controlled rupture of a brittle intermediate piece of the blocking device, which gives rise to a tensile mechanical pulse of rectangular shape, propagating along the first aluminum bar, the specimen and the second aluminum bar. The amplitude of the incident mechanical pulse is governed by the prestress in the steel bar and determines the loading rate of the plain concrete specimen.



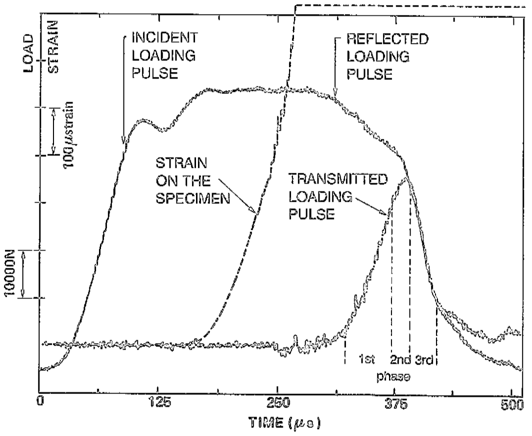


Fig.1: Hopkinson bar for dynamic tension testing of plain concrete.

Fig.2: Record of a tensile test on a concrete specimen by a modified Hopkinson bar.

The plain concrete specimen has the same cross section (6x6 cm) as that of the aluminum bars, to which it is glued with an epoxy resin. Aluminum was chosen as the bar material because of its transversal modulus, which is not so far from that of plain concrete. This last fact, together with some fine longitudinal cuts on the ends of the aluminum bars glued to the specimen, minimizes the constraint to transversal deformation of the concrete specimen.

A first strain gauge station on the incident bar measures the incident pulse ε_I and the reflected pulse ε_R. A second strain gauge station on the transmitted bar measures the pulse ε_T transmitted through the specimen.

The average instantaneous values of the stress and strain of the concrete, assuring uniaxial wave propagation and homogeneous stress distribution in the specimen, are obtained by the following equations:

$$\sigma(t) = \frac{AE\varepsilon_T(t)}{A_o} \quad (1)$$

where:
A = cross section of the aluminum bar
A_o = cross section of the concrete specimen
E = Young modulus of aluminum
t = time

and:

$$\varepsilon(t) = \frac{2C}{L_o} \int_o^t \varepsilon_R(t)dt \quad (2)$$

where:
C = elastic wave speed in aluminum
L_o = length of the concrete specimen

The strain of the concrete specimen is also measured by strain gauges directly glued on the specimen (Figure 1). A record of the measurements given by the strain gauges glued on the bars and on the specimens is given in Figure 2.

The compression test of plain concrete was performed by means of the Hopkinson bar sketched in Figure 3, which differs from the tension Hopkinson bar by two main characteristics:

- the prestressed bar and the incident bar are of aluminum of the same cross section in order to avoid buckling of the bar system;
- the brittle intermediate piece is placed at the end of the prestressed bar between the bar and the hydraulic actuator.

Once the brittle intermediate piece is broken, the end of the prestressed bar connected to it starts in the direction of the blocking device, giving rise to a compression pulse propagating along the incident bar and loading the plain concrete specimen. The theory and the measurements are the same as explained for the tension Hopkinson bar.

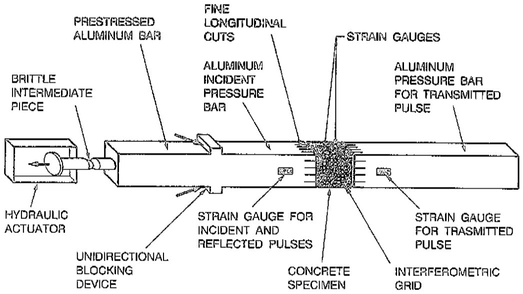


Fig.3: Hopkinson bar for dynamic compression testing of plain concrete.

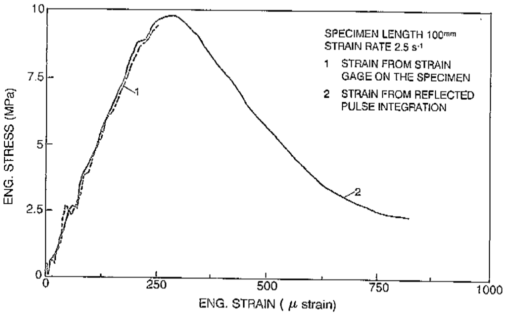


Fig.4: Stress strain curves of plain concrete by Hopkinson bar measurements and by strain gauge measurement.

3 PLAIN CONCRETE COMPOSITION AND SPECIMENS

The plain concrete composition was the following:

- water/cement ratio	0.5
- cement type	R425
- % sand (0.3 mm)	60
- % gravel (3-10 mm)	40
- aggregate quantity	1700 kg/m^3
- cement quantity	375 kg/m^3
- maximum aggregate size	10 mm

The specimens had a square cross section of 6x6 cm and the following lengths: 3, 5, 7, 10, 12 and 15 cm.

4 RESULTS AND DISCUSSION

The stress strain curves in tension of plain concrete at strain rates of 6x10 and 2.5 s (loading rate 10 N/mm s) were determined following two methods:

a) using the Hopkinson bar formulae (1) and (2) giving the stress and strain values at each instant of the test from the records of the transmitted and reflected pulses, respectively;

b) using the Hopkinson bar formula (1) for the calculation of the stress and the direct measurement of the strain on the specimen by means of the glued electrical strain gauge.

The two methods of measurement gave results which are in good agreement as far as the rising branch of the stress strain curve is concerned (Figure 4), while the falling branch of the curve could be measured only by the Hopkinson bar formulae (method a) because the strain gauge on the specimen broke when the highest strength was reached in the specimen.

The results obtained at low and high strain rate with specimens of different lengths are shown in Figure 5, where we observe that:

- at high strain rate the ultimate tensile strength is about 2.5 times the strength at low strain rate;
- at high strain rate the strain at the ultimate tensile strength is about two times larger than that at low strain rate.

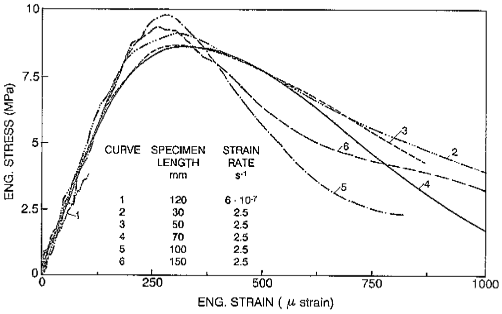


Fig.5: Stress strain curves by Hopkinson bar measurements of plain concrete specimens of different lengths.

The explanation of the two phenomena may be based on the fact that, in dynamics, the increase of the load is so fast that all the components of the mix contribute to the resistance against the external applied load and there is not sufficient time for the external load to follow the path of highest weakness through the mix. In fact, observation of the fracture surfaces of the specimens loaded in dynamics, which were usually normal to the load direction, showed a large amount of fractured coarse aggregate, as was also observed by Kormeling et al. (1980). From Figure 5 one may observe that the specimens having a length of up to 70 mm gave stress strain curves which are in good agreement, while longer specimens were characterized by multiple fracture caused by the larger stress gradients along the specimen due to wave propagation.

Observing the records of the incident, reflected and transmitted pulses versus time of Figure 2, we can distinguish three phases:

1st) transmitted pulse rising with about a constant slope and reflected pulse also increasing with a constant slope;

2nd) further nonlinear increase of the transmitted pulse up to its maximum; change in slope of the reflected pulse;

3rd) sharp decrease of the transmitted pulse and increase of the reflected pulse with the same constant slope - higher than during phase 1.

The transmitted and reflected pulses of the first phase give origin to the linear part of the stress strain diagram of Figure 5, where the material could be considered elastic. The transmitted and reflected pulses of the second phase give the highly nonlinear upper part of the stress strain diagram of Figure 5; during this phase, probably microcracks develop and coalesce (see also Kormeling et al., 1980). From the third phase transmitted and reflected pulses the descending branch of the stress strain diagram of Figure 5 is obtained. During this phase it is assumed that macrocracks propagate through the whole thickness of the specimen.

We have observed that the duration of the third phase has a nearby constant value of about 30 μs, resulting in a probable propagation speed of the cracks of about 2 km/s. Therefore, the simplification of using the initial cross section and the initial gauge length is too rough for the calculation of the stress and strain of the descending part of the diagrams of Figure 5. A better approximation may be reached by introducing an estimate of the true resisting cross section and of the true length of the specimen during the fracture process. An interferometric full field measurement of the strain will be applied in order to estimate the true resisting cross section and the true strain of the specimen during the fracture process.

Compression tests have been performed and the results will be ready at the time of the Conference.

CONCLUSIONS

Two Hopkinson bar apparatuses for tension and compression testing of plain concrete have been developed. At a high strain rate the ultimate tensile strength of plain concrete is about 2.5 times its strength at low strain rate, while the strain corresponding to the ultimate tensile strength is about two times larger than at low strain rates. Therefore, the ability of plain concrete to absorb energy up to the ultimate tensile strength is about five times larger than at a low strain rate. This property is probably due to the fact that all the components of the mix resist against the external dynamic load because there is no time for the load to follow the weakest resisting path. The precise estimate of the energy absorbed during the descending branch of the stress strain diagram requires further investigation, but it can be affirmed already now that at a high strain rate it will be much larger than at a low strain rate.

ACKNOWLEDGEMENTS

The authors are grateful to Professor Luigi Cedolin of the Politecnico of Milano for the helpful discussions and the preparation of the specimens.

REFERENCES

Davies, R.M. (1948). A Critical Study of the Hopkinson Pressure Bar, Phil. Trans. Roy. Soc., London, Ser.A, pp.240-375.

Kormeling, H.A., Zielinski, A.J., Reinhardt, H.W. (1980). Report N°5-80-3, Delft University of Technology, Stevin Laboratory.

Malvern, L.E., Tang, T., Jenkins, D.A., Gong, J.C. (1986). Dynamic Compressive Strength of Cementitious Materials, Materials Research Society Symposium, Vol.64, pp.119-138.

Albertini, C., Montagnani, M. (1974). Testing Techniques Based on the Split Hopkinson Bar, Institute of Physics, London, Conf. Ser. N°21, pp.22-31.