IMPACT FRACTURE PROCESS OF PLAIN CONCRETE WITH LARGE SIZE AGGREGATES BY MEANS OF HOPKINSON BAR BUNDLE

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ABSTRACT

A Hopkinson bar bundle technique is described, designed to measure the local mechanical characteristics over the cross-section of large cubes of plain concrete (200 mm side) subjected to impact loading.

It is shown that these experiments allow a more accurate measurement of the stress-strain diagram, also during the softening branch, and of the characteristics of the fracture process propagation under impact loading.

KEYWORDS

Hopkinson bar bundle, impact loading, plain concrete, fracture process.

INTRODUCTION

A precise description of the fracture process of plain concrete under high loading rate is of basic importance for the assessment of engineering structures against severe accidental loadings like those occurring in impacts, explosions and earthquakes. Such description must be gained from experiments performed on specimens of size sufficient to include aggregates of large size (at least 25÷30 mm) in the plain concrete mix because results obtained on micro-concrete (aggregate size 5÷10 mm) can not be safely extrapolated to the large aggregate plain concrete of real civil engineering structures. Therefore, an experiment has been conceived which foresees the high loading rate tensile testing of plain concrete cubes of 200 mm side with aggregate size of 25 mm, by means of a Hopkinson bar bundle. This bar consists of a bundle of 25 elementary Hopkinson bars working in parallel over the cross-section of the large specimen.

This paper describes the experiment and its capability of measuring the characteristics of the fracture process of plain concrete under high loading rate.

DESCRIPTION OF THE HOPKINSON BAR BUNDLE EXPERIMENT

The Hopkinson bar bundle is a special equipment enabling the correct characterization of the fracture process and of the softening branch of the stress-strain diagram, which is important for the evaluation of the energy absorption capability of the real material used in civil engineering structures.

The special equipment is sketched in Fig. 1 and consists of:

- a hydro-pneumatic head, prestressed bar and a blocking device;
- input and output Hopkinson bars subdivided into two specular bundles of elementary Hopkinson bars.

The apparatus can be used in a very large range of loading rates, typical of static, earthquake and impact loadings, which are obtained by a specific loading application mode.

The static and low loading rates can be realized by the direct action of the hydro-pneumatic head on the specimen, excluding the blocking device.

The medium and high loading rates are realized by using the device as a Hopkinson bar. In this case elastic energy is stored in the steel bar by prestressing it with the hydro-pneumatic head. Before beginning the test, the load is supported by the blocking device.

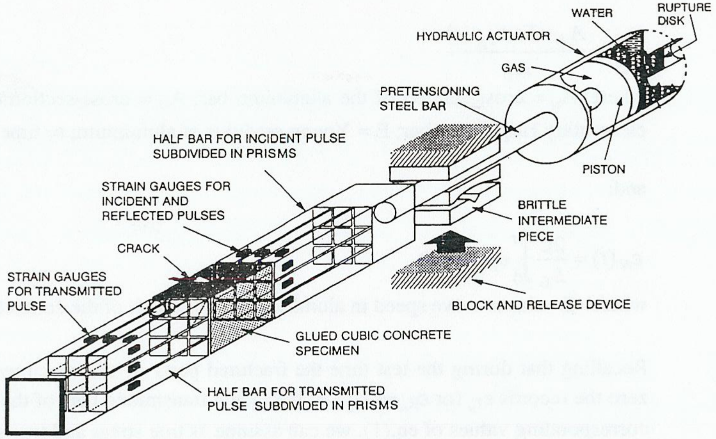

Fig. 1 - Bundle Hopkinson bar for dynamic tension testing of plain concrete

The test begins by deactivating the blocking device, which gives rise to a pulse with high loading rate propagation along the bundle of the input bars, the specimen and the bundle of the output bars.

The Hopkinson bar bundles were in reality constructed using two square aluminium bars of 20 cm side subdivided by electroerosion into 25 pairs of specular bars individually instrumentated with strain gauge stations; the two bundles have been installed in the Large Dynamic Testing Facility (Albertini- Montagnani, 1979) of the Joint Research Centre as shown in Fig. 2. The machine generates and sends a loading pulse linearly increasing up to a maximum of 2.5 MN into the bundle equipment for the testing of 20 cm side cubic specimens of plain concrete with real size aggregate (25-40 mm size).

A test with the LDTF-Hopkinson bar bundle is performed as follows:

- first a hydraulic actuator of maximum loading capacity of 5 MN, is pulling 32 cables of high strength steel having a length of 100m and the pretension stored in these cables is resisted by one grounded explosive bolt in the blocking device (fig.2)
- second operation is the rupture of the explosive bolt which gives rise to a tensile mechanical pulse with linear loading rate and duration of 40 ms, propagating along the Hopkinson bar bundle and bringing to fracture the plain concrete specimen

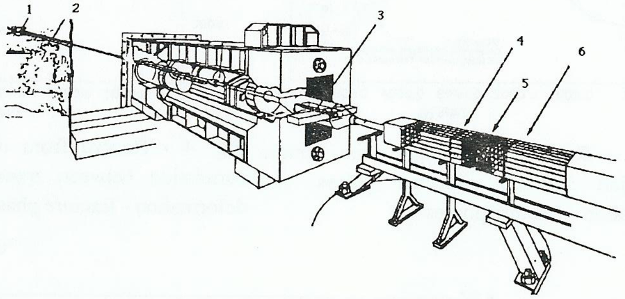

Fig. 2 - Experimental set-up: 1- hydraulic actuator; 2 - cables of pretension; 3- explosive bolt; 4- strain gauges in the incident bar bundle; 5 - specimen; 6 - strain gauges in the transmission bar bundle.

ANALYSIS OF AN EXPERIMENT IN ORDER TO DETERMINE THE TRUE STRESS-STRAIN DIAGRAM

During the fracturing process phase each pair of specular bars of the two bundles, which is individually instrumented with strain gauges (Fig.1), measures the incident, reflected and transmitted pulse ε_I , ε_R , ε_T , concerning only the portion of the specimen cross-section facing the cross-sections of this particular pair.

It is postulated that during the fracturing process each pair of the specular bars of the bundles will be in one of the following physical situations:

1. Facing an uncracked portion of the specimen cross-section, therefore measuring a small relatively reflected pulse ε_R and a large transmitted pulse ε_T (situation 1 in Figs. 3 - 4).

2. Facing a semi-cracked portion of the specimen cross-section, therefore in the measurement situation where ε_R is strongly increasing and ε_T strongly decreasing (situation 2 in Figs. 3-4)
3. Facing a cracked portion of the specimen cross-section, therefore measuring a reflected pulse ε_R of equal amplitude and of opposite sign to the incident pulse ε_I ,while the correlated transmitted pulse decreases to $\varepsilon_T = 0$ (situation 3 in Figs. 3 - 4)

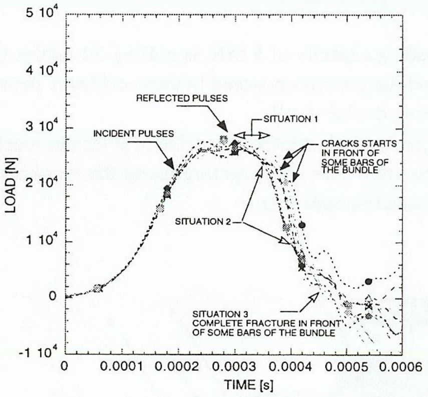

Fig. 3 - Record from input bars bundle correlation between reflected pulses and deformation - fracture phases

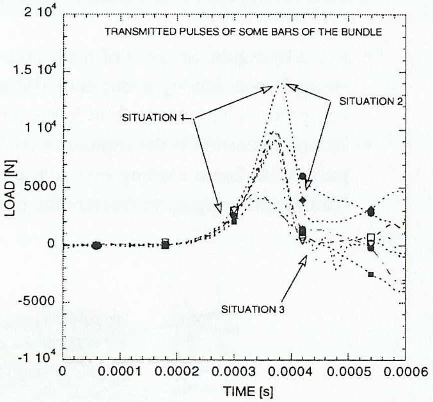

Fig. 4 - Record from output bars bundle; correlation between transmitted pulses and deformation - fracture phases

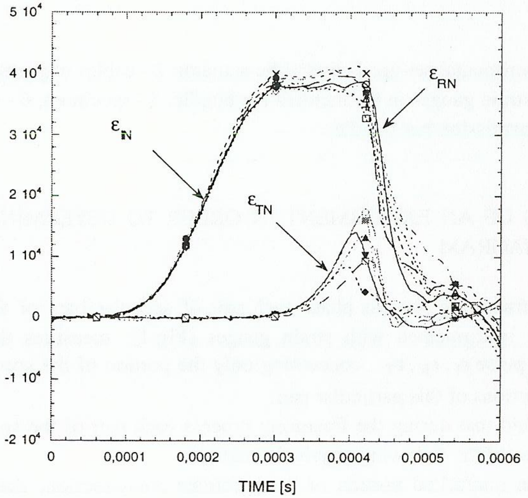

Fig. 5 - Records of a test by the LDTF-Hopkinson bar bundle

Each of the N(25) elementary Hopkinson bars of the bundle (including the inner bars) is instrumented as follows:

- a strain gauge station on the incident bar at 500mm from the interface incident bar-specimen, measuring the incident and reflected pulse ε_{I_N} ,and ε_{R_N}
- a strain gauge station on the transmitted bar at 500mm from the interface transmitted bar-specimen, measuring the transmitted pulse ε_{T_N}

From the record of the Nth elementary Hopkinson bar (Fig.5) we observe that after ~200 µs from the arrival time of the incident pulse the strain gauge station on the incident bar gives a measurement of the reflected pulse ε_{R_N} obtained from the difference between the amplitude of the incident pulse ε_{I_N} , measured before the time of $200 \cdot 10^{-6}$ s, and the actual measurement of the strain gauge; at the same time the strain gauge station on the transmitted bar measures the transmitted pulse ε_{T_N}.

The average instantaneous values of the stress and strain of the concrete facing the Nth elementary Hopkinson bar, assuming uniaxial wave propagation and homogeneous stress distribution in the specimen, are obtained by the following equations (Davies, 1948) :

$$\sigma_N = \frac{A_N \cdot E \cdot \varepsilon_{T_N}(t)}{A_0} \tag{1}$$

where: A_N = cross-section of the aluminium bar; A_O = cross-section of the concrete facing the elementary Hopkinson bar; E = Young modulus of aluminium; t= time

and:

$$\varepsilon_N(t) = \frac{2C}{L_0}\int_0^t \varepsilon_{R_N}(t)\,dt \tag{2}$$

where: C= elastic wave speed in aluminium; L_O = length of the concrete specimen.

Recalling that during the test time the fractured parts of the specimen cross-section reduce to zero the records ε_{T_N} (or $\varepsilon_{R_N} = -\varepsilon_{I_N}$) of the facing transmitted bars of the bundle and therefore the corresponding values of eq.(1), we can assume as true stress and true strain of the specimen the average of the stresses and strains of the X bars of the bundle where $\varepsilon_{T_N} \neq 0$ (or $\varepsilon_{R_N} = -\varepsilon_{I_N}$) as follows:

$$\sigma_{TRUE}(t) = \frac{\dfrac{\Sigma_1^X A_N \cdot E \cdot \varepsilon_{T_N}(t)}{A_0}}{X} \tag{3}$$

$$\varepsilon_{TRUE}(t) = \frac{\Sigma_1^X \dfrac{2c}{L_0}\int \varepsilon_{R_T}(t)\,dt}{X} \tag{4}$$

The results of this analysis are shown in Fig.6 where the time stress-strain curve of plain concrete obtained from the bar bundle measurements, analysed as shown before, is compared with the stress-strain curve which is obtained by measuring the incident, reflected and transmitted pulses ε_I ,ε_R, ε_T , on the whole part of the bar (not subdivided in bundle) and considering a constant resisting cross-section during the whole test.

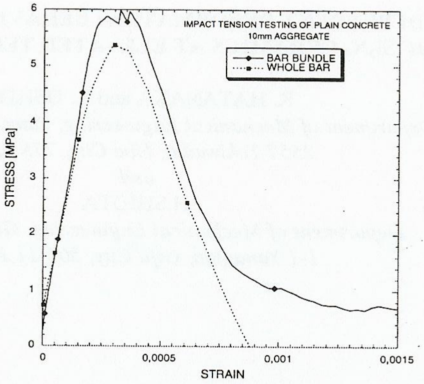

Fig. 6 - Stress vs. strain diagram from the whole bars measurements and from averaging the bar bundle measurements

Clearly, Fig. 6 shows that the Hopkinson bar bundle experiment and analysis allows a better definition of the stress-strain diagram of plain concrete under impact loading. A further increase of accuracy might be obtained by decreasing the cross-section of the bars of the bundle, in comparison to the specimen cross-section, in order to have a better accuracy in the measurement of eventual stress concentrations.

ANALYSIS OF AN EXPERIMENT IN ORDER TO STUDY THE IMPACT FRACTURE PROCESS

The first approximation analysis of the Hopkinson bar bundle records, concerning the study of the impact fracture process, is based on the assumption that the specimen cross-section facing a specular pair of bars of the bundle is completely fractured when the corresponding transmitted pulse of this pair is reduced to zero ($\varepsilon_{T_N}=0$), or equivalently when the corresponding reflected pulse ε_{R_N} is equal and of opposite sign of the incident pulse ε_{I_N} ($\varepsilon_{R_N}=-\varepsilon_{I_N}$).
The fracture propagation versus test time figures that have been obtained by application of this criterion to the records of a Hopkinson bar bundle experiment are shown in Fig. 7; the sequence of curves showing the value of total load acting on the specimen are drawn, measured at the same time with the showed fractured portion of the specimen cross-section. From Fig. 7 it can be stated that the total separation of the specimen in two halves takes place in about 77 microseconds which corresponds to an average fracture propagation speed of ~2500 m/s.

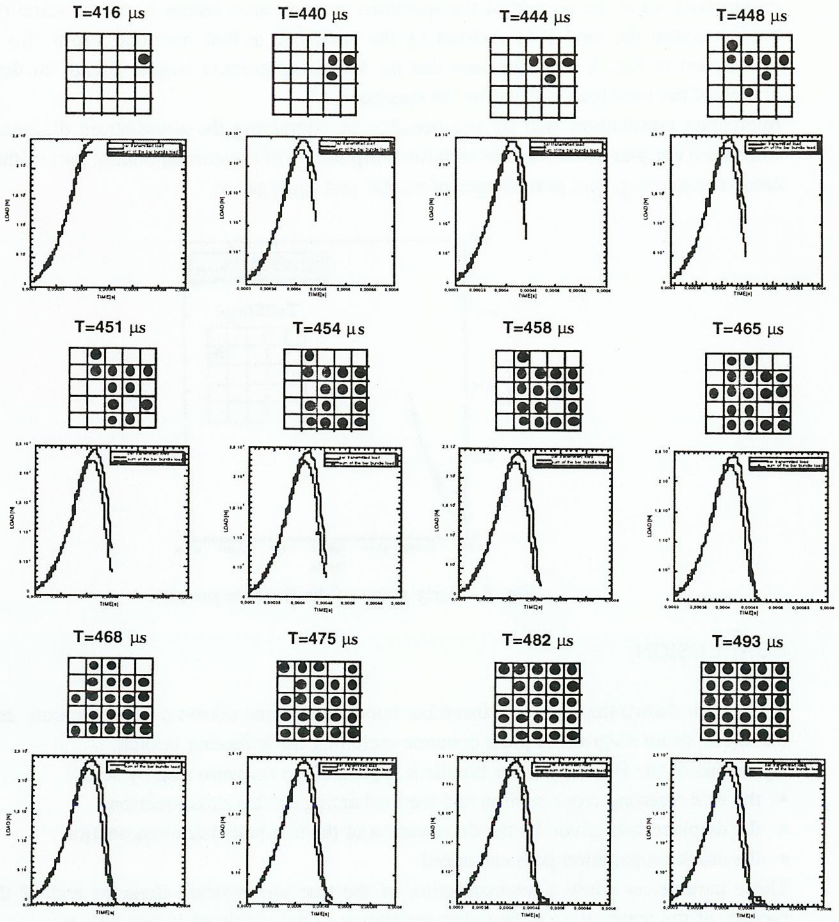

Fig. 7 - Fracture propagation through the specimen measured by bar bundle technique. Correlation with total load versus time.● = fractured cross-section of the specimen.

The fracture process of the specimen begins when the total load resisted by the specimen reaches its maximum value and it has a duration corresponding to the decrease time of the total load to zero. More detailed analysis of the fracture process will be performed by correlating the stress-strain diagrams concerning each part of the specimen cross-section facing each pair of the Hopkinson bar of the bundle.
An example of such detailed analysis is shown in Fig. 8, where as beginning of the fracturing process has been considered the moment in which the first of the bars of the bundle shows the

maximum load of the portion of the specimen cross-section facing it; on the same figure it has been reported the total load resisted by the specimen at that moment. From this correlation established in Fig. 8 it can be seen that the fracturing process begins already in the ascending branch of the total load resisted by the specimen.

Interesting correlations will be also possible by comparing the stress-strain diagrams obtained from each bar pair of the bundle with the morphology of the corresponding part of the specimen cross-section (e.g. mix percentages of mortar and aggregates).

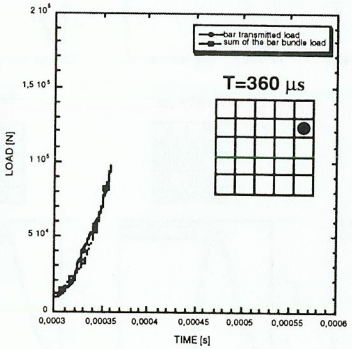

Fig. 8 - Early stage of the fracture process

CONCLUSION

It has been shown that the Hopkinson bar bundle technique allows a more accurate definition of the stress-strain diagram of plain concrete including the softening branch.

By means of the Hopkinson bar bundle it is possible to measure step by step:

- the true resisting cross-section and the load acting on that cross-section
- the displacement given by the deformation of the true resisting cross-section
- the crack propagation path and speed

These parameters allow a reconstruction of the true stress-strain diagram and of the fracture process of the material up to complete separation of the specimen in two halves.

It has also been shown that by this technique it is possible to follow in detail the impact fracture propagation process and to correlate local morphology of the specimen with the local measurement of mechanical characteristics.

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