LARGE HOPKINSON BAR METHODS FOR ADVANCED IMPACT TESTING OF STRUCTURAL CONTAINMENT COMPONENTS IN STEEL AND CONCRETE

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ABSTRACT

Large Hopkinson bar systems are proposed as transducers for a correct measurement of the response load and displacement of structural components in case of impact loading with stress wave propagation.

1. INTRODUCTION

The main performance of advanced techniques for impact testing of structures must be their capability of controlling and measuring wave propagation history.

Many studies of structural components response to impact loading are performed using falling or launched masses (Fig. 1) on the structural components where the loading history is measured by load cells and is affected by many uncertainties due to uncontrolled stress wave propagation [1].

The classical split Hopkinson pressure bar was developed [2] for the study of the mechanical properties of materials at high strain rate by strictly controlling and measuring the incident, reflected and transmitted stress waves acting on a specimen.

Herein, we suggest the extension after a proper modification of the Hopkinson bar method to the measurement of the response of structural components of containment shells.

2. THE BASIC HOPKINSON BAR METHOD

The basic configuration of the Hopkinson bar developed at JRC Ispra [3] consists (Fig. 2) of a prestressed bar, an incident bar, an output bar and a specimen inserted between the two last bars. On the release of the blocking device an incident tension pulse $\varepsilon_I$ propagates to the specimen where one part of the pulse is reflected $\varepsilon_R$ and one part is transmitted $\varepsilon_T$. 
Fig. 1. Schematization of the drop-weight experiment and wave paths.

Fig. 2. Schematization of the modified Hopkinson bar with prestressed bar loading device for tensile test.

The length of the incident bar and of the output bar are such that the reflections of the waves from the remote bar ends do not reach the specimen before the test is completed, allowing a clear record of the incident, reflected and transmitted pulses $\epsilon_i$, $\epsilon_r$ and $\epsilon_t$, by means of the two strain gauge stations on the incident and output bars.

The application of the uniaxial propagation theory of elastic stress waves along bars having small transverse dimensions with respect to the wavelength of the applied stress pulse allows the calculation of [4,5] the response loading and of the displacement history at both ends of the specimen.

3. THE LARGE DYNAMIC TESTING FACILITY (LDTF)
BASED ON TWO COUNTER-ACTING PRETENSIONED BAR SYSTEMS

We have shown [6] that a system consisting of two modified pretensioned Hopkinson bars, aligned along the same axis, counter-acting on a specimen placed in between, can be analyzed by the classical procedure reported in [2].

Based on this scheme of two counter-acting pretensioned Hopkinson bars we have designed and constructed the Large Dynamic Testing Facility (LDTF), in which the mechanical energy necessary to deform and fracture large specimens of high resistance and high elongation, is stored in two high-strength steel cables, each 100 m long, which can develop a load of 5 MN (Fig. 3).

Each of the two cables is pretensioned by an hydraulic actuator between a blocking device, consisting of two grounded explosive bolts, and the far end.

Once the two cables have been pretensioned, the four explosive bolts are synchronously (within 1 $\mu$s) broken by explosive charges, giving rise to two rectangular tensile pulses (of 40 ms duration, maximum amplitude 2.5 MN, rise time -250 $\mu$s) propagating to the specimen and deforming up to fracture at a maximum constant speed of 50 m/s.
Fig. 3. Large Dynamic Test Facility (LDTF).

The load-displacement characteristics of the specimen are calculated using equations derived in reference [6]:

\[
\text{LOAD} = E A_f (\epsilon_I + \epsilon_R + \epsilon_T)
\]  \( (6) \)

\[
\text{DISPLACEMENT} = 2G_0 \int_0^t (\epsilon_I - \epsilon_R - \epsilon_T) \, dt
\]  \( (7) \)

The load-displacement characteristics are recorded free from the effects of reflected waves for a duration of 40 ms corresponding to the travel time of the waves along the 100 m cables.

The maximum displacement imposed on the specimen ends is 1.5 m (0.75 m by each cable).

Using the LDTF large specimens of ASME SA 537 CL1 steel which included base material and a weld joint have been tested and the results are shown in Fig. 4.

**Fig. 4. Stress strain curves of ASME SA 537 CL1 steel.**
4. LARGE HOPKINSON BAR FOR TESTING REAL SIZE SHEET METAL BOXES

The deformation of thin sheet metal boxes is used as energy absorber in many safety devices and their use could also be envisaged in containment structures.

Consider as an example a sheet metal box of 500 mm length and having a square cross section of 75 mm each side and 1 mm thickness, which must be shortened by 250 mm at a speed ranging between 5.5 m/s (20 km/h) and 41.6 m/s (150 km/h).

These test conditions were obtained by using the LDTF modified as shown in Fig. 5 to test sheet metal boxes under compression load.

A 100 m long cable in high strength steel is prestressed under tension up to 5 MN by a hydraulic actuator.

At the beginning of the test the prestress stored in the cable is discharged on two grounded explosive bolts.

By exploding the two bolts a tension pulse of 40 ms duration is transmitted along the LDTF shaft and is applied as a compression pulse to the far end of the square sheet metal box being tested.

The other end of the square sheet metal box is supported by a square pyramid-cone connected to the output bar up to 100 m length.

The arms applying the pressure pulse to the square box, the pyramid-cone support and the output bar may have the same mechanical impedance as the square box.

Fig. 5. Compression test of sheet metal boxes by a large Hopkinson bar installed in the LDTF.

The propagation in the input and output bars of the LDTF can be analyzed by the monodimensional wave propagation theory [2] because the transverse dimensions of the bars are small in comparison with the pulse duration; therefore the response load and the displacement of both ends of the thin sheet metal box can be determined.

The two load-displacement characteristics of the box constructed by taking either the load at the input or the load at the output of the box are shown
in Fig. 6. The energy absorbed during deformation of the box shall be located between the two areas subtended by the two characteristics: the decision must be taken based upon a detailed study of the folding mechanism.

![Graph showing load-shortening characteristics at the input and output ends of the 75 mm side and 1 mm thickness square box.](image)

Fig. 6. Load - shortening characteristics at the input and output ends of the 75 mm side and 1 mm thickness square box.

5. LARGE ALUMINIUM HOPKINSON’S BAR FOR TESTING LARGE CONCRETE SPECIMENS

The difficult problem of testing plain concrete at high strain rate, under tension, has been first tackled with a small Hopkinson bar and microconcrete specimens [7].

We observed that even when testing microconcrete (aggregate of 8-10 mm) with a relatively short specimen we obtained results showing a stress gradient through the specimen and the stress strain curves by averaging between the values of load at the two specimen ends are an approximation of the mechanical properties at high loading rate of the microconcrete which therefore cannot be taken as representative also of the mechanical properties of concrete with large sized aggregate as used for real civil structures.

Therefore it has been decided to study the mechanical properties at high loading rate of plain concrete with (-25-40 mm) sized aggregate of real civil structures using large cubic specimens of 20 cm side, abandoning the unrealistic hypothesis of a load equilibrium through the gauge length of the specimen.

The experiment is shown schematically in Fig. 7; the cubic concrete specimen of 20 cm side is glued to two aluminium bars of 20 cm side installed in the central part of the LDTF. The two bars act respectively as the input and output bar of an Hopkinson bar system.

Each of the two aluminium bars is divided, by means of fine longitudinal cuts, into 25 symmetric couples of prismatic bars of 4 cm side, each of which is separately instrumented by strain gauge stations thus becoming a sub-Hopkinson's bar system.

The experiment is under completion. The experiment will be analyzed together with a numerical simulation of the experiment.
Fig. 7. Tension test of large concrete specimens by using a large Hopkinson bar installed in the LDTP.

6. CONCLUSIONS

It has been shown that the problems of impact testing of structural components of containment shells in steel and concrete can be solved with large Hopkinson bar systems as transducers for exact measurements of the loading, response and displacements histories at the ends of the components because they allow to control and measure the wave propagation caused by the impact. Refined stress and deformation distribution over the components can be calculated by FE programmes implementing the experimental quantities measured at the ends of the components.

7. REFERENCES