Electromagnetic Compressive Split Hopkinson Bar[*]

C. M. A. Silva, P. A. R. Rosa, P. A. F. Martins

IDMEC, Instituto Superior Técnico, TULisbon, Portugal

Abstract

This paper proposes a new design for the compressive split Hopkinson bar that makes use of the intense pressure created in a transient magnetic field formed by the passage of a pulse of electric current through a series of coils. The proposed technology enables to characterize the behaviour of materials under high strain-rates with a small acceleration path length of the striker bar and, because propulsion is purely electromagnetic, the overall performance can be easily controlled and nearly infinitely adjustable.

The presentation is focused on the design and fabrication of the mechanical, electrical and electromagnetic components of the new compressive split Hopkinson bar and includes results from two different testing applications to demonstrate the validity of the proposed concept.

Keywords

Design, Electromagnetic, Dynamic Testing

1 Introduction

The compressive split Hopkinson bar is a device for performing the mechanical characterization of materials at high strain-rates [1-4]. Currently installed apparatuses consist of two long slender cylindrical bars of the same diameter, called the incident and the output bars, and of a shorter cylindrical bar, called the striker bar that is most

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commonly propelled by an air gun against the incident bar. The air is generally supplied from a high pressure vessel and valves are utilized for controlling the firing pressure. The collision of the striker bar into the end of the incident bar generates a compressive stress wave that is partially transmitted throughout the specimen, placed in-between the incident and output bars, causing it to deform. The analysis of the stress wave in conjunction with the measurement of the strains in the incident and output bars by means of strain-gages makes it possible to determine the stress-strain curve of the testing material.

Major disadvantages of currently available compressive split Hopkinson bar systems can be summarized as the need for very-high air pressures for reaching high strain-rates, the lack of repeatability of the firing pressure, the high operation noise due to the instantaneous expansion of the air and the large overall length of the apparatus.

This paper proposes a new design for the compressive split Hopkinson bar that makes use of the intense pressure created in a transient magnetic field formed by the passage of a pulse of electric current through a series of coils. The magnetic field behaves like air being relief from a high pressure vessel and is capable of properly accelerating the striker bar against the incident bar. However, because the propulsion is purely electromagnetic, its overall performance can be easily controlled and is nearly infinitely adjustable. The operation conditions are very highly repeatable and, once the equipment has been set up for a particular testing method, the only extra variable to be taken into account is the material to be characterized.

The first part of the paper is focused on the design and fabrication of the main components of the electromagnetic compressive split Hopkinson bar and the last part includes a brief presentation of two different applications in the fields of material characterization and evaluation of armour vests.

2 Project, Design and Fabrication

Figure 1 presents an overall view of the compressive split Hopkinson bar installed at Instituto Superior Técnico-TULisbon. The main components can be divided into three main groups:

(i) Basic structural parts,
(ii) Specific mechanical and pneumatic parts,
(iii) Specific electrical and electromagnetic parts.

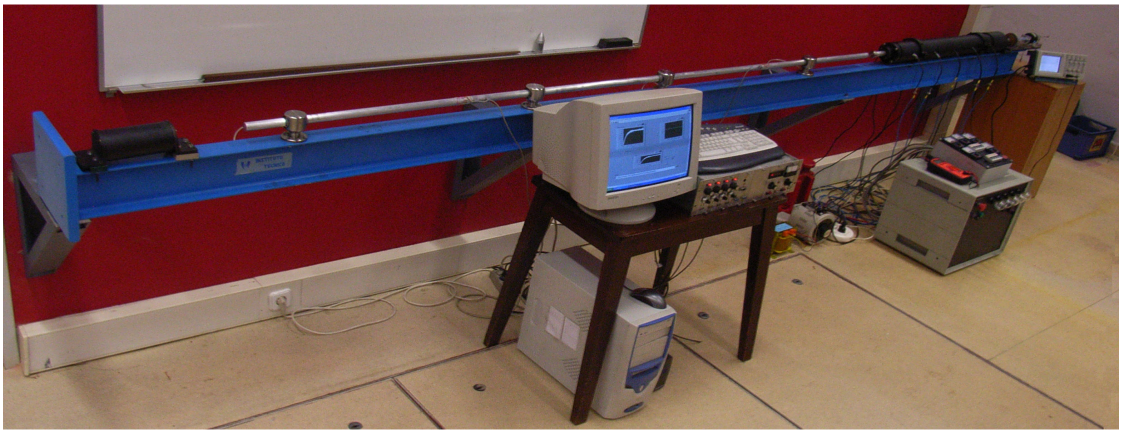

***Figure 1**: Electromagnetic compressive split Hopkinson bar installed at IST-TULisbon.*

Basic structural parts comprise components such as the structural I-beam and the support plates, which are independent of the type of testing (e.g. mechanical, fracture ...etc), operation conditions and materials to be characterized. These components are always to be utilized. Specific mechanical and pneumatic parts comprise those components such as the pressure bars, the air-bearings and the guiding tubes, whose design may be dependent on the type of testing, operation conditions and materials to be characterized. Specific electrical and electromagnetic parts include the components that provide the electrical energy to the electromagnetic actuator, e.g. the electrical circuits for charging and firing the bank of capacitors and the coils that generate the pressure to accelerate the striker bar against the incident bar. The design of the basic and specific parts will be described in what follows.

2.1 Basic Structural Parts

The Hopkinson bar is assembled on an I-beam steel structure with a length of 5 m that must account for the installation of the specific mechanical, pneumatic and electromagnetic parts. The stiffness of the I-beam is adequate for the structure of the bar because the impact and stress wave propagation preferentially occurs along the longitudinal direction of the bar. The overall length of the I-beam was chosen so that longer actuators can be added in the future with the objective of increasing the launching velocity and the kinetic energy of the striker bar. The support plates are utilized for attaching the I-beam to a concrete wall.

2.2 Specific Mechanical and Pneumatic Parts

The incident and output bars have 1.4 m length and 25 mm diameter. The bars are long in order to stabilize the one-dimensional stress wave propagation for a given pulse length and have a high length/diameter ratio so that a proper separation of the incident and reflected waves can be achieved during data acquisition.

The selection of the materials to manufacture the pressure bars is very much dependent on the materials to be tested. In fact, for increasing the signal-to-noise ratio, materials with adequate elastic modulus must be selected for the pressure bars so that high-resolution dynamic testing of low-strength materials such as lead and soft aluminium can also be performed. In addition, because the pressure bars must remain elastic during testing, the mechanical properties of the materials selected for its manufacture will greatly influence the maximum stress attainable by the test specimen. The Hopkinson bar fabricated by the authors has two different pairs of incident and output pressure bars. One pair is manufactured from high strength aluminium AA 6082-T651 (utilized in the mechanical characterization of lead, see Section 3) while the other is made of AISI M3 (tool steel).

An important advantage of the new proposed electromagnetic-based Hopkinson bar against conventional air-based Hopkinson bar systems is the possibility of easily changing the pressure bars and the striker bar because air-based systems usually require considerable amount of time and effort to open the testing apparatus and to change the bars. This advantage is particularly important for the striker bar to be loaded into the electromagnetic actuator because it provides additional control of the velocity and kinetic energy at the exit simply by changing its physical characteristics (e.g. mass).

Figure 2 shows two different types of striker bars. The first type consists of a long (1 m) and heavy (4.5 kg) bimetallic bar made of AA 6082-T651 aluminium with slotted hollow half-ring surface inserts of DIN St52.3 steel and is to be utilized when the current pulse passing through the coils is triggered by thyristor switches. The second type consists of short, low weight (250 g, 500 g and 750 g), DIN Ck45 steel bars which are to be utilized when the current pulse passing through the coils is triggered and controlled by IGBT's (insulated gate bipolar transistor). Further details on the electromagnetic actuator will be provided in Section 2.3.

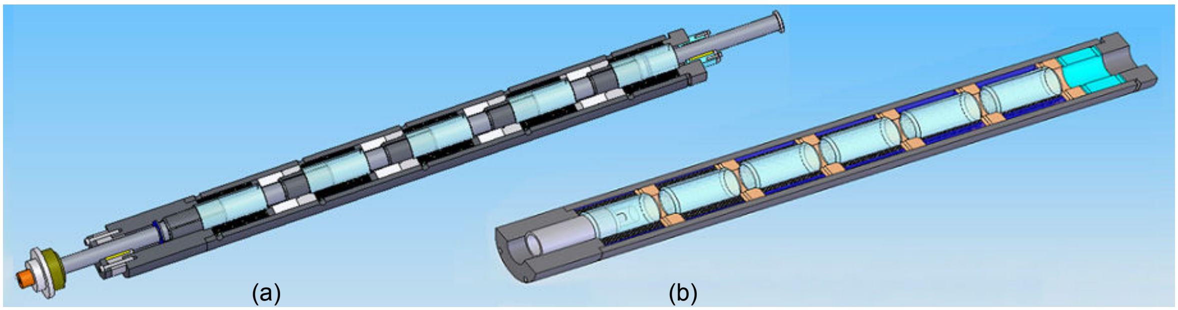

Figure 2: *Schematic representation of the coils and striker bars that are utilized when the current pulse is (a) triggered by thyristors or (b) triggered and controlled by IGBTs.*

Air-bearings (Figure 3a)) instead of contact bearings (e.g. ball-bearings, teflon-bearings... etc) were chosen to support and guide the pressure bars during high speed sliding. Unlike contact bearings, air-bearings utilize a thin film of pressurized air to provide a 'zero friction' load bearing interface between surfaces that would otherwise be in contact with each other. Being non-contact, air-bearings exhibit no starting or running friction and avoid the traditional contact bearing related problems of friction, vibration, wear, and lubricant handling, and offer distinct advantages in precision positioning and high speed sliding of the pressure bars.

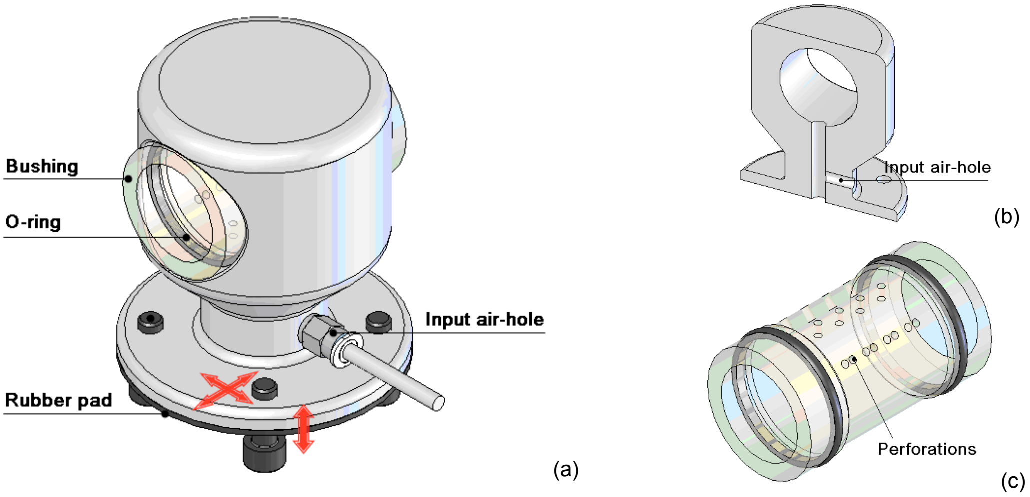

Figure 3*: Schematic representation of the air-bearing assemblies utilized in the bar.*

The air-bearings are also used as a system for aligning the electromagnetic actuator with the pressure bars and the momentum end trap (energy absorber). They are manufactured from a non-magnetic AISI 304L stainless steel and the air (supplied by the compressed air-network of the laboratory) is pumped through an orifice that is drilled in its lower-center region (refer to Figure 3b)). Acrylic guide bushings containing holes in the longitudinal direction are included with the purpose of splitting the pressurized air flow into different directions and reducing the friction forces that are applied to the pressure bars (Figure 3c)). The location of the air-holes and the selection of the operating air-pressure were chosen after performing experimental tests for measuring the static-friction force that allows relative motion between the pressure bars and the air-bearings. The tests were made with a compression dynamometer and three alternative locations for the air-holes were considered (refer to inset pictures provided in Figure 4).

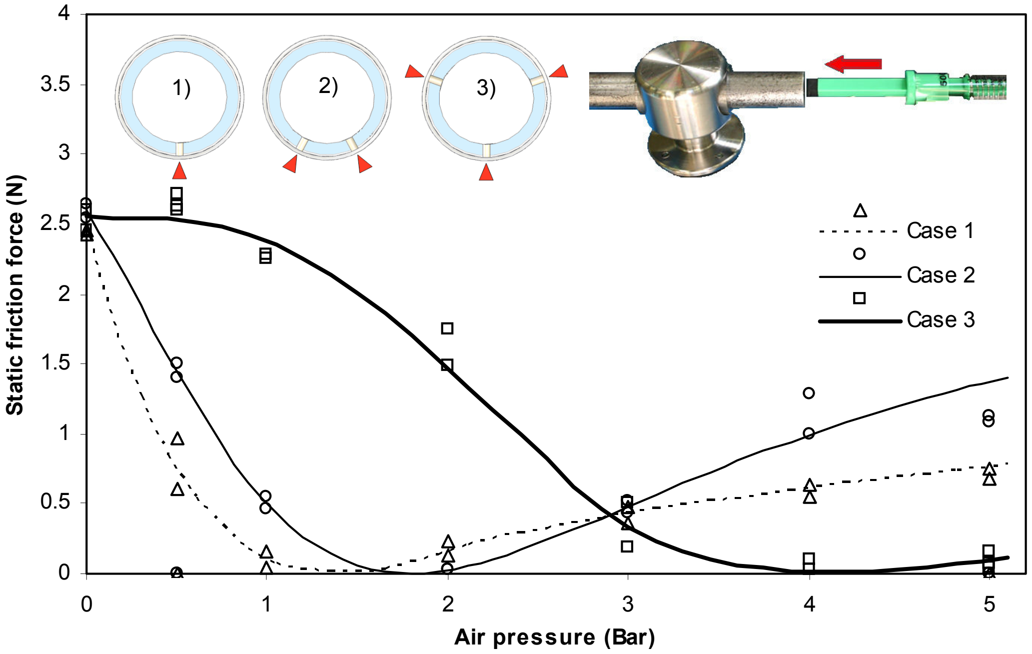

***Figure 4**: Friction force exerted on a bar as a function of the air-pressure utilized by the bearing and of the location of the air-hole perforations.*

Figure 4 shows that perforation solutions denoted as cases 1 and 2 offer low frictional opposition for air-pressures in the range 1 to 2 bar while the solution labelled as case 3 is more adequate for values of the air-pressure above 3.5 bar. Because the compressed air-network of the laboratory operates at a pressure up to 7 bar and since this case is less sensitive to air-pressure variations in the working range from 3.5 to 5 bars, it was decided to manufacture the acrylic bushings as depicted in case 3. The solution consists of three opposing perforations through which the pressurize air flows in order to build-up an air-cushion between the pressure bar and the surface of the bearing. In addition, it is worth notice that the acrylic bushings are easy to replace in case of damage and allow the utilization of pressure bars with slightly smaller and larger diameters than those initially specified in the original project of the electromagnetic Hopkinson bar.

2.3 Electrical and Electromagnetic Parts

The electromagnetic actuator consists of electrical circuits for charging and firing the banks of energy-storage capacitors (each with 6 mF) and a series of coils that generate the pressure to accelerate the striker bar against the incident bar. Two different types of electromagnetic actuators were conceived and designed by the authors (Figure 2); (i) a coil-spring and (ii) a coil-gun.

The coil-spring actuator combines the reluctance and induction electromagnetic features of the assembly between coils and striker bar. The reluctance draws from the very large positive magnetic susceptibility and attractive ferromagnetic properties of the slotted (to reduce eddy current losses) half-ring inserts of steel placed along the surface of the aluminium striker bar. The induction results from the repulsive forces originated by the eddy currents that are induced in the aluminium surface of the bimetallic striker bar when the coils are fired. The aluminium is paramagnetic and its magnetic susceptibility is much smaller than that of steel.

Figure 5 shows a schematic representation of the charging and discharging electrical circuits of the coil-spring electromagnetic actuator. To charge the capacitors, single-phase alternating current supplied with 230 V is converted to higher-voltage direct constant current by means of a charging circuit consisting of a variable-voltage transformer and a constant current rectifier system. The variable-voltage transformer is made of a variable-voltage regulator which can change the incoming line voltage from 0% to 100% and a transformer capable of producing 3.6 times the input voltage. This means that the overall rating of the variable-voltage transformer system is approximately 1000 V for a single-phase input line voltage of 230 V.

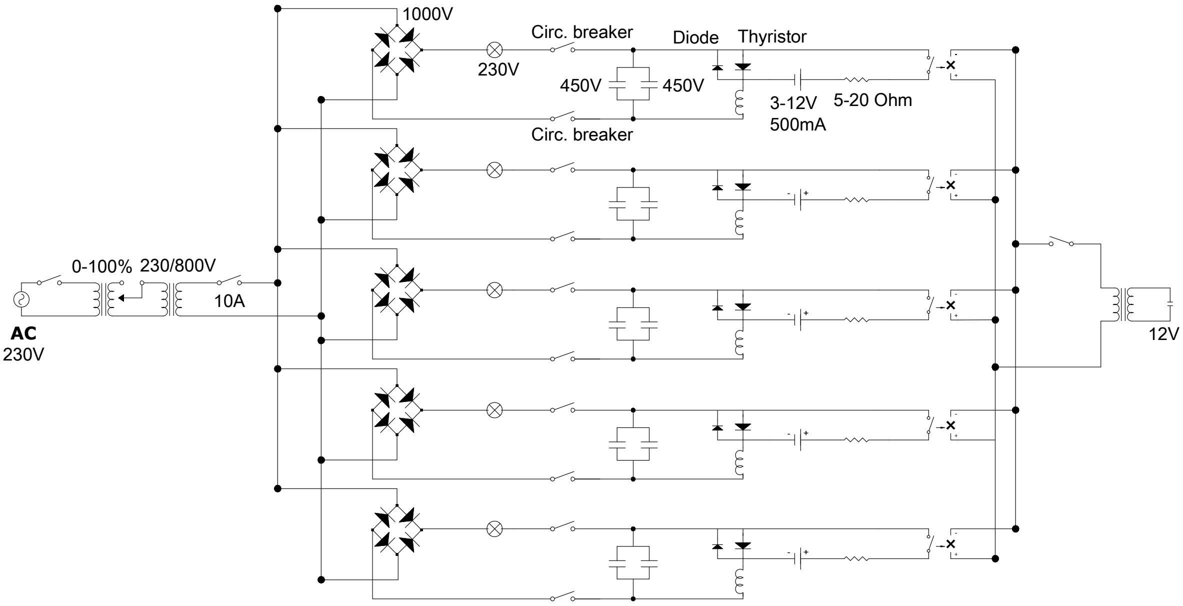

***Figure 5**: Schematic representation of the charging and discharging electrical circuits of the coil-spring electromagnetic actuator.*

Typical coils with eight windings, a total length of 92 mm, an external diameter of 80 mm and an internal diameter of 42 mm are currently being utilized.

Once the capacitors are charged the charging circuits are closed and the thyristor switches located in the discharging circuits are activated to simultaneously fire each capacitor into its associated coil. The resulting current pulse will only last for a few milliseconds and, therefore, the large switching times typical of thyristors are not capable of allowing the pulse to be terminated just as the slotted half-ring inserts of steel placed along the surface of the striker bar get to the middle of each coil. In fact, when there is no collision between the striker bar and the incident bar, the striker bar will stop and accelerate in the opposite direction into the magnetic equilibrium position – just like a spring returning to its equilibrium configuration.

When the striker bar collides against the incident bar, the striker bar achieves a large velocity very rapidly due to conservation of linear momentum. Figure 6 shows the velocity and the kinetic energy of the striker bar just before collision against the incident bar as a function of applied voltage. It is worth notice that the actual design of the electromagnetic actuator allows a single-phase 230 V directly inputted from the supply line without any intervening transformers to accelerate the 4.5 kg bimetallic striker bar to a kinetic energy level of nearly 0.5kJ (14.5 m/s) resulting in a velocity of the incident bar equal to 27.5 m/s. This gives an idea of the easy implementation-to-benefit ratio of the Hopkinson bar based on a coil-spring electromagnetic actuator.

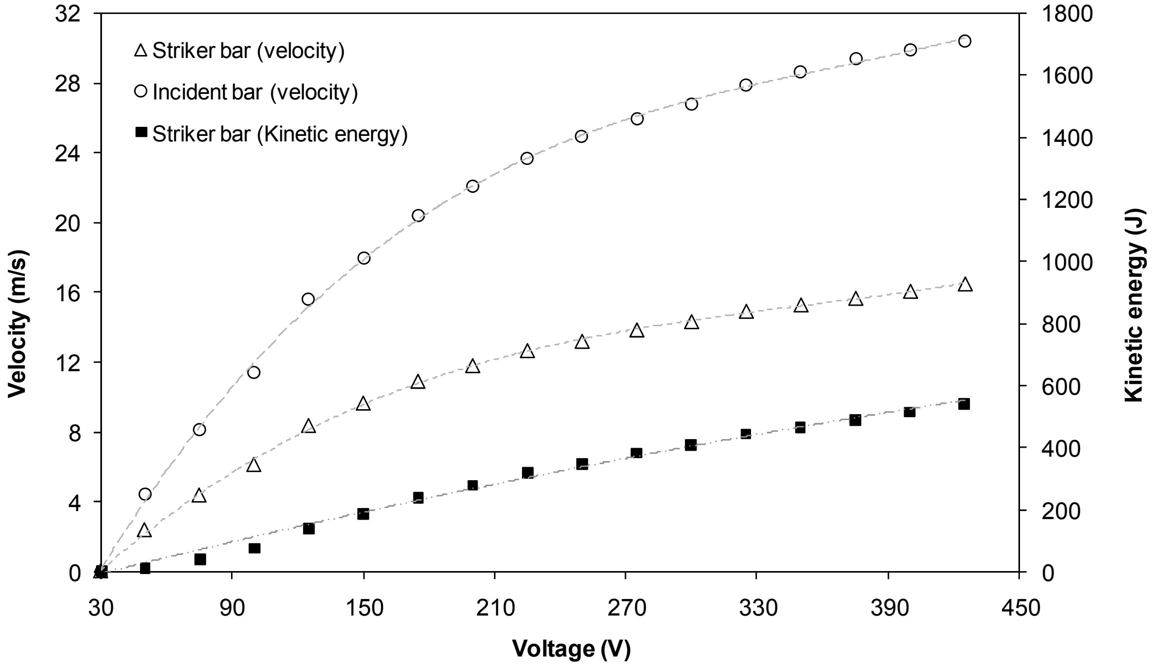

Figure 6: *Velocity and kinetic energy as a function of the applied voltage for the coil-spring electromagnetic actuator.*

The second type of electromagnetic actuator (coil-gun actuator) is based on a multi-stage reluctance actuator and is currently being fabricated by the authors. In general terms the main difference of the electrical circuit of the coil-gun actuator to that depicted in Figure 5 is to be found in the discharging circuit. IGBTs switches, faster then thyristors and intended to rapidly turn on and off, are utilized for a sequential fire of the bank of capacitors into the coils as the striker bar exclusively made of steel accelerates throughout the coil-gun. The IGBTs switches are also expected to considerably improve the efficiency of the launching, by extinguishing the electrical current pulse in each coil before the striker bar passes through its centre. Otherwise, the remaining energy in the capacitor bank will slow down the striker bar at the exit of each coil.

To conclude this section it is worth notice that the main advantage of the proposed electromagnetic concept derives from its high flexibility. Striker bars can be easily replaced, individual coils can be easily changed or temporarily switched off and the electrical circuits for charging and firing the banks of energy-storage capacitors can be selected so that the system behaves as a coil-spring or as a coil-gun electromagnetic actuator.

3 Results and Discussion

The proposed electromagnetic Hopkinson bar system based on a coil-spring actuator was utilized in two different types of applications; for obtaining the stress-strain curve of technically pure lead at high strain-rates and for evaluating the performance of armour vests for protection of human beings.

3.1 Mechanical characterization

The stress-strain curve of technically-pure lead was obtained by means of the proposed electromagnetic Hopkinson bar system for high strain-rates, in the range of 200 to 3000 s^{-1}, and by means of quasi-static measurements performed in a fully instrumented CNC hydraulic press The tests were performed on cylindrical specimens with an initial diameter of D_0=8 mm and a height-to-diameter ratio H_0/D_0=1. Specimens were lubricated with PTFE (polymer based lubricant).

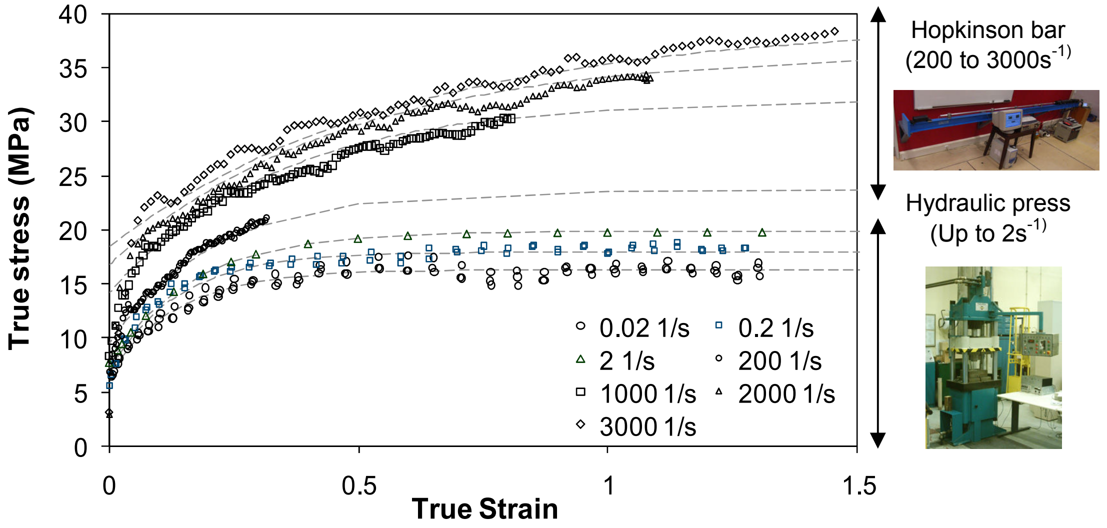

Figure 7: *Stress-strain curve of technically-pure lead obtained for different strain-rates. Pictures show the experimental apparatus utilized in the experiments.*

The experimental data resulting from the compression tests depicted in Figure 7 show good agreement with data available in the literature and indicate that technically pure lead presents significant strain-rate sensitivity.

3.2 Performance of armour vests

The performance of armour vests can be evaluated from the interaction between a projectile and a target. Classical evaluation procedures consist of qualitative observations and quantitative measurements of the impact-sustained damage. The remaining energy of the impact, not absorbed by the armours, which will be transmitted to human beings and equipments, is commonly not taken into consideration. This energy results in high forces that are applied in a very short time and its quantification is of great importance for the security of human beings and equipments.

Quantification of the remaining energy and of the magnitude of the applied forces can be performed in the proposed split compressive Hopkinson bar apparatus. The propulsion of the projectiles is achieved by means of a modified version of the tube-gun that allows shooting small projectiles. The magnetic auto-centring effect of the projectiles inside the tube-gun eliminates contact between the projectiles and the tube (unlike conventional systems propelled by air-guns) and make possible to shoot different types of projectiles and fragments.

The experiments were performed on two different types of armours with constant impact energy of 10 Joule. Figure 8 shows the magnitude of the impact force applied to the transmitted bar that result from the interaction between a 5.56 mm projectile and Kevlar and polycarbonate based armours. The magnitude of the impact force resulting from a reference shot performed without armour is include for comparison purposes. Results show that Kevlar based armours utilized in body vests perform better than polycarbonate based armours utilized in body shields.

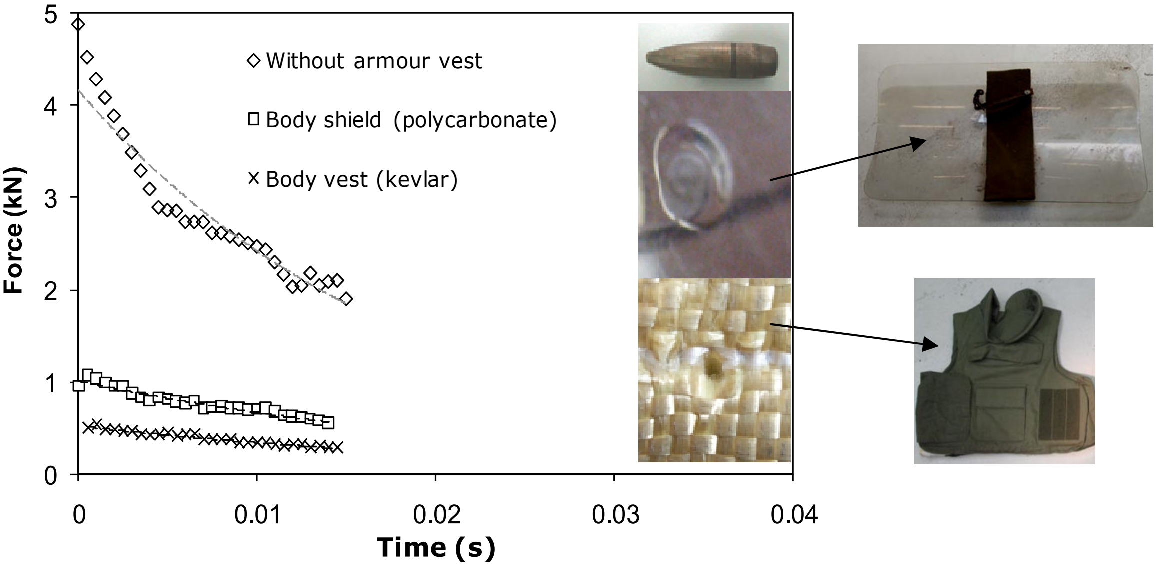

Figure 8: Force applied on body vests and body shields during the impact of a 5.56 mm calibre projectile with a kinetic energy of 10 J.

4 Conclusions

This paper presents a prototype of an electromagnetic compressive split Hopkinson bar. Special purpose mechanical, pneumatic, electric and electromagnetic parts are comprehensively described and special emphasis is placed on the presentation of the main engineering details of a flexible electromagnetic actuator that allows the striker bar to be accelerated by means of a coil-spring or a coil-gun based system.

The design of the electromagnetic compressive split Hopkinson bar offers distinct advantages in positioning and changing of the pressure bars (namely the striker bar) over conventional air-based systems which require considerable amount of time and effort to perform similar operations. Repeatability of the firing velocity, low operation noise and small overall length are other important advantages of the new proposed equipment.

The performance of the electromagnetic compressive split Hopkinson bar was demonstrated by means of experiments that were designed in order to evaluate the stress-strain curve of technically pure lead for high strain rates and the performance of armour vests currently utilized in the protection of human beings.

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