Report on

Experimental devices harvest for impact and explosion testing of materials and structures

Technical Committee Rilem-IEC (Impact and Explosion)

May 2020

Introduction

In the DAC meeting organized in Chennai (2017) it was decided to promote an action aimed at developing a stronger link between the experimental labs which have specific devices, often not fully used. The action could have contributed to revitalize RILEM association as “Labs link” and not only as “Experts link” as it appears nowadays, fully rediscovering its original mission.
In the framework of impact and explosion there are a lot of specific experimental devices all over the world: many of them are property of the armed forces and therefore they are not easy to manage for scientific purposes, but several devices are available in Universities or Research Centres and they could be part of an international network as RILEM, to optimize their use and favour the international sharing of the knowledge in this specific research field that counts a relatively small community. The results in the identification of fast dynamic behaviour of construction materials were never significantly compared and connected: a lot of doubts about their effectiveness could suggest the scientific community to fix some firm points to progress the knowledge in this specific fields.
The first step was to propose to Rilem Technical Council the constitution of a Technical Committee aimed at investigating the material parameters characterizing the high strain behaviour in concrete structures. The action was initially focused on attracting experts from Rilem, fib and ACI worlds. To achieve the goal we link *Rilem TC* with a *fib Special group of TG10.1* finalized to write the chapter §7.4.2 in the Model Code 2020 on the strategies to design a protected structure and with the *ACI 544* group interested to evaluate the benefits of fibres randomly distributed in the concrete to improve the fast dynamic toughness in concrete structures. After two years of activities we have gathered 37 members from 19 countries included European Community (EU), 11 of them are also Rilem members. The main objectives of the Committee were synthetized in the following:
1) to coordinate a database of the special devices oriented to investigate impact and explosion effects on materials and structures;
2) to introduce the state-of-the-art knowledge in a specific fib bulletin that could work as Model Code 2020 literature framework, aimed at guiding the designers to quantify the bearing capacity of conventional structures to these specific actions;
3) to propose and compare test methods to determine the parameters characterizing the high-strain behaviour of materials depending of the specific strain rate;
4) to analyse the variables which more affects the structural effects when subjected to these actions;
5) to develop new practical recommendations and design criteria for when an item is subjected to these phenomena.
The activity of the Committee is fully aligned to the Memorandum of Cooperation (MoC) signed on 29 November 2002 between the fib and RILEM beyond the activities defined in the Charter of the Liaison Committee of International Associations of Civil Engineering (LC) in order to improve concrete and concrete constructions and to stimulate research by making the technical expertise of both associations available to the other through bilateral contacts, meetings, conferences, publications, internet links, and any other activity as mutually agreed.
The Committee members were invited to seven meetings organized in Milano (July 4th 2018 and December 10th 2019), Madrid (November 11th 2018), Ispra (March 12th 2019), Bayonne (June 25th, 2019), Whistler (September 17th, 2019) and the last one was planned in Stuttgart on April 15th, but due to COVID-19 pandemic we were forced to an on-line meeting on MS Teams.
This issue represents the output of the first objective: the characteristics of 27 devices operating in experimental labs distributed in 10 countries oriented to investigate high strain rate problems are here collected.
The contribution is organized in a brief collection of resume descriptions of the devices, prepared by each institution responsible, in which the main mechanical characteristics, the problems investigated, the specific performance, the framework in which it is operating and the main references are indicated.

A detailed card organized in a .xls file according to a specific format is then attached for each specific device with some explaining pictures. The card was prepared by the responsible of the experimental device; the email address of the contact person to have further details and to plan research activities is also enclosed.
The wish is that this facility could contribute to favour an international network in the Rilem world between experimental labs and the experts who are working on this special research topic and could help the specific Institutions to improve and to maintain their own experimental devices, which, in case of reduced use, are often demounted.

Participants to the IEC meeting in Milan - July 4, 2018

Participants to the IEC meeting in MS Teams - May 4, 2020

POLITECNICO DI MILANO - Italy

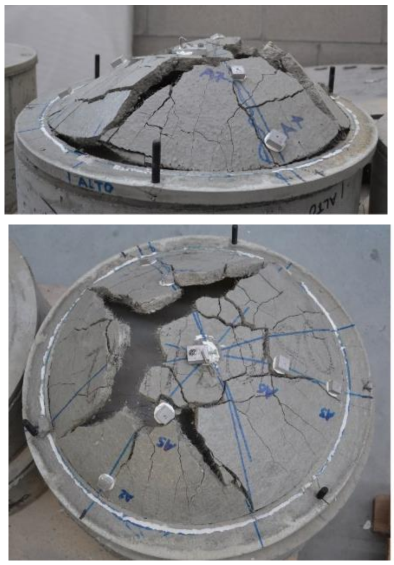
1. High Strain Rate Lab

1.1 Shock Tube facility

Shock tube equipment was designed and constructed in 2010 in the framework of a research project called ACCIDENT (http://www.interreg-italiasvizzera.it/progetti:rid=70) aimed at the investigation of tunnels exposed to exceptional loads. The shock tube has been designed to apply a shock wave with a maximum reflected pressure on the specimen lower than 3MPa and adopts a double diaphragms firing mechanism to maximize load repeatability. The shock wave maximum speed reached within the shock tube is equal to 3 Mach. The area of load application is a circular area of 480 mm diameter over which the pressure distribution is almost constant.
The duration of the shock wave application over the specimen is in the order of 20 ms and the tube has been designed to minimize the effect on the specimen of the interaction between the shock wave and the reflected rarefaction wave at least in the time interval interested by the test (1 second from the shock wave arrival). A proper set of pressure transducers can monitor the pressure history of the incident and of the reflected shock wave and the use of a proper set of accelerometers can be used to monitor the response of the specimen under investigation. A Data Acquisition System able to register signals at a sampling rate of 1MHz all the data for a time duration of 1 second that is generally enough to register the whole structural response of the tested element.
The end-chamber of the equipment can be modified to perform test according to several boundary conditions. Moreover, close to the end chamber of the shock tube, a gas burner allows to apply a fire curve to the specimen before or after the shock wave load. Up to know the following test conditions have been investigated:

- soil-structure interaction between concrete circular slab (60 cm diameter) and a column of granular soil (1.5 m long and placed behind the specimen; concrete specimen is resting on the soil) for tunnel lining safety design;
- compressive behaviour of crushable materials used to adsorb shock wave energy;
- bending test on simply supported R/C slabs with interaction with fire (an Hydrocarbon fire curve was applied to the front face of the specimen before applying the shock wave load) to evaluate the response of a floating-sea tunnel lining


a)


b)

a) Impact on protective foams; b) impact on HPFRC slabs [6].

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SUPSI – University of Applied Sciences and Arts of Southern Switzerland, Switzerland

2. DynaMat Laboratory

DynaMat Laboratory, inaugurated in 2006, is an advanced laboratory able to test materials in a large range of strain rate in tension, compression, and shear. This research infrastructure is aimed to understand the dynamic response of materials improving design and safety of products and structures by means of calibration and validation of numerical models. The laboratory acts as reference point to respond to broad interest from the scientific community and industry. An improved understanding of dynamic material behaviour requires optimized experimental techniques (as modified Hopkinson bar apparatus) as well as advanced experimental data acquisition technologies. On these experimental bases it is possible to adopt powerful new tools to investigate the physics of materials over several orders of magnitude in length and time, e.g. the multi-scale-material-modeling as well as integrated experimental-numerical approaches taking in account rate dependent material properties.
Since 2017 the Laboratory is part of the Roadmap of the research infrastructures of national relevance of the Swiss Confederation.
The core facilities of the Laboratory are based on the Modified Hopkinson Bar apparatus. Several set-ups are used to study the uni-bi-and tri-axial behaviour of the materials in a wide range of strain-rate tests ($1 \div 10^5$ s^{-1}). It is possible to perform tests in tension, compression, shear, torsion and bending for different materials at high strain-rates and in a large field of temperature (77÷1’500 °K). The materials tested are: metals, polymers, plain and fibre-reinforced concrete, composites, rocks, glass, bones, etc.
All facilities use systems of transient recorder (Pacific, HBM G2 and G3i) with maximum sample rate of 50 MHz, fast cameras (IDT- MotionPro Y4-S3 and Photron Fastcam Nova S12) with 1Mfps, electro-optical Extensometer H.-D. Rudolph GmbH (Model 200XR) and no-contact displacement transducers and a Digital Image Correlation (MatchID) system complete the set-ups. For the elevated temperature an Ambrell compact EASYHEAT induction water-cooled heating system with maximum power of 2.4 kW is used as well as homemade hoven and a system for low temperature.

2.1 Modified Hopkinson Bar 10mm (MHB 10)

The MHB 10 is used for the determination of the mechanical characteristics of materials using plate and round specimen of small dimension (2-3 mm diameter). It consists of two circular straight high strength steel bars, having a diameter of 10 mm, with a length of 9 and 6 m, respectively. The first 6 m of the longer bar is used as a pretensioned bar and the other 3 m as input bar. The second bar is entirely used as output bar. The cylindrical sample is screwed into input and output bars. The generation of an elastic wave of well-defined amplitude is obtained by means of suddenly release of the energy stored in the pretensioned bar. Maximum pre-load 600kN, range of strain rate 10^2 -10^3 in tension, 30 μs of loading rise time and 2.4 ms pulse duration. Applications: Strain rate behaviour of materials such as reinforcing steels (B500A/B/C and AISI304), VHSS (S690, S960), HSS, AHSS (Dual phase, Trip, Twip, BH, etc), alloys (Al, Ti, W, etc.) with combined extreme conditions of loading and elevated temperature.

2.2 Modified Hopkinson Bar 20mm (MHB 20)

The MHB 10 device consists of two circular aluminium bars with a diameter of 20 mm, having a length of 3 and 6 m acting as input bar and output bar, respectively. Specimens are glued or screwed to the input and output bars. The pulse is generated by means of pretensioning a high strength steel bar (C85). The pretensioned bar has a diameter of 12 mm (so as to have the same acoustical impedance as the aluminium bars) and a length of 6 m. It is directly screwed to the aluminium input bar at one end and is also connected to the hydraulic actuator. The dynamic test is performed by storing elastic energy in the pretensioned bar which is blocked at one end (near the connection with the input bar) by the blocking device and pulled by the hydraulic actuator (600 kN maximum load) at the other end. Tensile mechanical pulse of 2.4 ms duration, 50μs of loading rise time. Applications: study of the dynamic tensile behaviour of advanced fibre reinforced cementitious composites before and after high temperature exposure, UHPC, fine-grain rocks, polymers, bone, glass, composites.

2.3 Modified Hopkinson Bar 30mm (MHB 30)

The MHB 30 is used for the determination of the mechanical characteristics in compression and in indirect tension. It consists of a hydraulic actuator that put in tension a preloading bar thanks to a blocking ring placed at the extremity of this bar. The preloading bar, made of high strength steel, is 6m long and 12mm in diameter. This bar is connected to an aluminium bar with a diameter of 30mm and a length of 3 m, working as a input bar. The specimen is sandwiched between the input bar and another identical bar used as output bar. By pulling the pre-loading bar, it is possible to drive the test by the energy stored in it. The test starts when a fragile bolt positioned between the pre-stressed bar and the hydraulic actuator by suddenly breaks. Consequently, a rectangular stress wave pulse is generated and propagates through the input bar, the specimen and the output bar. By the strain gauges placed on the input and output bars, the test signals are obtained. Applications: study of the compressive response of cementitious materials, rocks and earthen materials, ceramics.

2.4 Modified Hopkinson Bar 60mm (MHB 60)

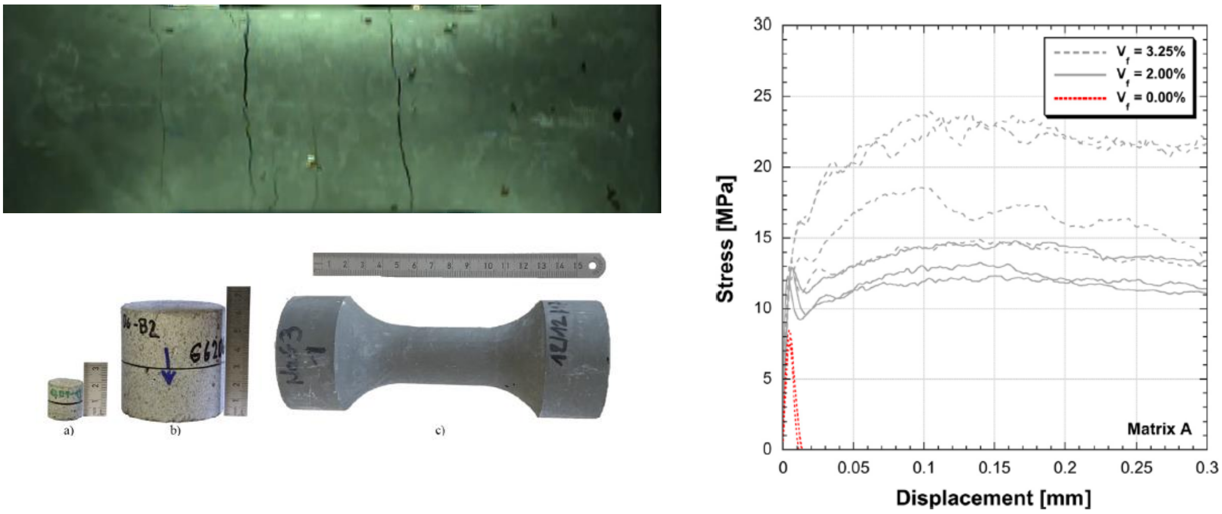
The MHB 60 is used for testing the specimens having a diameter of 60 mm (i.e. the notched cylinder and the dog-bone-shaped specimens). It consists of two bar (input and output bars) having 3 m in length and 60 mm diameter, the pretension bar is a Maragin bar of 34.8mm in diameter. Applications: study of the response of UHP(FR)C, rocks and quasi-brittle materials under dynamic compression tests in multi-axial conditions.

2.5 Hydro-Pneumatic Machine (HPM)

The HPM is used for the determination of the mechanical characteristics in intermediate strain rate (10^{-1}-10^{1}). It consists of a sealed piston that divide a cylindrical tank in two chambers; one chamber is filled with gas at high pressure (e.g. 150-180 bars), the other one is filled with water. The test starts by activating a fast-electro-valve, so the second chamber discharges the water through a calibrated orifice. The end of the piston shaft is connected to the specimen that is linked to the supporting structure through an instrumented bar. The specimen is tested at constant strain-rate, depending on the velocity of the gas expelling from the chamber regulated by the orifice.

2.6 3D-Modified Hopkinson Bar (3D-MHB)

The 3D-MHB is a Modified Hopkinson Bar apparatus designed to apply dynamic loading in materials having a tri-axial stress state. It consists of a pulse generator system (with pre-tensioned bar and brittle joint), 1 input bar, and 5 output bars. The stress rate applicable is of several TPa/s. At the present, only the first axis has been built and the system acts as a Modified Hopkinson Bar. It consists of a pre-tensioned bar (cylindrical bar: ø=56.5, L=1750 mm)), input and output bars (with square cross-section: 50 mm side; 2200 and 2100 mm in length, respectively). The total length of the 3D-MHB apparatus along the impact axis is of 7.82 m. The length becomes 8.80 m when the bumper system is installed. All bars are made of aged maraging steel. Characteristics: maximum preload 4MN, pre-straining load 2MN, compression mechanical pulse of 2.4 ms duration, 200μs of loading rise time. Applications: study of the response of UHP(FR)C and quasi-brittle materials in compression under multi-axial conditions.



Results on UHPC in dynamic direct tension [1] (device 2.2, 2.4)

DynaMat Laboratory view (device 2.1, 2.2, 2.3, 2.4).

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EUROPEAN COMMISSION – JOINT RESEARCH CENTRE, Europe

3. HOPLAB FACILITY (ELSA lab)

The ELSA HopLab is a specialised laboratory for the study of the behaviour of materials and structural components to very fast dynamic loads, such as those due to blast and impact, where knowledge of the material behaviour under high strain-rates is necessary. The laboratory has unique features with respect to the magnitude of the applied forces and the large size of the specimens to be tested. The facility is operated by highly experienced scientific and technical staff and is supported by specialists in numerical simulation.
HOPLAB laboratory is equipped with three high-speed digital cameras like IDT-Y4 able to perform at 4000 fps with maximum resolution (up to 200000 fps by reducing one dimension of the recorded image) or Photron SA1.1 able to perform at 5400 fps with maximum resolution (up to 675000 fps by reducing one dimension of the recorded image) and several dynamic sensors for the mechanical characterization of material and structures. Particular attention is addressed to the calibration of all adopted sensors and to the elaboration procedure of SHPB data.
(https://ec.europa.eu/jrc/en/research-facility/hopkinson-bar-facility)

3.1 Large Hopkinson bar for ductile materials
The HOPLAB facility for ductile materials is one of the biggest existing Hopkinson bar apparatuses with a length of more than 200 m and a bar diameter of 72 mm made of high strength steel. A statically pre-stressed high strength steel cable, which is the physical continuation of the input bar, is used to generate the impact loading pulse. Through pre-tensioning and suddenly releasing the cable, rectangular force pulses of up to 2 MN, 250 μs rise time and 40 ms duration can be generated and applied to the specimen. The cable pre-tensioning is effected by means of a hydraulic actuator electronically controlled and placed at one end ("west"), while the instantaneous release of its opposite end is achieved through breaking of a fragile bolt which sustained the pretension load. The fracture in the bolt is induced by a small detonation of explosive inserted in it. The high strength steel cable is 100 m long and has an equivalent diameter of 72 mm. The tensile pulse generated is transmitted to the actual input bar, to the specimen and to the output bar (which is about 90 m long). At the distal end of the output bar a hydraulic damper ("east") allows to dissipate the remaining energy emanating from the cable and transferred through the specimen to the output bar. By modifying the central part of the apparatus it is possible to exploit the tensile wave generated in order to perform different types of tests, as for example compression. The basic element of the second configuration is the introduction of the twin incident and transmitter bars (connected to high strength steel plates at their ends; between the plates a large specimen can be mounted and com- pressed as represented. Thanks to this "motion inversion frame" the available tensile pulse can be transformed into a compressive one on the specimen, which is thus compressed dynamically. Due to the high-strain rates reached during a dynamic test a high sampling-rate transient recorder is needed, moreover this recorder should be capable to acquire electrical signals in three different areas: west end, east end and specimen zone. These requirements are fulfilled by employing three different transient recorders (Nicolet Multipro with a maximum sampling-rate of 1 MHz) synchronized with the electrical signal that triggers the explosion of the fragile bolt. In the specimen zone the bar strain histories are recorded in several positions with strain-gage sensors, in which a full- bridge setup is adopted to compensate for bending and thermal effects. The recorded signals are conditioned by a high-speed strain gage conditioner (Vishay 2400 with cut-off frequency of 100 kHz).

3.2 Med-size Hopkinson for brittle materials
The Modified Hopkinson bar designed for the compressive and tensile characterization of brittle materials using large size specimens (concrete, glass, mortar, geo-materials etc.). The input and output bars of 132 mm diameter and 2.6 length can be made in aluminum or steel. The maximum

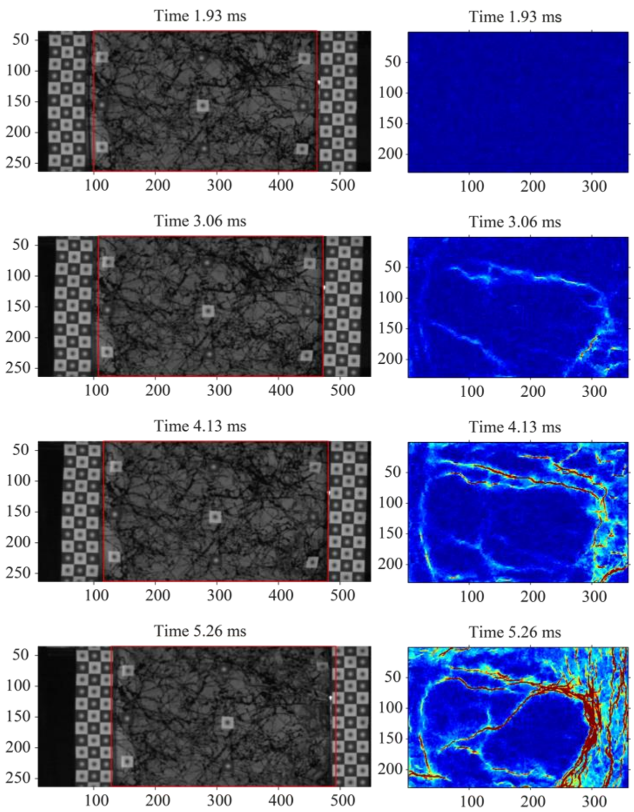
generated pulse is characterized by 0.7 MN amplitude and about 1 ms duration, it is generated using the pre-tensioned bar method and explosive bolt release. As described above for Large Hopkinson bar, semiconductor strain-gages and acquisition system are used for increasing sensitivity and precision.

3.3 Small-size Hopkinson Bars

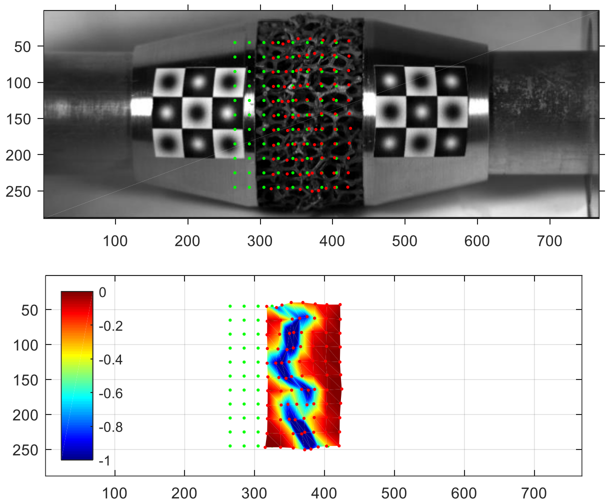
Four small Hopkinson bars were developed for testing different type of materials. At the moment, the setups available include:

- Apparatus for compressive testing of soft cellular materials. The equipment has aluminium bars with a diameter of 20 mm and is able to apply a maximum displacement of about 20 mm. The impulse is generated pre-stressing the input bar.
- Apparatus for compressive testing of brittle materials. The equipment has aluminium bars with a diameter of 50 mm or maraging steel bars with a diameter of 25 mm. The impulse is generated by a conventional gas gun and apply a maximum displacement of about 5 mm to the specimen.
- Apparatus for tensile testing of metals. The equipment has high strength stainless steel bars with a diameter of 10 mm and is able to apply a maximum displacement of about 5 mm. The impulse is generated pre-stressing the input bar.
- Apparatus for compression testing of metals. The equipment has high strength stainless steel bars with a diameter of 10 mm and is able to apply a maximum displacement of about 4 mm. The impulse is generated by a conventional gas gun.

Anyway, all setups just described are adjustable in term of bars, actuation and instrumentation to face particular requirements of the users.



Example of qualitative crack pattern evolution during a dynamic compressive test on dam concrete. (Device 1)



Dynamic compressive test on hybrid aluminium and polyurethane foams. (Device 3)

3.4 e-BLAST simulator

The electromagnetic BLAST simulator (e-BLAST) was designed and constructed in the 2014 for reproducing effects of blasts without the use of explosive materials. The facility produces repeatable, controlled blast load simulations on full-scale columns and other structural components. The simulator recreates the speed and force of explosive shock waves through the impact of calibrated masses which are accelerated by means of linear electric motor. For testing longer structural elements three synchronous electrical linear motors have been employed, and this innovative design has resulted in a more efficient, versatile and low-cost facility. The linear motor selected for the e-BLAST was the Siemens 1FN3 in the version explicitly developed for peak loads. Considering the motor characteristics and with the suitable acceleration stroke, the 1FN3 motor can accelerate a mass at a maximum velocity of about 16 m/s (1000 m/min with 3 phases power supply). It should be recalled that linear motors have a flat characteristic curve of maximum pushing force vs. velocity up to a certain velocity value. Beyond that (for higher motor velocities) the available motor force decreases falling to zero at the so-called “electrical stall”.

The linear motor requires an accurate displacement sensor in order to operate with a closed-loop feedback strategy. The displacement sensor adopted is the incremental linear encoder LIDA 287 (1 Vpp sinusoidal signal) with a precision of 2 micron and a length of 5 m. Thanks to the control system adopted it is possible to synchronize the motors with a precision in range of a nanosecond. The impacting mass is an instrumented mass composed of a rigid prismatic bar, light plates in the front, connected through some load cells to the heavy, main mass. In front of each aluminium plate a layer of polyurethane foam has been placed to smooth the pressure pulse and reproduce closer the blast pressure profile. The total mass of each impactor is approximately 44.84 kg (prismatic steel bar +3 aluminium plates + 3 piezoelectric loading cells + 2 bearings + 4 springs + 6 pins + 3 layer of polyurethane foam) and each impactor can reliably measure a maximum load of 990 kN (i.e. 3 load cells of 330 kN each).

The detailed list of instrumentation adopted and deployed for some experiments carried out on columns is given below:

- 2 acquisition boards GAGE Octopus of 8 channels each with 20 MSample/s per channel. Considering the test duration, a sampling frequency of 200 kHz has been adopted (pre-trigger 10000 points, post-trigger 100000 points).
- 1 High Speed camera IDT Y4 with 14 mm Nikkor lens. This camera films laterally the evolution of the whole experiment at a frequency of 800 fps (pre- trigger 800 frames, post-trigger 800 frames, different cameras and higher framerates can be used with the e-BLAST).
- 4 Charge Amplifiers Kistler 5015 for the conditioning of piezoelectric sensors.
- 4 Piezoelectric load cells Kistler 9106A (full scale 330 kN) placed at the reaction supports.
- 3x3 Piezoelectric load cells Kistler 9106A (full scale 330 kN) interposed between three aluminium plates and the main steel mass of the impactor.
- 3 Fork type photocell sensors optimized for the detection of small parts and with high switching frequency; the sensor placed in the lower axis is used to trigger the acquisition.

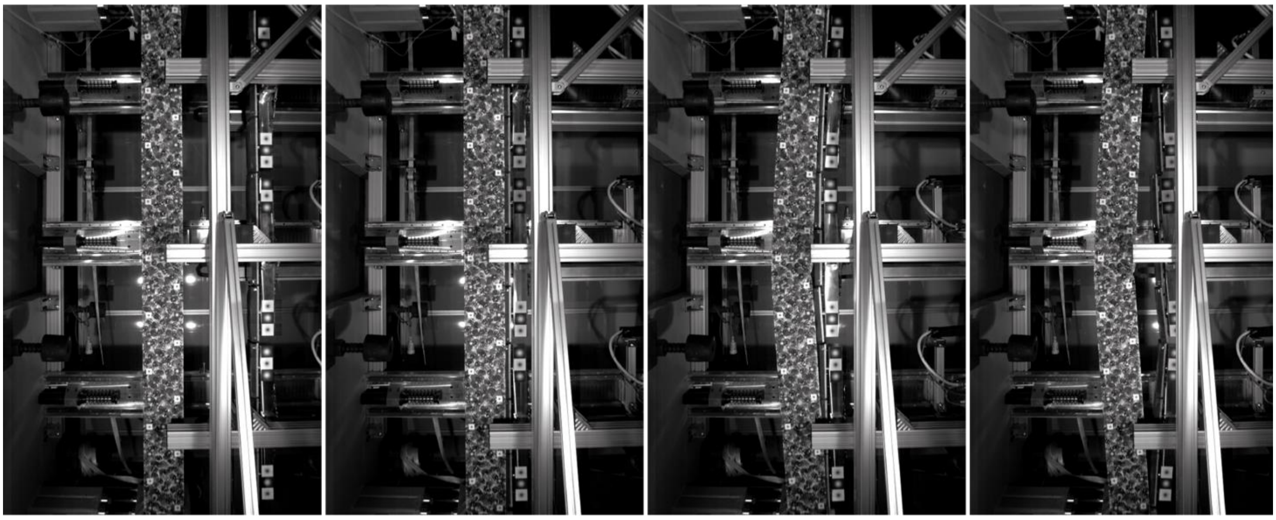


Photo frame sequence of an impact test performed on aluminum mullion (Device 4)

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4. Otto-Mohr-Lab

Next to its standard equipment for static fatigue testing and standard measuring equipment in short term measurements like high speed cameras, infrared vibrometers, acceleration sensors and the required data acquisition systems the lab operates two special features for material and structural testing.

4.1 Split-Hopkinson-Bar (SHB) uniaxial and biaxial

The two SHB are mainly used for structural compressive tests on a material level in a classical configuration. Booth are driven by compressed air with impactor energies up to approximately 2 kJ, which leads to impactor speeds up to 35 m/s. With bar length of 3 m and the standard diameter of 50 mm they are mainly used for testing cylindrical concrete specimens with geometries of 80 mm length in a strain rate range of 50-150 1/s. The experiments usually result in a stress-strain description of the dynamic response including all the shortcomings which are actually in discussion.
The biaxial representation of the same equipment aims to study multidimensional load scenario. With the change of the specimen geometry to cubes of 60 mm edge length they can be loaded in two perpendicular directions. The original claim, to generate an exact biaxial synchronized load impulse, is not reachable. So trustworthy experimental data can expected just for uniaxial dynamic experiments with a static pretension component.

4.2 Drop tower and accelerator

The drop tower facility with a maximum height of 11 m offers a wide range of possibilities to examine components under dynamic load. Two test configurations are available for different requirements on load and mass. In the classical free-fall configuration, a maximum height of 11 m is available to accelerate a drop mass by gravity. Masses of up to 2.5 t with a minimum mass of 500 kg are configurable. Specimen in the up to 2 m × 2 m × 1 m can be tested. A wide range of standard impactors are available as a modular system which can assembled as required. The accelerated configuration includes a compressed air driven 10 m long acceleration pipe to speed up projectiles to about 160 m/s from storage energies in the range of 250 kJ. The final speed depend on the mass and the compression energy. Since the accelerator diameter is 100 mm the projectile dimensions are reduced to this upper limit. The special 30 tons foundation on week pneumatic springs which can carry displacement amplitudes of max. 500 mm are adjustable in its stiffness and structural response to fully absorb transferred energy. With the equipped sensors the energy transferred can be measured and related to the incident amount.
Applications of booth configurations are classical impact experiments on arbitrary structures which fit into the clamping field. Since the affiliated institute deals with concrete, this is the major material of interest. Protection structure or layered combinations of them can be analyzed as well as the crashworthiness of components in the automotive industry.

View of the drop tower setup field with damaged sample


Biaxial loaded Split-Hopkinson Bar

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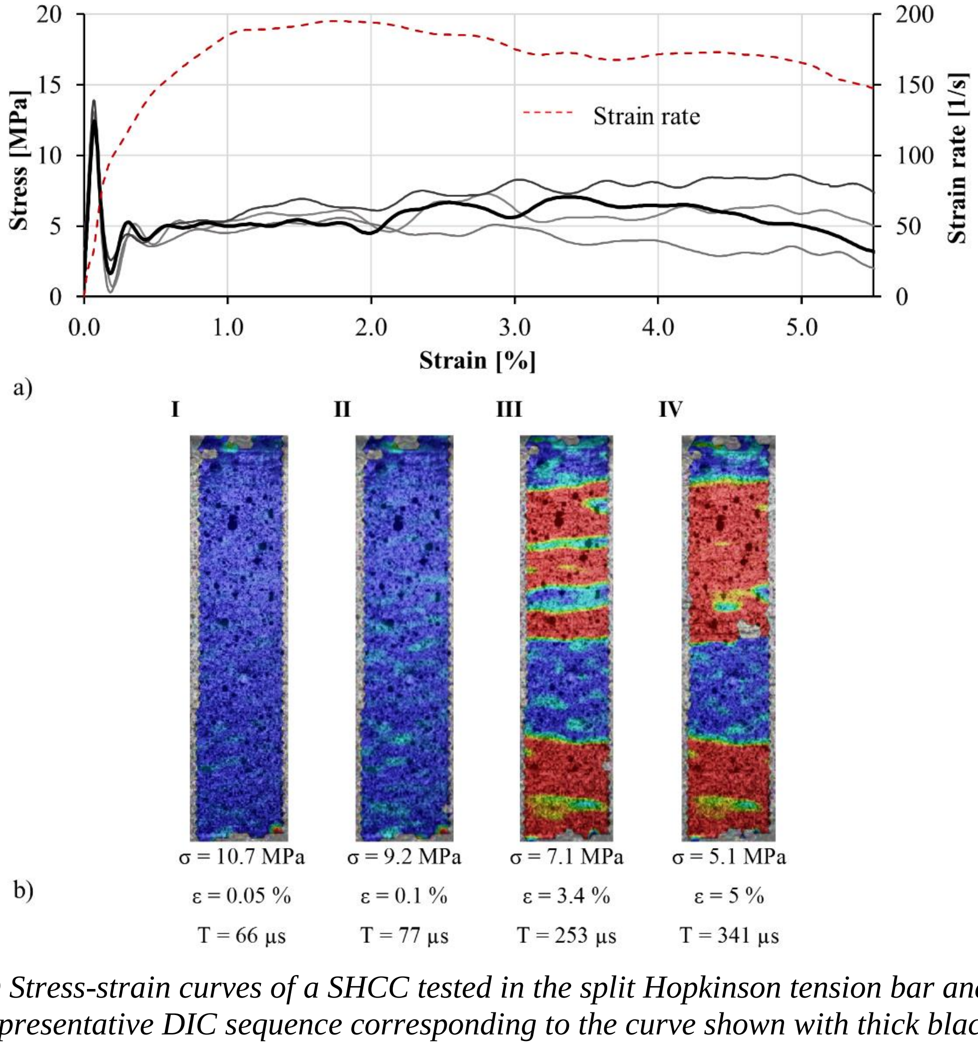
5. Institut of construction materials-Alfred Hütter lab

In the framework of the research training group GRK2250 (https://grk2250.de/), a split Hopkinson tension bar and a mini-Hopkinson bar were developed in the laboratory of Institute of Construction Materials at Technical University of Dresden. The aim was to investigate the mechanical behavior of strain-hardening cement-based composites at high strain rates.

5.1 Split-Hopkinson bar setups

The split Hopkinson tension bar is capable of generating a tensile stress wave with a duration of up to 0.5 ms. Various input waves and rise times are attainable through pulse shaping techniques. The setup has been used for investigating strain hardening cement-based composite (SHCC) and textile reinforced concrete (TRC). In addition to the conventional wave analysis in the split Hopkinson bar, high-speed stereo cameras are used for monitoring the impact experiments at frame rates up to 480,000 fps. Subsequently, the recorded frames can be used for digital image correlation (DIC) analysis. Moreover, the setup is equipped with a high-speed optical extensometer for measuring strain in specimens.

In conjunction with impact experiments on the composite level in the split Hopkinson tension bar, a mini-Hopkinson bar was developed for high-speed micromechanical experiments on constituent elements of composites, i.e., fiber and fiber-matrix bond. The setup is capable of performing impact fiber pullout and fiber tension tests at a displacement rate of up to 1800 mm/s. The results of the test setup can be used for explaining the performance of composites at high strain rates with regard to the rate dependency of their constituents.



a) Stress-strain curves of a SHCC tested in the split Hopkinson tension bar and,
b) a representative DIC sequence corresponding to the curve shown with thick black line.

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UNIVERSITY OF STUTTGART, Germany

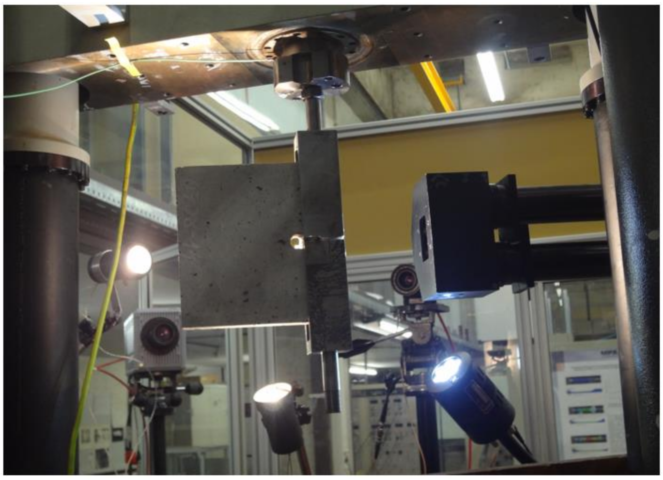
6. Material Testing Institute (MPA)

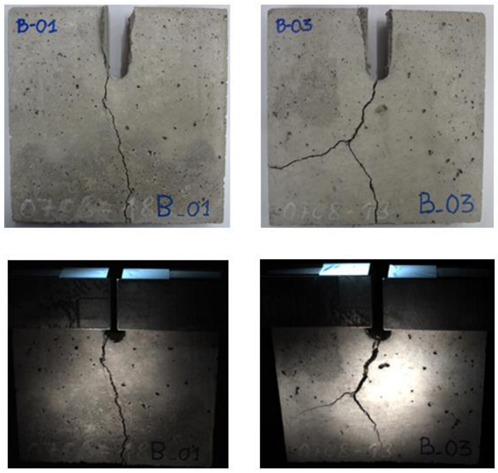
The below listed equipment for dynamic testing of materials and structures is currently available at the Material Testing Institute (MPA), University of Stuttgart. The department at which the equipment is available is mainly specialized for dynamic testing of ductile materials (e.g. metals). However, brittle (e.g. glass) and quasi-brittle (e.g. concrete) materials can also be tested.

6.1 Servo hydraulic fast breaking machine VHS
INSTRON servo-hydraulic high-speed testing machine is installed at the Material Testing Institute (MPA), University of Stuttgart. It is mainly used for dynamic tests on relatively small steel specimens, e.g. beams and compact tension specimens (CTS). However, recently the machine was also used to investigate dynamic fracture of relatively large concrete specimens, e.g. CTS and L-shaped geometries. The testing machine has load capacity of maximum 100 kN and the loading velocity up to 20 m/s. Dynamic loading on the specimen is provided by machine actuator (loading piston). The load cell built into the inner part of the loading piston (machine actuator) is used to measure applied load. KISTLER piezoelectric force sensor Type 9061A is employed to determine dynamic force. The load cell is connected to a charge amplifier with a highly insulating special cable. The vertical displacement is measured in relation to the point of load application by means of optical extensometer Zimmer OHG 200 X-5 No. 246. Together with the machine, FASTCAM-APX RS high-speed video camera with a maximum of 30000 frames per second is used to record the crack propagation. For instance, for L-shaped concrete specimen with dimensions in the range of 0.50 m, the imposed loading point displacement rates were varied from 0.25 mm/s up to 5000 mm/s. Due to safety reasons the tests were not performed for higher loading (displacement) rates.

6.2 Dropping Hammer Test Machine
Dropping hammer test machine was designed at the Material Testing Institute (MPA), University of Stuttgart. Maximum falling height is 10 m and Energy 20 kJ. It can be used for testing of materials and structural elements (e.g. RC slabs). For instance, the qualification tests on foam were performed at MPA Stuttgart (Germany) using a guided drop rack. Influence of temperature in a range from -40° to +80° C, humidity, cumulative loads and foam cells orientation were taken into consideration. In these drop tests, force and acceleration are measured, as well as deformations detected by optical measurement methods with a sampling rate of 100 kHz over the whole impact. From the measured data other quantities, such as energy absorption and compression strength of the foam can be determined.

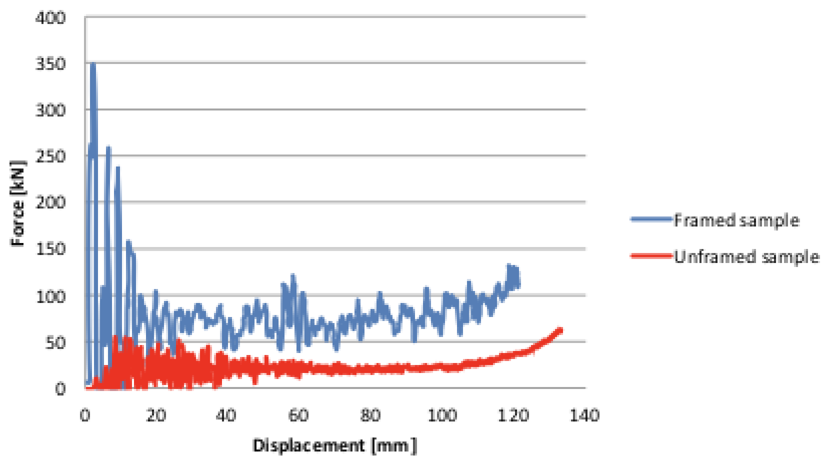
6.3 Split Hopkinson Pressure Bar (SHPB)
The split Hopkinson pressure bar (SHPB) or Kolsky apparatus for compression testing consists of a striker bar, incident bar (800 mm), transmitter bar (600 mm), with bar diameter of 20 mm and associated instrumentation for recording data. The incident and transmitter pressure bars are mounted on Teflon or nylon bushing to assure accurate axial alignment while permitting stress waves to pass without dispersion. The specimen is sandwiched between the two bars. The striker bar is accelerated by utilising a small gas gun apparatus. The size (length) of the projectile is in the range of 25 to 100 mm. The SHPB is mainly used for dynamic tests on metals.



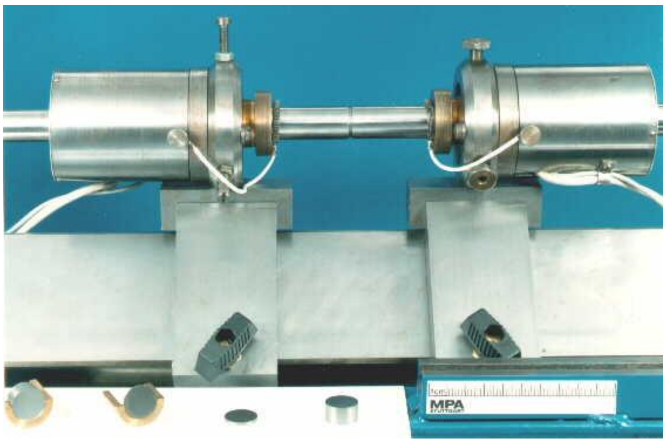


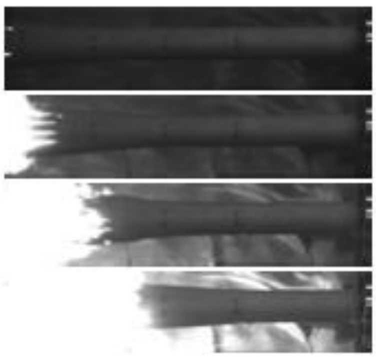
40 mm/s 1300 mm/s

Dynamic fracture tests on concrete Compact Tension specimens



Qualification test program of polyisocyanurate rigid foam for the use in type B(U)F packages





Split Hopkinson Bar experiment (left) and pipe expansion due to the pressure wave progress and multiple longitudinal cracks from the high-speed kamera (right)

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TNO-DEFENCE, SAFETY AND SECURITY, The Netherlands

7. Weapon Effects & Protection Center (WEPC)

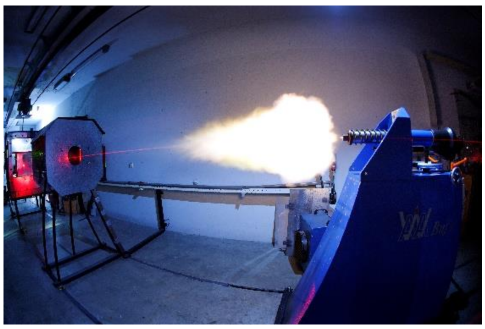
The Weapon Effects & Protection Center is the most highly advanced weapons testing center in Europe. The fully indoor facility offers full testing capabilities for ballistics, whole vehicles and laser weaponry. With advanced diagnostic and analytic technology, all manner of weaponry and defence materials can be accurately tested in a controlled environment. The fully indoor facility offers full testing capabilities for ballistics, whole vehicles and laser weaponry. With advanced diagnostic and analytic technology, all manner of weaponry and defence materials can be accurately tested in a controlled environment. For explosion tests exceeding the capabilities of the WEPC-facilities TNO has a specialized team to perform instrumented field tests recording highly dynamic events as a result of blast.
The customers of our facilities consist of defence ministries, the international defence industry as well as the civilian industry. Services range from qualification of bulletproof vests to testing spall liners against EFP's according to the latest STANAG standards and research campaigns on structural protection to close-in explosions. The WEPC is ISO/IEC 17025 accredited and also has a NEN-EN-ISO 9001:2008 management certificate.
For explosion and impact tests the large explosion bunker and the launching systems offer a wide scope of ballistic and explosion test conditions for infra structural elements.

7.1 Small caliber indoor shooting range
Caliber range up to 20mm; Velocity range= 200 – 1200 m/s; diagnostics to record velocities, yaw, behind target effects. HS video and HS-Xray; target dimensions max 800 x800 mm^2.

7.2 Mid and large caliber KE/HE indoor shooting range
Caliber range up to 105mm; Velocity range= 200 – 2500 m/s; diagnostics to record impact velocities and yaw, residual velocities, dynamic response (High Speed Digital Image Correlation) and behind wall (target) effects. Multiple X-ray pulsars (up to 1200 keV) and high speed cameras with up to 1 million fps with 100 frame capacity. Target dimensions up to 3000x 3000 mm^2 .

7.3 Debris launcher
Calibers: 30, 50, 78 and 105 mm; Masses up to 5 kg; velocity range (depending on mass) up to 2500 m/s. Instrumentation see 7.1.2. Target dimensions up to 3000x 3000 mm^2.

7.4 Large explosion target bunker, GKW
Target bunker suitable for full scale testing of impact, ballistic resistance of (RC) infrastructural elements as well as the damage and behind wall effects of close-in or contact charges.
Launchers for impact tests, see 7.1.2 and 7.1.3. Explosions up to 25 kg TNT equivalent HE material. Instrumentation, see 7.1.2 and blast pressure recordings. Max target dimensions 3000x 3000 mm^2 .
See for dimensions shooting ranges, GKW and summary facilities the excel-datasheet.



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TECHNICAL UNIVERSITY OF MADRID, Spain

8. Laboratory of Structures

The Laboratory of Structures of the Technical University of Madrid is located in the Civil Engineering School. The Laboratory is dedicated mainly to full scale testing of steel and concrete specimens or structures. In the last years, research has been carried out on shear and punching capacity, cracking, FRC, masonry structures, robustness, impact, and dynamic behaviour of structures.

8.1 Impact Machine

The impact machine at the Laboratory of Structures of the Technical University of Madrid can drop weight varying between 100 to 200 kg from a maximum height of 2.00 m minus the height of the specimen. It can accommodate specimens with a maximum width of 0.2 m and a maximum span of 2.0 m.

Until now, the machine has been used to study the behaviour of reinforced concrete to impact and how it can be improved by the use of steel fibre reinforced concrete (SFRC). Although centred on the behaviour of beam elements, these studies have also looked at the sensitivity of the mechanical properties of different SFRCs to the strain velocity. For this, tests have been carried out on prismatic material specimens.

Additionally, studies have been undertaken on the impact behaviour of beams reinforced with a thin layer of UHPFRC.

Impact test

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MILITARY UNIVERSITY OF TECHNOLOGY, Poland

9. Laboratory of Split Hopkinson Pressure Bars

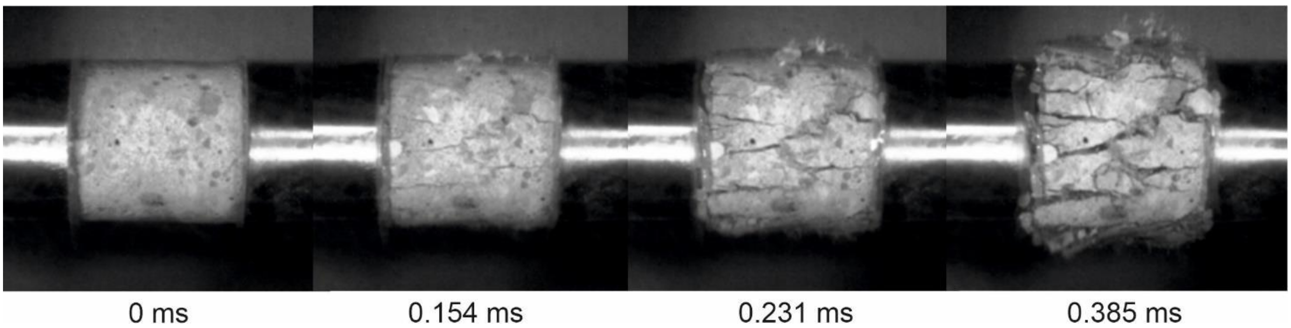
The Military University of Technology is the most advanced research Unit in Poland for investigation of the miscellaneous materials under dynamic conditions. Over the years, various research methods were adopted to analyse the response of different types of materials to high strain rates, e.g. electromagnetic expanding ring and Taylor impact test. The need of obtaining more information on the material properties under high strain rates necessary for development and numerical modelling forced the researches to developed the Split Hopkinson Pressure Bar arrangement.

9.1 Small Split Hopkinson Pressure Bar with a diameter of 6 mm or 12 mm

The first 12 mm SHPB stand on compression was built in 2012. Many modifications were made to perform high strain rate experiments of engineering metals and their alloys not only at compression, but also at tension and shear loading conditions. The total length of the facility is in the range of 4 m to 6 mm depending on the applied setup configuration. The diameter of the incident and transmitted bars which determine the dimensions of the samples can be equal to 12 or 6 mm. The used bar/tube materials are: MS350 maraging steel, 41CR4 steel and Al7075-T6 as well as plexiglass. The strain rates produced in the specimen are in the wide range of 1000-6000 s^{-1}. The small SHPB device was applied for testing of the following materials: structural steels, high-strength steel (e.g. Armox, nano-banitic steel), AHSS steel (e.g. Strenx S700M, Docol 800DP or Docol 1500M), tungsten alloy, titanium alloy, GumMetal, NiTi shape memory alloy, aluminium alloy, copper and its alloy, polymers and elastomers.

9.2 Large Split Hopkinson Pressure Bar with a diameter of 40 mm

The bigger SHPB available in Poland was built in 2016. The length of the large SHPB setup which is equipped with the bars with a diameter of 40 mm is about 12 m. The response of brittle materials to high compression strain rates can be examined in this facility. The large SHPB was also adapted for testing in direct impact configuration (Direct Impact Hopkinson Bar). The strain rates in the specimens can achieve the value of 400 s^{-1}. There are available bars made of C45 steel, Al6063 – T62 and Al7075-T6, and a hollow bar made of Al 6063-T62. Materials which were analysed with the use of the large SHPB device are: concrete and fibre reinforced concrete, composites, rocks, cellular structure materials, polymer foams and low strength metals.
The SHPB tests are performed with the use of the high-speed camera (Phanton V1612) which allows to track the damage process of the specimen. The applied Data Acquisition System is characterised by frequency response of 1 MHz and it is able to register signals at a sampling rate of 4 MHz.
Many years of experience of the research team in preparation and execution of SHPB tests allowed to develop research procedures that currently guarantee high reliability of the obtained dynamic test results.



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UNIVERSITÉ GRENOBLE ALPES, France

10. The Soils, Solids, Structures and Risks Laboratory

10.1 The ExperDYN platform

An experimental platform dedicated to the investigation of the mechanical the behaviour of brittle materials and their damage modes at high-strain-rates.

This experimental platform is dedicated to the characterization of the mechanical behaviour of various types of brittle materials (concrete, polycrystalline ice, high-strength concrete, rocks, ceramics, composites, brittle polymers) and their damage modes under high-strain-rates and impact loadings. This characterization is essential for the development of constitutive laws and micro-mechanics based modelling and to better understand the relationship between microstructure of the tested materials, their mechanical behaviour and the underlying damage mechanisms.

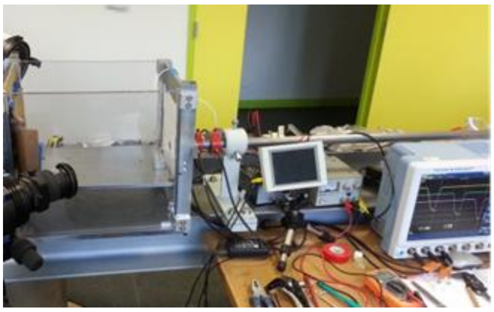
ExperDYN platform host a 50-mm-caliber gas launcher dedicated to the testing of geomaterials:

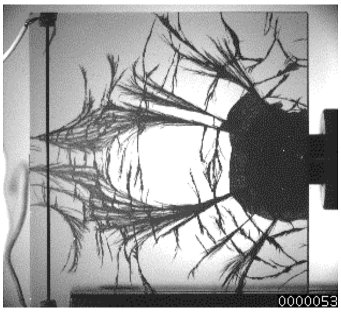
- Dynamic Punch-through shear (PTS) tests: analysis of the dynamic shear strength
- Dynamic tensile tests by the spalling technique: analysis of the dynamic tensile strength
- Rocking-spalling technique: analysis of the crack speed and dynamic fracturing

These experiments operate with full-field measurement technique (grid or DIC) and the Virtual Field Method is applied to process the data of ultra-high-speed imaging (Kirana, 5 Mfps, 924x768 pixels). Measurement of acceleration fields provides a direct measurement of forces and stresses in the tested sample.

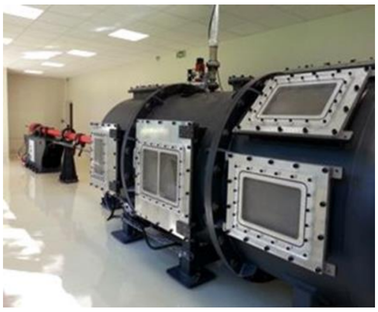
ExperDYN platform host a 20-mm-caliber gas launcher dedicated to the analysis of damage and fragmentation in brittle materials under impact loads:

- Edge-on impact tests: analysis of the fragmentation process with ultra-high-speed imaging and sarcophagus configuration (CT scan).
- Tandem experiments (it consists in a normal impact test followed by piercing impact test): analysis of the impact resistance of a fragmented media





The multi-calibre gas launcher developed within the framework of the Brittle's CODEX chair is a testing facility dedicated to the study and characterization of the mechanical response of materials and structures under very high strain-rates and ballistic impacts. It operates under vacuum with helium or nitrogen high-pressure gas. The 25 and 80 mm calibres are used to test the ballistic resistance performance and response of structures (bi-layer or multi-layer armour, concrete structures, composite structures, etc.) subjected to the impact of small to medium calibre projectile considering impact speeds ranging from a few hundreds to eleven hundreds of m/s. The 80, 100 and 120 mm calibres are used to perform plate-impact tests dedicated to characterization of the compression and tensile strength of materials in uniaxial strain-state at strain-rates ranging from 1E3 to 1E5 1/s. The use of large diameter textured impact plates, acting as a pulse-shaper, makes it possible to control the loading time and the loading-rate applied to the target. The instrumentation used in these tests is based on high-frequency laser interferometry and ultra-fast imaging.



10.2 GIGA Triaxial Press

A high-capacity press, called GIGA, was installed at Université Grenoble Alpes - 3SR laboratory in collaboration with CEA Gramat in 2004. This cooperative venture is part of a larger research project on the vulnerability of concrete infrastructure when subjected to impact.
The GIGA press is able to load cylindrical concrete samples 7 cm in diameter and 14 cm long up to a confining pressure of 0.85 GPa and an axial stress reaching 2.35 GPa. The confining fluid, i.e. di-2-ethylhexyl azelate, a non-volatile organic, inert and slightly-compressible liquid, is injected into the cell through an upper opening before being pressurized by means of a multiplying jack. The jack is loaded under pressure by a primary hydraulic circuit up to 25 MPa, and its sectional ratio equal to 40 enables obtaining a pressure 40 times greater than that of the primary circuit inside the confinement cell, i.e. reaching approx. 1 GPa with a maximal rate of pressure increase of 1.67 MPa/s.
The axial force is generated from a 13-MN jack placed underneath the cell; it is transmitted to the sample via a piston that passes through the lower cell plug. A displacement sensor positioned inside the press is then used to guide axial displacement of the jack, while an axial force sensor and a pressure sensor placed within the confinement cell measure the sample stress state. Both the confining pressure and axial jack displacement are servo-controlled, which offers a variety of loading paths: hydrostatic, uniaxial confined (commonly named triaxial), proportional, extensional and oedometric. The concrete strain measurements are performed by means of a LVDT sensor and gauges that are glued on the concrete samples. Gauge measurement on concrete is completely original for such levels of confinement. The LVDT sensor gives the length variation of the specimen which leads to a global measurement of the axial strain. By means of the axial gauge, the consistency of the signals can be checked, by giving an additional and local measurement of the strain.
More recently, PTS (Punch-Through-Shear) tests and interstitial pore pressure measurements have also been done in the GIGA press.

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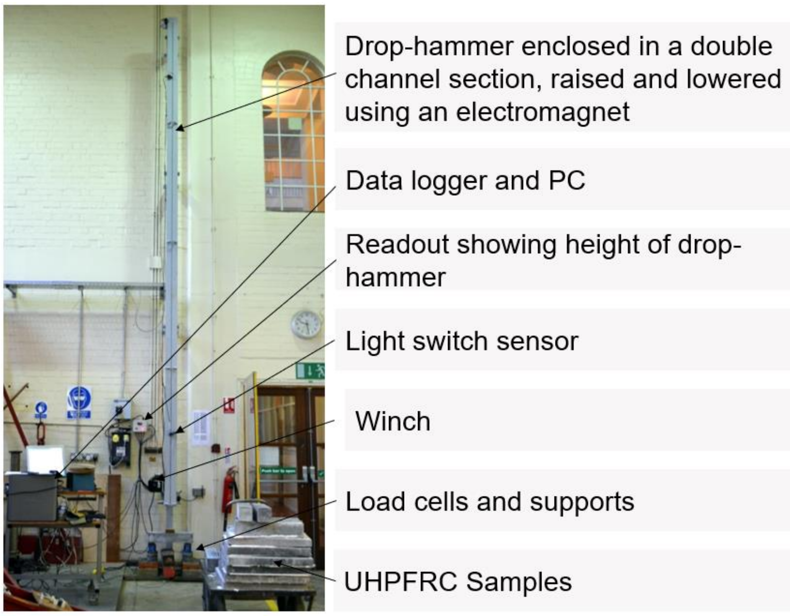
11. Structures Laboratory

The large structures laboratory at Queen's University Belfast is located in the School of Natural and Built Environment and more specifically in the David Keir Building. The laboratory is dedicated to large scale testing of steel and concrete specimens and structural elements. Research has been ongoing for a number of years on the impact resistance of Ultra High-Performance Fibre Reinforced Concrete (UHPFRC) and this has made use of inhouse designed and fabricated drop hammer test rig.

11.1 Drop Hammer Test Rig

Drop hammer or impactor has a hemispherical head. The impactor is housed in a double channel section with internal dimensions of 125mm by 115mm and height/length of 6m. The impactor is raised and lowered by an electromagnet. The maximum possible drop is 5m. The weight of the impactor can be 10 kg or 40 kg. The system is equipped by a data acquisition system with 64 channels with a maximum data acquisition rate of 500 kHz for a single channel use.



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