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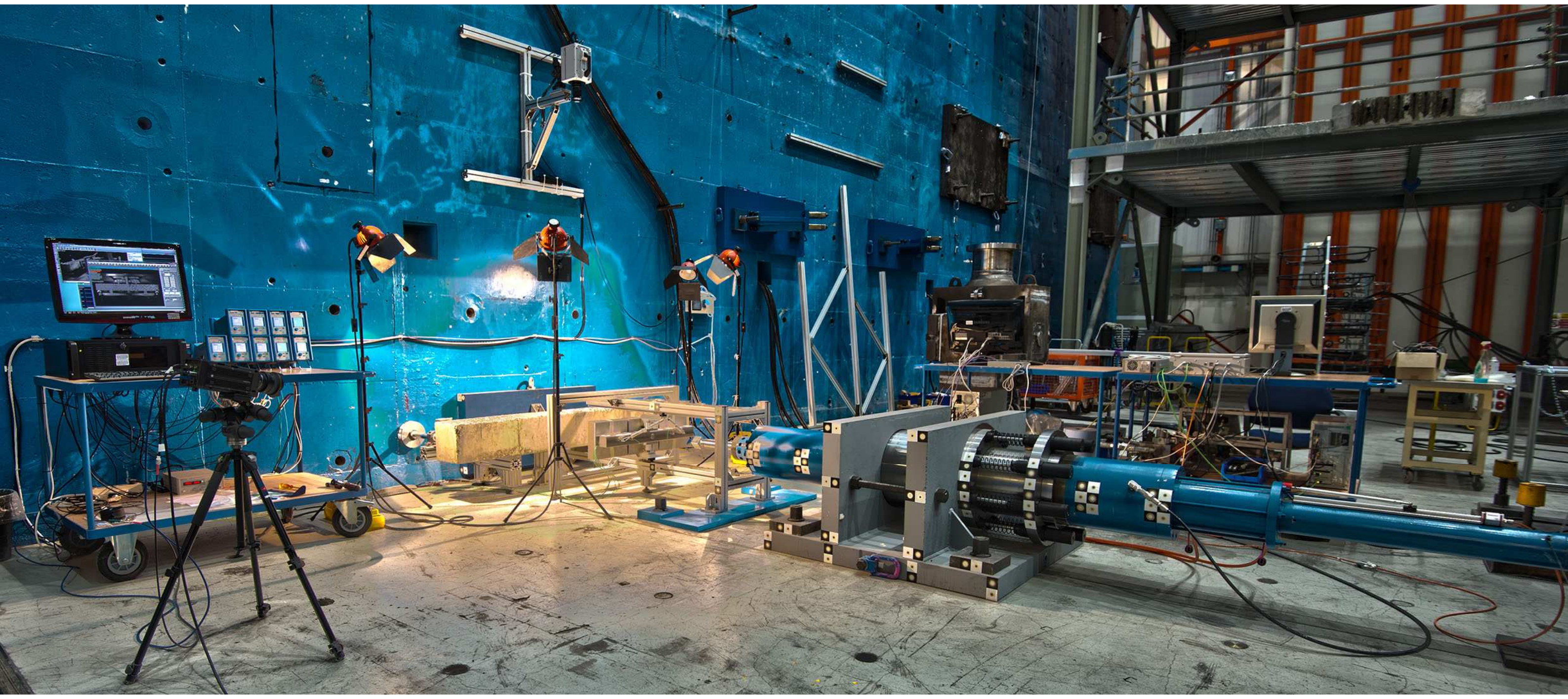

Blast Simulator project:
First tests on reinforced concrete beams

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Abstract

The Blast Simulator project involves the development of an apparatus able to reproduce the effects of a blast pressure wave on large scale structural components (such as columns, walls, etc.) with the objective to improve their strength in these severe loading situations. After a series of preliminary tests to assess the performance of the blast actuator for what concerns the energy capability, this technical report presents some results related to a test campaign on two full scale structural components, specifically two reinforced concrete beams.. With appropriate improvements made to the impactor, it has been possible to successfully bring the components to failure. A full suite of test parameters has also been recorded, valuable for guiding the numerical modelling. These experiments validate the potentiality of this kind of equipment to reproduce in a laboratory the effects of a blast explosion on full scale structural elements without using explosives. Further tests with the same experimental setup and with a new testing rig based on a more innovative technology (electrical linear motor) will be conducted in 2015 in the context of BUILTCIP project.

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European Laboratory for Structural Assessment

December 2014

1. Introduction

Critical infrastructures in fields such as energy, health, communication, government, transport etc. are made of physical structures, or are housed in physical structures. Such structures may naturally become the target of terrorist bombing attacks. Measures to protect them will certainly be taken, involving prevention, intelligence, detection, deterrence etc., but if everything fails, it is very important that the mechanical structure itself mitigates some effects of the explosion and maintains certain functionalities.

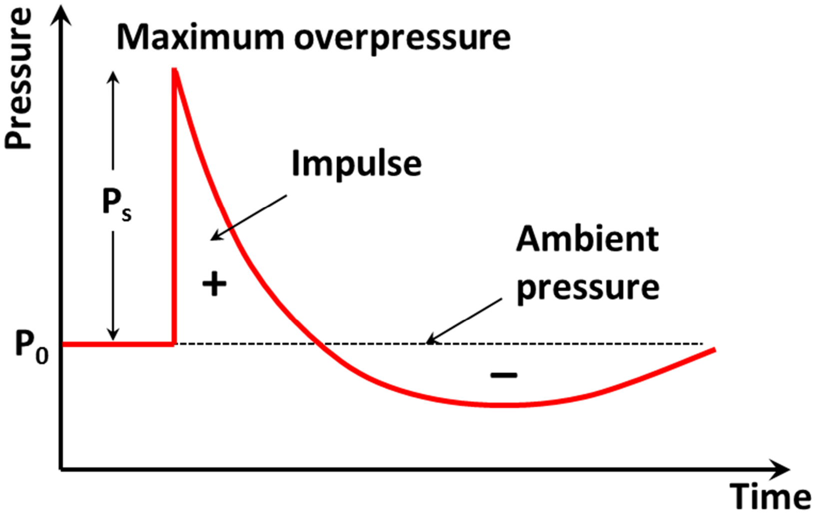

Figure 1. Blast wave pressure curve characteristics in free-air explosions

A typical pressure wave curve (which eventually will load a structure) at some distance from an explosion is shown in Figure 1. Its main characteristics concerning damaging effects on structures are the magnitude of the overpressure, the duration of the positive phase and especially its impulse, i.e., the area under the curve over the positive phase. This impulsive load will be delivered to a structure in a few milliseconds forcing it to respond or fail in a peculiar mode. This necessitates that models and design techniques for blast resistant structures be thoroughly validated with reliable data from field tests. However, such tests with actual explosions are expensive and they are usually performed within military grounds. Thus alternative testing methods are desirable, and this has been the case at the University of California in San Diego, where the first blast simulator facility has been built (2006). As claimed, the effects of bombs are generated 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 servo-controlled hydraulic actuators that punch properly the test specimens.

With the ongoing work a similar blast simulation capability is under development within the EU by the JRC. The staff of the ELSA Unit has a long and strong experience in the servo-controlled actuators. In fact some of these devices have been constructed in-house and relevant technology has been transferred to other European laboratories. Concerning the currently required fast actuators, an alternative design concept has been implemented, which is believed to be capable of generating impacting loads resembling closer those of the real explosions of Figure 1. This will allow the realistic testing of components to “simulated” explosions and will provide the necessary data for the verification and validation of the computer tools.

The development of this technology will be important both for the research and the practicing engineers and architects who need design rules and guidelines. Besides characterizing blast effects on structural systems, the methodology will contribute to evaluating technologies for hardening and retrofitting buildings and bridges against terrorist bomb attacks. Further, it will help in the investigation of the problem of progressive collapse, i.e., the phenomenon where a local failure propagates in a disproportionate manner to lead to global failure, like the building collapse in the Oklahoma City bombing.

2. Experimental setup

The blast simulator, as designed at the moment, is a small pneumatic/hydraulic facility and the sketch below summarizes the main parts of the apparatus (Figure 2).

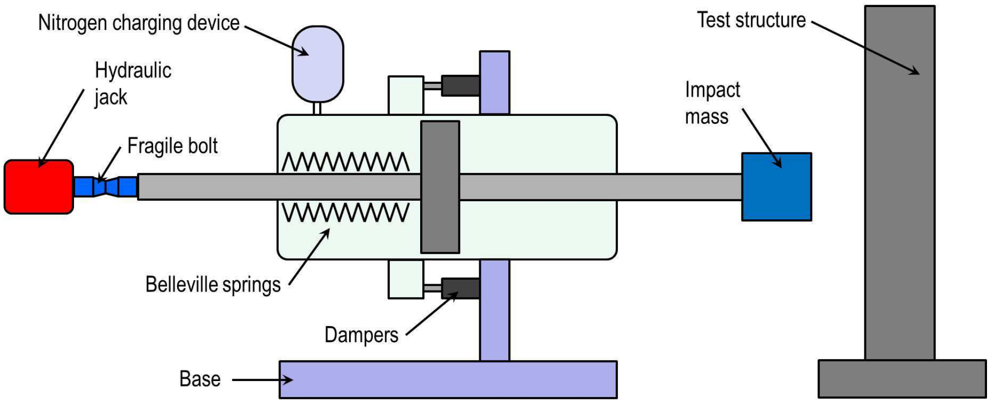

Figure 2. Sketch of blast simulator

The operating principle of the testing rig is quite simple: the shaft is pulled through a fragile bolt by a hydraulic jack and this action compresses a series of Belleville springs inside the blast actuator. At this point there is the option to also raise the pressure inside the active chamber of the blast actuator by charging it with nitrogen (maximum pressure 100 bar). By continuing the pulling of the shaft (or, by increasing the nitrogen pressure) the bolt suddenly breaks and the piston and shaft rapidly accelerate pushing the impacting mass, which is attached at the other extreme of the shaft. When the piston has done most of its stroke, it starts to decelerate and the impacting mass is detached from it and collides with the tested structure reproducing local pressures similar to those of a blast wave.

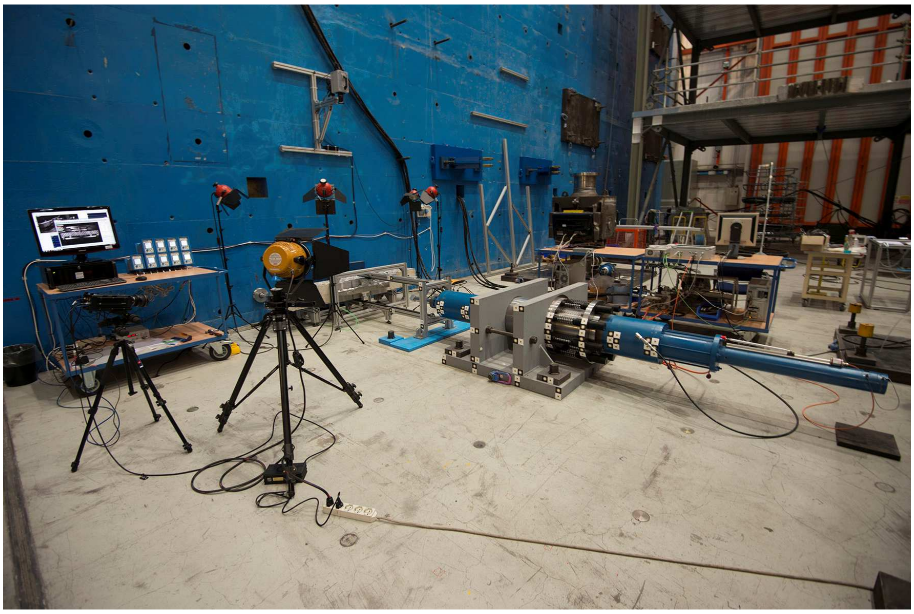

Figure 3. Final setup for blast experiments on RC beams

The implementation of this operating principle and details of the equipment have been presented together with some preliminary tests in the previous report "BLAST Simulator Project: Performance assessment and preliminary tests. Administrative Arrangement No JRC 32253-2011 with DG HOME Activity A5 – Blast Simulation Technology Development" Report EUR 26522 EN.

This report presents the work and some analyses of the test results concerning two real structural elements subjected to fast dynamic loads using the above-described blast simulator. The previous experience had indicated that in order to apply a pressure load comparable to that of a blast explosion some modifications of the actuator would have been necessary (Figure 3). These modifications mainly concerned the support of the specimen, the mass guiding system, the safety devices and especially the impacting mass.

The structural elements tested are two horizontally placed, simply supported beams of reinforced concrete. The setup is similar to a dynamic three point bending, where the dynamic loading is applied over an area on the central portion of the beam, as shown in Figure 4. The two horizontally reacting steel supports have a semi-cylindrical geometry and are connected through a bar to the Reaction Wall. The beam weight is vertically supported at two points by means of two Teflon sliders, which reduce horizontal friction during the test. The frame that supports the beam and the sliders is a modular structure made of aluminium profiles as is also the structure that supports the two linear bearing guides of the impacting mass.

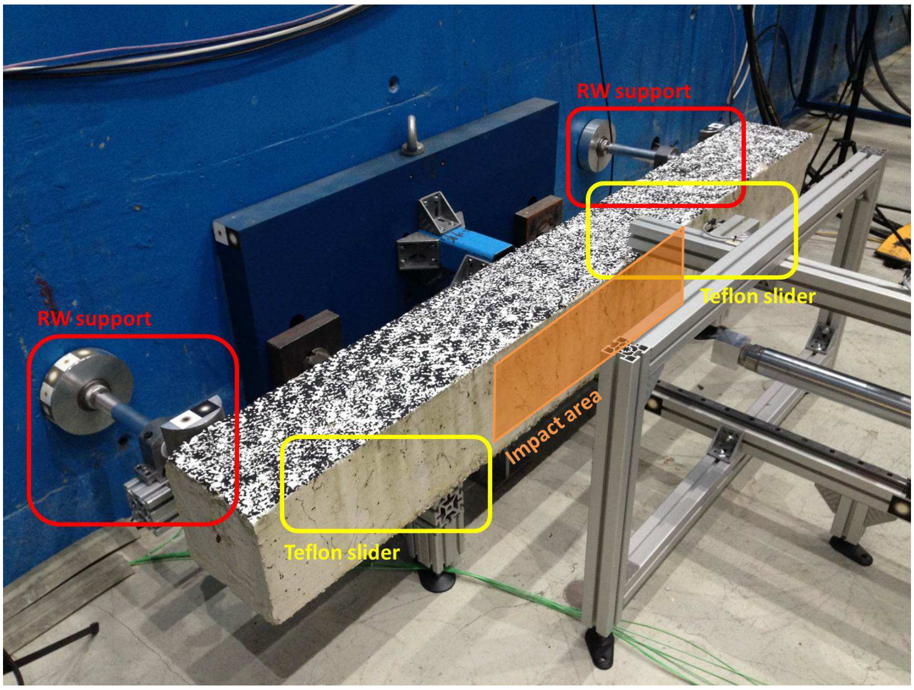

Figure 4. Blast simulator: specimen supports

This last frame has been considerably modified, with respect to the configuration presented in the previous technical report, in order to allow a complete optical accessibility to the specimen from the top, where a high speed camera is placed.

The impacting mass has probably undergone the major upgrade, compared with the mass proposed in the previous report, even though it is essentially based on the same principles as the old one: an instrumented mass composed of some rigid, light plates in the front, connected through some load cells to the heavy, main mass behind.

Specifically, the solution tested in this campaign is shown in Figure 5. The block of the impacting mass is composed of three aluminium plates (290 x 250 x 10 mm) connected with three independent piezoelectric load cells to a heavy stainless steel prismatic mass (75 x 75 x 850 mm). In front of the plate a layer of polyurethane foam has been placed to smooth the pressure pulse and reproduce closer the blast pressure history. The mass has been designed to slide on two linear bearing carriages and to rotate around two bearings rigidly connected to the carriages. These degrees of freedom reduce drastically the forces transmitted to the guiding rails, improving the safety and the lifetime of the equipment.

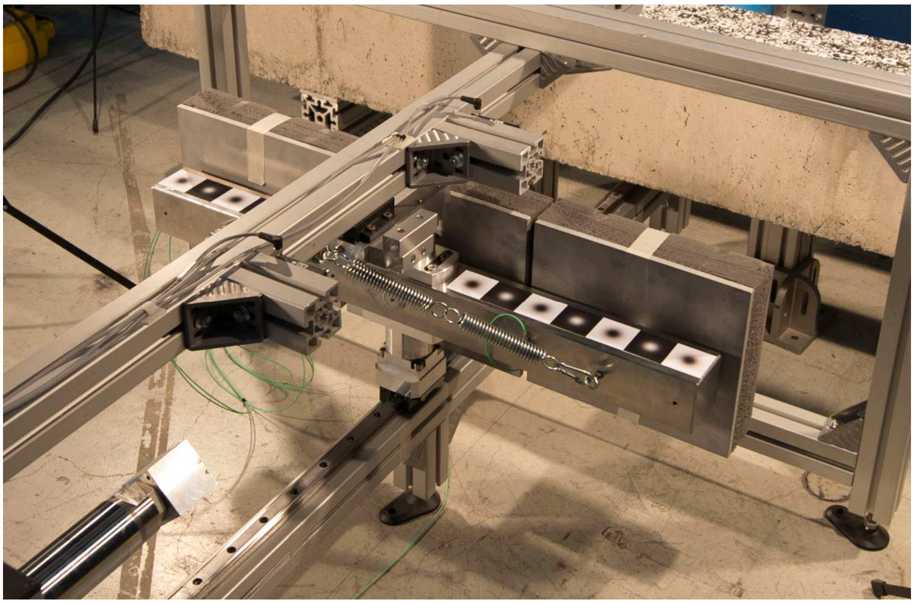

Figure 5. Blast simulator: impacting mass

As discussed in the next sections, after the first test two additional springs have been added (Figure 5), in order to control rotations and avoid possible misalignment of the impacting mass during its free movement before the impact. The impactor, in its current design, can reliably measure a maximum load of 990 kN, a value that has been largely exceeded during the last test presented in this report.

During the experiments all equipment is covered by a safety box (a mixed aluminium and polycarbonate panel structure) that protects the operators conducting the experiment from accidental debris. The safety box has been extended to properly cover the beam specimen in this test campaign. The proposed setup is fully compliant to the safety rules and procedures of JRC (see PDC “fast actuator experiments”).

3. Instrumentation

The instrumentation adopted during the test campaign on RC beams is practically the same as that described in the Report EUR 26522 EN. The differences concern only the triggering sensors and the numbers of transducers employed.

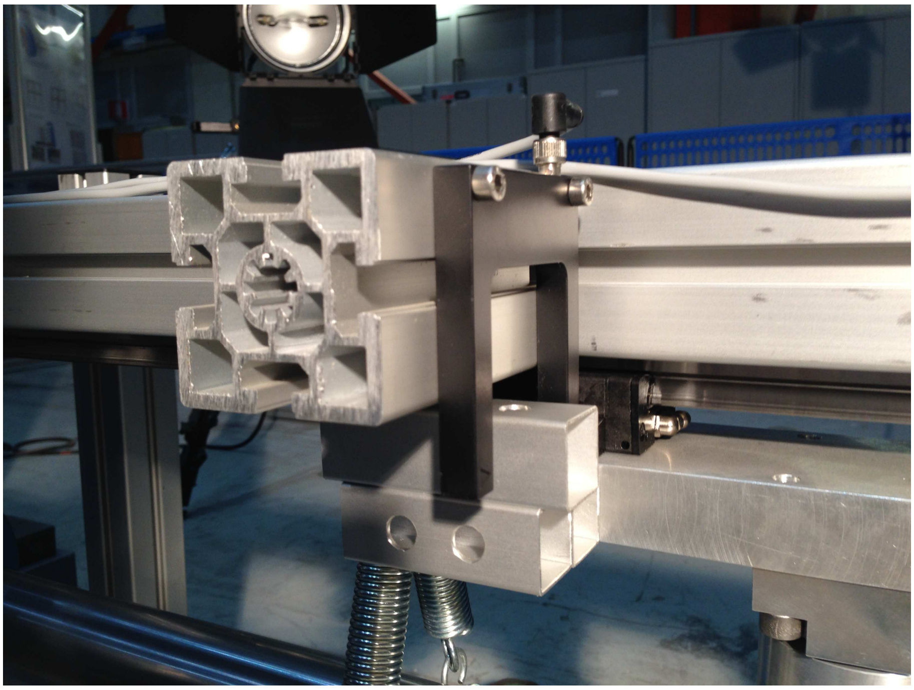

Figure 6. Blast simulator: detail of a triggering sensor

Figure 6 shows one of the triggering sensors adopted, which has a two-prong fork shape. The sensor is a photoelectric cell and it is used simultaneously for generating the triggering signal and as a speedometer. In practice a component of known length passes through the sensor fork and shadows, for a time proportional to its velocity, the sensing arm of the fork. An additional measurement of the instantaneous speed of the impactor before its collision with the specimen is thus produced.

The detailed list of instrumentation adopted and deployed during the experiments carried out 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).
- 1 High speed camera Photron SA1 with 21 mm Zeiss Distagon lens. This camera films the upper face of the specimen and impactor, for optical/photogrammetric analysis purposes, at a frequency of 5000 fps (pre-trigger 0 frames, post-trigger 5000 frames).
- 9 Charge Amplifiers Kistler 5015 for the conditioning of piezoelectric sensors.

- 2 Piezoelectric load cells Kistler 9106A (full scale330 kN) placed on the Reaction Wall supports.
- 3 Piezoelectric load cells Kistler 9106A (full scale 330 kN) interposed between the three aluminum plates and the main steel mass of the impactor.
- 2 Piezoelectric accelerometers Kistler 8202A (full scale 2000 g) mounted on the steel mass of the impactor to evaluate its acceleration and its possible rotation (in the experiment BLAST 17).
- 1 Piezoelectric accelerometer Kistler 8202A (full scale 2000 g) mounted on the central aluminum plate of the impactor to evaluate possible inaccuracies in the force measurement due to the plate inertia (in the experiment BLAST 17).
- 1 Piezoelectric pressure sensor Kistler 601H on the pressurized chamber of the blast actuator (in the experiment BLAST 17).
- 3 Photoelectric cells Pepperl Fuchs for triggering the data acquisition and for measuring locally the impactor velocity.

4. Experimental tests

This section summarizes some results of the tests performed with the blast actuator on two RC beams in order to evaluate the performance of this equipment and its capability to simulate the effects of a blast explosion without using explosives.

The tests have been conducted on full scale reinforced concrete beams of dimensions 250 x 250 x 2200 mm, manufactured with standard materials and reinforcement. The designed compressive strength of the concrete is around $f_{ck} = 20$ MPa with a maximum aggregate size of 20 mm. The reinforcement consists of 4 longitudinal deformed bars of 12mm diameter and stirrups of 8mm diameter spaced every 200mm, as shown in Figure 7.

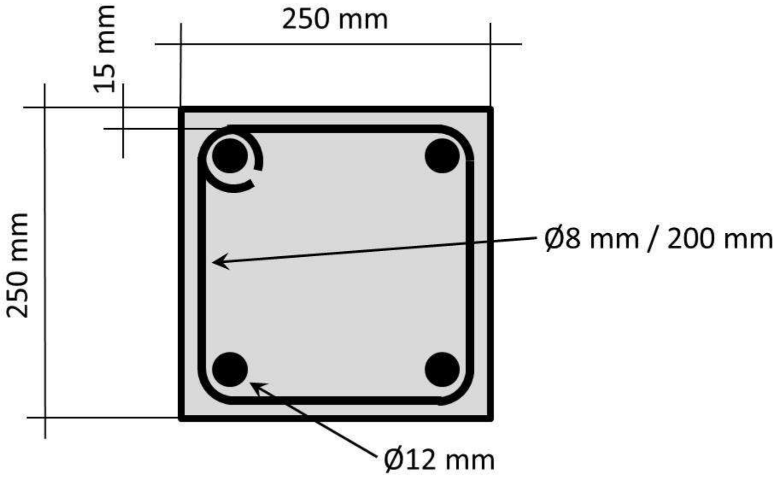

Figure 7. Reinforcement distribution in RC beams

Table 1 presents schematically the tests carried out and the test type with some additional information. The numbering follows the experiments already carried out with the blast actuator and presented in the previous technical report.

Table 1. Experimental tests performed

Test name	Impactor mass	Notes
Blast 14	40.7kg	Only spring, fragile bolt 5 mm
Blast 15	40.7kg	Only spring, fragile bolt 8 mm
Blast 16	40.7kg	Only spring, fragile bolt 9.25 mm
Blast 17	40.7kg	Spring + nitrogen (10 bar), fragile bolt 10 mm

The test campaign has been conducted taking into account safety issues due to the elevated levels of energy stored and quickly released during the experiments. For this reason and taking into account the high complexity of the equipment under operation, the energy involved during the experiments has been increased gradually.

The first three tests have been conducted on the same specimen with an increasing impacting velocity, and thus several of the testing parameters (especially the specimen damage state) are not well defined. Although these tests do not have a high scientific value, they have allowed a better knowledge of the equipment performance and of the test evolution. The tests have been performed by storing energy only in the actuator spring and a maximum velocity of about 12 m/s in the experiment "BLAST 16" has been reached. Following this test, the column has been judged to be overly damaged to continue with additional tests on it.

Experiment BLAST 17, on the contrary, can be considered to have a greater scientific value even though a series of experimental setbacks have occurred. The test has been performed by employing the energy of the springs and of pressurized nitrogen in order to increase the impact velocity of the mass (about 17 m/s). The beam has been seriously damaged and patterns of a shear failure mode have appeared (also typical of blast load failure).

A first analysis of the results has been made and some results in the form of images and diagrams are presented in the following. Figure 8 provides a general picture of the geometry of the impactor, the beam specimen and its supports, which helps in understanding the diagrams produced below for each one of the tests.

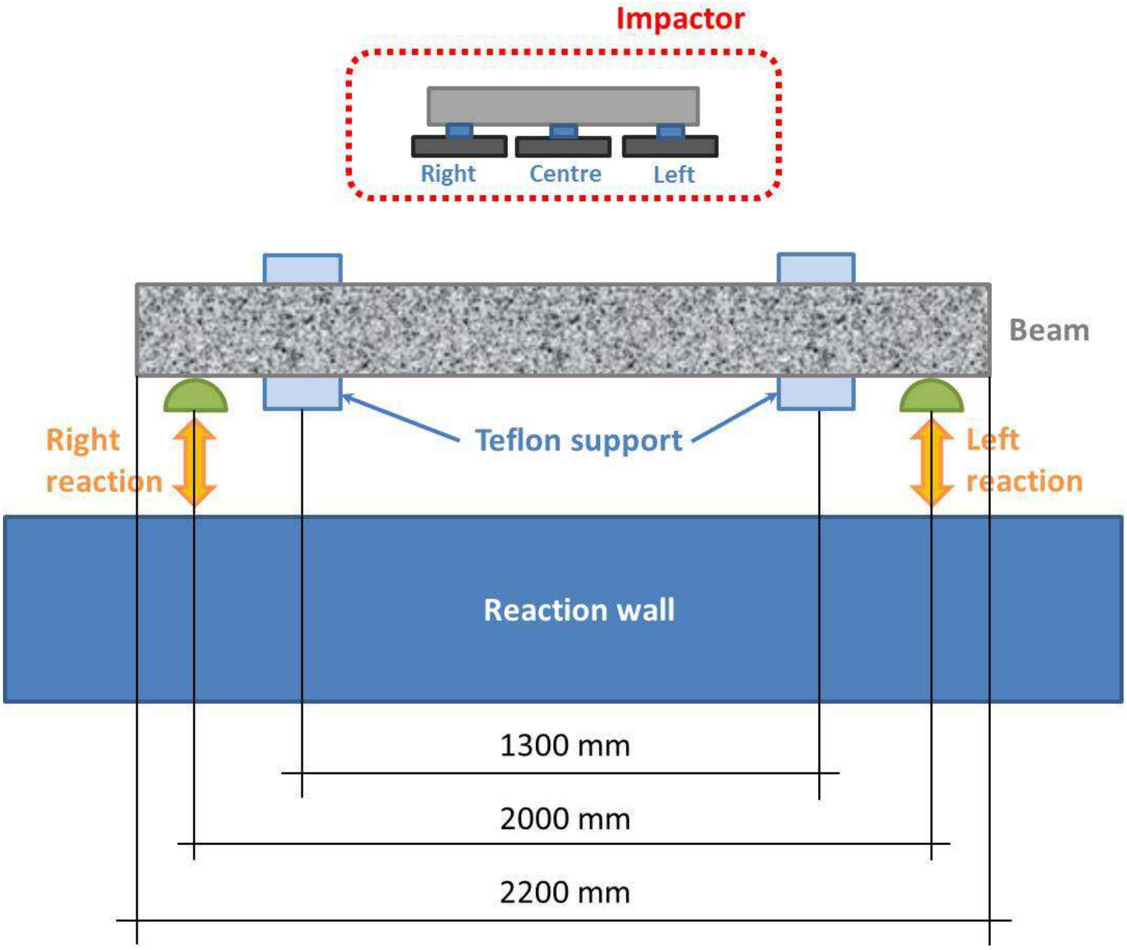

Figure 8. Schematic top view of the geometry of the experiments

Blast 14

Blast 14 experiment has been conducted on the first undamaged specimen. The energy has been accumulated only in the springs and the fragile bolt used has a notched section of 5 mm diameter. An impact velocity of approximately 3.6 m/s has been reached. The mass has impacted against the beam not perfectly parallel, as is immediately seen in the photo images and demonstrated by the not negligible differences in the velocities and displacements of the different targets along the mass. The left and right reactions are also unacceptably different. Therefore in the next tests a two-spring device, practically eliminating rotational tendencies of the impactor, has been added in order to avoid this undesired behaviour.

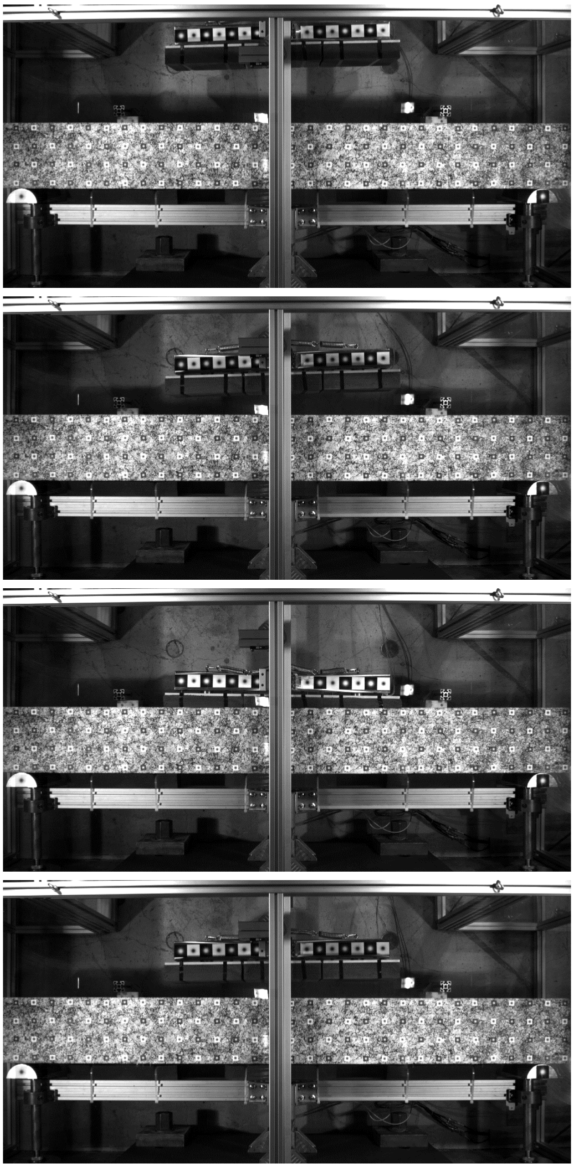

Figure 9. BLAST 14: High speed photo sequence

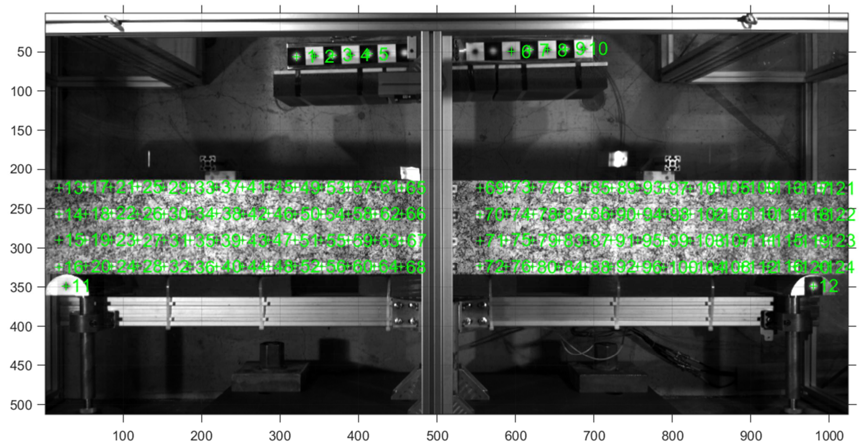

Figure 10. BLAST 14: Targets elaborated

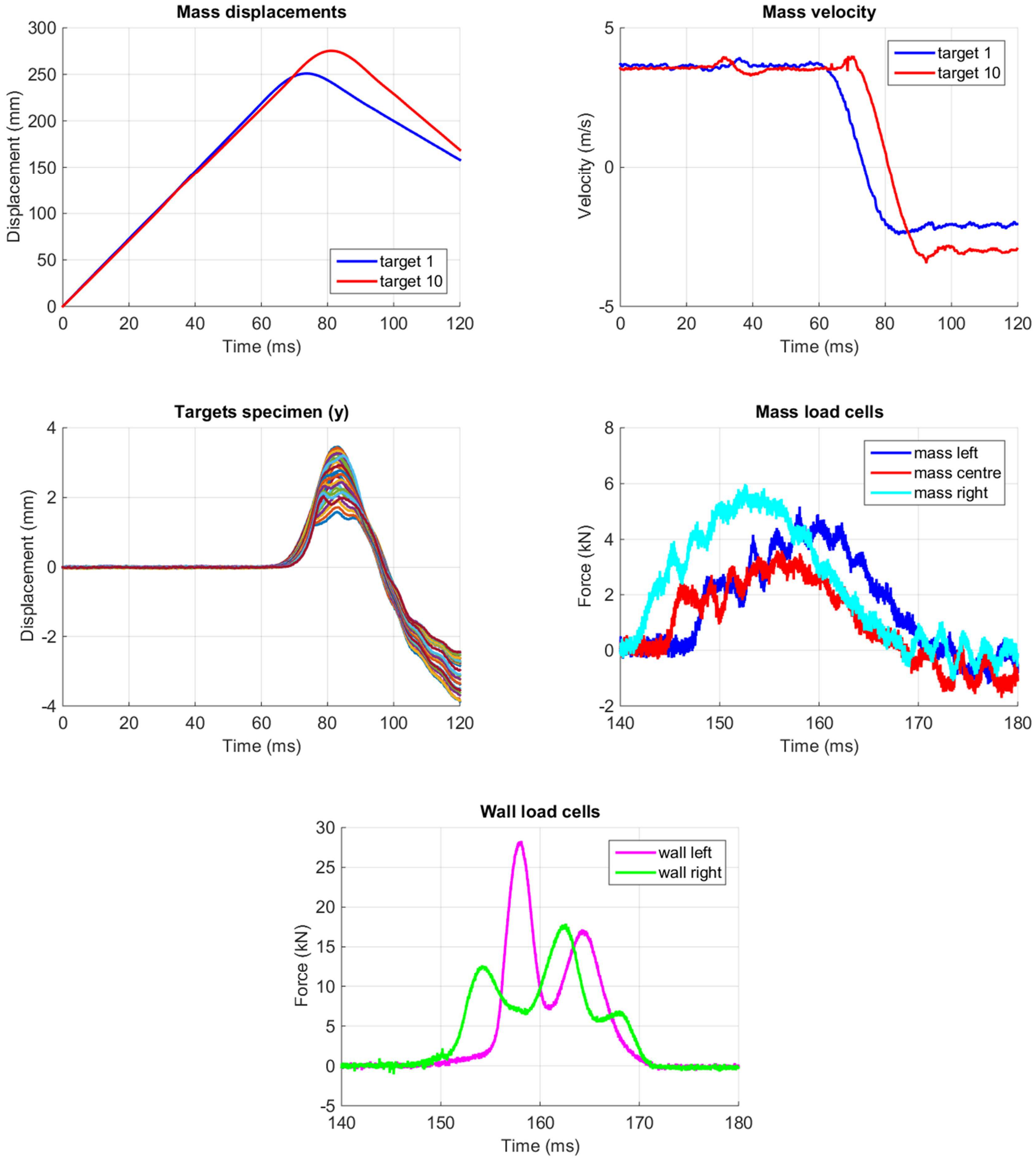

Figure 11. BLAST 14: experimental data elaborated

Blast 15

Blast 15 experiment has been conducted on the same specimen, probably not at all damaged from the previous experiment. The energy has been accumulated only in the springs and the fragile bolt used has a notched section of 8 mm diameter. An impact velocity of approximately 6.2 m/s has been reached. The mass has impacted against the beam practically parallel to the beam face, thanks to the two-spring device introduced above. This fact is underlined by the homogeneity in the mass displacements and in the force histories recorded by the three mass load cells. The beneficial effect of this device is thus demonstrated and its use is continued in all later experiments. The maximum deflection reached in the centre of the beam is about 8.6 mm, and this implies that some damage must have been incurred to the specimen, most likely in the form of internal concrete micro-cracking. Some hair-size cracks in the concrete were also visible in the central “tensile side” of the beam. However, no global residual deformations have been observed after the test.

Figure 12. BLAST 15: High speed photo sequence

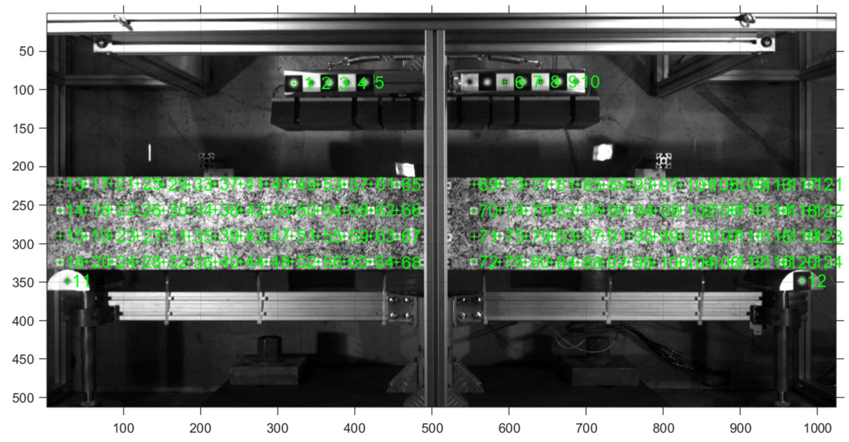

Figure 13. BLAST 15: Targets elaborated

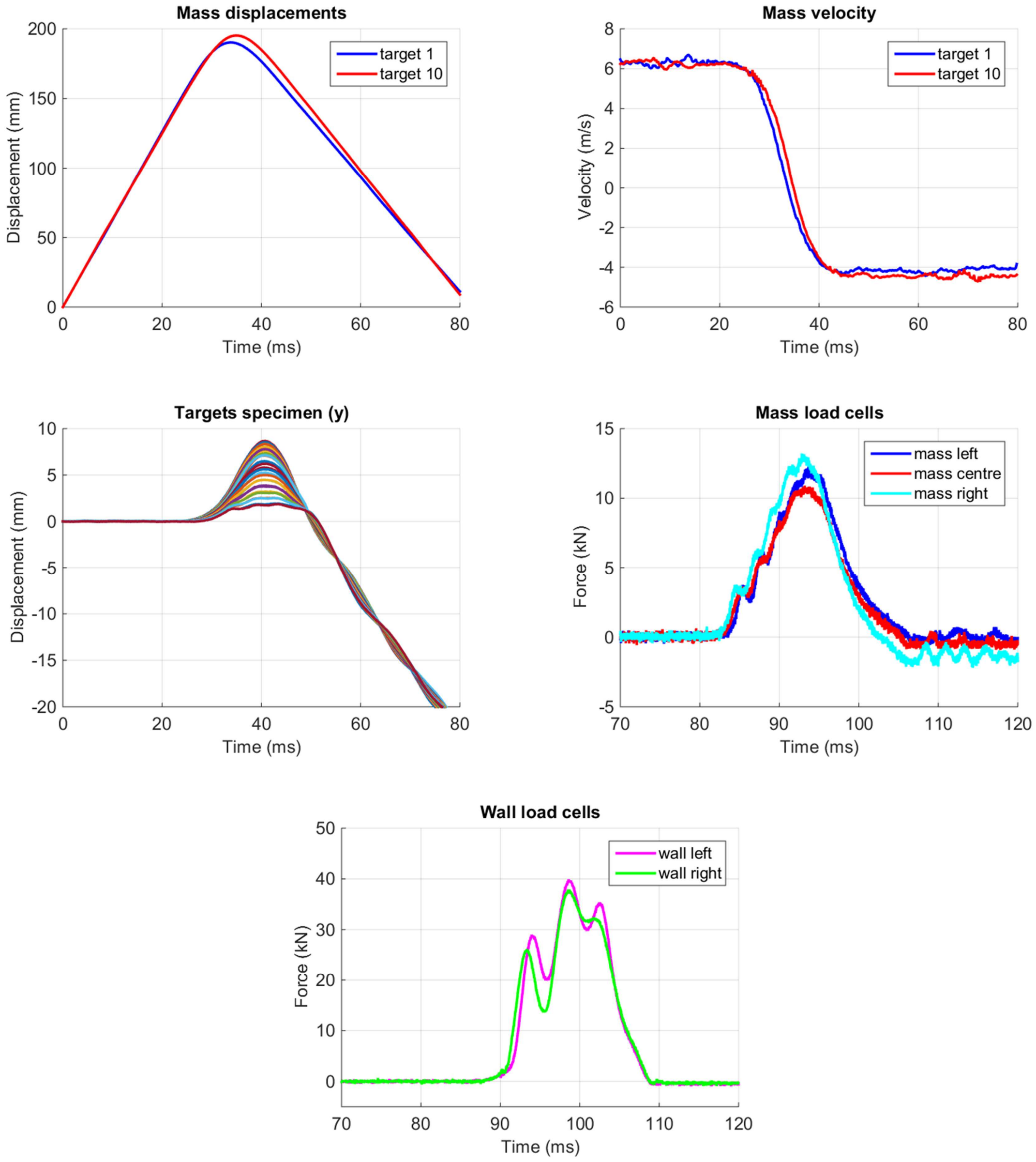

Figure 14. BLAST 15: experimental data elaborated

Blast 16

Blast 16 experiment has again been conducted on the first specimen, which, as explained above, must have been slightly damaged from the previous experiments. As before, the energy has been accumulated only in the springs and the fragile bolt used has a notched section of 9.5 mm diameter. An impact velocity of approximately 12 m/s has been reached. With the two-spring device in place, the mass has impacted against the column correctly, as its displacements and velocities diagrams confirm. However, the force applied by the central aluminium plate is smaller than the two lateral ones, most probably because the central zone of the beam has been weakened due to the previously induced cracking. Probably for the same reason, there is some asymmetry in the response and the left and right reactions are not acceptably “equal”. A global residual deformation is clearly visible. A permanent deflection of about 15 mm is observed in the centre of the specimen, indicating that damage must have also reached the steel reinforcement of the beam.

Figure 15. BLAST 15: High speed photo sequence

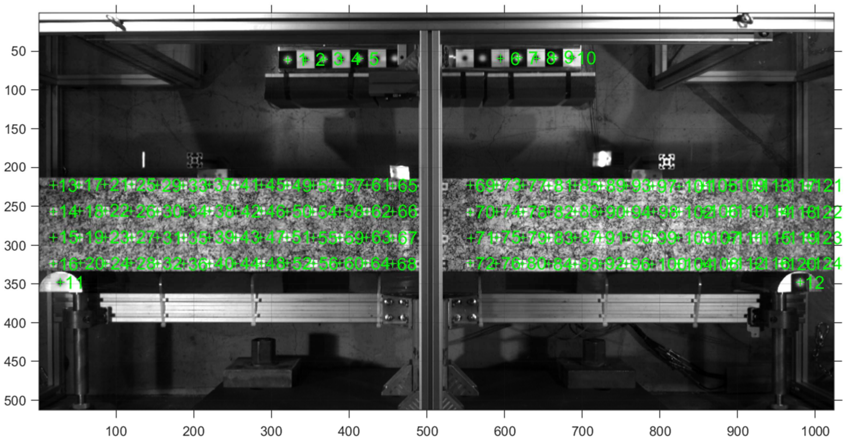

Figure 16. BLAST 16: Targets elaborated

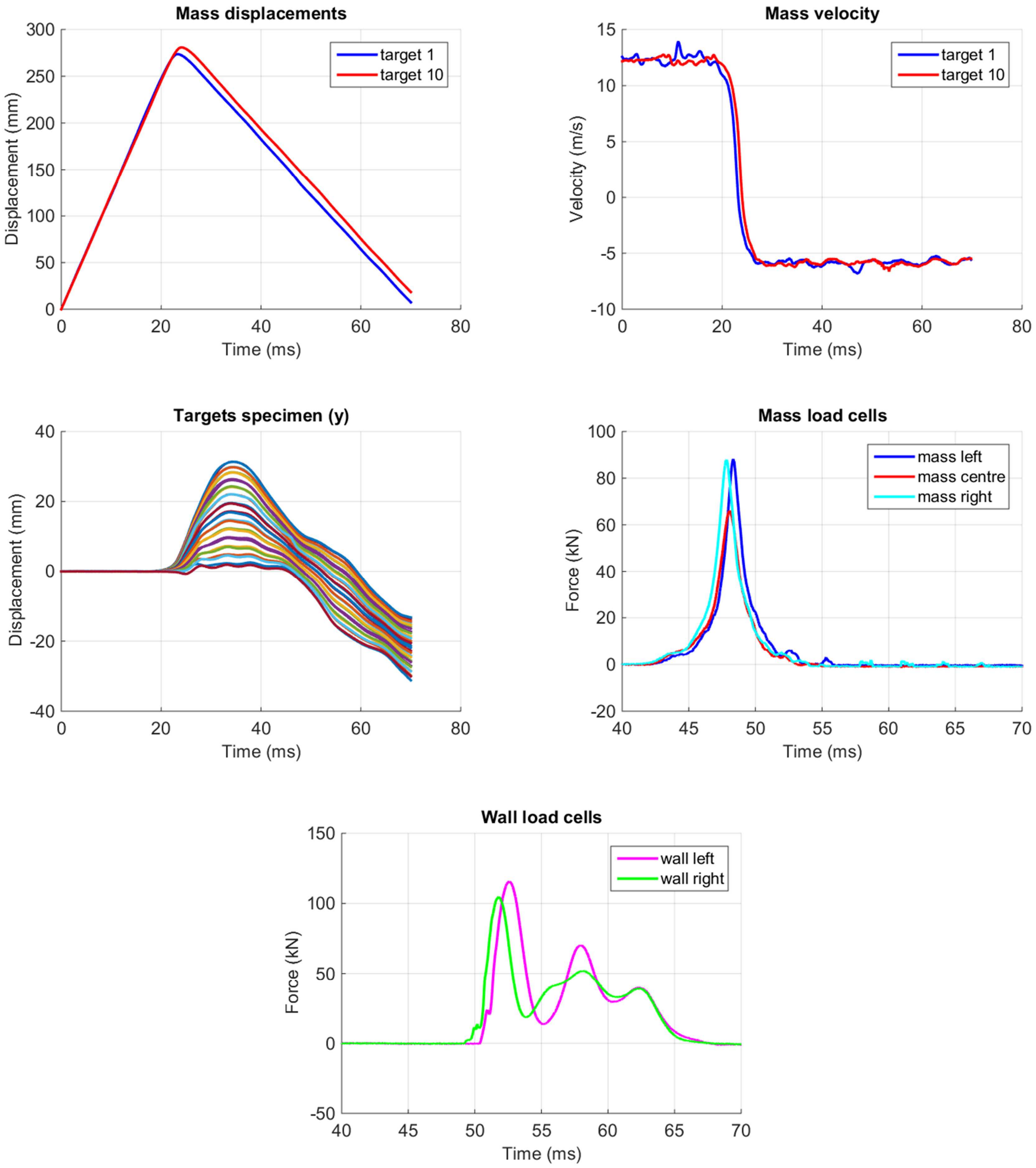

Figure 17. BLAST 17: experimental data elaborated

Blast 17

Blast 17 experiment has been conducted on the second undamaged specimen and can be considered as the first “scientific” test (in comparison with the previous start-up tests). The energy has been accumulated in the springs and also in the pressurized nitrogen (10 bar) and the fragile bolt used has a notched section of 9.5 mm diameter. An impact velocity of approximately 17 m/s has been reached. A residual deflection of more than 20 mm has been observed in the centre of the beam that implies damage also in the steel reinforcement. For this successful in many respects experiment, unfortunately all load cells of the impacting mass have gone beyond their linear measurement range (of 990 kN in total). For this reason the transmitted to the beam maximum force of 1240 kN, as recorded by the instruments, cannot be considered fully reliable. In addition, a problem has occurred in the transient recorder (due to an unexpected software bug), which has corrupted the sensors data. Fortunately the experimental data obtained with the high-speed camera and elaborated via optical and photogrammetric techniques are still useful for comparing test results with the ones produced via numerical codes.

Figure 18. BLAST 18: High speed photo sequence

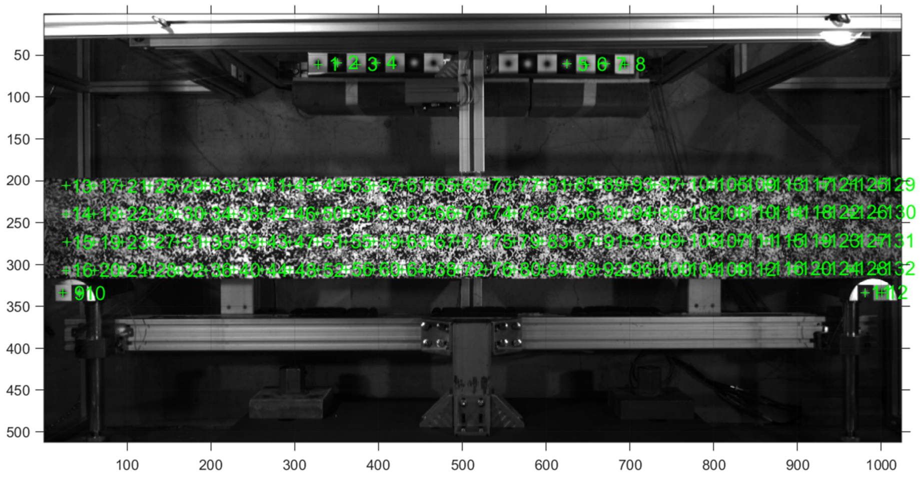

Figure 19. BLAST 17: Targets elaborated

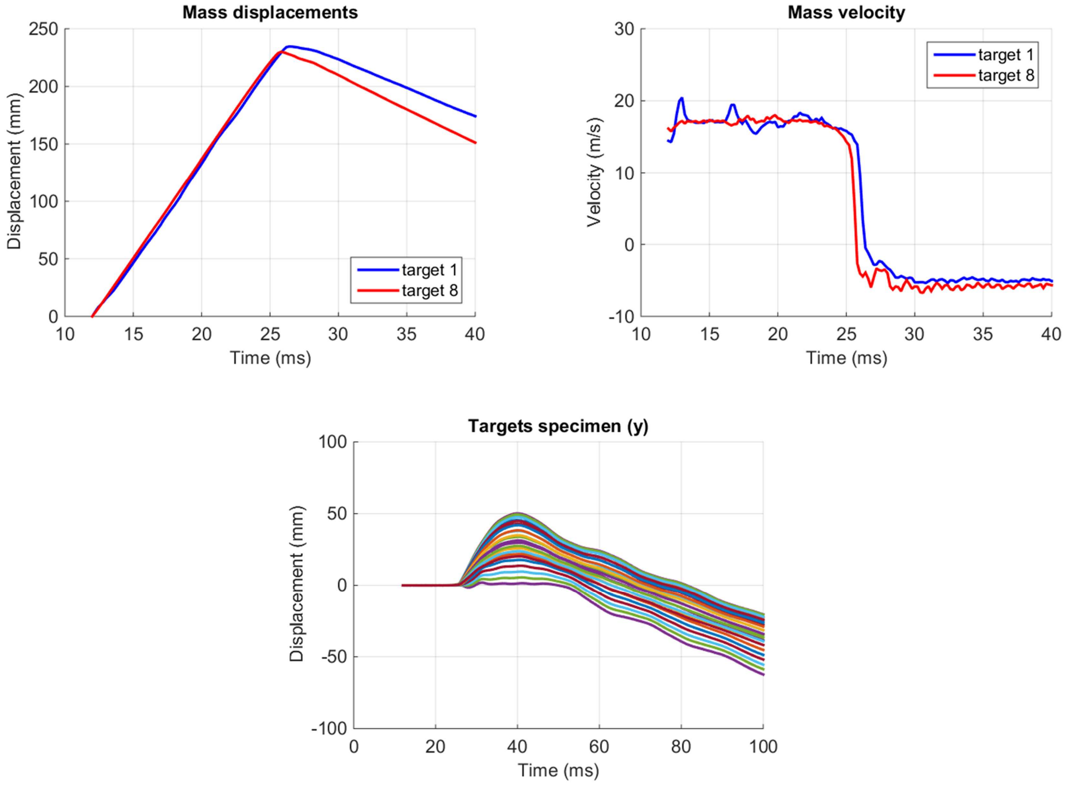

Figure 20. BLAST 17: experimental data elaborated

5. Further developments

The results obtained from these tests demonstrate that the developed blast actuator is capable of reproducing through impact the required pressure levels to bring a real structural member to failure. The test campaign on RC beams will continue in the first two months of 2015 with four additional tests. Two-three tests will be conducted at higher impact velocities, up to 20-25 m/s, to provoke and investigate a shear failure of the specimens. It is finally planned to test the last beam specimen after having first applied on it a layer of collapsible concrete, a low cost material that should reduce the effects of a blast pressure wave on structural elements.

To better perform these tests and avoid the load-cell saturation problem of "Blast 17", a new instrumented mass has been designed and will be available before the end of 2014. This modified impactor will be able to measure peak forces of up to 2 MN, loads that will probably be reached in the faster tests.

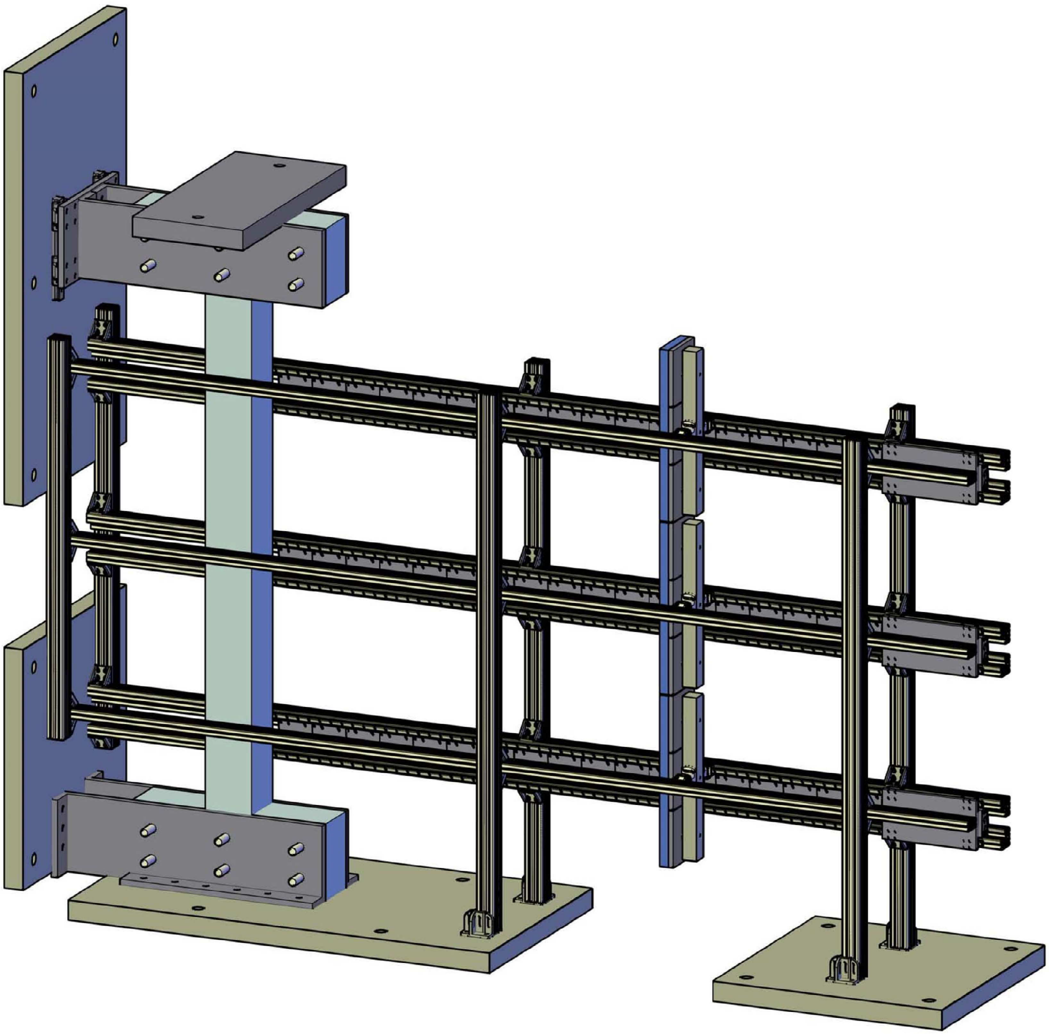

Figure 21. Blast simulator with electric linear motors

The activity with the current fast actuator will be concluded and terminated with these tests. However, all this work represents the basis of a forthcoming experimentation of another blast simulator facility that will be developed and tested in 2015 at the ELSA laboratory.

The new facility will adopt the same type of instrumented mass, developed for the pneumatic/hydraulic blast simulator, but it will be based on a different launcher technology. The impacting mass will be accelerated directly by an electric linear motor that will travel on the same rail of the impacting mass, as shown in the drawing proposed in Figure 21.

The design, which is in an execution stage, foresees three independent linear motors that accelerate three independent masses simultaneously. The facility could load a face of a full scale column of 3.5 m height with an applied peak force of up to 6 MN using an acceleration stroke 4 meter long.

The chosen technology and the developed design have two big advantages compared with the old solution: (a) a substantial reduction of the inactive accelerated masses (an electrical motor weighs 10 kg and the old blast actuator more than 1.5 tons!), and (b) the possibility of a relatively simple synchronization and control of two or more axes/impactors.

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