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e-BLAST simulator: final design, setup improvements and demonstration tests

Peroni Marco
Alessio Caverzan
Solomos George
Pegon Pierre

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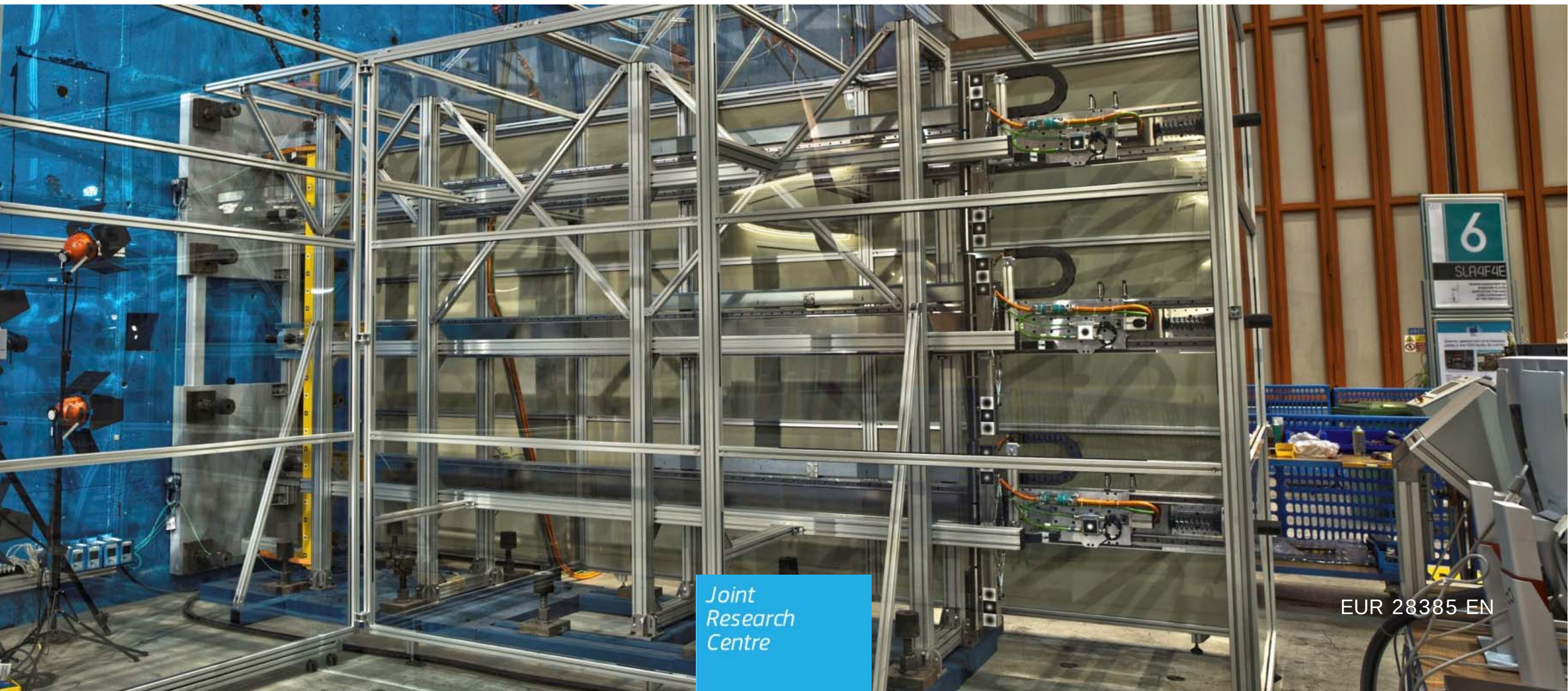

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Contact information
Name: Marco Peroni
Address: via E. Fermi, 2749, 21027 Ispra (VA), Italy
E-mail: marco.peroni@jrc.ec.europa.eu
Tel.: 0039 0332 78 9775

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Authors

Peroni Marco

Alessio Caverzan

Solomos George

Pegon Pierre

Abstract

The Electrical Blast Simulator (e-BLAST) activity involves the development of an apparatus capable of reproducing the effects of a blast pressure wave on large-size structural components (such as columns, walls, etc.) without the use of explosives but through the action of impacting masses. The work relates to the PROTECT project which deals with the protection and resilience of the built environment (critical buildings, transportation and energy infrastructure etc.) under catastrophic events such as blast and impacts.

The e-BLAST facility has been conceived and designed with the expertise acquired in the previous project "Blast Simulation Technology Development", supported through an Administrative Arrangement by DG HOME. Different from the prototype developed in that project, the e-BLAST exploits a recent technology that appears to be very promising in this particular research field. Specifically, three synchronous electrical linear motors have been adopted for accelerating the impacting masses. This choice has led to the development of a more efficient, versatile and low-cost facility.

The report presents in detail the final apparatus design, its components and their assembly, and a series of preliminary tests carried out in the ELSA laboratory in order to assess the performance of the enhanced e-BLAST. Finally, a brief description of further developments and feasible large-scale structural tests, planned to be performed with the new apparatus, are discussed.

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 (involving prevention, intelligence, detection, deterrence etc.) will certainly be taken, but if everything fails, it is very important that the mechanical structure itself mitigates some effects of the explosion and maintains certain functionalities.

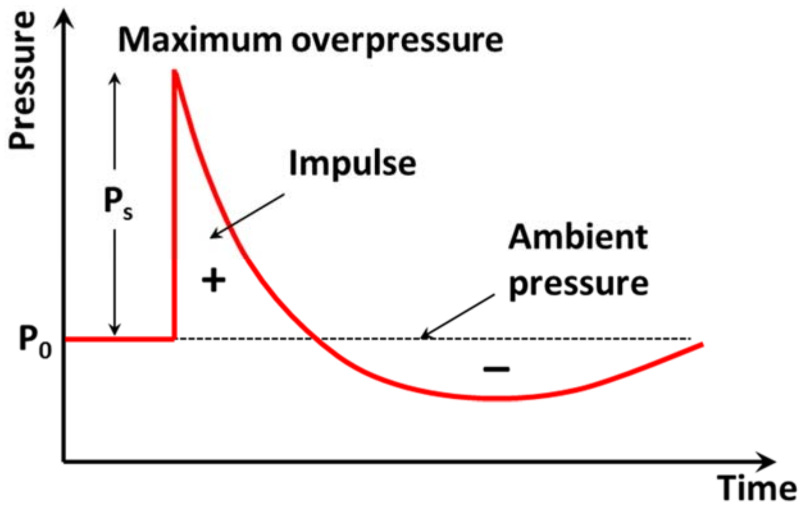


Figure 1 Blast wave pressure characteristics in free-air explosions

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 was built in 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 has been developed in 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 [1] and tested [2-3], which has proved capable of generating impact loads resembling closely those of the real explosions of Figure 1. This last feature has been also thoroughly investigated via advanced numerical simulations in order to ensure the possibility of reproducing blast loads using suitable impacting masses [4-5].
The fast actuator, as designed in [1], is a mixed pneumatic/mechanical equipment. Dubbed for short “g-BLAST”, it is based on a mechanical spring and pressurised nitrogen gas propulsion that can accelerate masses of about 50 kg to a maximum velocity of about 20 m/s. This has allowed the realistic testing of components to “simulated” explosions and has provided the necessary data for the verification and validation of

numerical simulation tools. This activity was conducted in the project “Blast Simulation Technology Development”, supported through the Administrative Arrangement No JRC 32253-2011 by DG HOME.

However, during the g-BLAST prototype testing a series of shortcomings has been experienced for which new technological solutions have been considered. The main drawbacks of the pneumatic/mechanical actuator include:

- Large “inactive” masses. The g-BLAST has a mass of 1.5 tons and the mechanical-damper support for one actuator reaches about 3 tons. It is obvious that these huge “inactive” masses, compared with the accelerated mass (of about 50 kg), create a problem, especially if several actuators must be simultaneously employed. In fact, the support must be stiff enough to resist the strong reaction force that the actuator generates during the operation.
- Synchronization problems. The only effective solution to synchronize more than one g-BLAST actuators to operate simultaneously is to adopt a mechanical fragile bolt, the fracture of which would be triggered by detonating a small explosive charge. This fact is in contrast with the main objective of avoiding any use of explosives during the experiments. In addition, also in the case of such a synchronized start of the different actuators (triggered by an explosive charge), there would be no certainty that the impacting masses would arrive to the tested specimen at the same instant.
- Test execution complexity. The operation of the g-BLAST involves different sub-actuators (the hydraulic jack for the pre-stressing of the mechanical spring and the booster for the pressurized nitrogen) that make the execution of a g-BLAST test quite complex and lengthy. In addition, the release of the shaft (with the attached impacting mass) starts when a critical stress is reached in the fragile bolt and this value varies, depending on the fragile material properties. For this reason, it is impossible to foresee with precision some test parameters, such as the starting time or the final impacting-mass velocity.

Different from the prototype developed in the previous project, the new e-BLAST facility exploits a recent technology that seems to be very promising in this particular research field. In principle, the fast actuator for the acceleration of the impacting mass has been replaced by a linear electric motor. Thus three synchronous electrical, linear motors have been adopted to design a more efficient, versatile and low-cost facility. The clear advantages of the new technology employed are discussed in the next Sections considering all aspects related to the design, assembly and operation of the facility. Particular attention has been paid to safety procedures and countermeasures due to the intrinsic dangerousness of this type of facility. Finally, a series of preliminary tests carried out in the ELSA laboratory in order to assess the performance of the new e-BLAST have been analysed and discussed and further improvements and testing capabilities are presented.

It is useful to remind that the development of this technology will be important for both 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.

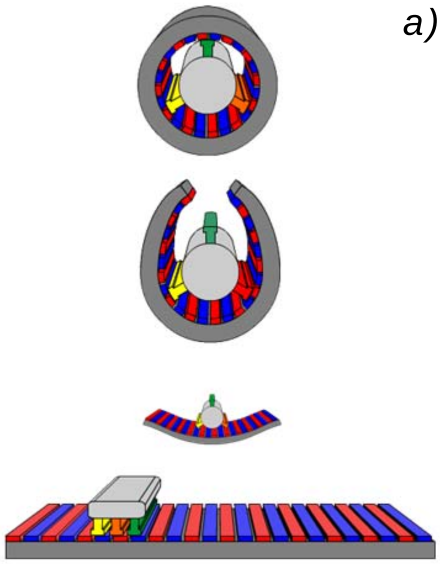
It is also appropriate to underline that the whole design of e-BLAST falls entirely within a new application field for the linear motor technology that exploits to a maximum the performance of the several components involved (the motors themselves, the guiding system and the feedback sensors), as is discussed below. For these reasons, in order to develop safely the apparatus a meticulous and systematic experimentation procedure has been implemented, essential for reaching satisfactory results.

2 Operation principle and final design

As stated before, the e-BLAST exploits a relatively new technology in the research and testing field, based on a particular class of electro-magnetic actuators: the electrical synchronous linear motors.

The linear motor has really come of age in the past decade through a dramatic increase in practical and beneficial industrial applications. The linear motor is often described simply as a rotary motor that has been rolled out flat (Figure 3), and the principles of operation are the same. The forcer (rotor) is made up of coils of wires encapsulated in epoxy, and the track is constructed by placing magnets (usually high power "rare earth" magnets) on steel (figure 2b).

a)



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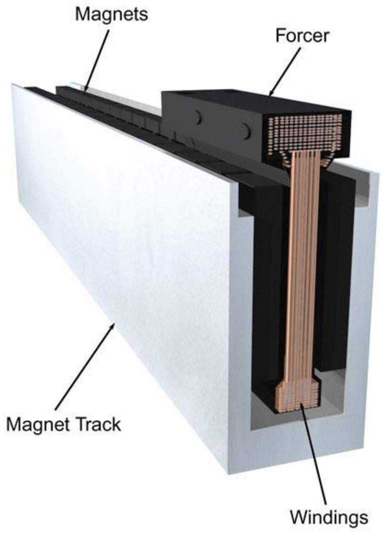


Figure 2 a) Sketch of synchronous electrical linear motor and b) typical industrial assembly

The forcer of the motor contains the windings, Hall-effect board, thermistor (to monitor temperature) and the electrical connections. In rotary motors, the rotor and stator require rotary bearings to support the rotor and maintain the air gap between the moving parts. In the same way, linear motors require linear guide rails to maintain the position of the forcer in the magnetic field of the magnet track. Just as rotary servomotors have encoders mounted to them to give positional feedback of the shaft, linear motors require positional feedback in the linear direction. By using a linear encoder, position is directly measured at the load for increased accuracy of the load position.

The control for linear motors is identical to rotary motors. Like a brushless rotary motor, the forcer and track have no mechanical connection (no brushes). Unlike rotary motors, where the rotor spins and the stator is held fixed, a linear motor system can have either the forcer or the magnet track move (most positioning system applications use a moving forcer and static track). With a moving forcer motor, the forcer weight is small compared with the load. However, a cable management system with high-flex cable is required. With a moving track arrangement, the motor must move the load plus the mass of the magnet track, but no cable management system is required.

Similar electromechanical principles apply whether the motor is rotary or linear. The same electromagnetic force that creates torque in a rotary motor creates a force in its linear counterpart. Hence, the linear motor uses the same controls and programmable positioning as a rotary motor.

In the next paragraphs each component of the e-BLAST facility will be presented as well as its design motivation. As a general remark, it can be stated that the whole facility philosophy is based on the concept of modular design. In this sense, the facility is composed of a series of single standard modules that must be arranged and assembled to reach an optimal solution. This is particularly important in dynamic tests where normally the testing facility must be adapted to the specimen to reach best results.

2.1 Axis module and impacting mass

The core component of the e-BLAST facility is the so called “axis module” that includes all sub-components essential to accelerate the impacting masses. This part is mainly composed of three elements: the linear motor, a low-friction railway system and a structural support frame.
An in-depth market search has been conducted in order to identify a commercial linear motor product having the most features comparable with the minimum requirements specified in the g-BLAST project. The linear motor finally selected for the e-BLAST design was the Siemens 1FN3 in the version explicitly developed for peak loads (Figure 3).

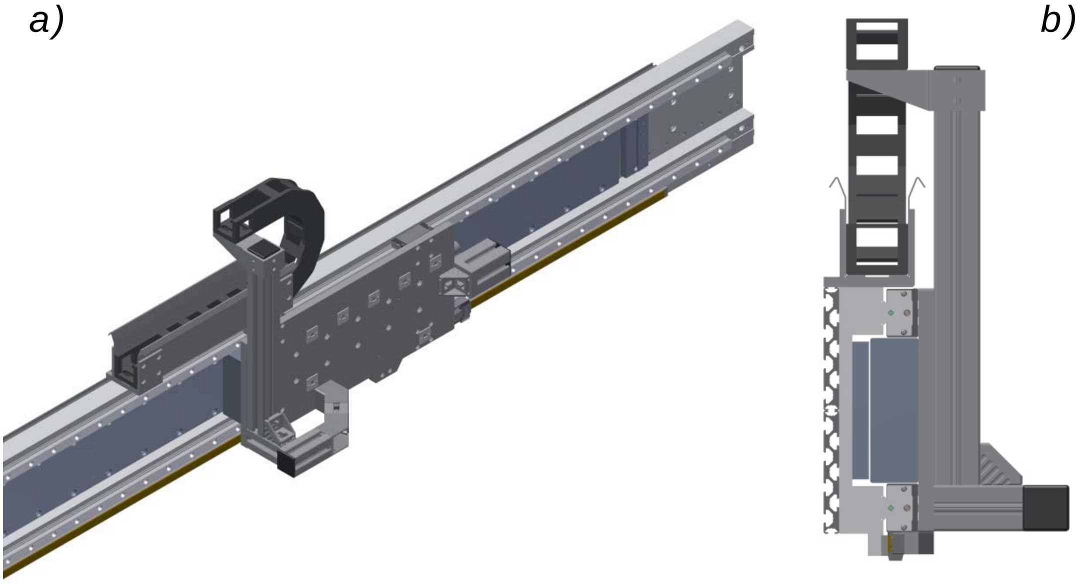


Figure 3 a) Final design of the e-BLAST axis module and b) cross-section detail

The linear motor is essentially composed of a primary section, that is the part connected to the power supply, and a secondary section composed of a series of passive high-intensity magnets. For the particular impulsive-load application, no additional cooling system has been adopted because the active cycle time is substantially lower than the inactivity time and overheating problems are improbable.

Figure 4a) Final design e-BLAST motor and chains, b) motor and impacting mass

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), which is fully compatible with the previous g-BLAST facility. 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”.
As reported in the motor datasheet, during its operation the attraction force between primary and secondary sections reach a value of 10.3 kN. This feature makes essential a suitable sliding system to ensure the maintenance of the operational gap between the two motor sections (that has a tolerance of some tenths of a mm) and limit friction forces due to this normal action. The solution adopted consists of a double linear bearing railway that ensures a high stiffness support (to keep constant the operational primary/secondary motor gap) with low friction due to the bearing technology. The linear bearings actually adopted are manufactured by INA and the data sheet is reported in annex B.
The structural support frame has been assembled using a series of aluminium structural elements: a) C-shape plates designed by ELSA and manufactured at the JRC, which have been properly assembled using b) “linear” elements manufactured by Bosch-Rexroth. The diagram of the section of the set “motor + railway + frame” is reported in Figure 3b. This new configuration guarantees a more rigid structure with respect to the initial tested set-up [3]. Figure 4 reports another view of the actual solution adopted. With respect to the previous set-up a thinner (15 mm instead of 30 mm) and lighter motor plate connects the four carriages, that slide on the two railways, and has been manufactured with high strength aluminium alloy to limit the weight (and consequently inertia phenomena) while maintaining a suitable stiffness. In order to protect the secondary magnets from metallic dust or unwanted contact between the two motor sections, a stainless steel sheet covers them (Figure 4a).
The axis module, as assembled with the proposed design, has an effective stroke of 4.20 m and very compact transverse dimensions of about 105 x 260 mm.

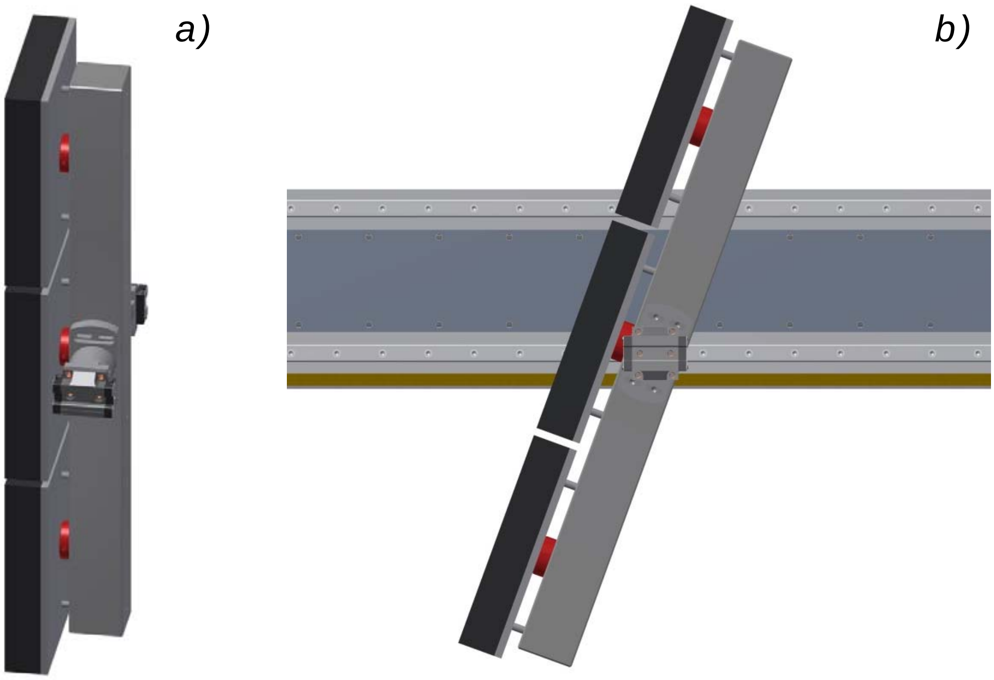


Figure 5 a) Impacting mass design and b) rotational degree of freedom of impacting mass

The impacting mass 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 and Figure 6. The block of one impacting mass is composed of three aluminium plates (290 x 100 x 10 mm) connected with three independent piezoelectric load cells to a heavy stainless steel prismatic mass (850 x 75 x 75 mm). 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 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.

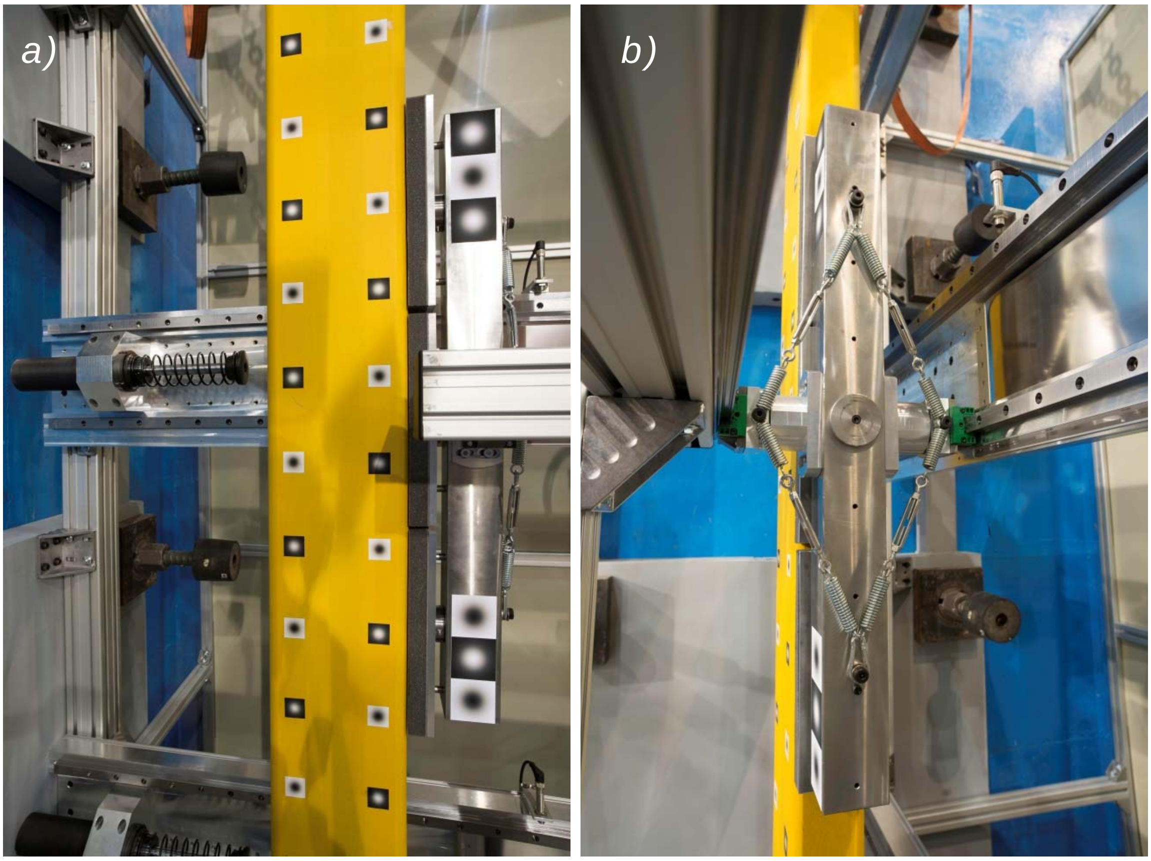


Figure 6 a) Impacting mass against the specimen and b) detail of stabilization springs

Four additional springs have been added (Figure 6b) 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 (i.e. 3 load cells of 330 kN each).
During the experiments the entire apparatus 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/column specimen in this test campaign. The proposed setup is fully compliant to the safety rules and procedures of JRC (see PDC “fast actuator experiments”).

2.2 Mechanical support frame

The mechanical support frame is characterised by a modular design and composed by a series of modular high-stiffness aluminium profiles, connected with suitable joints. The final design of the e-BLAST simulator, as per November 2016, is reported in Figure 7.

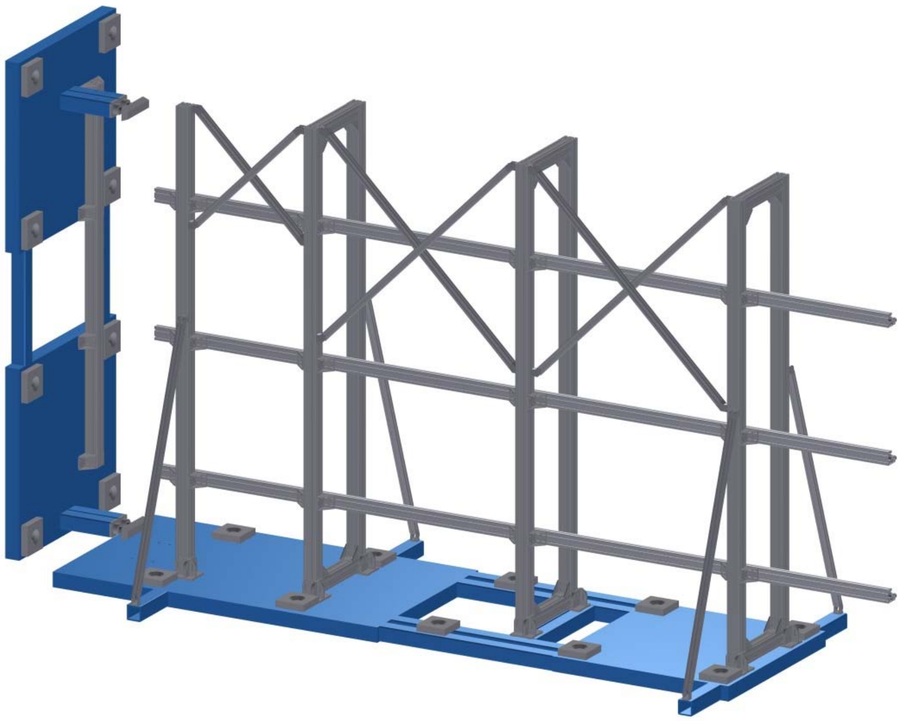


Figure 7 Mixed aluminium - steel frame of eBLAST simulator

The frame is characterized by a total height of about 3 m and a transverse dimension of less than 1 m. The axis modules can be easily translated vertically by simply changing the position of a series of joints. In practice, the specimen that can be tested in this configuration has a maximum height of 3.0 m and a width of 0.25 m. Obviously, the support frame can be changed to house specimens with different geometry by varying the number of axis modules and their position in order to accelerate different masses. In the current configuration, the support frame is placed on a rigid steel base connected to the ELSA strong-floor.

2.3 eBLAST instrumentation and control

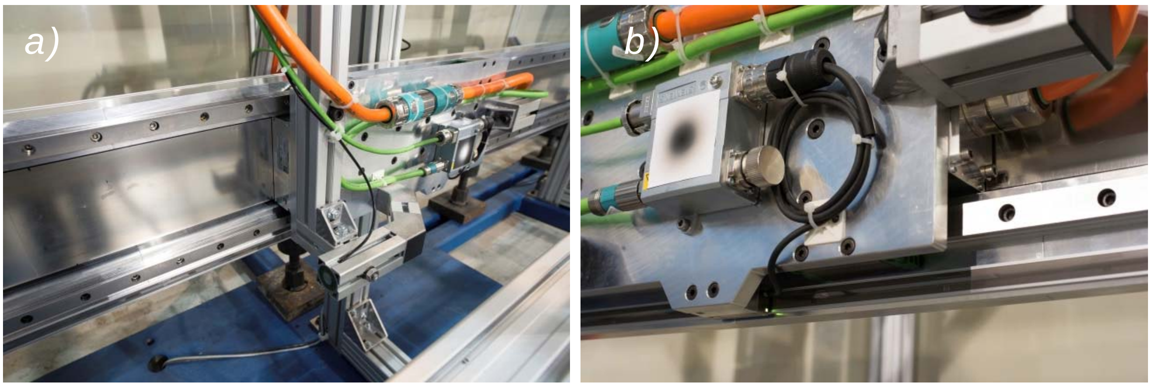


Figure 8 a) Detail of motor magnet and b) feedback linear encoder

A linear motor requires an accurate displacement sensor in order to operate with a closed-loop feedback strategy. The displacement sensor adopted in these firsts tests is the incremental linear encoder LIDA 287 (1 Vpp sinusoidal signal) with a precision of 2 micron and a length of 5 m, shown in Figure 8a. In detail, the scanning head is rigidly connected to the motor plate using a calibrated spacer to ensure the correct working gap between the scanning head and the optical scale tape. In particular the narrow tolerance of the gap (0.45 mm) has been verified with a dial gauge along the whole motor stroke. Finally, the steel scale tape has been mounted on the C-shaped aluminium plates using a series of aluminium extrusions to facilitate the assembly.
Two horizontally reacting steel supports with trapezoidal section are connected through a steel bar and plate to the Reaction Wall (Figure 9). In between the steel support and bars two piezo-electric load cells are placed in order to record the impact force transmitted to each support.

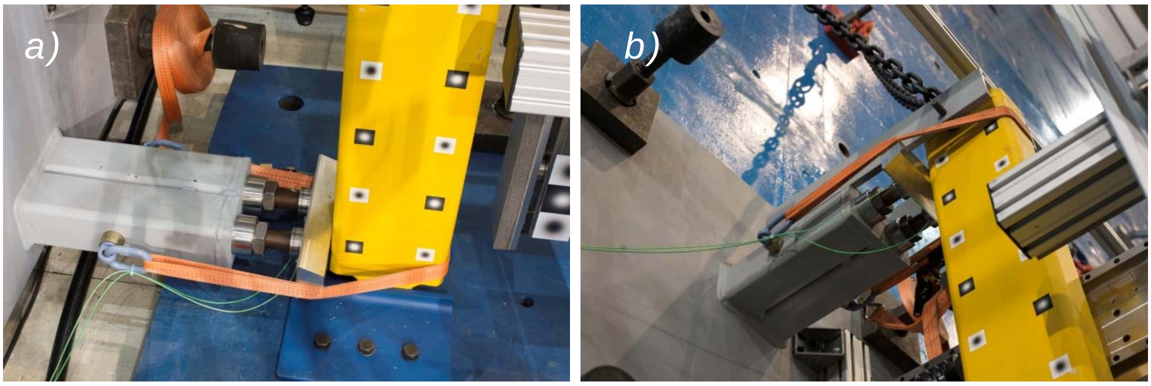


Figure 9 a) Lower and b) upper simple support configurations and constraints with demonstration steel column (yellow) specimen

An important piece of equipment adopted during the test campaign is a high-speed camera, an IDT Y4, that allows the recording of high-speed photo sequences during the tests. The camera greatly aids the comprehension of dynamic phenomena not easily visible at the naked human eye, as for example the motion of the cable chain. In addition, applying a series of computational algorithms to the high-speed photo sequence, quantitative data concerning the motion of a series of targets can be extracted. This technique facilitates the study of the frame oscillations without placing any accelerometers at different points of the frame. The only “drawback” is the requirement related to the fact that a suitable illumination (Figure 10a) must be provided in order to acquire “frozen” frames and avoid blurred images.
The detailed list of instrumentation adopted and deployed for 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).

- 4 Charge Amplifiers Kistler 5015 for the conditioning of piezoelectric sensors.

- 4 Piezoelectric load cells Kistler 9106A (full scale330 kN) placed at the reaction 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.

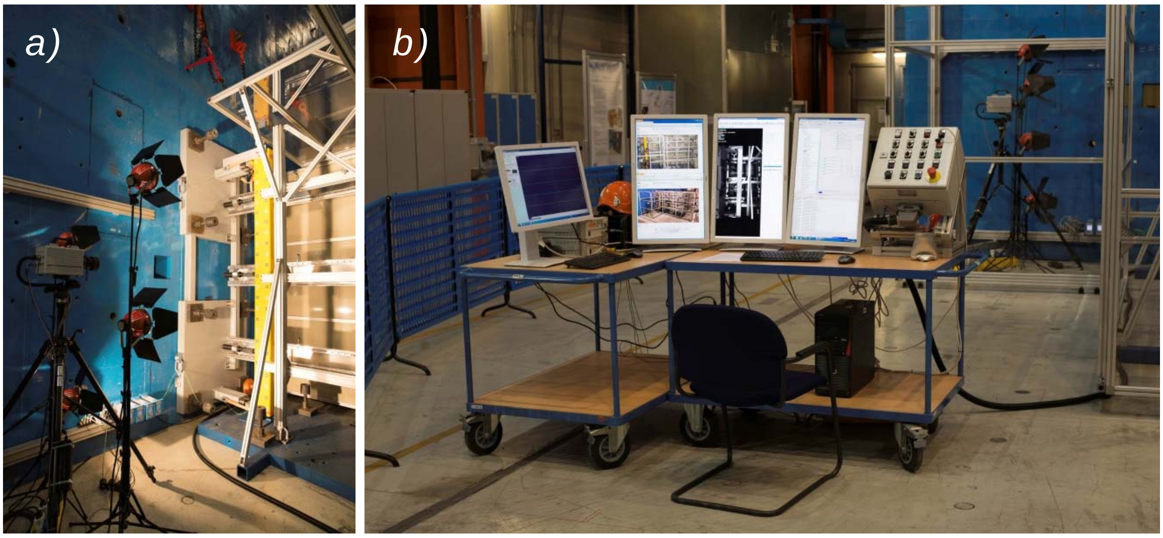


Figure 10 a) Optical instrumentation and b) control - acquisition console

The e-BLAST is essentially a high-performance electrical motor and, for this reason, it is provided by a high power supply and control unit (figure 10b). The main electrical devices necessary for the operation of the three independent linear motors are housed in a single electrical cabinet. The power supply unit (120 kW three-phase current) is common for the three motors and is directly connected to the global control unit of the system. The global control unit in then connected to the three single axis drives that supply and control each axis module. All motor power supply and control cables are directly connected to the cabinet, as is the centralized power cable. For all these very specific requirements, the cabinet has been manufactured and certified by an external supplier. To communicate with the control unit inside the power cabinet an operator command console (figure 9b) has been designed and assembled. This simple console allows a series of motor operations to be done and commands the execution of the working cycles stored in the internal CPU. The operator console provides also the connection between the control unit and an external PC in order to set motor parameters as well the working cycle parameters. All these features are managed with the Starter software provided by Siemens.

2.4 Safety devices and procedures

The blast actuator is in practice a device that accelerates a mass at a maximum velocity of approximately 15 m/s. This velocity is lower than the one reached with the old g-BLAST actuator. Although the first tests have been conducted without any impacting mass, the equipment moves quite fast under the action of an electromagnetic force of a maximum value of 5000 N. In contrast with the old blast simulator device, where only one measure was adopted to ensure safety conditions, in the new e-BLAST device three more different measures were implemented and adopted.

- **Measure 1.a) Covering safety frame.** As anticipated above, in order to avoid the presence of persons in the proximity of the equipment during the test a safety frame is placed all around the testing rig to totally prevent the access during the operation. The safety frame/box has an approximate size of 2m x 3m x 6m and is made of aluminum profile Bosch-Rexroth with Plexiglas panels 6 mm thick. The use of Bosh-Rexroth profile is justified by the need of flexibility in order to rapidly handle any changes in instrumentation and/or redesigns. In addition the Plexiglas panels guarantee the possibility of taking high speed-photo sequences of the experiments and have good capability of energy absorption for what concerns flying debris or direct impact. Finally, a switch has been mounted on the frame safety door in order to disable the electric motors system when the door is open.

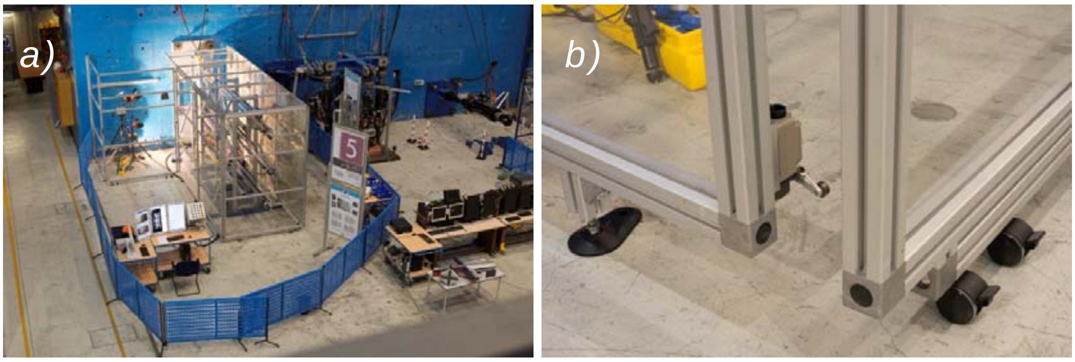


Figure 11 a) Aluminium - Plexiglas safety box and b) safety door switch

- **Measure 1.b) Software limits**. It is possible to set software displacement limits by means of the Starter software. Obviously, these limits work only with the control cabinet powered-on and they are not effective in case of accidental electrical interruption.

Figure 12 Operator command console with PC interface for the motor programming.

- **Measure 1.c) Electrical limits**. Even if the software limits were not properly set, the motion of each axis module would stop in a set of pre-designed positions. This is achieved thanks to a series of electrical limit switches placed on both ends of the electrical stroke of the motor (figure 13a). An additional switch is adopted to give to the single axis its “home” position. Obviously, also this safety countermeasure is not effective during an electrical blackout.
- **Measure 1.d) Mechanical dampers**. Should both previous countermeasures fail, a third measure has been implemented for stopping the motors. This result can be reached with a series of mechanical dampers that can absorb all the kinetic energy of the motors. Figure 13b shows the solution adopted with the hydraulic dampers (Model ACE MA64150EUM - Energy capacity 248,000 Nm/h) placed on the axis extremity of each module.

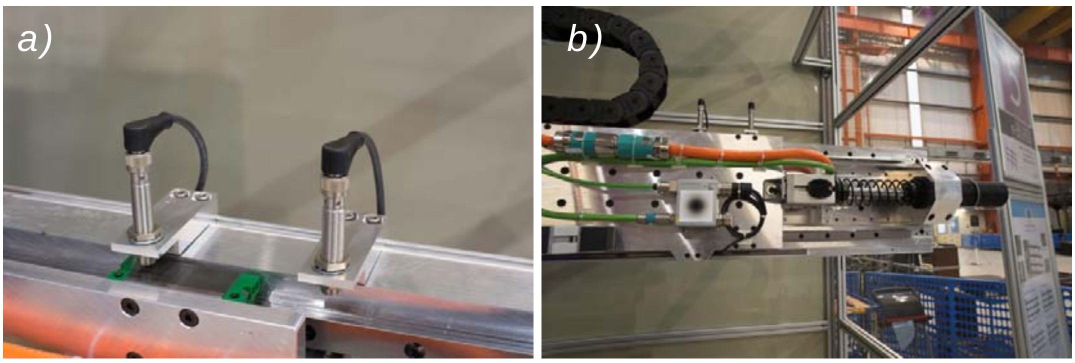


Figure 13 a) Electrical limit switches and b) hydraulic damper axis extremity

The intrinsic dangerousness of the e-BLAST simulator, due to the relatively high electrical power involved in the standard operation, requires additional precautions and procedures to be taken in order to avoid injuries or incidents.

- **Measure 2.a) Certified cabinet and unit**. For what concerns the electrical risk, all electrical devices in the power cabinet have been assembled and certified by a qualified operator, as was also done for the connection of the cabinet to the ELSA power plant.

Figure 14 a) Certified cabinet and b) unit

- **Measure 2.b) Mechanical system**. An ad-hoc mechanical system has been installed and certified in order to ensure a physical disconnection of the electrical power system when the cabinet is open and consequently the electrical linear motors do not work.

Figure 15 Systems installed in the cabinet for physical electric disconnection

- **Measure 2.c) Cable chains** guide and sustain the cables (the power supply and the command cable) during the motor working cycle. The cable chains allow the cables to be carefully unrolled and they avoid incidents due to inertia of the not negligible cable masses. In addition, the chain is guided with a metallic guide profile and has a width lower than the support frame (to reduce the risk of accidental collisions). This avoids that, due to chain misalignments, the chain impacts against the frame which sustains the axis modules.

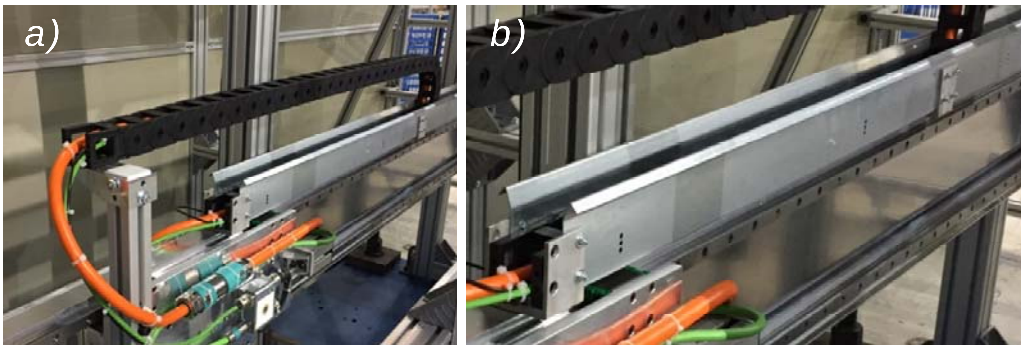


Figure 16 a) Cable chain and b) metallic guide

The system does not require breaking a fragile bolt, which was considered one of the main sources of noise in the old g-BLAST actuator, but the fast movement of the mechanical parts can generate a certain level of noise. This is not easily predictable because it depends on test parameters which can be changed during the explorative test campaign (for example velocity and acceleration of the electrical linear motors).

- **Measure 3.a) Safety frame / box (external envelope)**. The safety frame guarantees also a good acoustic insulation.

Figure 17 Different views of the safety box

- **Measure 3.b) Isolation headphones**. Restricted access to the test zone and use of personal safety devices, such as isolation headphones.

In the assessment campaign no flying debris have been generated during the test because no structural components had been tested. For the second phase with the actual testing, in case of an unpredictable and uncontrolled failure of the specimen, few debris would be generated, and they would be directed towards the Reaction Wall, where they would be stopped.

- **Measure 4.a) Safety frame / box (external envelope)**. In any case, the whole apparatus is placed inside the protecting box. The use of 6 mm thick Plexiglass panels protects against any danger due to flying debris which might be generated during a test. The technique has successfully been adopted and demonstrated for the old g-BLAST actuator during the previous experimental campaign.

2.5 Improvements in the final eBLAST design

To conclude this section it is worth underlining some of the main improvements of the final e-BLAST design compared with the previous set-up.

- A longer electric axis. The electric axis module, as assembled according to the proposed design, has an effective stroke of 4.20 m and this is substantially longer than the previous configuration.
- A stiffer assemblage. The structural support frame has been assembled using a series of aluminium structural elements: a) C-shaped plates designed by ELSA and manufactured at the JRC which have been properly assembled thanks to b) "linear" elements manufactured by Bosch-Rexroth. These choices have resulted in a stiffer modular electric axis than the initial design. Considering the mechanical support frame, the new set-up is characterised by an improved modular design and composed by a series of modular high-stiffness aluminium profiles, connected with suitable joints. The particular geometry adopted has produced a more rigid configuration.
- A compact electric axis. The adoption of a new design for the electric axis, in particular the C-shaped aluminium plates and the re-designed thinner alluminium motor plates, has led to a more compact configuration with respect to the initial one.
- A reduced friction. Thanks to the new design of the axis and the adoption of an improved carriage system it was possible to reduce significantly the friction in the three axes, as is highlighted in Figure 18 and in Table 1.

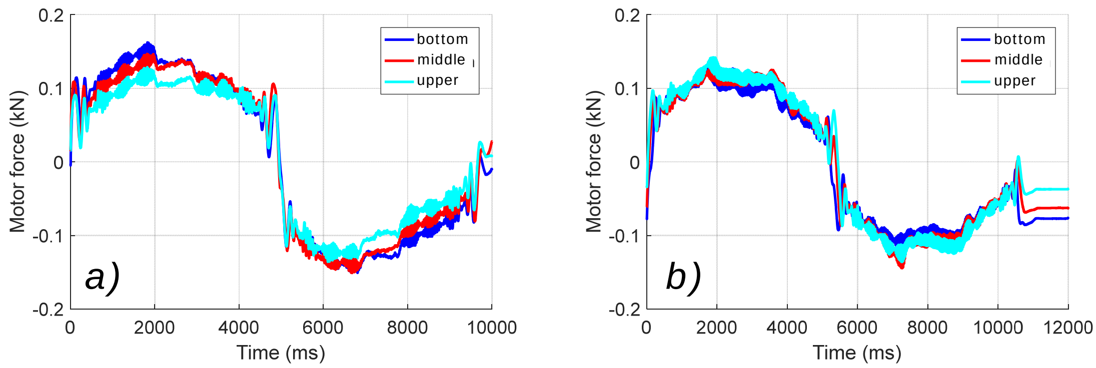


Figure 18 Motor friction at 1 m/s in a) 2015 and b) 2016 eBLAST design

	Average Friction Force (kN)		
Axis module	Axis 1 (bottom)	Axis 2 (middle)	Axis 3 (upper)
Old configuration	0.1	0.1	0.086
New configuration	0.083	0.085	0.084

Table 1 Motor friction values at 1 m/s

3 Demonstration tests

The operating principle of the testing rig is quite simple, as explained below:

1. **Positioning of masses**. At the beginning of the test the impacting masses are in contact with aluminium arms rigidly connected to the electrical linear motors. It is important to underline that the positioning procedure of the masses is remotely done without any physical interaction with laboratory staff and technicians. The motors are placed in the “home” position at the right ends of the supporting rail ways;

2. **Programme starting**. From the operator command console the engineer in-charge, who has a complete and clear view of the e-BLAST apparatus, starts remotely the programmed test;

3. **Acceleration of masses**. The electrical linear motors rapidly accelerate and pushing with their aluminium arms the impacting masses they make them attain the desired test velocity;

4. **Deceleration of masses**. When the electrical linear motors have done most of their preset stroke, they start to decelerate and the impacting masses detach from the motors;

5. **Impact of the masses**. After this detachment, the masses continue to move in the rails and collide with the tested structure reproducing local pressures similar to those of a blast wave; the masses bounce back from the specimen in the rails.

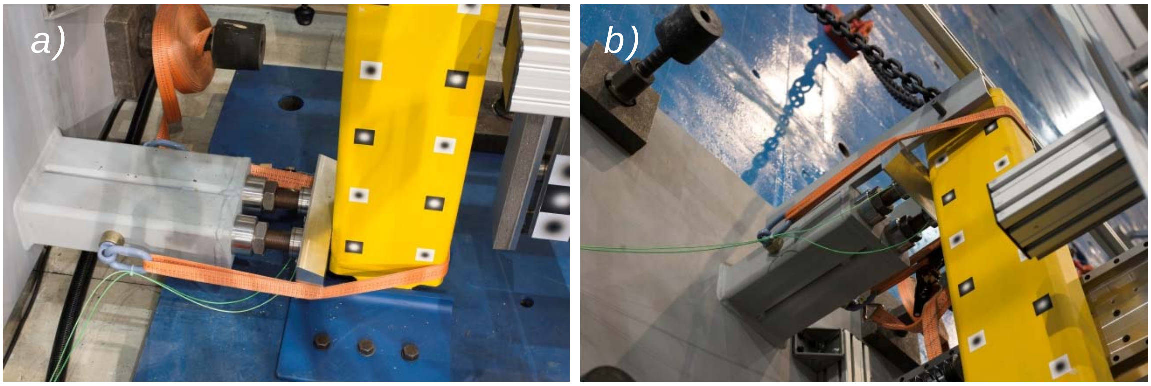
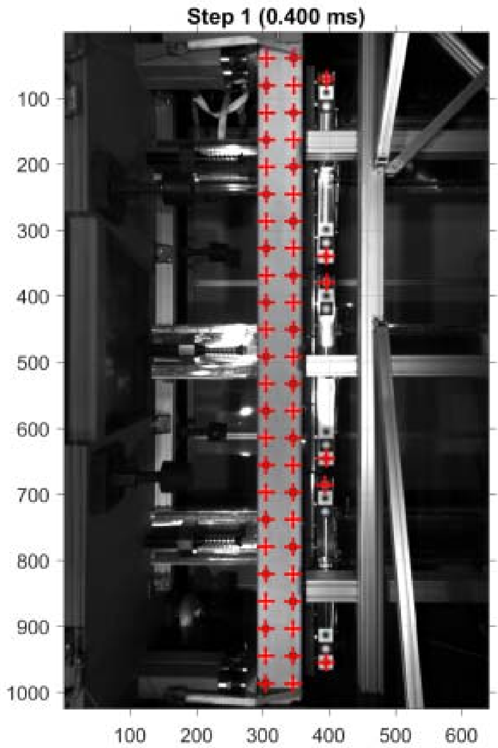


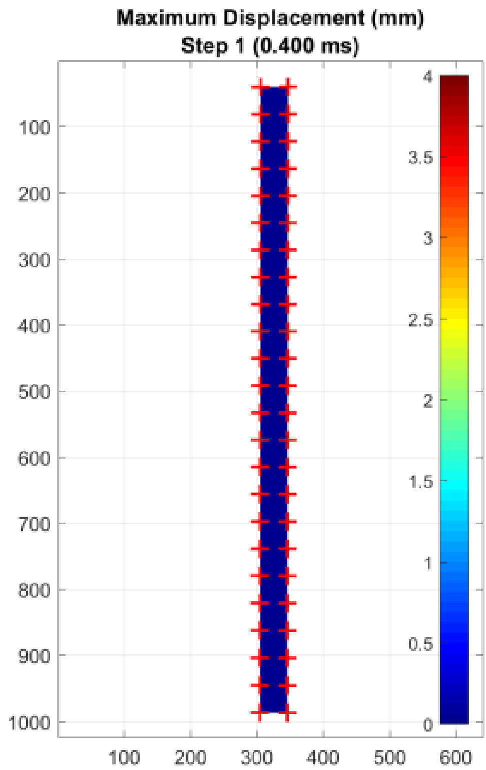
Figure 19 a) lower and b) upper constrains of demonstration steel column

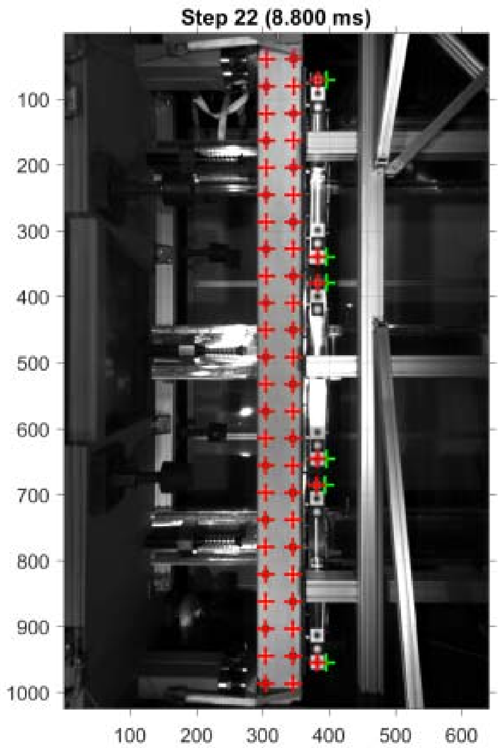
In the next paragraphs the results obtained during a series of test performed with the aim to calibrate the e-BLAST device are reported.

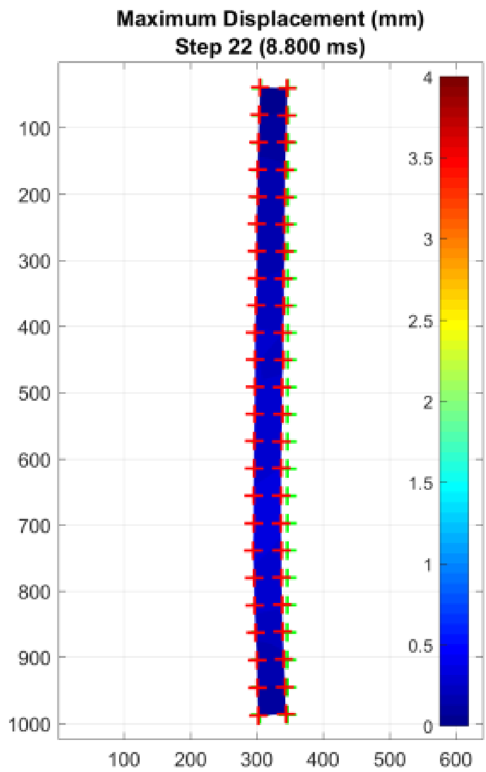
3.1 Test on rigid steel column at 5m/s

A first test has been performed with a reduced motor velocity (5m/s) on a stiff steel column in order to evaluate the performance of the whole equipment. The specimen has a fully elastic response. In Figure 20 some high speed photos at distinct instants of the test have been compared with the results obtained by employing a Digital Image Correlation (DIC) technique in real time. The DIC algorithms, applied to the discrete black and white marker squares of the specimen and the impacting masses, have been used to calculate local information such as displacement and velocity.


Step 1 (0.400 ms)


Maximum Displacement (mm)
Step 1 (0.400 ms)


Step 22 (8.800 ms)


Maximum Displacement (mm)
Step 22 (8.800 ms)

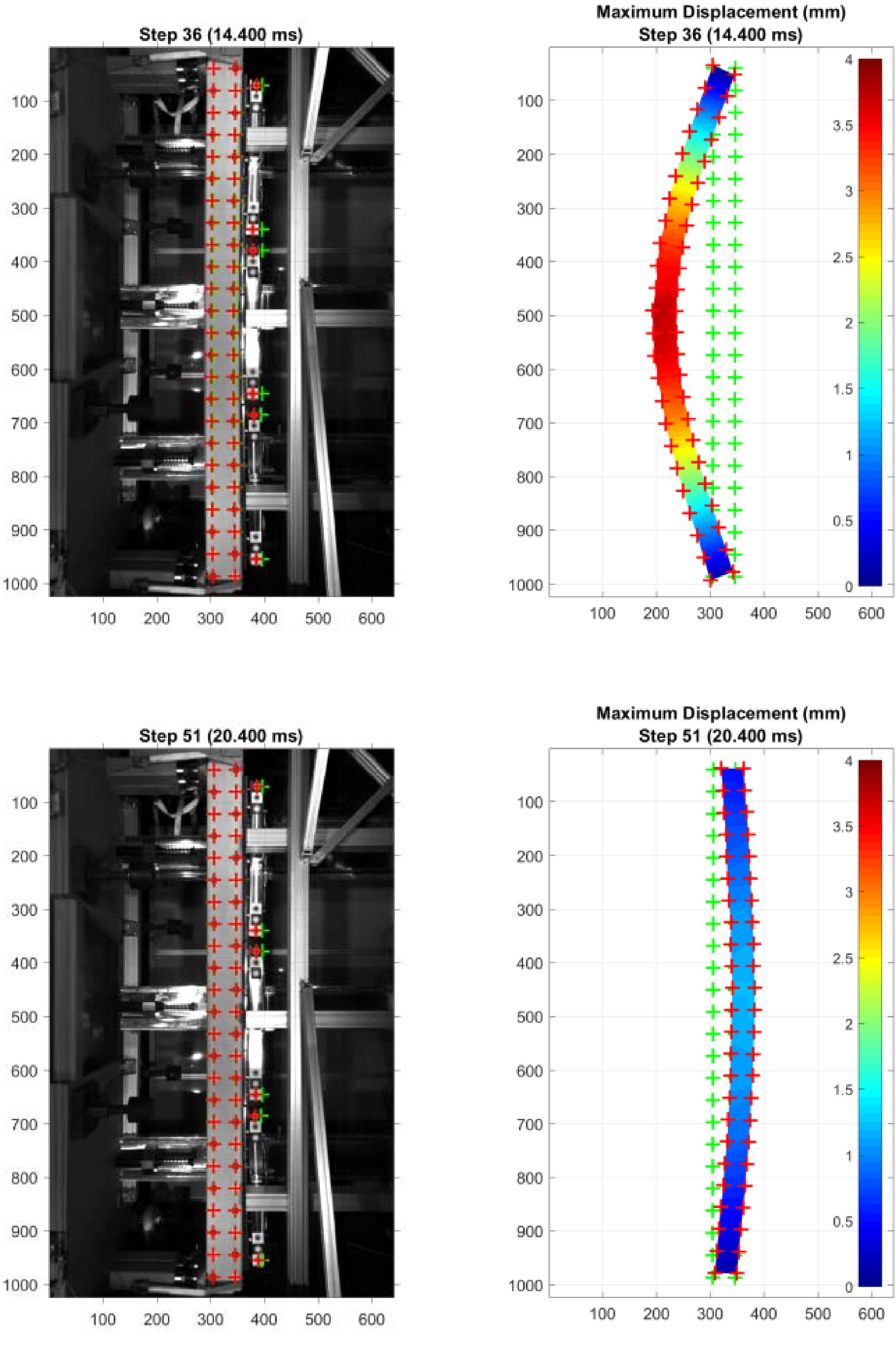


Figure 20 Example of displacement evolution during a dynamic test (numbers indicate pixels)

In Figure 21 the results in terms of displacements and velocities of the impact masses are reported.

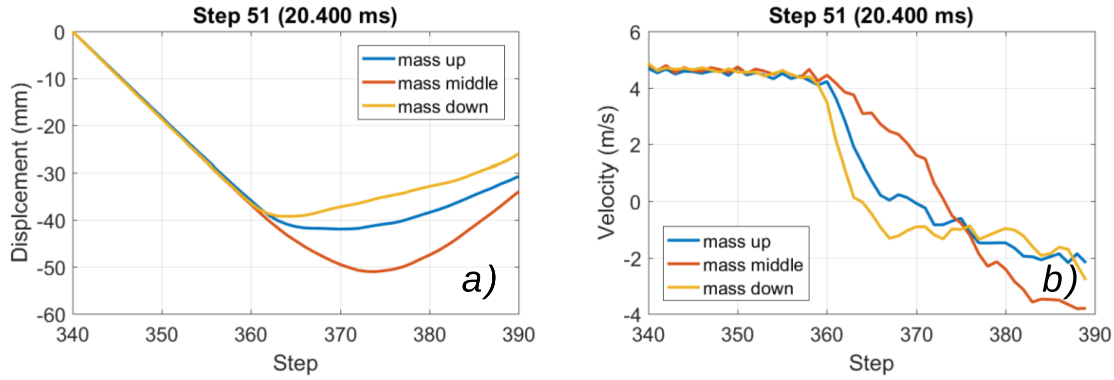


Figure 21 Digital Image Correlation results: a) displacement and b) velocity of the impact masses

During this phase of calibration tests, performed at 5m/s, a significant elastic rebound of the column specimen, resulting in its secondary impact with the central mass, has been observed. The rebound is mainly linked to the particularly stiff configuration of the column selected. In order to check the performance of the e-Blast system for larger mass velocities, a modified column has been prepared. Nine mechanical dampers (Model ACE MA64150EUM - Energy capacity 248,000 Nm/h) have been mounted along the axis of the column. In the next Subsection the results obtained in three different tests (named A, B and C) have been reported. Thanks to this new specimen configuration rebound effects have been practically eliminated, and mass velocities equal to 10m/s have been reached.

3.2 Tests on modified steel column at 10m/s

The results in terms of reaction forces obtained during the first test performed at 10m/s are reported in Figure 22. It is also noted that during this series of tests, the masses have been moved in a synchronous manner.

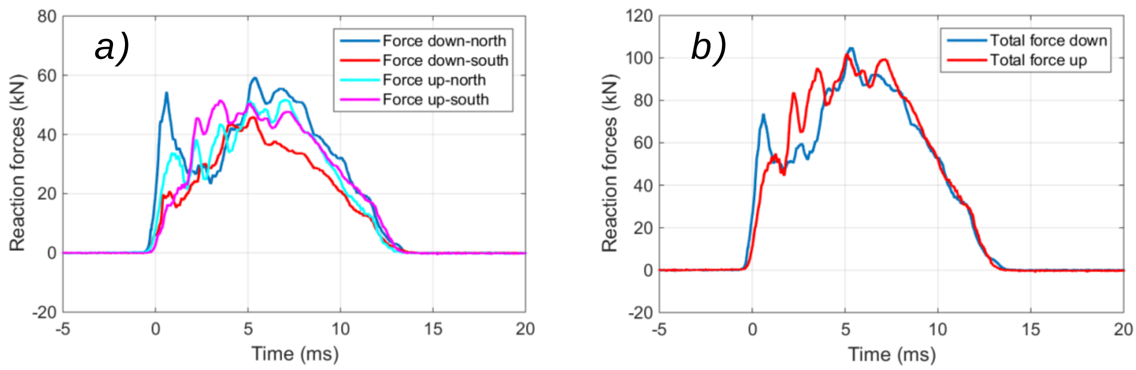
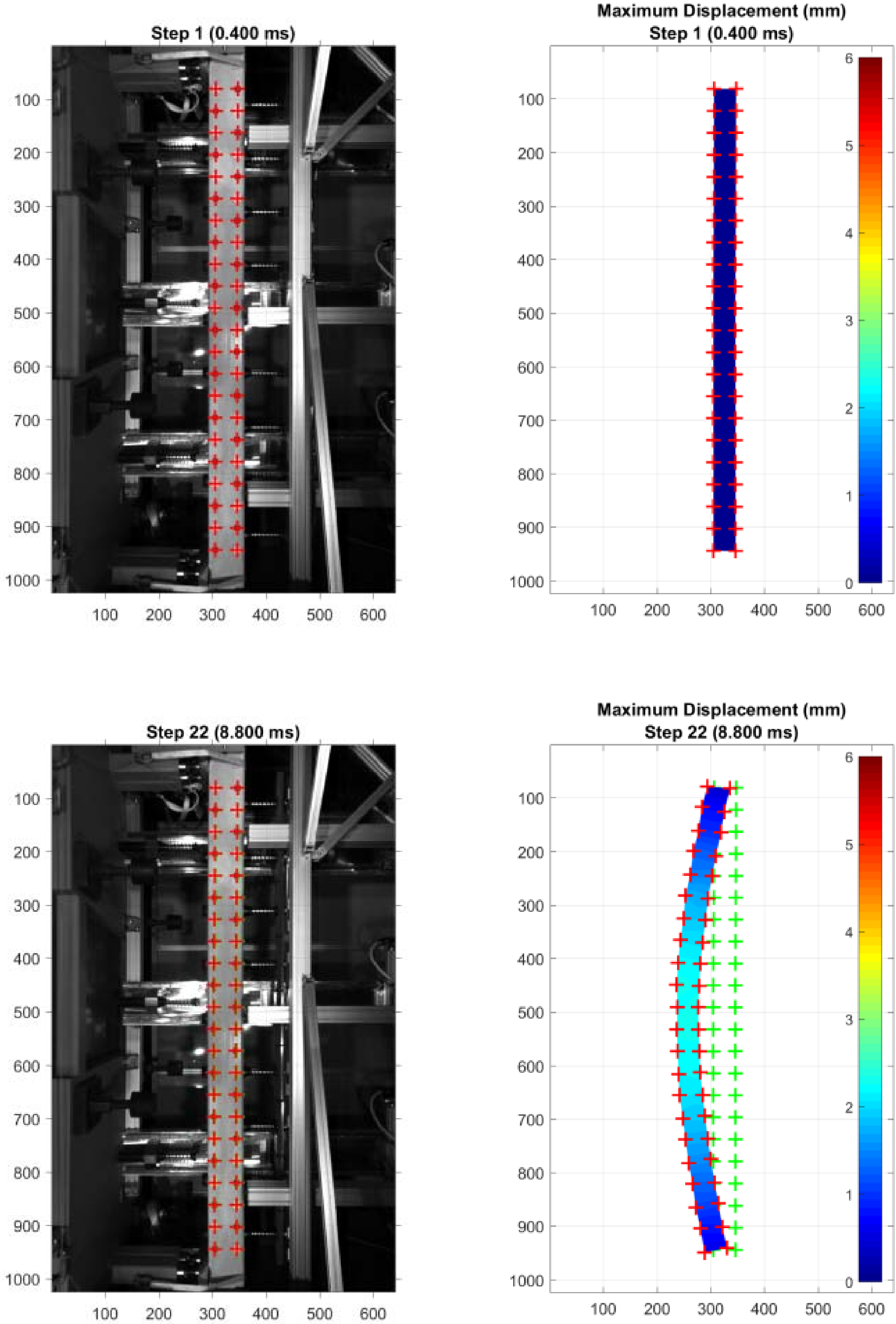


Figure 22 Reaction forces recorded during test A: a) single load cells and b) total forces

In Figures 23, 24 and 25 some high speed photo sequence of the tests A, B and C respectively have been compared with the results obtained by applying a Digital Image Correlation (DIC) technique in real time.


Step 1 (0.400 ms)
Maximum Displacement (mm)
Step 1 (0.400 ms)
Step 22 (8.800 ms)
Maximum Displacement (mm)
Step 22 (8.800 ms)
100 200 300 400 500 600 700 800 900 1000
100 200 300 400 500 600
0 1 2 3 4 5 6

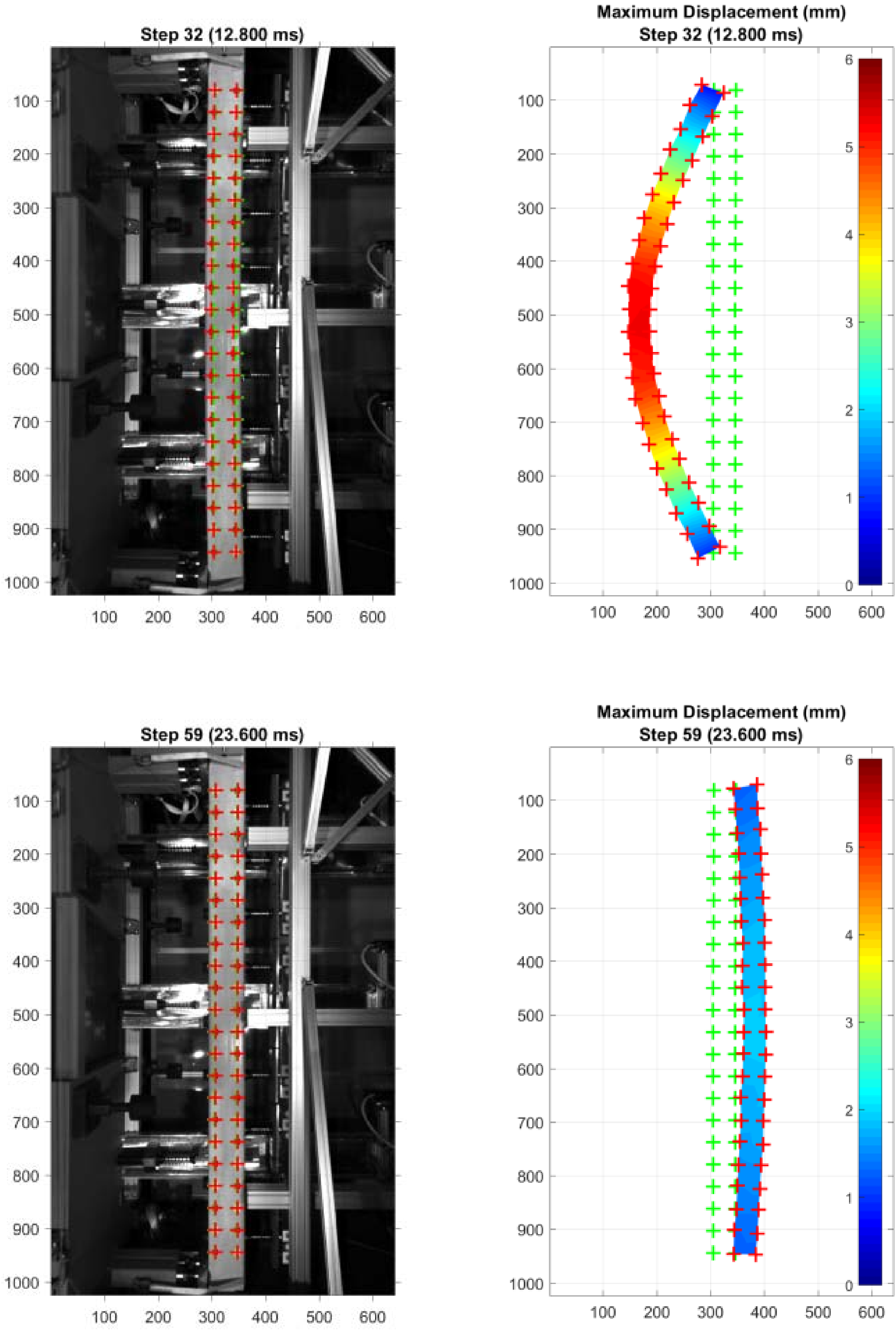
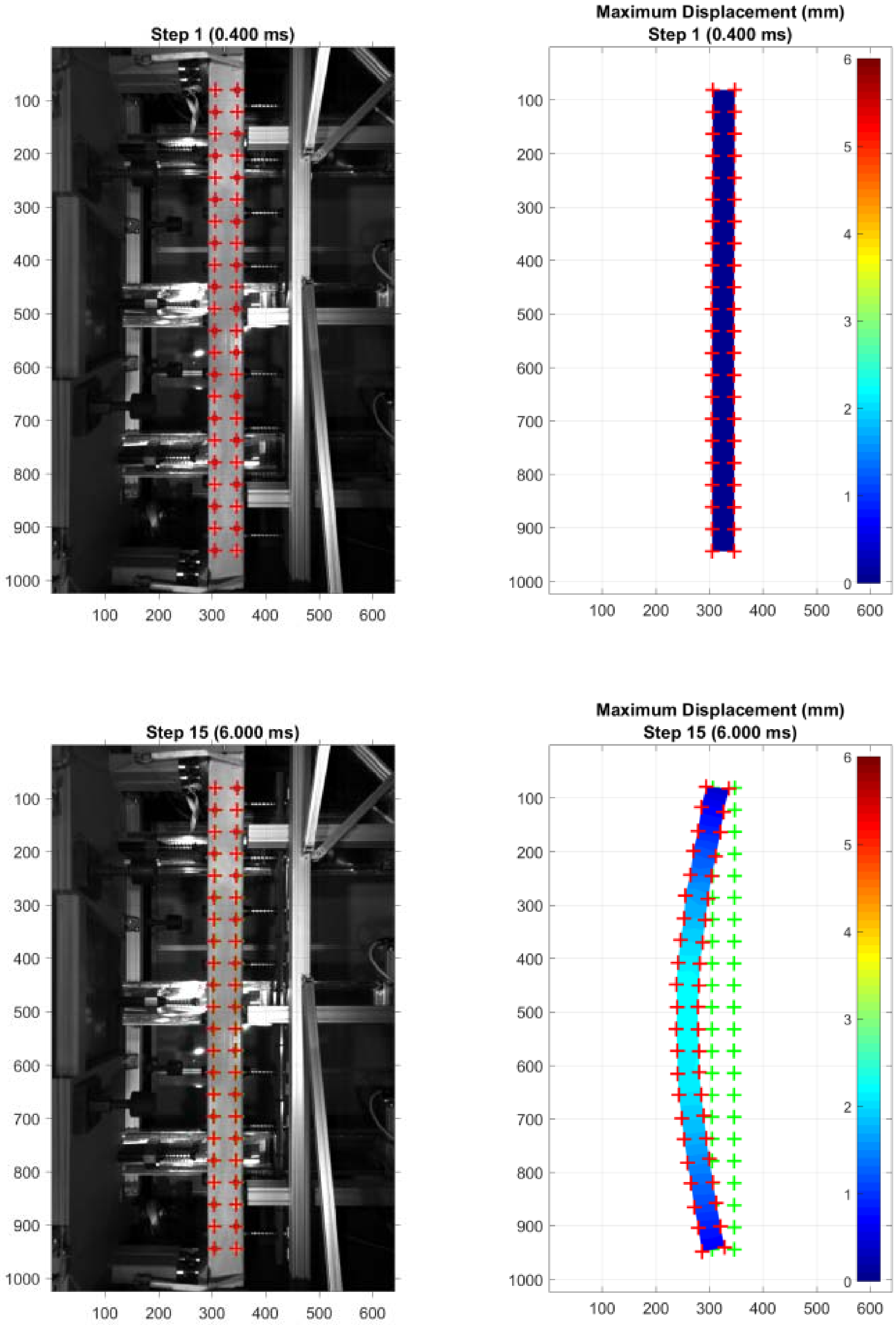


Figure 23 Example of displacement evolution during the dynamic test A (numbers indicate pixels)


Step 1 (0.400 ms)
Maximum Displacement (mm)
Step 1 (0.400 ms)
Step 15 (6.000 ms)
Maximum Displacement (mm)
Step 15 (6.000 ms)

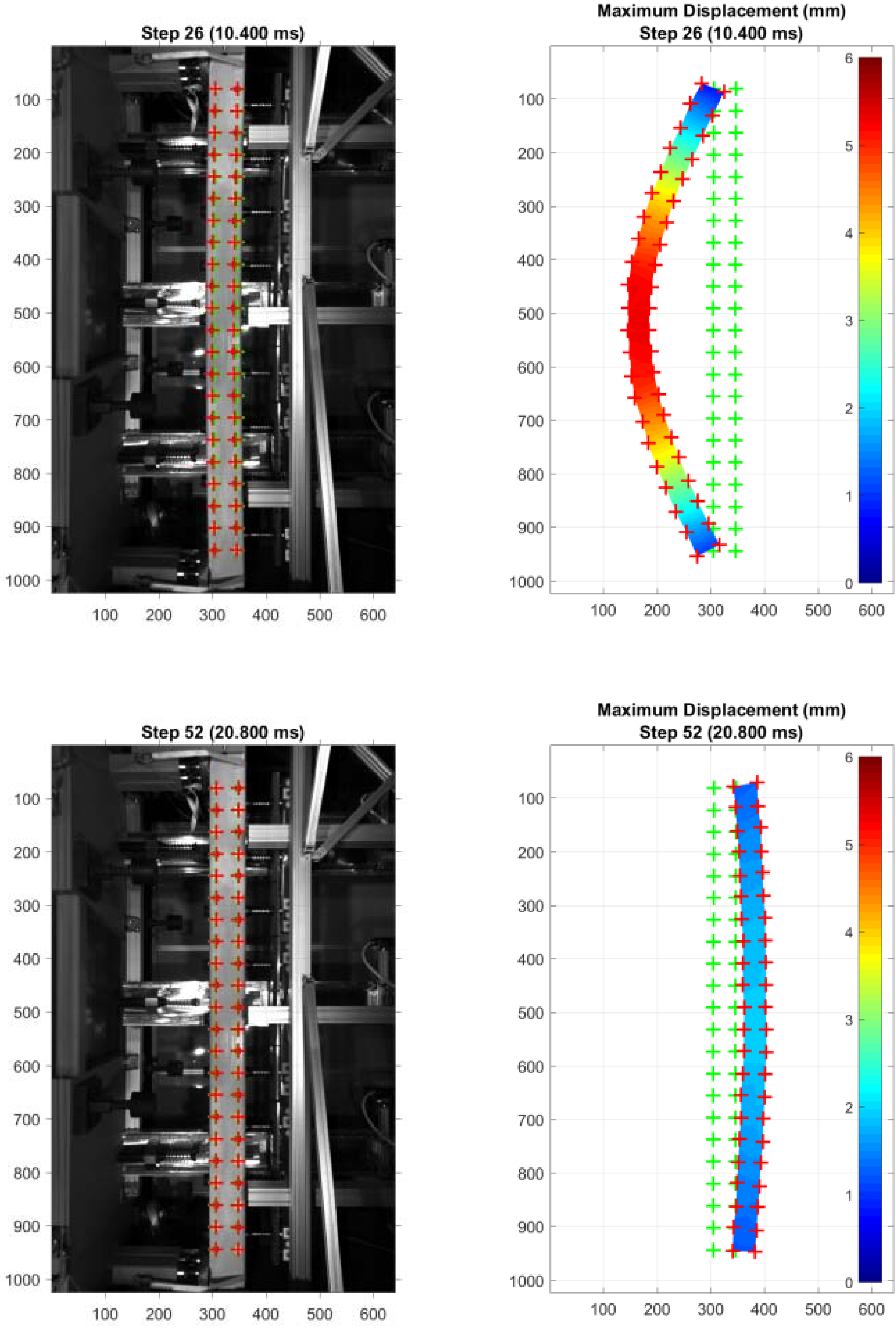
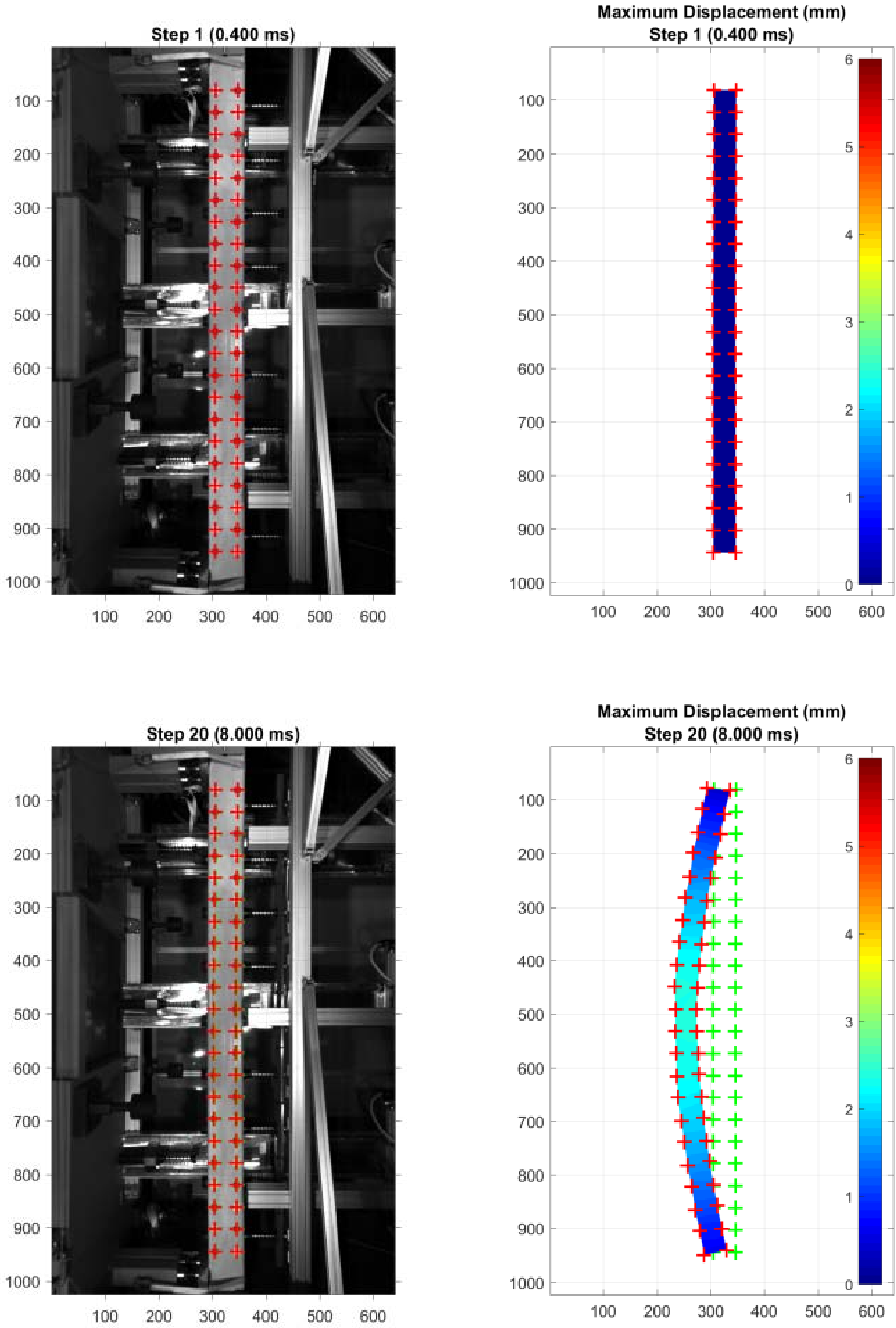


Figure 24 Example of displacement evolution during the dynamic test B (numbers indicate pixels)


Step 1 (0.400 ms)
Maximum Displacement (mm)
Step 1 (0.400 ms)
Step 20 (8.000 ms)
Maximum Displacement (mm)
Step 20 (8.000 ms)

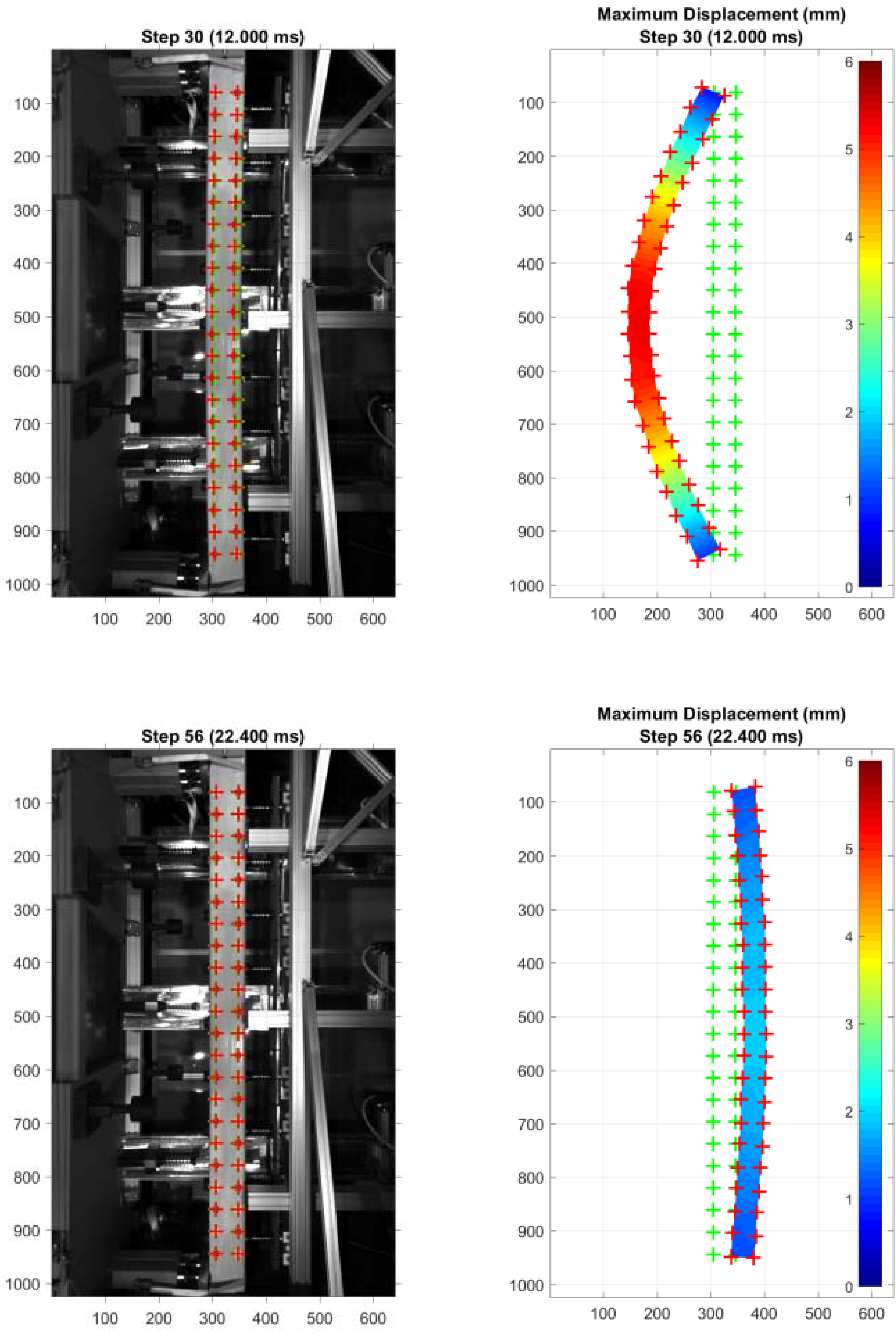


Figure 25 Example of displacement evolution during the dynamic test C (numbers indicate pixels)

In Figure 26 and Figure 27, the results in terms of reaction forces obtained, respectively, in the tests B and C are also reported. Given that the three tests A, B and C have been conducted under identical conditions, it is important to underline, as shown in the figures, the excellent repeatability of the results obtained with this new e-BLAST apparatus.

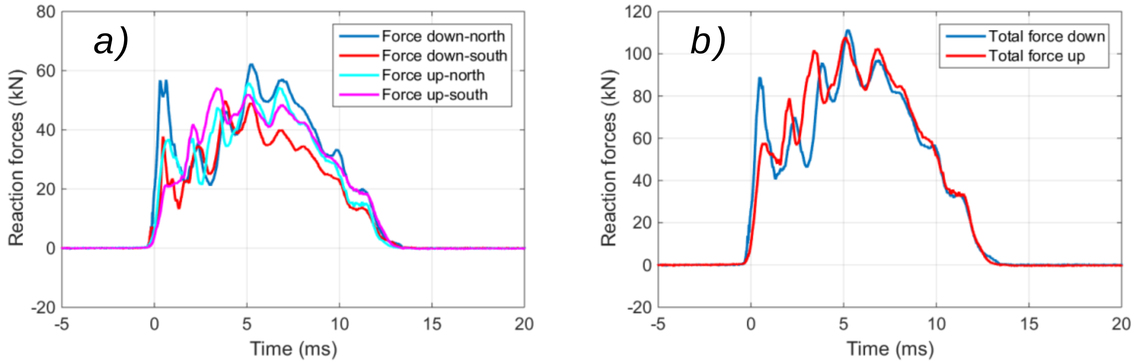


Figure 26 Reaction forces recorded during test B: a) single load cells and b) total forces

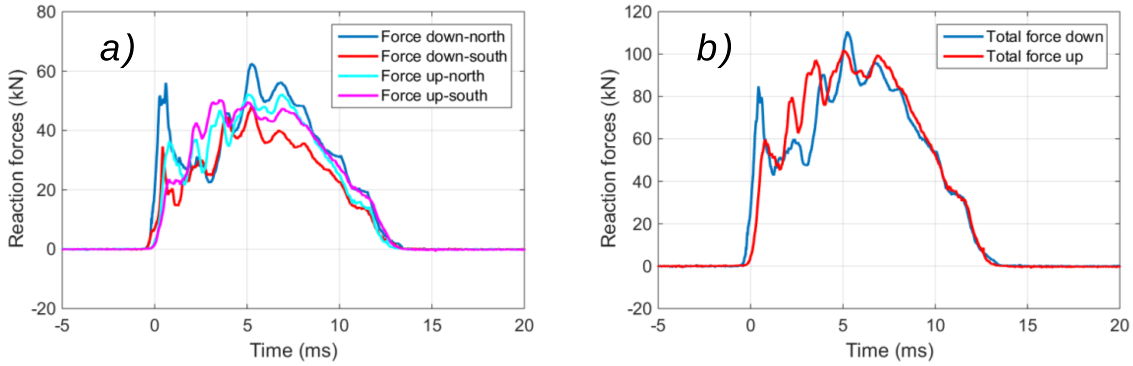


Figure 27 Reaction forces recorded during test C: a) single load cells and b) total forces

In order to underline the potentiality of the equipment in terms of precision, repeatability and synchronization the data related to force, velocity, error in synchronization and target of the motors have been plotted in Figures 28 and 29

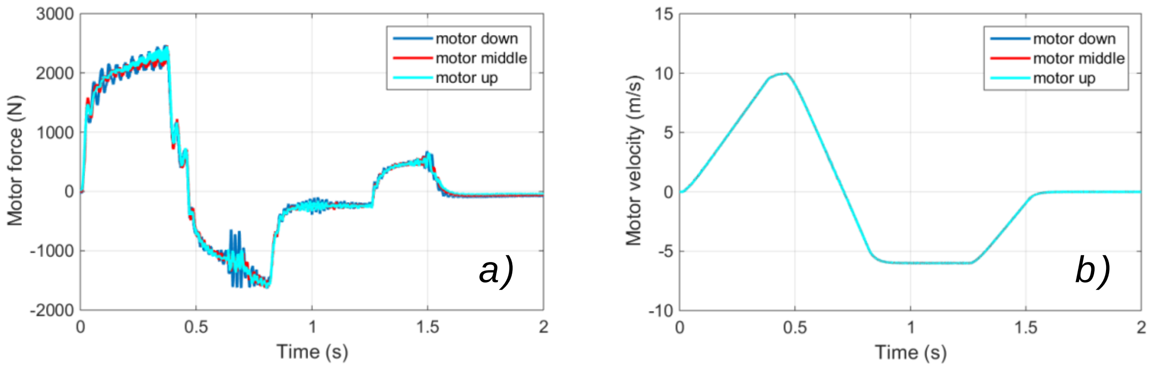


Figure 28 a) force generated by the motors and b) velocities reached by the motors

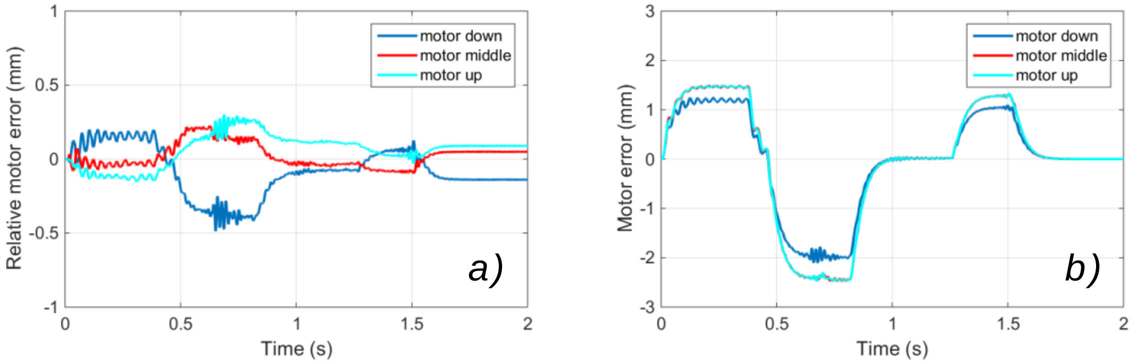


Figure 29 Errors recorded during test C: a) synchro and b) target

3.3 Tests on modified steel column with different motor velocity profiles

Finally, a test characterized by different velocities for the three motors has been conducted. This test has been instrumental in demonstrating the high degree of flexibility of the e-BLAST equipment.

In fact, thanks to the special control system adopted, which is characterized by high precision, it is possible to impose different profiles of accelerations, velocities and displacements for the three linear electric motors. In particular, in this test the velocity of the "middle motor" was 10% lower than the velocity of "down motor", while the velocity of the "up motor" was 20% lower than the velocity of the "down motor". Thus, the lower part of the column is impacted first, followed by the successive impacts of the middle and upper part at some milliseconds later.

The results in terms of reaction forces obtained during the test are reported in Figure 30. A delay is clearly seen in the recorded forces in the lower and upper support, as is intuitively expected.

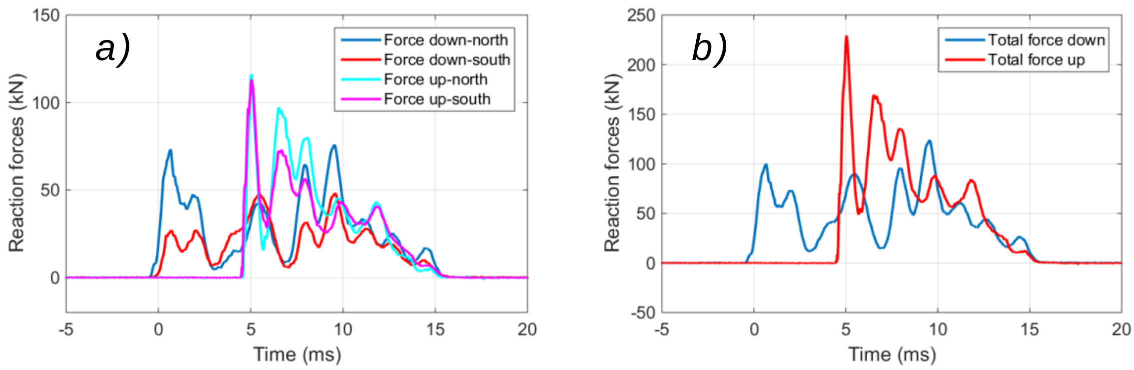
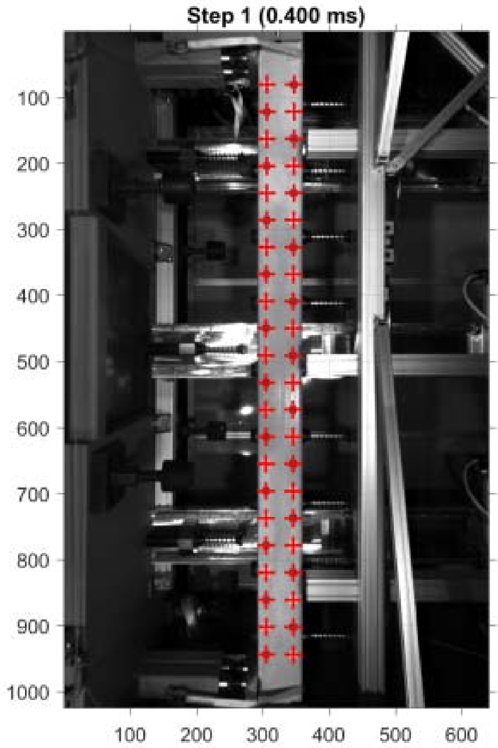
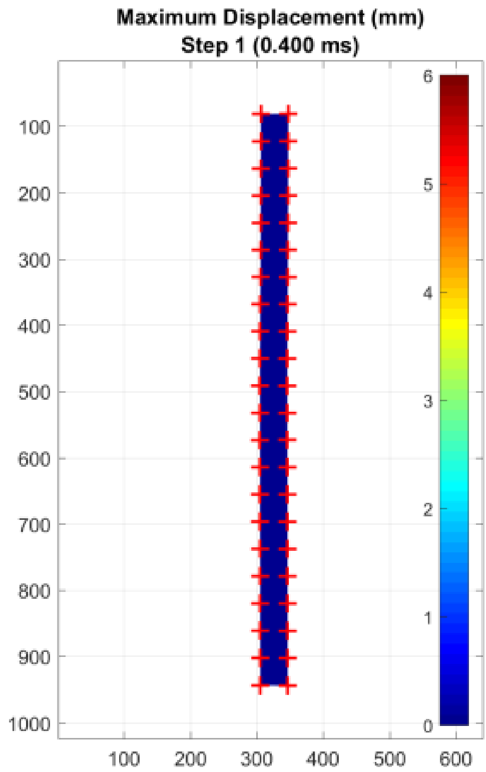
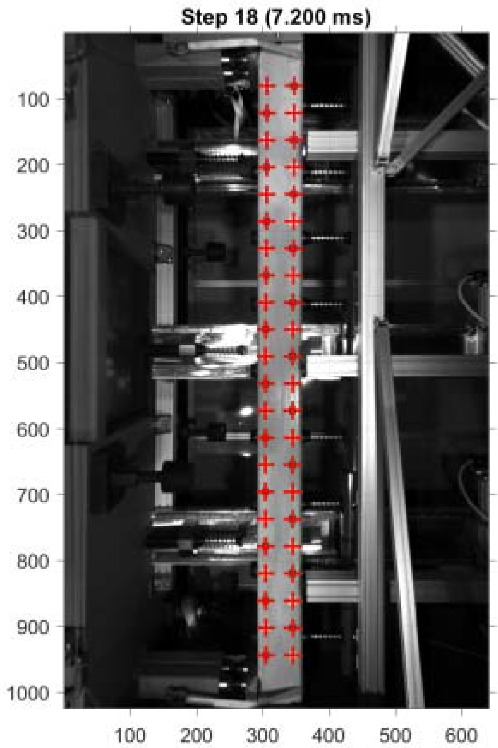


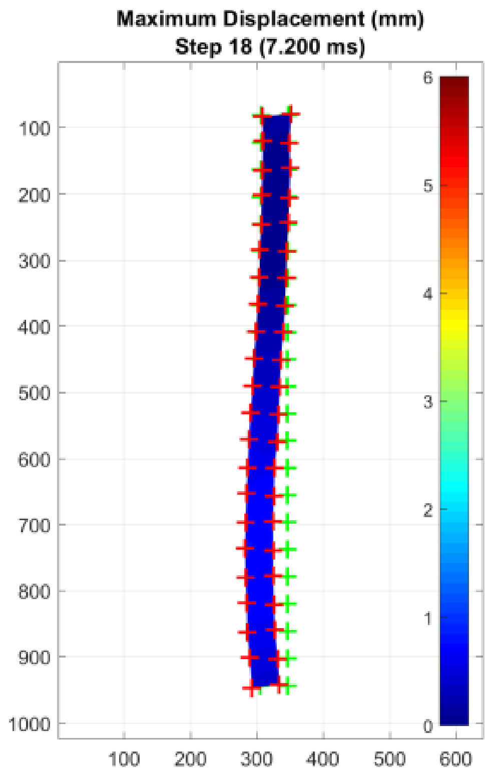
Figure 30 Reaction forces recorded during test: a) single load cells and b) total forces

In Figures Figure 31 high speed photo sequence of the test has been compared with the results obtained by applying a Digital Image Correlation (DIC) technique in real time.


Step 1 (0.400 ms)


Maximum Displacement (mm)
Step 1 (0.400 ms)


Step 18 (7.200 ms)


Maximum Displacement (mm)
Step 18 (7.200 ms)

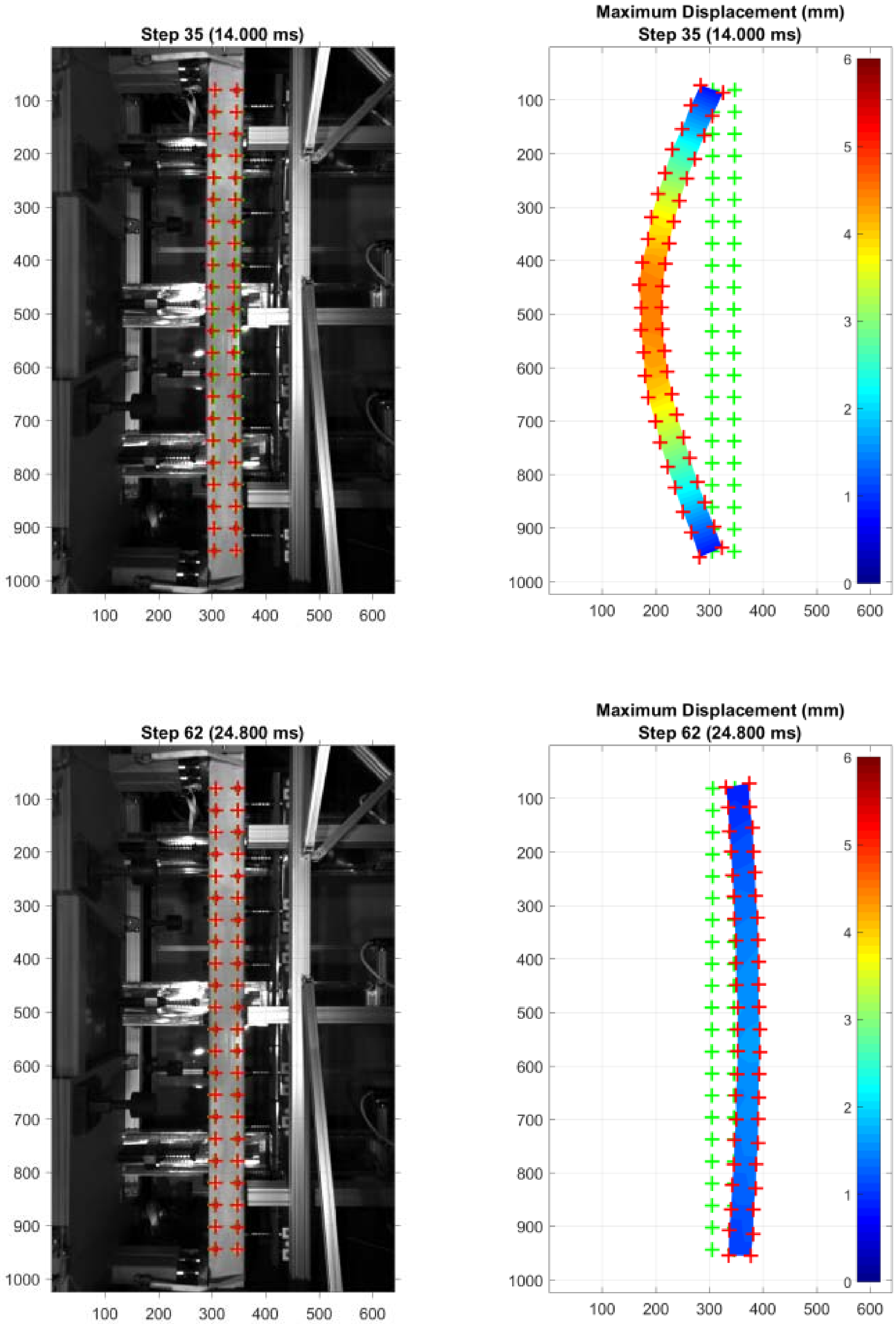


Figure 31 Example of displacement evolution during the dynamic test (numbers indicate pixels)

4 Conclusion

The philosophy of design, the features and the assembly of the new Electrical Blast Simulator (e-BLAST) apparatus have been presented, along with a series of preliminary tests carried out in the ELSA laboratory in order to assess its performance. The e-BLAST facility involves the development of an apparatus able to reproduce the effects of a blast pressure wave on large structural components (such as columns, walls, etc.) without using explosives. Properly configured masses should through impact produce on the specimen pressures equivalent to those of a blast wave.

The e-BLAST exploits recent technological advances for the propulsion of these impacting masses. Specifically, synchronous electrical linear motors have been employed for accelerating the impacting masses, and this has allowed the design of a more efficient, versatile and low-cost facility. The whole apparatus design has been thoroughly investigated together with the motivations and the consequences of the strategy adopted.

Several modifications and improvements have been implemented aiming at enhancing the capabilities of the apparatus and satisfying the needs and requirements of future experimentation. These include: a stiffer modular electric axis, a stronger mechanical support frame, a new design for the electric axis in particular the C-shaped aluminium plates and the re-designed thinner alluminium motor plates, adoption of an improved carriage system, which has made possible to reduce significantly the friction in the three axes, etc.

A series of operational tests using a steel column specimen has been carried out at a maximum impact velocity of 10 m/s in order to assess the new apparatus performance in terms of acceleration capabilities and repeatability of the results. The tests have been performed with three impacting masses of about 50 kg each and an acceleration stroke of about 4.2 m. The synchronization among the motion of the three masses has proven to be fully adequate for the simulation of blast wave phenomena. Testing with operator-imposed different velocities for the three masses has also been successfully carried out. In addition, the entire experimentation has been substantially simplified, when compared with the previous generation of blast simulator prototypes.

Load cells are currently installed on the impacting masses, for enabling the measurement of the pressures developed, and actual tests with the apparatus are envisaged to start shortly.

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Annex A – eBLAST testing procedure

Test Responsible ____

Test Operators ____

Operation	**Check**
Close the access to the ELSA east hall and verify the presence of non-authorized personnel	☐
Switch on the POWER SUPPLIES of i) motors control cabinet, ii) lamps, iii) motor magnets, iv) high-speed cameras iv) and v) additional sensors	☐
Control test PC: Launch motor control software, connect the remote control and verify operation work cycles	☐
Control test PC: Launch acquisition software for the high speed camera and load configuration files for the tests	☐
Control test PC: if necessary set the acquisition tool of motor drive	☐
Transient recorder PC: Launch acquisition software for transient recorder and load configuration files for the tests (board 3842-2)	☐
Transient recorder PC and Control test PC check the triggering of digital acquisition systems	☐
Command console: enable motor smart line, Push "Torque ON" button and start with the motor home procedure	☐
Command console: switch on mass magnets, move motors against the masses and repeat the home procedure	☐
Switch off the mass magnets	☐
Switch on lamps	☐
Control test PC: press "shading", record, trigger in on SA1 software	☐
Control test PC: arm acquisition in motor control software	☐
Transient recorder PC: arm the acquisition boards of transient recorder	☐
Start the test pushing the "Launch" button	☐
Switch off lamps	☐
Transient recorder PC and Control test PC save transient recorder and high-speed camera acquisitions	☐

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