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DYNAMIC SENSITIVITY OF MULTI-BLOCK STACKS SUBJECTED TO PULSE BASE EXCITATION – EXPERIMENTAL EVIDENCE AND NON SMOOTH CONTACT DYNAMICS SIMULATIONS

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Abstract. *Experimental and computational dynamic sensitivity study of Multi-Block Stacks subjected to Pulse Base Excitation is considered. Advanced non contact optical measuring technique based on the GOM Aramis and Pontos systems, as well as the corresponding processing software (displacement history of control sensor points, with a high resolution high speed cameras) have been applied to replace conventional displacement measuring systems and accelerometers. The Non Smooth Contact Dynamics (NSCD) time integration simulation framework SOLFEC http://code.google.com/p/solfec/ is adopted here for comparative NSCD analyses, including a sensitivity study on interface characteristics, as a validation process. Series of test experiments were conducted and recorded on a bespoke platform with and without lateral constraints in the Oxford Impact Engineering Laboratory and Rijeka University Structural Dynamics Laboratory for an extensive series of controlled pulse base excitation tests of multi block stacks configurations. Impact is generated by a pin-ball mechanism with spring and a wooden projectile, attached to an optical bench. For the NSCD simulations the base was subjected to a constant acceleration over a finite time, thereby facilitating the characterisation of multi block stacks tumbling modes of failures (global or partial), as a function of stop gap distance. Creation of well documented benchmarks for the validation of simulation paradigms for discontinuous media will be extremely valuable for researchers and code developers (non smooth contact dynamics, discrete elements, discontinuous deformation analysis), as well as for safety case engineers and industry regulators.*

1 INTRODUCTION

In order to understand as well as to predict the highly nonlinear mechanical response of natural and/or engineered discontinuous, blocky systems, comprising changing and evolving contact conditions and friction between their components or constituent parts, it is important to develop reliable analytical capabilities for simulations of such systems. In spite of extraordinary advances in nonlinear computational mechanics and simulations paradigms, the validation and verification of their predictive powers remains one of the main challenges in the field for their incorporation into industry relevant procedures. It can be safely argued that a major research attention in nonlinear structural dynamics today has noticeably moved from a reliable response of a specific structural system to a specific excitation towards a generic predictive capability for a class of structural configurations.

There are a number of structures that are inherently discontinuous, either as a matter of convenience (e.g. ease of construction in structural masonry or dry stone walling) or as a deliberate strategy to avoid extensive thermal stresses (e.g. graphite cores in Advanced Gas Cooled Reactors, AGR, in nuclear power plants). Often these structures are deliberately discontinuous, organised as stacked and/or interlocked assemblies with a regular pattern and technologically intended gaps and clearances, allowing for limited sliding and rocking in between contacts during their dynamic response. Frequently, these structural assemblies are by themselves a vital safety critical component of an entire structural system (or form a crucial part of) and there is a growing need to be capable of predicting their behaviour under both static and dynamic (impact, seismic) conditions. This is particularly true with ageing and degradation of such systems (e.g. AGR cores), where the safety considerations with respect to their life extension may be paramount for the integrity assessment process of the entire plant operation. Moreover, some of the safety critical ‘non structural’ components (e.g. large control cabinets) need to be treated as un-anchored blocky structures in their seismic assessment.

Structural reliability and integrity assessment procedures are largely formulated for continuum structures and their extension to consider discontinuous structural assemblies or configurations is not adequate. Computational simulation frameworks for the analysis of blocky systems therefore often rely on some form of a homogenisation technique (simplified or complex), leading to a whole series of equivalent nonlinear continuum models [2-5]. Such idealisations then allow for the structural integrity and reliability assessment procedures to follow well established routes, developed for continuum structures and supported by a series of well recognised benchmarks, both computational and experimental. In particular, the homogenisation process allows for a reasonably straightforward dynamic characterisation (e.g. spectral signature, eigen frequencies and mode shapes for response spectrum techniques in earthquake considerations are easily evaluated) of what are in reality discontinuous, ‘blocky’ structures, for which no eigen problem can be formulated.

This contribution comprises preliminary results of both experimental and computational dynamic sensitivity study of Multi-Block Stacks subjected to Pulse Base Excitation. Advanced non contact optical measuring technique based on the GOM Aramis system [1] and the corresponding processing software (displacement history of control sensor points, with high resolution high speed cameras) have been applied to replace conventional displacement measuring systems and accelerometers. The Non Smooth Contact Dynamics (NSCD) [2] time integration methodology SOLFEC http://code.google.com/p/solfec/ [3] is adopted here, which effectively ignores the high frequency content of the contact interactions. Instead of a specified interpenetration-force relation, this paradigm employs the complementarity relation between the relative velocity and the contact force at an existing contact point: either the velocity is such that the bodies separate and the contact force is zero, or the force is such that interpenetration is prevented and in consequence the relative velocity is zero. This velocity-force complementarity relation is added as an algebraic constraint to the implicitly integrated momentum balance and the ensuing nonlinear contact problem is therefore solved implicitly at every time step in order to find the contact forces and the velocities of contacting blocks.

2 CONTROLLED PULSE BASE EXCITATION EXPERIMENTS

A comprehensive series of experiments was conducted at the Oxford Impact Engineering Laboratory on a bespoke platform for a controlled double pulse base excitation, inspired by the classic ingenious simple test device at Roorkee University, Fig 1. [4].

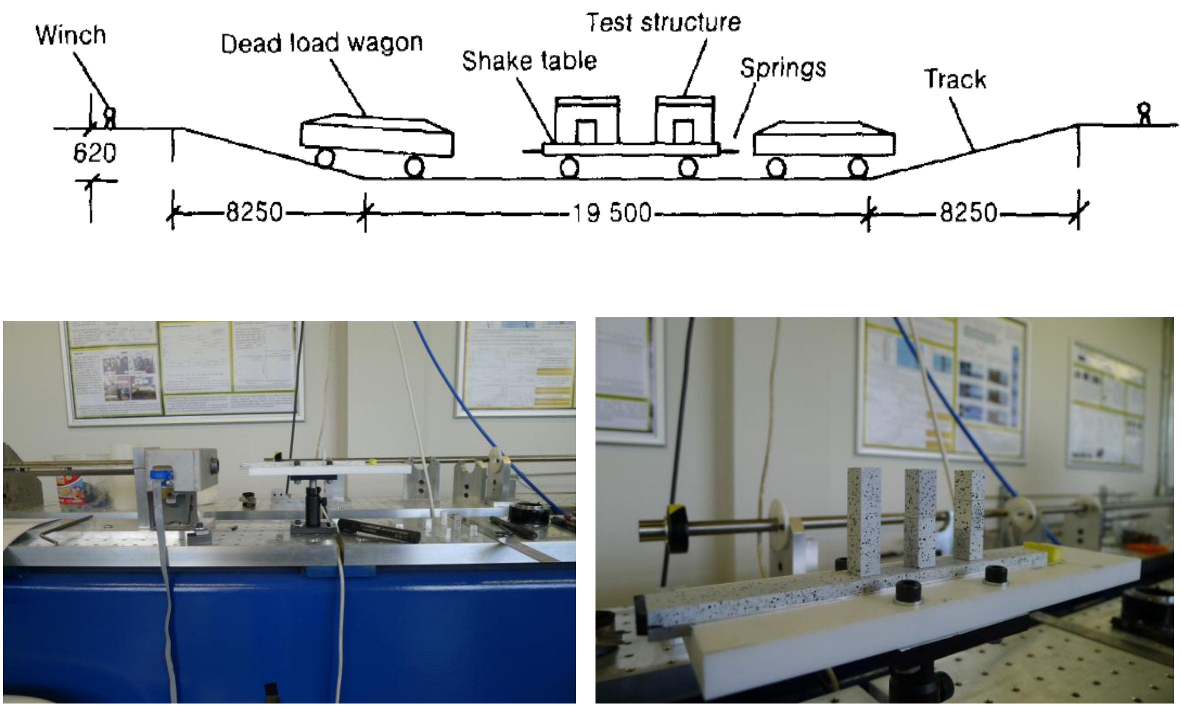


Figure 1: Original Roorke University Platform and its conceptual small scale counterpart ROORI-1 at Oxford

2.1 Block stack experiments with no lateral constraints

The experimental setup (named ROORI-1 as an homage to Roorke and Rijeka Universities) comprised an impact device, Fig 2 (a pin-ball mechanism with spring which was used to launch the wooden projectile) attached to an optical bench, with a teflon base and stopper aligned to the impact device and attached to the optical bench as well. A foam cushion was glued to the stopper, whereas a rubber cushion was glued to the front face of the aluminum base. Aluminum base was positioned at a predefined distance from the stopper (BD). The base excitation scenario implies an initial impulse (different intensities controlled by different pin-ball spring positions, denoted IM) followed by a reverse impulse (provided by the base hitting a stopper), after a given time delay (controlled by the block stopper distance BD).The shapes of the initial and reverse impulse are controlled by rubber cushions.

On top of aluminum base a single block or a stack of two or three blocks was positioned (and aligned to the impact device and teflon base). Every experiment was recorded with the Phantom video camera with a resolution of 800x600 pixels and the frame rate of 2000 fps.

The camera was triggered by a laser-beam curtain. Figure 1 illustrates the experimental setup of the bespoke platform.

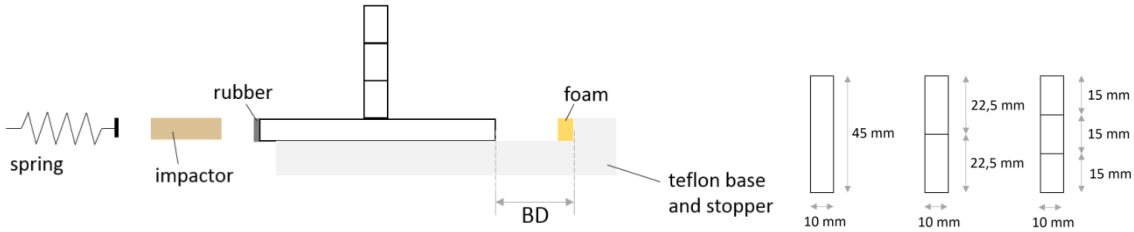


Figure 2: Scheme of series of experiments of dynamic sensitivity of multiblock structures

Initially, all the contact surfaces between each of the blocks and the bottom block and the base were kept smooth. Subsequently, the contact surfaces were made non smooth by the sand paper using a standard procedure of scraping aluminium surface along the sandpaper surface. Each set of experiments was repeated three times. A comparison between three repetitions shows repeatability of initial conditions as well as the repeatability of dynamic behaviour of the blocks. All the experiments were triggered manually and a good repeatability was achieved, especially for non smooth inter block contact surfaces, however for some scenarios with smooth contact surfaces, the responses appeared quite sensitive to small changes in initial conditions (Fig 3).

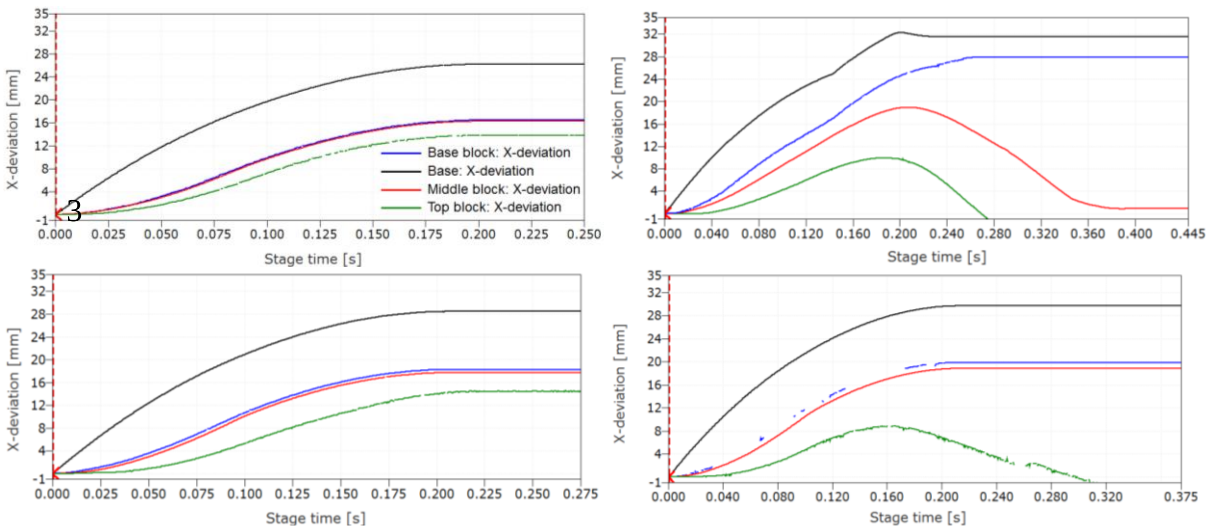


Figure 3: Displacement of base, bottom, middle and top block from four repetitions of experiment B3_IM10_BD4 (3 blocks, spring trigger position 10, distance to stopper 4 cm) – smooth contact surfaces. Note that the base history is repeated well from one test to another, whereas the horizontal displacements of the upper blocks can be quite different

Every video was converted into a series of images (in .jpg format). Each series of images was post processed using Aramis v6.3.1-0 software for optical deformation and displacement analysis. Since the resolution of the images was 800x600 pixels, each pixel represents approximately 0.18 mm. Choice for the facet size needs to be optimised, as it depends on speckle pattern, pixel size and scale in which a behaviour is observed. Velocities obtained using the facet size 10x10 pixels show largest scatter of results, while velocity obtained using the facet size 30x30 pixels converge to a distinct smooth trend (Fig 4).

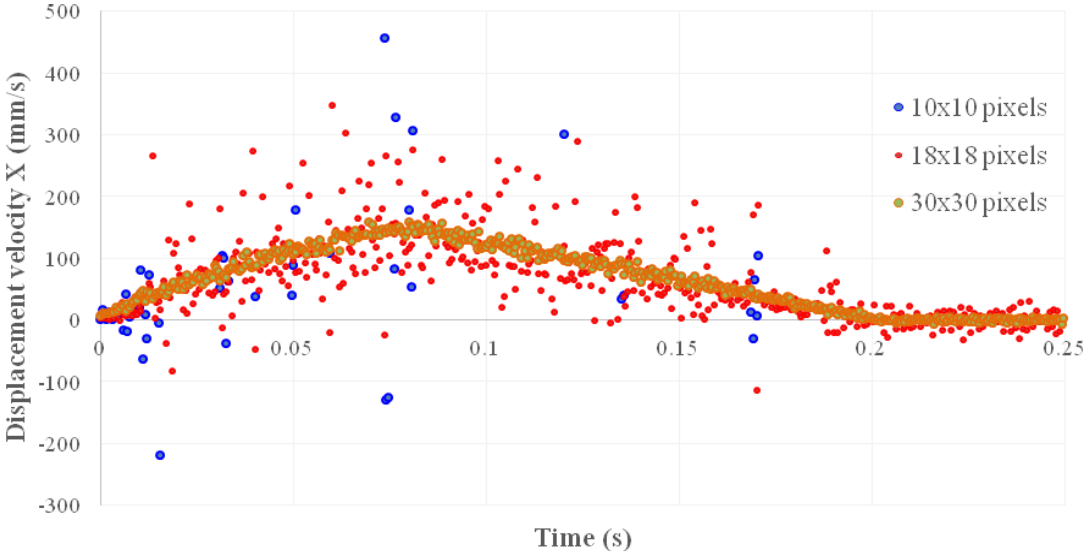


Figure 4: Velocity of the bottom block for a three blocks stack using different Aramis facet resolutions

The overturning conditions for a slender block subject to a single shock of constant base acceleration of a finite duration can be analytically established [7]. However, when the block of the same overall geometry is considered as a stack composed of three blocks, it is easy to conclude that for a single impulse an overtopping as the entire stack should always prevail over any partial overtopping (overtopping of a top block, or overtopping of two upper blocks). The existence of a second, reverse impulse and the time delay between the two impulses may affect the mode of overturning, depending on the timing of the second impulse. Within this study, a preliminary attempt has been made to provide a simple dynamic characterisation of discontinuous blocky stacks, through qualitative synthesis of experimental results, where only the eventual outcome (or mode of overturning) of each experiment carried out is recorded. The final configuration of the stack of three blocks (Fig 5) is used to classify each experimental result into one of four possible overturning modes

- Mode A – a stack of three blocks remains stable,
- Mode B – top block from the stack of three blocks overturns as a result of either rocking, sliding or combined motion,
- Mode C – top and middle blocks from stack of three blocks overturn as a result of either rocking, sliding or combined motion,
- Mode D – entire stack of three blocks collapses as a result of either rocking, sliding or combined motion.

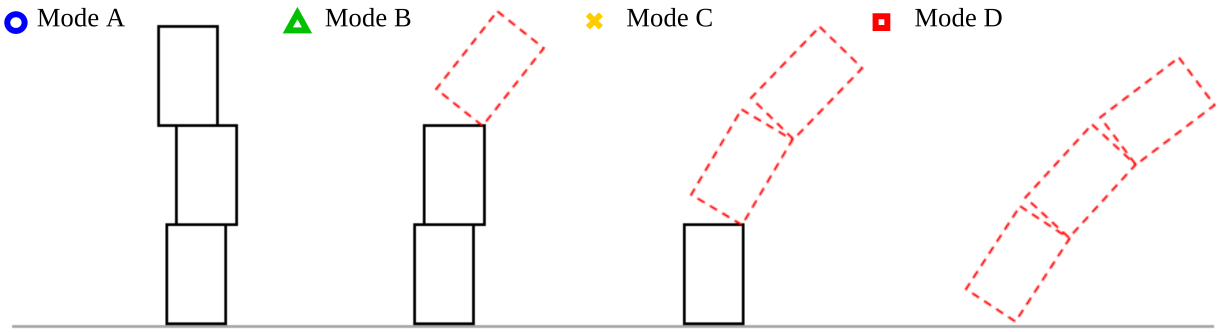
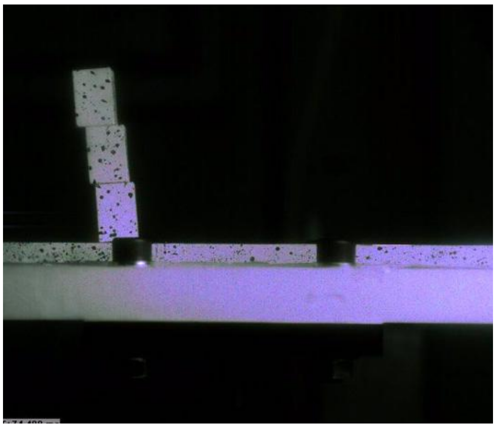
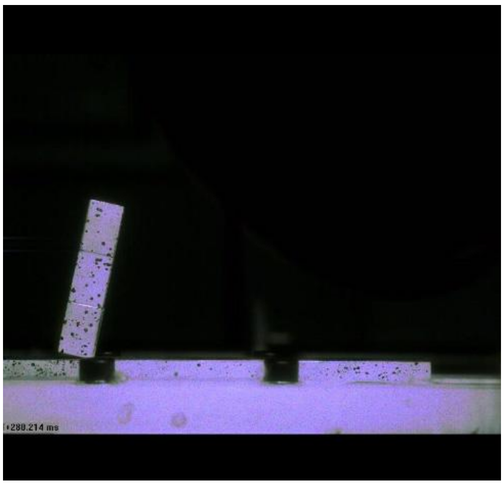


Figure 5: Possible overtopping modes of the stack of three blocks

Deformation of the spring in pin-ball mechanism (IM) induces kinetic energy put into system via the initial impact between the projectile and the aluminium base. The subsequent impact of the aluminium base with the stopper (via foam cushion) completes the pulse by a counter shock. The counter shock depends on the distance between aluminium base and the stopper (BD), as well as the amplitude of the initial impact. Due to the friction between the aluminium base plate and the teflon subsurface, there are experimental scenarios where the base comes to a rest before ever reaching the stopper. Typical block centroids horizontal displacement time histories as processed from video images are illustrated below (Fig 6) for pulse experiments for a stack of three blocks with smooth contacts surfaces (predominantly sliding mode) and with non smooth surfaces (predominantly rocking mode).



smooth



nonsmooth

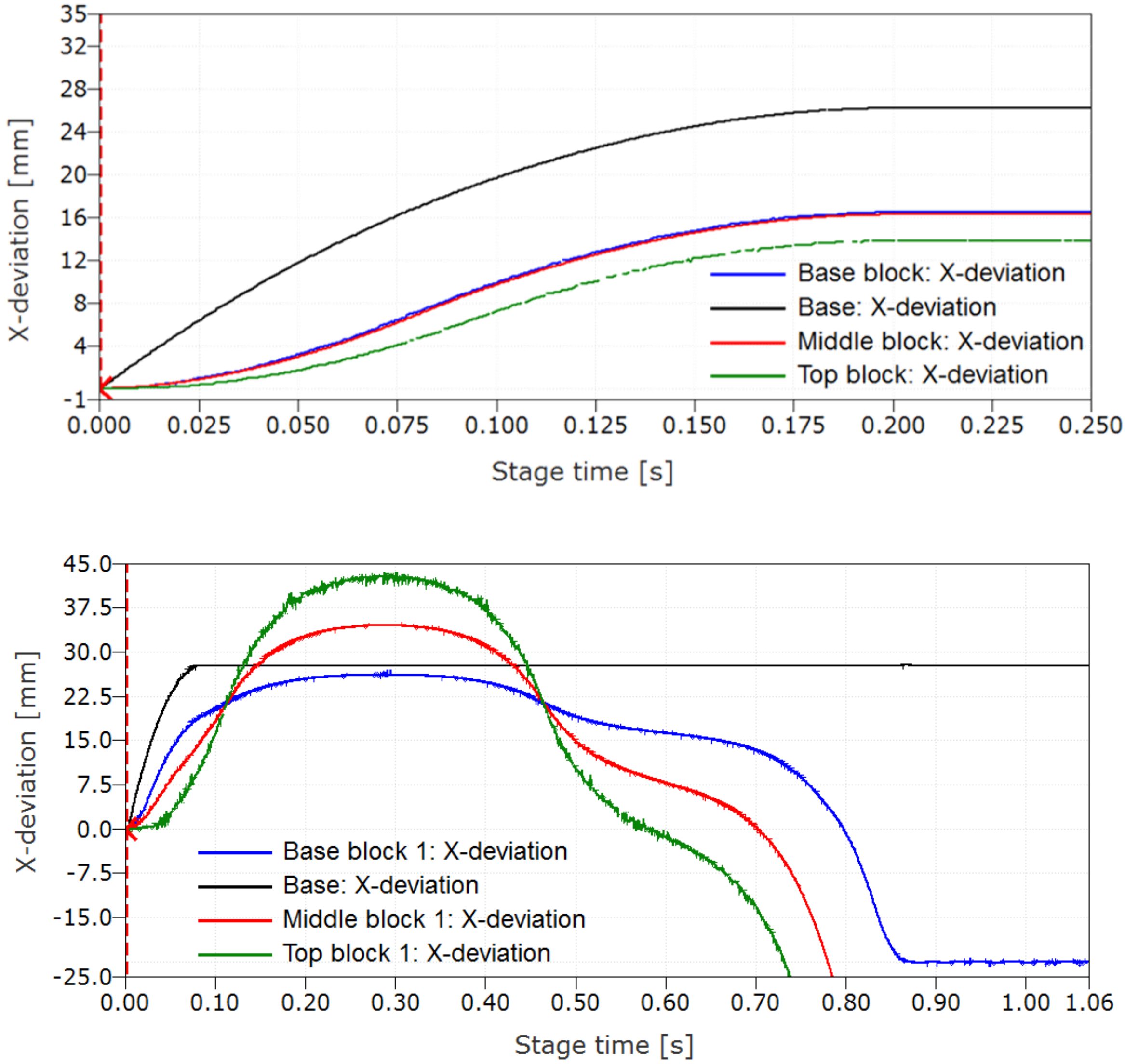
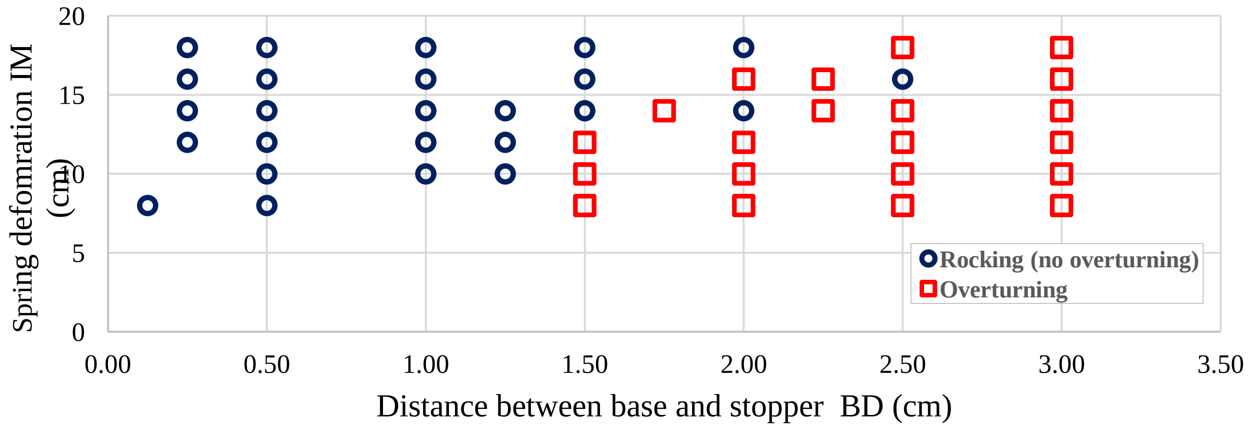
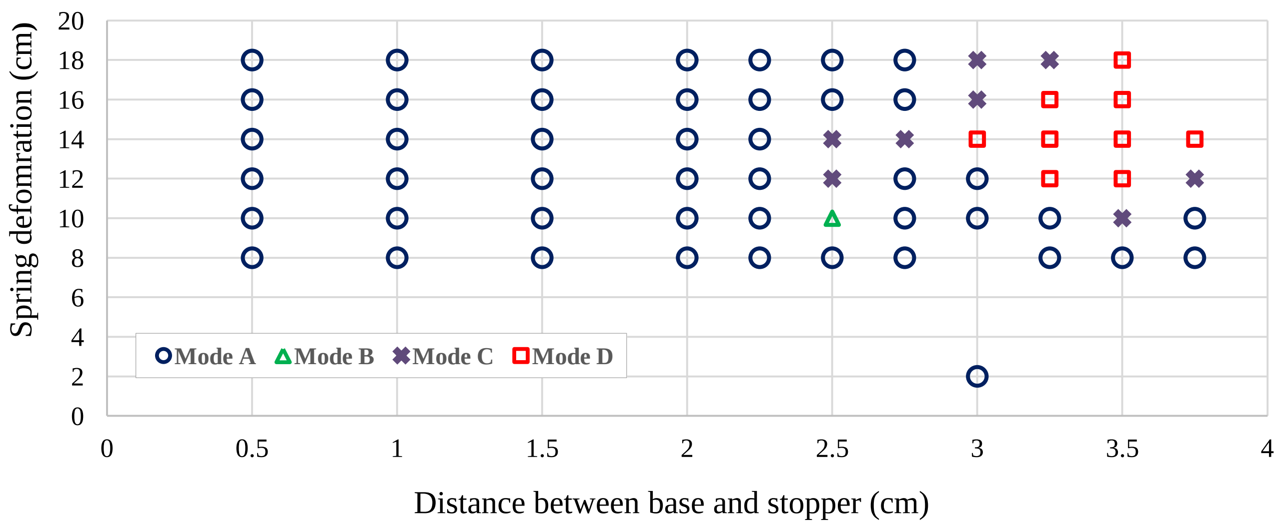


Figure 6: Typical horizontal displacement histories for the base and blocks centroids, for the case of smooth (above) and non smooth (below) contact surfaces, for the experiment with a single impulse, i.e. with no stopper. Note the rocking response for the non smooth case, whilst the smooth case induces block sliding only.

It is reasonable to expect that a mode of overturning is influenced by the amplitude and the duration of the dynamic pulse. Sensitivity of the failure mode following a counter shock for a specific experiment is here noted within the 2D parameter space (Fig 7), defined by the distance between aluminium base and the stopper and the trigger point for the pin ball spring, for the two cases of a single slender block and a stack of three blocks with the same overall dimension, with all non smooth contact surfaces.



(a) Single block 10/10/45 mm



(b) Stack of 3 blocks 10/10/15 mm

Figure 7. Overturning modes for a single block (a) and a stack of same overall dimensions, comprising three blocks (b) with non smooth (below) contacts related to the pin ball spring trigger position (IM) and the distance between the aluminium base and the stopper (BD). Mode A Rocking, Mode B Top block overturning, Mode C Top 2 blocks overturning, Mode D entire stack overturning

2.2 Block stack experiments with lateral constraints

Per analogiam to the series of experiments without lateral restraints, another series of experiments was conducted with a variation of side wall constraints spacing, distance from the aluminium base to the stopper and the level of spring trigger (Fig 8). Every experiment was again recorded with the Phantom video camera with resolution of 800x600 pixels and frame rate of 2000 fps. The camera was again triggered by a laser-beam curtain.

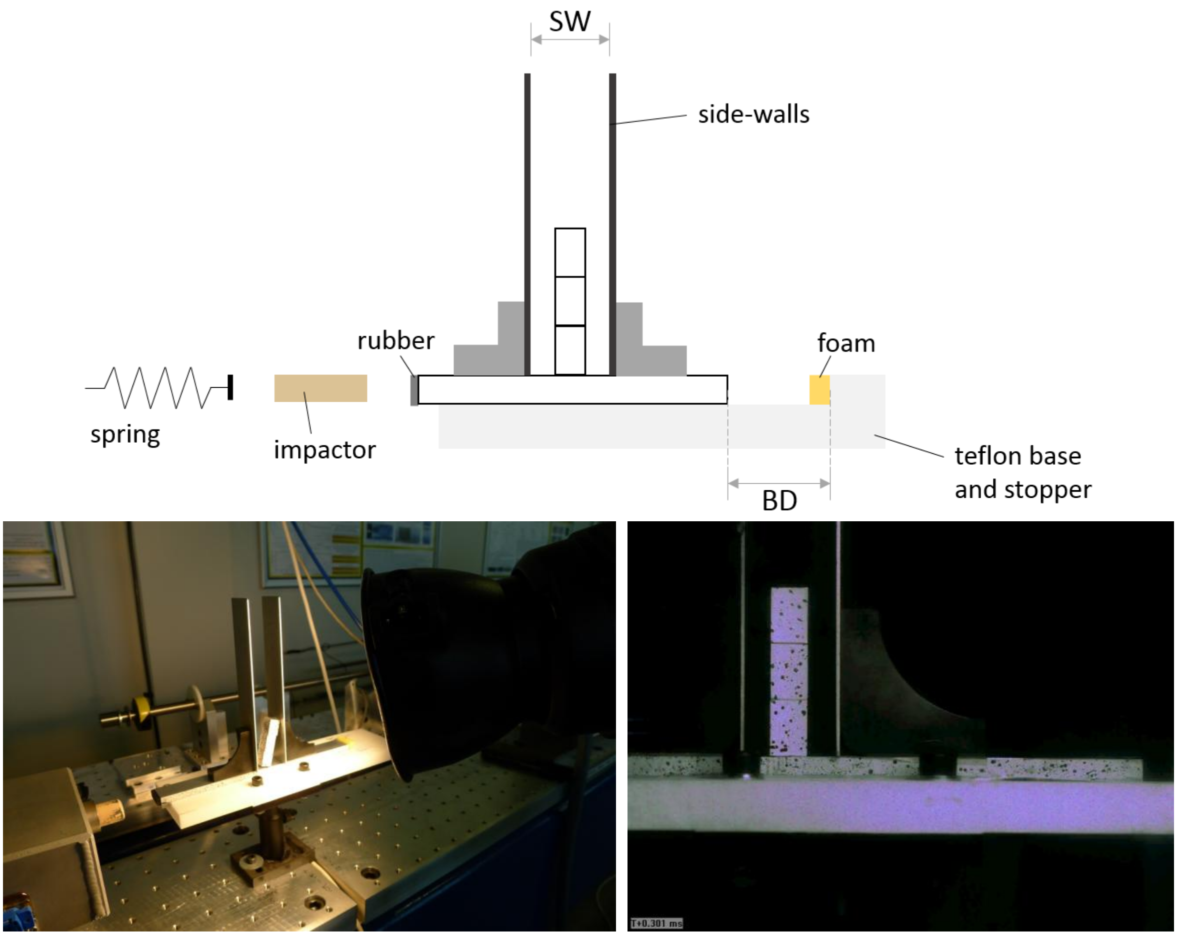


Figure 8: Scheme of series of experiments of dynamic sensitivity of multiblock structures including lateral side-walls constraints

Typical high speed video images and time histories of the block centroids horizontal displacements processed with ARAMIS software are illustrated below, Fig 9.

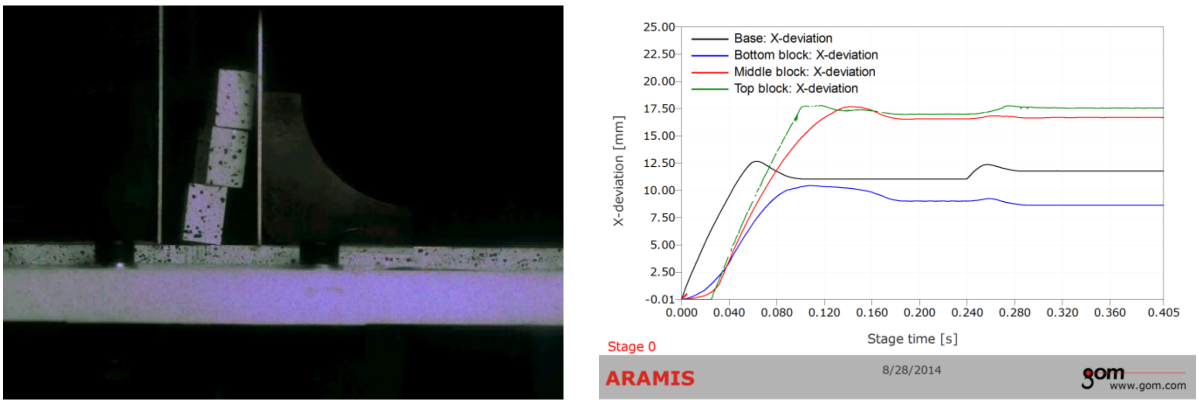


Figure 9: Time histories of the block centroids horizontal displacements, indicating intermittent contacts with lateral constraints

Fuller results are available on the project website http://mbsdynamics-ukf.gradri.uniri.hr/.

3 NSCD SIMULATIONS

Comparative Non Smooth Contact Dynamics studies were conducted with SOLFEC http://code.google.com/p/solfec/ [3]. For the simulations (Fig 10), the base was subjected to a constant acceleration (linear rise of velocity) over a fixed finite time (0.005 sec), giving rise to a series of different peak base velocities. All blocks were assumed to be rigid. Coefficient of restitution for both normal and tangential direction were set to zero. Coefficient of friction (base/Teflon base) is adopted as 0.26. In the experiment, the surface of the blocks is either smooth or non smooth after sandblasting. The coefficient of friction between blocks is taken as 1.3 when the blocks are smooth, whereas for the non smooth case, the simulations were made with the coefficient of friction in the range of 1.3 to 2.7. Simulation consequences of a series of different block and base grid subdivisions were explored (for the purpose of contact detection, as all the blocks are assumed rigid) on Fig 12 .

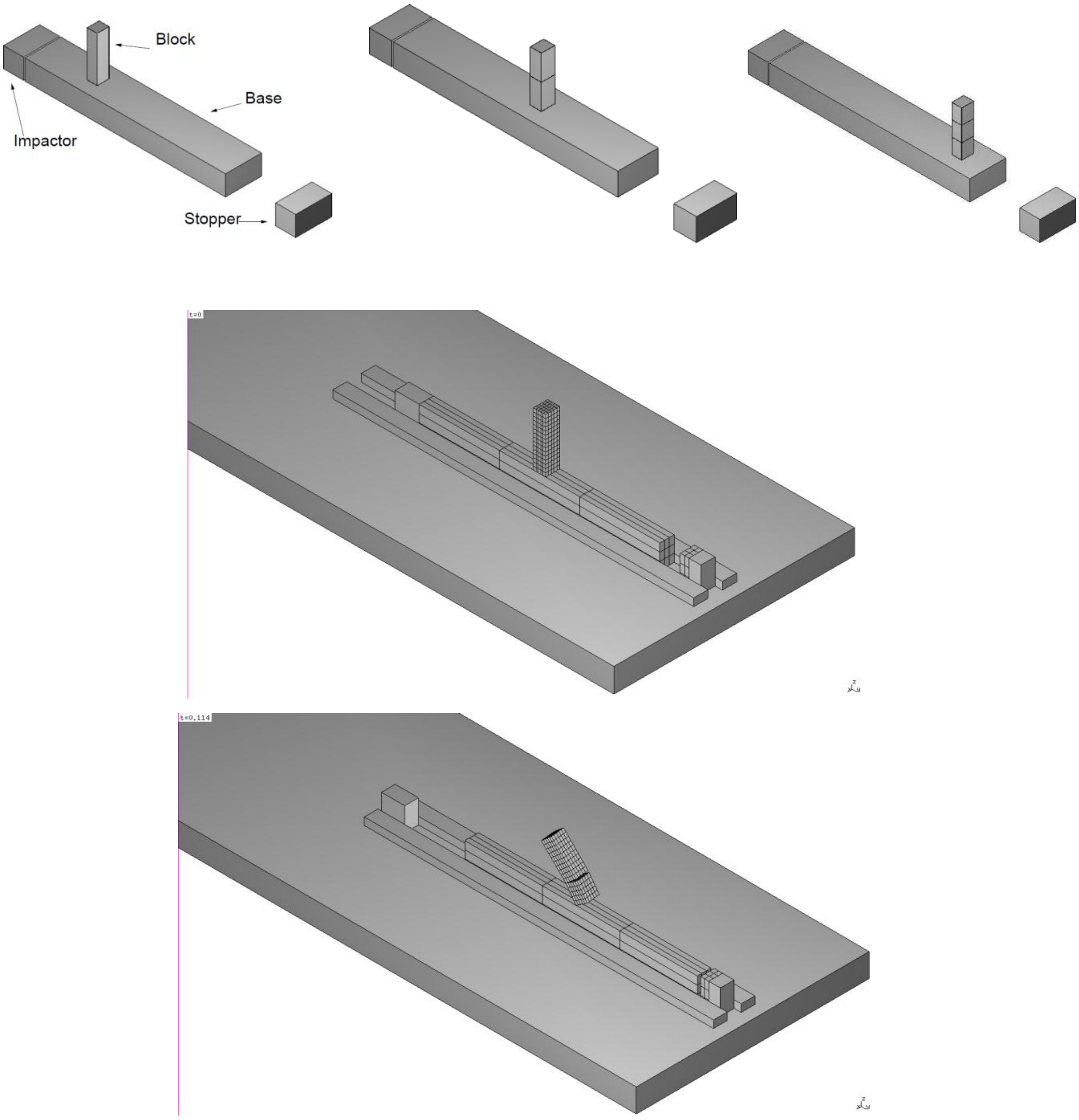


Figure 10: SOLFEC NSCD simulations of the ROORI-1 experimental set up

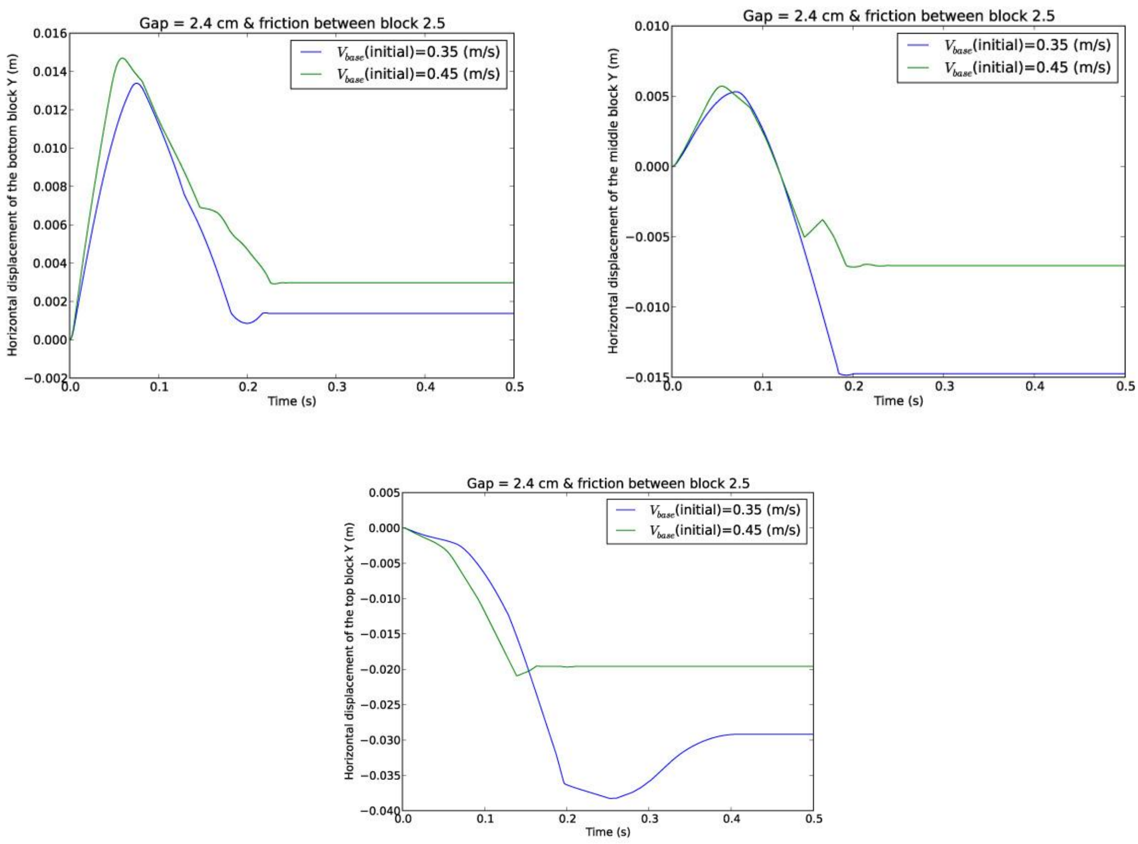


Figure 11: Horizontal displacement time histories for the block centroids (top, middle and bottom) for the two pulse excitation scenarios with peak base velocities (0.35 m/sec and 0.45 m/sec)

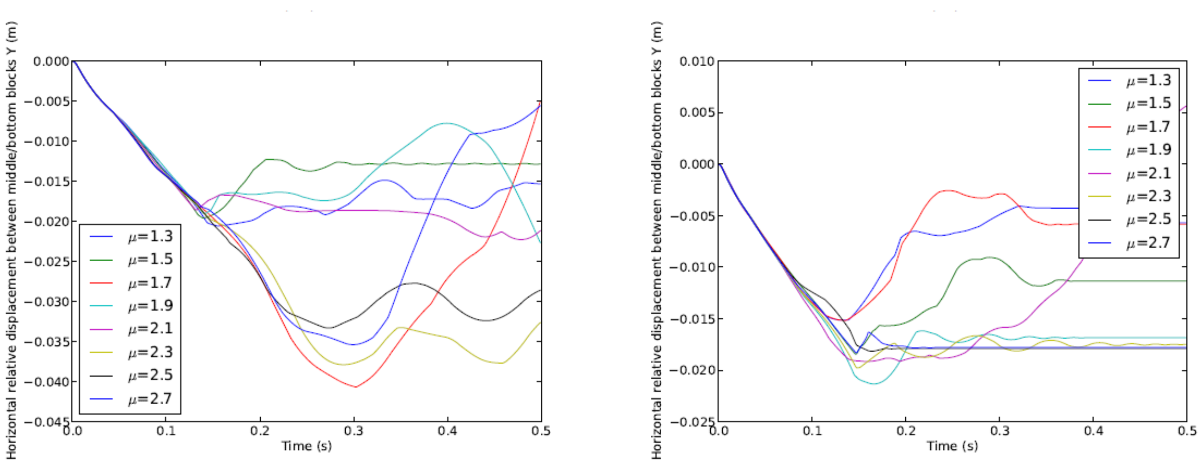


Figure 12: Time evolution of the horizontal relative horizontal displacement between the middle and bottom blocks, with the grid on the left (1, 1, 1) and a finer grid on the right (3, 3, 3).

Based on an extensive series of analyses, a qualitative characterisation of the multi block stack tumbling modes of failures (global or partial) are illustrated (Fig 13), due to various conditions of pulse excitation (parametrised here by the peak base velocity and the distance between the base and the stopper). Different states of the block stack system (or modes of failure) at the end of simulations were distinguished (Mode A - block stack remains stable on the base, Mode B - overturning of the top block, Mode C - overturning of the top and middle blocks - mode C, Mode D - overturning of the entire stack).

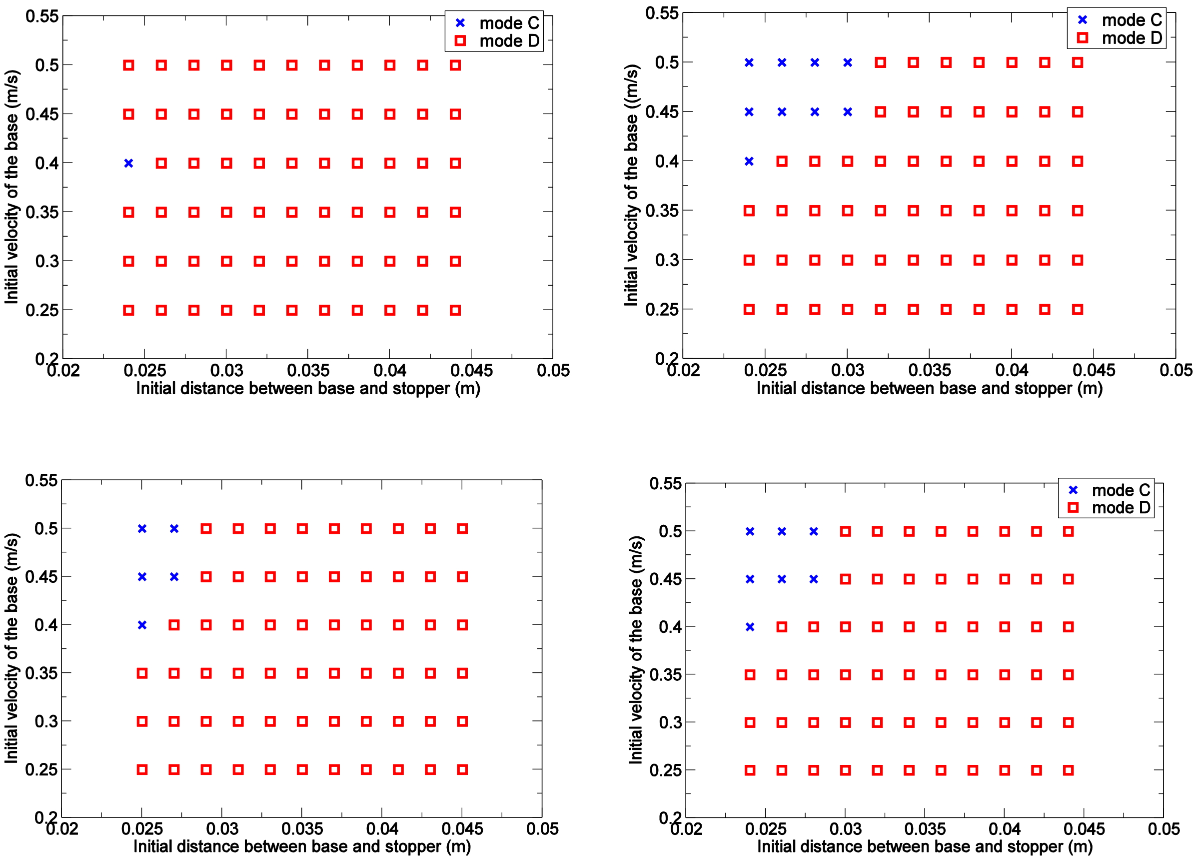


Figure 13: Three Blocks Stack Overturning Mode Characterisation

Several NSCD SOLFEC analyses for the stack overturning study with lateral constraints at different distances (Fig 14) were also conducted

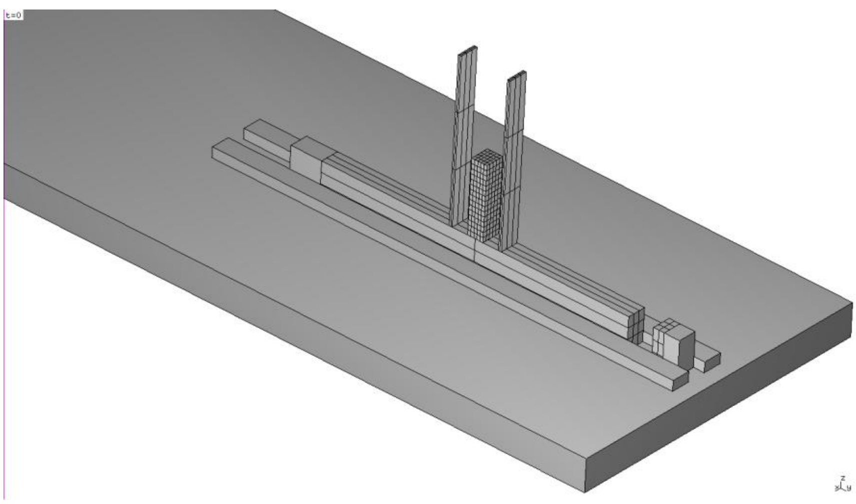


Figure 14: Three Blocks Stack Study with Lateral Constraints

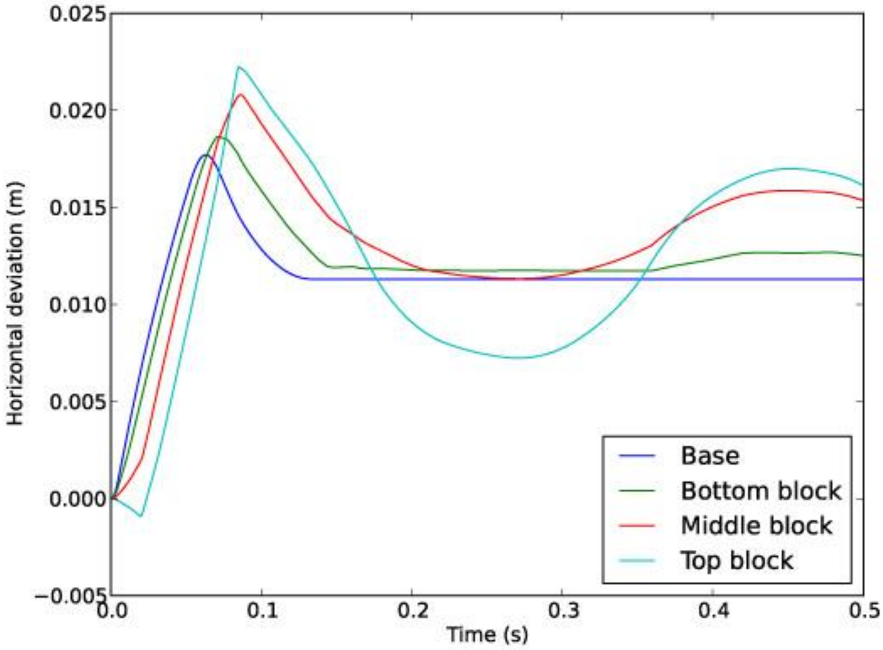


Figure 15 Block Centroids Horizontal Displacements Time Histories for the three Blocks Stack Study with Lateral Constraints

Figs 15 illustrates the three block centroids time histories, as well as the base time history for a double pulse experiment the constraint wall gap of 3 cm, stopper distance of 2.3 cm, and the peak base velocity of 0.4 m/s. Coefficient of restitution is set to zero. Fig 16 illustrates the final stack configuration.

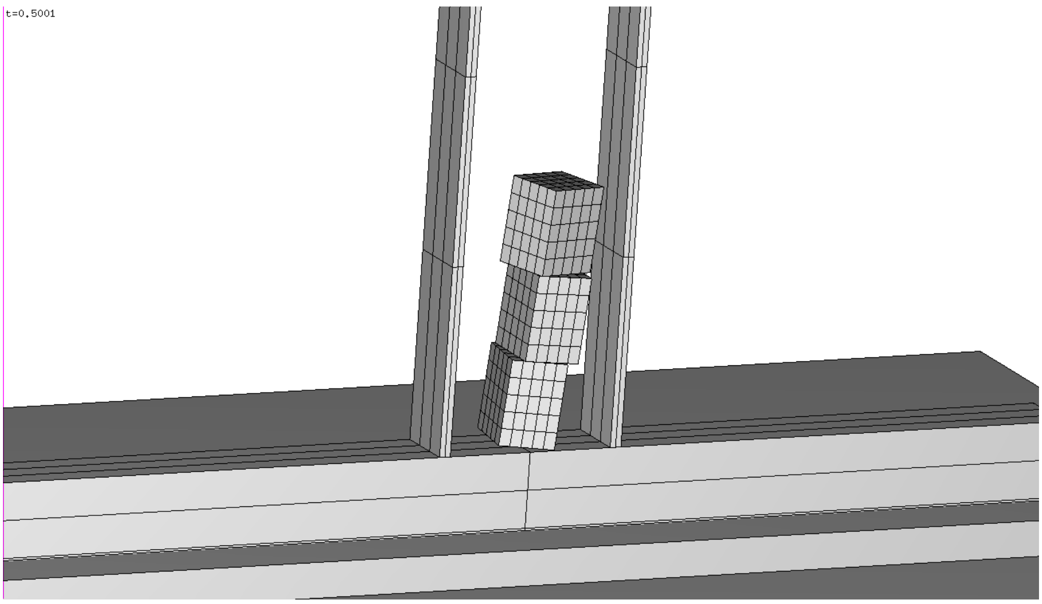


Figure 15 Final post impulse configuration for the three Blocks Stack Study with Lateral Constraints

4 CONCLUDING REMARKS

Apart from very specialist benchmarks, there is a general lack of suitable, well controlled benchmarks problems to validate predictive capabilities of non smooth contact dynamics simulations relevant for multi block structural configurations, with a regular construction pattern and/or clearances. Closed form analytical benchmarks are largely restricted to two dimensional single or double rigid block structural assemblies [5], typically concerned with rocking and overturning conditions due to harmonic or step base excitation of specific amplitudes. In addition, computational intricacies of non smooth dynamics problems are considerable [6].

The presented novel small scale benchmarks aim to expand on the limited database of suitable benchmarks for discontinuous blocky assemblies under dynamic conditions, and to eventually contribute to a library of well documented and well controlled experimental evidence to support and validate computational simulation paradigms (non smooth contact dynamics, discrete elements, discontinuous deformation analysis) as well as to inform the design of larger scale experimental programmes.

It is believed that the creation of a well documented set of benchmarks for the validation of simulation paradigms for discontinuous media will be extremely valuable for researchers and code developers, as well as for safety case engineers and industry regulators. Evidence on dynamic performance attributes and quasi resonance sensitivities for multi body structural assemblies will facilitate better understanding of their structural performance, and will be used as a design and/or forensic tool, as well as a rational basis for the risk assessment. Advanced engineering simulations in industry and regulatory bodies will directly benefit from research results.

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