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Overturning of multiple-block stack - dynamic sensitivity parameters and scaling effect

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Abstract. There is a general lack of well controlled benchmarks to validate predictive capabilities of computational simulations relevant for multiple-block structural configurations with clearances (DEM and non-smooth contact dynamics, NSCD). Closed form analytical benchmarks are largely restricted to 2D single or double rigid block stacks, typically concerned with rocking and overturning conditions due to harmonic or step base excitation. Herein both experimental and computational dynamic sensitivity study of multiple-block stacks subjected to pulse base excitation are examined. Advanced noncontact optical measuring technique (GOM Aramis and Pontos system and the associated processing software) have been applied to replace conventional measuring techniques.

The NSCD simulation framework SOLFEC 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 impulse at an existing contact point. This velocity-impulse 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.

Series of test experiments were conducted in the Oxford Impact Engineering Laboratory on a bespoke platform for a controlled pulse base excitation. Impact is generated by a pin-ball mechanism attached to an optical bench, where the teflon guide and stopper were aligned to the impact device and also attached to the optical bench. Rubber cushions were used to control the shapes of the initial and reverse impact signal. Every experiment was recorded with Phantom or Photron video camera with frame rate of 2000 fps.

Comparative SOLFEC analyses were conducted as a validation study. For the simulations the base was subjected to a constant acceleration of a finite duration until the required base velocity was achieved. Overturning modes in simulations and experiments were characterized as a function of projectile velocity (or indirectly by initial velocity of the base) and the stop gap distance. The conducted set of benchmarks for the validation of simulation paradigms for discontinuous media is believed to be valuable for researchers and code developers (NSCD, DEM, DDA), 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 including 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 order to promote 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 represent by themselves a vital safety critical component (or form a crucial part) of an entire structural system and there is a growing need to be capable to predict 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 unanchored or partially anchored blocky structures in their seismic assessment.

Structural reliability and integrity assessment procedures are largely formulated for continuum structures and their direct 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 multiple-block stacks subjected to pulse base excitation. Advanced non contact optical measuring technique based on the GOM Aramis and Pontos (http://www.gom.com/metrology-systems.html) system and the corresponding processing software have been applied to replace conventional displacement measuring systems. The non smooth contact dynamics (NSCD) simulation framework SOLFEC (http://code.google.com/p/solfec/) is adopted here, which effectively ignores the high frequency content of the contact interactions.

2 Experimental set-up and simulation platform

2.1 Experimental set-up and preliminary notes

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.

The experimental setup (named ROORI-1 as an homage to Roorke and Rijeka Universities) comprised an impact device (a pin-ball mechanism with spring which is used to launch a wooden projectile) attached to an optical bench, with a teflon base and a stopper aligned to the impact device and attached to the optical bench as well (Figures 1 and 2).

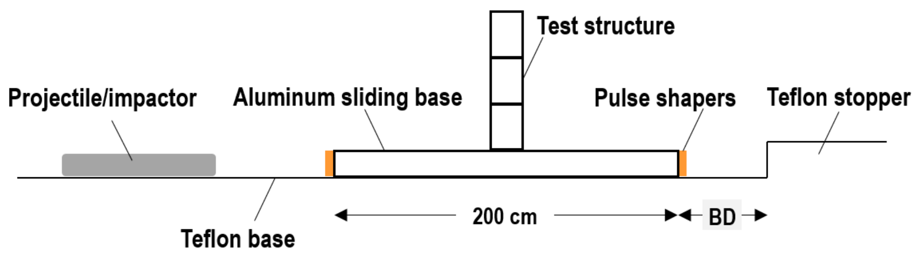

Figure 1: Experimental set-up scheme at Impact Engineering Laboratory in Oxford

A rubber cushion was glued to the front and back face of the aluminum base to act as a pulse shaper. 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 the 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 (Figure 3). Every experiment was recorded with either the Phantom or the Photron video camera with a resolution of 800x600 pixels and a frame rate of 2000 fps. The camera was triggered by a laser-beam curtain.

All of the inter blocks contact surfaces were made non smooth (to prevent sliding) by the sand paper using a standard procedure of scraping aluminium surface along the sandpaper surface. All the experiments were triggered manually and a good repeatability was achieved, however for some scenarios the responses appeared quite sensitive to small changes in initial conditions.

Every video was converted into a series of images (in .jpg format). Each series of images was post processed using GOM Aramis v6.3.1 software for optical deformation

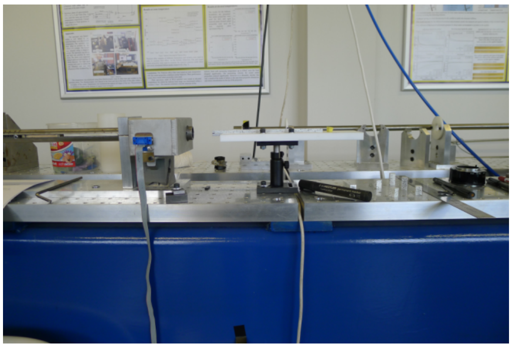

Figure 2: Experimental set-up at Impact Engineering Laboratory in Oxford

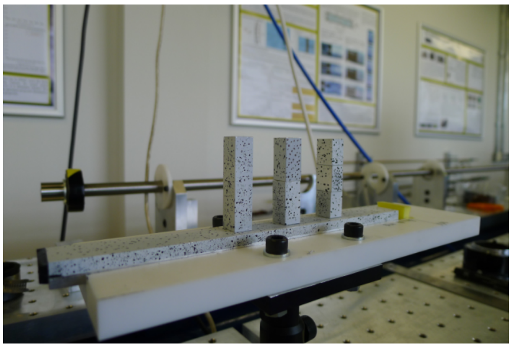

Figure 3: Test structures at Impact Engineering Laboratory in Oxford

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.

The wooden impactor used to induce the excitation was cylindrical with a length of $0.079\ m$, diameter $0.0179\ m$ and mass $0.0081\ kg$. Roughness of the base-block interface and each of the interblock surfaces was achieved by using sandpaper with P60 grit. Simple experiments showed that the interblocks and the block-base surfaces had friction coefficient of 0.54, while the friction coefficient between the base and the teflon support was 0.23. The dimensions of the base were the following: length $0.2\ m$, width $0.02\ m$ and thickness $0.01\ m$.

2.2 NSCD software Solfec

Comparative Non Smooth Contact Dynamics studies were conducted with SOLFEC, 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.

3 Controlled pulse base excitation experiments and NSCD simulations

3.1 Experiments with single blocks

A series of experiments with the pulse type base excitation and the single block aluminium samples on two different scales was carried out. The smaller scale (*Scale 1*) samples dimensions are $h_1 = 45\ mm$, $b_1 = 10\ mm$ and $l_1 = 10\ mm$, while the larger scale (*Scale 2*) dimensions are $h_2 = 90\ mm$, $b_2 = 20\ mm$ and $l_2 = 20\ mm$.

To characterize the final state of the sample on top of the aluminium base as a result of controlled pulse, each experiment and each simulation is illustrated using modes of overturning based on the outcome of the experiment (see Figure 5):

- Mode of overturning **A** if the block remained stable at the end of the experiment and

- Mode of overturning $\mathbf{B_L}$ or $\mathbf{B_R}$ if the block overturned to the left or to the right side, respectively.

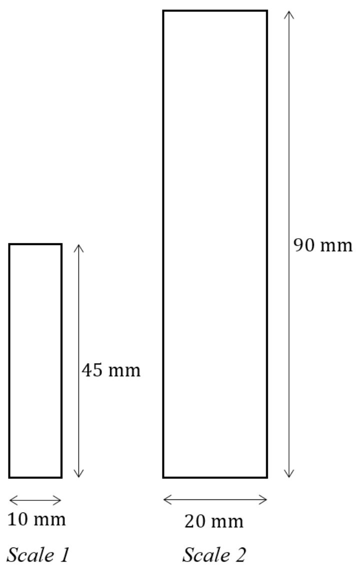

Figure 4: Samples of single block on two scales

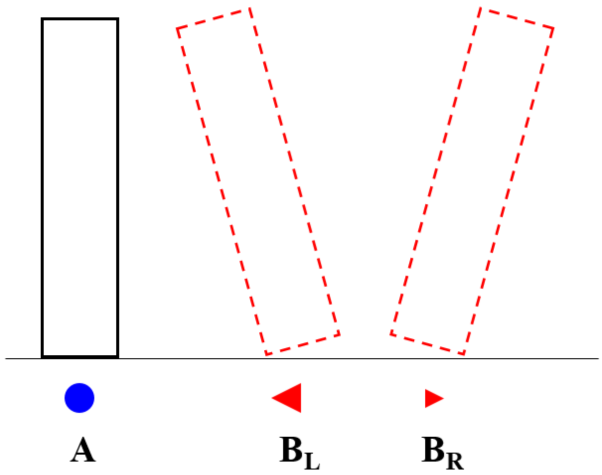

Figure 5: Modes of overturning of a single block

Scale 1

Experimental results of the overturning behaviour of a single block (*Scale 1*) due to pulse-type base excitation are shown in Figure 6 as a function of the distance between the aluminium base and the stopper on the horizontal axis and the projectile velocity on the vertical axis. For low projectile velocities the aluminium base does not reach high enough velocity to overturn the block (experiments with projectile velocity between 1 and 2 $\frac{m}{s}$ in Figure 6). For higher projectile velocities the block starts rocking but if the distance between the aluminium base and the stopper is small, the base goes through a counter-impact which results in an acceleration in opposite direction, causing the block to start rocking around the opposite corner. This behaviour of the base results in block stability even for very high projectile velocity (left part of the graph in Figure 6).

Results from computational simulations of the overturning behaviour of the previously shown experimental results are shown in Figure 7 with respect to the distance between the

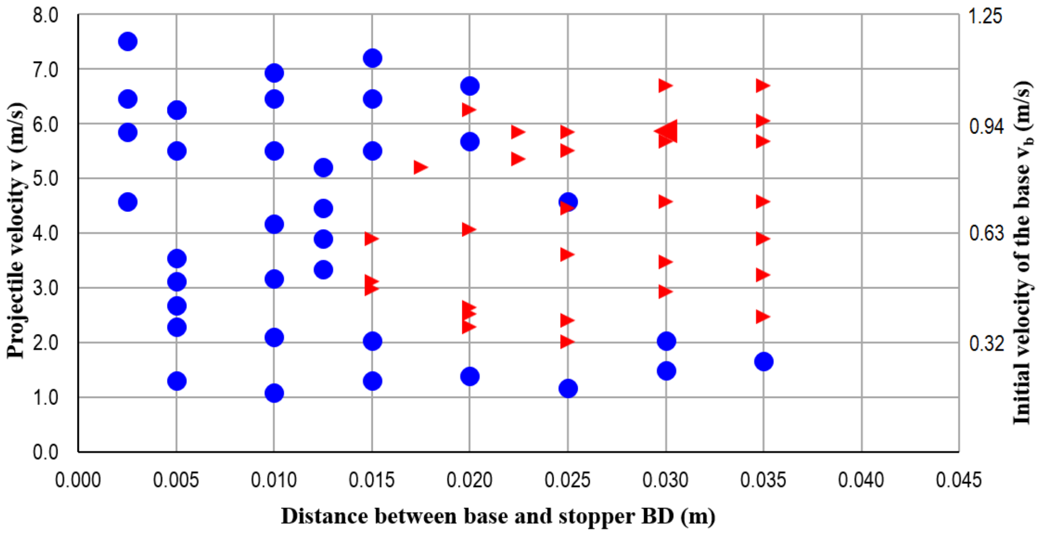

Figure 6: Modes of overturning from experiments with a single block (*Scale 1*) due to pulse-type excitation

aluminium base and the stopper on horizontal axis and the initial velocity of the aluminium base at the vertical axis. Separate restitution study concluded that the initial velocity of the base was directly proportional to the projectile velocity.

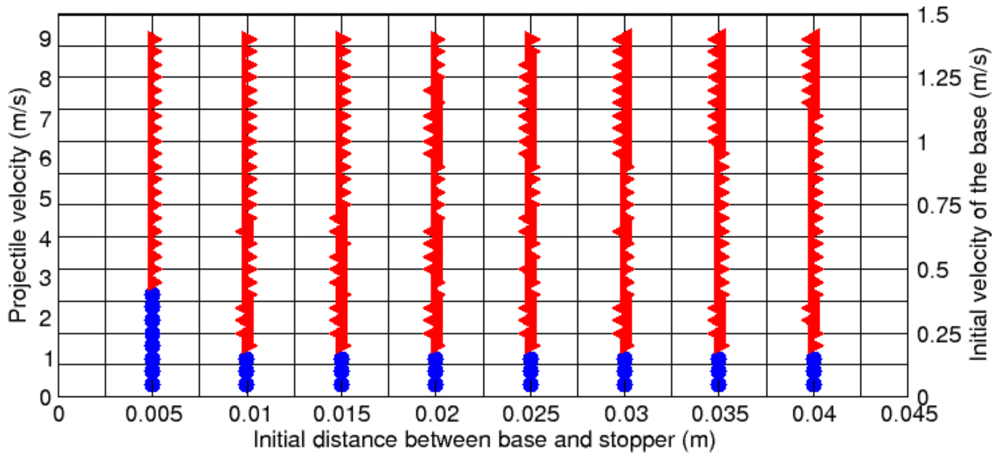

Figure 7: Modes of overturning from computational simulations of the dynamic behaviour of a single block (*Scale 1*) due to pulse-type excitation

Simulations showed overturning of the block with initial conditions which resulted in block being stable at the end of experiments. Simulations underestimate the region of stability of a single block with given dimensions.

Scale 2

Experimental results of overturning behaviour of a single block (*Scale 2*) due to pulse-type base excitation are shown in Figure 8. In comparison to the experimental results for smaller single block, as expected larger projectile velocities are required to overturn the larger block. Larger block is also more stable than the smaller one with respect to the distance between aluminium base and the stopper.

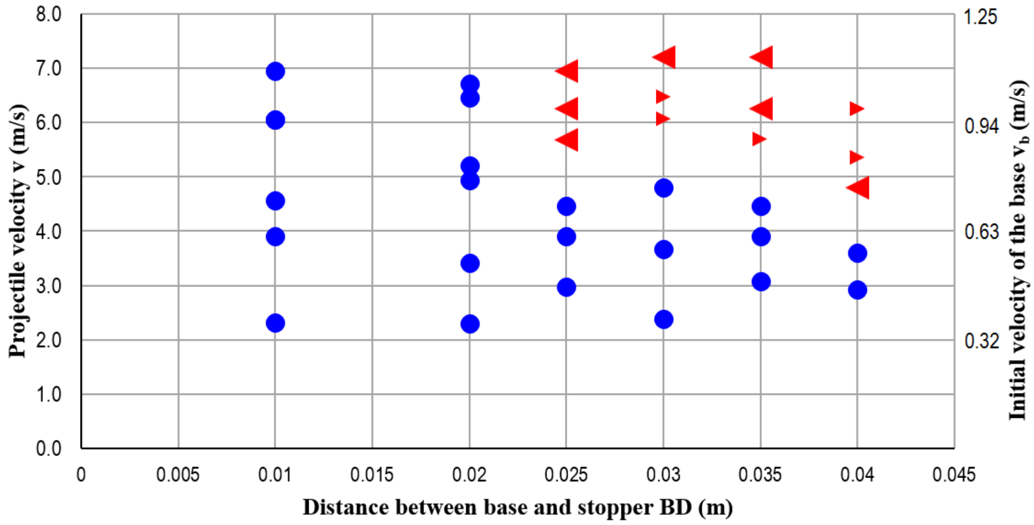

Figure 8: Modes of overturning from experiments with a single block (*Scale 2*) due to pulse-type excitation

Results from computational simulations of rocking behaviour of the previously shown experimental cases are shown in Figure 9.

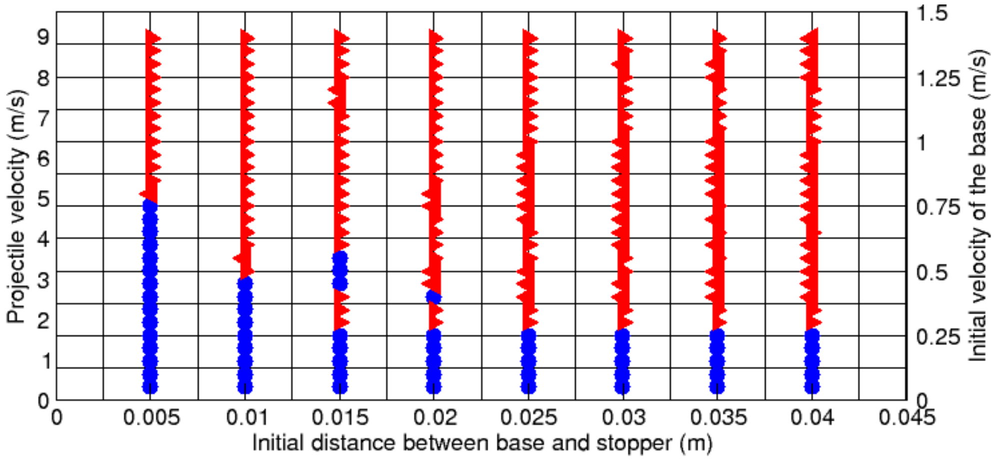

Figure 9: Modes of overturning from computational simulations of the dynamic behaviour of a single block (*Scale 2*) due to pulse-type excitation

Results from simulations are comparable to experimentally obtained results with respect to the range of distances between the base and the stopper, but experiments show that stronger impacts are required to overturn the block than the ones obtained from simulations.

3.2 Experiments with stacks of three blocks

A series of experiments with pulse type base excitation and stacks comprised of three blocks, on two different scales, set one on top of another was carried out. The smaller scale (*Scale 1*) samples dimensions are $h_1 = 15\ mm$, $b_1 = 10mm$ and $l_1 = 10\ mm$, while the larger scale (*Scale 2*) samples dimensions are $h_2 = 30\ mm$, $b_2 = 20\ mm$ and $l_2 = 20\ mm$.

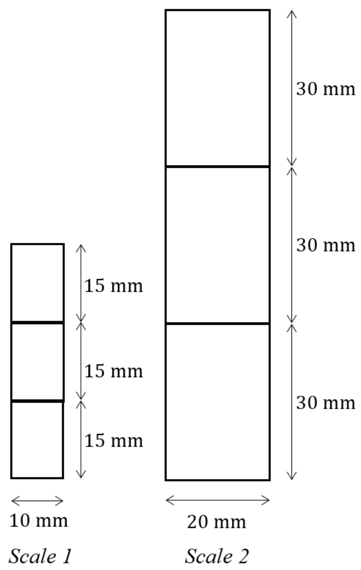

Figure 10: Sample of stack of three blocks on two scales

Each experiment and each simulation is categorised using modes of overturning based on the outcome of the experiment (see Figure 11):

- Mode of overturning **A** if all the blocks from the stack remained stable at the end of experiment,
- Mode of overturning $\mathbf{B_L}$ or $\mathbf{B_R}$ if the top block from the stack overturned to the left or to the right side, respectively,
- Mode of overturning $\mathbf{C_L}$ or $\mathbf{C_R}$ if the two upper blocks from the stack overturned to the left or to the right side, respectively, and
- Mode of overturning $\mathbf{D_L}$ or $\mathbf{D_R}$ if the whole stack overturned to the left or to the right side, respectively.

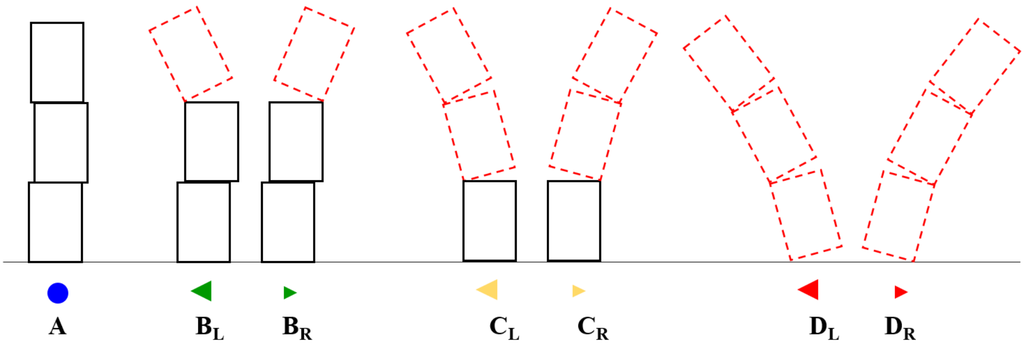

Figure 11: Modes of overturning of stack of three blocks

Scale 1

Experimental results of overturning behaviour of the stack of three blocks (*Scale 1*) due to pulse-type excitation are shown in Figure 12. Impacts with the projectile velocity lower than 3.5 $\frac{m}{s}$ are not resulting in overturning of any of the blocks. Impacts with higher velocities result in different modes of overturning (Figure 11).

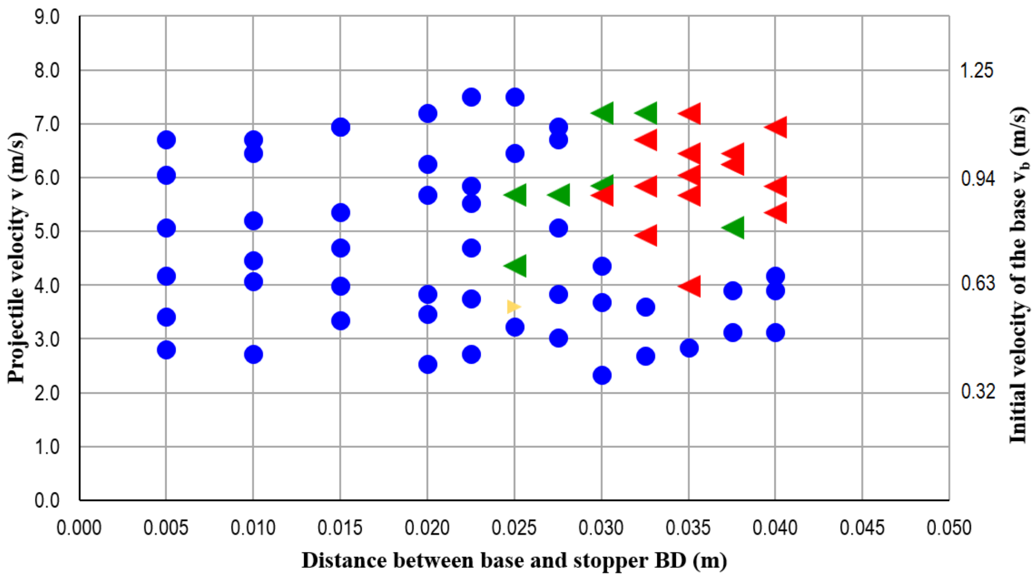

Figure 12: Modes of overturning from experiments with a stack of three blocks (*Scale 1*) due to pulse-type excitation

Results from computational simulations of rocking behaviour of the previously shown experimental cases are shown in Figure 13. Simulations underestimate the stability range of the stack of three blocks both with respect to distance between the base and the stopper and the velocity of the base (i.e. in experiments blocks remain stable for larger impact velocities). Experiments show that stronger impacts are required to overturn the block and the distance between the base and the stopper (controlling the time delay of the counter-shock) can result in stability of the stack even for stronger impacts (the left part of the graph in Figure 12 shows a stable stack, while the left part of the graph in Figure 13 shows different modes of overturning).

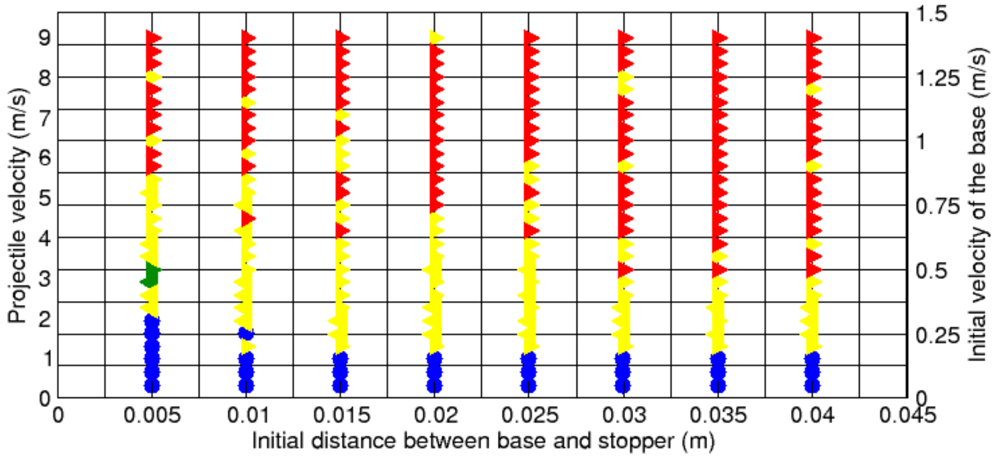

Figure 13: Modes of overturning from computational simulations of the dynamic behaviour of a stack of three blocks (*Scale 1*) due to pulse-type excitation

Scale 2

Experimental results of the overturning behaviour of a stack of three blocks (*Scale 2*) due to pulse-type excitation are shown in Figure 14. In comparison to the experimental results for the stack with smaller blocks, the stack with larger blocks requires higher projectile velocities to overturn. The stack with larger blocks indicates a larger stability region with respect to the distance between the base and the stopper.

Results from computational simulations of the overturning behaviour of the previously shown experimental cases are shown in Figure 15. Regions of stack instability obtained from simulation and experiments are comparable for the larger stack of blocks (*Scale 2*), even though modes of overturning are different.

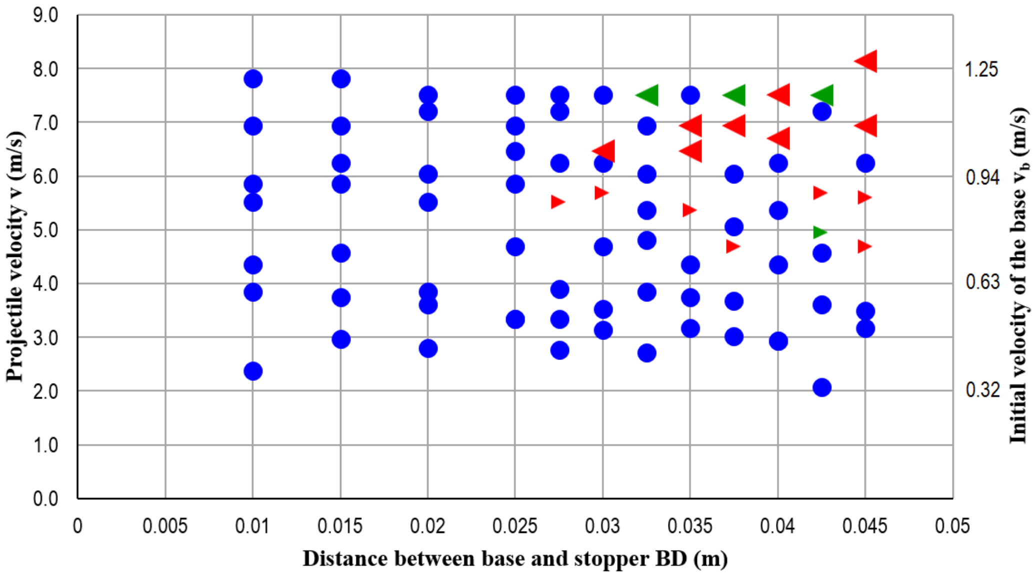

Figure 14: Modes of overturning from experiments with a stack of three blocks (*Scale 2*) due to pulse-type excitation

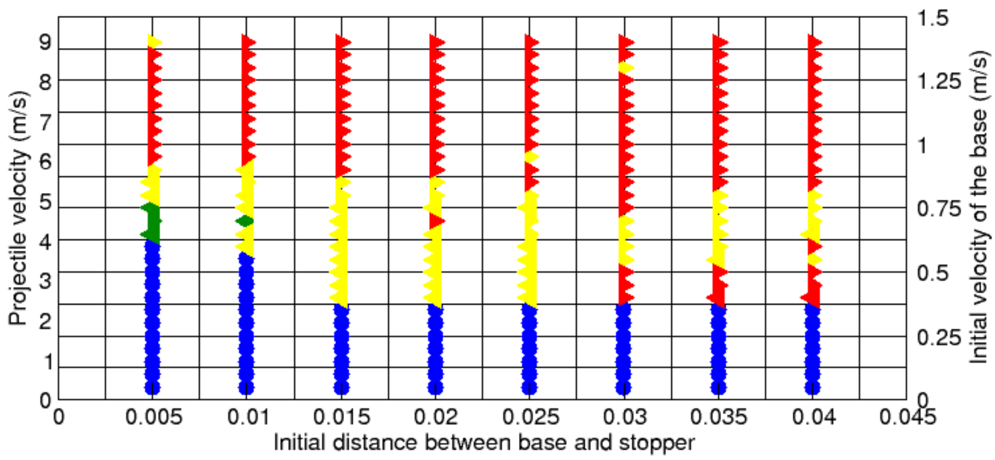

Figure 15: Modes of overturning from computational simulations of the dynamic behaviour of a stack of three blocks (*Scale 2*) due to pulse-type excitation

4 Excitation signal and detailed study of overturning modes

The excitation history comprises four parts (Figure 16):

(a) First impact between the projectile and the base (via a rubber cushion),

(b) Sliding of the base with a decrease in velocity due to friction between the base and the teflon surface,

(c) Second reverse impact between the base and the stopper (via a rubber cushion) and

(d) Sliding in the opposite direction again with a decrease in velocity due to friction between the base and the teflon surface.

Constant base acceleration of finite duration was induced by a linear velocity increase controlled by two parameters - the rise time (which was $0.25\ s$ in all simulations) and the peak base velocity.

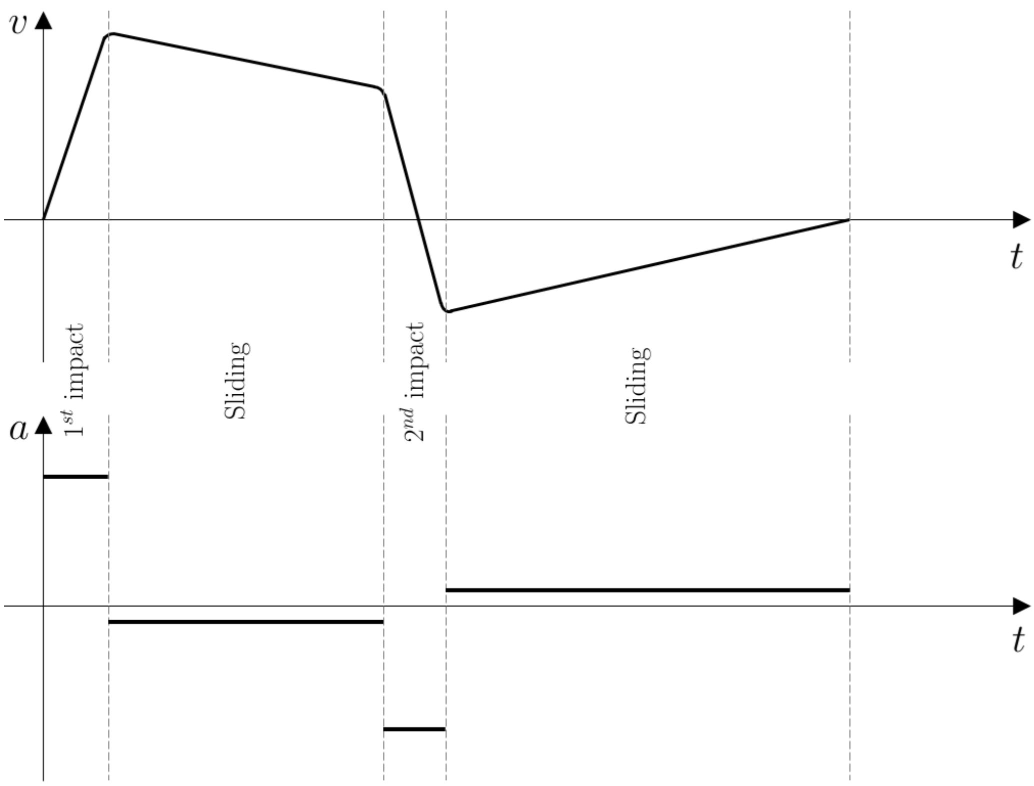

Figure 16: Base velocity history obtained from the experiments

Previous sections classified the characterisation of the final overturning modes as the outcome of an experiment or a simulation (stable, overturning forward and overturning backward), without considering how these eventual overturning modes have been achieved. Near the boundary of the stability region, it is to be expected that small changes in the excitation condition (projectile velocity and/or BD) and small perturbations may influence the overturning mode. As an illustration, Figure 17 illustrates the large differences of the eventual overturning modes for the two cases with very similar projectile velocities - these differences in the outcome are primarily associated with a different time instant of the counter-shock, which in turn is related to a larger distance between the base and the stopper.

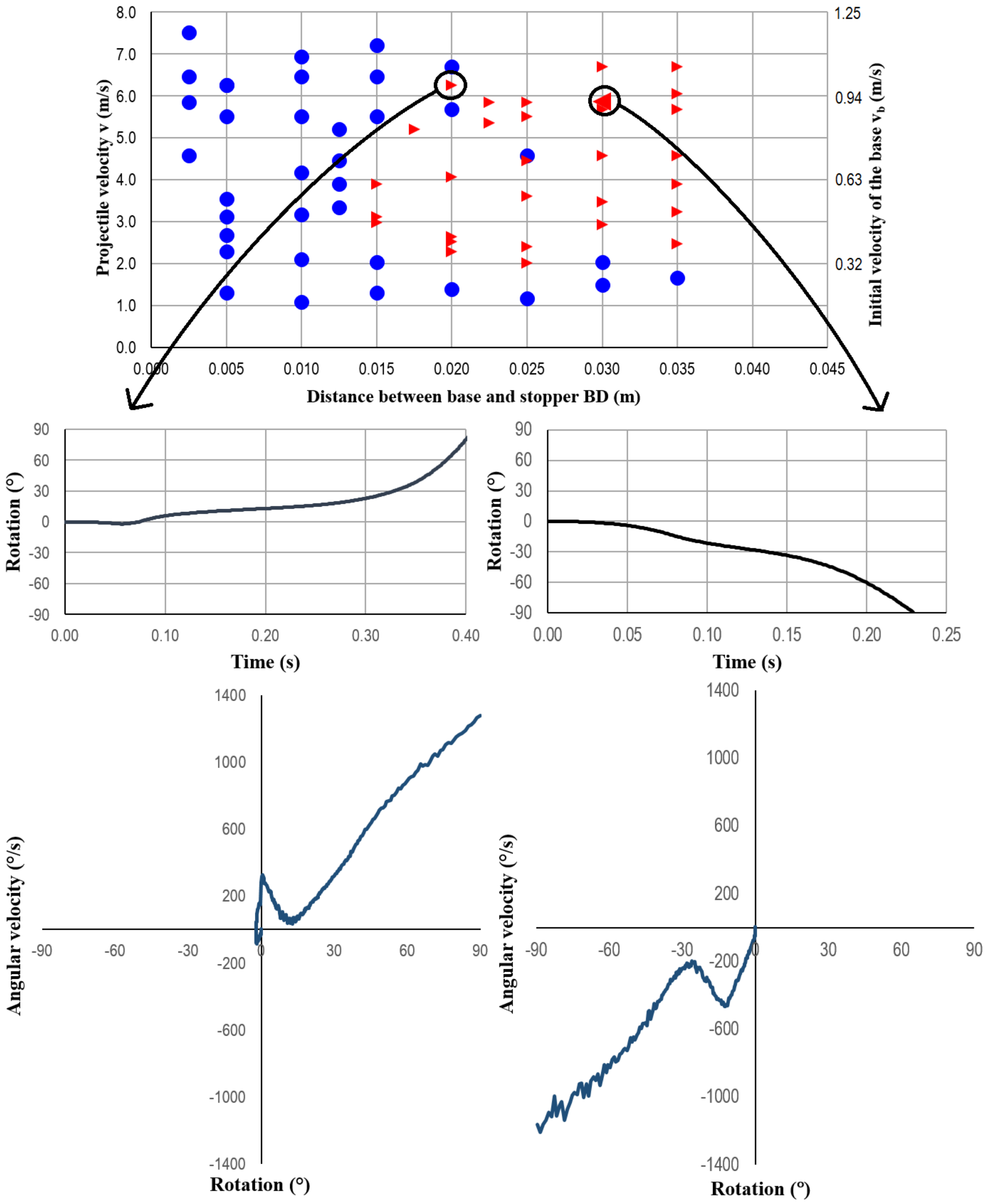

Figure 17: Rotation histories and phase-plane views of rotations from two experiments with a single block (*Scale 1*) and initial conditions BD 2 cm and $v = 6.25\ \frac{m}{s}$ (graphs on the left side) and BD 3 cm and $v = 5.86\ \frac{m}{s}$ (graphs on the right side)

The graphs on the left side of Figure 17 show the case where the block started rocking about its left edge due to the initial acceleration of the base, but when the counter-shock of the base with the stopper happened the block started rocking back and finally ended rocking around its right corner and overturning to the right side. The graphs on the right side of Figure 17 show the case with similar projectile velocity but with larger distance between the base and the stopper (hence longer time of free travel of the base), where the block started rocking around its left edge and when the counter-shock happened it started to rotate back to initial vertical position but the angular velocity at that point was such that the block ended finally overturning to the left side.

Tracing details of the overturning histories adds not only an additional angle in the interpretation of the eventual overturning modes (the time instant of the counter-shock while the block is either leaning forward or backward as a result of the initial shock) - it also provides additional more detailed information as a part of the benchmarking and validation of various simulation frameworks.

5 Conclusions

Preliminary results of both experiments and computational simulations related to single and multiple blocks overturning study due to controlled pulse excitation are shown.

The coarse characterisation of the final overturning modes was argumented by a more detailed study tracing the manner the eventual overturning modes have been achieved. Although broad agreement between experiments and simulations is achieved, further studies are needed, in particular in relation to the simulation of the dissipation mechanisms on block interfaces as well as on the block-base interface.

Acknowledgement

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