REVIEW OF LABORATORY EXPERIMENTS

"Evidence based characterization of dynamic sensitivity for multiblock structures – computational simulation and experimental validation"

(13 July – 22 July 2014, Begbroke Science Park, Impact Engineering Laboratory, Oxford)

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Rijeka, 20th of October 2014

1. Test experiments

Scheme of series of test experiments done in Oxford Impact Laboratory is shown in Figure 1. The course of the experiment was the following:

1.) Impact device (a pin-ball mechanism with spring and a wooden projectile) was attached to optical bench,
2.) Teflon base and stopper were aligned to the impact device and attached to optical bench,
3.) Foam cushion was glued to the stopper,
4.) Aluminum base was positioned at a defined distance from the stopper (BD – distance between the aluminum base and the stopper within which is the foam cushion),
5.) Rubber cushion was glued to the aluminum base,
6.) A single block was glued on top of aluminum base,
7.) Pin-ball mechanism was used to launch the wooden projectile.

Every experiment was recorded with Phantom video camera with resolution of 800x600 pixels and frame rate of 2000 fps. The camera was triggered by laser-beam curtain.

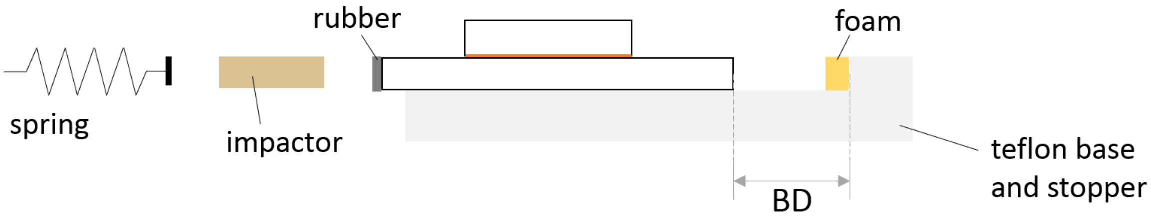

Figure 1. Scheme of series of test experiments

List of test experiments is the following:

IM – mark for spring deformation; BD – distance between aluminum base and stopper
IM 6 BD 2
IM 8 BD 2
IM 10 BD 2
IM 10 BD 3
IM 12 BD 2
IM 12 BD 3
IM 14 BD 3
IM 16 BD 3

Test experiments were carried out as a brief study of repeatability of the launch of wooden projectile. Since the pin-ball mechanism is based on spring deformation energy it is possible to calculate the energy from spring deformation (blue dashed line in Figure 2). Another way to measure energy of the projectile after launch is to measure its velocity, which was measured using two laser curtains at distance of 25 mm (red dashed line in Figure 2). Last, projectile energy transformed to the system with aluminum base and block after the impact can be obtained from the measured velocity of the system just after the impact. There is an instant loss in energy during the launch of the project as well as during the impact of projectile with the base.

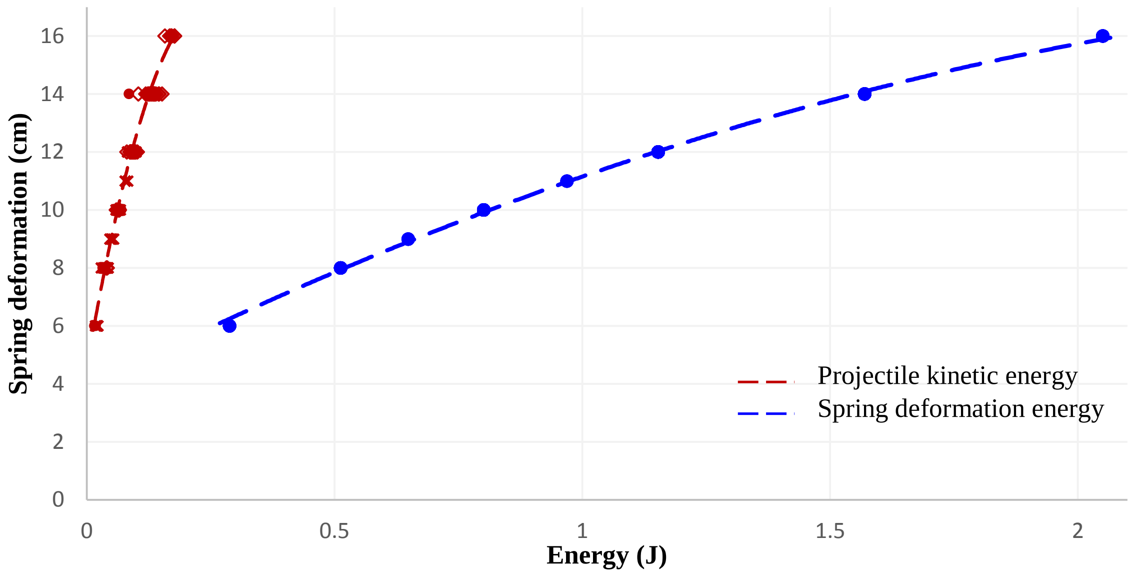

Figure 2. Dependance of energy in the system on deformation of the spring in pin-ball mechanism

Figure 2 shows there is a large difference in projectile kinetic energy level and spring deformation energy level. During the launch of the projectile, certain amount of energy is conserved in the system as spring kinetic energy because the used spring consists of four segments that are not interconnected. Certain part of energy is lost from the system due to friction between projectile and tube within which the launch happened. Approximately 91,4 % of spring deformation energy is lost or conserved in the spring and only about 8,6 % was transferred to kinetic energy of the projectile (Figure 3 and Figure 4).

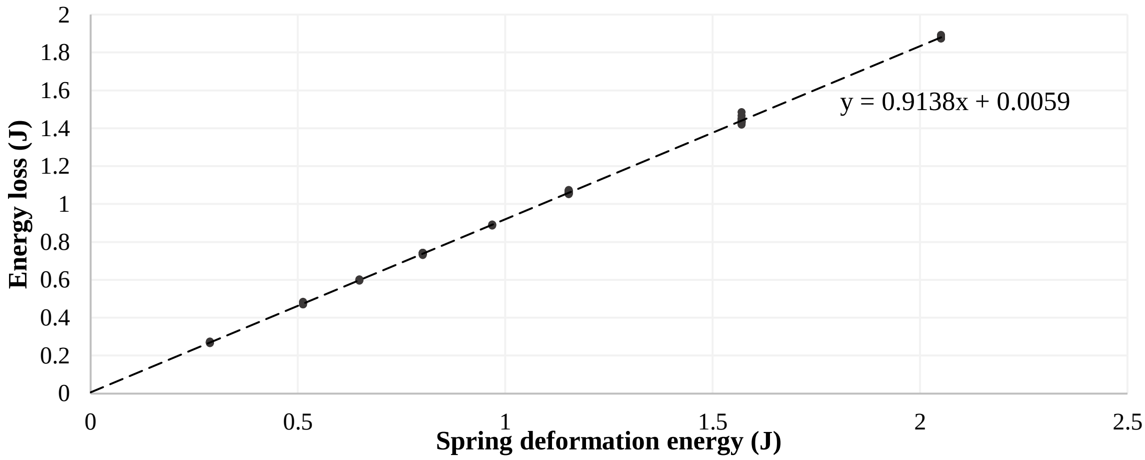

Figure 3. Energy loss during projectile launch compared to spring deformation energy

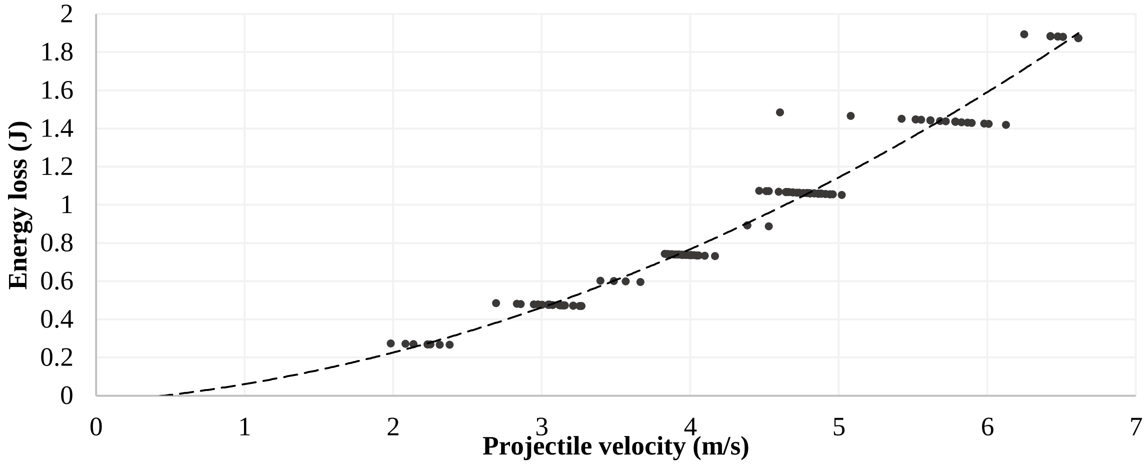

Figure 4. Energy loss during projectile launch compared to projectile velocity

2. Experiment series without side-walls

2.1. Experiments

2.1.1. Methodology and list of set-ups

Scheme of series of experiments done in Oxford Impact Lab (with either one, two, three or five aluminum blocks settled on the aluminum base) is shown in Figure 5. The course of the experiment was the following:

1.) Impact device (a pin-ball mechanism with spring and a wooden projectile) was attached to optical bench,
2.) Teflon base and stopper were aligned to the impact device and attached to optical bench,
3.) Foam cushion was glued to the stopper,
4.) Aluminum base was positioned at a defined distance from the stopper (BD – distance between the aluminum base and the stopper within which is the foam cushion),
5.) Rubber cushion was glued to the aluminum base,
6.) 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),
7.) Pin-ball mechanism was used to launch the wooden projectile.

Every experiment was recorded with Phantom video camera with resolution of 800x600 pixels and frame rate of 2000 fps. The camera was triggered by laser-beam curtain.

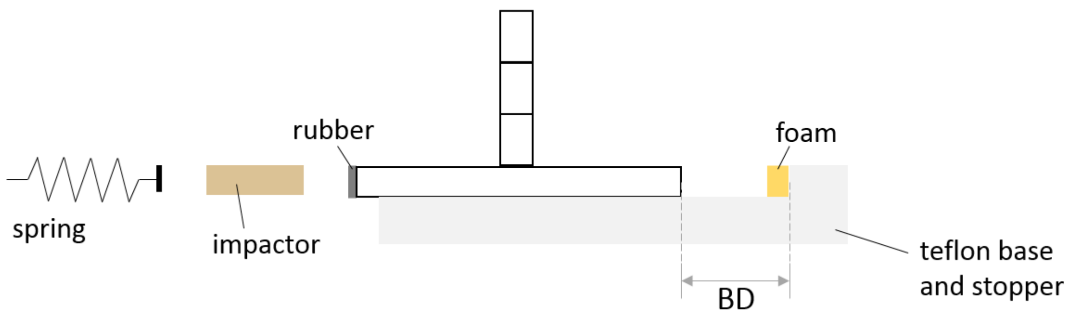

Figure 5. Scheme of series of experiments of dynamic sensitivity of multiblock structures

Dimensions of the block and stack of two or three blocks used in experiments are shown in Figure 6.

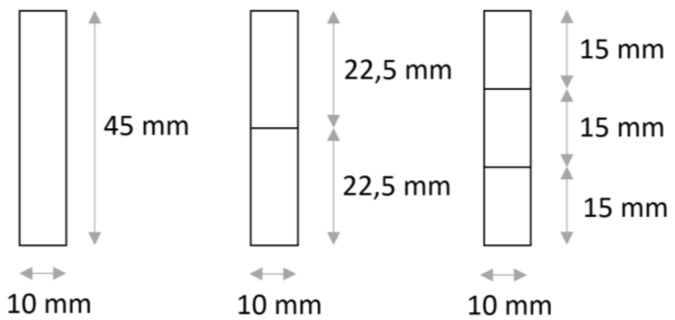

Figure 6. Dimensions of one block and stacks of two or three blocks used in experiments

First all the contact surfaces between each of the blocks and bottom block and base were smooth. List of experiments with all contact surfaces (between the blocks and blocks and base) smooth is the following:

Number of blocks	IM – mark for spring deformation; BD – distance between aluminum base and stopped
1	IM 6 BD 2 IM 8 BD 2 IM 10 BD 2 IM 12 BD 2
2	IM 9 BD 3 IM 11 BD3 IM 12 BD3
3	IM 8 BD 3 IM8 BD 4 IM10 BD 3 IM 10 BD 4
5	IM 8 BD 2

Than the contact surfaces were roughened using sand paper and a standard procedure of scraping aluminum surface along the sandpaper surface shaping trajectories in shape of number eight. List of experiments with all contact surfaces roughened is the following:

Number of blocks	IM – mark for spring deformation; BD – distance between aluminum base and stopped
1	IM 6 BD 2 IM 10 BD 1 IM 10 BD 2
2	IM 9 BD 3
3	IM 8 BD 3 IM8 BD 4 IM10 BD 3

Each set-up of the experiment was repeated three times. A comparison between three repetitions shows repeatability of initial conditions as well as repeatability of dynamic behavior of the blocks.

2.1.2. Repeatability and improvements to be made

Since all the experiments were triggered manually a high level of variation in initial conditions can be present due to human influence. Furthermore, there are imperfections in the methodology and used equipment that can cause variations in level and nature of dynamic excitation introduced to the system even though it is a result of equal initial conditions. A repeatability study based on results after post-processing videos of all the experiments is shown below.

2.2. Post-processing using Aramis v6.3.1-0

Every video was extracted into 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.

2.2.1. Limitations and level of accuracy

Since the resolution of the images in this case is 800x600 pixels, each pixel represents approximately 0,18 mm. Aramis divides each image into facets (areas with dimensions defined by number of pixels in each direction). Regarding this, it should be defined what the optimal size of facets to be used in post processing is. Facet size depends on speckle pattern, pixel size and scale in which a behavior is observed. [1]

From Figure 7 it can be seen that the largest single color area in pattern on block surfaces is approximately of size 2x2 mm^2, thus minimum size of a facet which satisfies the condition that there is at least one dark spot in each facet is approximately 12x12 pixels.

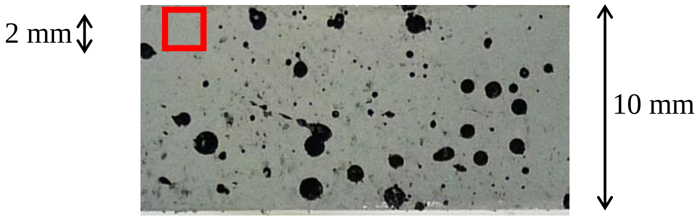

Figure 7. Representative pattern area and density of speckle

When it comes to rigid body motion, maximum facet size is limited by size of rigid bodies which are observed.

A comparison of results for displacements of bottom block from stack of three blocks obtained using three different sizes of facets is shown in Figure 8. Aramis analysis with facet size 10x10 pixels (blue marks in Figure 8) wasn't able to obtain results from every figure from video. Analyses with facet sizes 18x18 and 30x30 pixels (red and green marks in Figure 8) resulted in complete set of data obtained from each figure from video with maximum difference between the results within 0,1 mm.

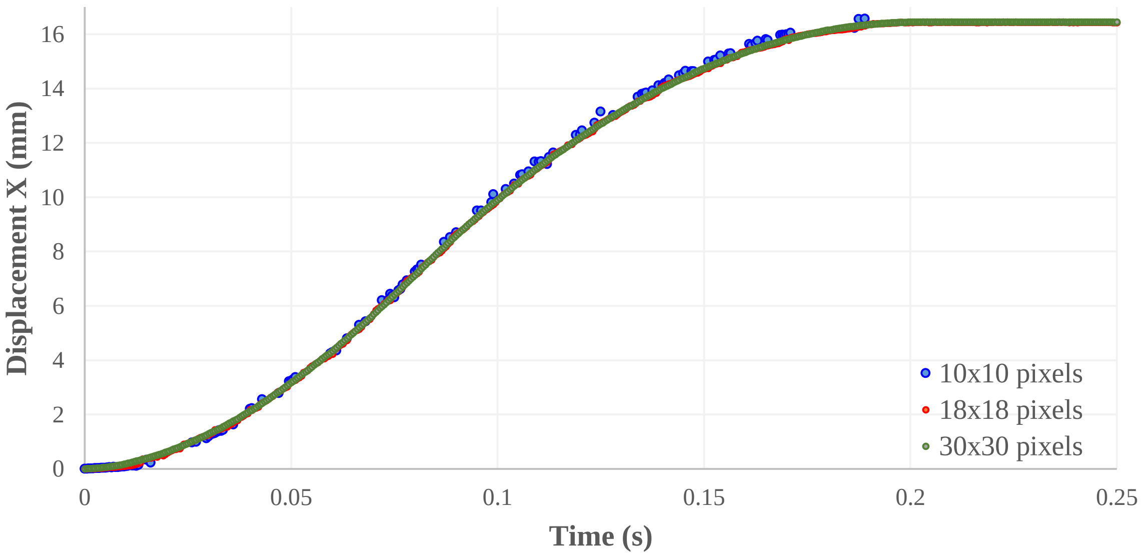

Figure 8. Displacement of bottom block from stack of three blocks in experiment B3_IM10_BD4

When obtaining displacement velocity by differentiating displacement data lower amount of noise is noticed when using larger facets, which is shown in Figure 9. Displacement velocity obtained using facet size 10x10 pixels shows largest dissipation of results, while displacement velocity obtained using facet size 30x30 pixels shows distinctly shows a trend line.

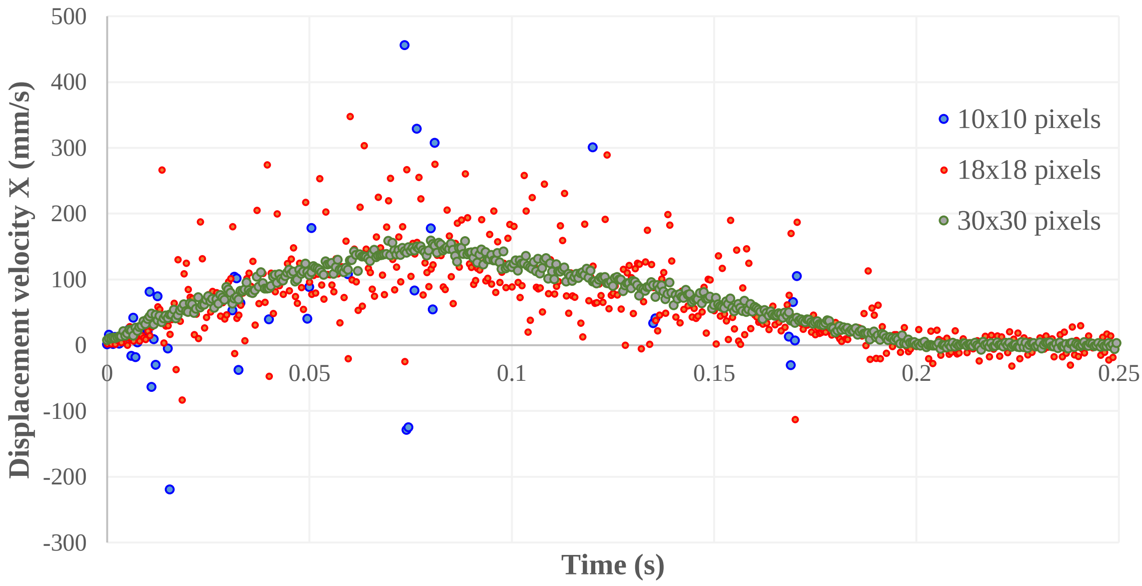

Figure 9. Displacement velocity of bottom block from stack of three blocks in experiment B3_IM10_BD4

Another advantage in using larger facets is shorter analysis time, provided that facet step size is not varied, because there is less points in which Aramis calculates results.

If post-processing is done correctly and an appropriate facet size is used, results obtained from Aramis usually show noise level within ±0,1 mm [1] and deviation from results obtained using standard measuring methods (such as LVDTs and micrometers) within 5 % [?].

2.2.2. Results

As already stated, displacement data is directly obtained from Aramis software. Velocities and accelerations are then calculated using numerical differentiation. For this reason low amount of noise in displacement data results in high amount of noise in velocity and acceleration data.

As a repeatability study four repetitions of experiment with three aluminum blocks settled on aluminum base with smooth contacts B3_IM10_BD4 is shown below (Figure 10). Velocity of the projectile in these four repetitions is the following:

Experiment	Repetition	Velocity of projectile (m/s)
B3_IM10_BD4	1	3,894
	2	3,906
	3	3,975
	4	4,001

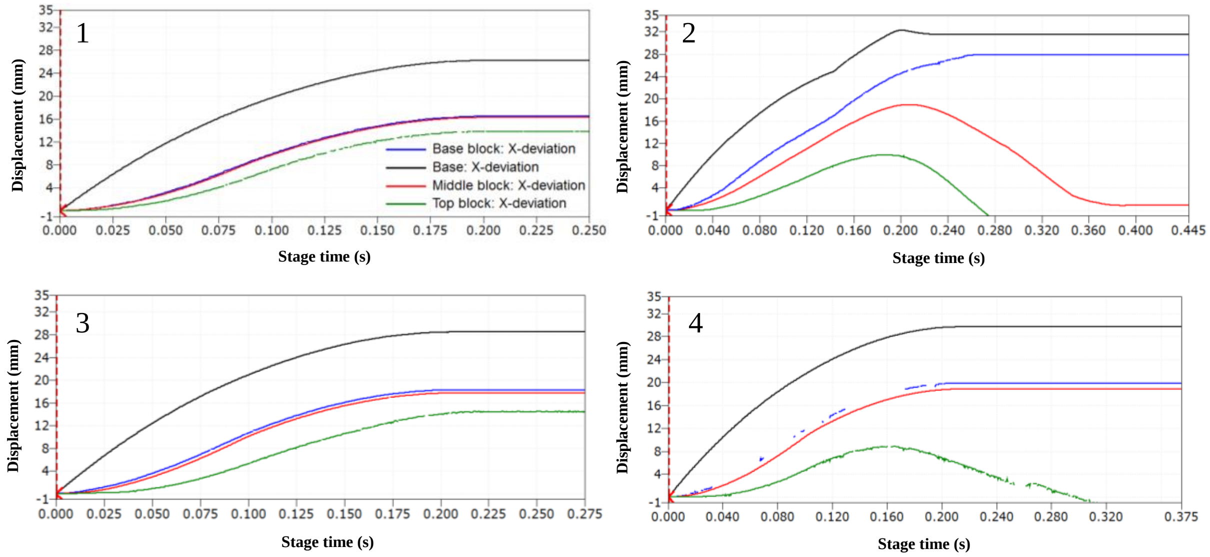

Figure 10. Displacement of base, bottom, middle and top block from four repetitions of experiment B3_IM10_BD4

In search of a parameter that could enable dynamic characterization of discontinuous blocky structures, a form of synthesis of results obtained from experiments is suggested. In this synthesis only the outcome of each experiment carried out is observed. Configuration of the stack of three blocks at the end of the experiment is used to classify each experiment into one of four possible modes of failure defines as follows (Figure 11):

- Mode A – stack of three blocks is stable,
- Mode B – top block from stack of three blocks has fallen as a result of either rocking, sliding or combined motion,
- Mode C – top and middle blocks from stack of three blocks had fallen as a result of either rocking, sliding or combined motion,
- Mode D – whole stack of three blocks has collapsed as a result of either rocking, sliding or combined motion.

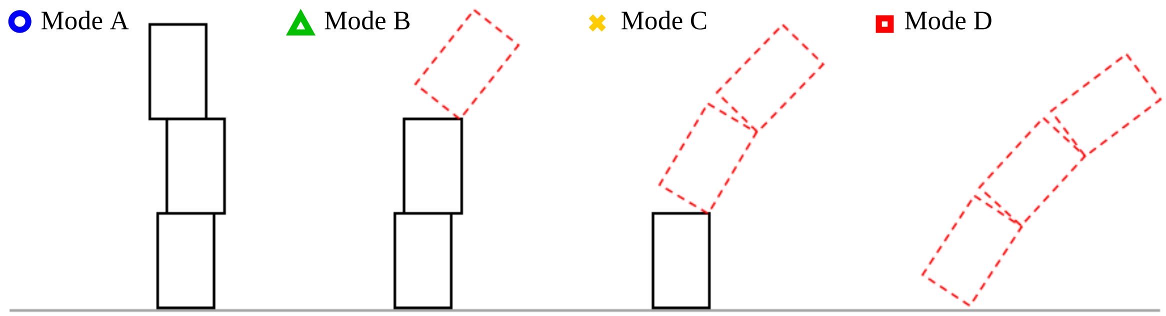

Figure 11. Modes of failure of stack of three blocks

It is expected that mode of failure is related to amplitude and duration of dynamic. Deformation of the spring in pin-ball mechanism (IM) indirectly produces kinetic energy put into system via impact between projectile and aluminum base. This corresponds to the first dynamic excitation and is quantified using projectile kinetic energy below. Impact of the aluminum base with the stopper (via foam cushion) corresponds to second dynamic excitation or a counter-excitation. Counter-excitation depends on the distance between aluminum base and the stopper (BD), as well as the amplitude of the first excitation. Counter-excitation can exist or not exist since in some cases the base settles before ever reaching the stopper. For this reason, the counter-excitation is quantified in two ways: with only distance between aluminum base and stopper and with kinetic energy of the system just before the impact with the stopper obtained from estimating the translational velocity of the system at that moment from Aramis' velocity time-history (from raw results with high level of noise).

Mode of failure in all the experiments with stack of three blocks with all contacts smooth, therefore with dominant sliding motion, with respect to kinetic energy of the projectile and distance between base and the stopper is shown in Figure 12, while the same is plotted with respect to base kinetic energy just before impact between base and stopper on horizontal axis in Figure 13.

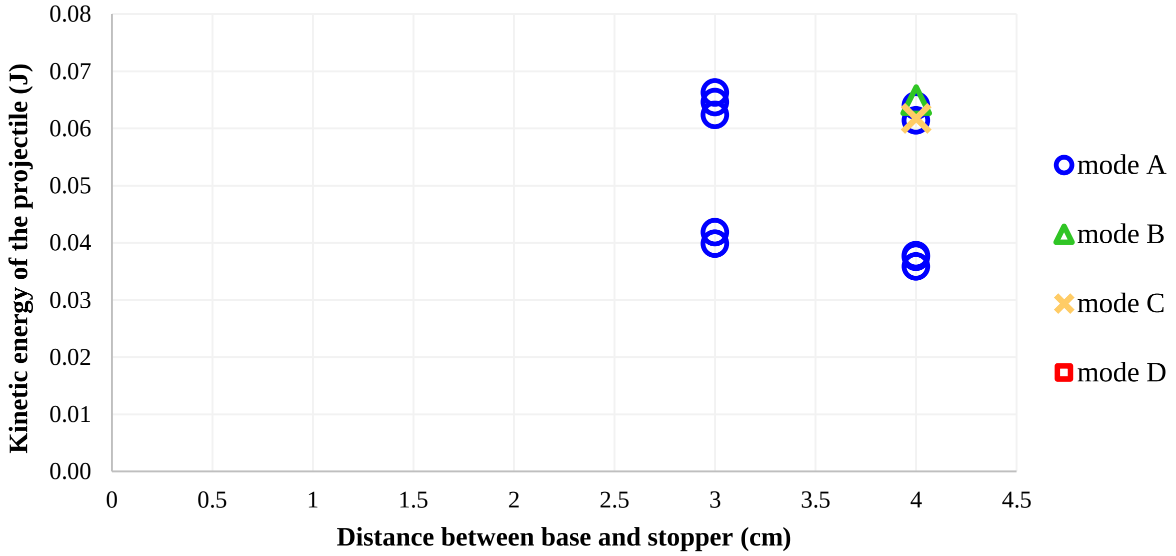

Figure 12. Modes of failure of stack of three blocks with all contacts smooth related to kinetic energy of the projectile and distance between aluminum base and stopper

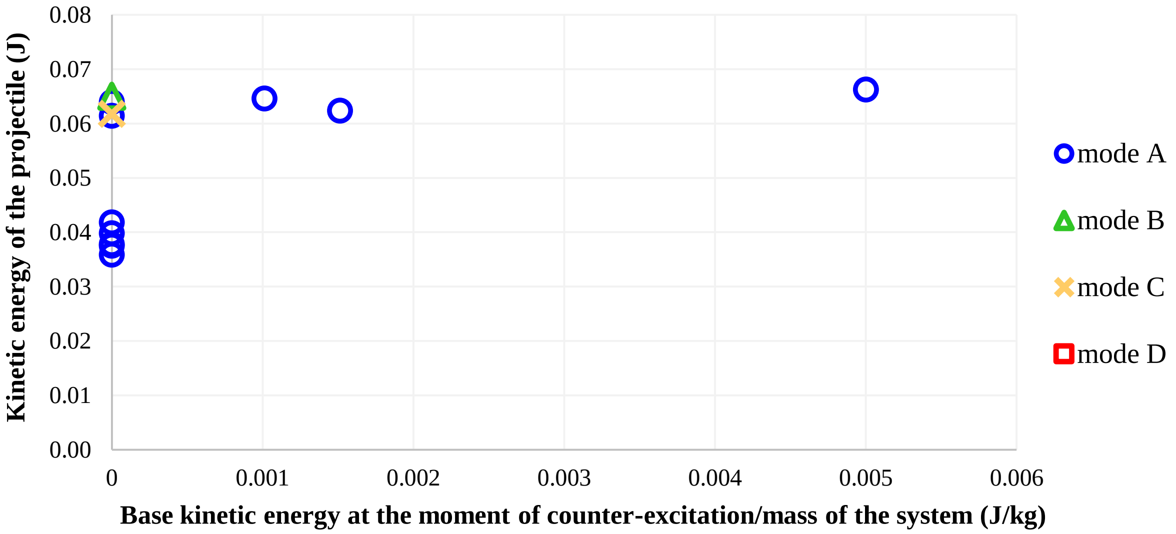

Figure 13. Modes of failure of stack of three blocks with all contacts smooth related to kinetic energy of the projectile and counter-excitation

Mode of failure in all the experiments with stack of three blocks with all contacts roughened, therefore with dominant rocking motion, with respect to kinetic energy of the projectile and distance between base and the stopper is shown in Figure 14.

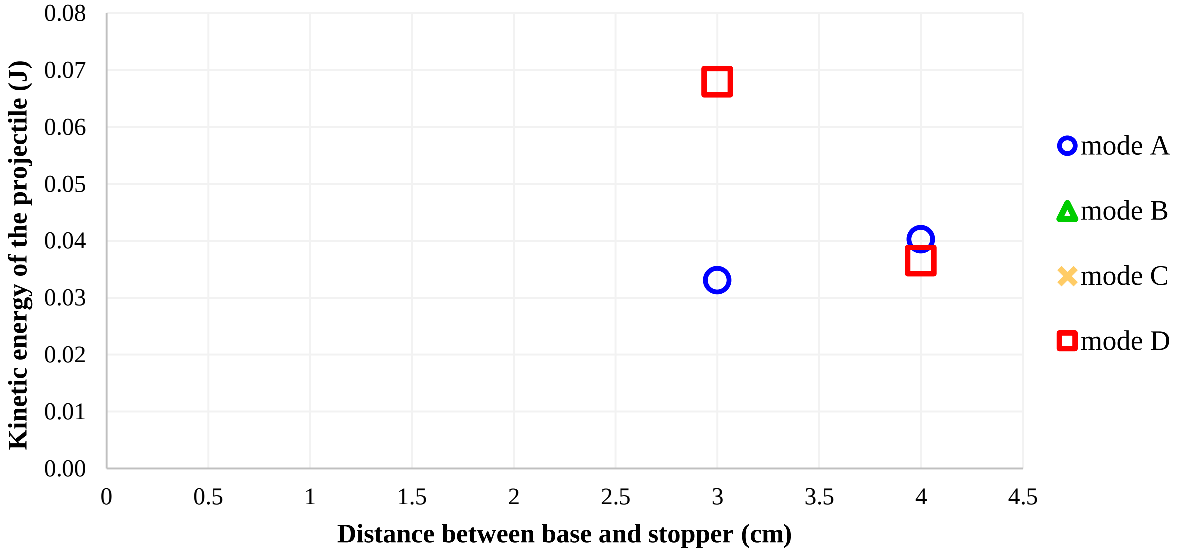

Figure 14. Modes of failure of stack of three blocks with all contacts roughened related to kinetic energy of the projectile and distance between aluminum base and stopper

3. Experiment series with side-walls

Scheme of series of experiments done in Oxford Impact Lab (with either one, two, three or five aluminum blocks settled between side-walls on the aluminum base) is shown in Figure 15. The course of the experiment was the following:

1.) Impact device (a pin-ball mechanism with spring and a wooden projectile) was attached to optical bench,
2.) Teflon base and stopper were aligned to the impact device and attached to optical bench,
3.) Foam cushion was glued to the stopper,
4.) Side-walls were attached to the aluminum base,
5.) Aluminum base was positioned at a defined distance from the stopper (BD – distance between the aluminum base and the stopper within which is the foam cushion),
6.) Rubber cushion was glued to the aluminum base,
7.) 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),
8.) Pin-ball mechanism was used to launch the wooden projectile.

Every experiment was recorded with Phantom video camera with resolution of 800x600 pixels and frame rate of 2000 fps. The camera was triggered by laser-beam curtain.

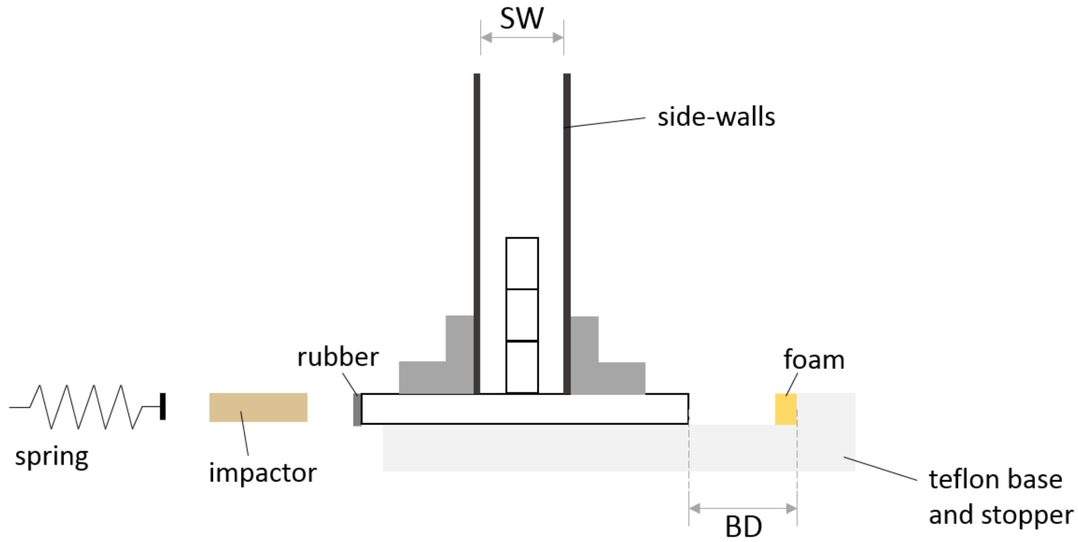

Figure 15. Scheme of series of experiments of dynamic sensitivity of multiblock structures between side-walls

List of experiments with all surfaces smooth is the following:

Number of blocks	SW – distance between side-walls	IM – mark for spring deformation; BD – distance between aluminum base and stopped
3	2,5	IM 8 BD 4 IM10 BD 4 IM12 BD2 IM 12 BD 3 IM 12 BD 4 IM 14 BD 2 IM 14 BD 3

		IM 14 BD 4 IM 16 BD 3
3	3,0	IM 10 BD 4 IM 12 BD 2 IM 12 BD 3 IM 12 BD 4 IM 14 BD 2 IM 14 BD 3 IM 14 BD 4 IM 16 BD 3
5	3,0	IM 16 BD 2

Than the contact surfaces were roughened using sand paper and a standard procedure of scraping aluminum surface along the sandpaper surface shaping trajectories in shape of number eight. List of experiments with all surfaces roughened is the following:

Number of blocks	SW – distance between side-walls	IM – mark for spring deformation; BD – distance between aluminum base and stopped
3	2,5	IM 9 BD 2 IM 12 BD 2 IM 12 BD 3 IM 14 BD 3
3	3,0	IM 12 BD 2
5	3,0	IM 12 BD 2

Each set-up of the experiment was repeated three times. A comparison between three repetitions shows repeatability of initial conditions as well as repeatability of dynamic behavior of the blocks.

3.1. Results from Aramis

List of references

1.) Picker, V., Optimisation and Validation of the ARAMIS Digital Image Correlation System for use in Large-scale High Strain-rate Events, Maritime Division, Defence Science and Technology Organisation, Australia, 2013