

École polytechnique de Louvain

Small-scale shake table tests of 2D blocky assemblies: design, experimental testing, and camera-based block tracking

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Academic year 2022–2023

Master [120] in Civil Engineering

Acknowledgements

Before getting to the heart of the matter, I would like to thank all those who have contributed to the success of this thesis and to the wonderful five years of study that led up to it. This journey was full of ups and downs but the people who accompanied me made it more enjoyable by generously offering their support, encouragement and guidance.

First of all, I would like to express my special gratitude to my esteemed supervisors, João Saraiva Esteves Pacheco de Almeida and Michele Godio, whose precious guidance, unfailing support and responsiveness to my inquiries were crucial in making this thesis possible. Their knowledge in the field and willingness to provide feedback at any stage of the process greatly contributed to the quality of this work.

Then, I would like to extend my sincere appreciation to Stefania Lo Feudo, who not only served as my reader but also assumed the role of a dedicated supervisor. Without her contributions, half of this work would never have seen the light of day. Despite her incredibly busy schedule, she has often invested her time to help me achieve this work. Every comment she offered held immense relevance, showcasing her expertise and profound understanding of the subject matter.

Moreover, I would like to express a special thank to Igor Bouckaert, my fabulous and esteemed co-supervisor. Igor's availability at any time, his exceptional ability to understand my feelings and his positive outlook have been fundamental in helping me overcome challenges and stay motivated. His guidance has left a lasting impact, and I am truly fortunate to have had him as a mentor throughout this journey.

Next, I would like to thank Alex Bertholet for his availability and ability to respond to each of my requests, and above all for our long discussions, Sophie Labrique and Masoumeh Ebrahimi for their kindness and generosity in respectively lending me the material to setup the recording and the cameras to record my experiments.

It is impossible to forget to mention the precious support of Marine Poudrel and Héloïse Nolf, members of the Makilab who became friends, for their patience to teach me how to use the laser cutting machine and for the discussions and laughter during the long hours confined in the lab.

Moving forward, I would like to thank all of my friends - whether from school or beyond - who have been instrumental in my success by answering my questions, explaining difficult concepts or simply providing a friendly ear when I needed it.

Last but certainly not least, I would like to thank my beloved family for their love, support, and encouragement. Mom and dad, I cannot thank you enough for your sacrifices, your unwavering belief in me, and your constant encouragement to pursue my passions. Bélinda, your energy has always been a source of happiness that putted smiles on my face during the most challenging times. I want to express my profound gratitude and love to you all for being my rock throughout this journey.

PS : the creator of ChatGPT also needs to be thanked for this life-changing invention that helped me improve the overall quality of this work.

Abstract

In recent years, the world has witnessed a rise in the frequency of natural disasters, largely attributed to increasing greenhouse gas emissions. Among these disasters, earthquakes represent the most devastating one, resulting in human casualties and extensive material damage. Unreinforced masonry (URM) is the most commonly used construction materials around the world thus it is particularly important to study and understand its behavior under seismic conditions. The advancement of earthquake engineering plays a crucial role in assessing existing structures and designing resilient new ones.

The main objective of this thesis is to contribute to the knowledge and understanding of 2D small scale dry-stacked masonry assemblies subjected to earthquake loading. The tests carried out in this thesis hold significant value as they represent the first experimental verification for this particular type of structure. Indeed, these tests serve a crucial role in validating the precision and reliability of the numerical simulations as documented in prior research papers. This validation is achieved by comparing acceleration values and rocking phenomenon through both numerical and experimental testing methodologies.

The testing process involves crafting blocks through laser-cut wooden pieces, assembling them into hollow structures, and filling them with coarse sand. The investigation continues by assessing the capabilities of the brand new shake table, known as ATOM, to determine the critical acceleration causing a rocking phenomenon in these assemblies, ultimately leading to collapse. Verification of the recorded acceleration values is achieved through a comparison between the data from the shake table software and those obtained from an external accelerometer placed on the structure.

Beyond shake table testing, this thesis employs a multi-faceted IT approach that includes image undistortion, extraction, and analysis. By tracking the positions of pairs of targets affixed to each full brick throughout the experiments, a dedicated tracking code computes the actual displacements of the bricks during the entire testing procedure. These displacement data are then used to accurately represent the behavior of each structure under dynamic loading conditions.

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Chapter 1

Introduction and Objectives

1.1 Motivation

In recent years, the world has witnessed a significant rise in the frequency and intensity of natural disasters, mainly due to the alarming increase in greenhouse gas emissions. Among these calamities, earthquakes stand out as one of the most devastating and unpredictable disasters. Even though seismic events are not new phenomena, the impact due to their sudden and violent movements can be devastating often resulting in major economic losses and tragic loss of life.

Recent studies have identified Wallonia and its neighboring regions as areas in Europe with a potential for substantial economic losses due to their extensive exposure and vulnerability to earthquakes [1]. In these regions and even in many others across the world, the architectural heritage predominantly comprises Unreinforced Masonry (URM) houses, owing to its abundance, ease of production, and cost-effectiveness [2] [3].

The seismic event that struck the city of Liege in 1983 serves as a poignant reminder of the destructive power of earthquakes. During this earthquake, around 16,000 houses were damaged and an astonishing 95% of these structures were built using masonry [4]. This historical disaster makes it vital to assess the structural behavior of typical masonry houses in this identified area to predict and prevent potential damage in future low- to medium-intensity earthquakes.

As we look to the future, it becomes imperative to comprehend and mitigate the risks associated with earthquakes. Advancements in earthquake engineering, combined with a deep understanding of masonry wall behavior, will pave the way for targeted retrofitting strategies and improved building codes.

1.2 Research Novelty and Objectives

The field of earthquake engineering has limited documentation on dynamic experimental testing of small scale masonry assemblies using a shake table. However, this thesis seeks to address this gap by conducting dynamic tests on such masonry assemblies with the innovative shake table ATOM. The originality of this research lies in its contribution to the scarce body of documentation on experimental trials, marking the first-ever experimental validation for several numerical simulations conducted on 2D masonry assemblies.

Additionally, this thesis aims to evaluate the reliability of the shake table ATOM, which has not been previously used for testing small scale masonry structures. This thesis will also assess the reliability of filled wooden blocks to accurately replicate the behavior of real masonry structures.

Moreover, this thesis will incorporate a computer-oriented approach by developing a customized code for target tracking. This code will accurately assess the displacements of individual targets throughout the entire testing process, thereby enhancing the precision of numerical evaluations and modeling of the masonry assemblies' behavior under dynamic loading conditions. This integration of computer-oriented analysis further enhances the significance and comprehensiveness of the research findings.

1.3 Organization of the Thesis

This document begins by presenting the current state of research in small scale masonry assemblies. In the third chapter, we describe the experimental setup developed for testing small-scale blocky assemblies as well as the followed testing procedure. We also explain the device configuration and measurement instruments used to record relevant data. Chapter four involves implementing a code for a target tracking application. We explain the whole computer oriented process going from camera calibration to displacement and rotation calculation. Then, in the fifth chapter, we analyze experimental results from small-scale blocky assemblies tests and compare them with numerical simulations. Lastly, we summarize our findings regarding small-scale masonry assemblies' seismic behavior. We highlight the significance of our results for understanding and enhancing masonry structures. Furthermore, we discuss opportunities to improve experimental and numerical methodologies for future research in this field, concluding the document with the future directions of our work.

Chapter 2

State of Art

In this chapter, the objective is to present the different experimental methods used to conduct tests on masonry assemblies. This section aims to offer to the reader a comprehensive overview of the subject and set the stage for the subsequent sections of the thesis.

Various experimental methods exist to assess the behavior of structures under load. They can be divided in two categories : quasi-static and dynamic testing.

2.1 Quasi-Static Tests

Structural testing methodology is predominantly determined by a singular parameter: time. The response of a structure is fundamentally different depending on whether a load is applied for a brief or extended duration. In scenarios where time impacts structural behavior, it is classified as dynamic testing. Conversely, when the behavior of the structure is independent of time, it is classified as static testing. However, even though it is feasible in a numerical way, in practice, minor time-dependent effects may still be present in static tests. This is why, in experimental terms, these types of tests are referred to as quasi-static. Quasi-static testing involves an incremental loading with a relatively low increment in order to minimize any dynamic effects that may occur.

2.1.1 Foundation Settlement

The first testing approach involves inducing differential displacements at one or more supports of the structure. These displacements can either be applied horizontally or vertically. In the first scenario, the displacements are progressively increased until the structure collapse. Conversely, in the latter scenario, the displacements are incremented until a predetermined condition is met, such as a specific level of deformation or adherence to a failure criterion (such as the formation of cracks or excessive tilting). Throughout these experiments, detailed recordings are made to observe the failure mechanism of the structure. The value of displacements is determined through displacement sensors strategically placed on the structure. This method aims to replicate the effects of soil settlement, which can result from various factors including soil consolidation, fluctuations in moisture content, and other environmental influences. To illustrate this testing approach, two examples will be presented : one involving horizontal displacement and the other vertical displacement, both induced at support.

Vertical Displacement applied at Support:

In an experiment done by Portioli et al [5], wall panels were constructed with dry jointed tuff masonry blocks with dimensions of 200x100x50 mm. They have one side fixed while the other one permitted both horizontal and vertical movements. Two test specimens were prepared for experimentation. The labels assigned to these specimens are based on the increasing number of courses. For instance, the label '8C' corresponds to the specimen with eight courses in height, and similarly, '12C' refers to the specimen with twelve courses in height.

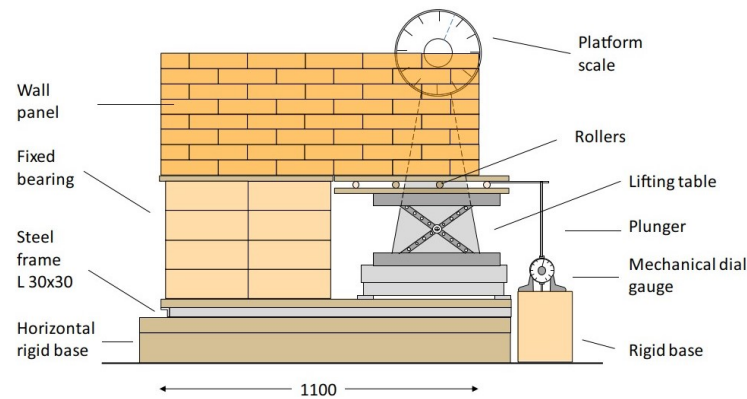


Figure 2.1: Front view diagram of the experimental test setup [5]

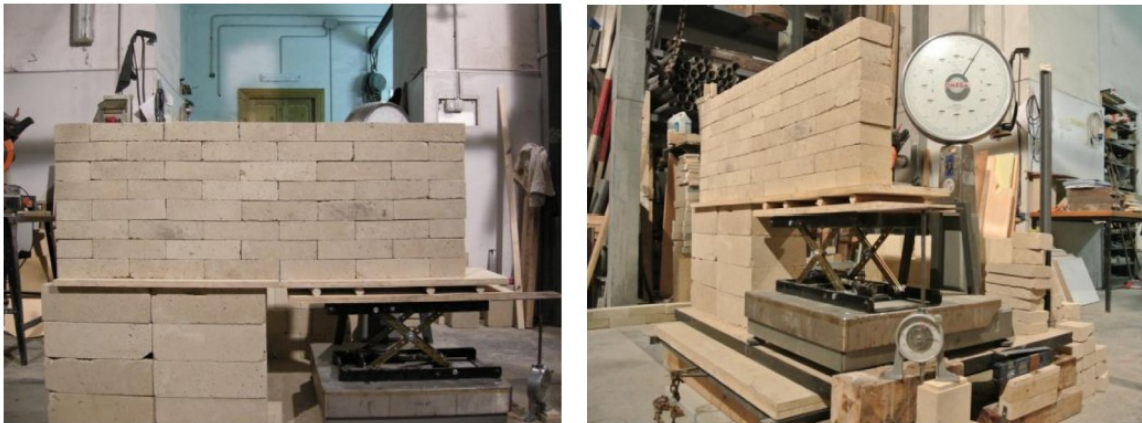


Figure 2.2: Front and lateral view of the experimental test set up [5]

To induce foundation settlements, a lifting table was employed, allowing to produce vertical displacements. The displacement procedure involved incremental steps of 1.0 mm each until structural collapse occurred. Throughout this process, weight changes were constantly monitored using the platform, which corresponded to the decreasing support reaction due to vertical displacement at the bottom right edge of the panel. The failure of the wall panel is considered to occur when the decreasing support reaction reaches stability, indicating a steady state load. This approach ensures that incremental displacements no longer lead to weight losses at the support.

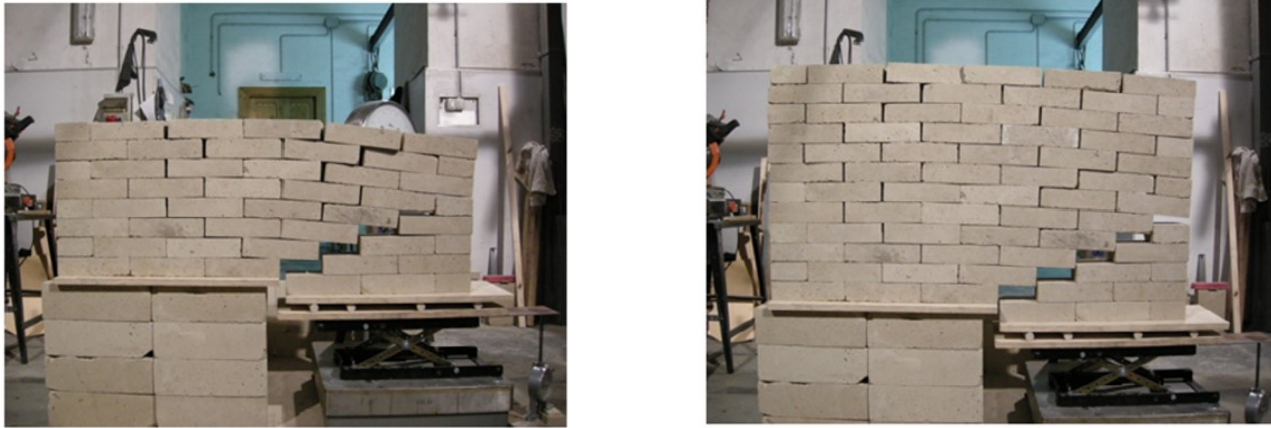


Figure 2.3: Deformed shape of the wall samples 8c and 12C at vertical displacement = 50 mm [5]

Video cameras are placed parallel and perpendicular to the structure to record the tests and highlight the failure mode. Vertical displacements were tracked using a mechanical dial gauge. The results are thus expressed in terms of base reaction at the support f_s , crack pattern and damage evolution.

Numerical simulations were conducted to model foundation settlements. This program yields two main outputs: the calculated base reaction at the support and a visual representation of the associated collapse mechanism. To solve the mathematical programming challenges, the Mosek optimization software was employed.

Experimental results for base reaction at the support are compared for both specimens between numerical and experimental testing. It can be noted that these values are slightly different from the experimental ones, due to inherent imperfections of the tuff masonry block assemblage.

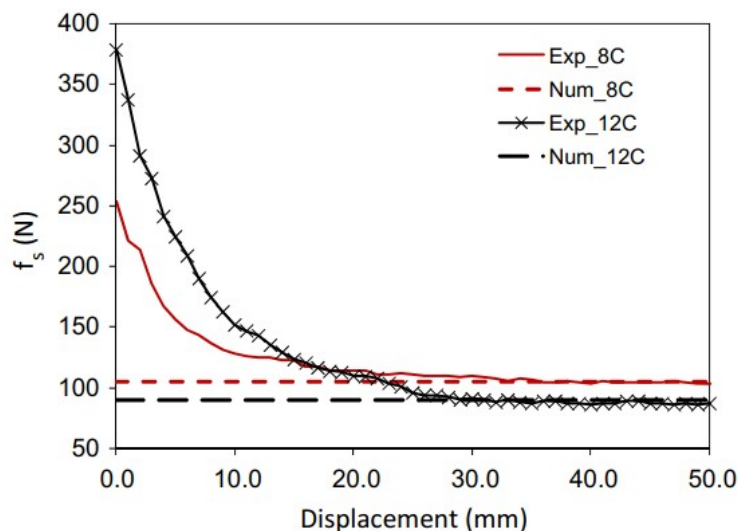


Figure 2.4: Base reaction vs. vertical displacement [5]

When comparing the experimental outcomes in figure 2.3 with the numerical ones in figure 2.5, it is evident that the collapse mechanisms are in good agreement. [5]

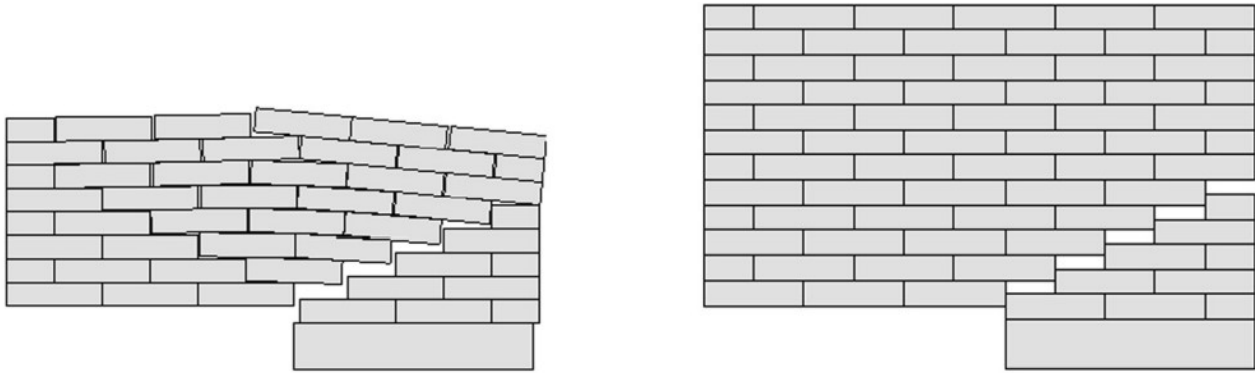


Figure 2.5: Plot of the failure modes at vertical displacement = 50 mm [5]

Similar experiments and analyses are present in the existing literature, encompassing a range of contexts. For instance, the work by Smoljanovic et al. [6] has compared the results between numerical simulations and experimental tests for both 2D dry-stacked masonry structures and other 3D constructions. Additionally, Dalgic et al. [7] have explored similar dynamics involving half-scale mortared masonry buildings.

Horizontal Displacement applied at Support:

In the study conducted by Foti et al. [8], a different approach to foundation settlement testing was employed. In this article, various types of displacements were applied to the support, including diagonal, vertical, and horizontal movements. However, our focus here will be specifically on the horizontal displacements that were introduced to the support. The experimental specimens consisted of dry-assembled masonry cross-vaults with a radius of 0.5 meters. The cross-vaults were constructed using predominantly 3D-printed cubic blocks filled with concrete, each with a side length of approximately 5 cm. These blocks were arranged in an orthogonal weaving pattern. In such a configuration, the blocks are organized in rows following the generators of the cross vault. This differs from a parallel weaving pattern, where the blocks are arranged in rows according to the direction of the barrel vaults that generate the cross vault.

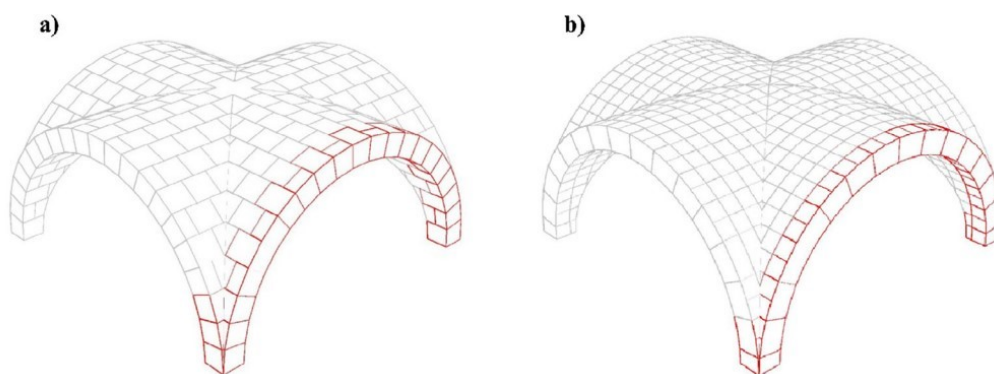


Figure 2.6: Computational model with a) orthogonal weaving and b) parallel weaving [8]

Differential displacements were impressed at one support of the vault by a mechanical system connected to the base block. Using a comparator, it was possible to record the displacement value when the vault collapsed. In addition, the positioning of cameras in multiple angles allowed to observe the collapse mechanisms.

In scenarios involving in-plane horizontal displacements, collapse is defined by the emergence of an arch mechanism. This mechanism features three distinct, alternating, and asymmetrical hinges situated at the intrados and extrados of the vault, appearing on the side directly impacted by the applied displacement. This is illustrated in the below figure 2.7 taken during the experimental tests.

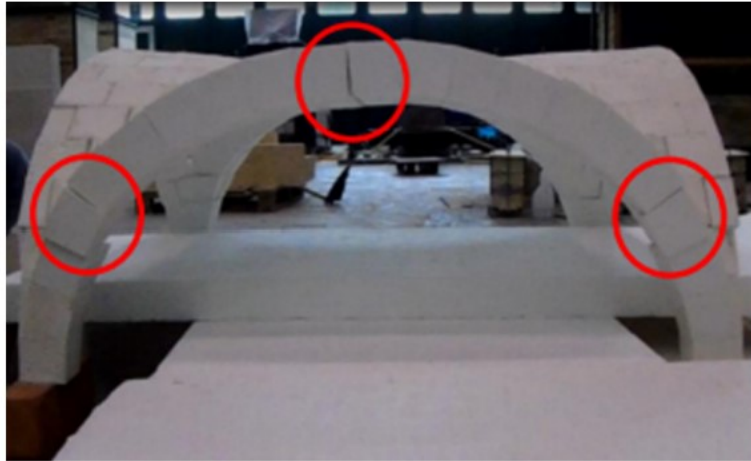


Figure 2.7: Collapse caused by arch mechanism [8]

Nevertheless, in the test done in this paper, the vault collapsed due to a relative sliding problems between the blocks close to the support and not for activation of an arch-mechanism as displayed on below figure 2.8



Figure 2.8: Limit state before collapse: damage mechanism [8]

A numerical model of the vault has been realized for comparison purposes with the specimen vault. It has the same geometry and mechanical characteristics of the experimental specimen. In the case of horizontal displacements, the kinematic system is characterized by the presence of a 3-hinged arch mechanism and by important relative slidings of the blocks along the diagonal. The collapse took place for a displacement of 56 mm and the activation of a 3-hinged arch mechanism as displayed on below figure 2.9. In the laboratory, instead, while observing this mechanism, the vault collapsed for other problems of instability, i.e. the presence of local hinges.

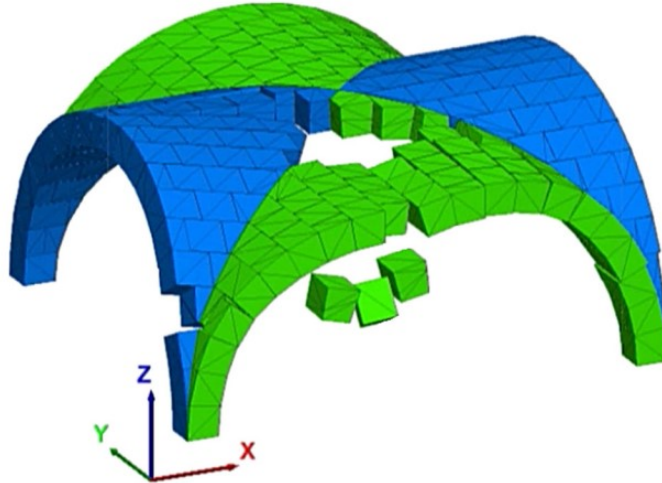


Figure 2.9: Numerical limit state before collapse [8]

From the comparison between the experimental and numerical results, a lack of compatibility has been observed between the failure mechanisms and magnitudes of ultimate displacements. This problem is explained by the idealized geometry of the computational models, which do not fully capture the imperfections present in real structures. Additionally, numerical results often overestimate the experimental ones due to errors occurring during the real tests. Achieving the same level of geometric and mechanical perfection in numerical models and in experimental ones is almost impossible to get. [8]

Displacement direction	Collapse displacement (mm)			
	Physical model		3DEC	
Vertical	16	13	25.5	45
Horizontal	14	27	47.5	56
Diagonal	76.5	48	73	78

Figure 2.10: Comparison between results from three distinct experimental tests and corresponding numerical simulations [8]

The existing literature features similar tests conducted in various contexts. For instance, a study from Theodossopoulos et al. involving a 1:4 scale replica of the Church of Holyrood Abbey compared its experimental behavior with the numerical one modeled by ABAQUS software [9]. Additionally, Torres et al. made reports about tests focused on vertical cyclic displacements conducted on a full-scale timber cross vault [10]. Another paper from Ferrero et al. delves into tests performed on scaled dry-joint masonry arches subjected to inclined support displacements [11].

2.1.2 Quasi-Static Loading

Another widely known approach involves the application of lateral loads directly onto the structure. These forces can either be concentrated or distributed across the structure. They are incrementally applied, often using hydraulic jacks or similar controlled devices and they gradually increase until a predefined limit is reached or until the assembly displays notable deformation. During this loading process, data related to the applied load and displacement are continuously recorded. Cracking patterns and deformations are monitored using tools such as strain gauges, displacement sensors, or other measuring instruments that are strategically positioned on the assembly.

A paper authored by Orduña [12] provides an illustrative example in which a constant vertical load is applied at the upper part of a dry-stone masonry wall and an incremental in-plane horizontal load is applied to the side of it. Masonry pieces had dimensions $200 \times 200 \times 100$ mm. For the validation of the results presented by Lourenço et al. [13], the two extreme cases were considered: SW.30 and SW.250. In these cases, additional vertical loads of 30 kN and 250 kN, respectively, are applied on top of the structure for validation purposes.

The figure 2.11 clearly shows that, during the experimental process, the SW.30 wall did not crack unlike the SW.250 one, where stone cracking are represented as blue lines. The blocks located at the bottom of the models and at the left side of the first rows represent the restraints provided by the foundation. Their implementation aims to prevent horizontal displacement of the lower part of the structure.

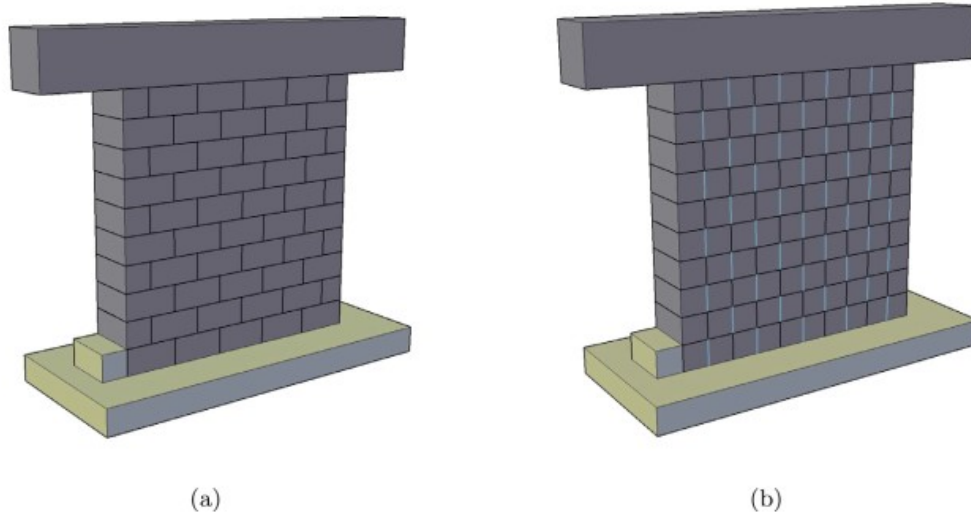


Figure 2.11: Dry-jointed masonry wall numerical models; (a) SW.30 and (b) SW.250 [12]

In this scenario, as depicted in below figure 2.12, the plot showcases the curves of two experimental models, along with those derived from a finite element non-linear analysis conducted by Lourenço et al. [13], and a numerical block model approach developed in the current paper. The graph represents the correlation between two crucial parameters: P , the applied lateral force, and u , the displacement of the structure. The chart highlights that the experimental curves are significantly scattered. Despite this scattering, both numerical methodologies closely align with the experimental trend, indicating their efficiency in accurately capturing the structural behavior.

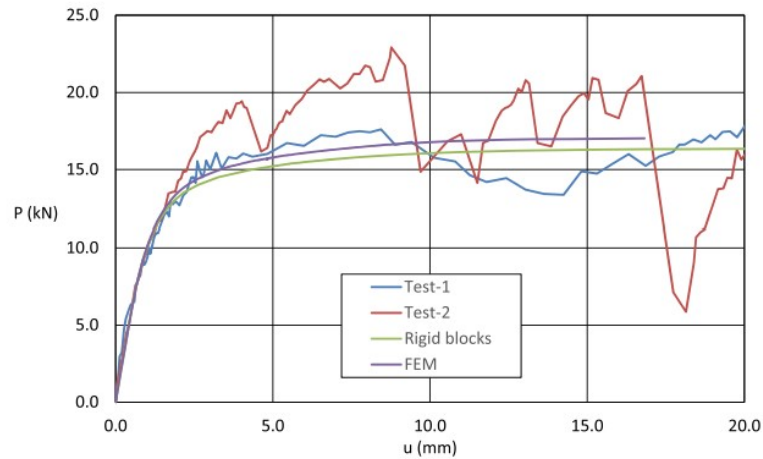


Figure 2.12: SW.30 wall lateral force vs. displacement graph [12]

The following figures, namely figures 2.13a–d, present a sequence of displaced configurations within the rigid block model, each corresponding to varying degrees of top beam horizontal displacement. The transition in non-linear behavior becomes evident as it shifts from sliding and separation between blocks, depicted in figure 2.13a, to the emergence of more prominent diagonal bracing and rocking of individual pieces, illustrated in both figures 2.13b and c. This progression culminates in a distinctly pronounced rocking mechanism, showcased in figure 2.13d. Remarkably, this observed behavior correlates with the outcomes seen in both finite element analysis (FEM) [13] and the physical experiment.

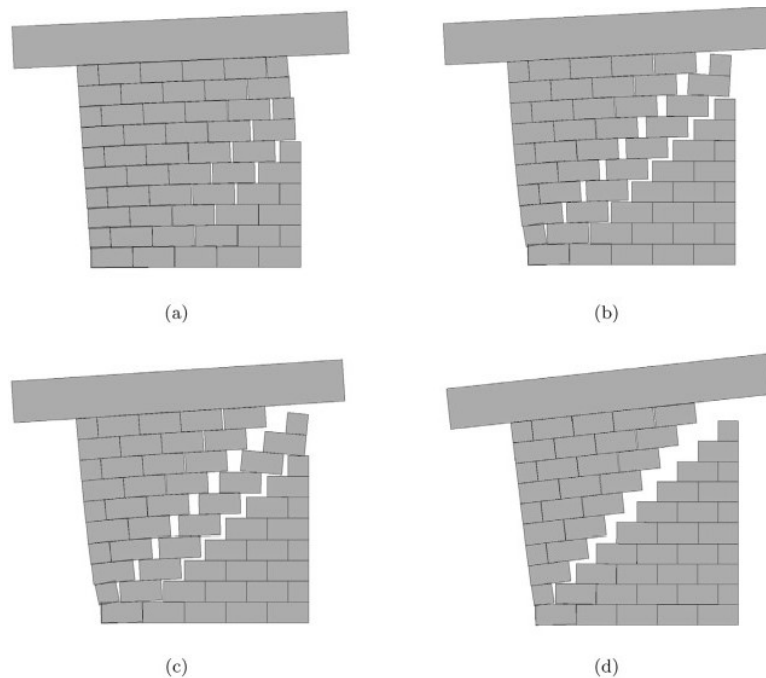


Figure 2.13: Wall SW.30 displaced configurations; (a) $u = 1.5$ mm; (b) $u = 5.3$ mm; (c) $u = 6.5$ mm; (d) $u = 26.6$ mm [12]

In particular, the ultimate failure mechanism, as depicted in figure 2.13d, exhibits a significant resemblance to the final incremental deformed mesh of the FEM analysis, as displayed in figure 2.14e, and the experimental configuration at the conclusion of testing, showcased in figure 2.14f. The depiction in figure 2.14e illustrates the areas where the minimal stresses ultimately lead to collapse, together with the incremental displaced configuration of the FEM model.

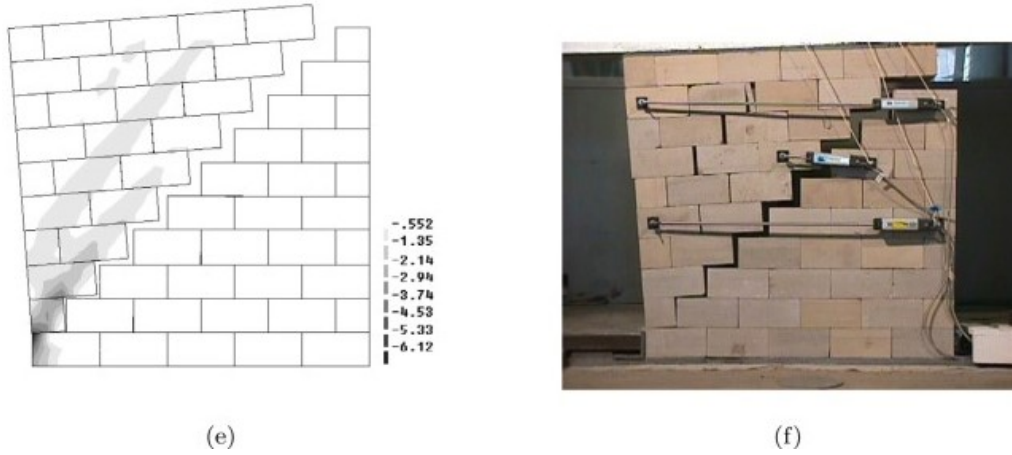


Figure 2.14: Wall SW.30 displaced configurations; (e) FEM and (f) experimental [12]

Below figure 2.15 presents the same chart as previous figure 2.12 for wall SW.250. After examination of the different curves on the chart, the experimental results reveal similarities with those displayed by the rigid block model and FEM analysis in terms of initial stiffness, failure mechanisms and load-displacement behavior. This example helps to validate even more the effectiveness of the numerical models in capturing the observed behavior in the experimental setting.

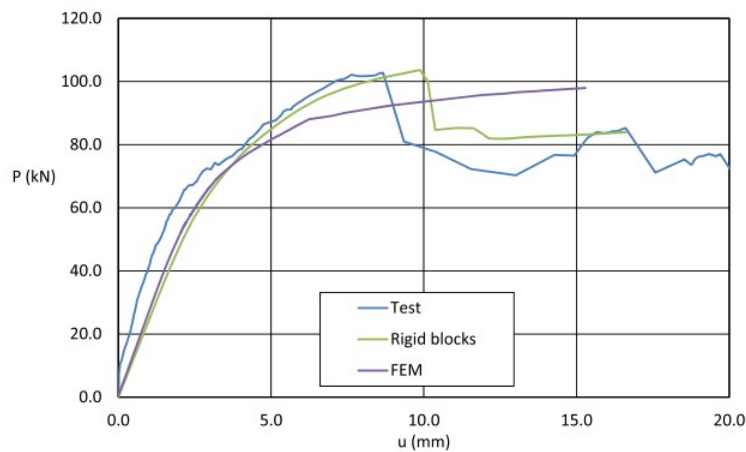


Figure 2.15: SW.250 wall lateral force vs. displacement graph [12]

Results presented by this article show that numerical results propose high level of accuracy in terms of load-displacement curves, displaced and failure mechanism configurations. This affirmation is confirmed by Lourenço et al. [13]. Furthermore, the initial stiffness is remarkably similar between numerical and experimental tests thanks to two aspects : the ability of the numerical model to follow closely the geometry configuration of experimental specimens and a very good material characterisation. [12]

The existing literature demonstrates the application of a similar method to evaluate various types of structures. For instance, this approach has been employed to examine strengthened masonry arches via FRP retrofitting in a study conducted by Oliveira et al. [14]. Additionally, researchers, like Okail et al. and Kusumastuti et al., have explored confined masonry walls subjected to incremental horizontal loads, comparable to the methodology previously described [15], or cyclic horizontal loading [16].

2.1.3 Tilting Tests

However, the previous method of applying concentrated lateral loads to structures might not always accurately model seismic forces, primarily due to the distributed nature of mass within the structure. In response, an alternative testing approach has been developed, involving a tilting plane machine. This testing technique addresses the limitations of the previous method by leveraging gravity forces, which uniformly load every location in proportion to its mass. In this setup, given the slow inclination speed of the table to mitigate dynamic effects on the structure, the angle of inclination is recorded and can be correlated to a force that would be applied to the structure if it were on a flat surface. Additionally, tests are recorded using cameras to emphasize cracking patterns.

In a study by Restrepo Vélez et al. [17], a comprehensive investigation was conducted involving a total of 42 distinct configurations of small-scale dry stone masonry wall specimens. The objective was to replicate the majority of out-of-plane collapse mechanisms proposed by D'Ayala and Speranza [18]. These mechanisms, denoted as A to G, are illustrated in the below figure 2.16.

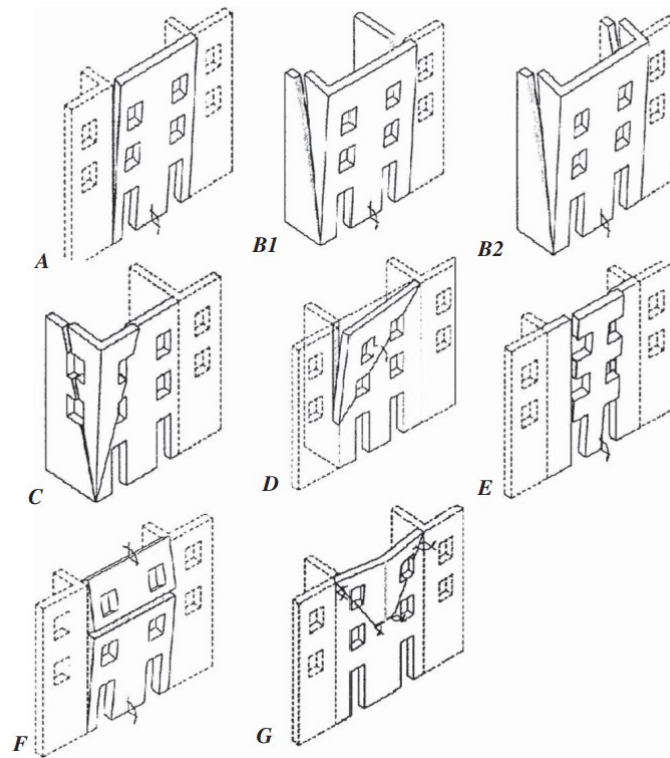


Figure 2.16: Illustration of out-of-plane failure mechanisms [18]

These configurations vary according to various factors : the length of their walls, the presence and position of openings, the staggering ratio, the quality of the connection between walls, the existence of overburden loads in the out-of-plane and in the in-plane walls, and the number of stories.

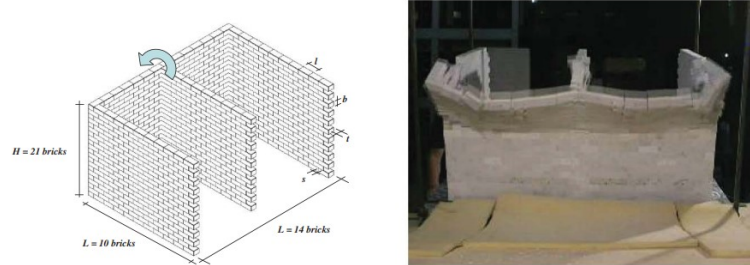


Figure 2.17: Configuration and collapse mechanism for test S21 [17]

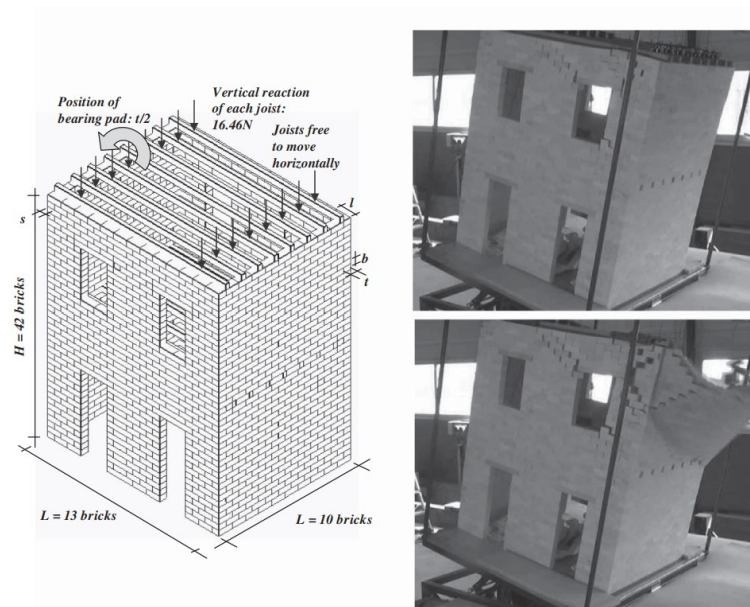


Figure 2.18: Configuration and collapse mechanism for test S42 [17]

The outcomes of the tests are presented through comprehensive explanations of the corresponding collapse mechanisms and are quantified using a collapse load multiplier λ . This multiplier was determined using a plumb line positioned on one side of the testing device, which was appropriately calibrated to convert the horizontal measurement into an angle of inclination.

Test	Mechanism	λ	Test	Mechanism	λ
S1	G	0.254	S21	A-B2	0.244
S2	G	0.226	S22	B2	0.197
S3	G	0.244	S23	A-G	0.144
S4	G	0.161	S24	A-G	0.156
S5	G	0.349	S26	F	0.259
S6	G	0.208	S27	C	0.375
S7	A-B2	0.291	S28	C	0.300
S8	A-B2	0.362	S29	C	0.288
S9	A-B2	0.352	S30	A	0.255
S10	A-B2	0.213	S31	A	0.177
S11	D	0.097	S32	F	0.293
S12	D	0.129	S33	F	0.215
S13	D	0.181	S34	G	0.217
S14	A-D	0.251	S35	A	0.168
S15	A-D	0.199	S36	G	0.320
S16	A-D	0.139	S37	D	0.126
S17	A-D	0.207	S38	D	0.055
S18	A-D	0.230	S39	A-F	0.339
S19	A-D	0.151	S41	A-F	0.423
S20	A-B2	0.285	S42	B2	0.236

Figure 2.19: Summary of the experimental tests on dry stone masonry [17]

As a conclusion, by looking at the observed collapse mechanism it is possible to note that: a) in numerous cases, the sliding and rotation of various portions of the wall manifest not solely along distinct, well-defined lines as depicted in the idealizations of figure 2.16, but rather exhibit a more distributed nature, both in the overturning facades and return walls; b) the majority of the observed failure mechanisms represent hybrid forms instead of completely distinct mechanisms. These observations are explained by the fact that dry masonry walls have a greater number of internal kinematic degrees of freedom than what is implied by the mechanisms illustrated in figure 2.16, where the "rigid blocks" have dimensions significantly larger than those of individual stone units. [19].

This widely adopted approach has been applied to numerous benchmarks. Among these, tests have been conducted on small scale dry-stacked cross-vaults by Milani et al. [20], as well as 2D and 3D dry-stacked masonry panels by Grillanda et al. [21], among others. An alternative tilting table configuration is also depicted in the image below [22].

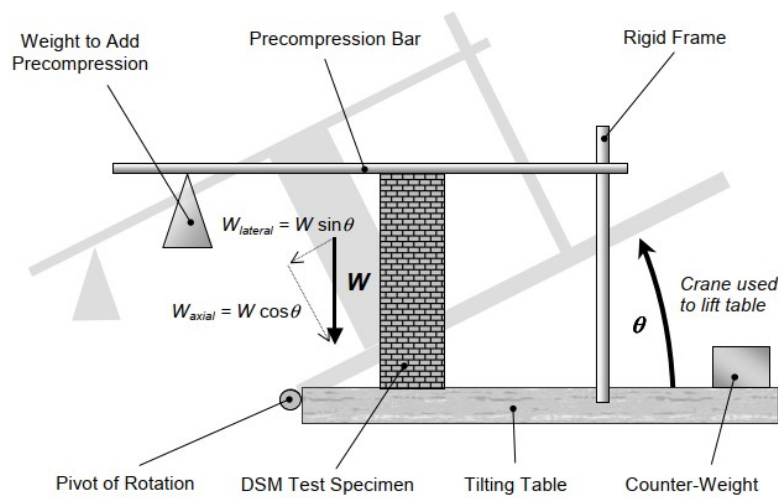


Figure 2.20: Alternative tilting table configuration [22]

2.2 Dynamic Tests

As previously explained, dynamic testing distinctly differs from quasi-static methods due to the significant influence of time on structural behavior. According to the available literature, a single dynamic testing method for masonry assemblies has been identified: shake table testing.

2.2.1 Shake Table

This dynamic method involves the application of signals with sufficient duration to exert effects on the behavior of structures. Thanks to one or several piston strokes in most of the cases, the test plate is moved with customized in-plane displacement, speed, or acceleration profiles for specified time intervals. Throughout these tests, the resulting data, encompassing displacement, speed, or acceleration values, are meticulously captured alongside the observed collapse mechanisms via camera recordings.

In a paper written by Bui et al. [23], experimental tests were conducted on a rectangular masonry structure assembled using sugar blocks. The purpose of the study was to evaluate the influence of the box behavior under harmonic seismic loading. The concept of "box behavior" in masonry houses refers to the structural behavior where the interconnected walls, floors, and roof act collectively like a sturdy box to distribute loads evenly and provide stability, ensuring that the building can withstand various forces such as earthquakes.

A self-made vibrating table able to sustain a harmonic load with constant amplitude and variable frequency was constructed with wood and mounted on a metal plate as displayed in figure 2.21. The harmonic load was applied using a hydraulic jack.

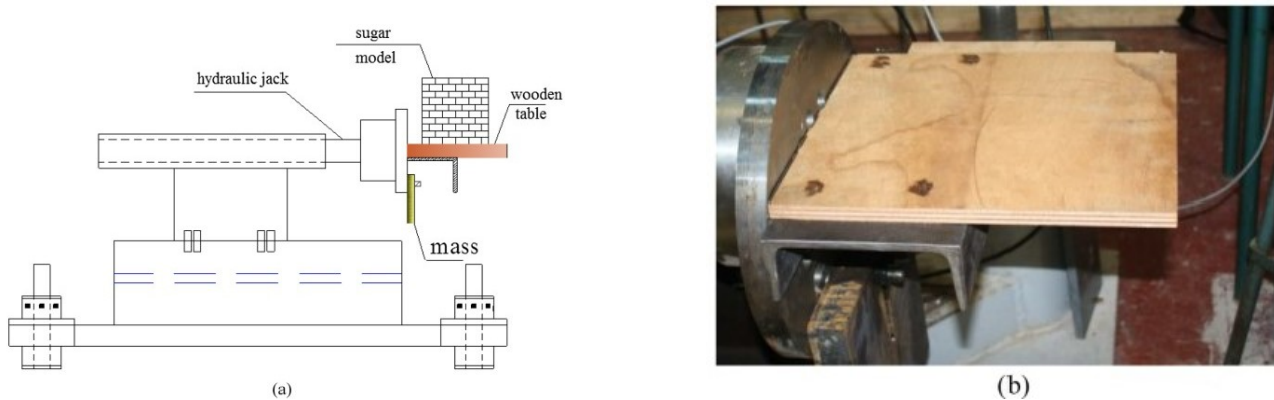


Figure 2.21: Example of shake table set up [23]

The analysis of the obtained results revealed that the predominant mode of failure manifests in the primary load-bearing walls of the structure, mainly due to bending stresses. Notably, the extensive damage to these primary walls also induced cracking and, in certain cases, partial collapse of the secondary walls. Figure 2.23 illustrates the localized failure modes identified through the experimental investigation. This figure serves to compare the observed experimental failure patterns with those predicted by the numerical model. Remarkably, the Discrete Element Method (DEM) successfully replicates the experimental failure modes with a worthy level of accuracy.

In the pursuit of comprehensively representing the physical system, numerical models were meticulously developed to simulate the wall dimensions and the specific loading scenarios as encountered in the experiments. A visual comparison between the experimental and numerical outcomes, depicted in figure 2.22, highlights the differences between the two. These disparities are attributed to the effects of scale and the inherently heterogeneous behavior of the masonry blocks, which, in this context, are constructed from sugar.

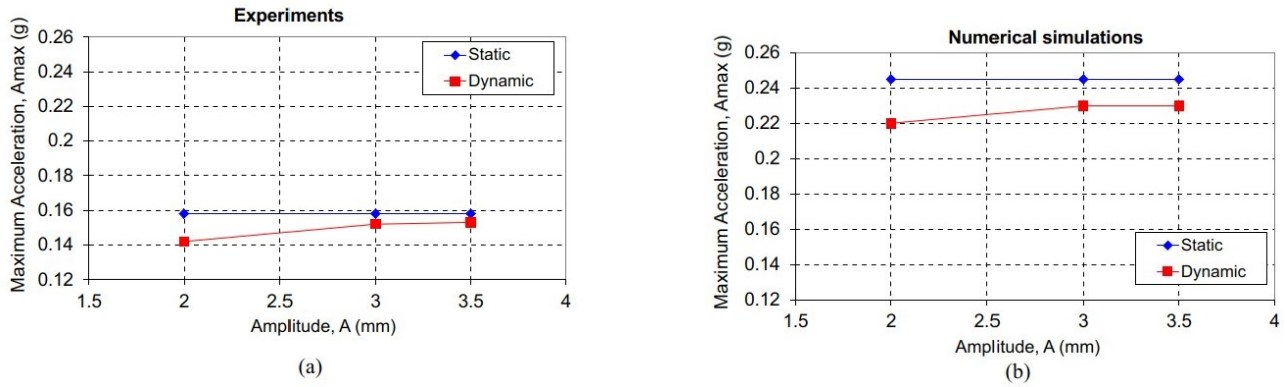


Figure 2.22: Maximum acceleration vs. amplitude obtained from: (a) experiments; (b) numerical simulations [23]

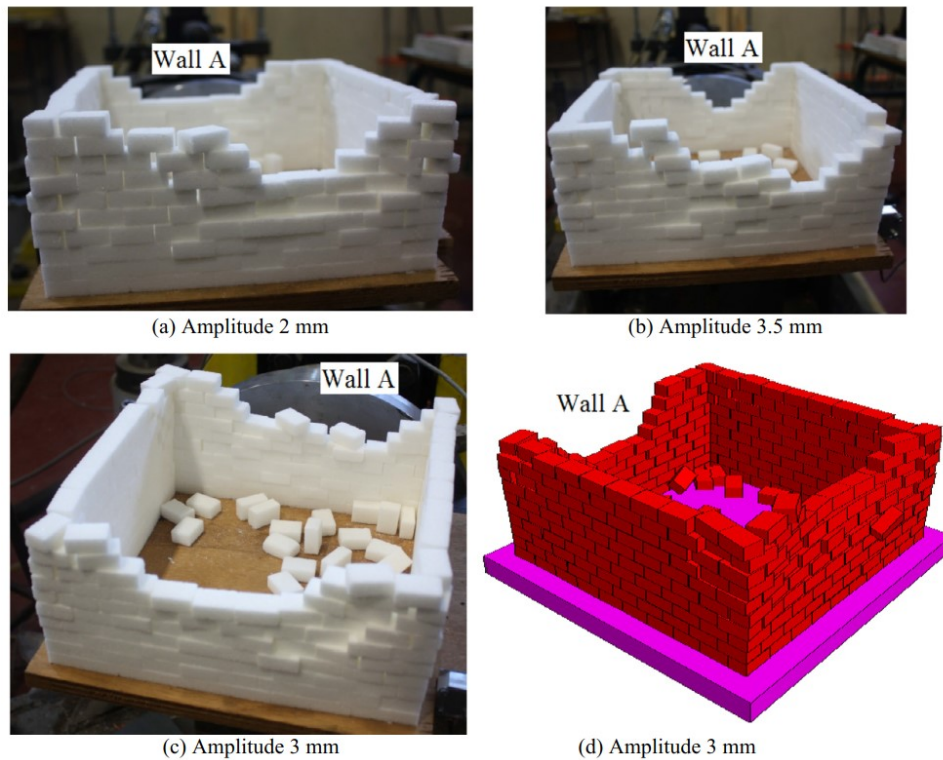


Figure 2.23: Failure modes for the rectangular masonry structure [23]

In summary, the numerical predictions, particularly in terms of the critical angle, showed a notable overestimation when compared to the experimental findings. This discrepancy is primarily due to the influence of scale effects. The nature of the block-to-block interface prove

to be more complex than what the Coulomb friction model used in this study. It can often occur that even the most sophisticated friction model may not fully capture the experimentally observed friction behaviors due to the influence of certain random factors (e.g. variations of normal pressure force or inhomogeneous asperity of contacting surfaces, etc.). Moreover, when dealing with smaller specimen dimensions as in this study, the influence of factors like inhomogeneous contacting surface asperities and other stochastic variables could be amplified. [23].

Until now, a wide range of benchmarks has been investigated, encompassing various scale factors and shake table dimensions. These include studies on unreinforced masonry buildings without RC elements [24] [25] [26] or with them [27] [28], fiber-reinforced masonry walls [29], and retrofitted masonry walls with FRP [30] [31]. Furthermore, experiments have been conducted on reduced-scale replicas of existing iconic structures, such as the Katholikon of Dafni Monastery in Attica, Greece [32], the Fossanova Church [33], and the Dey Mosque in Algiers [34], all subjected to real earthquake loadings recorded in the past.

2.3 Choice of Tests

Based on the review of literature, a notable absence of dynamic tests on 2D masonry assemblies can be highlighted, despite the availability of numerical simulations. This research gap prompted the strategic choice to concentrate on 2D dry-stacked small scale masonry assemblies, capitalizing on the capabilities of the brand new shake table ATOM.

The justification behind opting for dry-stacked assemblies is multiple. Primarily, real-world masonry structures frequently contain damaged mortar. By focusing on dry-stacked assemblies, the results obtained tend to be more conservative than those from mortared joints, where the mortar provides additional structural resistance. Additionally, the absence of mortar accelerates the assembly process, significantly enhancing test repeatability. Furthermore, the elimination of mortar from the structures reduces costs.

Through literature, two articles have been identified as relevant as they both contain a set of six 2D benchmarks suitable for shake table testing, which will be further explained in following sections. Every benchmark exhibits variations in its geometry, the number of openings, and the number of stories. These wall configurations are composed of bricks with dimensions measuring 0.4×0.175 meters. Their representation hereunder are plotted for a displacement of the upper right corner of the wall equal to 0.2 meters.

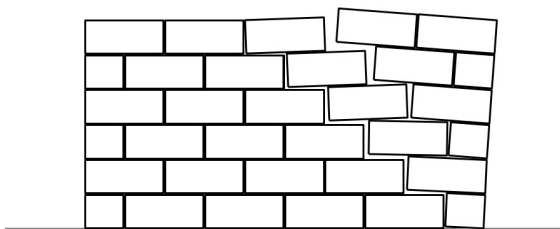


Figure 2.24: Benchmark 1 [35]

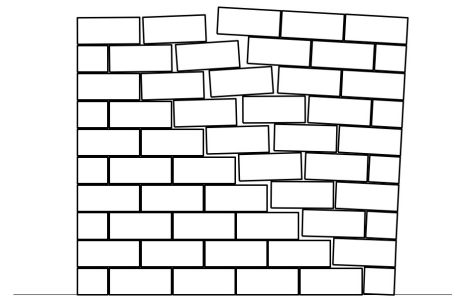


Figure 2.25: Benchmark 2 [35]

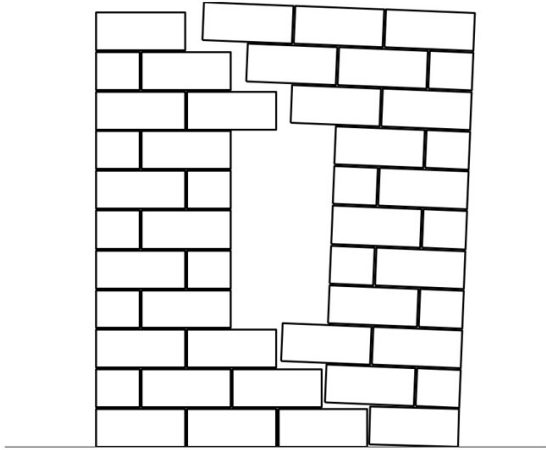


Figure 2.26: Benchmark 3 [35]

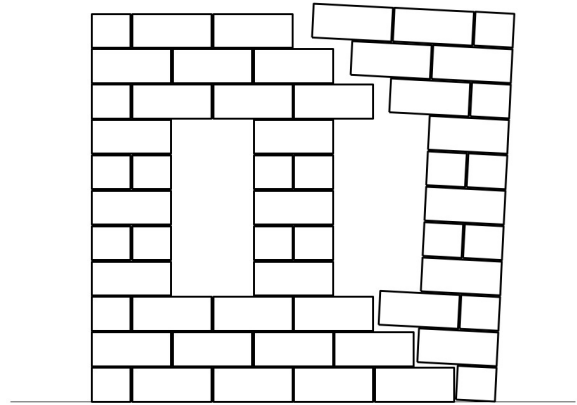


Figure 2.27: Benchmark 4 [35]

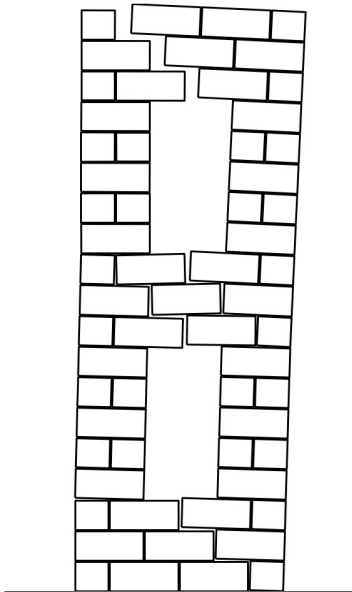


Figure 2.28: Benchmark 5 [35]

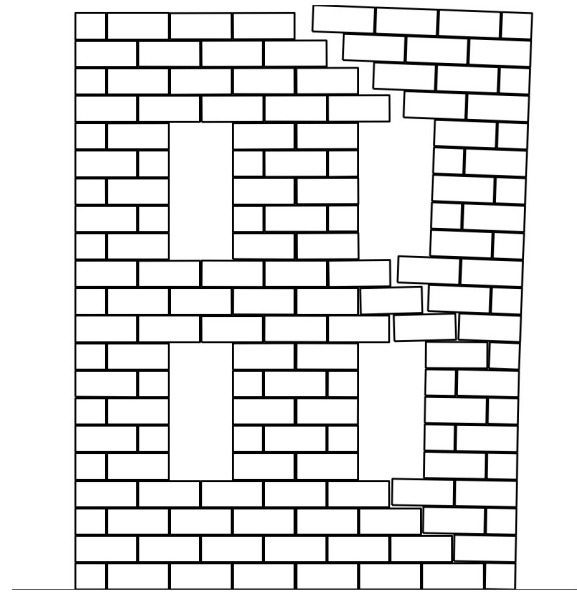


Figure 2.29: Benchmark 6 [35]

The first article speaks about numerical simulation of the masonry assemblies. The simulation involves applying horizontal in-plane load on the left side of the structure to imitate an earthquake-type loading. The results are denoted by the load factor α which amplifies the vector of applied loads f_L . For a full block, the vector is represented as $(\alpha, 0, 0)$, while for an half block, it is $(\frac{\alpha}{2}, 0, 0)$. Additionally, the self-weight loads f_D are given by $(0, -1, 0)$ for a full block and $(0, -1/2, 0)$ for an half block.

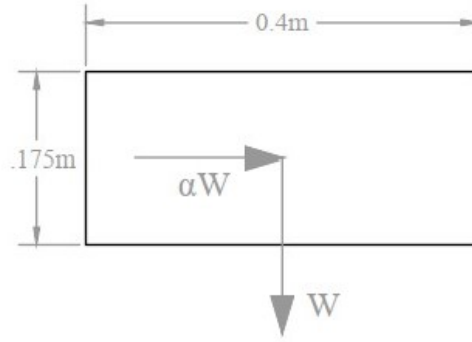


Figure 2.30: Representation of the forces exerted on each brick [35]

Four distinct numerical methods are used to calculate the load factor α , depending on various equations. The objective is to determine the boundary value at which the structure collapse. Each method gives a value of load factor α for the different benchmarks considered. Additionally, the computing time and the percentage of difference between each method's results are given. [36]

Example	Size $b \times c$	LP		MCP		MPEC		
		α	secs	α	secs	α	% diff	secs
1	33×83	0.64286	1.5	0.64285	1.3	0.63898	0.6	4.9
2	55×141	0.58000	2.0	0.56368	4.0	0.55742	4.1	9.3
3	46×102	0.37383	1.6	0.31078	1.5	0.31078	20.3	4.8
4	55×116	0.33195	1.7	0.26374	2.0	0.26374	25.9	5.6
5	61×120	0.23964	1.7	0.21584	2.4	0.20863	14.9	6.1
6	146×345	0.34782	5.7	0.29725	35.6	0.29577	17.6	232.0

Figure 2.31: Comparison of computational results for each method [35]

The second paper aims at evaluating the open-source software package LMGC90, which is based on the Discrete Element Method, as a tool for modelling masonry structures under seismic conditions. In this software, the contact law between the blocks is defined as a rigid-plastic law, while the failure between them is described using a Coulomb friction criterion with a friction coefficient $\mu = 0.65$ and zero tensile strength. After 10 seconds of runtime, the load factor α is linearly increased at a rate of $5 * 10^{-4}/s$. This rate is considered sufficiently low to maintain the system in quasi-static conditions until the collapse mechanism is formed.

The value of α_{max} represents the maximum horizontal reaction observed at the support, divided by the total weight of the wall. A reduction in the horizontal reaction, despite a continuous linear increase in the total applied horizontal force, indicates that equilibrium is no longer satisfied and part of the applied horizontal force is being converted into kinetic energy.

As a result, the figures clearly exhibit very similar cracking patterns to those shown in figures 2.24-2.29 from the first article, all for an equal displacement of the upper right corner of the wall. The values of load factor α in the current study closely align with the ones obtained in the first article, with a maximum difference of 0.8%. This slight difference can be attributed to the

variation in laws used between the two software. For example, the UDEC software incorporates parameters such as dilatancy or tangential stiffness for the contact law between blocks, while LMGC90 does not consider them.

	α_{max} Sharp edges		% Error
	Ferris [8]	LMGC90	
Wall 1	0.643	0.640	-0.5
Wall 2	0.564	0.565	+0.2
Wall 3	0.359	0.358	+0.3
Wall 4	0.264	0.266	+0.8
Wall 5	0.216	0.216	+0.0
Wall 6	0.297	0.295	-0.7

Figure 2.32: Comparison of computational results in the paper from Ferris et al. [36] and LMGC90 software [35]

This paper also introduces an alternative model featuring rounded corners for the bricks. This adjustment was made to account for imperfections in brick corners, which is proved to give a more realistic behavior compared to the previous model with sharp corners. Notably, the variation in outcomes is also attributed to modifications in the contact law, which is no longer exclusively perfectly plastic.

	α_{max} Rounded edges		% Error	Sharp edges [8]	% Difference between sharp and rounded edges
	UDEC	LMGC90			
Wall 1	0.577	0.578	+0.2	0.643	-10.1
Wall 2	0.495	0.512	+3.46	0.564	-9.2
Wall 3	0.325	0.321	-1.24	0.359	-10.6
Wall 4	0.236	0.242	+2.7	0.264	-8.3
Wall 5	0.157	0.175	+11.2	0.216	-19
Wall 6	0.219	0.216	+1.6	0.297	-27.2

Figure 2.33: Comparison of computational results from both software and between sharp and round edges [35]

These results will be saved and later compared with the experimental ones obtained during the course of this study. This comparison will help validate the accuracy and reliability of the numerical simulations and help develop new software simulating earthquake's loading.

Chapter 3

Experimental Setup

After a large review of the existing literature on masonry assemblies testing, this chapter will provide detailed information about the various equipment used as instrumentation to conduct the tests and record data. Additionally, a step-by-step methodology will be explained, outlining the precise testing procedure employed to ensure the experiments are carried out effectively. By presenting both the setup and procedure, this chapter aims to offer a comprehensive overview of the experimental aspect of the study.

The instrumentation for the testing phase is divided into two categories : the equipment used for conducting the tests and the devices employed for recording the data.

3.1 Testing Setup

3.1.1 Shake Table

For the first category, a shake table was used. The latter consists of a plate that can carry loads up to 50 kg on which the benchmarks were positioned. This machine can move a distance of 125 mm in each direction when centered. This movement is achieved through a piston stroke of 250 mm which allows for a maximum speed of 800 mm/s.

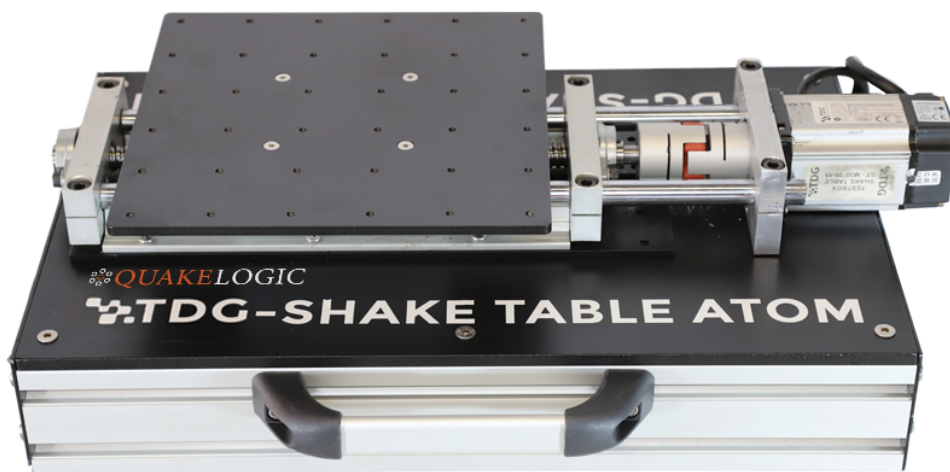


Figure 3.1: Shake table

Before going further, we need to define the cardinal points of the table. To do that, let's consider the direction of the table's movement when it is in motion. The positive movement goes from the piston to the right of the below representation. To maintain consistency, we will consider the direction towards the piston as the west. East and west are parallel to the piston axis, and north and south are perpendicular to it. The cardinal points are thus organised as follows :

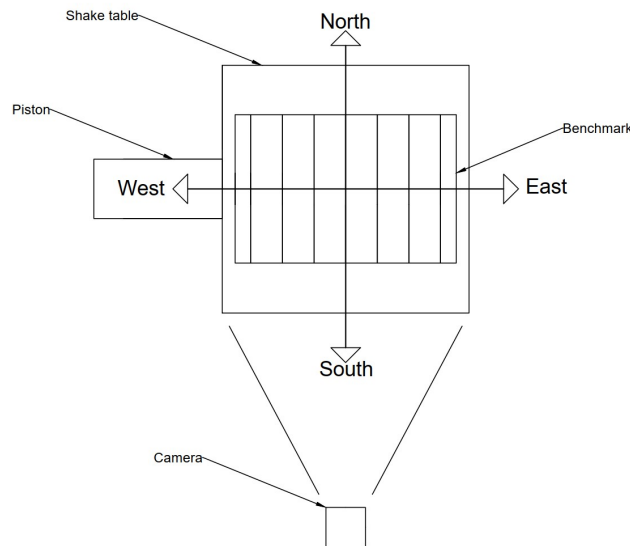


Figure 3.2: Plan view of the cardinal points of the system

A dozen options of signal forms, such as sinusoidal, triangle, shock, and more, can be induced by the shake table. However, for our specific study, the focus was directed towards the square signal as we can see below on figure 3.4. Each signal was determined by three parameters: amplitude, frequency and number of cycles. The number of cycles can be infinitely large but amplitude and frequency are obviously limited in the area delimited by the x- and y-axis and the limit frequency range curve on the plot below.

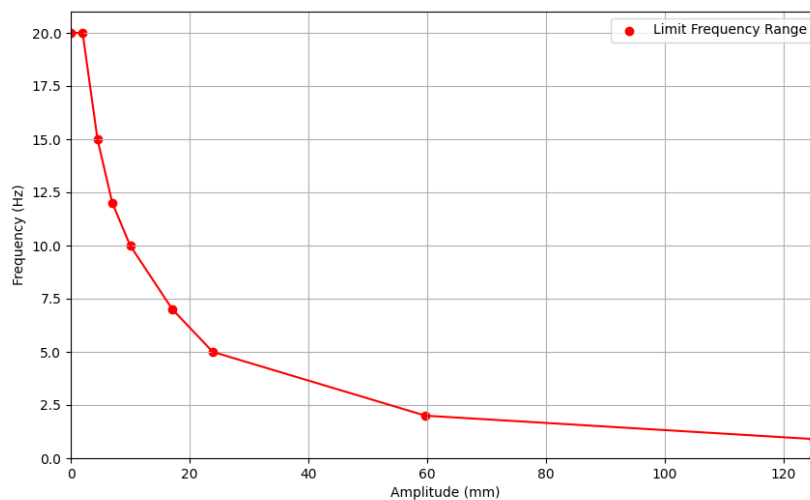


Figure 3.3: Amplitude-Frequency range

Due to limitations with the EasyTest ShakeTable software, the application of a gradually increasing acceleration, simulating quasi-static tests as explained in the state-of-art chapter, was not possible. As a result, a single and constant acceleration was chosen to be applied from the shake table to the structure. This acceleration could be correlated to the constant horizontal force that was considered in the numerical tests thanks to the second law of Newton, offering a reliable alternative for our testing setup as developed below in equations 3.1-3.6.

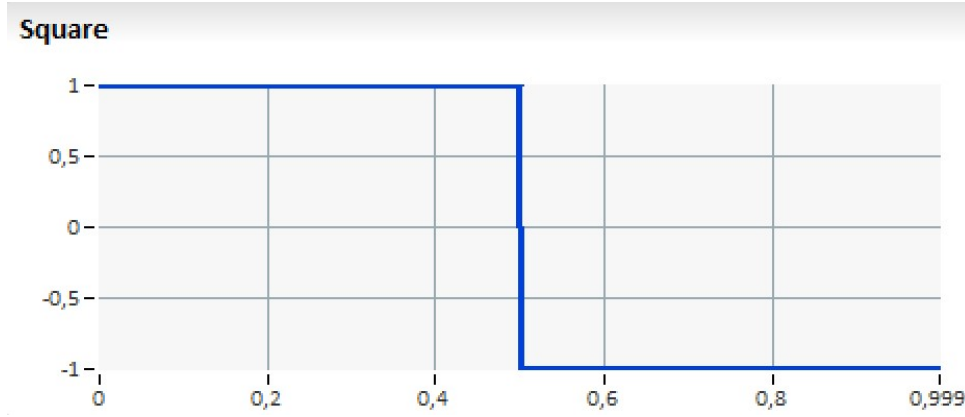


Figure 3.4: Square signal. X-axis : time and y-axis : amplitude

Testing the benchmarks requires a well-defined process, considering the time-consuming assembly of the largest benchmark for example, which consists of 108 full blocks and 38 half blocks. This assembly can take around 15-20 minutes and we estimated that a minimum of twenty tests would be required for each benchmark, making efficient planning and preparation essential for conducting successful tests.

To prepare the testing process, each test needs to be carefully planned in advance. This includes calculating the specific parameters for each test and the acceleration increment between consecutive tests. The parameters refer to the variables of the software that will be adjusted during the test, such as the frequency and the amplitude that are combined to calculate the acceleration of the table. The increments determine the step size for each increase or decrease of acceleration between each test.

Testing Process

To illustrate the testing process, we will consider the fourth benchmark 2.27. As observed in the paper [35], a load factor of approximately 0.265 induces a collapse. Now, a question arises: how can we establish the correlation between this load factor and the acceleration of the table ? Given that the structure is in motion along its horizontal axis, let's explore the following relationships:

$$\sum F = ma \quad (3.1)$$

$$F_{applied} = ma_{table} \quad (3.2)$$

$$\alpha W = ma_{table} \quad (3.3)$$

$$\alpha = \frac{ma_{table}}{W} = \frac{ma_{table}}{mg} \quad (3.4)$$

$$\alpha = \frac{a}{g} \text{ or } a = \alpha g \quad (3.5)$$

If we look at our EasyTest ShakeTable software, we clearly see that the acceleration is expressed as :

$$a = Ag \quad (3.6)$$

where A represents the amplitude which is provided as a parameter along with the frequency. This means that the amplitude from our software is simply equal to the load factor α from the literature.

The logical approach says that the initial test should have an acceleration smaller than the numerical value of 0.265g, which induces the collapse. To achieve precise results down to 0.01g, a systematic testing strategy was put in place.

At the outset, we decided to start with an arbitrary acceleration of 0.05g, which is less than half of the critical value. This choice allows us to reduce the number of tests until we reach the numerical critical value. Indeed, each test was incremented by 0.05g step.

Upon reaching a point where an acceleration, of 0.1g in our example, exhibits no failure mechanism, whereas a larger increment, of 0.15g here, induce collapse, we refine the acceleration increment to 0.01g to reach the required precision.

At this stage, our primary objective is to precisely identify the acceleration that triggers the rocking phenomenon. For instance, in our example, we find this critical value to be 0.14g. To confirm this finding, we conduct three separate tests with the structure subjected to this acceleration. Additionally, we run three more tests at a slightly lower acceleration of 0.13g, where no rocking occurs.

Load Configurations

To find the frequency that causes the shake table to move a certain distance, we need to take into account the limitations of the table, as indicated on the plot 3.3. Since the amplitude is already determined (as a multiple of the gravity acceleration, g), our objective is to identify the frequency corresponding to the maximum achievable displacement for a given acceleration.

For instance, let's consider two examples: an acceleration of 2g and an acceleration of 1g. The shake table's limitations allow for a maximum displacement of 25mm at 2g acceleration and 50mm at 1g acceleration.

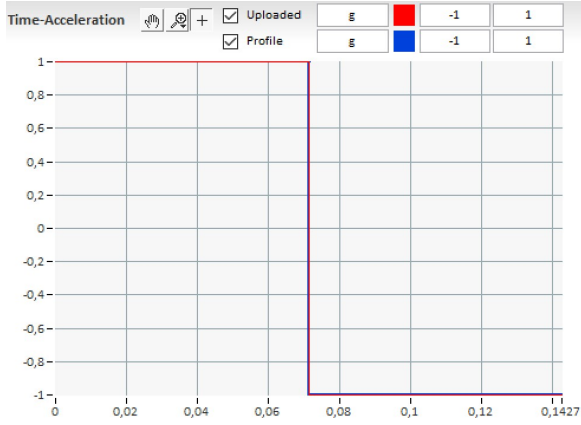


Figure 3.5: Acceleration of 1g

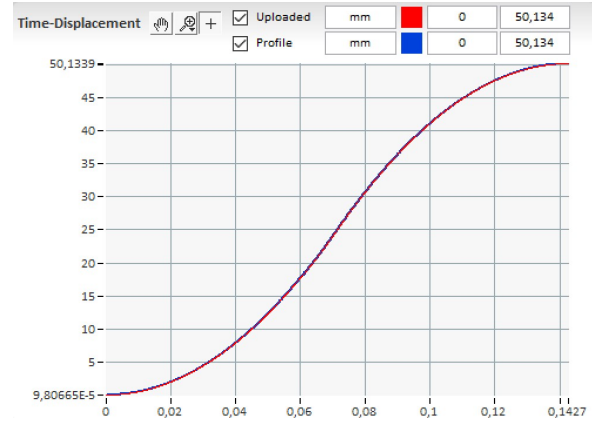


Figure 3.6: Displacement for an acceleration of 1g

To determine the frequency that achieves these displacements, we rely on the following equations, considering that "D(t)" represents the displacement at a certain time:

$$D(t) = \frac{1}{2}at^2 \quad (3.7)$$

$$T = \sqrt{\frac{2D}{a}} \quad (3.8)$$

$$f = \frac{1}{T} \quad (3.9)$$

To calculate each frequency corresponding to any amplitude, a code has been developed. The results obtained from this code have been validated and confirmed. The selected accelerations, taking into account the limitations of the shake table, are sorted as follows:

- For a displacement of 200mm, the maximum induced acceleration reaches 0.16g.
- For a displacement of 100mm, the maximum induced acceleration reaches 0.6g.
- For a displacement of 75mm, the maximum induced acceleration reaches 0.85g.
- For a displacement of 50mm, the maximum induced acceleration reaches 1.3g.
- For a displacement of 25mm, the maximum induced acceleration reaches 2g.

3.1.2 Bricks

3.1.2.1 Dimensions Choice

Before speaking about dimensions, it is important to clarify the terminology used in this part when speaking about the benchmarks. When referring to the benchmark from the literature with its standard size, we will refer to it as the "prototype." Conversely, when discussing the reduced version of the benchmark, where we applied a scale factor to each of its dimensions, we will refer to it as the "model."

The table measures 250x250mm, but the largest prototype, displayed on figure 2.29, has a width equal to $7 \times 0.4\text{m} = 2.8\text{m}$. As a result, the minimal scale factor found was $\lambda = 12.5$, as it would yield a width of $7 \times 0.4 / 12.5 = 7 \times 0.032\text{m} = 224\text{mm}$ for the model. To be precise, later in the process, we opted to fix an upper wood table, that will be shown later on figure 3.14 that was significantly larger than 250mm. This would have allowed us to consider a smaller scale factor but, unfortunately, the decision came too late in the fabrication process. Nevertheless, we assumed that even with a smaller scale factor, it would not have significantly altered the final results.

Furthermore, the same prototype represents both the largest and highest benchmark considered. With a height of approximately 294mm for the model, we decided to set the depth of each brick at 150mm. This choice, allowing for a scale factor of 2 between the height of the model and the depth of the brick, aimed to minimize any potential out-of-plane effects.

The dimensions of the 2D brick prototype are 400x175mm for the width and height, respectively. In contrast, the dimensions of the 3D brick model are 32x14x150mm for the width, height, and depth, respectively.

3.1.2.2 Comparison between Materials considered for Fabrication

During the brick fabrication phase, three main materials were evaluated: sugar, polylactic acid (PLA) for 3D printing, and wood through laser cutting. The initial material tested on the shake table was sugar to discover the capabilities of the shake table.

However, in addition to the lack of modular dimensions that was already eliminatory, it was soon evident that sugar blocks were not suitable for the experiments as the sugar blocks presented another critical issue : they tend to crumble easily. This crumbling results in debris that could potentially damage the piston stroke. Considering these limitations and drawbacks, sugar was excluded as a viable material for masonry assembly in the shake table tests.



Figure 3.7: Sugar blocks assemblies

As an alternative to sugar blocks, 3D printing imposed as an improvement as it offered the advantage of customizing the size of the bricks according to specific requirements. Additionally, the surface of the 3D printed blocks was smoother and more uniform compared to wooden blocks, which earned it the initial preference.

Therefore, a small block with dimensions of $0.32 \times 0.14 \times 0.16 \text{ m}$ was prepared to test the printing machine. However, during the printing process, the machine indicated a printing duration of an hour. This estimated time raised concerns as the priority was to test structures assembled with blocks that are 10 times larger, which would increase significantly the time consumption.

Considering the significant time and cost implications of 3D printing for larger-scale experiments, the attention shifted to wooden blocks. The laser cutting process for wooden blocks proved to be much faster, taking only 10 seconds for the same small block that would have taken an hour to 3D print. Moreover, the initial wooden blocks were made from off-cuts of wooden boards, making them cost-effective as it was considered a recycling approach. The cost was primarily based on the use of the laser cutting machine rather than the cost of the wood itself, making this option way more cheaper than 3D printing.

This choice of wooden blocks provided the most practical and efficient solution, striking a balance between cost-effectiveness, production time, and flexibility in dimensions.

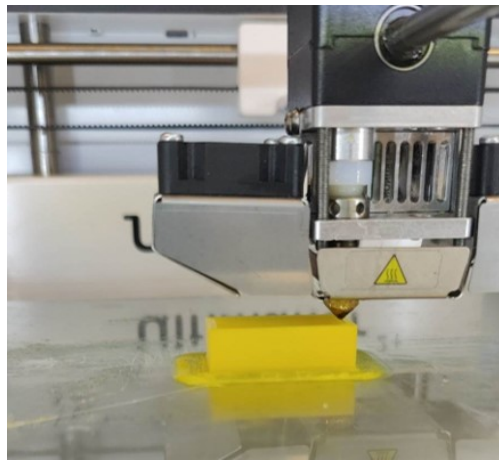


Figure 3.8: 3D printing of block

Now, let us review the advantages and drawbacks of each material :

- **Sugar**

- Advantages:

- Lowest cost
 - Easiest and fastest to acquire

- Drawbacks:

- Limited choice of dimensions
 - Limited durability: crumbles
 - Crumbling can damage the piston stroke

- **Polylactic Acid (PLA) for 3D printing**

- Advantages:

- Highest durability
 - Great flexibility for dimensions
 - Great precision

Drawbacks:

- Most expensive
- Takes the most time to be created

- **Wood through Laser Cutting**

Advantages:

- Great flexibility for dimensions
- Great precision
- Much faster than 3D printing
- Cheaper than 3D printing

Drawbacks:

- More slippery than 3D printing
- Block faces are not always flat → discontinuity in the sandpapering

3.1.2.3 Fabrication Steps

1. File Creation

To cut each part composing our bricks, as depicted in figures 3.10 and 3.11, we need to create a DXF file with drawings of each part. We accomplish this by using the website Boxes.py, which allows us to input the desired dimensions for the width, depth, and height in millimeters. These dimensions define what the website calls a "closed box" which will serve as the casing for our bricks, as explained in the subsequent steps. When specifying the dimensions for each part, we have to take into account the width of each panel, where each one of them has a depth of 3mm.

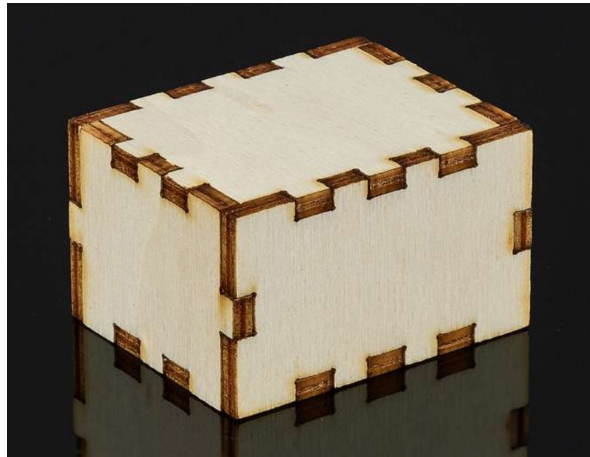


Figure 3.9: Example of box made out of laser cutting

2. Laser Cutting

Once the DXF file is uploaded to the corresponding software linked to the laser cutting machine, specific parameters must be defined, including the power and cutting speed. Additionally, a crucial step called z-axis calibration needs to be performed.

Z-axis calibration involves setting the correct distance between the laser head and the material being cut. This calibration ensures proper focus and alignment of the laser beam at various working heights above the material surface. Achieving precise calibration is vital for obtaining accurate and consistent cuts across the entire cutting area.

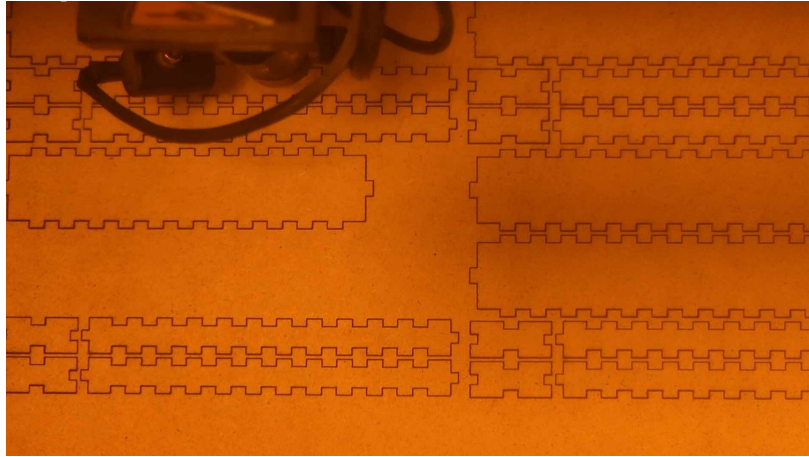


Figure 3.10: Laser cutting of wooden plates

3. Parts Assembly and Gluing

In theory, during the assembling process, the different parts of the bricks do not require gluing together to form a rigid box. However, in practice, the precision of laser cutting may not be perfect in a way that each piece fits perfectly and collects rigidly with the other. Furthermore, each brick needs to be filled, as explained in the following step. In the case that one brick opens during testing, the coarse sand inside would scatter everywhere and this could damage the piston stroke or other components of the system.

If we look at each part of the box on figure 3.11, we see that the top and bottom parts are already named correctly but the other ones are not. Thus, in order to visualize better and according to the system displayed on figure 3.2, we can say that wall 1 and 3 are respectively the north and south parts, in the axis of the camera, and wall 2 and 4 are the east and west parts, in the axis of the piston stroke.

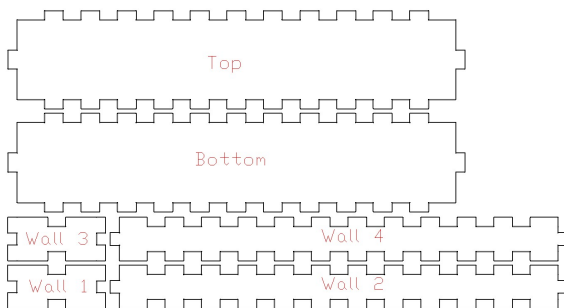


Figure 3.11: Different parts of a full brick



Figure 3.12: Parts assembly and gluing

4. Bricks Filling

Each part, with the exception of the north one in figure 3.11, is assembled and glued together. Leaving the last part unglued keeps the box open, facilitating the filling process with coarse sand. Once the brick is filled, the final part is glued to close the box, completing the assembly of the brick. Coarse sand was selected as its large particle size allows for easy manipulation and ensures that it does not escape through any potential small holes or gaps in the brick.

The weight of all the pieces was measured after filling. The 40 half bricks had weights ranging between 30 and 32 grams, with an average weight of 31.36 grams. On the other hand, the 112 full bricks had weights between 66 and 74 grams, with an average weight of 69.82 grams.

These results confirmed that our filling method was effective, as it yielded similar weights for the bricks with minimal deviation. The consistency in weight indicates a reliable and uniform filling process, which is essential for ensuring accurate and consistent results during the subsequent tests and analysis.



Figure 3.13: Coarse sand

5. Bricks Painting

One purpose of the tests is to track targets glued on the south side in figure 3.11. To ensure easy detection by the tracking program, these targets are designed in black and white, enhancing the contrast. Additionally, the bricks themselves are painted in black to further increase the contrast.

6. Top and Bottom Sandpapering

One of the primary drawbacks of using wood, particularly when painted, is its inherent slipperiness. This characteristic poses a risk of falsifying the results during testing, as the table's acceleration could cause the structure to slide instead of rocking, leading to inaccurate data. To address this issue, several solutions have been devised:

- **Upper Wood Table:** To further stabilize the setup, an upper wood plate is added and fixed onto the initial plastic one. This additional layer of wood enhances the friction between the ground and the first layer of bricks. Moreover, the larger size of the upper wood plate prevents any bricks from falling and potentially causing damage to the piston stroke or other components, ensuring a safe and secure testing environment.



Figure 3.14: Upper wood table

- **Sandpapering the Bricks:** To counteract the slipperiness of wood and paint, the bricks are sanded to create a rougher surface texture. Sandpapering enhances the friction between the bricks and the table or between the bricks, minimizing the risk of sliding during testing.

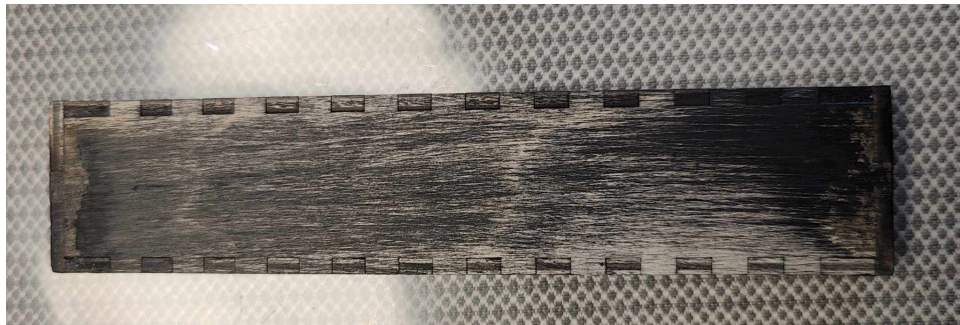


Figure 3.15: Top of the brick sandpapered with abrasive paper

7. Targets Gluing

As previously mentioned, targets are glued to the north and south parts of each full brick to record their displacement during testing. Initially, two targets were glued to each brick to also capture their rotation. However, after coding the target detection process, calculating the rotation proved to be really complex and this area of improvement will be addressed and explained in more detail later. Due to the objective of calculating rotation, half blocks do not have targets attached. Indeed, their thin structure made it impossible to glue two targets.

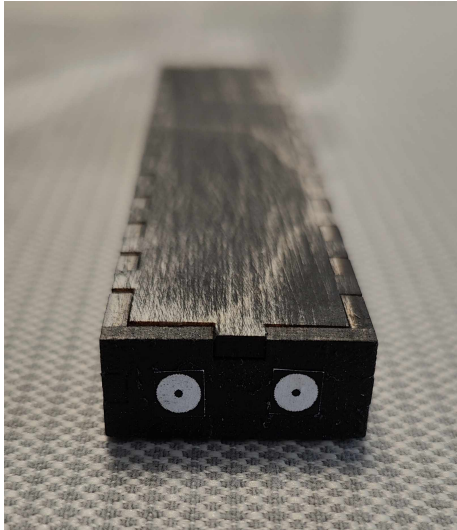


Figure 3.16: First type of target

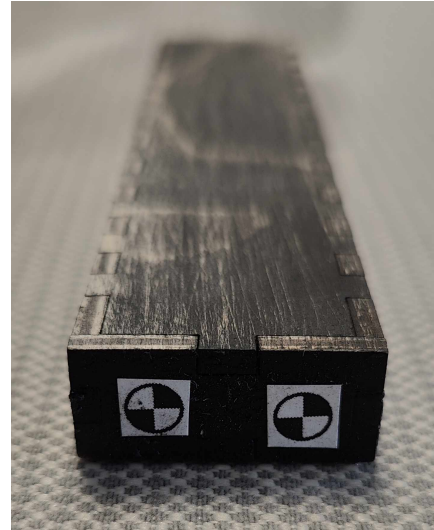


Figure 3.17: Second type of target

3.1.3 Casing and Windows

To assemble the bricks and create various configurations of walls while ensuring their straightness, casings were crafted using wood laser cutting. These casings are then glued at each corner, except one. The purpose of leaving one corner unglued is to facilitate the removal of the casing after the successive layers of bricks have been dry-stacked into it.

To ensure easy placement of the bricks into the casing, its internal dimensions are made 2mm wider in each direction. This additional space allows for smooth insertion of the bricks. However, the extra clearance alone is not sufficient to enable the casing to slide freely from bottom to top without unintentionally moving the bricks.

Hence, leaving one corner unglued allows the casing to be opened, providing a lateral removal method. This process ensures that the casing can be taken out without disturbing the stacked bricks, thereby preserving their alignment and configuration.

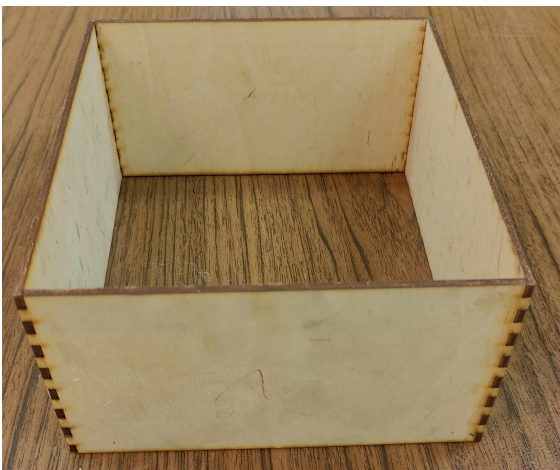


Figure 3.18: Casing for benchmark 1



Figure 3.19: Casing for benchmark 6

Once the bricks are assembled into the casing, the entire structure is carefully positioned on top of the upper wood table on the shake table. To ensure proper alignment with the camera, engravings are made on the upper wood table, running parallel to the sides of the table as displayed on figure 3.14. These engravings serve as visual guides, helping to position the casing correctly and ensure the bricks are parallel to the camera.

After the casing is removed, the process of creating the openings representing the windows on the facade is carried out. Small empty blocks, designed through laser cutting, are strategically placed at the locations where the windows will be. These blocks are inserted during the stacking of the bricks, mimicking the future window openings.

Upon removal of the casing, the blocks simulating the windows can be easily extracted by gently pushing and sliding them in the north-south axis. This results in openings in the facade, as depicted in the following images.



Figure 3.20: Benchmark 4 with and without blocks at openings

3.2 Recording Setup

3.2.1 Accelerometer

This compact device serves a dual purpose by recording both in-plane (x- and y-axis) and out-of-plane (z-axis) acceleration. While an accelerometer is already integrated into the table, an additional one can be magnetized onto a L steel situated on the wood plate as shown in figure 3.14.

The role of this extra accelerometer is to verify whether the acceleration induced by the table corresponds to the acceleration recorded on the wood plate. By comparing the readings of both accelerometers, we can assess the consistency and accuracy of the table's movements.



Figure 3.21: Accelerometer Recovib Tiny

3.2.2 Camera

Logically, data recording is a central aspect of the experiment, and for this purpose, a GoPro Hero9 Black was strategically chosen and positioned in front of the shake table as displayed on figure 3.2. Using a GoPro offers several advantages for this application.

The GoPro can record at a high frame rate per second (in this case, 120 fps). This high frame rate allows for capturing fast movements and rapid changes in position accurately. This is particularly crucial when tracking the targets' displacement and ensuring precise measurements during the testing process.

Additionally, the GoPro records videos at a high image resolution (in this case, 2.7K). The high resolution ensures that the recorded footage contains detailed information, making it easier to locate and identify the targets in each frame. Having clear and detailed images significantly reduces the possibility of blurring caused by the shake table's movements, enhancing the accuracy of the target detection process.

By combining the high frame rate and image resolution capabilities of the GoPro, the experiment can acquire high-quality data, enabling accurate tracking of the targets throughout the testing procedure.

Chapter 4

Code Implementation

This chapter focuses on the computer-oriented aspects of the thesis, specifically the implementation of Camera Calibration and Target Tracking codes. Step-by-step instructions will be provided to guide readers through each aspect of the code. The goal is to offer practical insights into the IT aspect of this thesis, providing readers with hands-on experience in vision-based applications.

4.1 Camera Calibration

4.1.1 Concept Definition

Camera Calibration is a crucial technique used to correct lens distortions in videos, ensuring accurate measurements, especially in target tracking applications, as demonstrated in our study.

To perform Camera Calibration effectively, we printed a checkerboard consisting of a mesh of black and white squares. This checkerboard pattern serves as a reference for the computer vision system during the calibration process.

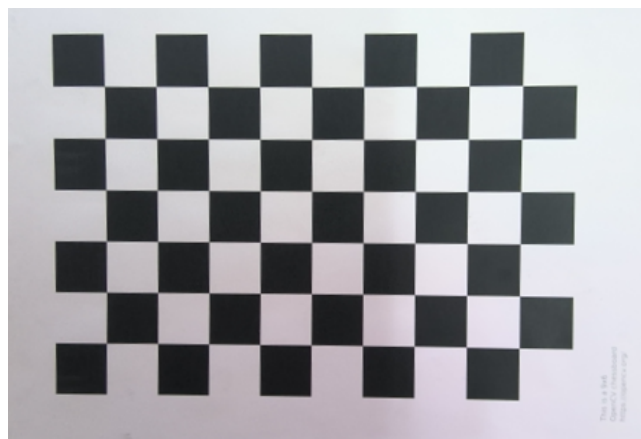


Figure 4.1: Checkerboard for calibration

A series of images were captured from various angles with the GoPro. By analyzing these images, the computer "learns" the specific distortions introduced by the camera lens and how they affect the captured scene.

During the calibration process, the computer identifies the key points and patterns on the checkerboard in each image. It then compares these detected points to their known positions on the physical checkerboard. By analyzing the discrepancies between the observed and expected positions, the computer can accurately model the lens distortions and correct them.

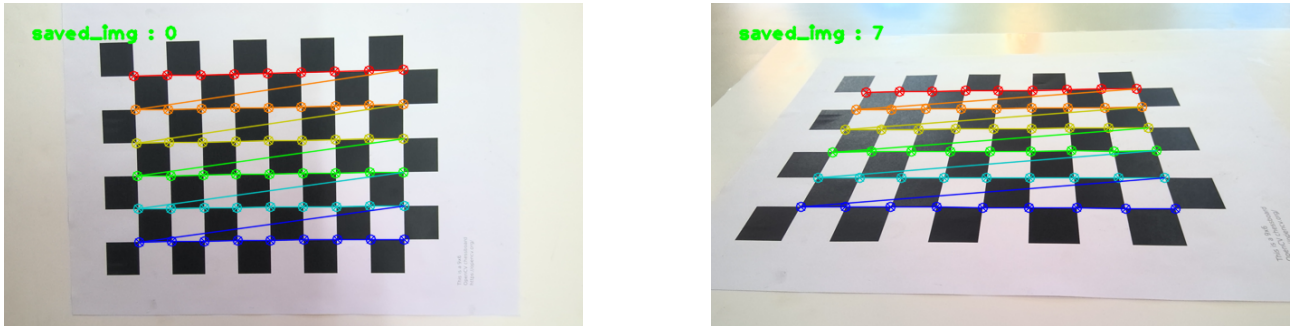


Figure 4.2: Detected checkerboard from various angles

As a result of this calibration, the camera's intrinsic parameters, such as focal length and principal point, are determined, along with the lens distortion coefficients. Armed with this information, subsequent images or frames can be rectified, ensuring precise measurements and improving the accuracy of target tracking in our study.

4.1.2 Undistorting Algorithms

4.1.2.1 OpenCV Python

To perform it, the first step consists in filming the checkerboard from various perspectives following some specific settings :

- Using the wide lens of the GoPro camera to have a lens distortion and capture a broad field of view, encompassing the entire checkerboard pattern in the frame.
- Set the video resolution to the desired level wanted for the future tests. In our case, we choose a 2.7K resolution.
- Choose the fastest shutter speed to capture sharp, high-quality frames without motion blur.
- Turn off any stabilization which could introduce additional distortions and reduce the efficiency of the calibration.

The next steps are as follows :

1. Drag and drop the recorded video onto the *opencv_video_calib.exe* file from the GitHub repository of the YouTube channel *WalkWithMe* [37]. This action will initiate the camera calibration process, analyzing the video at 2 frames per second.
2. A terminal window will open, printing messages about the detection of the checkerboard on each frame.
3. The outputs of the calibration process will be a camera matrix, a list of distortion coefficients, and an undistorted video of the checkerboard. These results will be saved in a *calib_data* folder.

4. To undistort other videos, we drag and drop them onto the *opencv_video_undistort.exe* file. This will produce undistorted videos, which will be stored in a *Result* folder.

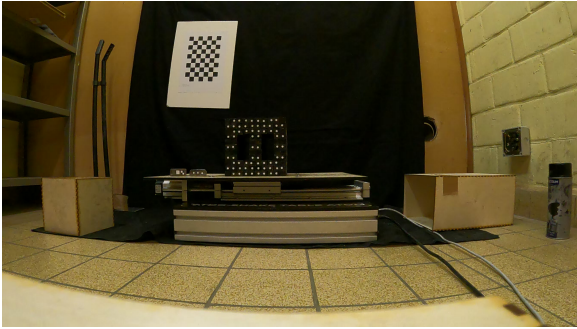


Figure 4.3: Distorted image

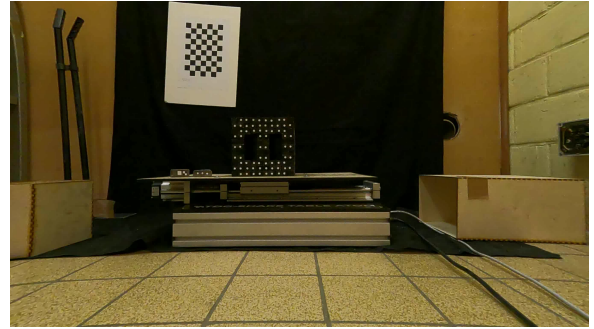


Figure 4.4: Undistorted image with OpenCV Python

4.1.2.2 DaVinci Resolve

Furthermore, we can use a software called DaVinci Resolve for video undistortion. This alternative approach provides us with the opportunity to compare the same video undistorted using two different methods, enhancing the versatility and accuracy of our analysis. The procedure is described hereunder.

Once the project has been created and the video has been imported using the "Import" subsection in the "File" section of the software, we need to create a timeline by simply dragging and dropping the video from the media pool into the timeline space located below.

After accessing the "Edit" section below the timeline in the software, the next step is to open the "Inspector" section located at the top-right corner of the interface. Within the "Inspector," we will find a "Lens Correction" subsection that provides essential tools for correcting lens distortions.

To initiate the correction process, look for the "Analyze" button within the "Lens Correction" subsection. Clicking on this button will prompt the software to analyze the video thoroughly. During this analysis, DaVinci Resolve examines various aspects of the video, such as the floor tiles and the checkerboard on the wall, to determine the appropriate distortion coefficients required for precise undistortion.

Upon completing the analysis, the software applies the identified distortion coefficients to the video, resulting in an undistorted version that can be compared to other undistortion methods.

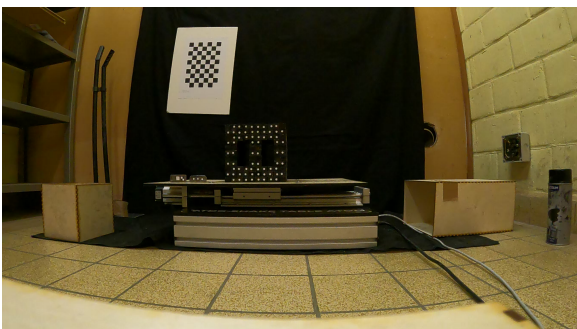


Figure 4.5: Distorted image

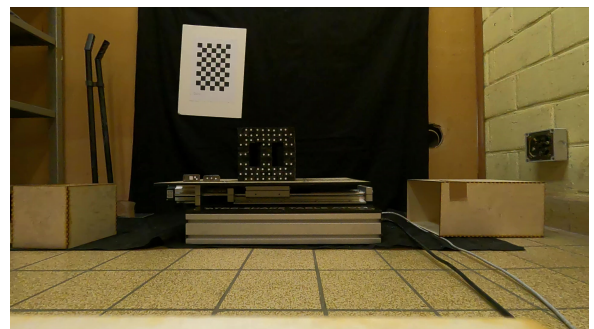


Figure 4.6: Undistorted image with DaVinci Resolve

Comparing the results from OpenCV and DaVinci Resolve reveals a noticeable distinction between the two images. For instance, if we examine the floor tiles, it becomes apparent that they remain distorted in the image from OpenCV, as well as the shake table. During the calibration process, the program generates a text file where several variables are denoted such as a vector of 5 values called "dist" which we found correspond to radial and tangential distortion coefficients upon further investigation. In contrast, DaVinci Resolve employs a single value, actually the first value from OpenCV's list. This first value, referred to as "k1", represents the primary radial distortion coefficient, which largely accounts for the lens curvature-induced radial distortion. Two potential conclusions can be drawn from this information: either DaVinci Resolve employs a simplified distortion model that uses only k1 for undistortion, or they also use the other distortion coefficients but do not display them, given their lesser significance. Considering the results from both methods, it appears that DaVinci Resolve provides a more trustworthy undistorted image, implying that the second assumption is more likely to be accurate.

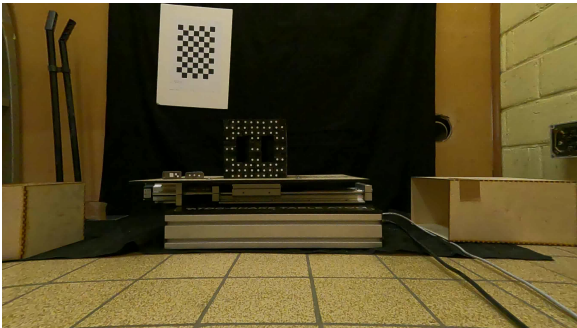


Figure 4.7: Undistorted image with OpenCV Python

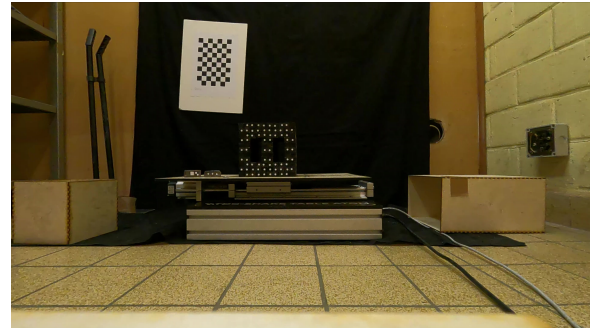


Figure 4.8: Undistorted image with DaVinci Resolve

In each video undistorted using DaVinci Resolve, the primary radial distortion coefficient "k1" was determined to range between 0.26 and 0.268, whereas it was measured as 0.28 using OpenCV Python. This coefficient is crucial for rectifying the curvature of lines in the distorted video. The value obtained from the second method appears to be excessively high, leading to an overcorrection of the distortion. In an attempt to rectify this issue, we lowered the coefficient to 0.265 for the OpenCV Python method. However, while this adjustment did result in a marginal improvement as the floor tiles straighten, it still did not achieve the level of undistortion quality achieved by DaVinci Resolve. This suggests that the other undistortion coefficients and other variables should be modified in order to achieve comparable results.

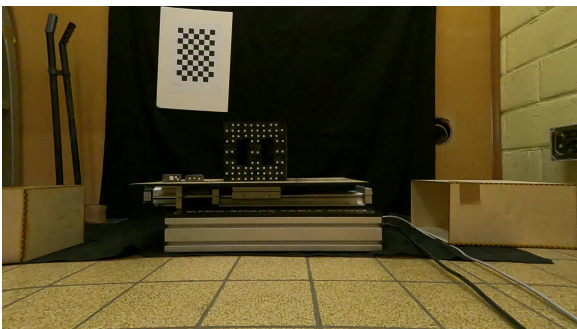


Figure 4.9: Original distortion coefficient

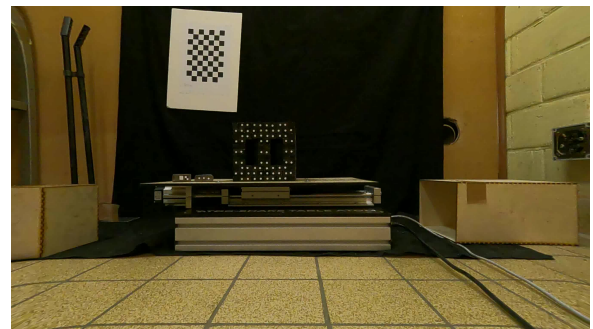


Figure 4.10: Modified distortion coefficient

4.2 Frame Extraction

Frames were extracted from the video using the ffmpeg software to simplify data analysis and enable target tracking. By executing the ffmpeg command, frames were efficiently extracted and saved as individual image files, which were later used for analyzing the masonry wall experiments and tracking the targets.

The extraction process captures 119.88 frames per second from the video, as it corresponds to the frame rate, and each frame is given a filename in the format "extracted-image-X" where X represents the frame number. These extracted frames are then stored in the designated folder named "images-to-process" for further analysis.

4.3 Target Tracking Code

This thesis aims to analyze the behavior of masonry assemblies subjected to ground motion. As mentioned before, targets were placed on full bricks to calculate their displacements accurately. The description will cover target detection, coordinate and displacement calculations, and post-processing of data. An example based on the fourth benchmark will be used to show the different outputs of the code.

4.3.1 Image Manipulation

During the processing of each frame, it is first read and then converted to gray scale. This manipulation enhances the contrast and simplifies the process of detecting targets. Indeed, by working with gray scale images, we eliminate color complexities and focus solely on the intensity variations in the image as this aids in distinguishing the targets from the background more effectively.

4.3.2 Target Detection and Filtering

This part is almost entirely inspired by the class document from Lo Feudo et al [38]. In image analysis, specific regions can be detected based on shared properties among a group of pixels, such as brightness or color. The detection of these regions allows us to extract their positions in the image for further processing. For instance, the Maximally Stable Extremal Regions (MSER) algorithm, known as one of the region detection algorithms, was employed in our study to track the targets attached to the bricks and measure their displacements accurately.

MSER regions are detected and represented in the original image. As clearly shown in figure 4.11, this detection process include regions that are not actual targets and requires filtering to extract the relevant regions. The filtering process involves compliance with three requirements : circularity, pixel intensity and redundancy.

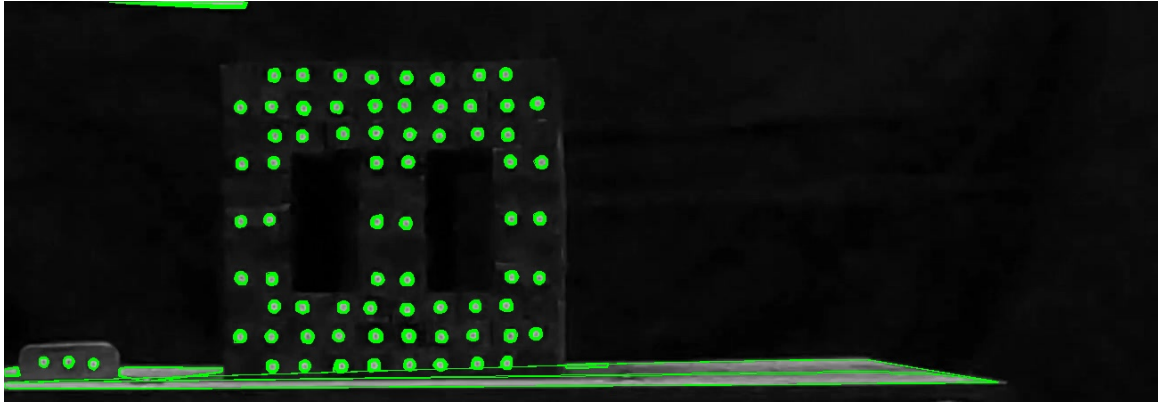


Figure 4.11: All MSER regions detected in the first frame

4.3.2.1 Circularity Check

To filter out non-target regions, the first feature considered is circularity. Even though they appear as ellipses due to perspective, all our targets are circular in shape. Circularity index is defined as $C = 4\pi A/P^2$, where A is the area and P is the perimeter of the region.

The more the value tends towards 1, the more this means that the region detected is round because $A = \pi R^2$ and $P = 2\pi R$ thus, for a perfect circle, the circularity is equal to one. For each detected region, the circularity index is calculated and only the regions and contours with a circularity index greater than a specified threshold value are stored.

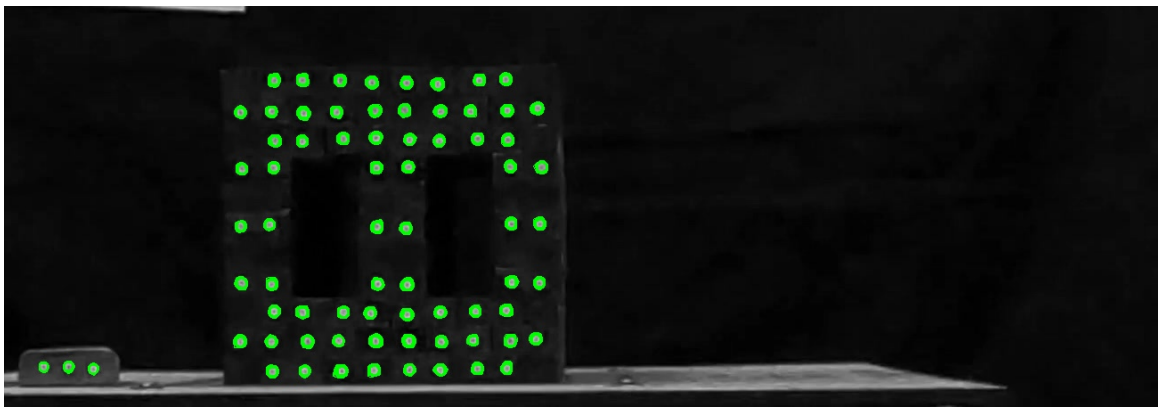


Figure 4.12: Circularity regions detected in the first frame

4.3.2.2 Pixel Intensity Check

The second feature is centered around analyzing the pixel intensity of the target region. As our targets have a darker center compared to the mean intensity of the surrounding region, this process is designed to filter out any circular patterns in the image that are not actual targets, such as bolted joints of the shake table. However, in our specific case, we have cropped the video to focus solely on the structure, leaving only the structure and possibly a portion of the checkerboard in the frame. As a result, the first filtering process is already effective in identifying all the targets accurately. This second process now serves as a double-check and is primarily employed to calculate the center of each target, providing further validation and enhancing the accuracy of our target tracking.

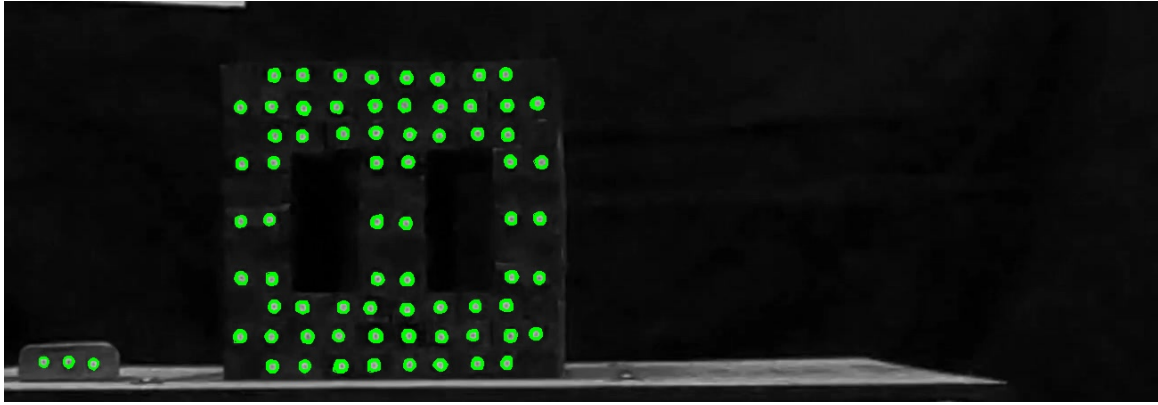


Figure 4.13: Intense pixel regions detected in the first frame

4.3.2.3 Redundancy Check

As shown in figure 4.13, the algorithm draws thick green lines around each elliptical-shaped target. This thickness results from multiple overlapping regions for each target detected by the MSER algorithm. To remove redundant regions, we adopt a method that involves creating a bounding box around each contour. By doing so, we obtain a unique bounding box and its corresponding indices for each target.

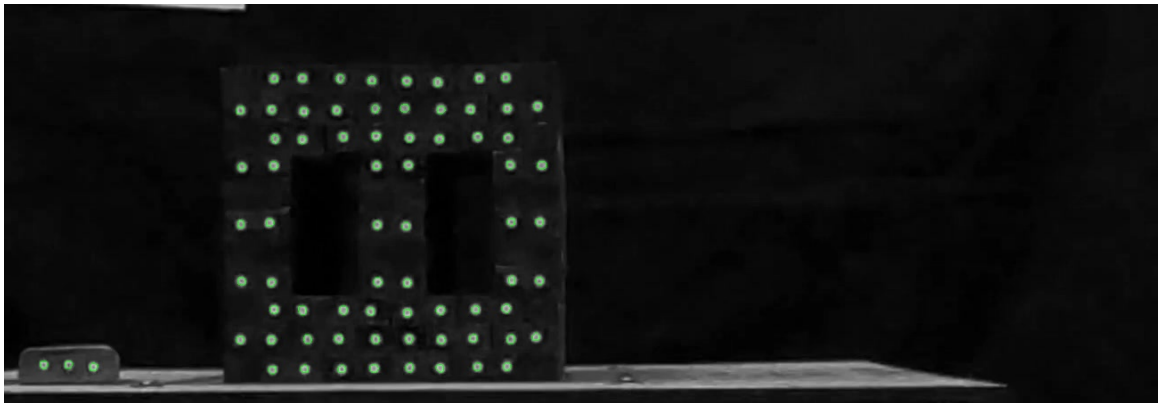


Figure 4.14: Unique regions detected in the first frame

4.3.2.4 Center Evaluation in Target Detection

Following the filtering process, the next step involves calculating the center of each target. To achieve this, we compute the average centroid of the concentric ellipses that compose one target and store its coordinates. The center's coordinates serve two purposes: first, they are essential for calculating each target's displacement, and secondly, they enable to number the targets in a logical and systematic manner.

Pseudo-code:

1. For each bounding box:
 - (a) Calculate the minimum and maximum corner coordinates of the bounding box.
 - (b) For each centroid:
 - i. Check if the centroid lies within the bounding box region. If it does, save it.

- (c) Calculate the mean centroid of the saved centroids, convert it to integers and save it.
2. Remove duplicate mean centroids from the list and return the final list of mean centroids.

4.3.3 Target Numbering

As detailed in subsection 4.3.2.2, the coordinates of each target's center have been stored in a list. To assign numerical labels to the targets, we sorted this list based on their positions, considering a left-to-right and top-to-bottom order. By numbering the targets in ascending order, the three targets on the left side of the image, representing the table's displacement, are consistently assigned as the first three targets, regardless of the benchmark being tested. This systematic numbering simplifies the identification and retrieval of the specific targets that represent the table's displacement in all benchmark scenarios.

Pseudo-code:

1. Sort the target's center list based on the x-coordinate of each element, and store it in another list.
2. For each element in the sorted list:
 - (a) Put the right index as text at the corresponding coordinates on the image.
 - (b) Save the index and its corresponding coordinates.
3. Draw green contours around targets.
4. Return the modified image and the index and coordinates list.

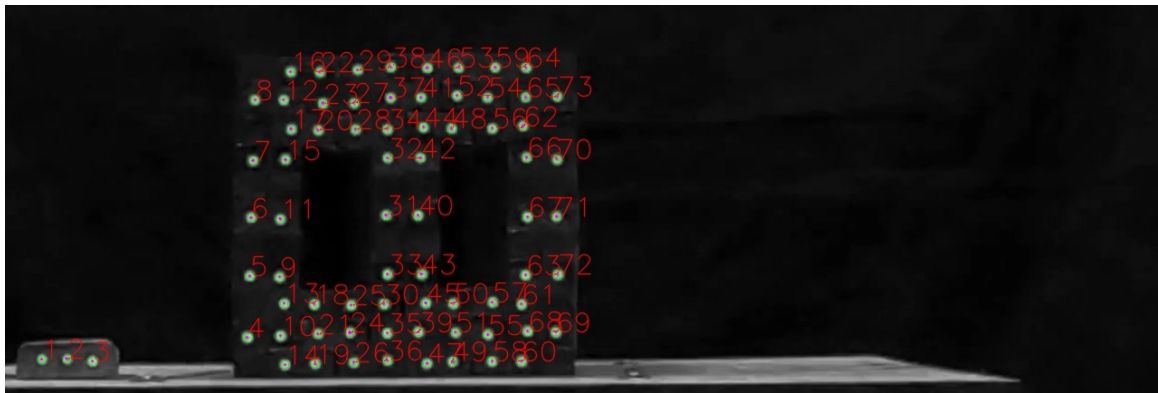


Figure 4.15: Filtered and numbered targets in ascending order

4.3.4 Unit Conversion : Pixel to Millimeters

As the coordinates are expressed in pixels, distances are also represented in pixels. However, to obtain distances in millimeters, we need to perform a conversion. To achieve this, we identify a known distance on the image that remains consistent across all benchmarks. In our case, we use the radius of each target, which measures 2.7mm.

Since the fourth benchmark contains 73 targets as displayed in figure 4.15 and considering that they might not have the same pixel size due to imperfect alignment of the bricks, we calculate the mean radius using the stored perimeter and area from the circularity check process in subsection 4.3.2.1. Additionally, we calculate the minimum and maximum radii and their standard deviation relative to the mean.

These values, along with other relevant data, are stored in an Excel file, which will be discussed later. As an illustration, considering our example and images with a resolution of 2.7K (2704x1520 pixels), the mean radius measures around 5.9 pixels, with a minimum of 4 pixels and a maximum of 8.8 pixels. With each pixel equivalent to 0.45mm, we obtain the corresponding minimum radius of 1.8mm and the maximum radius of 4mm. These values demonstrate the relevance of our unit conversion, allowing for accurate distance measurements in millimeters for the targets' displacements.

4.3.5 Iterative Processing of Frames

The process described in subsection 4.3.2 is applied iteratively to the subsequent frames composing each video. However, there are two important changes during this process, both related to the circularity check and the numbering method. As targets move across frames, their representation becomes blurred, making their detection more challenging. To address this, after processing the first three frames, the threshold value in the circularity check is significantly lowered to detect targets even when they appear more elliptical or blurred.

However, this reduction in the threshold value also leads to the detection of additional MSER regions that are not actual targets, such as the squares composing the checkerboard. To accurately identify the real MSER regions corresponding to targets and avoid wrong numbering, we employ a numbering approach based on Euclidean distance. For each target's coordinates in the previous frame, we compare them to the new coordinates of the MSER regions in the current frame. This comparison allows us to correctly renumber the targets and filter out irrelevant MSER regions.

Each time a MSER region is numbered, corresponding to the new position of a target, it is excluded from consideration in the numbering of the next target, ensuring that no wrong numbering occurs. Additionally, the circularity check threshold value is maintained high for the first three frames, as the structure does not move significantly in these frames. This helps establish a stable numbering reference for subsequent frames when the structure starts moving, ensuring accurate and consistent target numbering throughout the entire video sequence.

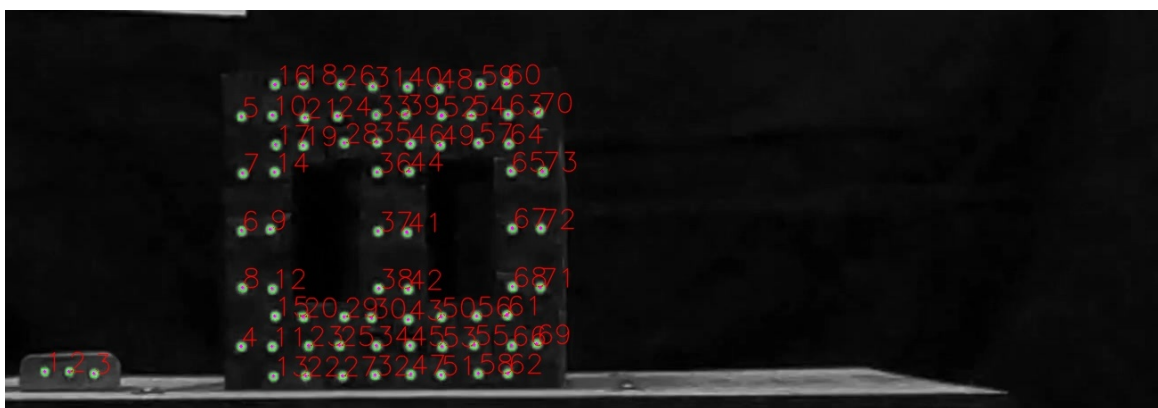


Figure 4.16: First frame numbering

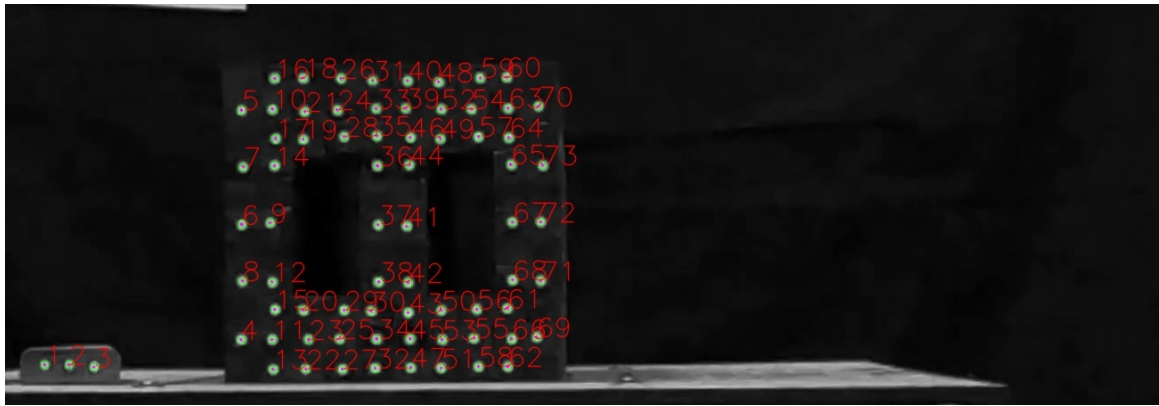


Figure 4.17: Third frame numbering



Figure 4.18: 120th frame numbering

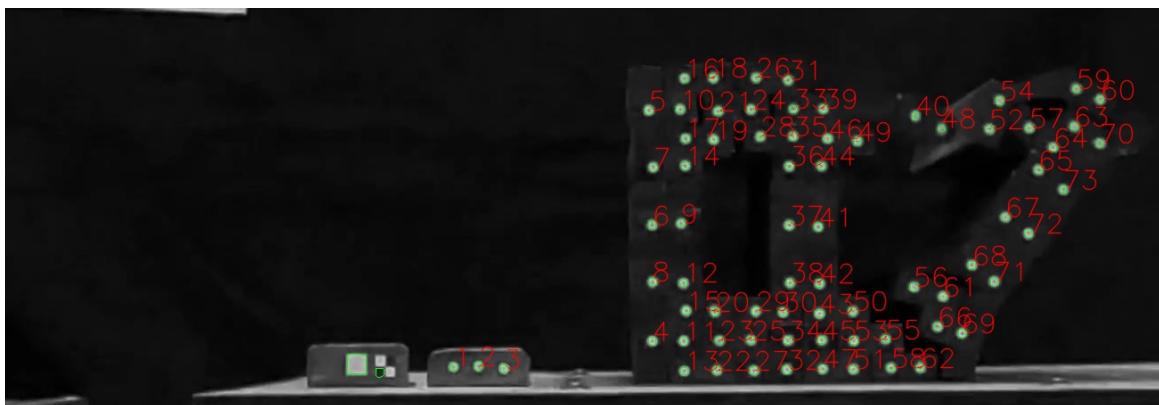


Figure 4.19: Last frame numbering

4.3.6 Displacements Calculation and Plot

Upon close examination of the above figures, one may notice the presence of pink patches in the center of each target. These pink patches are, in fact, arrows that connect the coordinates of a target in the current frame with the corresponding coordinates of the same target in the next frame. These connecting links display the displacement of each target between consecutive frames.

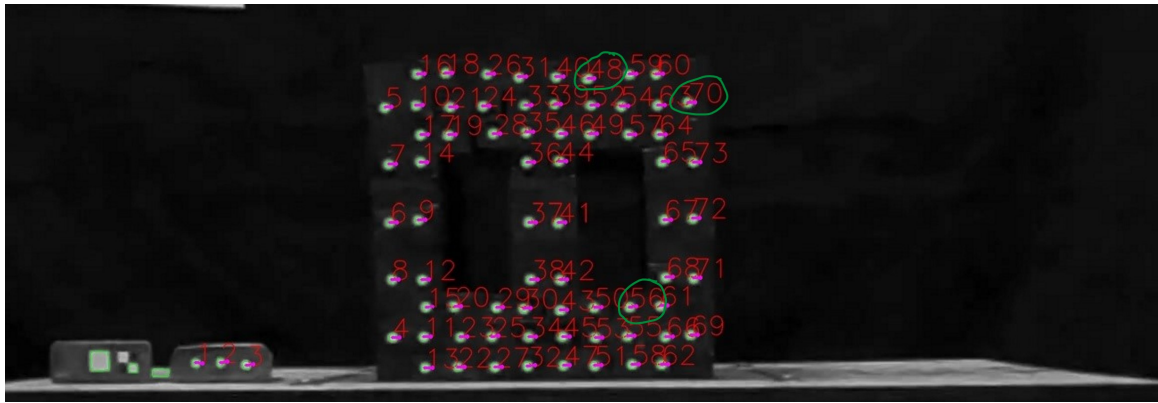


Figure 4.20: 63rd frame displaying the pink arrows

After displaying the displacement of each target between two frames, it is natural to present the complete displacement of a target throughout the entire video. To achieve this, the coordinates of the target from each frame are plotted on a graph, with the x-axis corresponding to the horizontal coordinates and the y-axis representing the vertical coordinates.

It is important to note that the y-axis ascends from top to bottom, as the $(0,0)$ coordinates are positioned on the top-left corner of each image. This graphical representation provides a comprehensive view of the target's movement trajectory over time, allowing us to observe its overall displacement pattern and dynamics throughout the video sequence.

In this upper figure 4.20, our attention will be directed towards targets showcasing significant movements and circled in green. These include the targets located in critical areas such as the bottom-right corner (56th target) and the top-right corner (48th and 70th targets).

For the 56th target located at the bottom-right corner, the target clearly goes up when the rocking phenomenon starts. However, the video stops before the conclusion of the rocking motion as we can see in figure 4.19. Consequently, the displacement plot is expected to exhibit a slight "bump," indicating an upward and downward movement but, in this example, the plot only reflects an upward trajectory.

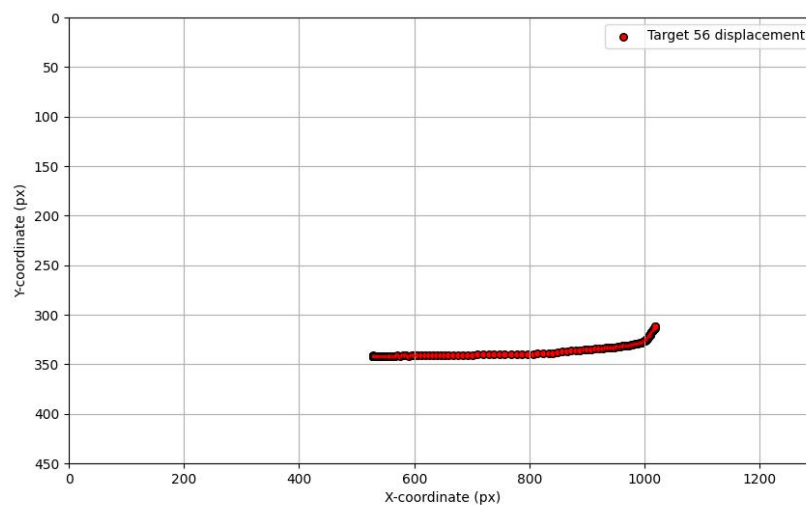


Figure 4.21: 56th target displacement located in the bottom-right corner

Regarding the targets located at the top-right corner, these targets clearly move downward as the rocking phenomenon appears. In the case of the 48th target, it undergoes a vertical descent due to its free-fall within the window opening as it detaches from the rest of the overturning part of the wall, as displayed in figure 4.19. Conversely, for the 70th target, the rotational movement of the structure induced by the rocking phenomenon is faithfully illustrated through the trajectory of the target.

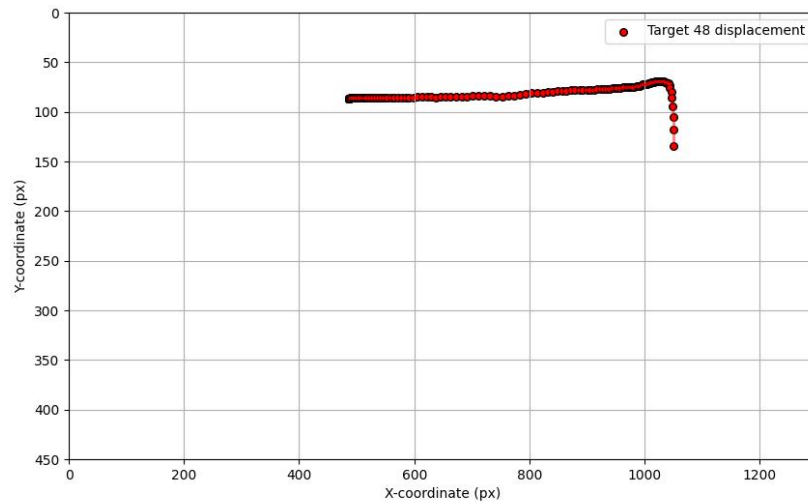


Figure 4.22: 48th target displacement located in the top-right corner

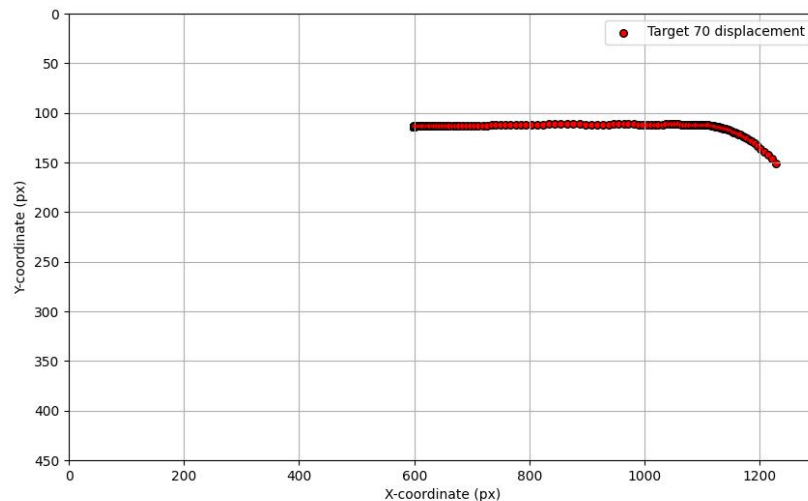


Figure 4.23: 70th target displacement located in the top-right corner

To enhance the visualization of target displacements on individual frames extracted from the video, the optical flow technique can be employed. This involves drawing green curves onto each frame to illustrate the movement of the targets. This method helps to identify key moments of interest, such as the onset and progression of the rocking phenomenon, but also provides a more comprehensive and simultaneous visualization of the displacements of all targets.

In the first following image captured just before the onset of the rocking phenomenon, the optical flow visualization clearly showcases the horizontal displacement of the table. Moving to the subsequent image, the lines representing the optical flow start to exhibit curvature, indicating the emergence of the rocking motion.

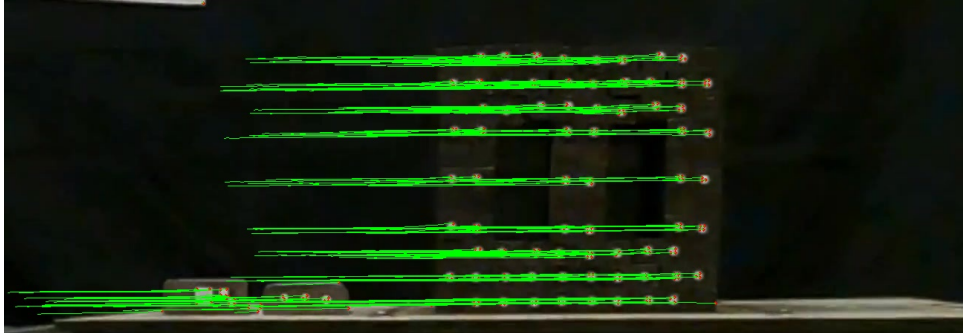


Figure 4.24: Before the rocking phenomenon

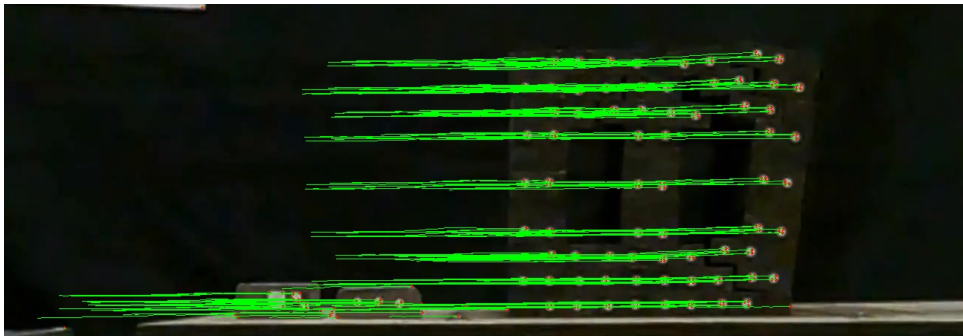


Figure 4.25: At the start of the rocking phenomenon

As the rocking phenomenon progresses, the lines in the optical flow visualization become notably shorter. This phenomenon can be attributed to the deceleration and stop of the table's movement, leading to reduced motion within the structure. Since the optical flow analysis considers a fixed number of frames, the decreasing movement of the table results in shorter optical flow lines.

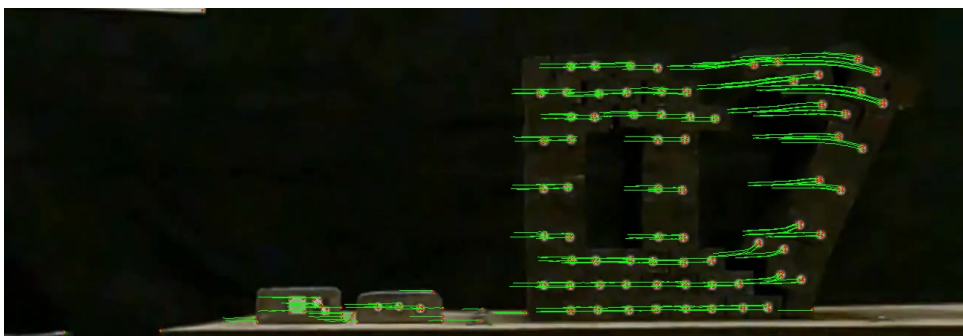


Figure 4.26: At the end of the rocking phenomenon

At the end of the video, the majority of the curves are very short, indicating the end of both table movement and most target displacements. Notably, in the bottom right corner, distinct curves can be observed going up, marking the beginning of the bump illustrated in figure 4.21.

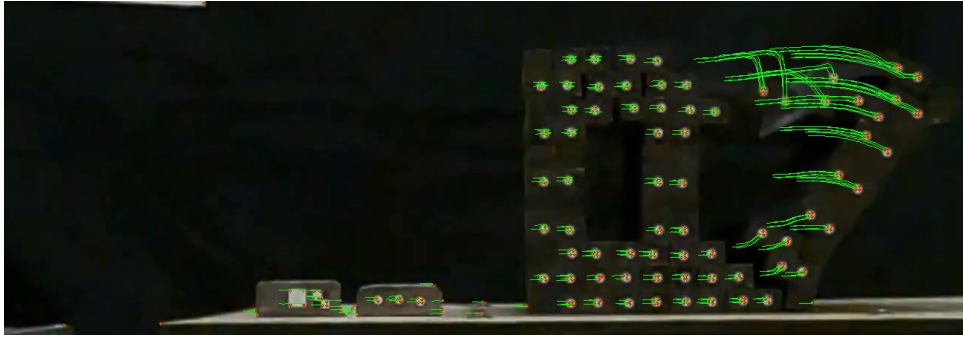


Figure 4.27: At the end of the video

As expected, the displacement of each target between two frames is calculated using its pair of coordinates. We calculate the displacements along the horizontal and vertical axes, and combining these two allows us to compute the total displacement. However, it's important to note that these calculated displacements are not solely the displacements of the bricks themselves. They represent the combined displacement of the target and the table.

To obtain what we refer to as the relative displacement of each target, we need to isolate the effect of the table's displacement. This is accomplished by subtracting the displacement of the table from the calculated displacement of each target. As previously mentioned, the displacement of the table is computed based on the first three targets. To account for any slight variations, we consider the displacement of the table to be the mean of the displacements of these three targets.

By performing this adjustment, we obtain the relative displacement of each target, which provides a more accurate representation of the bricks' actual movement, removing the influence of the table's motion from the measurements.

4.3.7 Post-processing of Experimental Data

For future research on the numerical testing of the same benchmarks, data concerning the relative displacement of each target throughout the entire video could be valuable. To facilitate this, information such as the radius sizes, unit conversion, and relative displacements are systematically exported and compiled into an Excel file.

Upon close inspection, rotations are also included in the Excel file for each target between each pair of frames. However, it has been discovered that these rotation values are incorrect. The reason behind this discrepancy is that the rotations were calculated solely based on the displacement of one target. For example, while a target might move by 45 degrees to the bottom right, resulting in a calculated angle of 45 degrees, this does not necessarily mean that the brick undergoes a corresponding rotation.

The ideal approach to calculate rotation would involve using the two targets fixed on each brick. Unfortunately, this process would have been time-consuming, and the focus was directed towards other aspects of the research. As a result, the rotation calculation remains an area for improvement in future works on this subject.

4.3.8 Target Tracking for Second Target Type

As shown in figure 3.17, an additional type of target has been fixed on the opposite side of the bricks. These targets were subjected to the same testing process as the previously mentioned targets.

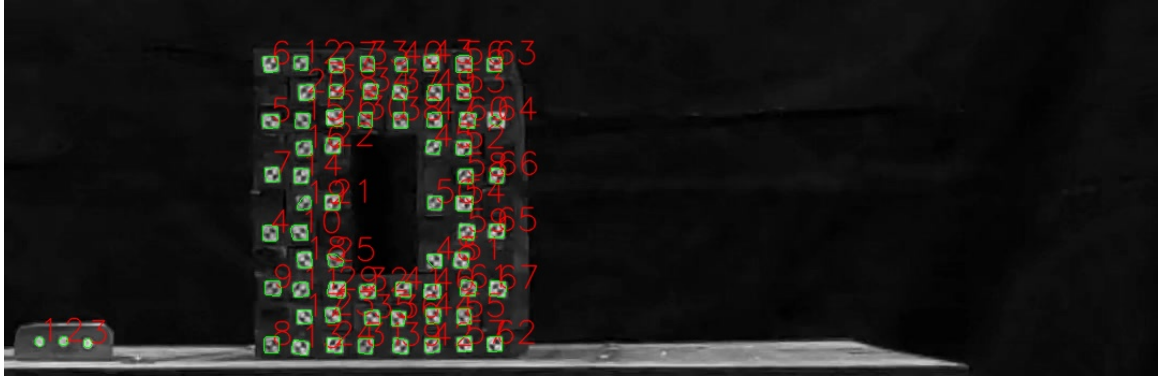


Figure 4.28: Second type of target detection

The results obtained from the process have shown interesting findings, but they are not yet sufficient to be considered fully accurate. Upon closer examination of figures 3.17 and 4.28, it becomes apparent that the MSER regions detected are not precisely representing the targets themselves but rather the white square surrounding each target. For instance, in figure 4.29, the 64th MSER region correctly outlines the exact contours of the target, while the 56th MSER region draws the white square around it. This indicates that the code successfully identifies the correct zone for each target but draws the outline of the white square instead of the exact target region. This could lead to issues, especially concerning unit conversion.

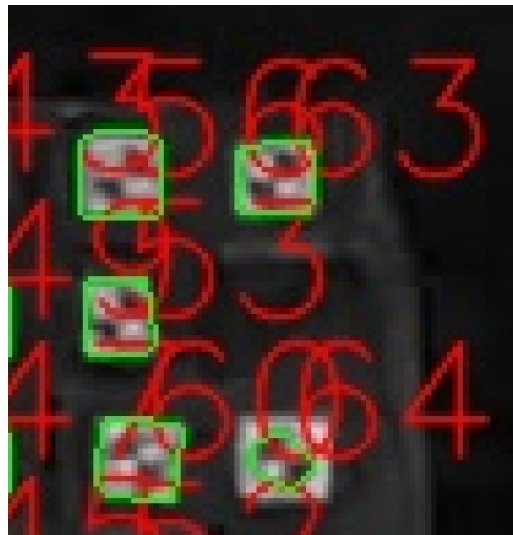


Figure 4.29: Zoom on 56th and 64th MSER regions

As for the rotation calculation issue, re-cutting and re-gluing each target would be time-consuming thus this approach was not pursued further. Instead, the research direction was shifted towards more promising and productive aspects. Nevertheless, the presented figures demonstrate the effectiveness and validity of the code to track the regions of interest. With

certain refinements to the target detection process, the code has the potential to allow the comparison of target tracking across different target types.

4.3.9 Possible Alternative Target Types

During the exploration of OpenCV Python, we came across a new type of targets known as ArUco targets, which are square-shaped rather than circular, on the Youtube channel *AiPhile* [39]. Consequently, in this case, the previous target detection code became obsolete due to the change in the target's form. However, we were able to develop a new code to detect these ArUco targets, and it turned out to be straightforward to implement. The same code proved capable of detecting up to nineteen different types of targets, making the process even more efficient. The code also facilitated the calculation of coordinates for the detected targets with ease.

The transition from circular to rectangular targets could have been easily accomplished, and the results obtained with the new targets were highly promising, as evident in the figures provided below. However, by the time we discovered these new targets, the previous circular targets were already affixed to the bricks. Changing the targets on all the bricks would have been time-consuming, and the subsequent post-processing would have required even more effort. Consequently, we decided to prioritize other aspects of the research, especially since the code for the first type of target was not fully functional at that time. Thus, these ArUco targets remains today a possible improvement as it would allow to compare the target tracking using a different method and even more different target types.

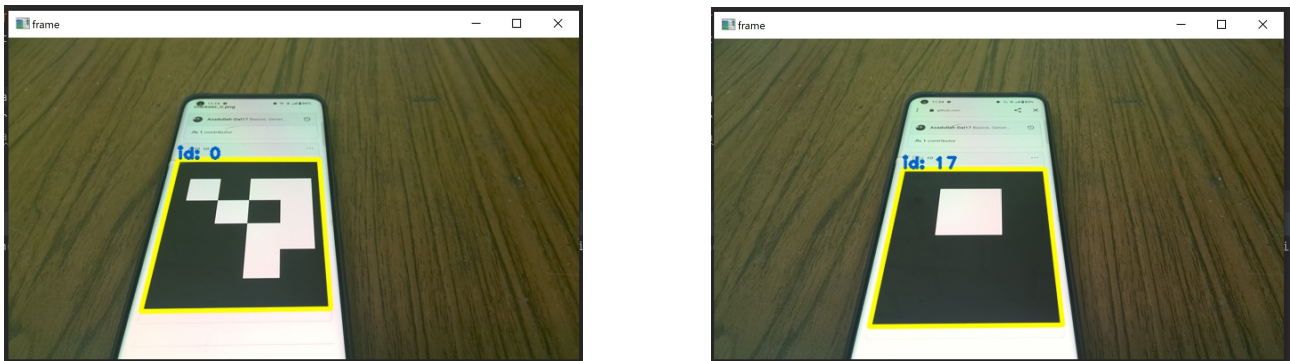


Figure 4.30: ArUco targets detection

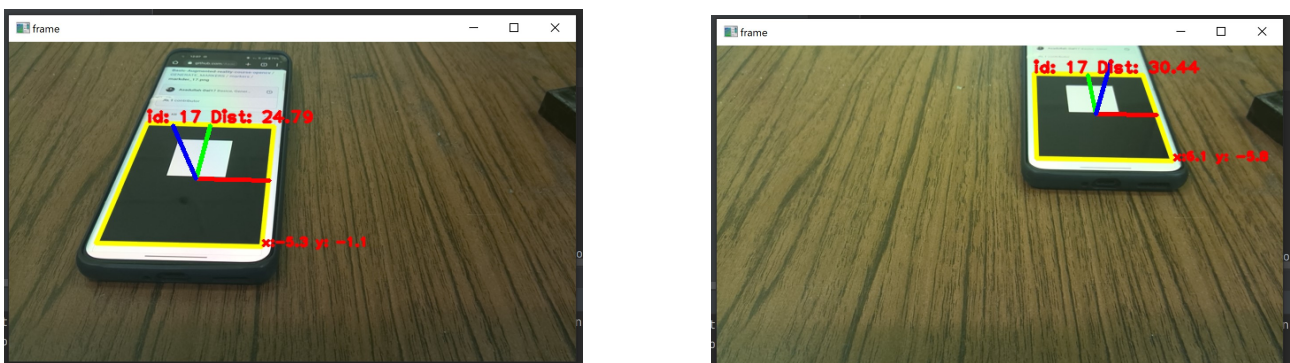


Figure 4.31: ArUco coordinates calculation

Chapter 5

Analysis of Experimental Results

After describing all the phases of test preparation and the code-oriented section, it is now time to present the test results for each benchmark and compare them with the numerical results. Prior to that, the friction coefficient was measured to consider its potential impact, especially in case of sliding. Following this, a comparison will be made between the acceleration recorded by the accelerometer placed on the shake table and the accelerometer placed on the wooden table adjacent to the structure.

5.1 Experimental Calculation of Friction Coefficient

To calculate the friction coefficient, a straightforward and effective method was devised. The casing used for benchmark 6 was placed on a table, and a brick was positioned on top of it. By manually tilting the casing slowly, the brick was encouraged to slide due to the force of gravity. The inclination had to be extremely gradual to minimize any potential dynamic effects induced by the process.

Once the brick began to slide, the inclination was stopped, and the angle of inclination was measured using a bracket. The procedure and setup are depicted in the figures below, demonstrating the setup at start and finish. In this example, the measured angle of inclination was 28 degrees.



Figure 5.1: Friction coefficient measurement at start and finish

The process was repeated 5 times on both opposite faces of 10 different bricks, resulting in a total of 100 tests. The measured angles varied slightly for each brick side's test, with a maximum difference of 6 degrees for each brick's side. The total range of angles varied from 25 to 35 degrees, with an average of 29.58 degrees. To convert degrees into friction coefficients, we used the following formula :

$$\mu = \tan(\theta) \quad (5.1)$$

Applying this formula to our values, the friction coefficients were found to range from 0.466 to 0.7, with an average of 0.568. In the referenced article [35], the friction coefficient μ was defined as 0.65, corresponding to an inclination angle of 33.02 degrees. Comparing these values, we can observe that they are relatively close, suggesting that the sliding effect will not significantly impact the overall results.

5.2 Comparison between Numerical and Experimental Results

Before delving into the analysis of the results for each benchmark subjected to various accelerations, it is essential to mention that rigorous testing and validation measures were taken for each specific acceleration. When drawing conclusions for a particular acceleration, such as the observation of rocking at 0.14g for benchmark 4, the same acceleration and one slightly smaller by 0.01g were independently tested three times each. This approach was adopted to confirm and validate the observed behavior at these specific values and enhance the reliability and robustness of the analysis.

5.2.1 Comparison Criteria

Before comparing the results for each benchmark considered, several important aspects need to be discussed and defined. First and foremost, the load factors expressed in figure 2.33 will be compared to the experimental results. These values indicate the potential creation of failure mechanisms that have not yet been identified.

In the field of structural dynamics, a failure mechanism of masonry assemblies refers to a phenomenon that leads to the collapse of a wall. Failure can occur in both in-plane and out-of-plane directions. For our study, we are focused on in-plane failure mechanisms, and there are three main types that have been identified: sliding shear failure, rocking, and diagonal cracking. These failure mechanisms are illustrated in the figure below:

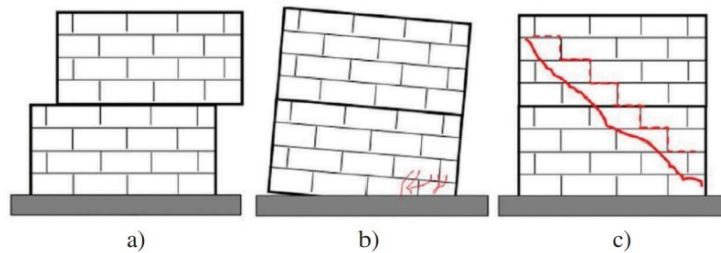


Figure 5.2: Typical in-plane failure modes of masonry walls: (a) sliding shear failure; (b) rocking; and (c) diagonal cracking [40]

Within the scope of our study, failure will be considered in a specific case: when the wall has been damaged during the process due to a rocking phenomenon, causing a permanent change in the wall's configuration from its initial state. For instance, if bricks on the top layers fall due to sliding, as it will be observed later in benchmark 1 for example, this is not considered as failure. Similarly, if a rocking phenomenon occurs and part of the wall rotates but then returns to its initial position, as it will be observed later in benchmark 4 for example, it is not considered as failure.

The reasoning behind these choices lies in the fact that our tests involve dry-stacked masonry to ensure easy duplication of experiments and for conservative reasons as a dry-stacked structure is less resisting than a mortar-jointed one. Indeed, in real-life scenarios, mortar is often damaged or present between the bricks, acting as a glue that provides additional stability. Thus, if our experimental results indicate that the induced acceleration is sufficient to make the wall overturn but not break, the same acceleration in a real-life scenario would not be enough to cause rocking because the mortar would provide additional resistance.

The same justification applies to sliding; bricks on the top layers will not fall due to sliding as they are connected with mortar to other bricks, providing additional support. It is essential to note that this interpretation is the one we decided to adopt, and it may vary for other researchers as there is no single truth in this context. The chosen criteria for defining failure are based on our specific experimental setup and the behavior of dry-stacked masonry walls, taking into account the presence and function of mortar in real-life scenarios.

5.2.2 Benchmark 1

It is important to note that explaining the dynamic behavior of structures solely through extracted frames can be quite challenging. To enhance the comprehension of the upcoming explanation, the analyzed videos have been provided on a Google Drive whose link is given in the last appendix. These videos aim to assist readers in gaining a clearer understanding of the concepts discussed.

5.2.2.1 Sliding of Bricks in Top Rows

For accelerations ranging from 0.01g to 0.5g, there is no sliding observed in the first bottom row of the masonry wall. Instead, the wall undergoes bending as the shake table induces movement in the bottom rows while the top rows remain relatively stationary. Shortly after the movement of the table began, the top rows start moving to the right as they follow the motion induced by the bottom ones, resulting in an opposite bending. However, a few bricks on the top left part fall due to sliding. Within this range of acceleration, the structure is considered intact at the end of the movement if we follow the assumptions made earlier.

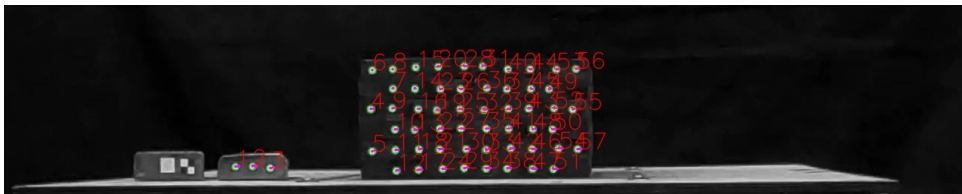


Figure 5.3: Benchmark 1 at 1st frame for a 0.5g acceleration



Figure 5.4: Benchmark 1 at 8th frame for a 0.5g acceleration

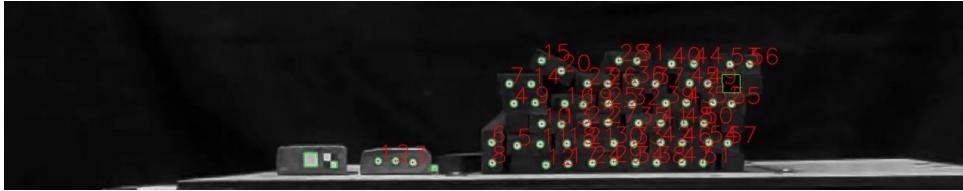


Figure 5.5: State of structure at end of test

5.2.2.2 Sliding of Bricks in First Bottom Row

For accelerations ranging from 0.55g to 2g, a portion of the first bottom row's bricks slide on the table, while the rest of the row follows the movement induced by the shake table. This difference can be seen on the below figures as the distance between the first three targets and the structure decreased while it remained constant for smaller accelerations. Throughout the acceleration phase, the masonry wall deforms slightly. However, after the acceleration is completed, the top layers of the wall exhibit a delayed response compared to the bottom layers, resulting in bending on the right part of the wall.

The extent of bending on the right part of the wall decreases as the acceleration increases because the overall displacement becomes smaller which reduces the delay. The sliding of the first bottom row's bricks may be attributed to a few factors, such as the friction coefficient, which could be too small for this range of acceleration, or variations in the face of the bricks or the upper wood table, which may not be precisely flat.

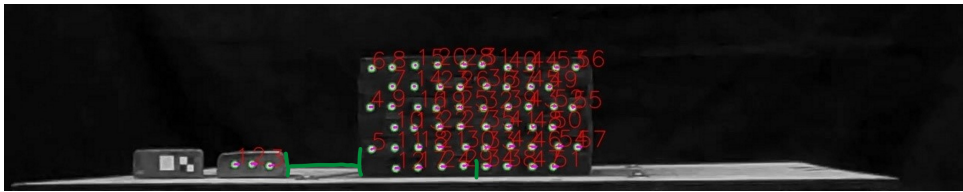


Figure 5.6: Benchmark 1 at 1st frame for a 0.55g acceleration

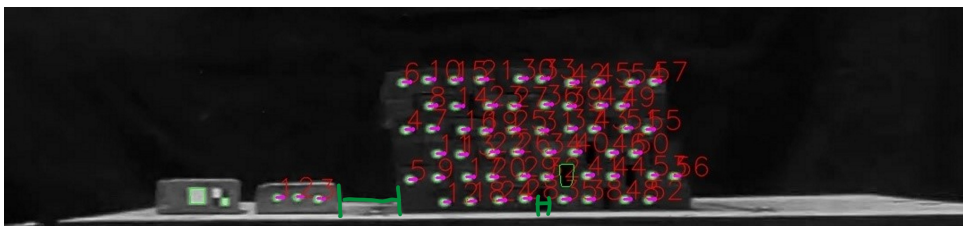


Figure 5.7: Benchmark 1 at 22nd frame for a 0.55g acceleration

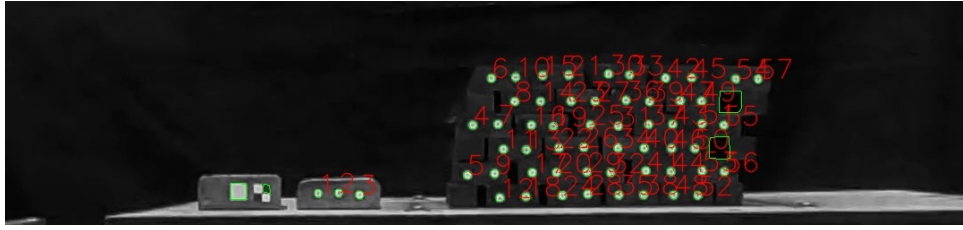


Figure 5.8: State of structure at end of test

The decision to apply a maximal acceleration of 1.5g was based on the capabilities of the shake table, which could achieve such acceleration over a relatively short distance of 25mm. The literature suggested that a rocking phenomenon would likely be observed at an acceleration of around 0.64g. However, when the structure was subjected to the induced acceleration of 1.5g on the limited distance, it did not exhibit significant movement, and the process was too short to allow for the development of a possible rocking phenomenon. Additionally, the sliding of the first bottom layer's bricks further hindered the formation of rocking.

As a result, we had to assume that, under these specific conditions, the creation of a rocking phenomenon was impossible to reproduce. While we couldn't improve the capabilities of the shake table, there are potential improvements that can be made in the future. For instance, the bricks can be made heavier by changing the filling to concrete or altering the material of the brick to increase the friction coefficient.



Figure 5.9: Benchmark 1 at 1st frame for a 1.5g acceleration

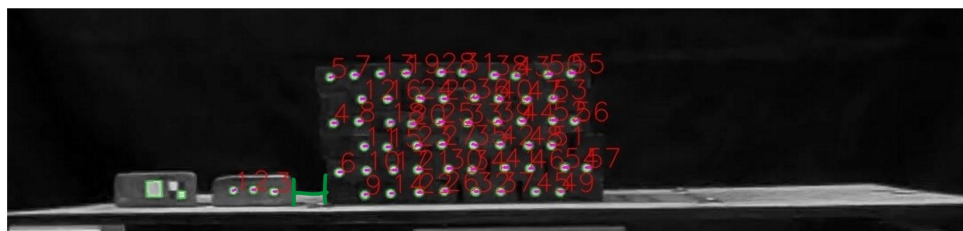


Figure 5.10: Benchmark 1 at 12th frame for a 1.5g acceleration

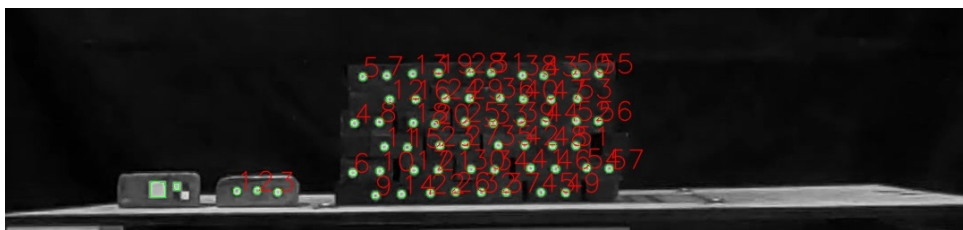


Figure 5.11: State of structure at end of test

5.2.3 Benchmark 2

5.2.3.1 Sliding of Bricks in Second Bottom Row

For accelerations ranging from 0.01g to 0.9g, there is no sliding observed in the first bottom row of the masonry wall. However, the bricks located on the second bottom row slide during the displacement of the table, resulting in the inclination of the lateral parts of the wall. Once the table comes to a stop, the left part of the wall returns to a straight position as the bricks settle back to a flat orientation after being tilted. Within this specific range of acceleration, the structure is considered intact at the end of the movement, based on the assumptions made earlier.

The change in behavior observed, where the first bottom row does not exhibit sliding while the second bottom row does, is likely influenced by the flat imperfections of the bricks and the friction coefficient between them. As mentioned earlier, the bricks were sandpapered after being painted to increase the friction coefficient since the painted surface tends to be slippery. This sanding process may have resulted in variations in the friction coefficient between each pair of bricks, leading to different behaviors in response to the applied acceleration.

Furthermore, the presence of additional rows above the second row may have contributed to the sliding behavior. The weight of the rows above the second row could have exerted downward pressure on the second row, potentially hindering its uniform movement with the first row during the acceleration phase.

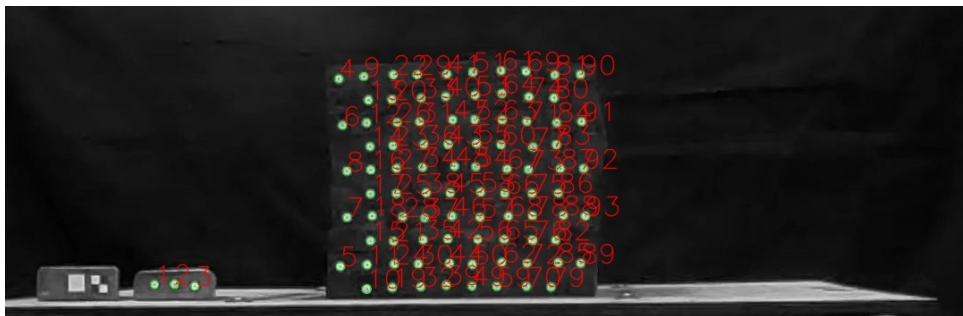


Figure 5.12: Benchmark 2 at 1st frame for a 0.85g acceleration

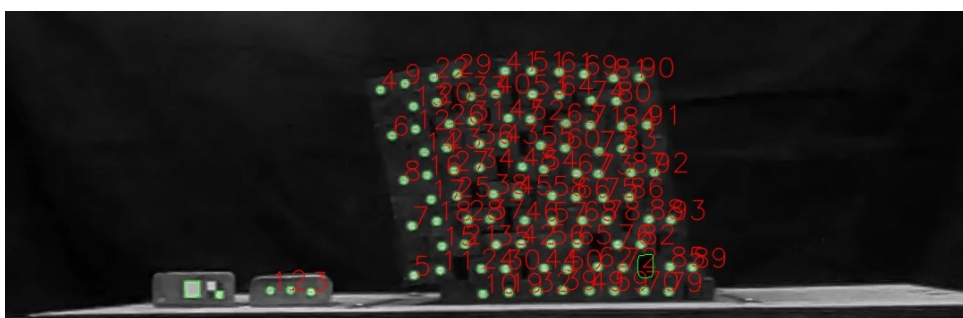


Figure 5.13: Benchmark 2 at 20th frame for a 0.85g acceleration

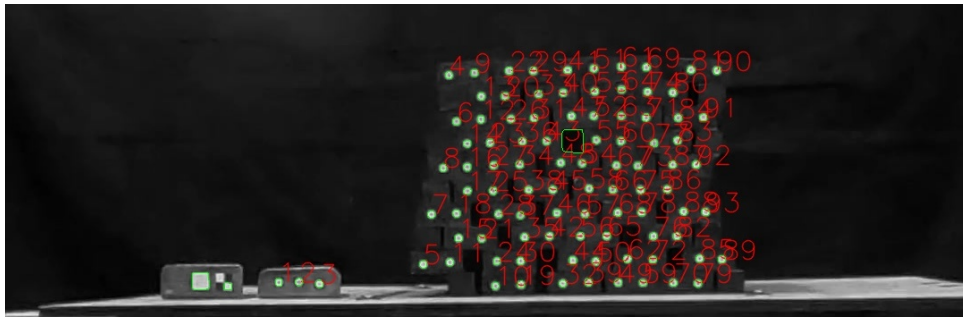


Figure 5.14: State of structure at end of test

5.2.3.2 Sliding of Bricks in First Bottom Row

For accelerations ranging from 0.95g to 2g, the wall exhibits similar behavior as benchmark 1 did for accelerations ranging from 0.55g to 2g. Indeed, a portion of the first bottom row's bricks slide on the table, while the rest of the row follows the movement induced by the shake table, causing small deformations and delayed response of other rows.

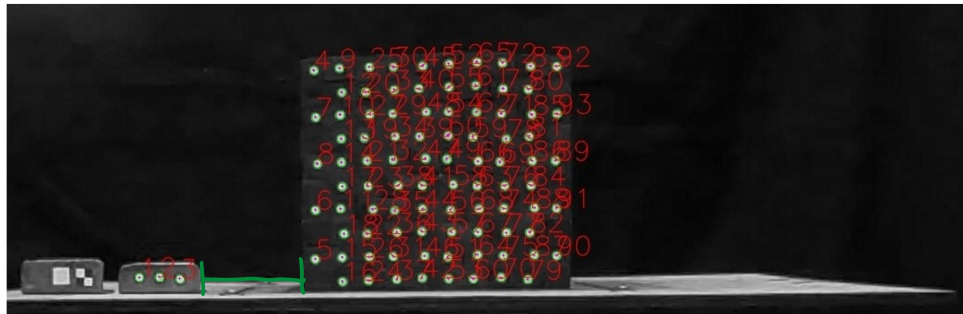


Figure 5.15: Benchmark 2 at 1st frame for a 0.55g acceleration

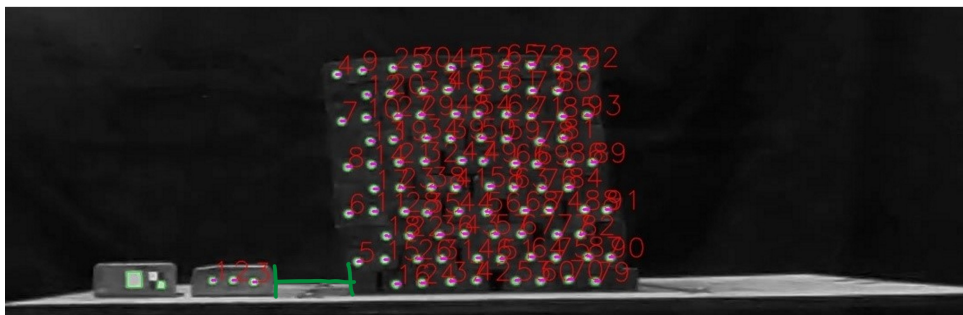


Figure 5.16: Benchmark 2 at 46th frame for a 0.55g acceleration

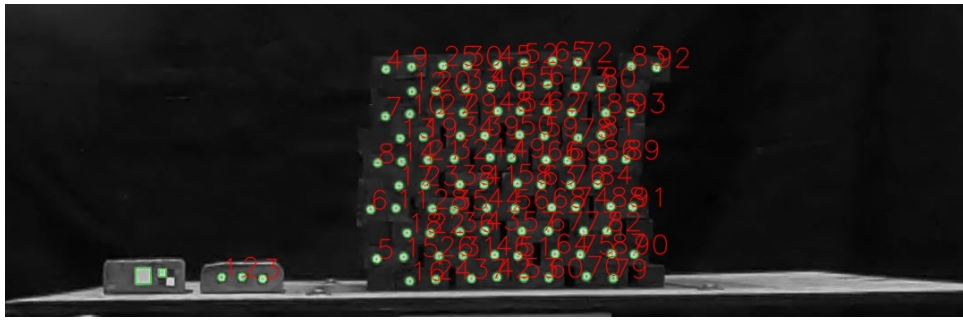


Figure 5.17: State of structure at end of test

Unfortunately, a rocking phenomenon was not observed during the testing phase for benchmark 2. The lack of rocking can be attributed to similar factors as observed in benchmark 1. Despite an increase in the number of rows in the wall, which increased the total weight and made the structure more slender, these changes, combined with the capacity limitations of the shake table, were insufficient to induce the desired rocking behavior.

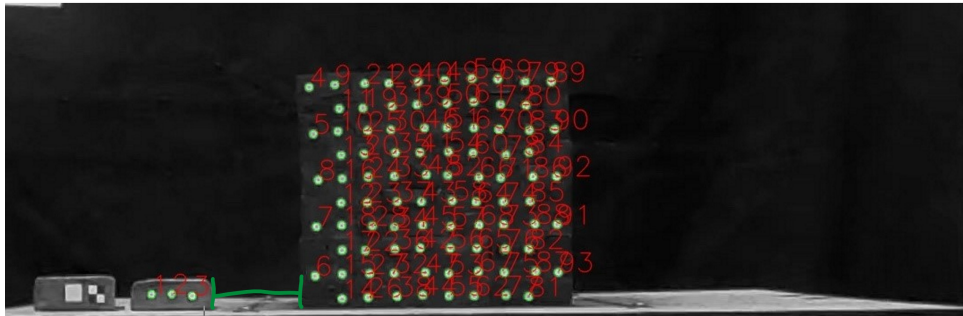


Figure 5.18: Benchmark 2 at 1st frame for a 1.5g acceleration

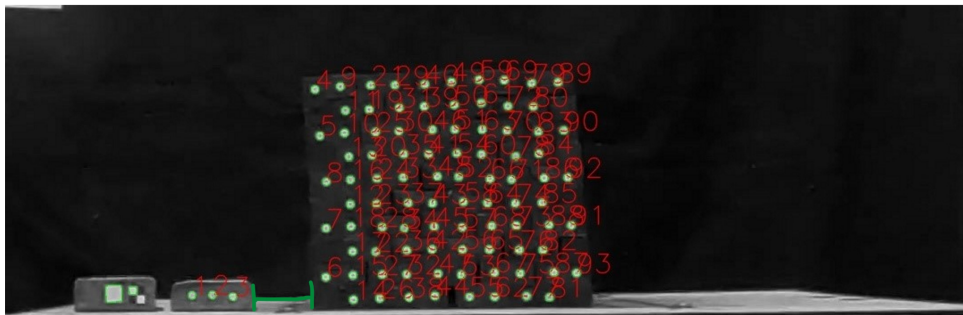


Figure 5.19: Benchmark 2 at 11th frame for a 1.5g acceleration

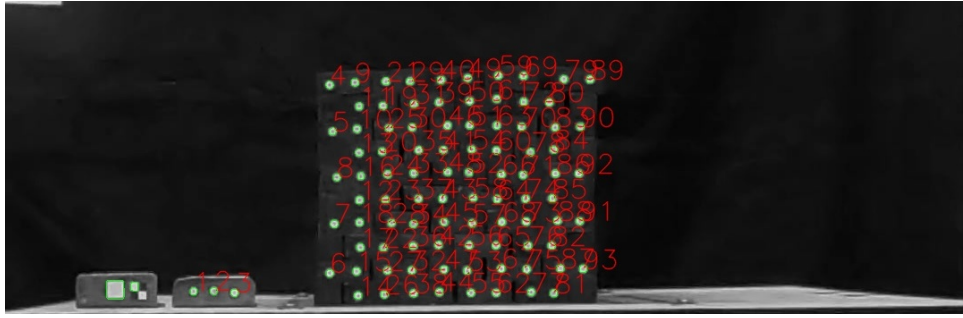


Figure 5.20: State of structure at end of test

5.2.4 Benchmark 3, 4 and 5

While differing in their number of stories and windows, three benchmarks exhibit a consistent pattern of behavior across respective various accelerations. As a reminder, benchmark 3 consists of a single-story wall with one window, while benchmark 4 contains two windows. On the other hand, benchmark 5 comprises a two-story wall with one window on each story. The pattern of behavior can be summarized in the following three steps.

5.2.4.1 Incomplete Rocking Phenomenon

For accelerations slightly less than the critical acceleration threshold, an interesting behavior is observed. As the table moves, a rocking phenomenon begins to develop in the masonry wall. However, after a certain point, the bricks come back to an almost initial position, essentially reforming the wall's initial configuration with only a few minor adjustments in the positions of some bricks. Within this specific range of acceleration, the structure is considered intact at the end of the movement, based on the assumptions made earlier.

Benchmark 3 :

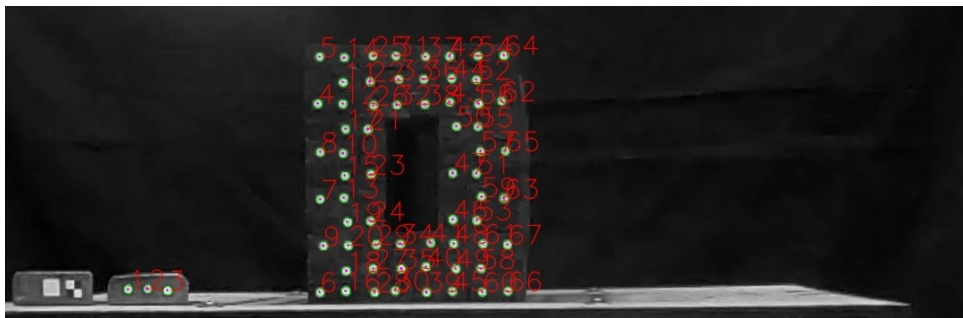


Figure 5.21: Benchmark 3 at 1st frame for a 0.2g acceleration

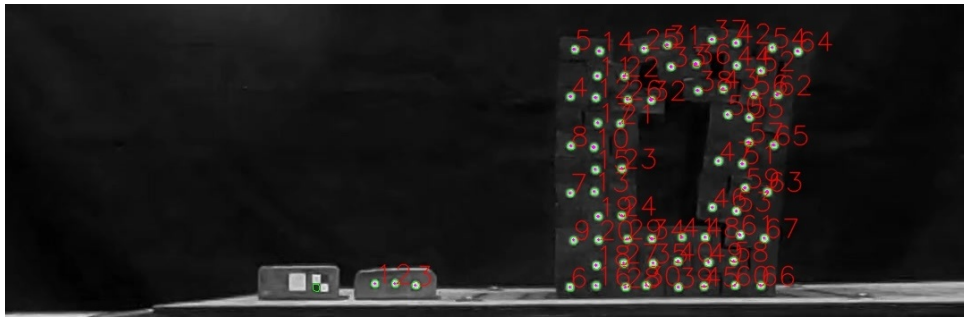


Figure 5.22: Benchmark 3 at 71st frame for a 0.2g acceleration

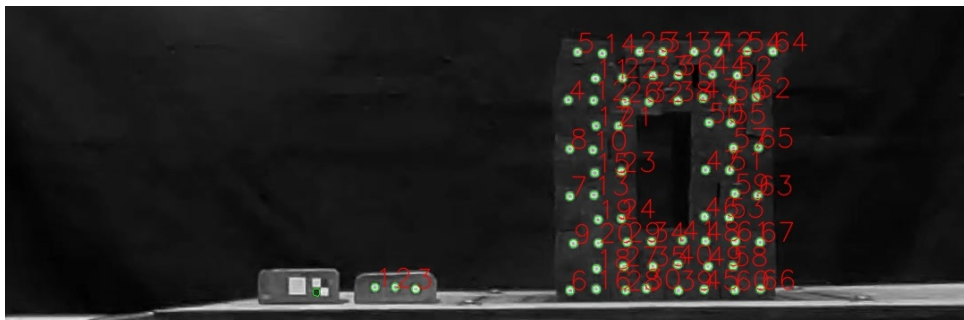


Figure 5.23: State of structure at end of test

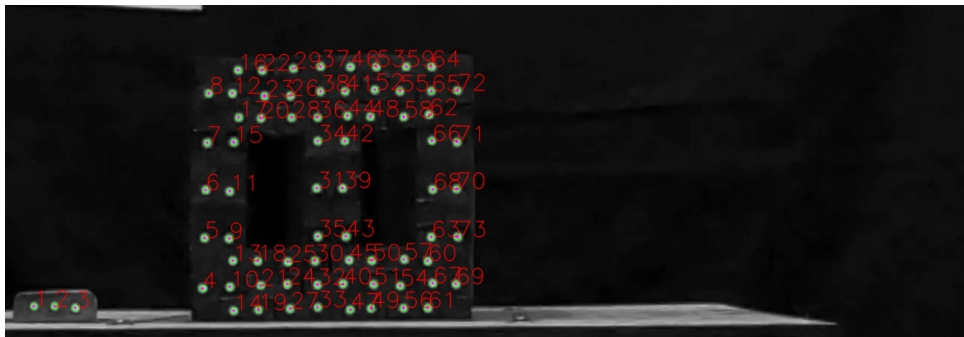
Benchmark 4 :

Figure 5.24: Benchmark 4 at 1st frame for a 0.13g acceleration

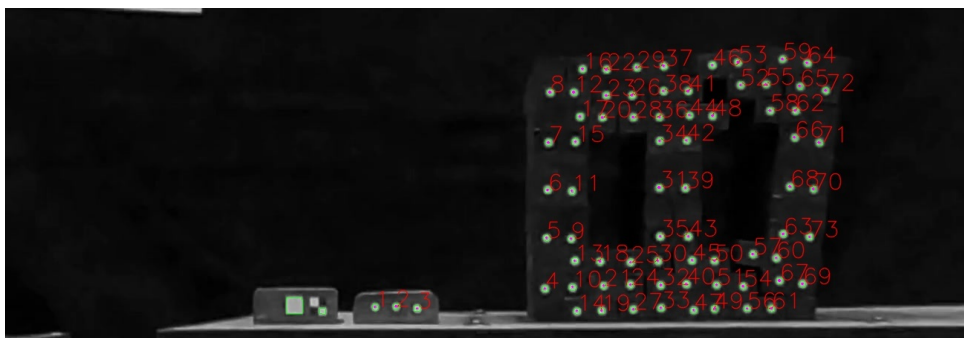


Figure 5.25: Benchmark 4 at 106th frame for a 0.13g acceleration

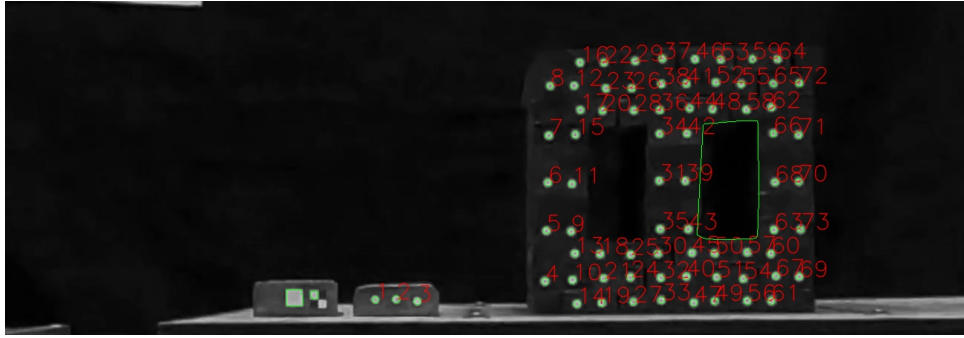


Figure 5.26: State of structure at end of test

Benchmark 5 :

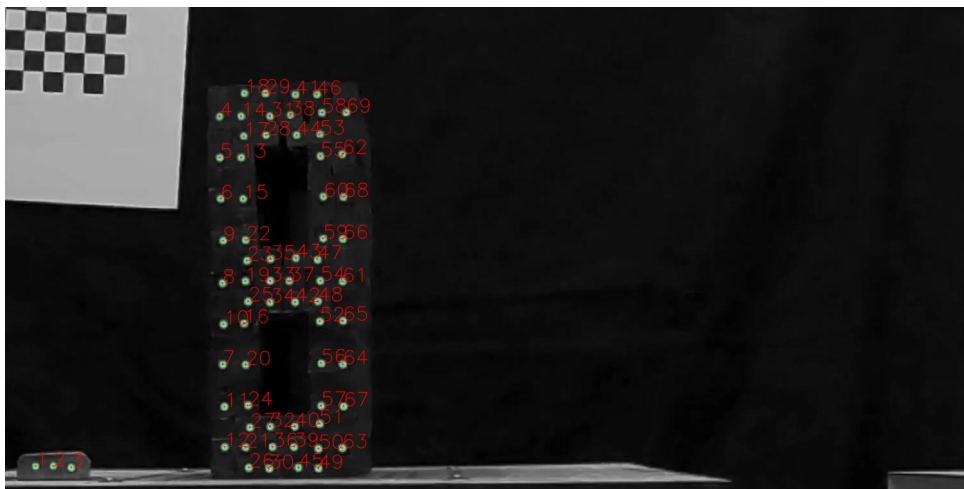


Figure 5.27: Benchmark 5 at start for a 0.07g acceleration



Figure 5.28: Benchmark 5 at finish for a 0.07g acceleration

5.2.4.2 Rocking Phenomenon

For an acceleration equal to the critical acceleration threshold, the rocking phenomenon is fully evident, resulting in the collapse of the structure. During the movement, the right part of the

wall comes off and falls, and at the end of the process, the wall configuration is different from its initial state. The observed behavior clearly indicates that the applied acceleration has exceeded the threshold for stability.

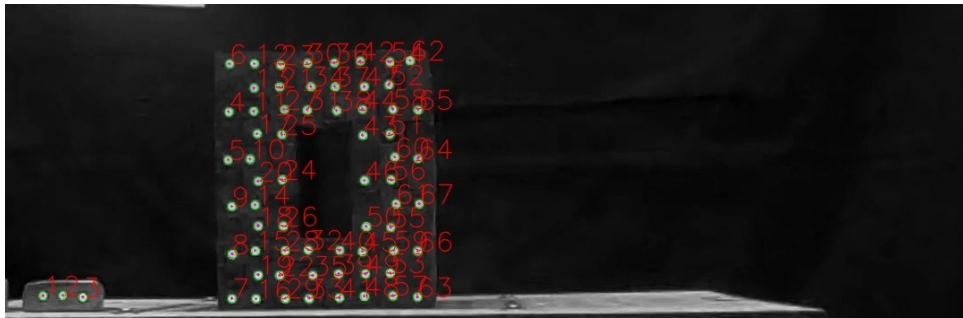


Figure 5.29: Benchmark 3 at 1st frame for a 0.21g acceleration

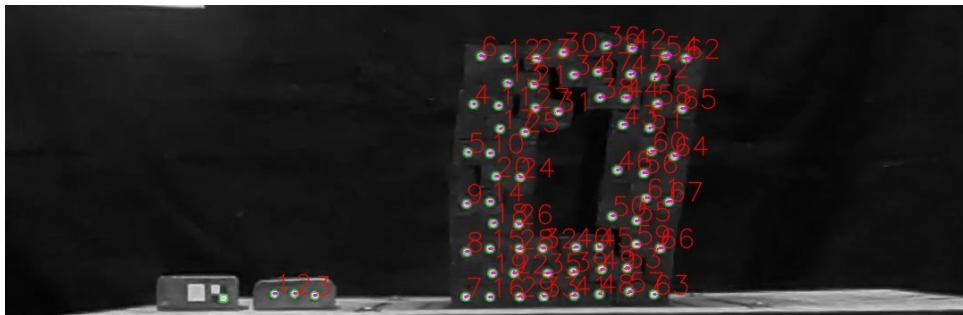


Figure 5.30: Benchmark 3 at 53th frame for a 0.21g acceleration

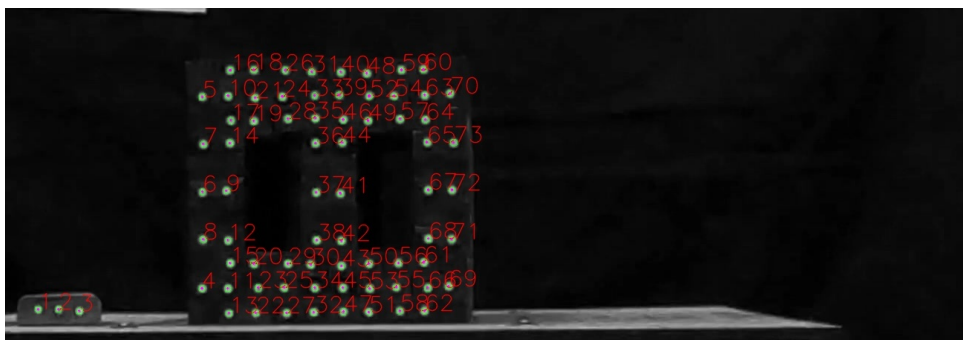


Figure 5.31: Benchmark 4 at 1st frame for a 0.14g acceleration



Figure 5.32: Benchmark 4 at 119th frame for a 0.14g acceleration

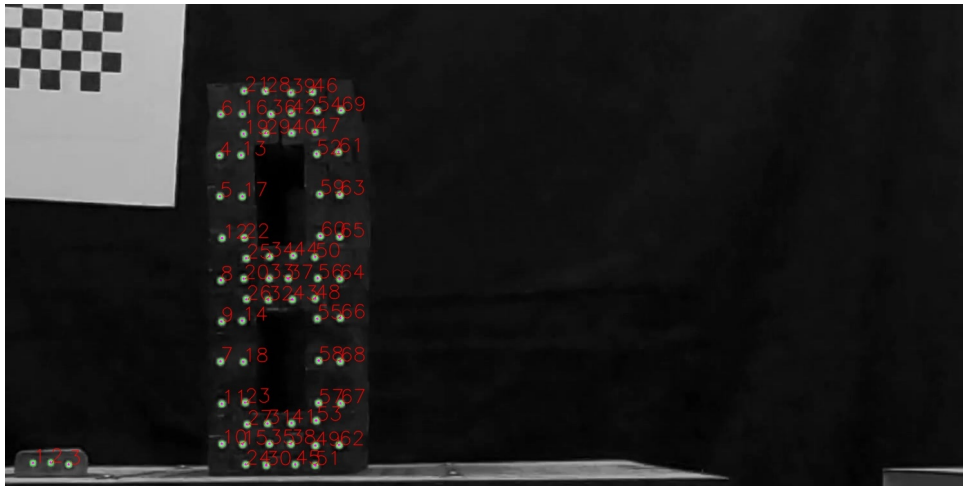


Figure 5.33: Benchmark 5 at 1st frame for a 0.08g acceleration



Figure 5.34: Benchmark 5 at 152nd frame for a 0.08g acceleration

Benchmark 3 :

When analyzing the parts of the wall and particularly the individual bricks involved in the rocking phenomenon, distinct patterns emerge between the numerical and experimental tests. In the upper part of the wall, the diagonal crack remains consistent for both benchmarks, as indicated by the green markings in the figures below.

However, for the bottom side of the wall, a slight difference can be observed between the numerical and experimental figures. In the numerical simulation, the diagonal crack starts at the middle of the window, while in the experimental figure, it consistently starts at the bottom right corner of the window, causing the crack to translate a brick to the right. This implies that the numerical simulation results may be slightly safer, as a larger number of bricks are involved in the rocking phenomenon, leading to a more significant failure mechanism compared to the experimental results.

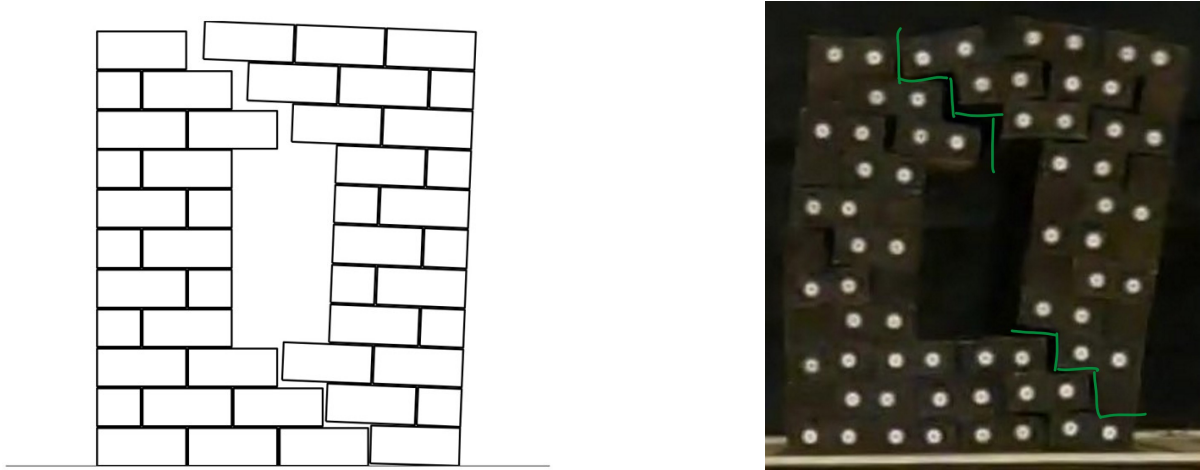


Figure 5.35: Comparison of numerical and experimental rocking phenomenon

Benchmark 4 :

For this benchmark, identical patterns emerge between the numerical and experimental tests in the upper and lower sections of the wall, as indicated by the green markings in the figures below.

This precise correspondence between the numerical and experimental results indicates a very strong correlation in the behavior observed from both numerical simulations and experimental tests. It highlights the validity and accuracy of the numerical model in capturing the actual behavior of the masonry wall under dynamic loading conditions.

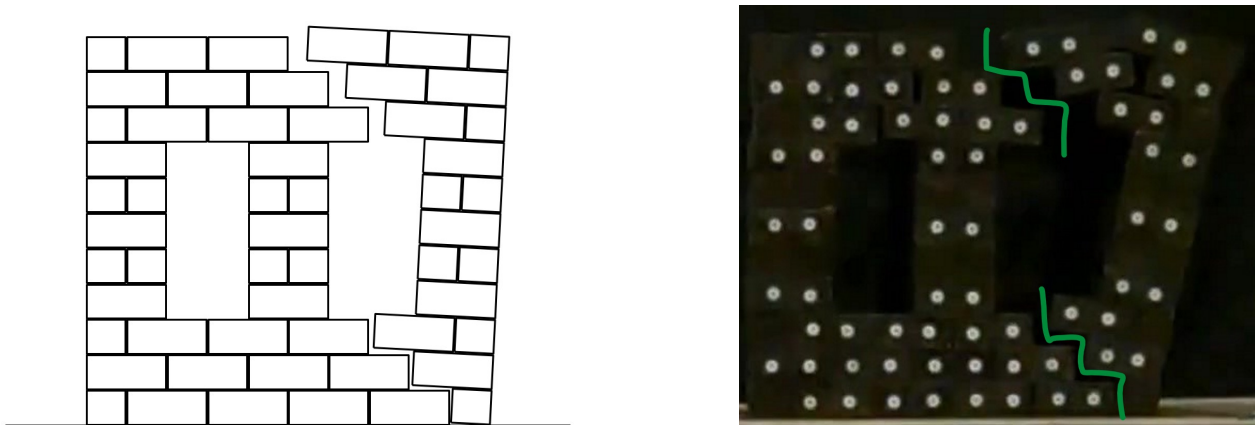


Figure 5.36: Comparison of numerical and experimental rocking phenomenon

Benchmark 5 :

When analyzing the fifth benchmark, distinct patterns emerge between the numerical and experimental tests. On top of the second floor and between the two floors for both numerical and experimental results, the diagonal cracks exhibit consistency in both the numerical and experimental results for both benchmarks, as indicated by the green markings in the figures below.

However, for the bottom side of the first floor, a significant difference can be observed between the numerical and experimental figures. In the numerical simulation, the diagonal crack initiates from the middle of the bottom side of the window. However, in the corresponding experimental scenario, no cracking is observed. Consequently, in the experimental setup, no bricks positioned in the bottom or right section of the first floor are affected by the rocking phenomenon. This implies that the numerical simulation results may be way safer, as a way larger number of bricks are involved in the rocking phenomenon, leading to a more significant failure mechanism compared to the experimental results.

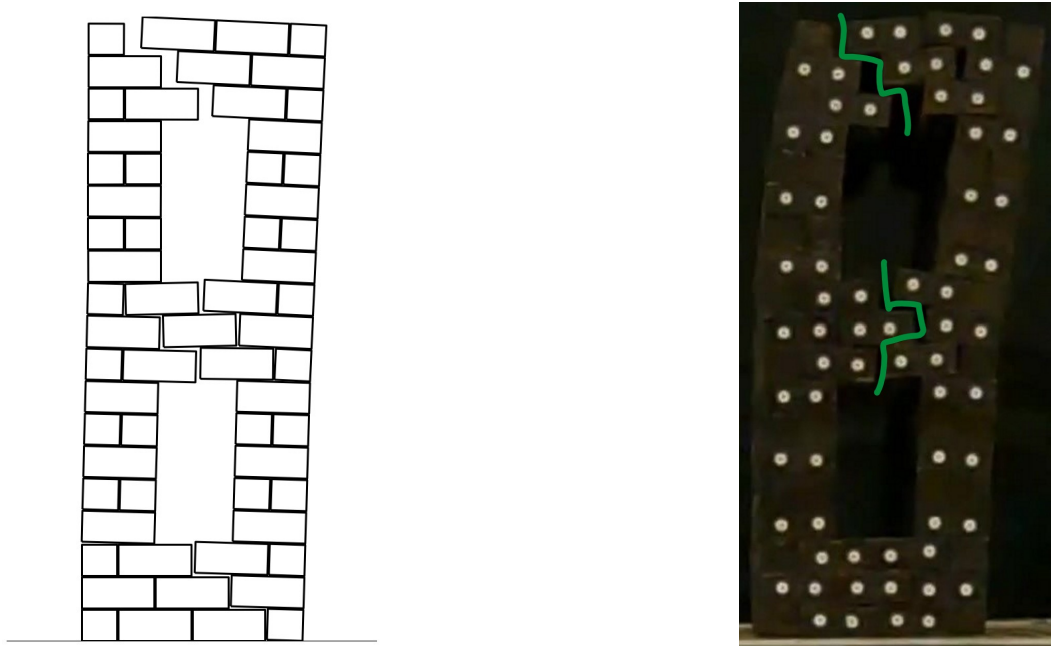


Figure 5.37: Comparison of numerical and experimental rocking phenomenon

5.2.4.3 Alternative Rocking Phenomenon

Benchmark 3 :

For accelerations greater than the critical threshold value, the same rocking phenomenon occurs, but with some variations. As depicted in Figure 5.39, during the movement of the table, a rocking motion starts from the middle of the top side of the window, similar to the previous case, but this time, the diagonal cracking goes up to the left, the opposite direction.

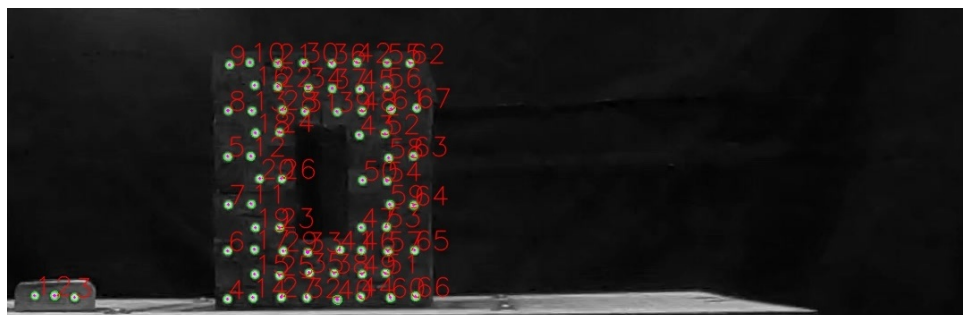


Figure 5.38: Benchmark 3 at 1st frame for a 0.25g acceleration

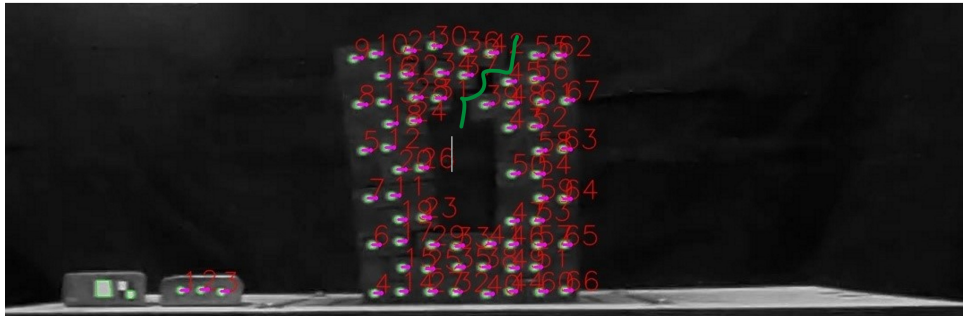


Figure 5.39: Benchmark 3 at 39th frame for a 0.25g acceleration

When the table's movement stops, the left part of the wall returns to its initial position, transferring all the accumulated kinetic energy to the right part of the wall, resulting in the expected rocking phenomenon.

Furthermore, in addition to the rocking phenomenon, more bricks are involved in the collapse. In the left part of the wall, a diagonal crack forms from the bottom left corner of the window and extends upward to the left. This crack causes the bricks above it to fall to the right, leading to increased structural damage.

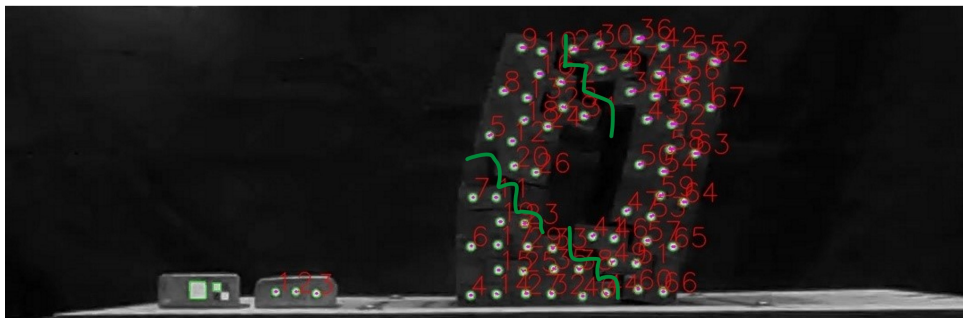


Figure 5.40: Benchmark 3 at 60th frame for a 0.25g acceleration

Benchmark 4 :

For benchmark 4, the same rocking phenomenon occurs, but with variations similar to benchmark 3. As depicted in Figure 5.42, the motion of the table induces a similar pattern of diagonal cracking but going to the opposite direction as already seen in benchmark 3.

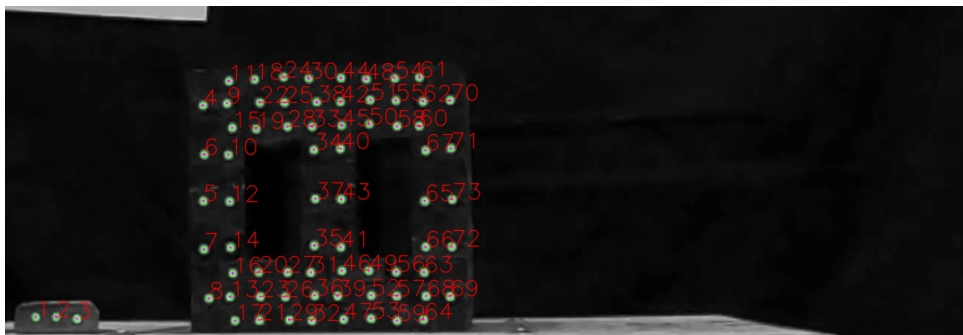


Figure 5.41: Benchmark 4 at 1st frame for a 0.16g acceleration

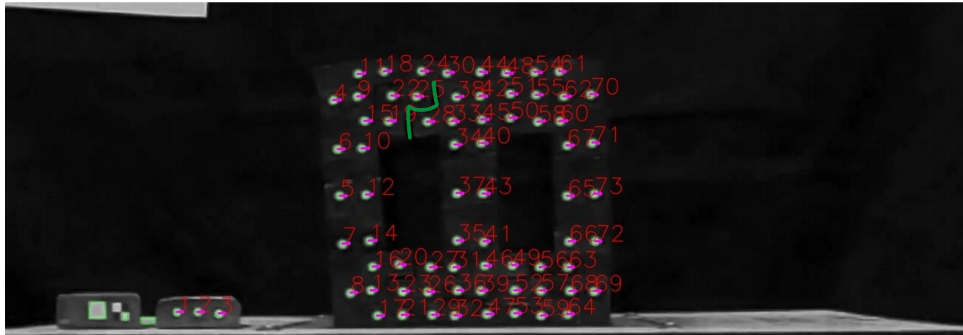


Figure 5.42: Benchmark 4 at 67th frame for a 0.16g acceleration

When the table's movement stops, the same behavior to that observed in benchmark 3 appears, where the rocking phenomenon arises due to the transfer of accumulated kinetic energy.

At an acceleration of 0.16g, no more bricks are involved in the collapse. The left part starts bending to the right but then returns to its initial position. However, it appears evident that for higher accelerations, a diagonal crack will form in the left part of the wall, leading to bricks falling to the right and causing increased structural damage.

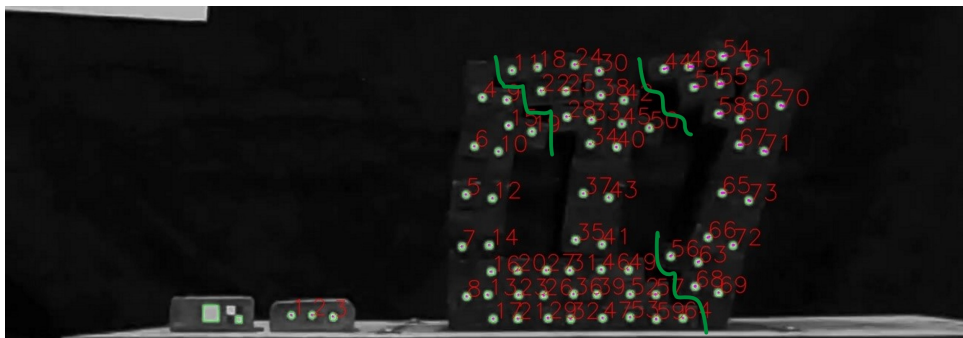


Figure 5.43: State of structure at end of video

Benchmark 5 :

For benchmark 5, a similar combination of opposite cracking and transfer of kinetic energy, as explained for benchmarks 3 and 4, appears. The only minor distinction lies in the form of the cracking, which is not diagonal as previously observed. This is illustrated in Figure 5.45.

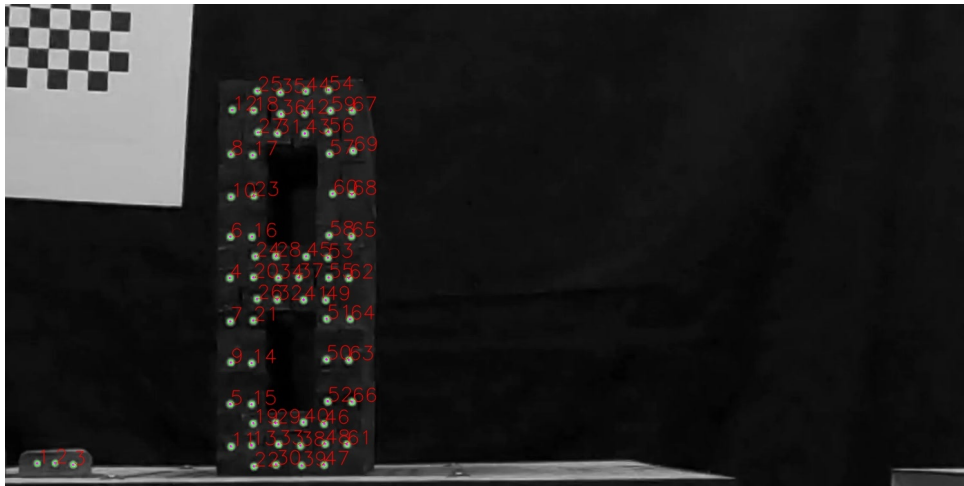


Figure 5.44: Benchmark 5 at 1st frame for a 0.1g acceleration

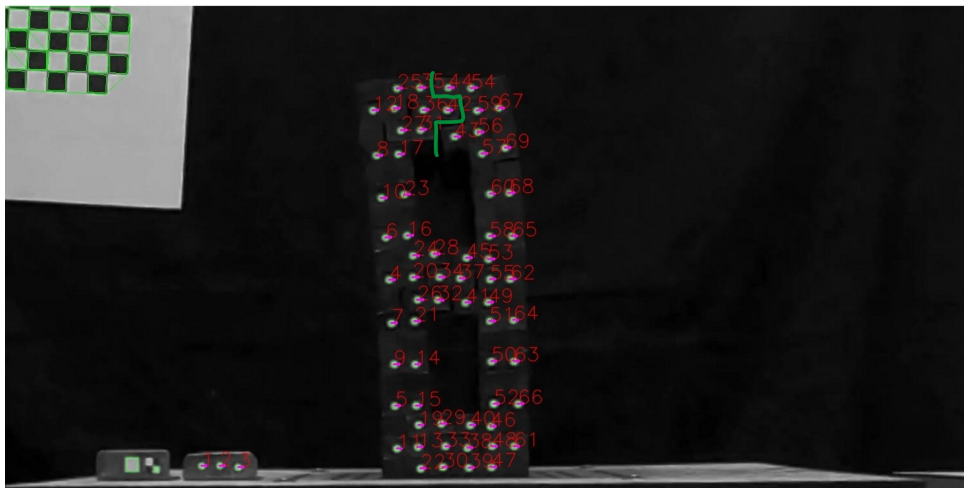


Figure 5.45: Benchmark 5 at 64th frame for a 0.1g acceleration

Furthermore, in addition to the rocking phenomenon, more bricks are involved in the collapse. On the left part of the second floor, a diagonal crack forms more or less in the middle of the left side of the wall and extends upward to the left. This crack causes the bricks above it to fall to the right, resulting in increased structural damage and a more significant structural failure.

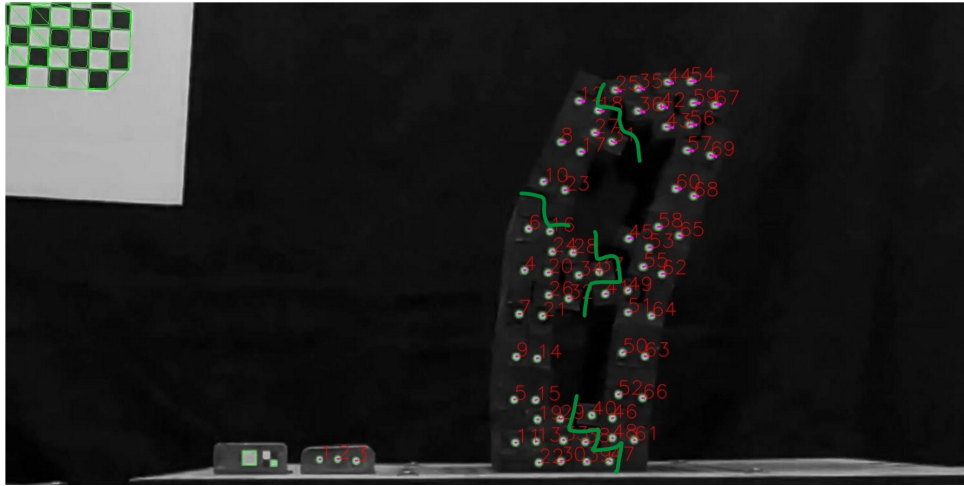


Figure 5.46: State of structure at end of test

5.2.5 Benchmark 6

5.2.5.1 Incomplete Rocking Phenomenon

In contrast to the preceding three benchmarks analyzed, the latest benchmark demonstrates a distinct behavior. The previous three benchmarks showed a significant change in behavior around a specific value.

Before reaching this critical threshold, a partial rocking phenomenon was observed, causing the bricks to momentarily deviate from their initial positions. However, once the critical acceleration value was achieved or surpassed, the accumulated kinetic energy became sufficient enough to trigger a complete rocking phenomenon. This phenomenon subsequently caused the detachment and collapse of the right portion of the wall, and even more sections if the acceleration limit was exceeded, resulting in significant structural damage.

For this benchmark, the latter behavior is always appearing for both accelerations smaller than $0.11g$, equal to $0.11g$ and greater than it with some differences obviously. For accelerations smaller than $0.11g$, the transferred kinetic energy is insufficient to create a complete rocking phenomenon, making the bricks momentarily deviate from their initial positions. Thus, as before, within this specific range of acceleration, the structure is considered intact at the end of the movement, based on the assumptions made earlier.

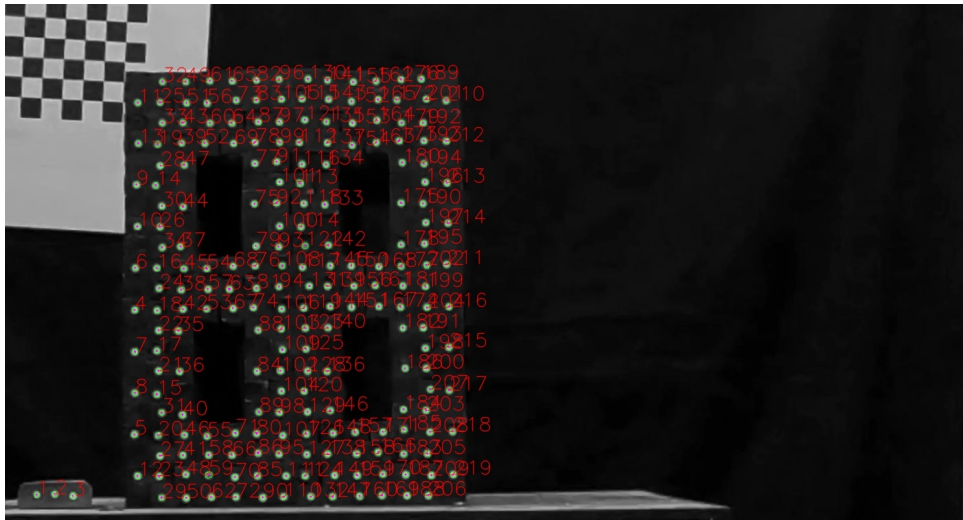


Figure 5.47: Benchmark 6 at 1st frame for a 0.11g acceleration

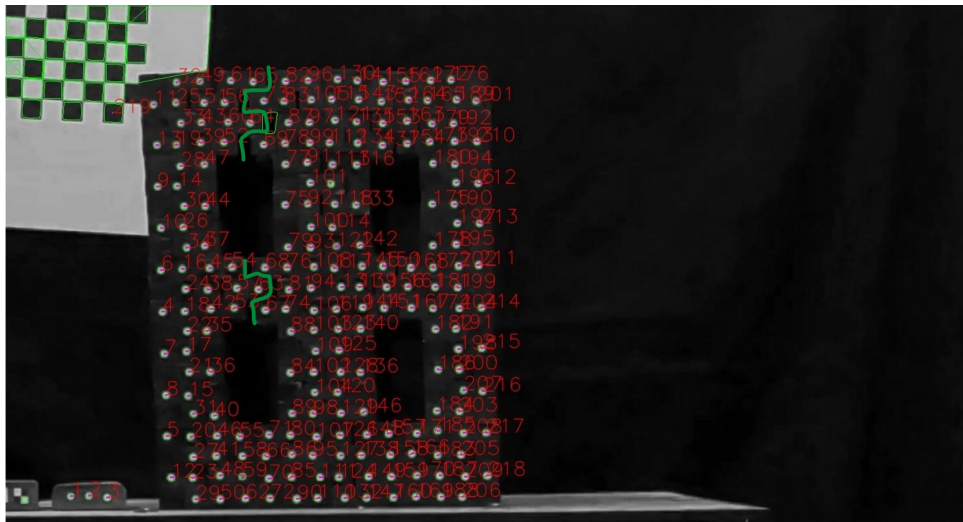


Figure 5.48: Benchmark 6 at 43rd frame for a 0.11g acceleration

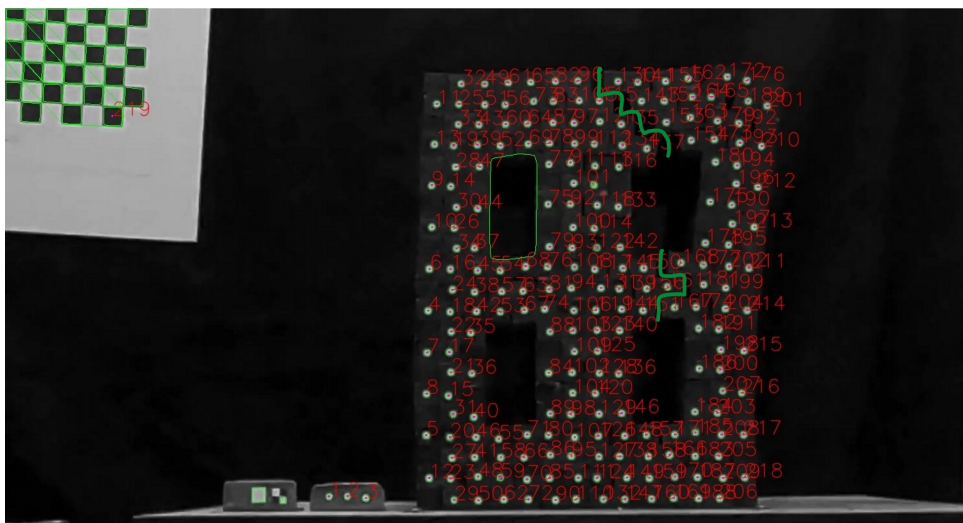


Figure 5.49: Benchmark 6 at 111th frame for a 0.11g acceleration

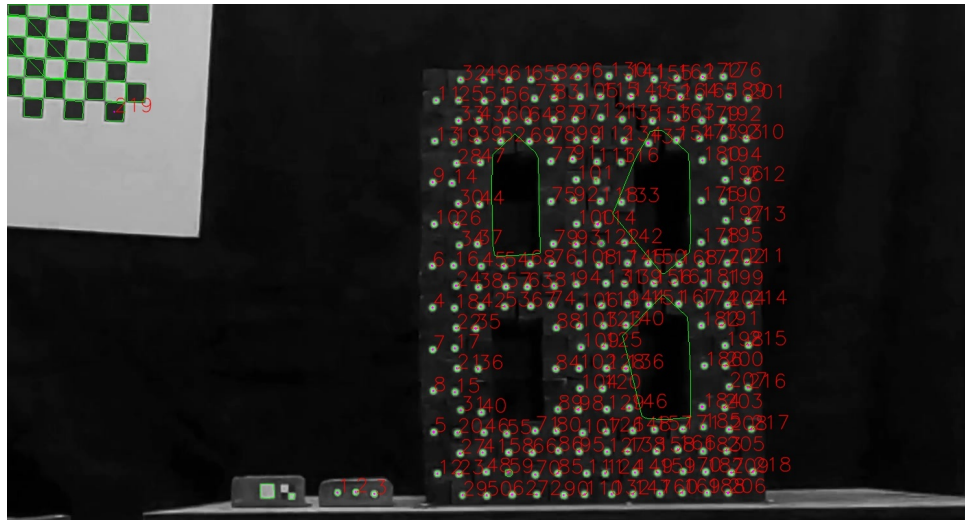


Figure 5.50: Benchmark 6 at last frame for a 0.11g acceleration

5.2.5.2 Rocking Phenomenon

For an acceleration of 0.11g, the rocking phenomenon is fully evident, resulting in the collapse of the structure. The transferred kinetic energy is sufficient to cause the wall to overturn significantly, completing the rocking phenomenon. At the end of the process, the wall configuration is different from its initial state, indicating that the applied acceleration has exceeded the threshold for stability. The collapse of the wall confirms the critical value of acceleration for this specific benchmark.

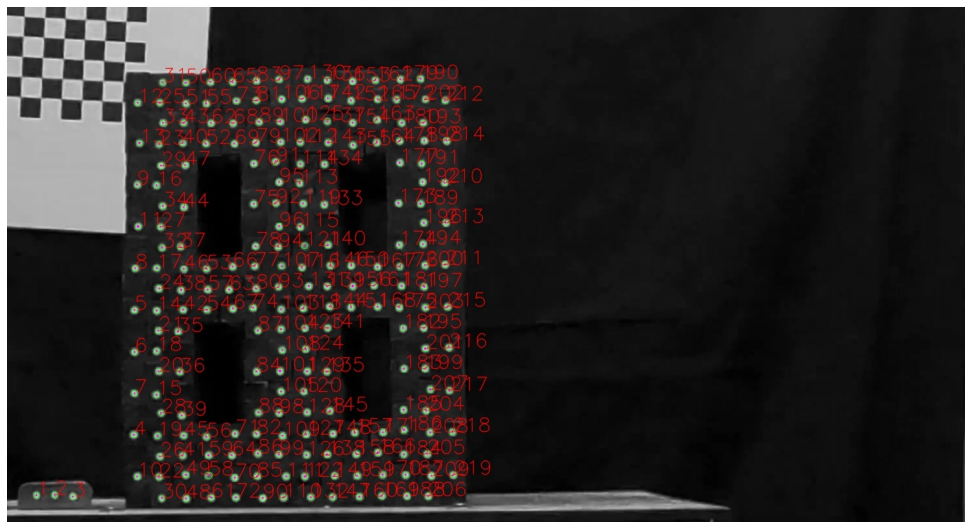


Figure 5.51: Benchmark 6 at 1st frame for a 0.12g acceleration

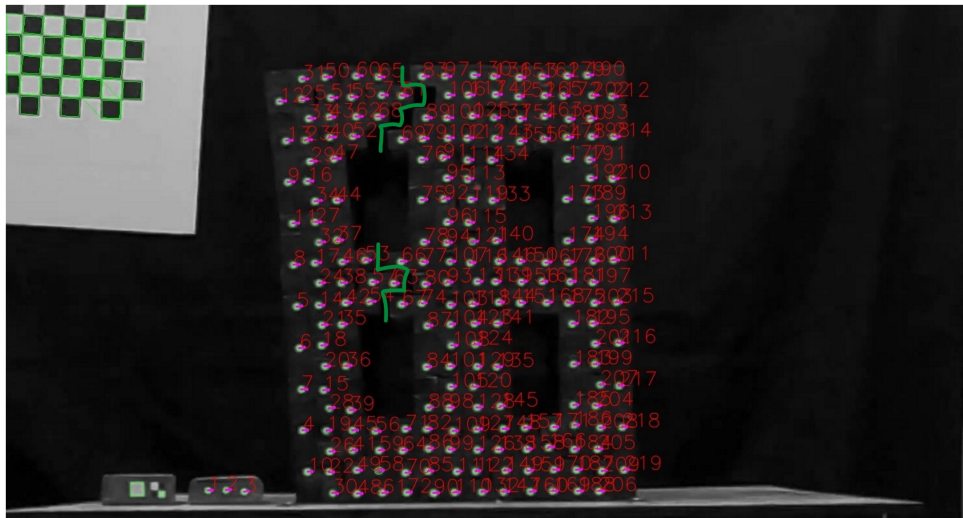


Figure 5.52: Benchmark 6 at 66th frame for a 0.12g acceleration

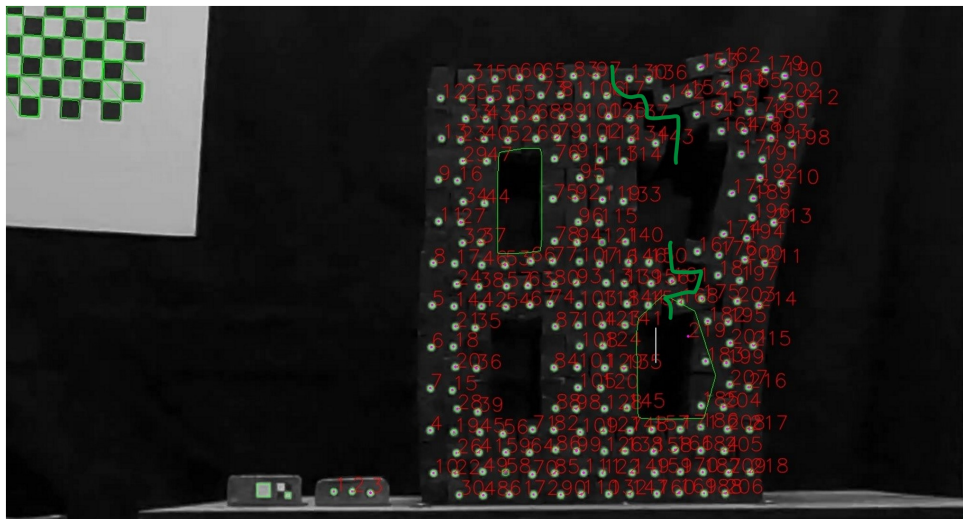


Figure 5.53: Benchmark 6 at last frame for a 0.12g acceleration

When analyzing the parts of the wall and particularly the individual bricks involved in the rocking phenomenon, distinct patterns emerge between the numerical and experimental tests. On top of the second floor and between the two floors for both numerical and experimental results, the diagonal cracks exhibit consistency in both the numerical and experimental results for both benchmarks, as indicated by the green markings in the figures below.

However, a slight difference can be observed between the numerical and experimental figures for the bottom side of the first floor. In the numerical simulation, the diagonal crack starts at the middle of the bottom side of the right window and develops downward to the right. On the other hand, in the experimental test, nothing happens in this area. This difference may be attributed to the fact that the rocking phenomenon is caused by the transferred kinetic energy, unlike the previous three benchmarks. As the development of the rocking phenomenon is not explicitly described in the literature, and it may not be fully represented in the numerical simulation, this hypothesis could explain the difference in behavior observed between the two tests.

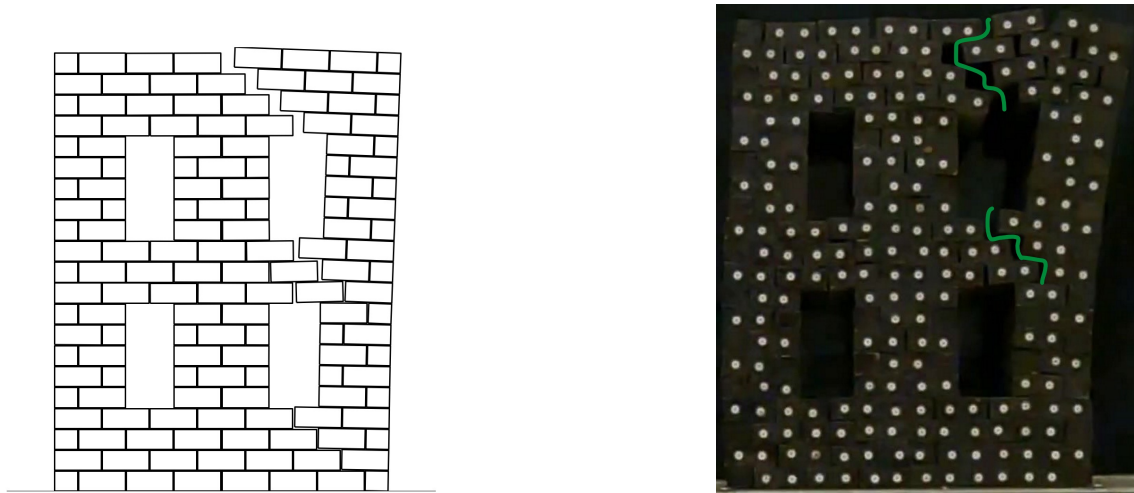


Figure 5.54: Comparison of numerical and experimental rocking phenomenon

For accelerations greater than 0.12g, the same rocking phenomenon occurs, but the structural damage increases. Indeed, in addition to the rocking phenomenon, more bricks are involved in the collapse. On the left part of the second floor, a diagonal crack forms more or less in the middle of the left side of the wall and extends upward to the left. This crack causes the bricks above it to fall to the right, knock the central part of the second floor and make them fall together, resulting in increased structural damage and a more significant structural failure.

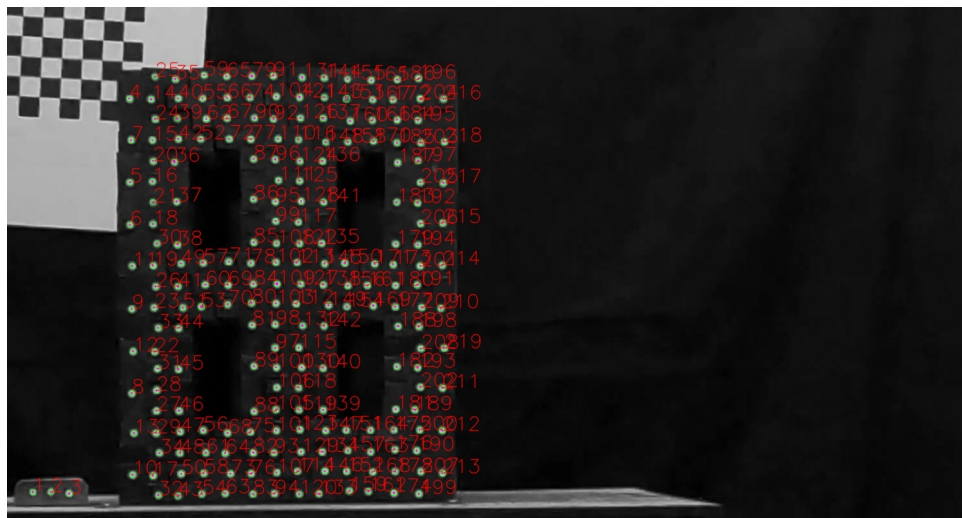


Figure 5.55: Benchmark 6 at 1st frame for a 0.15g acceleration

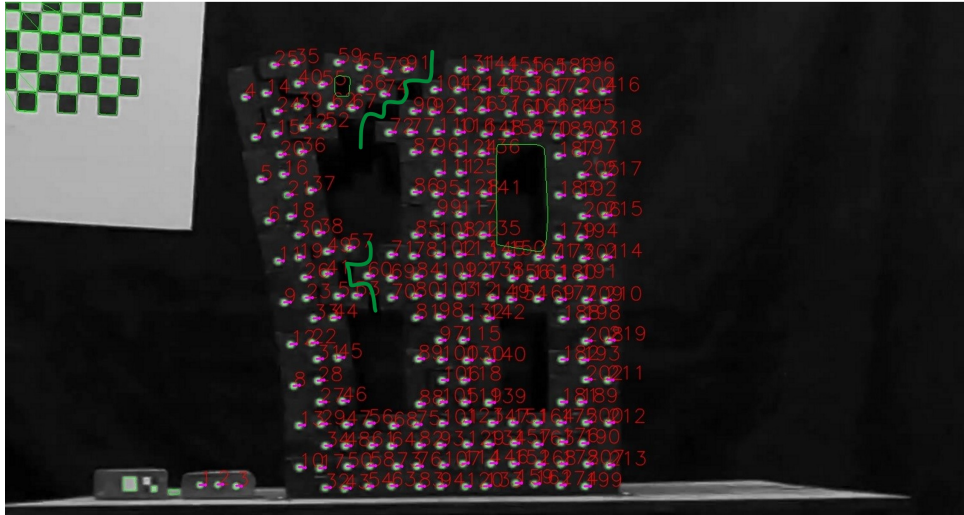


Figure 5.56: Benchmark 6 at 57th frame for a 0.15g acceleration

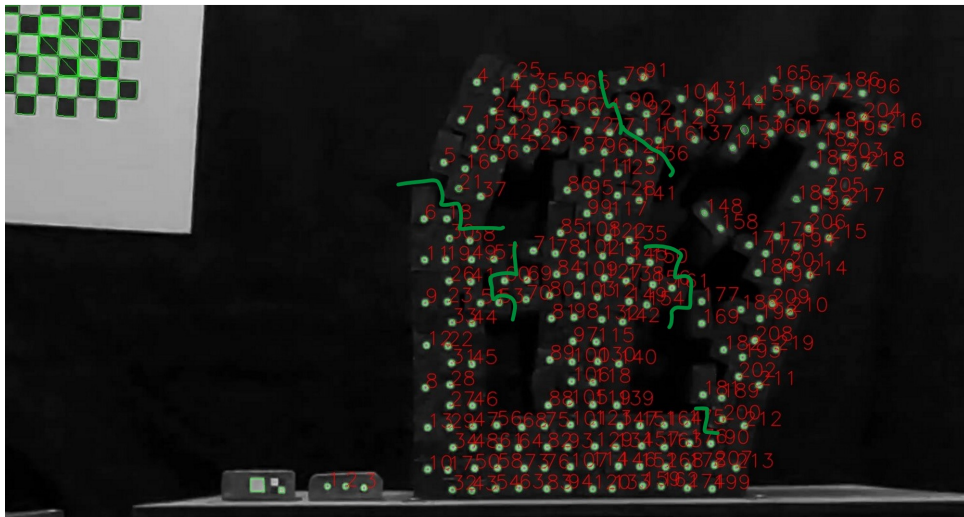


Figure 5.57: State of structure at end of test

The comparison between numerical and experimental critical load factors is summarized in the following table. It is evident that the numerical values are way overestimated for the last four benchmarks, while they appear to be way underestimated for the first two.

	Numerical α	Experimental Amplitude	Difference [%]
Benchmark 1	0.577	>2	>71.15
Benchmark 2	0.495	>2	>75.25
Benchmark 3	0.321	0.21	-34.58
Benchmark 4	0.236	0.14	-40.68
Benchmark 5	0.157	0.08	-49.04
Benchmark 6	0.216	0.11	-49.07

5.3 Comparison of Acceleration between Shake Table and Recovib Accelerometers

To improve the reliability of the acceleration values cited in the previous subsection and to validate the accuracy of the acceleration data provided by the shake table, an accelerometer was attached to the L metallic piece of the shake table, where the first three targets were placed. This accelerometer recorded the table's displacement during the tests, allowing us to compare and validate the acceleration induced by the shake table with the actual measured acceleration.

The accelerometer placed on the shake table was capable of recording the acceleration in all three dimensions. To ensure accurate measurements, we positioned the accelerometer in a way that the y-axis acceleration was minimized and as close to 0 as possible. This allowed us to maximize the x-axis acceleration and make it as close as possible to the acceleration recorded by the shake table during the tests.

5.3.1 Data Manipulation and Key Concepts

The raw acceleration data recorded by the accelerometer is displayed in the image below. As evident, the data appears highly noisy, making it challenging to extract reliable values directly. To address this issue, we applied a low-pass filter to the data, using specific cut-off frequencies for each acceleration considered.

A low-pass filter is a technique that process the signals. It is used to attenuate high-frequency components from the signal, while retaining the smoother and lower-frequency components. In our case, the accelerometer data recorded during the tests are very noisy so this technique is useful as the noise often contains high-frequency components.

The cut-off frequency is a crucial parameter in the low-pass filter as it defines the boundary between the "stopband," where higher frequencies are attenuated, and the "passband," where lower frequencies are allowed to pass through unaffected. For the following accelerations considered, the cut-off frequency range between 30 and 50 Hz.

Please note that the text labels on both axes of the plots generated from the external accelerometer data cannot be effectively enlarged.

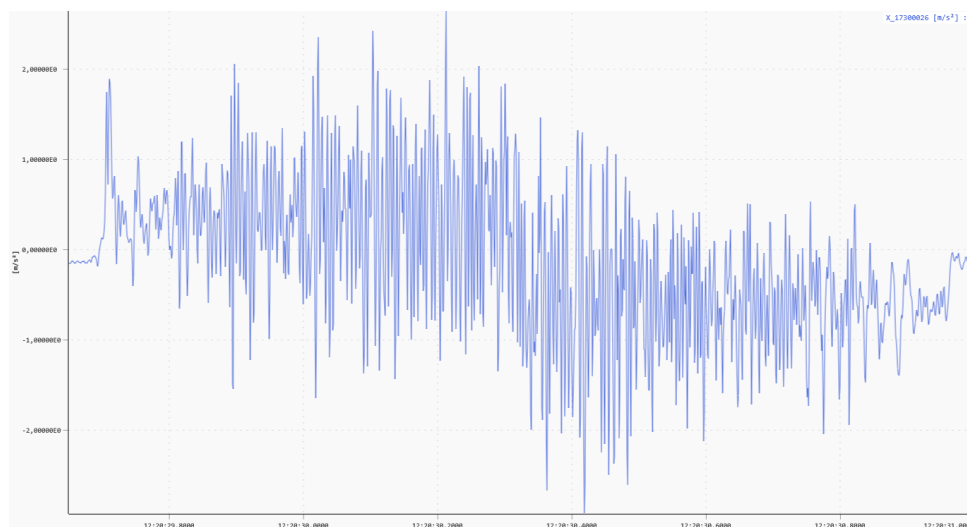


Figure 5.58: Without low-pass filter



Figure 5.59: With low-pass filter

5.3.2 Data Comparison

The two images presented below provide a comparison between the theoretical acceleration (red curve) set at 0.05g and the acceleration recorded by the accelerometer on the shake table (blue curve) on the first image, along with the filtered signal obtained from the outer accelerometer on the second image. It is evident that the signal recorded by the accelerometer in the shake table is not precisely constant and exhibits fluctuations, ranging between 0.02g and 0.08g, with an initial peak at 0.1g.

Despite the signal's slight variations, we can still consider the theoretical value of 0.05g as a reliable reference. This is because all the rocking phenomena recorded in the previous section occurred after the application of the acceleration, and the recorded acceleration has a mean very close to the theoretical value of 0.05g. Thus, for the analysis and comparisons conducted earlier, we can confidently rely on the theoretical value as a representative measure of the applied acceleration during the tests.

Additionally, when comparing the blue signals from both images, a striking similarity in their shapes can be observed, highlighting the peak acceleration at the beginning, among other features. Although the units in the second image are represented in $[m/s^2]$ instead of $[g]$, we can deduce that the acceleration range lies approximately between 0.1 and 0.7 $[m/s^2]$, corresponding to 0.12g and 0.72g, respectively. Despite the slight approximation caused by the lack of detailed ordinate information in the right-hand image, the values obtained from both accelerometers appear to correspond closely with each other. This further reinforces the reliability of the theoretical acceleration and the effectiveness of the low-pass filter in producing consistent results for the recorded acceleration.

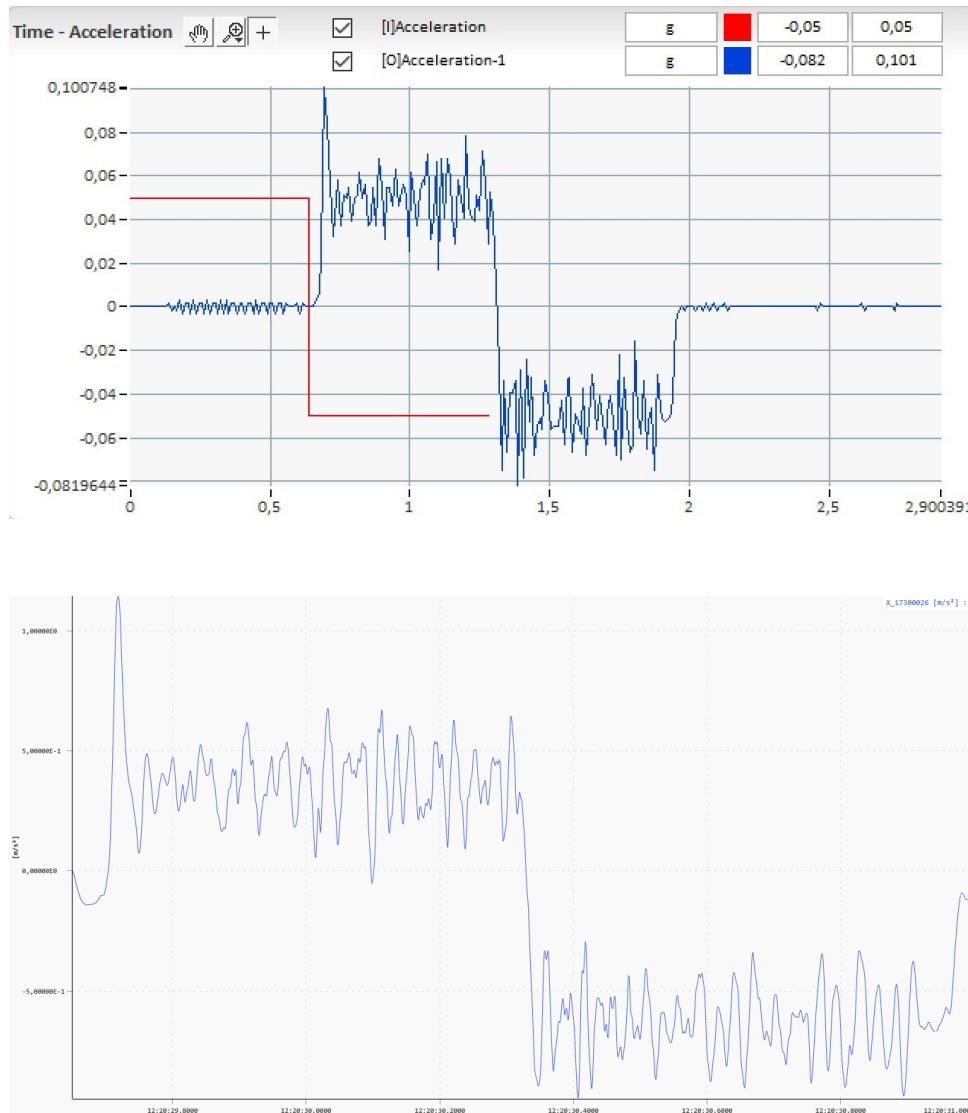


Figure 5.60: Comparison between shake table and accelerometer

The acceleration in the previous figures was applied over a distance of 200mm, whereas the acceleration for the next 4 frames considered is 0.2g and is applied over a distance of 150mm.

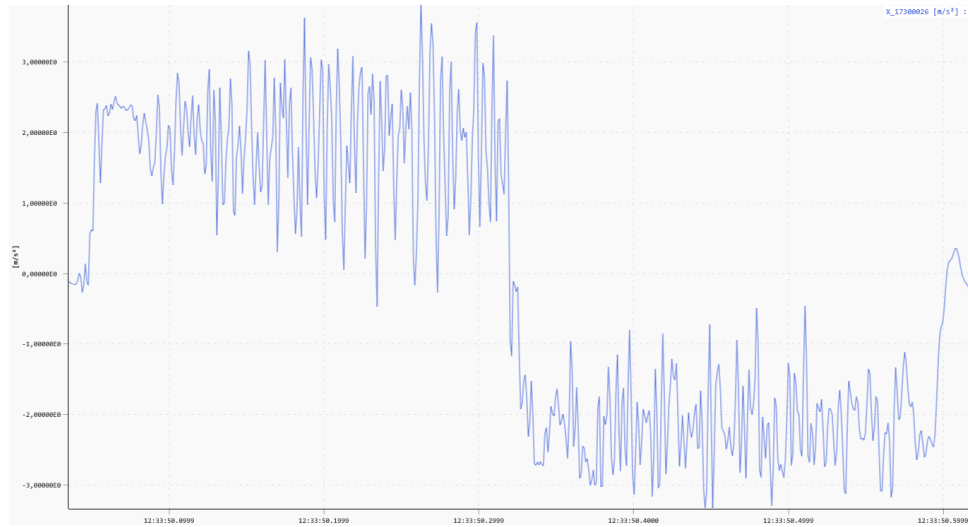


Figure 5.61: Without low-pass filter



Figure 5.62: With low-pass filter

Upon observation of the following images, it becomes evident that the acceleration signals are less noisy for both accelerometers as highlighted by the reduced range of acceleration. A notable difference between the two images lies in the initial peak value, which is more pronounced in the first image.

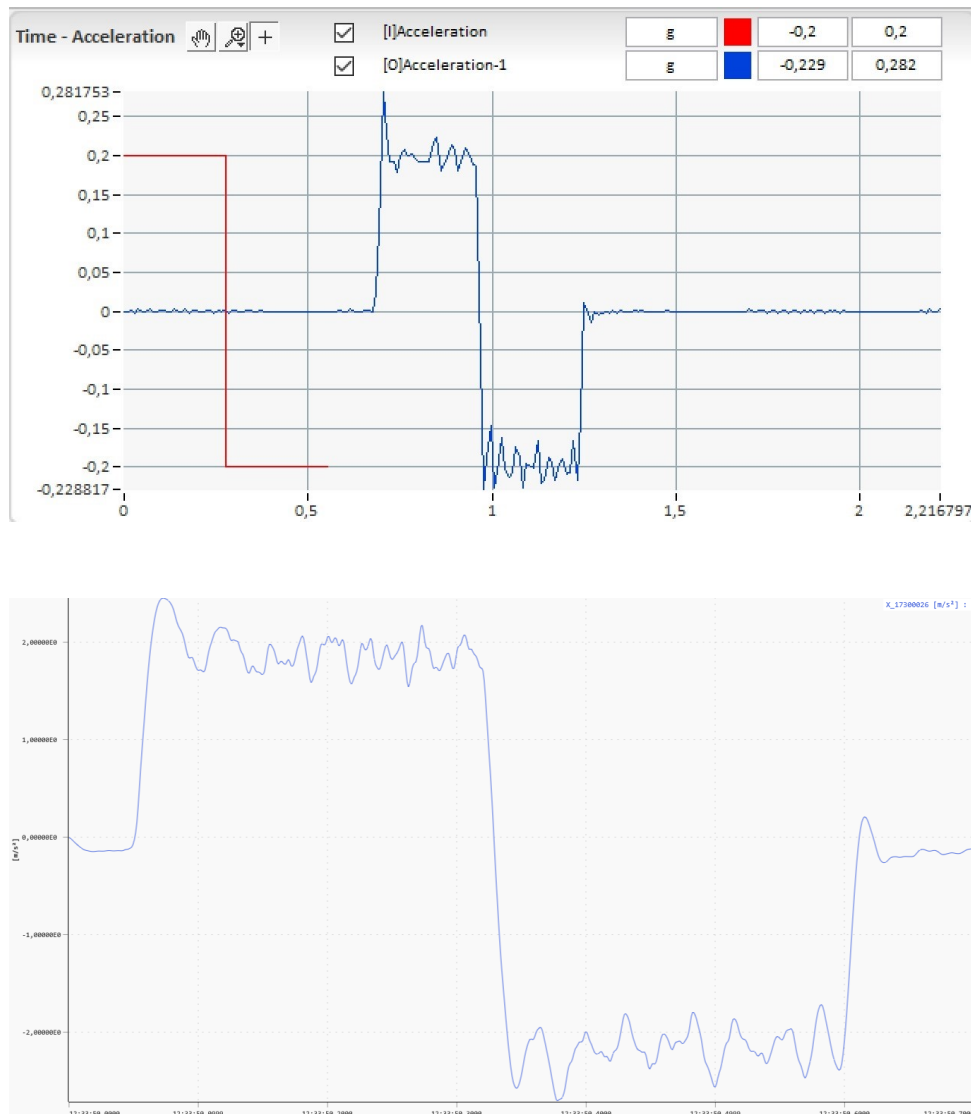


Figure 5.63: Comparison between shake table and accelerometer

When the displacement is decreased even further to 100mm, we can observe that the acceleration curve becomes even smoother and more constant, which further confirms the trend observed previously.

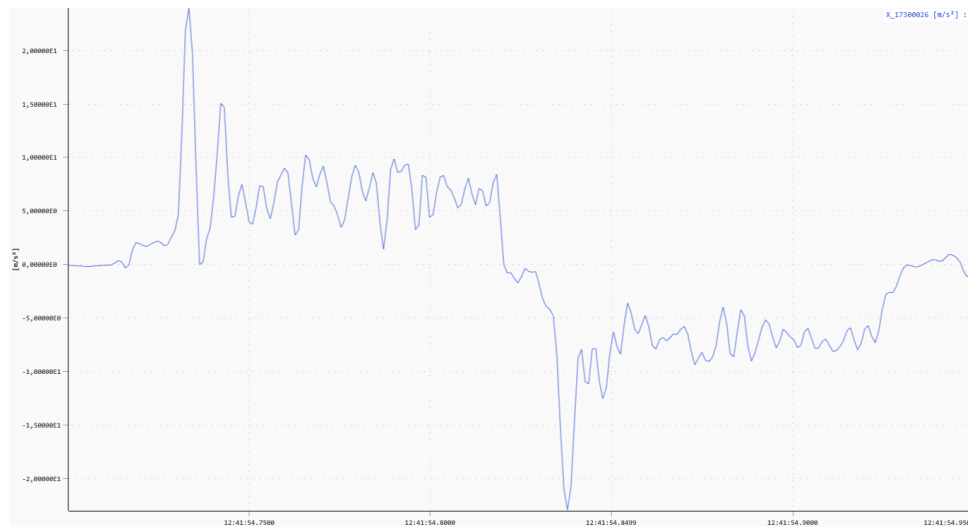


Figure 5.64: Without low-pass filter

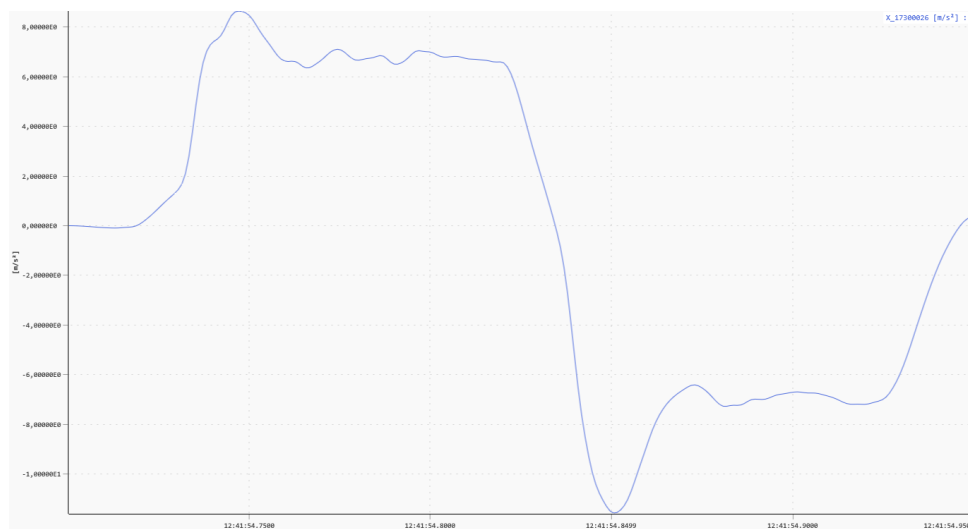


Figure 5.65: With low-pass filter

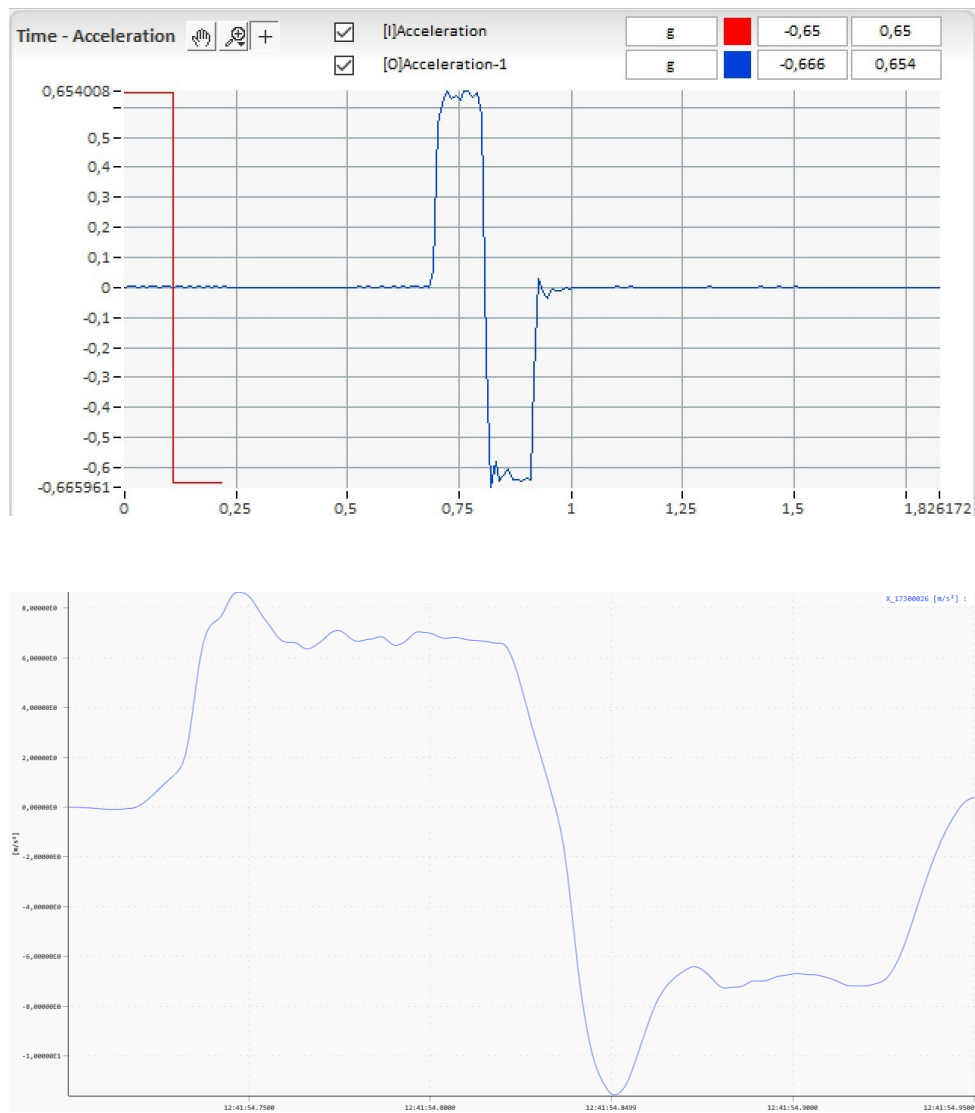


Figure 5.66: Comparison between shake table and accelerometer

The minimal displacement of 25mm combined with a maximum acceleration of 2g was considered irrelevant for our study, as it was concluded that the short duration of application was insufficient to create any significant rocking phenomenon in the first two benchmarks. Another argument to support this conclusion is that both following images of the acceleration data show a sinusoidal-like pattern rather than a constant acceleration. The absence of a flat plateau in the acceleration curve indicates that the acceleration is not maintained at a constant level but varies over time. In the context of our study, this sinusoidal-like acceleration profile is not relevant, as we are primarily interested in analyzing the behavior of the structure under constant acceleration conditions.



Figure 5.67: Without low-pass filter

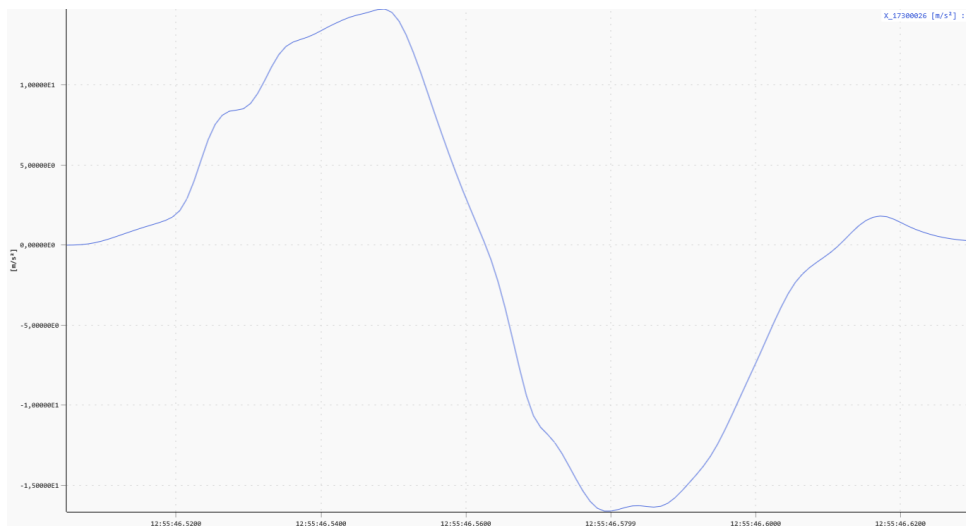


Figure 5.68: With low-pass filter

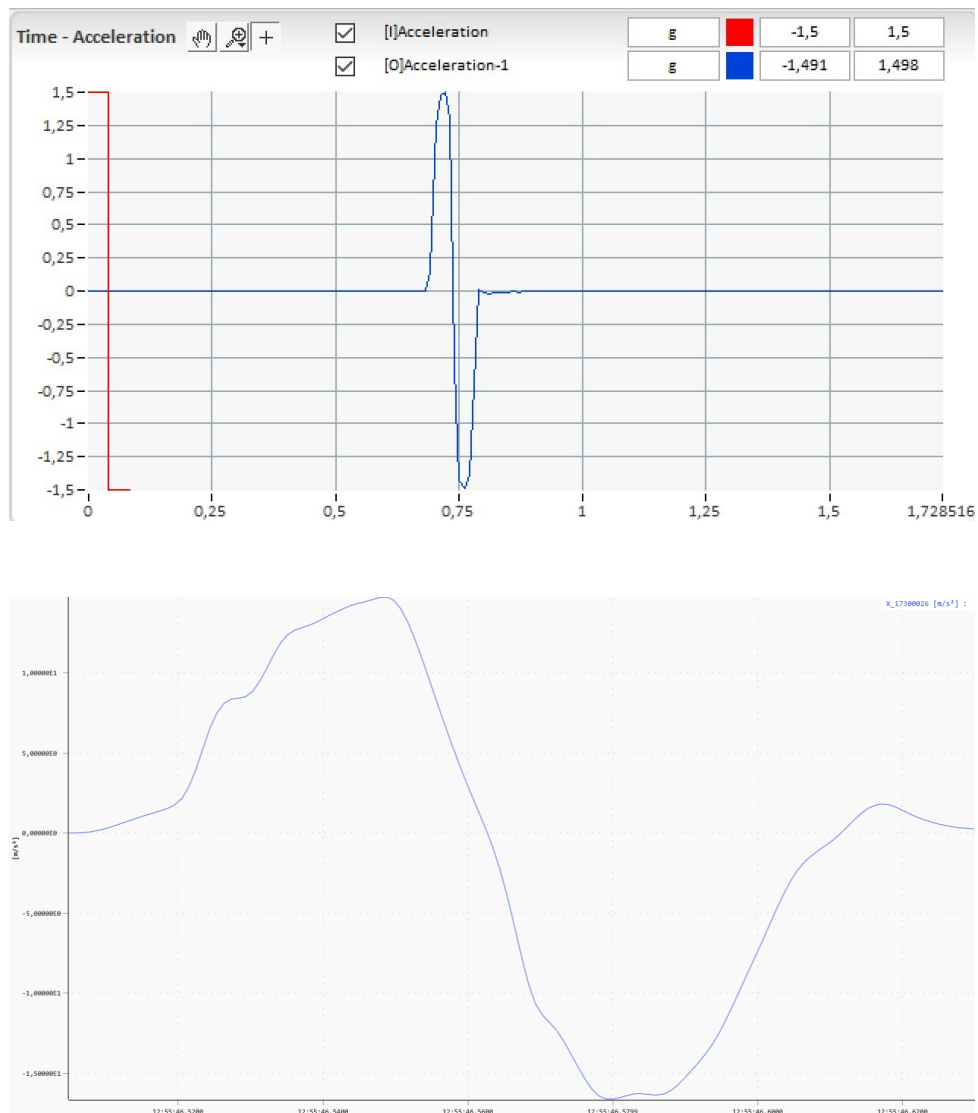


Figure 5.69: Comparison between shake table and accelerometer

Chapter 6

Conclusion

6.1 Summary of the Results

In conclusion, the shake table ATOM used in our experimental setup has proven to be highly reliable from an instrumental standpoint. It consistently delivered relatively precise accelerations. This reliability allowed us to conduct a comprehensive investigation into the behavior of masonry assemblies under seismic conditions.

Furthermore, we found an impressive correlation between the accelerations recorded from the shake table and those measured using an accelerometer placed directly on the table. This alignment underscores the consistency and accuracy of the shake table's performance, validating its crucial role in providing precise and realistic seismic simulations.

Our experimental setup demonstrated a remarkable level of accuracy in correlating the behavior of masonry assemblies between numerical and experimental results. This close correlation reaffirms the validity of the numerical models and provides strong support for the robustness of our experimental approach.

The undistortion process applied to the videos captured during the tests showcased its reliability in faithfully representing the actual behavior of the masonry assemblies. This process ensured that the extracted data about positions and displacements were highly dependable.

The code developed for target detection on frames exhibited outstanding reliability in accurately identifying and tracking targets throughout the experiments. This allowed us to extract accurate data on target positions and displacements, contributing significantly to the overall precision of our study.

In summary, our experimental setup, supported by the reliable shake table, undistortion process for videos, and target detection code, has yielded highly reliable results. The accurate correlation between experimental and numerical data enhances our confidence in the findings and broadens our understanding of masonry assemblies behavior under seismic conditions. These outcomes pave the way for more robust analyses and offer valuable insights for designing safer and more resilient structures in earthquake-prone regions.

6.2 Improvements for Future Works

In this thesis, we have made significant progress in the field of testing small-scale dry-stacked masonry assemblies using a shake table. However, this study can be seen as a point of departure, not arrival as it lays the foundations for further advancements, and in this section, we will make an exhaustive list of potential improvements for future works.

Future workers will need to consider the acquisition of a more advanced shake table that can deliver greater accelerations. This enhancement is crucial to determine the critical acceleration threshold leading to the collapse of the masonry assemblies in benchmark 1 and 2.

In addition to the increasing of accelerations in case of new shake table, investigations need to be made to improve the sliding resistance of the bricks used in the masonry assemblies. This may involve exploring alternative materials for filling the bricks or changing the composition of the exterior body of the brick.

Instead of the basic method used in this thesis, an improved method must be developed to accurately measure the friction coefficients between the bricks and between the bricks and the shake table.

The code used for target detection needs to be refined to encompass a wider range of potential target types. Furthermore, the calculation of the rotation must be improved as the pairing of targets has not been developed at the moment.

Throughout this work, the rocking phenomenon in the existing 2D benchmarks was measured for a fixed combination of acceleration and distance. However, it is possible that other combinations, such as lower acceleration and higher distance, could also produce similar results. By investigating multiple combinations and their corresponding outcomes, we can establish a failure domain. This domain will be represented by a curve that distinguishes between combinations causing no damage and those resulting in the rocking phenomenon and structural damage.

Finally, the future tests can extend the experimental testing to 3D masonry assemblies as these types of structures allow to evaluate the out-of-plane behavior, in addition to the in-plane one.

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Appendix A

Boxes.py

To fabricate the wooden boxes representing the outer body of our bricks, we generated a DXF file using the Boxes.py website. This DXF format contained the precise shapes of the wooden components to be cut, as illustrated in the image below.

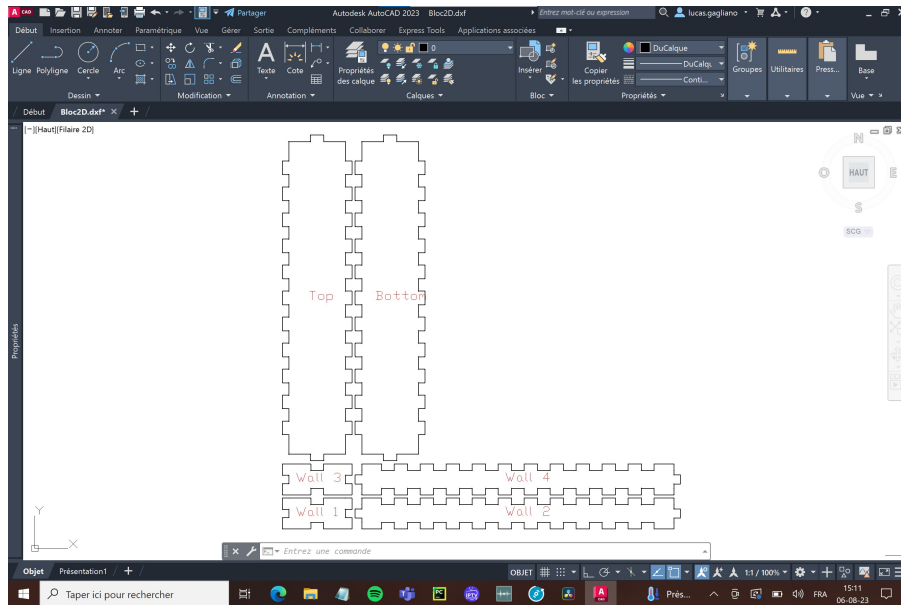


Figure A.1: DXF file

The website's user interface is intuitive and easy to grasp as the instructions for defining parameters are well-documented on the website. We primarily adjusted the thickness of the wooden plates to be cut, the file format for the generated design, and the reference parameter. The reference parameter involves a rectangle that is included in the file to adjust machine settings. However, since we didn't require it, we set its value to 0 to remove it as it would result in unnecessary cutting time and wood wastage. Other parameters shown in the image below remained unaltered for our purposes.

Fully closed box

► **Settings for Finger Joints**

▼ **ClosedBox Settings**

x inner width in mm (unless outside selected)

y inner depth in mm (unless outside selected)

h inner height in mm (unless outside selected)

outside ☒ treat sizes as outside measurements ⓘ

▼ **Default Settings**

thickness thickness of the material (in mm) ⓘ

format format of resulting file ⓘ

tabs width of tabs holding the parts in place (in mm)(not supported everywhere) ⓘ

qr_code ☐ Add a QR Code with link or command line to the generated output

debug ☐ print surrounding boxes for some structures ⓘ

labels ☒ label the parts (where available)

reference print reference rectangle with given length (in mm)(zero to disable) ⓘ

inner_corners style for inner corners ⓘ

burn burn correction (in mm)(bigger values for tighter fit) ⓘ

Figure A.2: Boxes.py interface

Appendix B

Easytest ShakeTable

This software is intricately connected with the shake table, empowering us to construct customized signals and transmit them to the shake table for execution. Upon launching the software, the interface depicted below appears. The initial step involves configuring the piston parameters, which are conveniently provided in a handbook furnished during the shake table acquisition. After this setup is complete, activating the shake table involves clicking the "Disabled" button. It is recommended to subsequently select the "Go to Zero Point" button while ensuring the accompanying checkbox on the right is ticked. This action allows the software to know the table's position at any given time along with the piston's length.

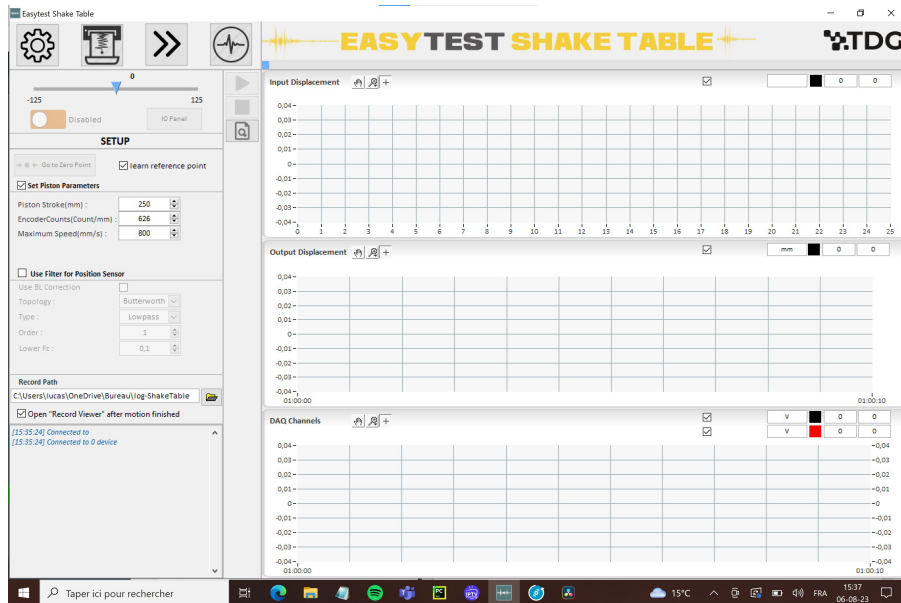


Figure B.1: Launching interface

In case where the shake table's function is limited to applying constant or sinusoidal displacements, users can select the "Easy Mode" option by selecting the third prominent square in the row where the first square is marked with a gear symbol. Upon activation, a choice between "Point" or "Sine" displacement types becomes available. "Point" signifies a constant displacement, while "Sine" represents a sinusoidal one. The parameters for the former include the desired displacement and speed. On the other hand, for the latter, users can determine the amplitude, frequency, and the number of cycles to be executed at the specified amplitude.

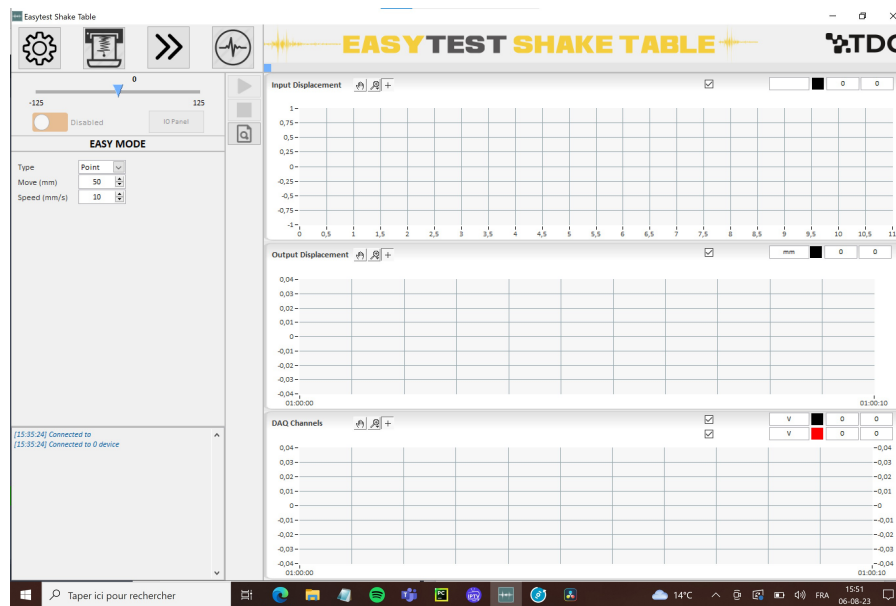


Figure B.2: Constant displacement

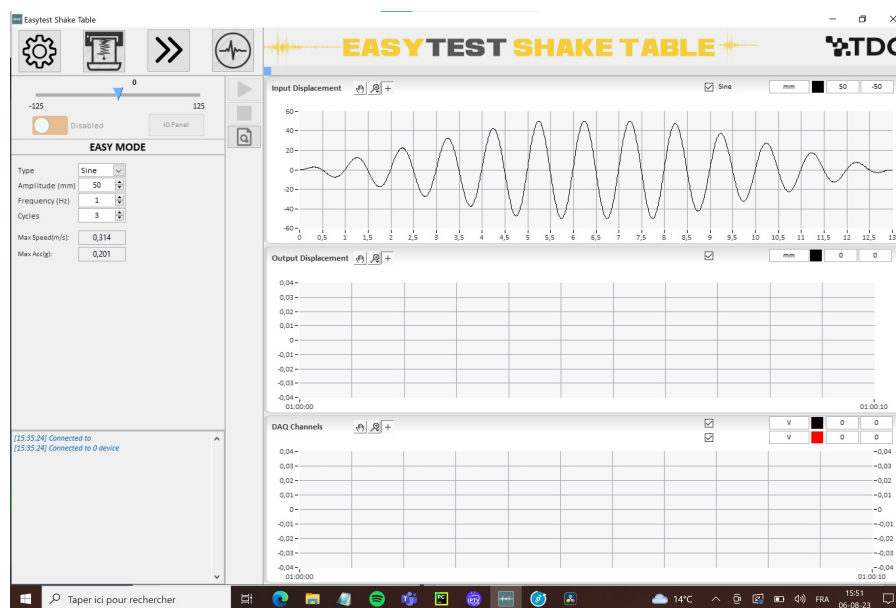


Figure B.3: Sinusoidal displacement

If users intend to apply customized signals, they can opt for the "Profile Mode" by selecting the fourth prominent square. To access the profile menu, users simply need to click on the small square labeled with the letter "M".

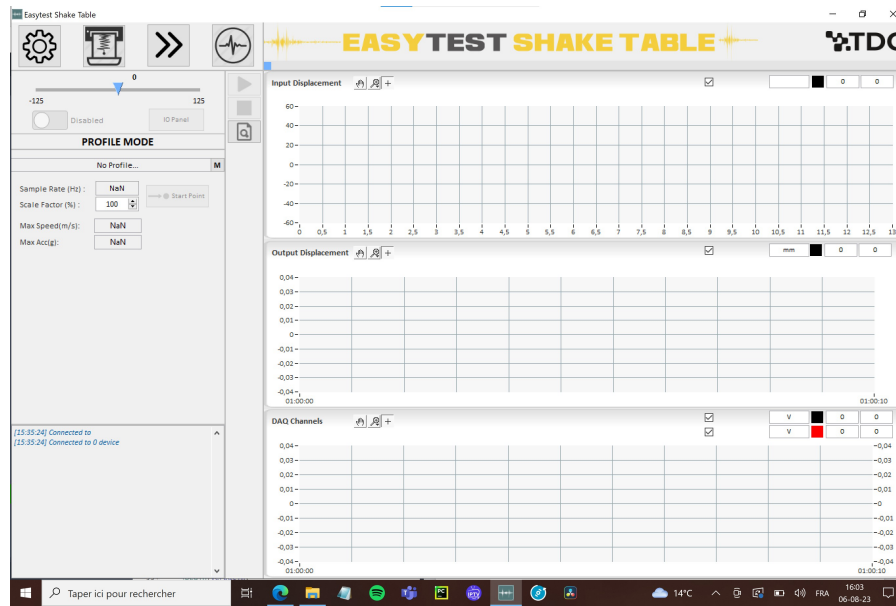


Figure B.4: Profile mode

Once opened, users need to click on the middle square located in the top-left corner labeled "Signal Generator".

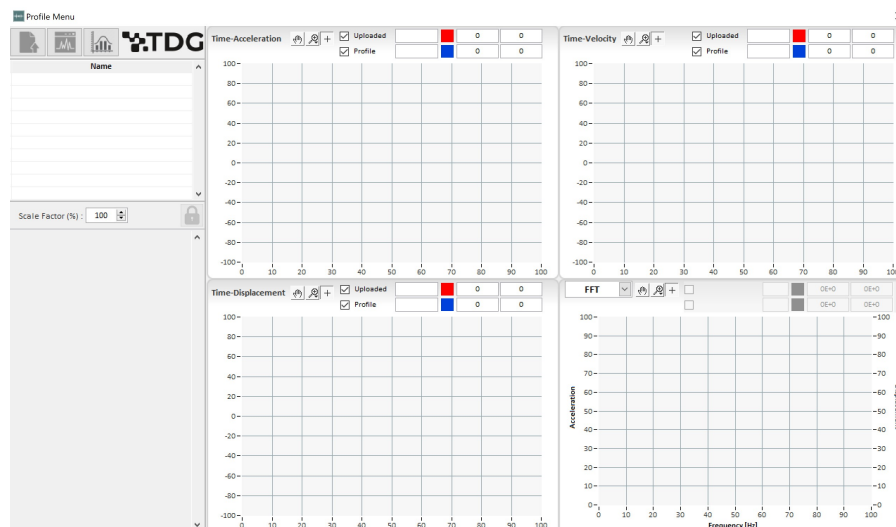


Figure B.5: Profile menu

In this section, the customized signal configuration depends on several parameters. First, the desired signal shape must be selected from the available list. Subsequently, the sample rate is adjusted as per the specific requirements, and the amplitude and frequency are set using the previously outlined equations in chapter three. For sinusoidal signals, the number of cycles can also be specified. Once these parameters are defined, the signal can be named, and the user has the option to indicate whether the signal represents displacement, velocity, or acceleration, along with the corresponding unit of measurement.

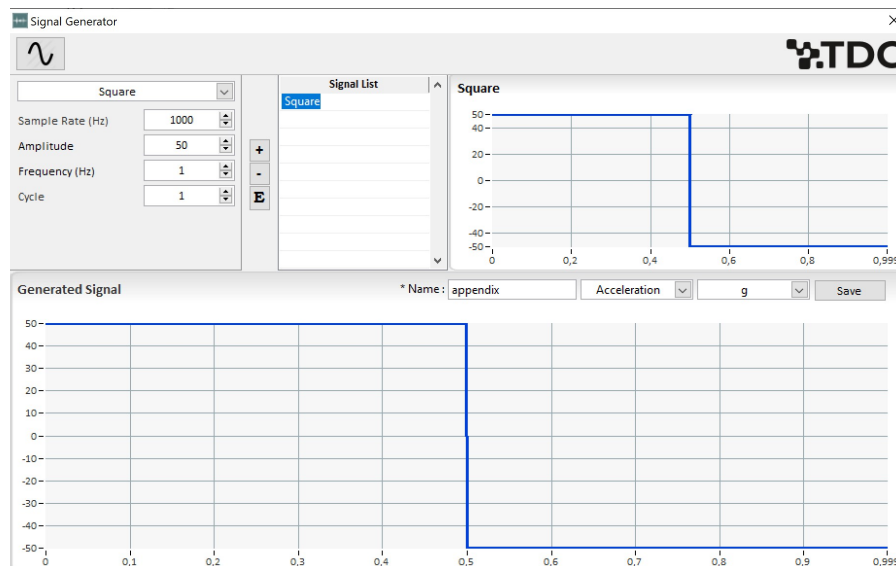


Figure B.6: Signal generator

Once the customized signal is saved, the software generates various plots depicting displacement, velocity, and acceleration, based on the chosen parameters. The resulting signal is automatically stored in a designated folder on the home screen of the computer.

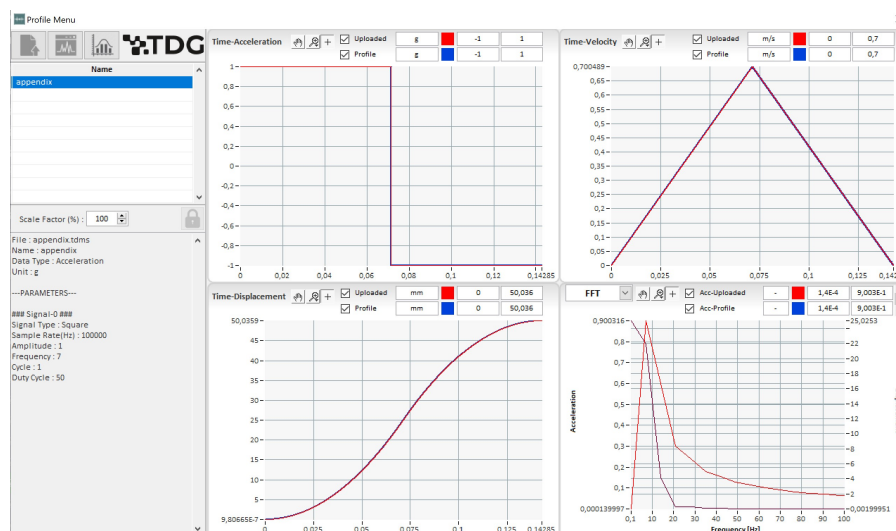


Figure B.7: Created profile

Appendix C

GIMP

After designing the targets in AutoCAD, they should be resized appropriately to fit on the bricks. Since the exported image from AutoCAD may have an unknown real-world size, resizing is necessary. The software GIMP can be used for this purpose, enabling the targets to be adjusted in relation to an A4 paper. This involves creating a new image with dimensions of 210x297mm, which can be accomplished through the "File" section in the upper menu.

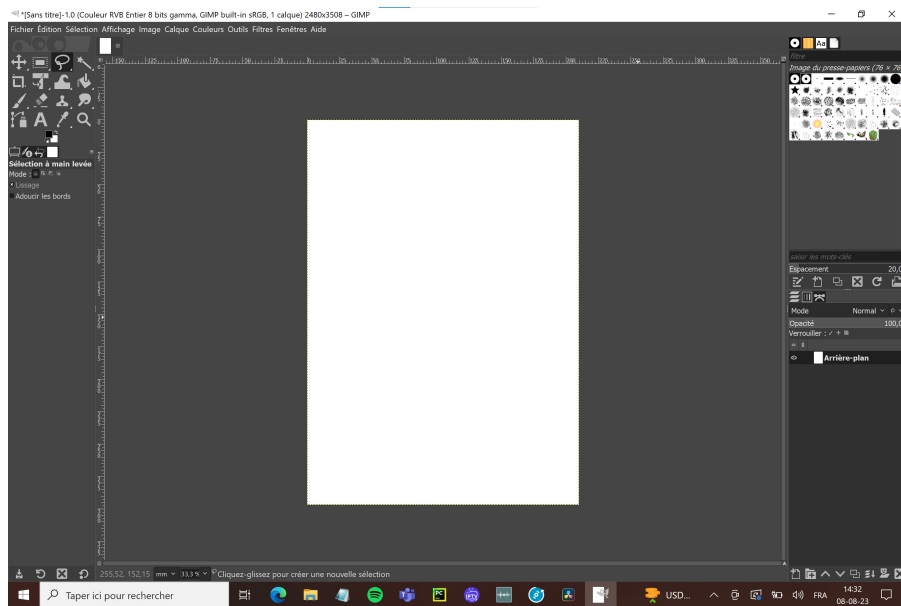


Figure C.1: A4 paper created

Upon opening the target image via the "File" section, resizing can be achieved using the "Scale and size of the image" option located within the "Image" section.

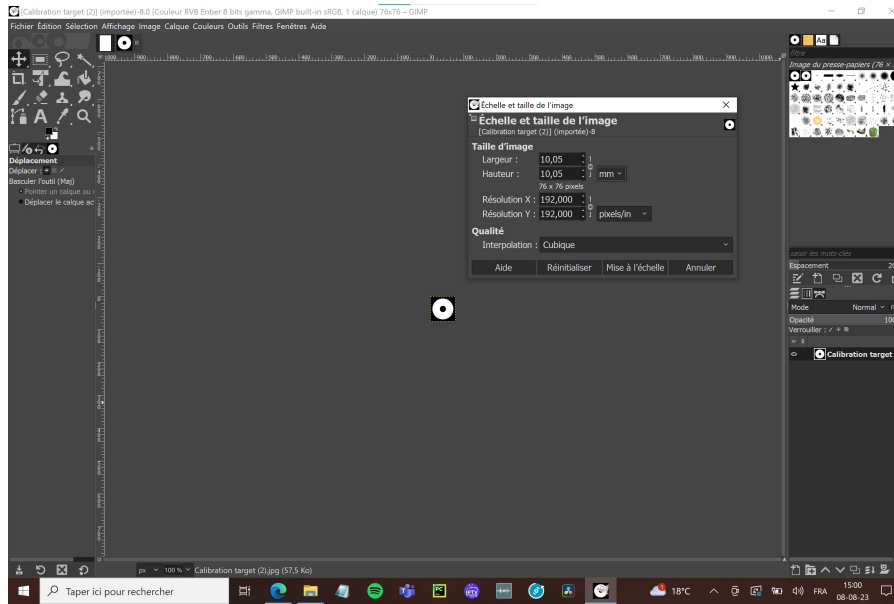


Figure C.2: Target resizing

Once the desired dimensions are inputted, proceed to copy and paste the target onto the A4 paper. To efficiently populate the A4 sheet with multiple targets, execute a cyclic procedure: copy the entire set of targets, paste it onto the sheet, and then merge the layers. Repeat this cycle until the A4 paper is filled with the desired number of targets.

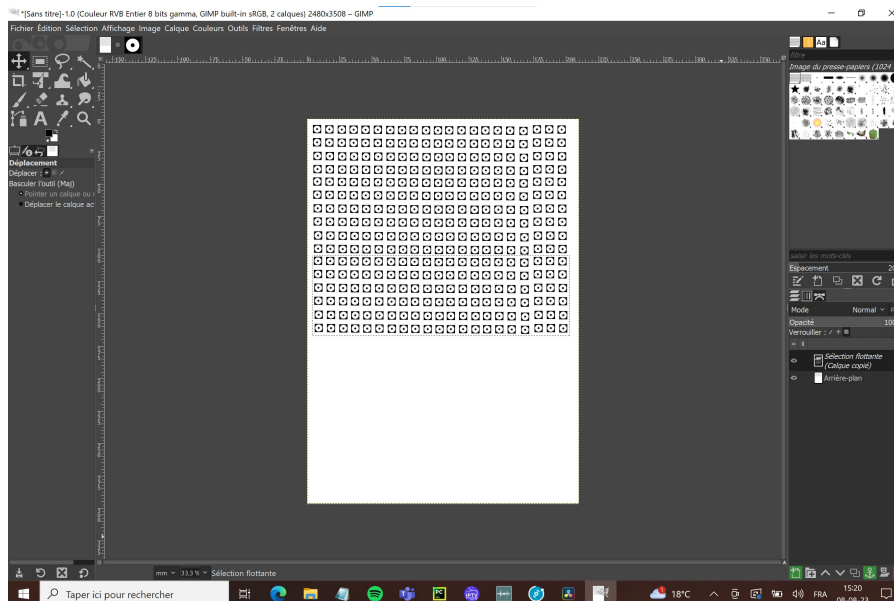


Figure C.3: A4 paper with all targets

Appendix D

GoPro Quik

During the camera calibration process, there are two distinct phases: intrinsic and extrinsic calibration. While the intrinsic calibration was previously explained, the extrinsic calibration remains to be discussed. This calibration pertains to determining the real-world position of the camera. In order to avoid performing extrinsic calibration before each video, the camera was positioned in a fixed location and has remained stationary since. However, a challenge arose: how to efficiently capture and retrieve videos and images from the GoPro camera without touching it? To address this, two wireless options were considered.

The initial option involves using the GoPro Quik mobile application. This application primarily serves for setting the recording parameters, providing video previews, recording videos and reviewing recorded content.

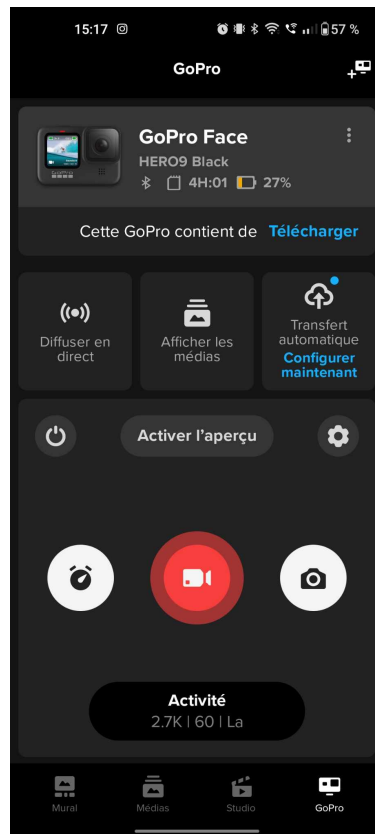
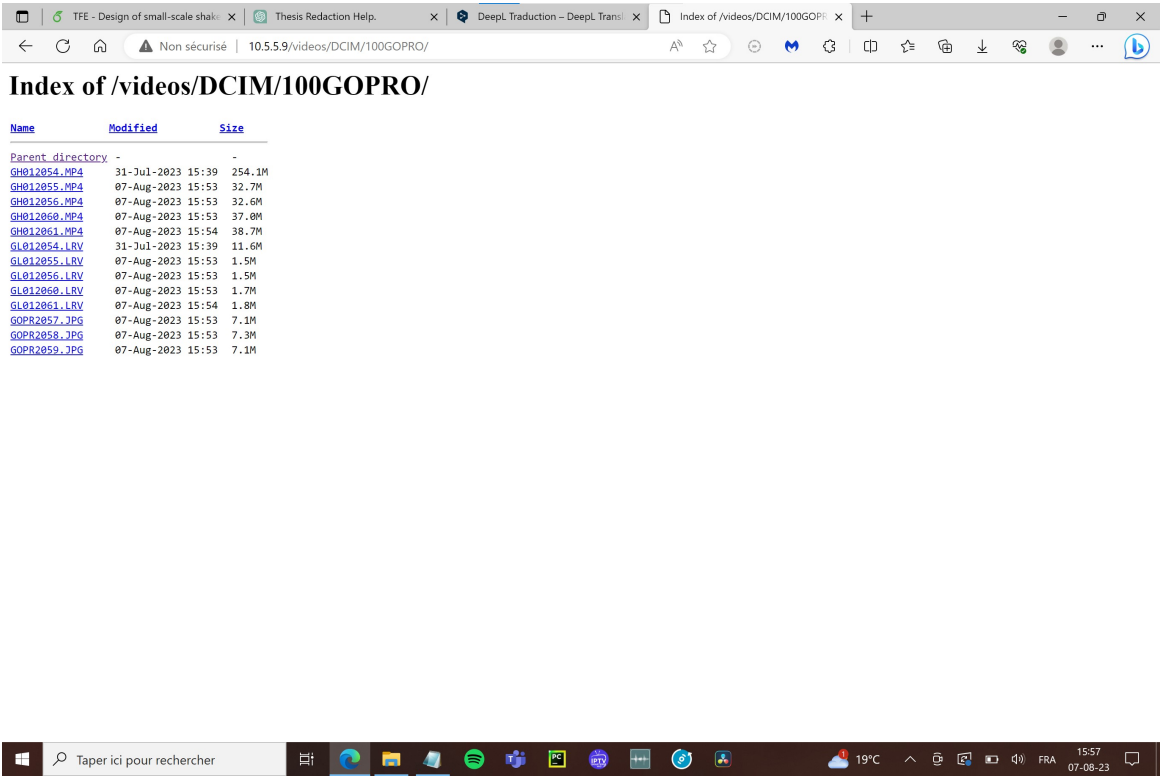


Figure D.1: GoPro Quik

The alternative approach includes establishing a connection between the computer and the GoPro’s Wi-Fi network. Once this connection is established, accessing the following web address grants access to all the files stored in the GoPro: <http://10.5.5.9/videos/DCIM/100GOPRO/>



Appendix E

FFMPEG

To extract frames from each video while maintaining the actual frame rate of 119.88 fps, various methods were attempted. However, only one effective option resembled a code, yet it remained relatively straightforward. To achieve this, the outlined procedure needs to be followed after downloading the "ffmpeg.exe" file:

1. After opening the terminal, write "cd" + the path to the folder where you want to put the images. For example, the following line can be written :

```
cd C:\Users\lucas\OneDrive\Bureau\target-tracking\images-to-process
```

2. Once done, write the following code line :

```
ffmpeg.exe -ss start_time -t duration -i "path_to_video"  
-qscale:v 2 -r frame_rate extracted_image_name
```

For example, the following line can be written :

```
ffmpeg.exe -ss 00:00:00 -t 00:00:05 -i  
"C:\Users\lucas\OneDrive\Bureau\Memoire\Videos\Tests benchmarks\  
Benchmark 6\Impulse\200mm\Benchmark 6 - Impulse 0,15g - 200mm.mp4"  
-qscale:v 2 -r 119.88 extracted-image-%4d.jpg
```

Appendix F

DaVinci Resolve

After understanding the purpose of this software, let's delve into its usage. Upon launching the application, initiate by creating a new project. Once the project is loaded, proceed to import the video that requires processing using the "File" section located in the upper menu. Upon successful loading, a new timeline is generated by dragging and dropping the video into the designated space below, as illustrated in the provided image:

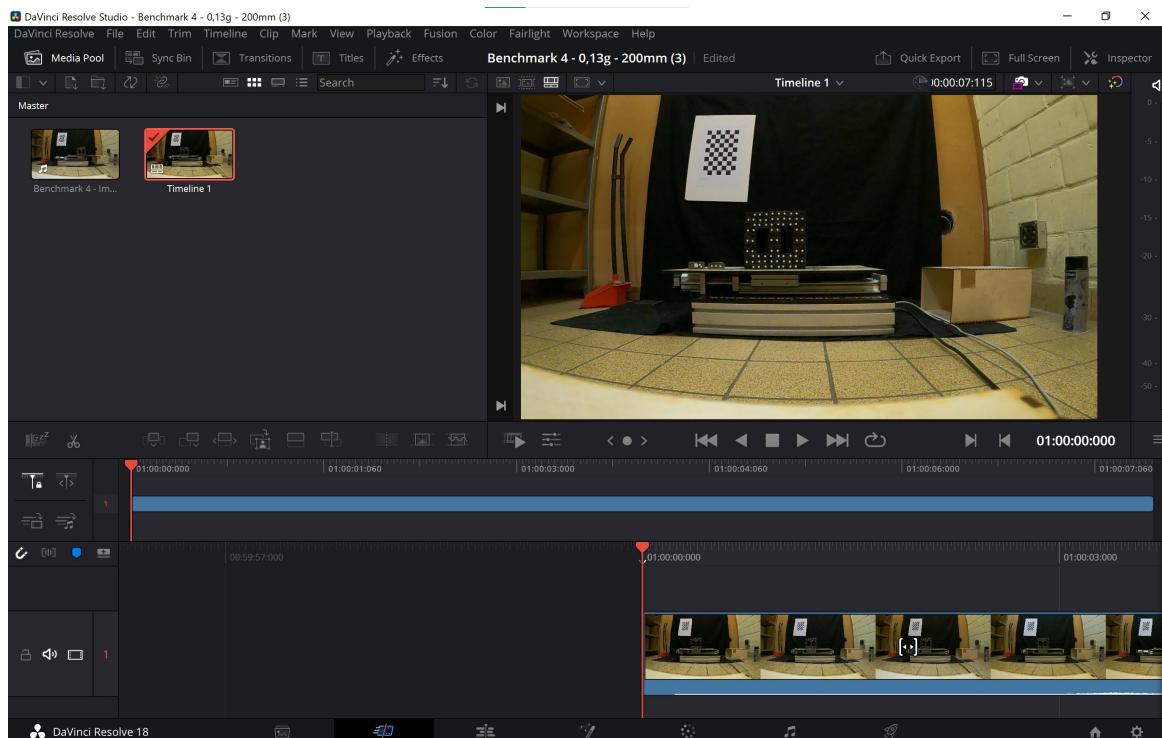


Figure F.1: Timeline creating

To rectify the video distortion, access the "Edit" window by selecting the third icon from the bottom menu. Following this, open the "Inspector" menu by clicking the top-right corner icon. Upon scrolling through the menu, locate the "Lens Correction" section. The undistortion process is straightforward: simply click on the "Analyze" button within this section. This action also calculates the previously mentioned distortion coefficient.

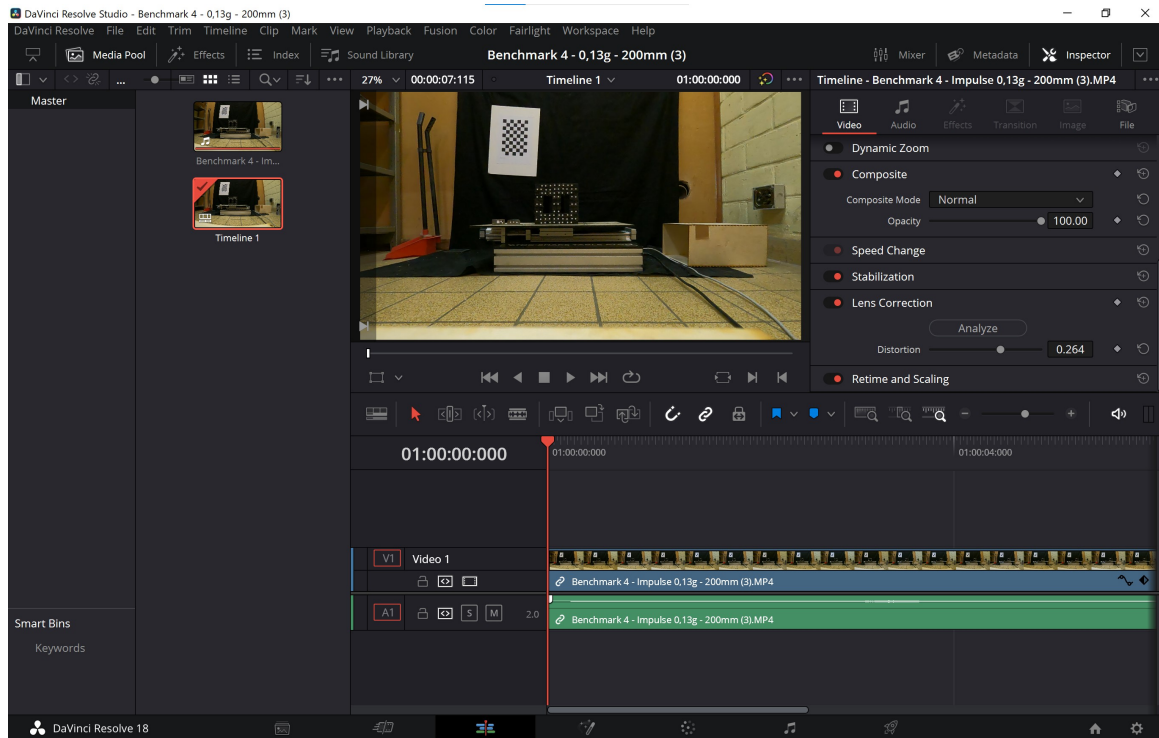


Figure F.2: Video undistortion

To export the corrected video, access the "Export" window by selecting the last icon from the lower menu. Enter the desired name and location for the undistorted video, then add it to the render queue and initiate the rendering process.

Appendix G

Recovib

Upon launching the Recovib application, a menu featuring various options becomes visible. For our specific purposes, our attention will be directed towards the "Recovib Tiny" and "Recovib Viewer" sections.

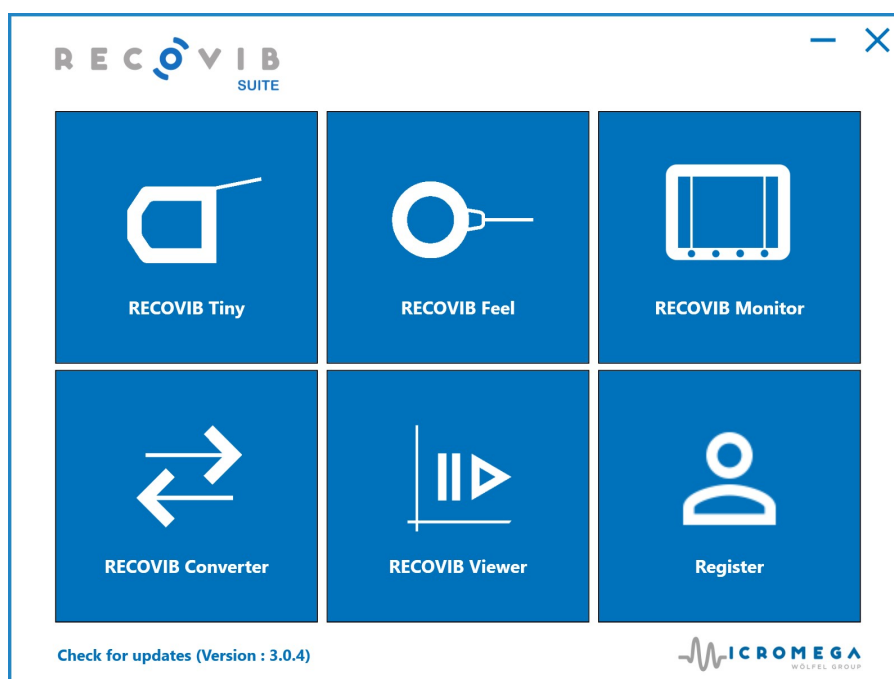


Figure G.1: Main menu

The "Recovib Tiny" section is used to add a sensor by entering its serial number and establishing a wired connection to the computer. This section is also used to prepare the accelerometer for recording or to obtain its measurements.

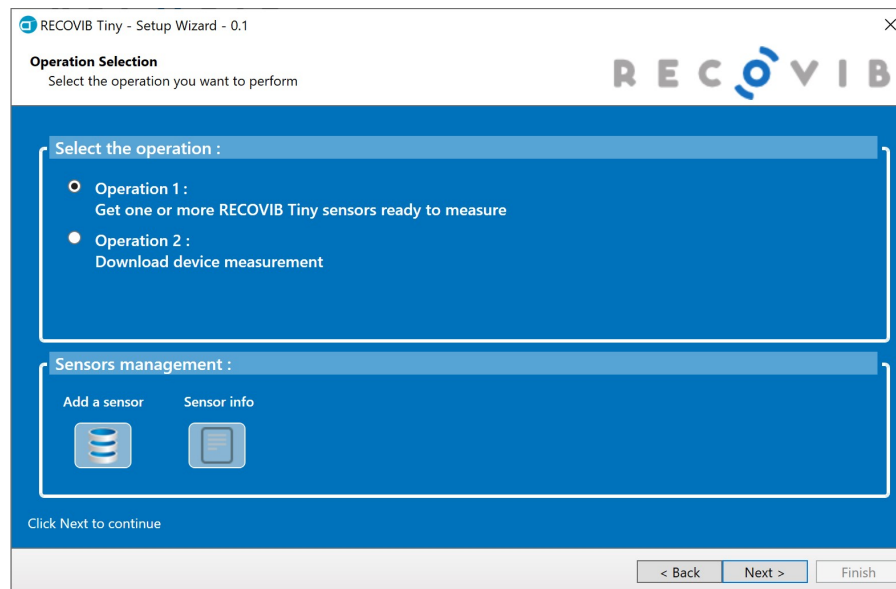


Figure G.2: Operation selection

During the preparation phase, users are required to specify the measurement interval of time. This can be accomplished by defining the start and stop date and time, or alternatively, by setting a start delay and duration for the recording.

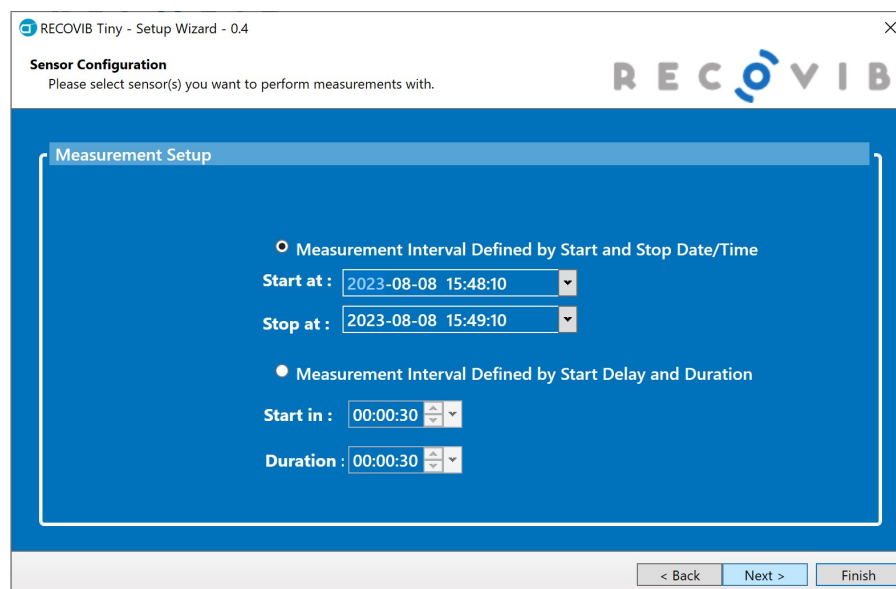


Figure G.3: Sensor configuration

After downloading the recorded measurements, they can be visualized and analyzed within the "Recovib Viewer" section. To access the measurements, users should click on the folder icon located in the bottom-right menu, then select the folder containing the downloaded data. Once loaded, the record's settings become accessible. Within the first section, users can manipulate the signals from each acceleration direction. For instance, they can apply a low-pass filter, as previously described, to refine the data for analysis.

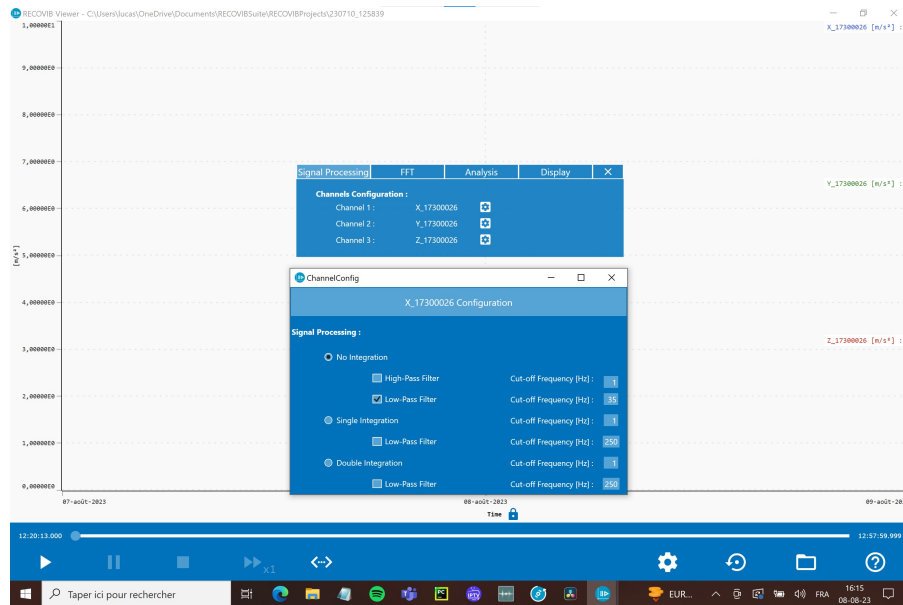


Figure G.4: Low-pass filter

In the last settings section, users have the option to select the specific segment of the measurement they wish to visualize. They can also choose, among others, the acceleration direction and decide whether to display the data in a temporal or frequency-based format.

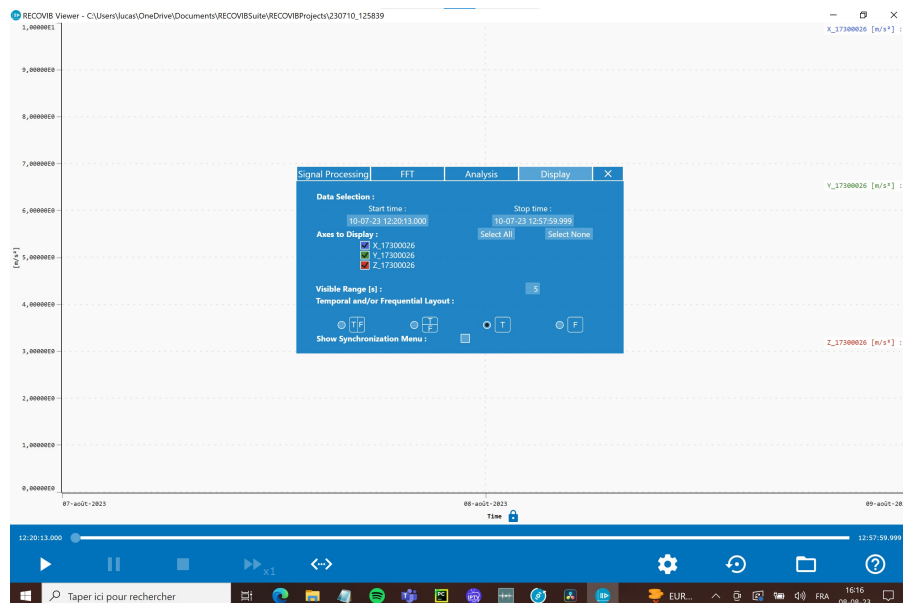


Figure G.5: Display settings

To visualize the entire downloaded recording, users can click on the double arrows icon located in the bottom-left menu. Upon doing so, users can zoom in on specific regions by creating a rectangle with the mouse around the desired section. This intuitive zooming feature enables detailed examination of specific segments within the recorded data.

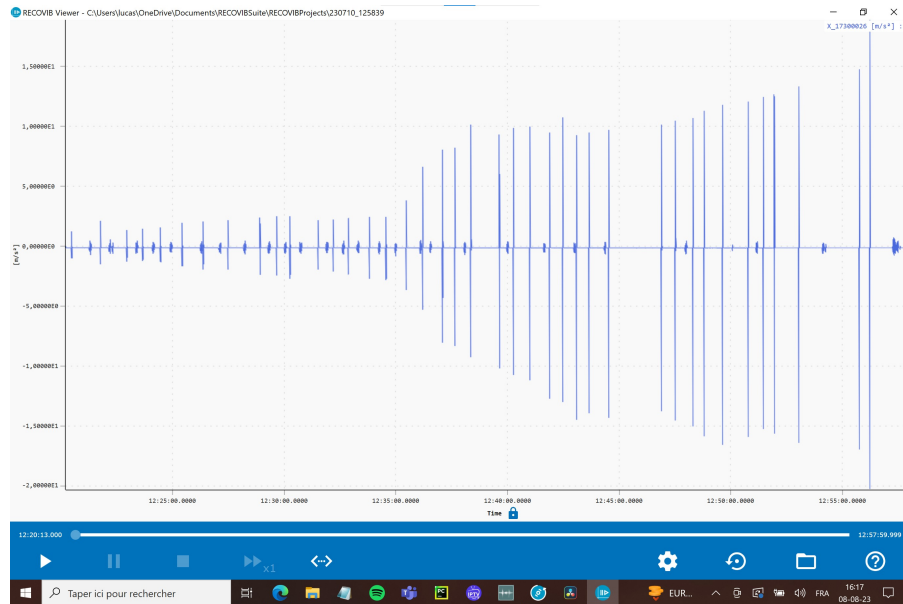


Figure G.6: Full recording

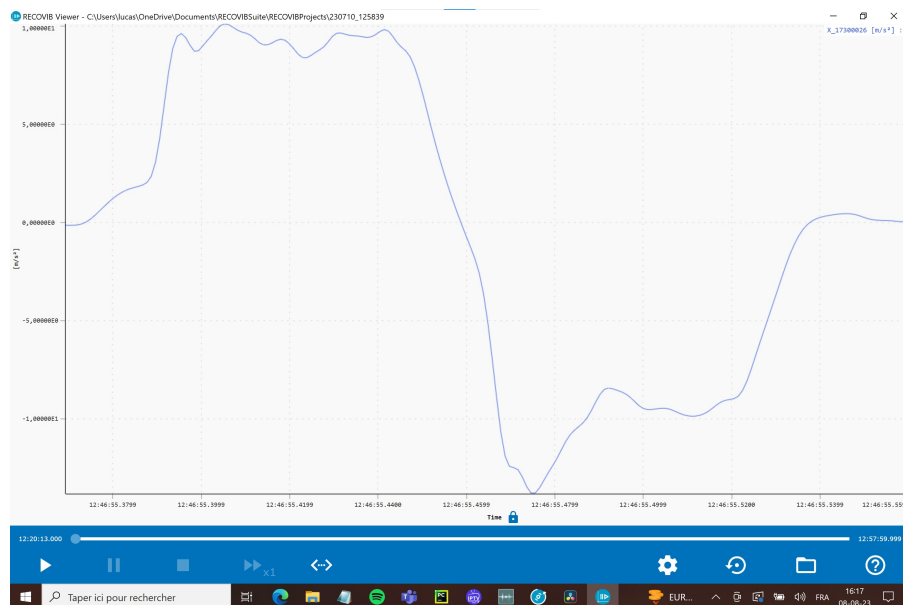


Figure G.7: Zoom on specific acceleration

Appendix H

Google Drive

Throughout this thesis, a significant number of videos have been recorded and subjected to analysis. However, due to the impossibility to print videos in hard copy, we have opted to present frames extracted from each video. To facilitate a comprehensive view of the results through videos, including all the processed images for each test, and to prevent the thesis from becoming excessively lengthy, a Google Drive link has been provided. The code made during this thesis will also be downloaded there along with videos and images. Here is the provided link:

https://drive.google.com/drive/folders/1frs3MB2NiB68U657HK36i1rVxjYcdZBY?usp=drive_link

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