LNEC-BUILD-1
Modelling Predictions and Analysis Cross Validation

Arup, Eucentre, the Delft University of Technology (TU Delft) and Modelling and Structural Analysis Konsulting (Mosayk)

Date September 2017

Editors Jan van Elk & Dirk Doornhof

General Introduction

Many of the buildings in the Groningen field area are terraced unreinforced masonry buildings. A program to assess the response of these building to earthquakes was therefore initiated. This program built on the experimental and modelling program into the properties of URM building materials, wall elements and wall units.

A typical Groningen terraced house built using materials from the Groningen area by builders from the Groningen area, was tested at the shake-table of Eucentre in Pavia, Italy (Ref. 1). Although the building was at the end of this test program seriously damaged, the building had not collapsed. This left questions on the remaining capacity of the structure and its ability to resist larger seismic movements before (partially) collapsing. The test in Eucentre was therefore followed-up with further tests at the laboratory of LNEC in Lisbon, Portugal (Ref. 2 to 6). Here the upper floors of the building tested in Eucentre were re-built in the LNEC laboratory and subjected to movements measured at the base of the upper floors in Eucentre.

This report presents the results of four different modelling approaches used by Arup, Eucentre, the Delft University of Technology (TU Delft) and Modelling and Structural Analysis Konsulting (Mosayk) to predict the performance of the shake table test. The four Consultants used different analysis software: LS-DYNA, TreMuri, DIANA and Extreme Loading for Structures (ELS), respectively. This report describes experimental tests carried out in the LNEC laboratory in Lisbon (Portugal) (Ref. 2). These tests have been purposely extended to include partial collapse of the test specimen. This occurred at much higher shaking levels (peak ground acceleration) than those that are expected in the Groningen area.

The main reasons for extending these tests to higher shaking levels are as follows:

- Tests to seismic actions higher than expected allow one to measure the available excess capacity for the buildings to resist the earthquake action, which is fundamental to appropriately calibrate numerical models of the buildings, and then account for the fact that some buildings of a given typology may be of poorer construction or use lower quality building materials, and are thus weaker than anticipated for buildings of that typology. If the experimental tests show that the specimen is able to withstand even these severe ground motions, then the calibrated numerical models can confidently be used to confirm that that even the weakest building in the same typology will be able to resist the ground motions expected in Groningen.
- The Eucentre and LNEC laboratories in Pavia (Italy) and Lisbon (Portugal) have been set up with the primary objective to study the impact of tectonic earthquakes in Southern Europe in the area from Portugal – Italy – Greece to Turkey. The research for Groningen could have delayed progress relevant to the impact of tectonic earthquakes in this region. However, by extending these tests to larger ground motion values, more typical of tectonic earthquakes, we have made these experiments also relevant to Southern Europe and other areas of the world, where tectonic earthquakes cause higher ground motions.

After the collapse test of the upper floors of the terraced house, also the roof construction was individually tested (Ref. 5 and 6).

References

1. Eucentre Shake-table Test of Terraced House Modelling Predictions and Analysis Cross Validation, staff from ARUP, Eucentre (Pavia) and TU Delft, November 2015 [this document also includes; (1) Instruments full-scale test-house Eucentre Laboratory, (2) Protocol for Shaking Table Test on Full Scale Building (Eucentre) V_1, and (3) Selection of Acceleration Time-Series for Shake Table Testing of Groningen Masonry Building at the EUCENTRE, Pavia, all three by staff from Eucentre (Pavia)],
2. Collapse shake-table testing of terraced house (LNEC-BUILD1), Eucentre and LNEC (U. Tomassetti, A. A. Correia, F. Graziotti, A.I. Marques, M. Mandirola, P.X. Candeias), 1st September 2017.
3. Using the Applied Element Method to model the shake-table testing of two full-scale URM houses (EUC-BUILD1 and EUC-BUILD2), Mosayk (D. Malomo, R. Pinho), 31st October 2017.
4. Using the Applied Element Method to model the collapse shake-table testing of a URM cavity wall structure (LNEC-BUILD1), Mosayk (D. Malomo, R. Pinho), 31st October 2017.
5. Shake-table test up to collapse on a roof substructure of a Dutch terraced house (LNEC-BUILD2), Eucentre and LNEC (A.A. Correia, A.I. Marques, V. Bernardo, L. Grottoli, U. Tomassetti, F. Graziotti), 31st October 2017.
6. Using the Applied Element Method to model the collapse shake-table testing of a terraced house roof substructure (LNEC-BUILD2), Mosayk (D. Malomo, R. Pinho), 31st October 2017.

NAM

Title	**LNEC-BUILD-1** **Modelling Predictions and Analysis Cross Validation**	**Date**	September 2017
		Initiator	NAM
Autor(s)	**Staff of Arup, Eucentre, the Delft University of Technology (TU Delft) and Modelling and Structural Analysis Konsulting (Mosayk)**	**Editors**	Jan van Elk and Dirk Doornhof
Organisation	Arup, Eucentre, the Delft University of Technology (TU Delft) and Modelling and Structural Analysis Konsulting (Mosayk)	**Organisation**	NAM
Place in the Study and Data Acquisition Plan	Study Theme: Seismic Response of Buildings (URM) Comment: Many of the buildings in the Groningen field area are terraced unreinforced masonry buildings. A program to assess the response of these building to earthquakes was therefore initiated. This program built on the experimental and modelling program into the properties of URM building materials, wall elements and wall units. A typical Groningen terraced house built using materials from the Groningen area by builders from the Groningen area, was tested at the shake-table of Eucentre in Pavia, Italy (Ref. 1). Although the building was at the end of this test program seriously damaged, the building had not collapsed. This left questions on the remaining capacity of the structure and its ability to resist larger seismic movements before (partially) collapsing. The test in Eucentre was therefore followed-up with further tests at the laboratory of LNEC in Lisbon, Portugal (Ref. 2 to 6). Here the upper floors of the building tested in Eucentre were re-built in the LNEC laboratory and subjected to movements measured at the base of the upper floors in Eucentre. This report presents the results of four different modelling approaches used by Arup, Eucentre, the Delft University of Technology (TU Delft) and Modelling and Structural Analysis Konsulting (Mosayk) to predict the performance of the shake table test. The four Consultants used different analysis software: LS-DYNA, TreMuri, DIANA and Extreme Loading for Structures (ELS), respectively. This report describes experimental tests carried out in the LNEC laboratory in Lisbon (Portugal) (Ref. 2). These tests have been purposely extended to include partial collapse of the test specimen. This occurred at much higher shaking levels (peak ground acceleration) than those that are expected in the Groningen area.		

	The main reasons for extending these tests to higher shaking levels are as follows: • Tests to seismic actions higher than expected allow one to measure the available excess capacity for the buildings to resist the earthquake action, which is fundamental to appropriately calibrate numerical models of the buildings, and then account for the fact that some buildings of a given typology may be of poorer construction or use lower quality building materials, and are thus weaker than anticipated for buildings of that typology. If the experimental tests show that the specimen is able to withstand even these severe ground motions, then the calibrated numerical models can confidently be used to confirm that that even the weakest building in the same typology will be able to resist the ground motions expected in Groningen. • The Eucentre and LNEC laboratories in Pavia (Italy) and Lisbon (Portugal) have been set up with the primary objective to study the impact of tectonic earthquakes in Southern Europe in the area from Portugal – Italy – Greece to Turkey. The research for Groningen could have delayed progress relevant to the impact of tectonic earthquakes in this region. However, by extending these tests to larger ground motion values, more typical of tectonic earthquakes, we have made these experiments also relevant to Southern Europe and other areas of the World where tectonic earthquakes cause higher ground motions. After the collapse test of the upper floors of the terraced house, also the roof construction was individually tested (Ref. 5 and 6).
Directliy linked research	(1) Shake table tests (2) Fragility curves for building typologies (URM) (3) Risk Assessment
Used data	Experiments
Associated organisation	NAM
Assurance	Arup, Eucentre, the Delft University of Technology (TU Delft) and Modelling and Structural Analysis Konsulting (Mosayk)

Client: Nederlandse Aardolie Maatschappij

Arup Project Title: Groningen Earthquakes - Structural Upgrading

LNEC-BUILD-1: Modelling Predictions and Analysis Cross Validation

229746_031.0_REP2004

Issue | 8 September 2017

Job number 255090

Arup bv
PO Box 57145
1040 BA
Amsterdam
The Netherlands
www.arup.com

ARUP

Contents

B2 Post-Test Refined Simulation List of Figures

Executive Summary

LNEC-BUILD-1 is a full scale building shake table test coordinated by the European Centre of Training and Research in Earthquake Engineering (Eucentre). This experiment is part of a large-scale testing campaign focused on studying the seismic behaviour of modern Dutch terraced houses. The specimen is the top portion of a two-storey masonry cavity wall system with reinforced concrete slabs and a timber roof [1]. The geometry and construction details resemble those of the top portion (i.e., above the first floor) of the full scale terraced house tested at Eucentre in 2015 (EUC-BUILD-1) [2].

The dynamic testing was carried out on the shake table in the Laboratório Nacional de Engenharia Civil (LNEC), which shook the structure in its longitudinal direction (i.e., the direction parallel to the front and back walls of the terraced house) and simultaneously in the vertical direction. The loading protocol consists of a series of horizontal and vertical earthquake records scaled to multiple levels of peak acceleration [1].

This report presents the results of four different modelling approaches used by Arup, Eucentre, the Delft University of Technology (TU Delft) and Modelling and Structural Analysis Konsulting (Mosayk) to predict the performance of the shake table test. The four Consultants used different analysis software: LS-DYNA, TreMuri, DIANA and Extreme Loading for Structures (ELS), respectively.

All Consultants performed a blind prediction before the experiment took place. Following the execution of the shake table test and distribution of laboratory results, the four Consultants then performed a post-test refined simulation of the test house, in which each team updated the models in order to address the limitations experienced during the blind prediction phase.

Following the blind prediction of LNEC-BUILD-1, all of the models had been updated based on the observed behaviour of the dynamic test specimen, leading to a greatly improved simulation (of the behaviour in comparison to the blind prediction models). The most influential changes that led to the improvement of the results are the following:

- Application of recorded input motions in lieu of the loading protocol that was provided prior to the execution of the laboratory test;
- Assigning weaker properties to the joint between second floor slab and longitudinal walls. It is not known whether the joint properties were inherently weak (as might be inferred from the construction method, but contradicts observations from EUC-BUILD1) or whether the observed weak behaviour was solely due to transportation damage;
- Assigning of masonry material properties with the latest masonry characterisation test results

These changes also led to a reduction in dispersion among the results simulated by the four Consultants, exemplifying the benefit of performing the blind and post-test refined prediction exercise in the increasing knowledge of failure mechanisms that can occur for this type of structure and on the extent of how different modelling assumptions can affect the governing behaviour captured by the numerical models.

The following lessons learnt and future recommendations are raised:

- All of the numerical models appear to be sensivitive to the input masonry material properties. Also, higher strength material properties do not necessarily indicate a more robust structure, nor vice-versa, because the failure mode may change to one that is less

(or more) ductile. Furthermore, the relative strengths of the different material properties may promote one failure mode or another. Thus, it is important to understand not only the variety of material property values that can exist over a wide range of test specimens and, moreover, in real buildings, but also the influence of the *combination* of material parameters on the global behaviour of the structure.

- Incorporating the actual condition of pertinent connections led to significant improvement in capturing the global behaviour exhibited in the laboratory test. Nevertheless, one can conclude that even with a dedicated laboratory test, the condition of a particular connection across a multitude of similarly constructed buildings can easily lie between a number of possible conditions. Thus, it is important to consider all viable conditions for critical connections when assessing the possible range of behaviour of structures.
- The studies that have been conducted so far through the cross-modelling validation exercise have not yet drawn significant attention to the effect of the vertical input motion on the behaviour of the LNEC-BUILD-1 specimen. Therefore, it is suggested that dedicated component-level tests are undertaken with and without vertical motion in order to study the effect.

1 Background and Introduction

Currently, limited data is available on the seismic response of various construction typologies specific to Dutch practice. Therefore, benchmarking and cross-validation against existing and newly planned experimental data are needed in order to study material characteristics and the response of components and full buildings in order to validate and continue to update the current standard-of-practice.

In order to fulfull this aim, a large scale testing campaign that focused on a wide-range investigation of the seismic behaviour of terraced houses was organised in 2015 by Nederlandse Aardolie Maatschappij (NAM) in collaboration with Arup, European Centre of Training and Research in Earthquake Engineering (Eucentre) and Delft University of Technology (TU Delft). The aim of the testing campaign was (1) to better understand the seismic behaviour of URM terraced houses and (2) to calibrate and validate a variety of numerical models and associated modelling and analysis approaches that can then be used to analyse different URM structures found in the region. The comprehensive testing campaign included material characterization tests, various wall pier component tests and a dynamic laboratory test of the full-scale Dutch terraced house replica identified as EUC-BUILD-1 (see Figure 1) [2].

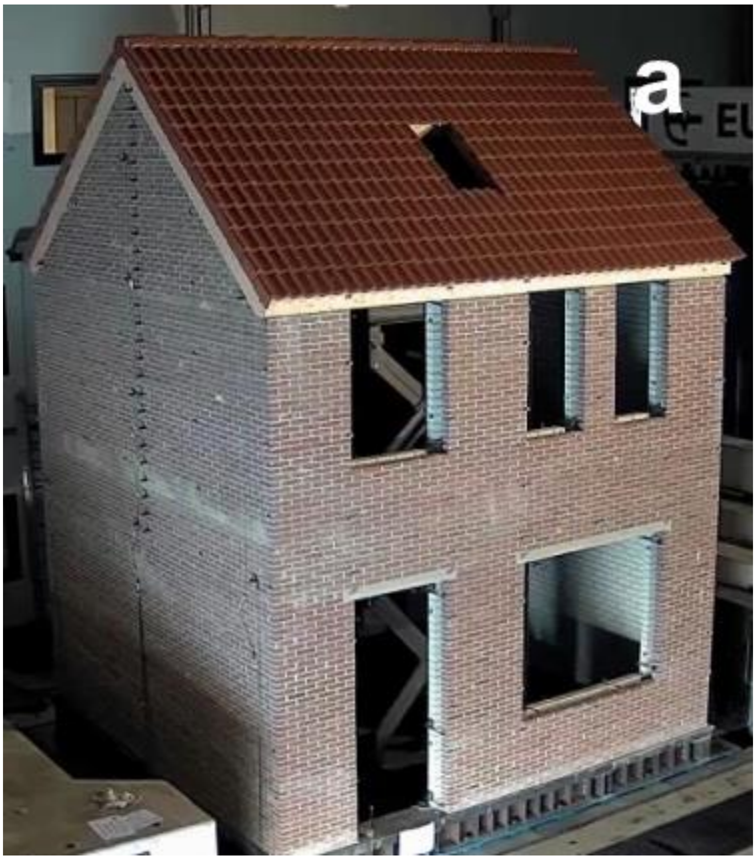


Figure 1 EUC-BUILD-1 built in Eucentre, Pavia, Italy [1]

The dynamic testing of EUC-BUILD-1 was carried out by Eucentre on the uniaxial shake table in the Eucentre laboratory in Pavia, Italy, which shook the specimen in its longitudinal direction (i.e., the direction parallel to the front and back walls of the terraced house). The loading protocol consisted of a series of earthquake records scaled to multiple levels of peak ground acceleration (PGA). The series of input records are based on two original records consistent with the seismic hazard in the field [2].

Arup, Eucentre and TU Delft participated in the cross-modelling validation exercise for this testing campaign, each using a different analysis software: LS-DYNA, TreMuri and DIANA, respectively. Once the models had been calibrated against the material characterization tests and wall pier component tests, all teams performed a blind prediction of the EUC-BUILD-1 test before the experiment took place. Following the execution of the shake table test, Arup, Eucentre and TU Delft then performed a post-test refined simulation of the test house that included refinements made to the models to address the limitations experienced in the blind predictions. This pre- and post-test prediction exercise was greatly beneficial in increasing the understanding of how to model such a structure in various analysis softwares in order to capture the observed behaviour [1].

Nevertheless, the knowledge-gaining process is a continuous one, and more information on the behaviour of URM terraced houses was still desired. EUC-BUILD-1 sustained the entire test series—up to a 0.31g PGA event (i.e., EQ2 scaled to 200%)—without collapse [2], so gaining knowledge on potential collapse mechanisms for this particular type of structure was one of the areas that required further study. As a result, the LNEC-BUILD-1 testing campaign was organized with the main motivations being the study of the various damage limitation states up to collapse, as well as the study of potential failure mechanisms of modern Dutch terraced houses. The specimen was designed as the top portion of a two-storey masonry cavity wall terraced house, with geometry and construction details resembling those of the top portion (i.e., above the first floor) of EUC-BUILD-1 (see Figure 2).

Figure 2 LNEC-BUILD-1 built in LNEC, Lisbon, Portugal [1]

This report presents a description of the LNEC-BUILD-1 test program and summarises the full cross-modelling validation process that was undertaken by four Consultants. The four Consultants include Arup, Eucentre and TU Delft, as in previous years, with the addition of Modelling and Structural Analysis Konsulting (Mosayk). The four Consultants used different analysis software: LS-DYNA, TreMuri, DIANA and Extreme Loading for Structures (ELS), respectively.

Following the description of the laboratory test program, this report presents blind predictions produced by the four Consultants and a comparison between the seismic behavior captured by the blind predictions and the behavior exhibited in the laboratory test. This is followed by a presentation of the refinements made to the models based on these comparisons, which produced improved predictions of the structure's seismic behaviour. Final conclusions and further recommendations are subsequently provided.

The performance of the numerical model and comparison against the laboratory test is evaluated in terms of force vs. displacement hysteresis loops, acceleration vs. drift incremental dynamic analysis plots and damage plots.

2 Laboratory Test Program

LNEC-BUILD-1 is the full scale building shake table test coordinated by Eucentre in May 2017 in the Laboratório Nacional de Engenharia Civil (LNEC). This experiment is part of an ongoing large-scale testing campaign focused on studying the seismic behaviour of modern Dutch terraced houses, which was first a focus of study in the testing campaign carried out at Eucentre in 2015 [2]. Two of the main purposes of this test included the investigation of potential collapse mechanisms for this particular type of structure and the cross-modelling validation of a variety of numerical models and associated modelling and analysis approaches that can be used to analyse different URM structures found in the Groningen region.

The specimen information (Section 2.1), test set-up and execution (Section 2.2) and summary of laboratory test results (Section 2.3) are provided in the subsequent subsections below.

2.1 Specimen Information

The design of LNEC-BUILD-1 was based on the top portion of a typical Dutch terraced house, which consists of an unreinforced masonry cavity wall system with reinforced concrete slabs and a timber roof. The dimensions of the specimen are 5.82 m in the longitudinal direction and 5.46 m in the transverse direction. The height of the specimen is 4.93 m.

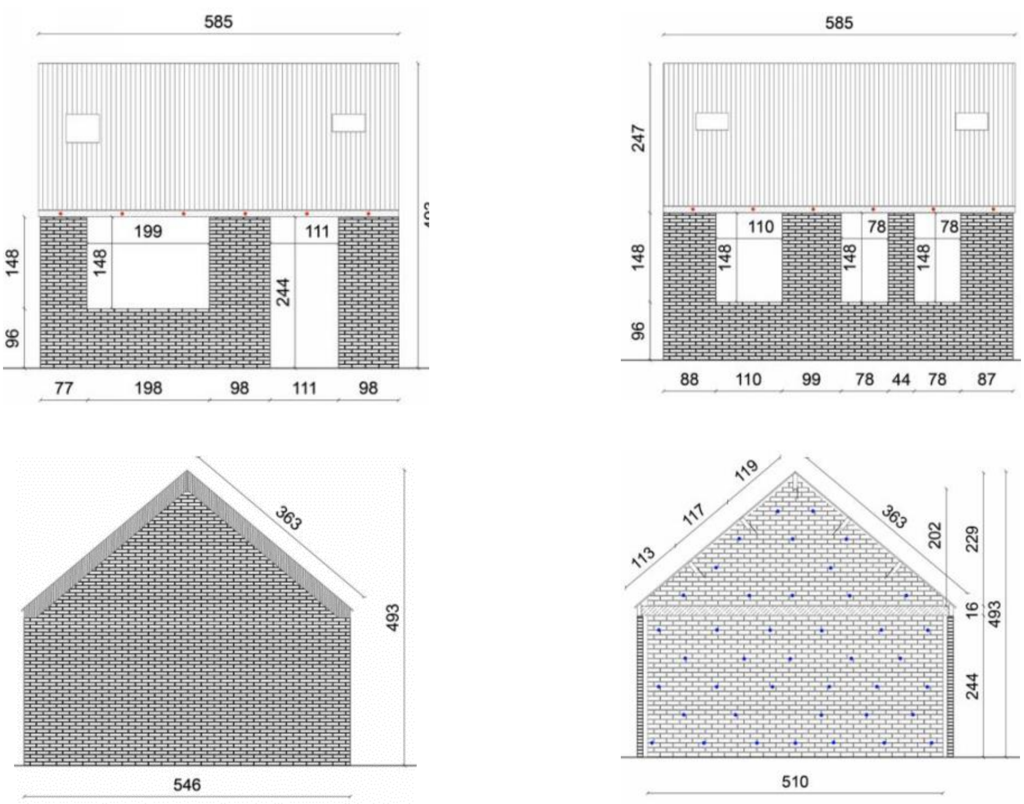


Figure 3 Elevation views of LNEC-BUILD-1 test house: front wall facade (top left), back wall facade (top right), end wall facade (bottom left), and party wall inner leaf (bottom right) [1]

Because of the specimens relation to EUC-BUILD-1, unless otherwise stated the nomenclature presented in Figure 4 will be used through the report.

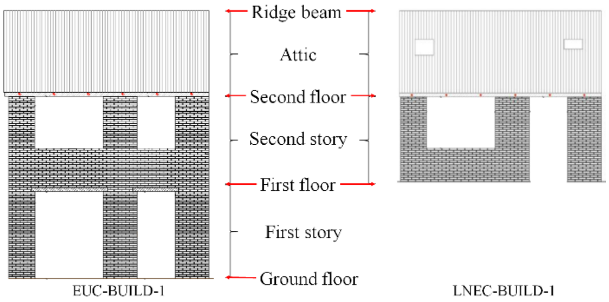


Figure 4 Nomenclature used throughout report

The inner leaf of the cavity wall was constructed of calcium silicate (CaSi) bricks. The outer leaf, which was located along only three facades in order to replicate a single unit test house at the end of a block, was constructed of perforated clay bricks. Each leaf was roughly 100 mm thick. Both the inner and outer leaves were constructed with the units laid in a running bond pattern, and this bond pattern was continuous at the corners such that orthogonal walls were interlocked to one another. The gap between the leaves was approximately 80 mm. As this structure had been designed with typical details found in terraced houses in the region, only the inner leaves in the transverse direction were load-bearing; the outer leaves did not contribute to the dominant gravity system. The transverse walls were built up to roof level, forming triangular gable walls above the second floor level.

A series of steel ties that are 3.1 mm in diameter connected the two leaves.

The connection designs took into account the detailing that was common in the Groningen region in the late 1960s. The concrete second floor was fully supported by the inner leaves along the transverse walls. After the floor was placed and deflected under gravity loading, the gap between the top of the longitudinal inner leaves and the bottom surface of the second floor was filled with mortar (see Figure 5).

The roof consisted of 18 mm thick timber tongue-and-groove planks that supported clay roof tiles, which are common in Dutch terraced house construction. The timber planks were nailed to timber purlins, which in turn spanned in the longitudinal direction from gable wall-to-gable wall. The ends of the timber planks were nailed to a timber beam, which was connected to the edge face of the concrete second floor via post-installed threaded bars along the longitudinal facades of the structure. The gap between the top of the longitudinal outer leaves and the bottom surface of the timber beam was also filled with mortar after the deflection of the second floor (see Figure 5).

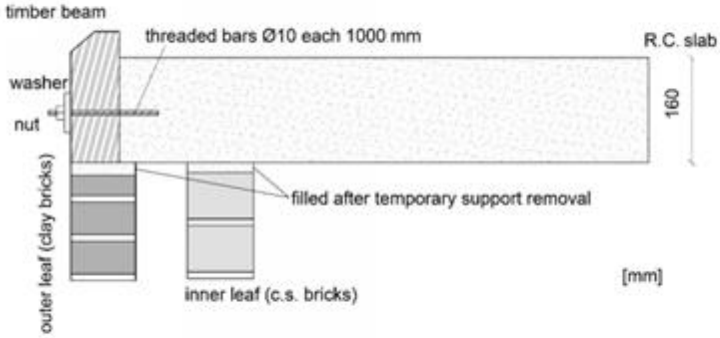


Figure 5 Construction detail of connection between the second floor slab and the longitudinal walls [1]

Material tests were performed by Eucentre on calcium silicate and clay masonry samples in order to characterise the masonry material used to construct the test specimen. The following table shows the results of the material tests.

Table 1 Latest mechanical characteristics of masonry material provided by Eucentre [1]

Symbol	Material property [units]	Average value for calcium silicate	Average value for clay
ρ	Mass density [kg/m^3]	1800	1839
E_{m-1}	Masonry Young's modulus [MPa] (33% f_m)	7955	13118
f_m	Masonry compressive strength [MPa]	9.80	19.39
f_w	Flexural bond strength of mortar joints [MPa]	0.36	0.19
f_{v0}	Masonry (bed joint) initial shear strength (cohesion) [MPa]	0.45	0.41
μ	Masonry (bed joint) shear friction coefficient	0.48	0.75

2.2 Test Set-Up & Execution

The test specimen was built on a mixed steel and reinforced concrete foundation and was afterwards transported to the shake table. The shake table is able to translate in two directions—a single horizontal direction and vertical direction. The orientation of the specimen on the shake table was such that it was shaken horizontally in its longitudinal direction, as was also done for the EUC-BUILD-1 specimen (see Figure 6).

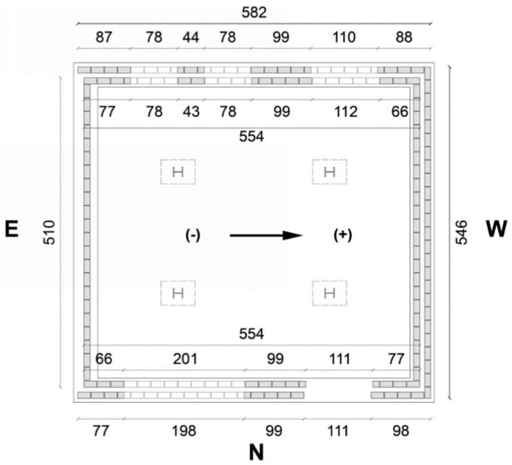


Figure 6 Plan view of the LNEC shake table, with the arrow indicating the horizontal direction of the shaking table motion [1]

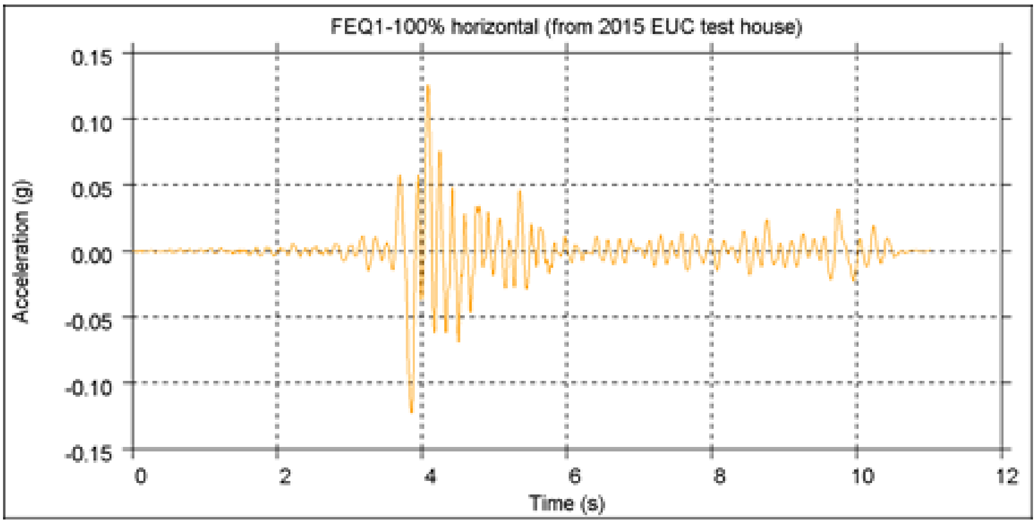
The loading protocol consisted of a series of earthquake records scaled to multiple levels of peak acceleration. The two original records that had been previously selected for the test series of the EUC-BUILD-1 test in 2015 were used for the LNEC-BUILD-1 test in order to allow for a level of comparison between the two experiments [1].

The horizontal loading protocol consisted of the measured first floor accelerations from the following ground motions employed in the testing of EUC-BUILD-1: EQ1-100%, EQ1-150%, EQ2-100%, EQ2-150% and EQ2-200%. These records were scaled in order to produce the entire horizontal loading protocol [1].

The vertical loading protocol consisted of vertical ground accelerations from the same records as the selected horizontal accelerations (at 100%), synchronized, and scaled to the same levels of intensity as the ground horizontal accelerations [1].

The horizontal and vertical accelerations were applied simultaneously.

As an example, the original two sets of signals (at 100%) are illustrated in Figure 7 and Figure 8. Regarding the horizontal records, please note that FEQ refers to first floor accelerations, as opposed to ground accelerations.



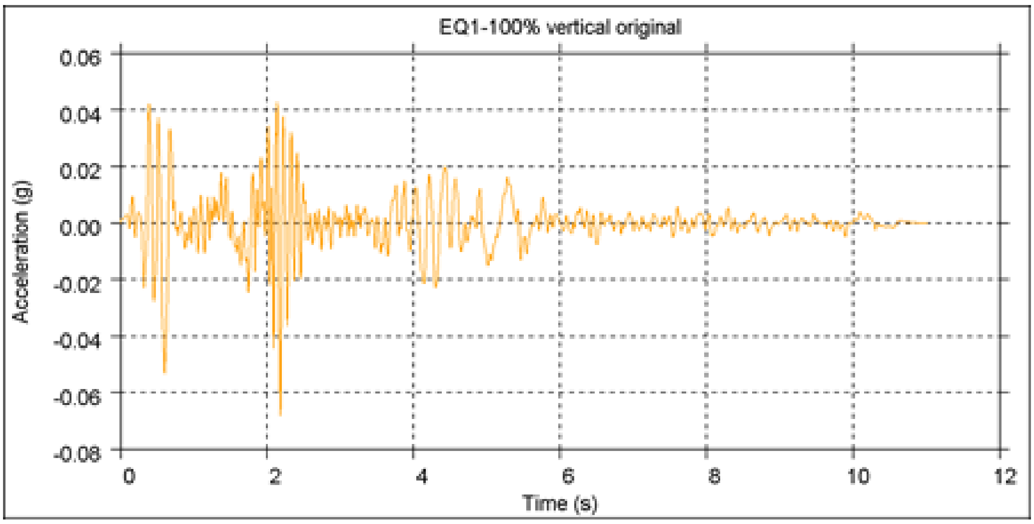


Figure 7 FEQ1-100% horizontal acceleration time history (top) and EQ1-100% vertical acceleration time history (bottom)

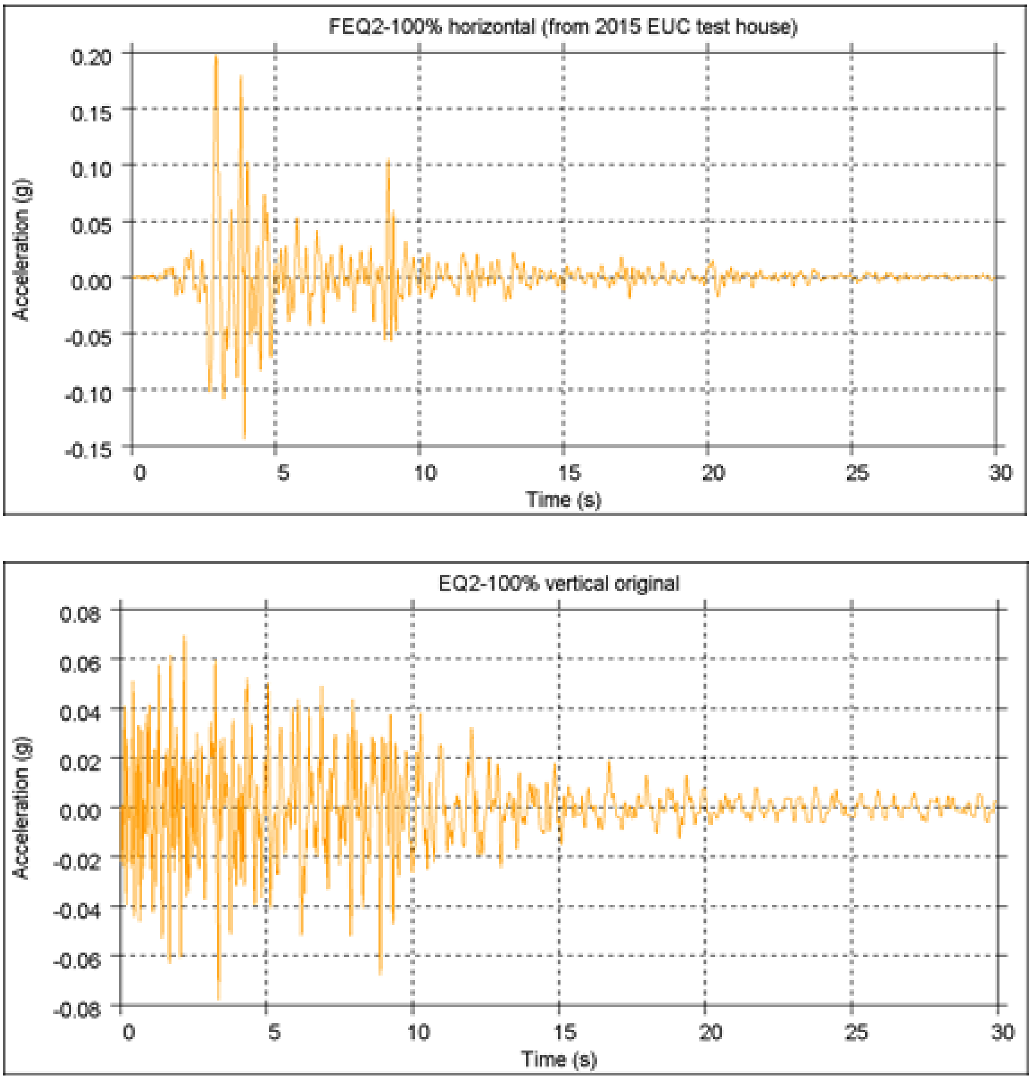


Figure 8 FEQ2-100% horizontal acceleration time history (top) and EQ2-100% vertical acceleration time history (bottom)

The test sequence applied to LNEC-BUILD-1 is shown in Table 2 below.

Table 2 Summary of applied test sequence in terms of PFA (horizontal direction) and PGA (vertical direction) [1]

Test Name	**PFA horizontal [g]**	**PGA vertical [g]**
(F)EQ1-50%	0.06	0.04
(F)EQ1-100%	0.12	0.08
(F)EQ1-150%	0.15	0.12
(F)EQ2-50%-C	0.14	0.05
(F)EQ2-50%	0.10	0.07
(F)EQ2-100%	0.22	0.10
(F)EQ2-150%	0.38	0.21
(F)EQ2-60%-C	0.13	0.05
(F)EQ2-120%-C	0.30	0.13
(F)EQ2-200%	0.39	0.18
(F)EQ2-300%	0.63	0.34

As reported by Eucentre in [1], the foundation elements deflected during the transportation of the structure to the shake table. As a result, the structure suffered slight damage prior to the execution of the test. Sketches provided by Eucentre that illustrate this initial damage are reproduced in Figure 9 below.

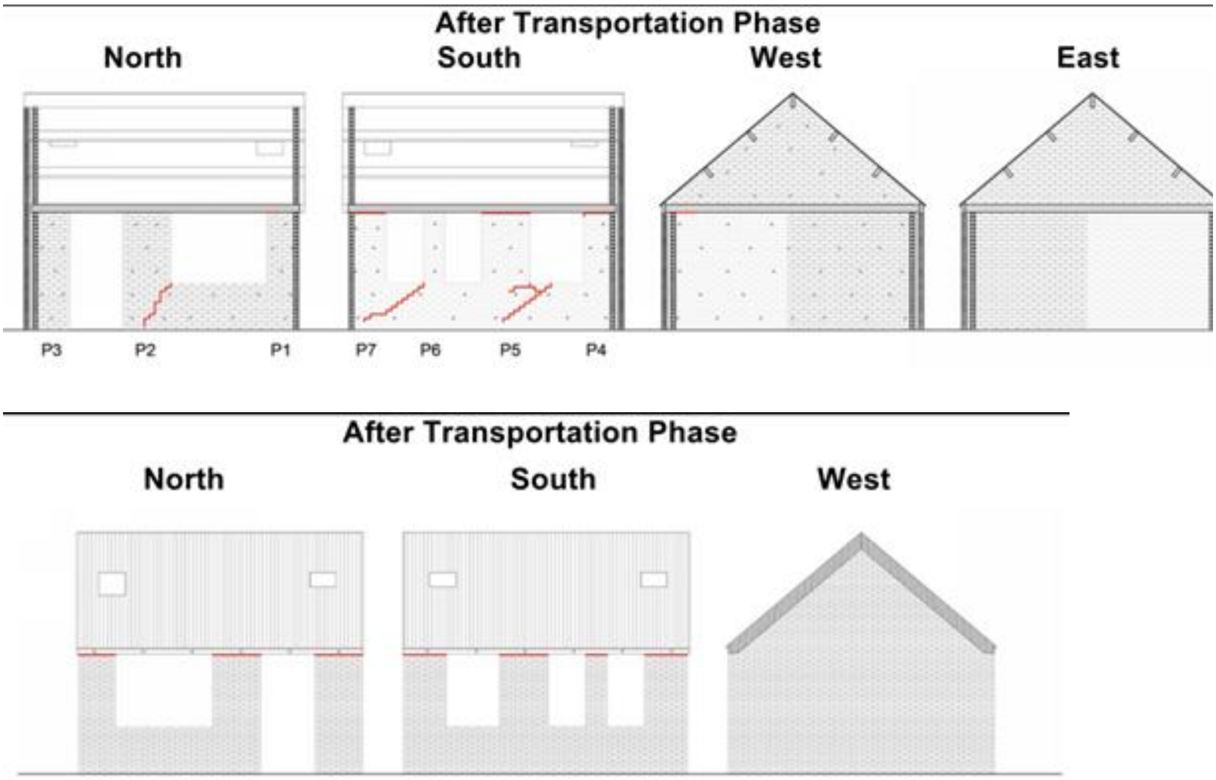


Figure 9 Crack pattern in the inner calcium silicate leaf (top) and the outer clay leaf (bottom) after transportation phase [1]

2.3 Summary of Laboratory Results

The first significant sign of structural damage in the LNEC-BUILD-1 test specimen, in addition to the damage reported during the transportation phase, was characterized by rocking of the longitudinal piers, which occurred during EQ1-150% (see Figure 10).

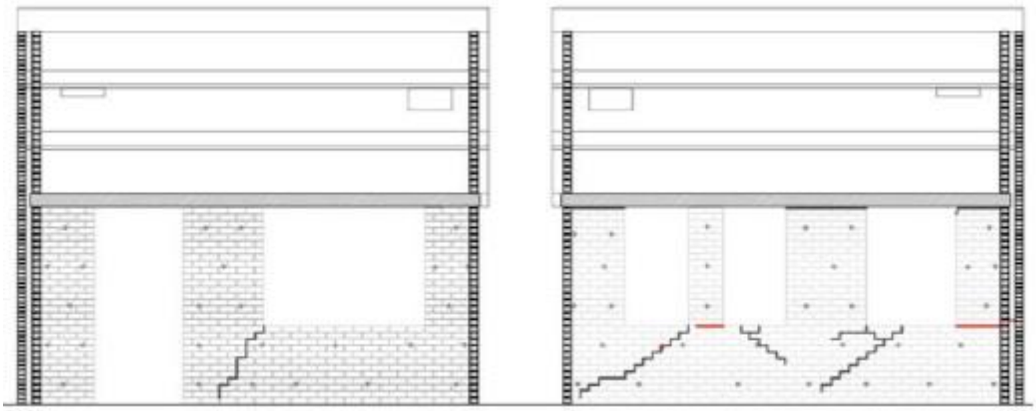


Figure 10 Damage reported in front/back inner leaves after the application of EQ1-150% [1]

During EQ2-100 and EQ2-150%, pre-existing cracks continued to open and propagate through the structure. During EQ2-150%, the end wall experienced out-of-plane damage (most likely due to flange effect). Based on the instrumentation data, sliding of the floor slab relative to the piers was also observed during this level of motion.

The application of EQ2-200% led to an increase in the amount of damage of the structure. Nevertheless, the structure experienced interstorey drifts less than or equal to 1% and reached a stable position by the end of the motion. Up through this motion, the specimen generally exhibited a larger amount of drift in the attic storey in comparison to the second storey (see Figure 11).

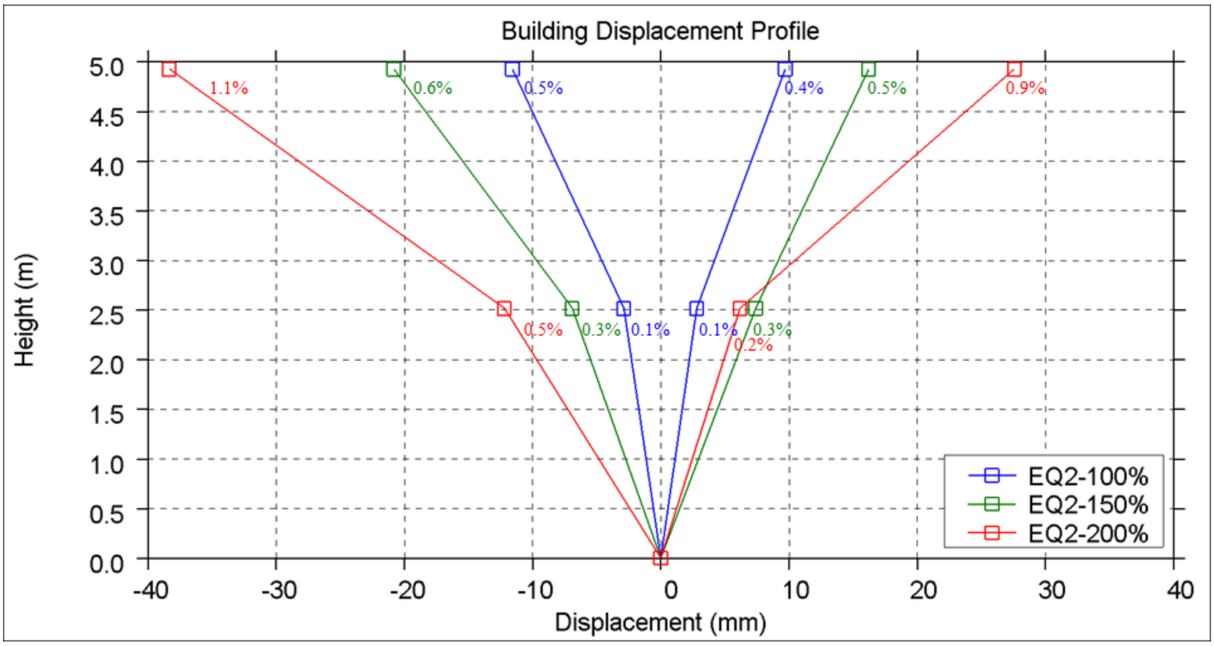


Figure 11 Building displacement profile graph, which plots the positive and negative direction displacement envelopes of the second floor and ridge relative to the first floor [mm] versus building height [m], where 0m is the base of LNEC-BUILD-1. This graph shows the evolution of the displacements of LNEC-BUILD-1 from EQ2-100% to EQ2-150% to EQ2-200%. Also displayed are interstorey drift values based on vertical storey heights (i.e., 2520 mm for second storey, 2410 mm for attic)

During the application of EQ2-300%, the interstorey drift of the second floor exceeded 4% (see Figure 12, red box) and eventually out-of-plane collapse of the party wall occurred. This partial collapse was caused by the rocking of the longitudinal piers, which uplifted the floor slab enough to disengage from the top of the transverse party wall. The transverse wall, left with no constraint at the top, collapsed out of plane due to its own inertia during the rest of the applied motion. The longitudinal inner leaf piers also experienced a large amount of damage during this level of motion, and the slab was left supported by the outer leaf longitudinal piers and connecting outer leaf end wall, which left the specimen on the verge of complete collapse (see Figure 13 and Figure 14).

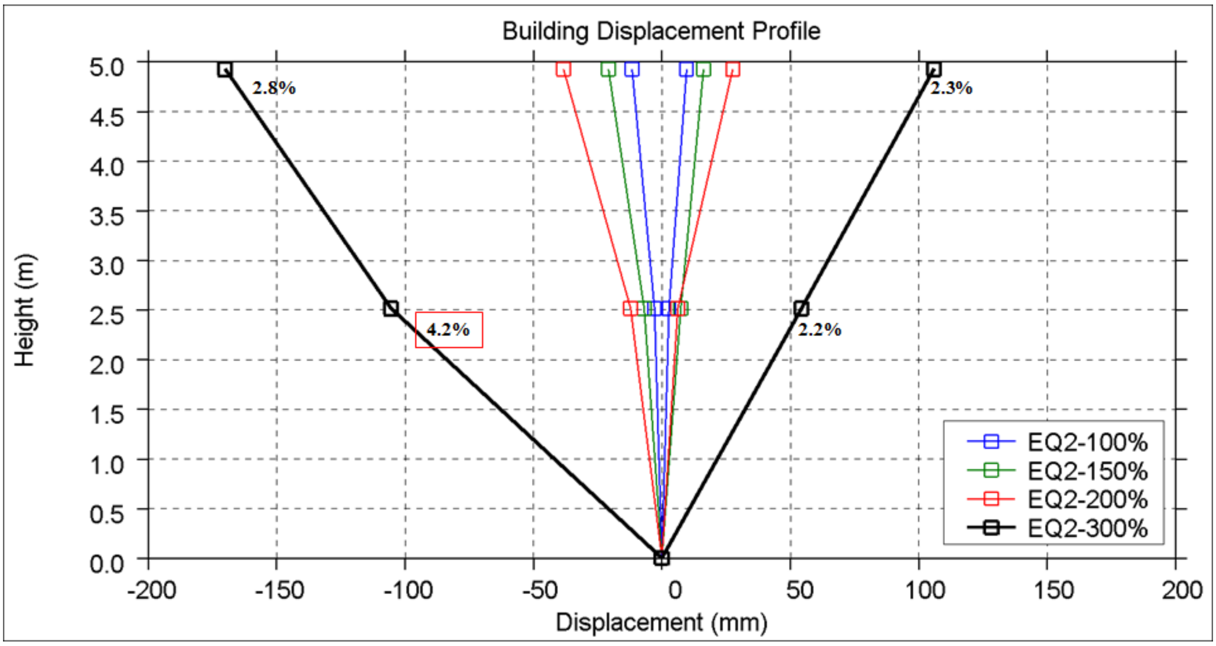


Figure 12 Building displacement profile graph showing the evolution of the level displacements of LNEC-BUILD-1 from EQ2-100% through to EQ2-300%. Also displayed are interstorey drift values based on vertical storey heights (i.e., 2520 mm for second storey, 2410 mm for attic) for EQ2-300% only.

Figure 13 Photo of specimen at the end of EQ2-300%

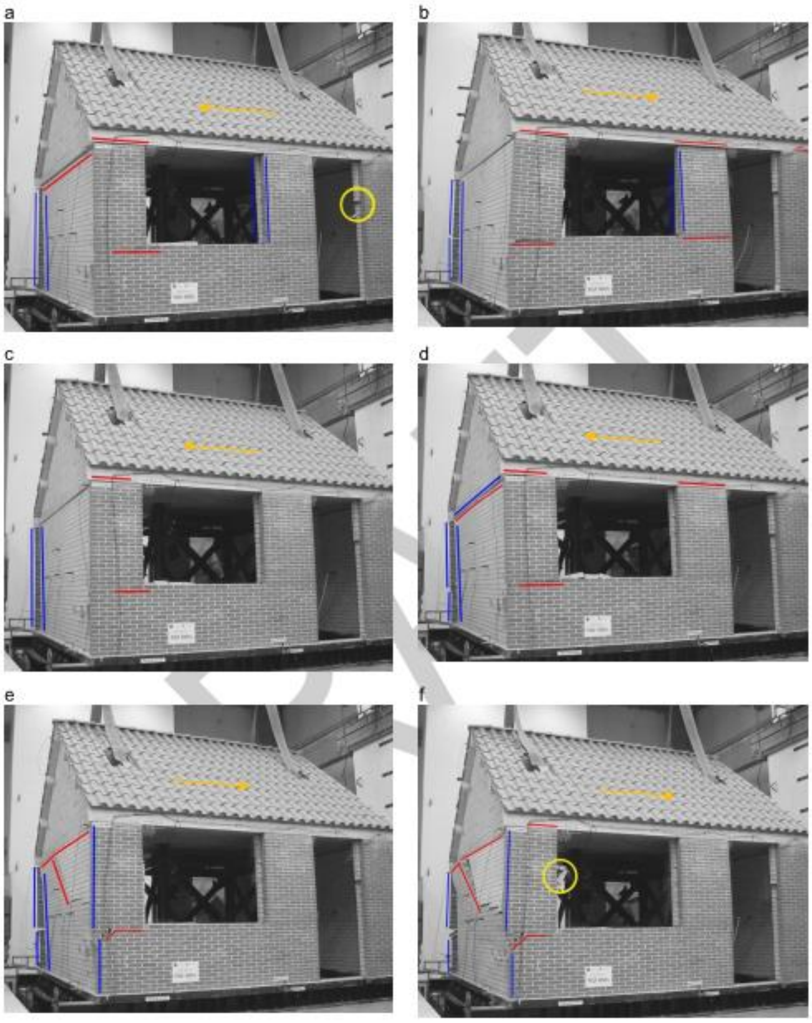


Figure 14 Photos of collapse mechanism during EQ2-300% [1]

The LNEC-BUILD-1 dynamic test was designed and conducted in a similar fashion to the EUC-BUILD-1 dynamic test up to the input motion of EQ2-200%—the final motion applied to EUC-BUILD-1. Although the material properties, wall-opening configurations, and bottom boundary conditions of the clay outer leaf facades were different between the two specimens, the test protocols of the two were essentially alike. Nevertheless, it is important to note that disparity between the results of two similar experiments is always expected because of the inherent variability that exists in many aspects of this type of test, including the properties of the shake tables, use of masonry material, curing conditions, manner of construction, laborers etc.

Figure 15, Figure 16 and Figure 17 below show the incremental dynamic analysis (IDA) graphs that plot the second storey interstorey drift ratio (IDR), attic IDR and ridge displacement, respectively, against the peak horizontal first floor accelerations for each test over the duration of the loading protocol up to input motion EQ2-200%. This is to illustrate the inherent disparity between the results for the two dynamic tests.

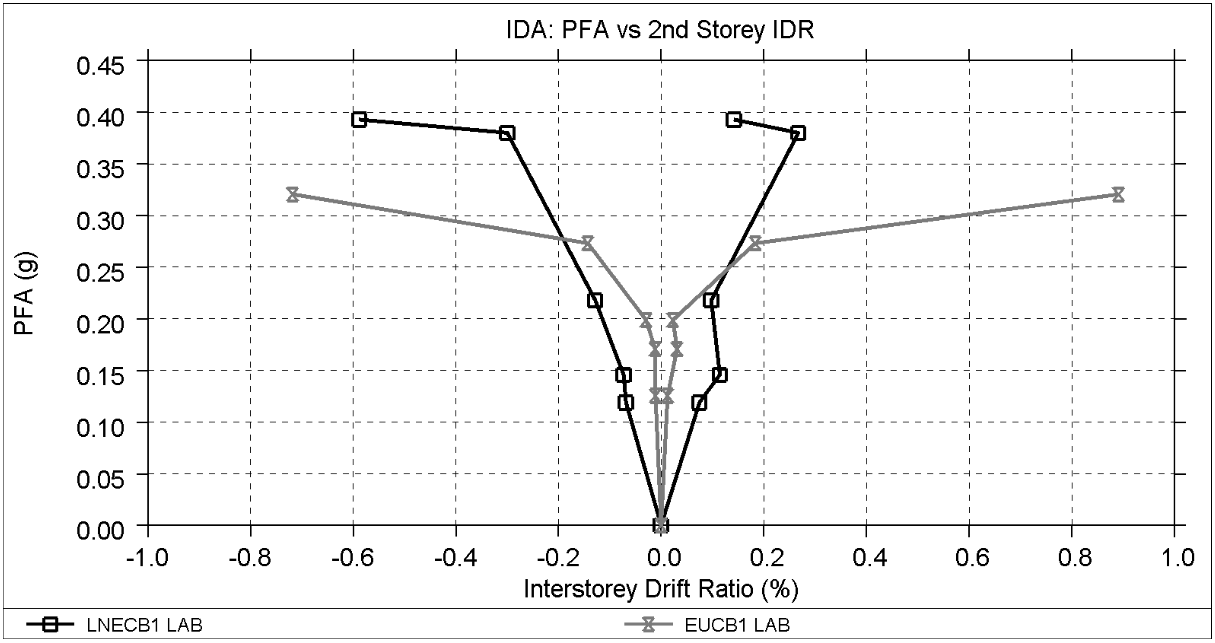


Figure 15 IDA: PFA vs. second storey IDR plots the PFA [g] of the first floor vs. the positive and negative direction IDR envelopes of the second storey [%] for each test. Results from the LNEC-BUILD-1 lab test is plotted against the EUC-BUILD-1 lab result up to input motion EQ2-200%.

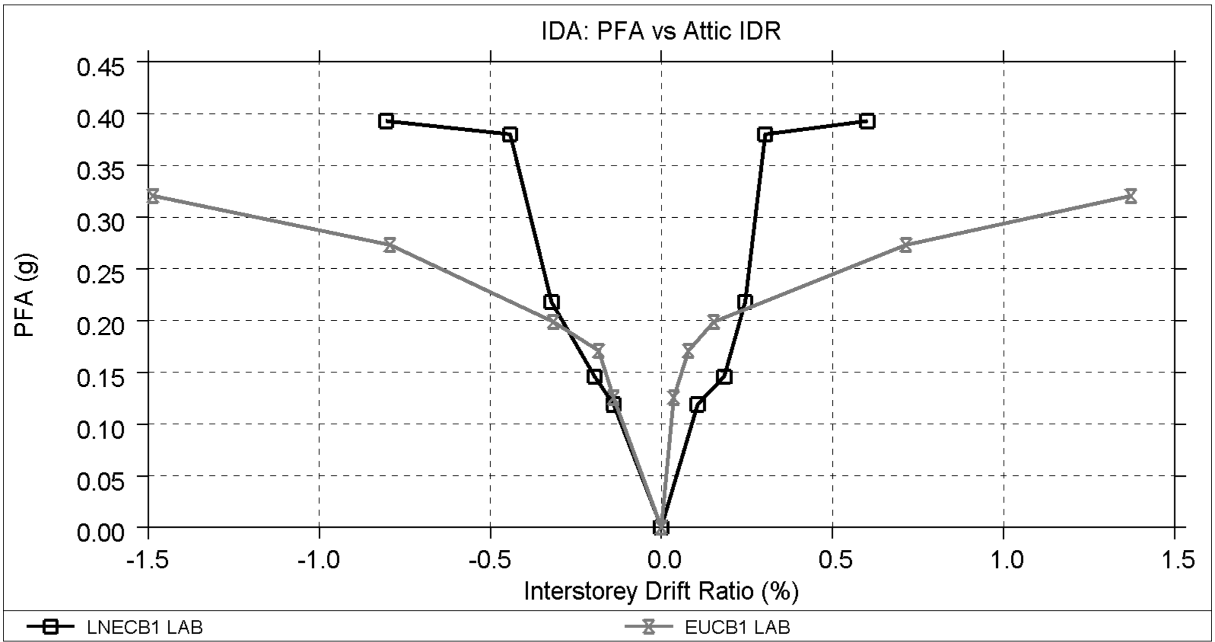


Figure 16 IDA: PFA vs. attic IDR plots the PFA [g] of the first floor vs. the positive and negative direction IDR envelopes of the attic storey [%] for each test. Results from the LNEC-BUILD-1 lab test is plotted against the EUC-BUILD-1 lab result up to input motion EQ2-200%.

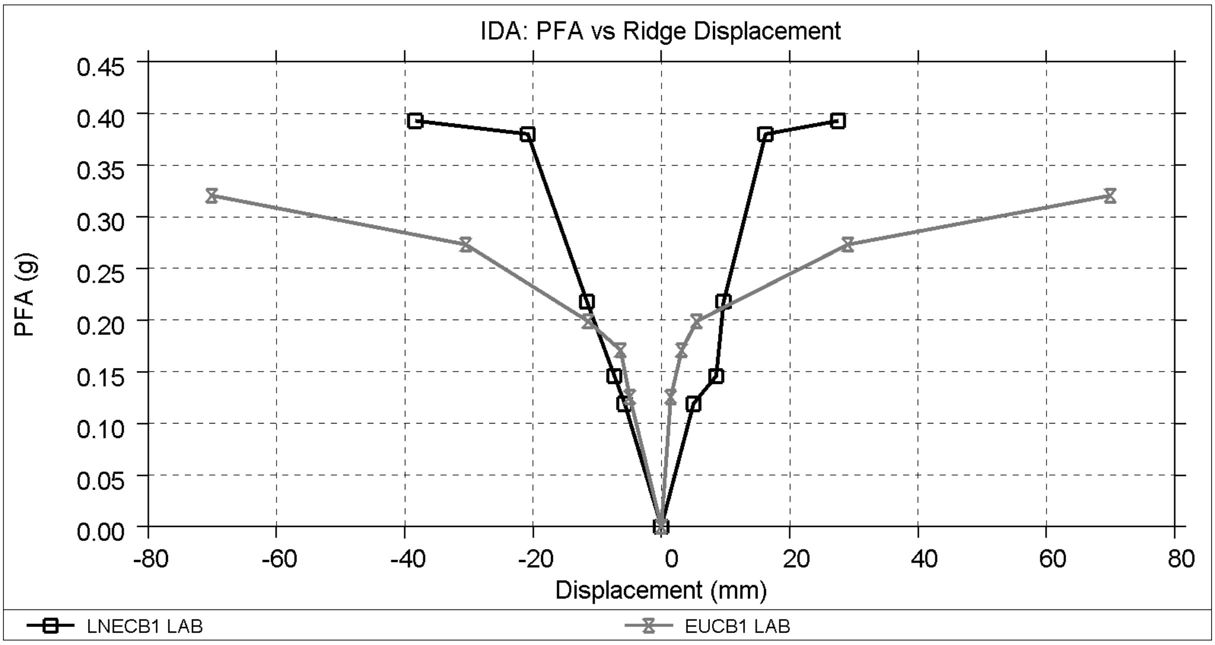


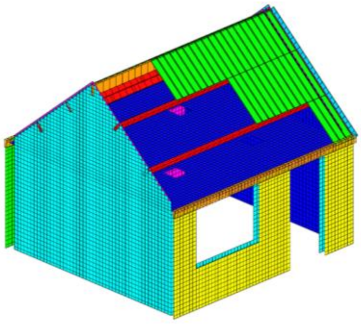
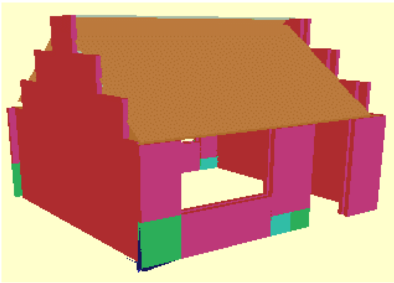
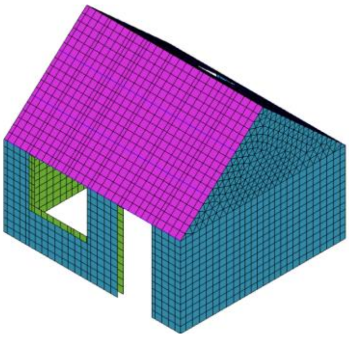
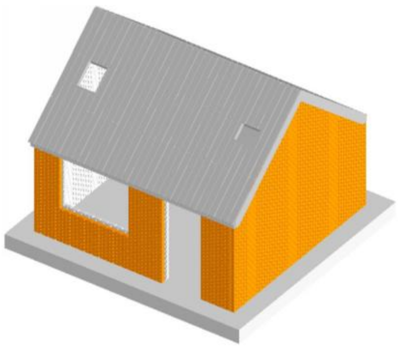
Figure 17 PFA vs. ridge displacement plots the PFA [g] of the first floor vs. the positive and negative direction displacement envelopes of the ridge beam relative to the first floor [mm] for each test. Results from the LNEC-BUILD-1 lab test is plotted against the EUC-BUILD-1 lab result up to input motion EQ2-200%.

3 Cross-Modelling Exercise Overview

3.1 Numerical Modelling – Consultants and Software

Arup, Eucentre, TU Delft and Mosayk participated in the cross-modelling validation exercise for the LNEC-BUILD-1 testing campaign. Each Consultant used a different analysis software to model the LNEC-BUILD-1 test specimen. A summary table describing each software and general modelling approach is provided below.

Table 3 Numerical modelling consultants and software summary table

Arup	**Eucentre**
Software: LS-DYNA Explicit time integration scheme Finite element modelling. Masonry modelled using fully integrated shell elements with damage lumped at each integration point and crack plane directions are pre-defined to model mortar bonds. 	Software: TreMuri Implicit time integration scheme Equivalent-frame modelling strategy based on the effective non-linear macro-element modelling approach 
TU Delft	**Mosayk**
Software: DIANA Implicit time integration scheme Finite element modelling. Masonry modelled using shell elements with the Total Strain Rotating Crack Model (TSRCM)—derived for initially isotropic materials with secant-based unloading/reloading curves 	Software: ELS Implicit time integration scheme Applied element method—micro-element modelling. Masonry modelled using small rigid units connected by linear and nonlinear springs. 

3.2 Procedure of Blind Prediction and Post-Test Refined Simulations

All Consultants performed a blind prediction before the experiment took place by simulating the shake table test of the LNEC-BUILD-1 specimen according to the loading protocol provided by Eucentre [3] using the models presented in Table 3. Blind prediction modelling assumptions made by the four Consultant were based on the specimen and test set-up information received by Eucentre prior to the execution of the test [3].

Following the execution of the shake table test and distribution of laboratory results, the four Consultants compared their own results against the experiment results. They each then performed a post-test refined simulation, in which each team incorporated refinements in the models that aimed to address the limitations experienced during the bind prediction phase.

The summary results of both the blind predictions and post-test refined simulations produced by each Consultant are compared to one another in the following sections in order to determine the level of dispersion among the models in comparison to the laboratory results and how much this dispersion is improved due to the post-test refinements made after the laboratory results were shared.

4 Blind Predictions

4.1 Blind Prediction Models

As introduced in Section 3, each consultant created a numerical model of the LNEC-BUILD-1 specimen in their individual software package (see Table 3). Blind prediction modelling assumptions made by the four Consultant can be found in Appendix A1.

4.2 Summary of Results and Comparison against Lab

This section covers the blind prediction results for each consultant in comparison to the lab results. For more information on the modelling approach adopted by each consultant, please refer to the individual consultant's blind prediction report [4] [5] [6] [7].

Observations on the comparisons are highlighted below.

With the exception of Eucentre, none of the Consultants predicted clear rocking behaviour as early as EQ2-100%.

All of the Consultants predicted a larger amount of drift in the attic storey in comparison to the second storey up through EQ2-200%, which is consistent with the LNEC-BUILD-1 laboratory result (see Figure 18).

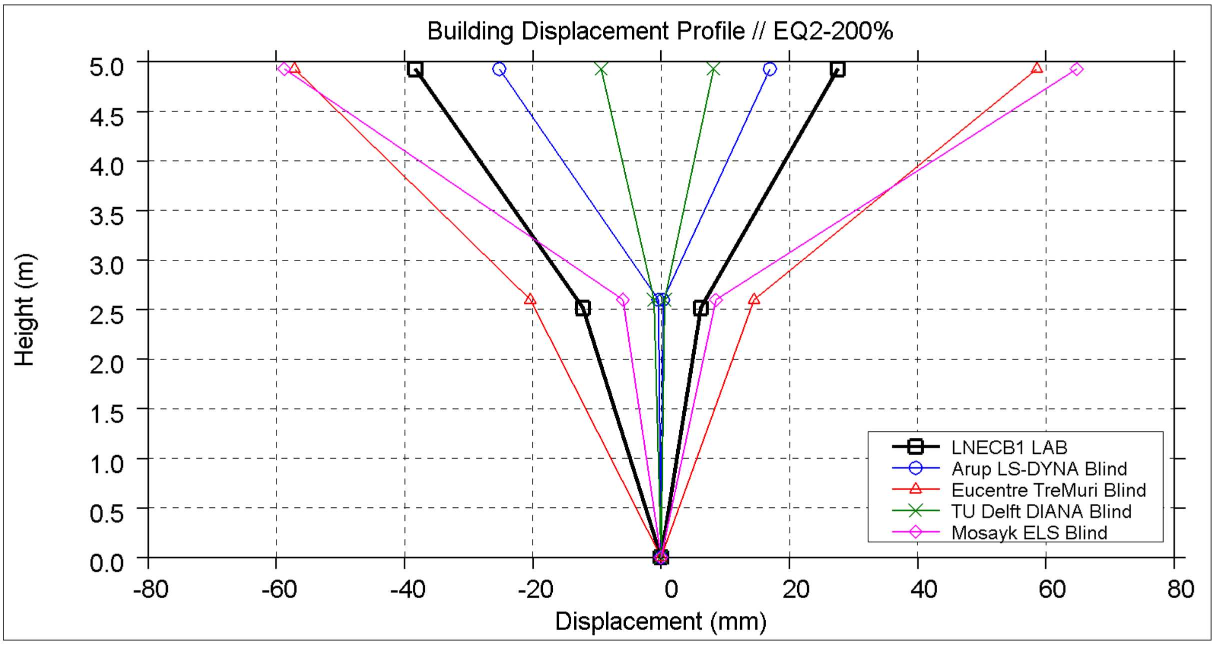
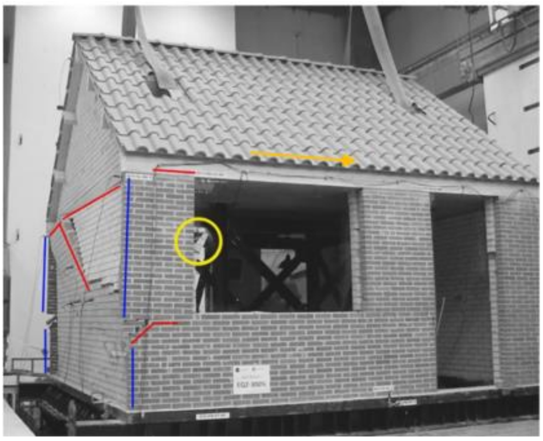


Figure 18 Building displacement profile graph of the LNEC-BUILD-1 lab results and the Consultants' blind prediction results for EQ2-200%.

None of the consultants predicted the out-of-plane collapse of the party wall that occurred during the application of EQ2-300% due to the uplift of the slab and resulting loss of constraint at the top of the wall. Rather, most Consultants predicted collapse of the gables or the roof at levels of input motion different from one another, and one did not predict collapse at all (see Figure 19).

Lab


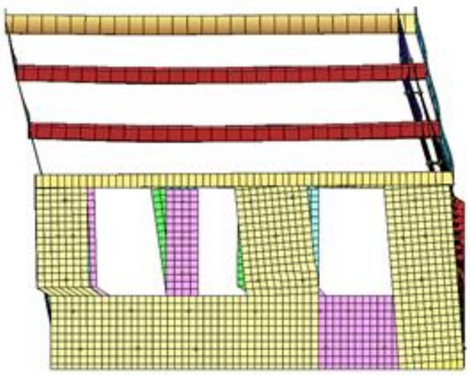
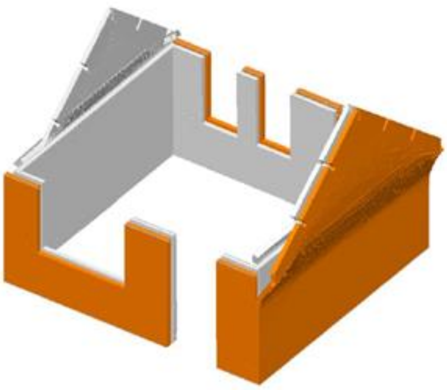
Arup / LS-DYNA	Eucentre / TreMuri
 Magnified 5x	NA
TU Delft / DIANA	**Mosayk /ELS**
NA (no collapse)	 Magnified 2x

Figure 19 Deflected shape at moment of collapse of the LNEC-BUILD-1 lab specimen (top) and the four Consultants' blind prediction numerical models (if applicable)

Table 4 below provides a summary of the numerical results of each Consultant's blind prediction analysis in comparison to the LNEC-BUILD-1 laboratory results.

Table 4 Blind prediction results summary table in comparison to the LNEC-BUILD-1 lab results

	LNEC Lab	**Arup**	**Eucentre**	**TU Delft**	**Mosayk**
Software	---	LS-DYNA	TreMuri	DIANA	ELS
Collapse mechanism	Out-of-plane failure of CaSi [transverse] party wall	Collapse of gables due to out-of-plane rocking	Collapse of roof indicated by relative roof displacement > 100 mm	No collapse	Collapse of gables due to out-of-plane sliding at gable base/top of transverse walls
Collapse Horizontal input motion (PFA)	EQ2-300% (0.63g)	EQ2-400% (0.66g)	EQ2-400% (0.61g)	--- ≥ EQ2-600% (1.03g)	EQ2-250% (0.40g)
Peak floor drift (%) [1]	4.4	0.03[3]	1.4[4]	≥ 0.6	0.9
Peak roof drift (%) [2]	2.0	2.2[3]	2.6[4]	≥ 0.8	3.15
Peak ridge displacement (mm)	170	78[3]	108[4]	≥ 37	124
Base shear (kN)	160	145[3]	124[4]	≥ 188	105

[1] Floor interstorey drift ratio = second floor horizontal displacement relative to the first floor divided by the storey height (2520 mm). Peak drift occurs during collapse input motion unless noted otherwise

[2] Roof interstorey drift ratio = ridge horizontal displacement relative to the second floor divided by the inclined roof length (3500 mm). Peak drift occurs during collapse input motion unless noted otherwise

[3] Peak value occurs at EQ2-300%

[4] Since simulated collapse occurs not long after the start of EQ2-400%, this value reflects results up to EQ2-300% only

It is worthwile to note that while the blind prediction results do not seem extremely widespread, there is some dispersion among the results as well as in comparison to the LNEC-BUILD-1 laboratory results. This is evident in the incremental dynamic analysis (IDA) graphs that plot the second storey interstorey drift ratio (IDR), attic IDR and ridge displacement against the peak horizontal floor accelerations for each test over the duration of the loading protocol (see Figure 20, Figure 21 and Figure 22, respectively).

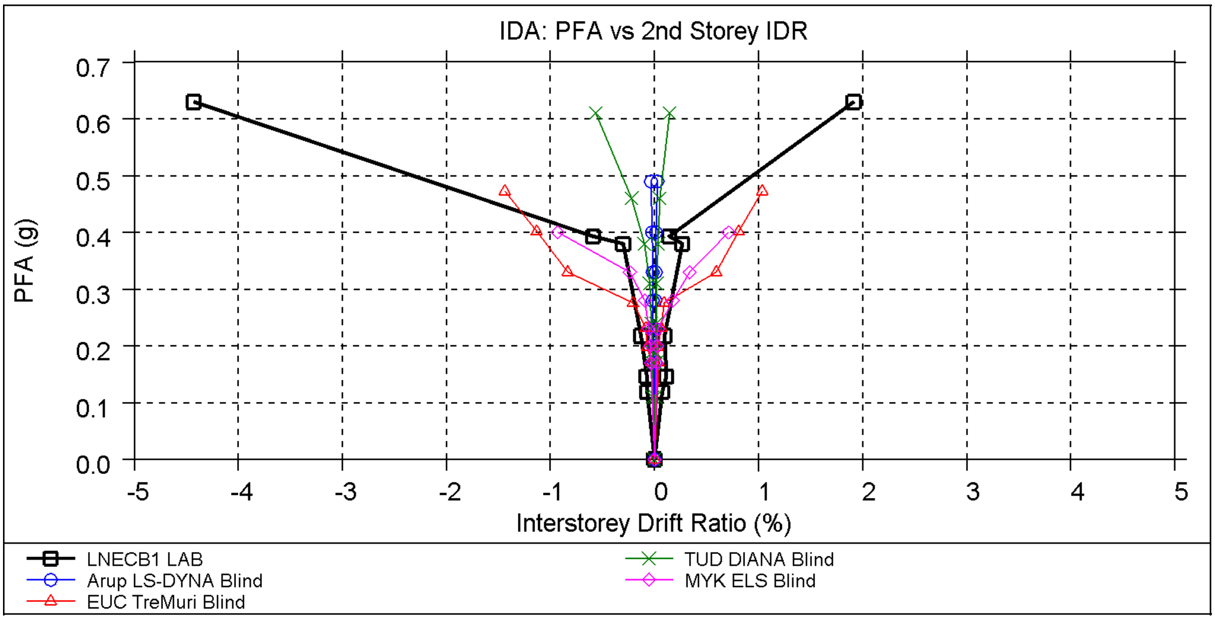


Figure 20 IDA: PFA vs. second storey IDR plots the PFA [g] of the first floor vs. the positive and negative direction IDR envelopes of the second storey [%] for each test. Results from the Consultants' blind predictions are plotted against the LNEC-BUILD-1 lab result.

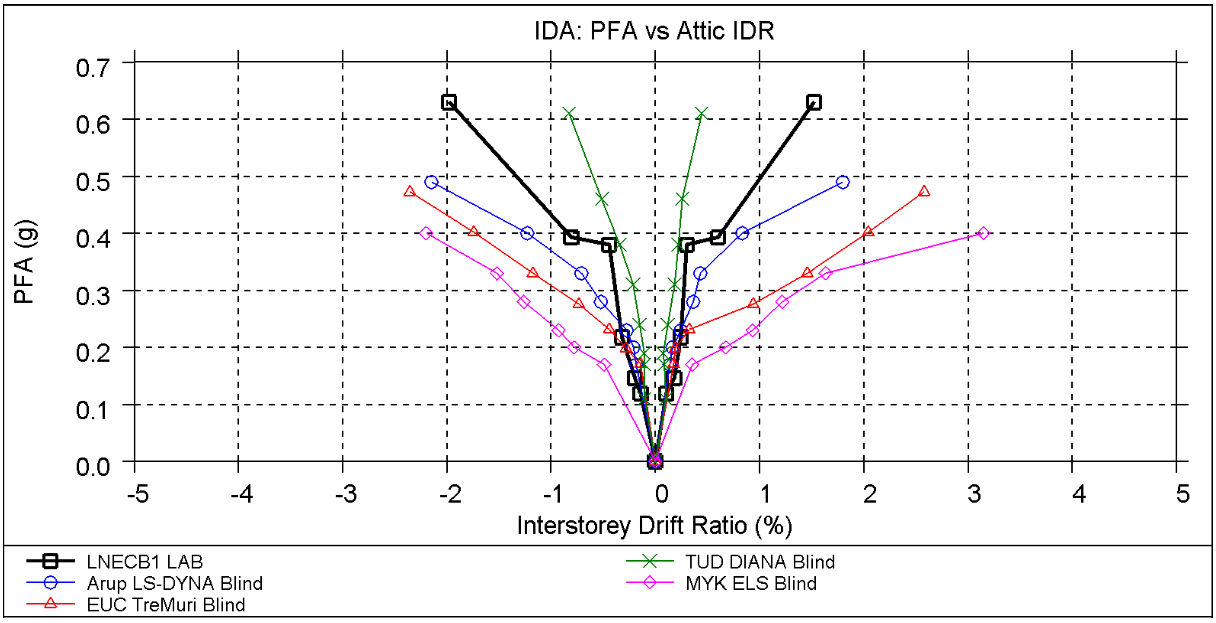


Figure 21 IDA: PFA vs. attic IDR plots the PFA [g] of the first floor vs. the positive and negative direction IDR envelopes of the attic storey [%] for each test. Results from the Consultants' blind predictions are plotted against the LNEC-BUILD-1 lab result.

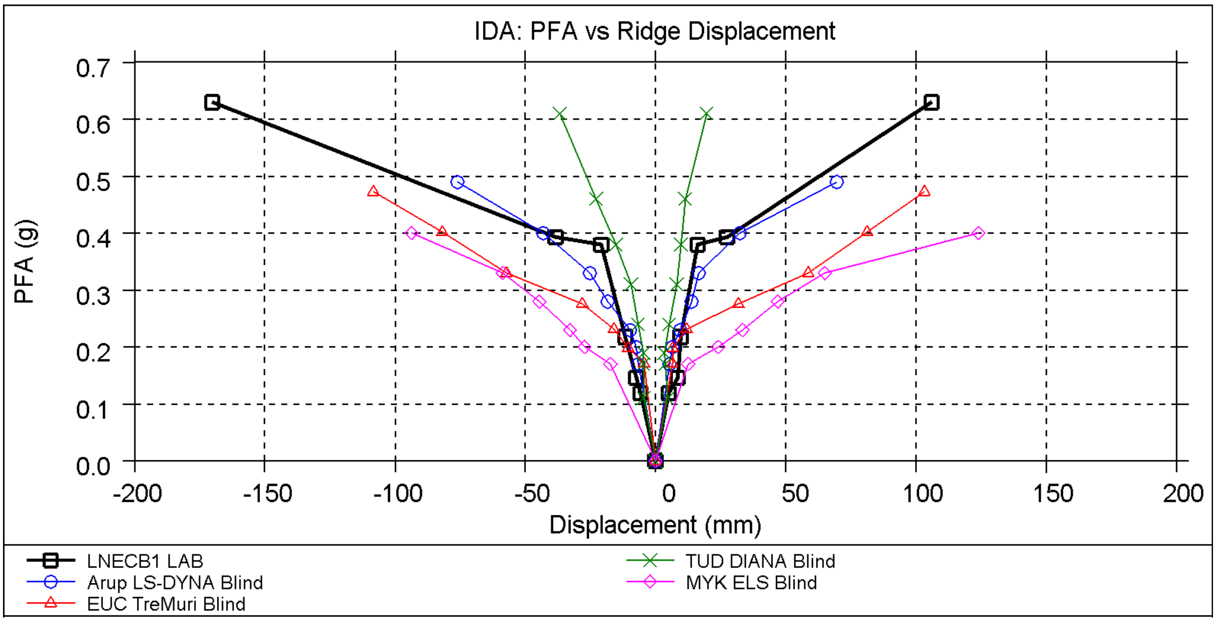
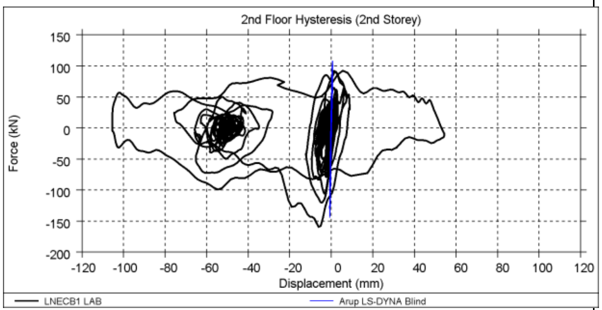


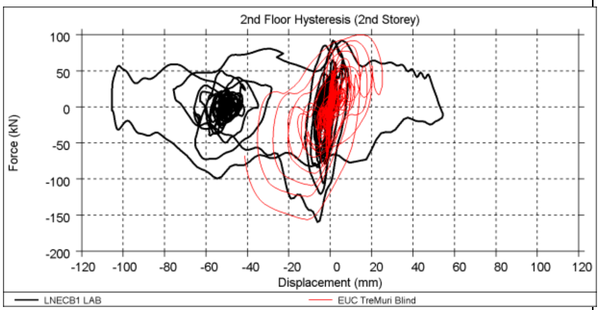
Figure 22 IDA: PFA vs. ridge displacement plots the PFA [g] of the first floor vs. the positive and negative direction displacement envelopes of the ridge beam relative to the first floor [mm] for each test. Results from the Consultants' blind predictions are plotted against the LNEC-BUILD-1 lab result.

Lastly, the second floor hysteresis graphs in Figure 23 below further illustrate the dispersion among the Consultants' blind predictions as well as the mismatch between the blind predictions and the LNEC-BUILD-1 laboratory results, largely attributed to the underestimation of the rocking of the longitudinal piers and the lack of the final collapse mechanism that was exhibited in the laboratory.

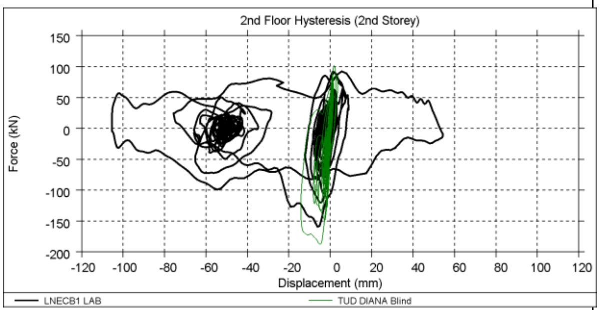
Arup / LS-DYNA



Eucentre TreMuri



TU Delft / DIANA



Mosayk / ELS

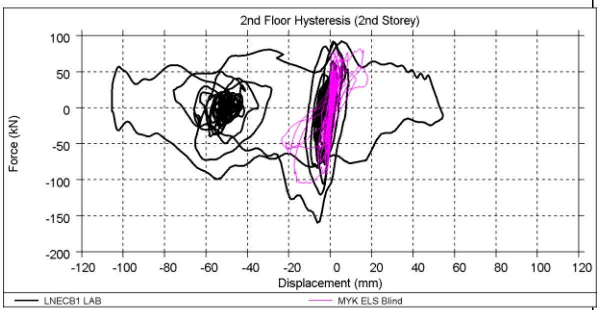


Figure 23 Second floor hysteresis for each of the four Consultant's blind prediction compared against the LNEC-BUILD-1 lab result. Second floor hysteresis is defined as the total second storey shear [kN] vs. second floor (i.e., second floor) horizontal displacement relative to the first floor [mm].

5 Post-Test Refined Simulations

5.1 Refinements to Modelling Approach

In light of the observations highlighted in Section 4.2, the four Consultants compared their own results against the experiment results and made refinements to the models in order to address the limitations experienced during the blind prediction phase. Across the board, the following changes were made by all of the Consultants based on their own comparisons and study:

- The recorded input motions [1] were applied to the models in lieu of the loading protocol that was provided prior to the execution of the laboratory test [3];
- Initial damage that occurred during the transportation phase of the specimen [1] was considered in the modelling of the connections between the second floor slab and the longitudinal piers and, for Eucentre's TreMuri model, in the initial effective longitudinal-pier heights; and
- The estimated masonry material properties [3] that were used in the blind prediction models were updated according to the latest masonry characterisation test results that were completed after the execution of the shake table test (see Table 1) [1].

More information on the individual refinements made to the models can be found in Appendix A2.

5.2 Summary of Results and Comparison against Lab

This section covers the post-test refined results for each consultant in comparison to the lab results. For more information on the modelling approach adopted by each consultant, please refer to the individual consultant's post-test report [7] [8] [9] [10].

Observations on the comparisons are highlighted below:

All Consultants improved their simulations in capturing the rocking of the longitudinal piers, most likely attributed to the implementation of more accurate masonry material properties and the application of the recorded motions in lieu of the time histories supplied before the execution of the laboratory test.

All Consultants improved their prediction in terms of storey drifts, most likely attributed to the improved modelling of the weak joint between the second floor slab and and longitudinal walls (see Figure 24 and Figure 25).

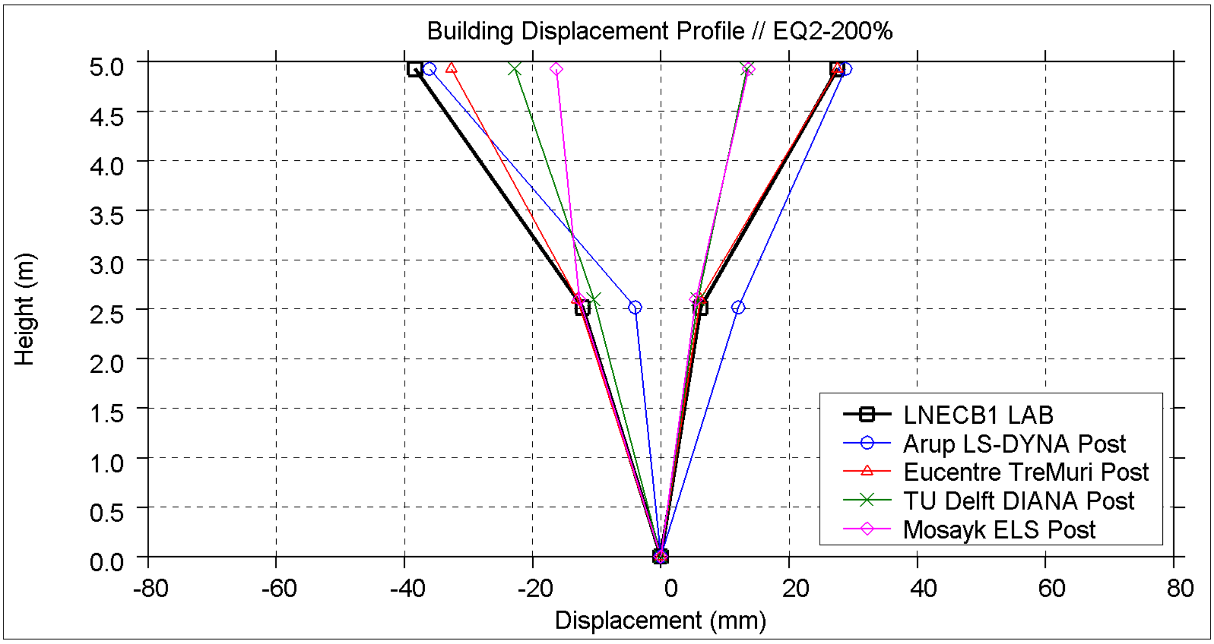


Figure 24 Building displacement profile graph of the LNEC-BUILD-1 lab results and the Consultants' post-test refined results for EQ2-200%.

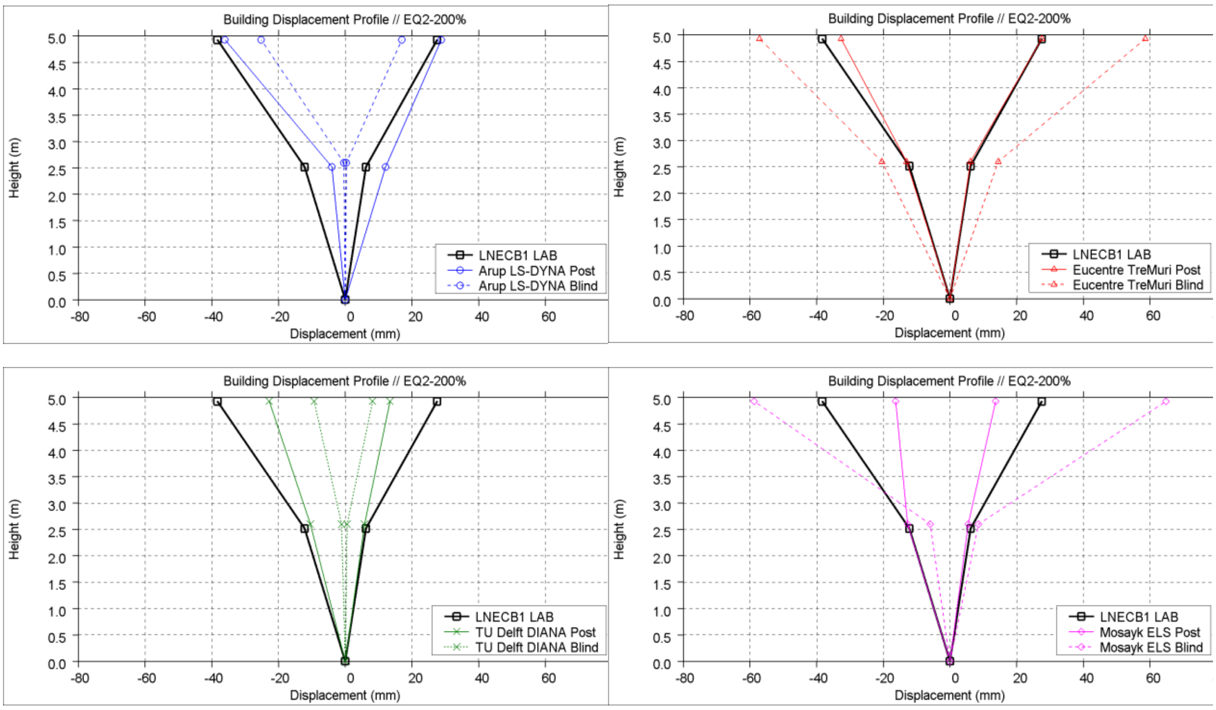


Figure 25 Building displacement profile graph of the LNEC-BUILD-1 lab results and both the blind prediction (dashed) and post-test refined results (solid) for EQ2-200% for Arup (top left), Eucentre (top right), TU Delft (bottom left) and Mosayk (bottom right).

Most Consultants predicted the uplift of the slab that occurred during the application of EQ2-300% and resulting loss in capacity, but most struggled with capturing the out-of-plane collapse of the party wall that occurred due to the resulting loss of constraint at the top of the wall (see Figure 26).

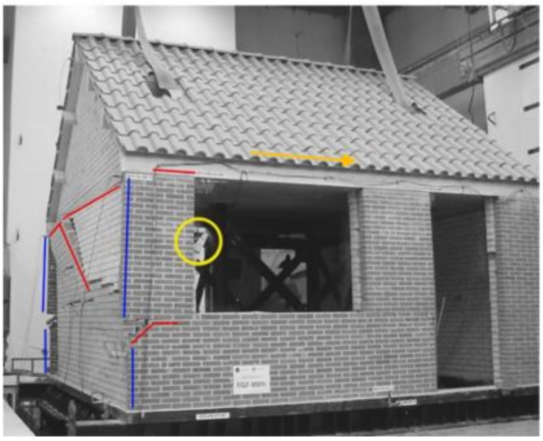
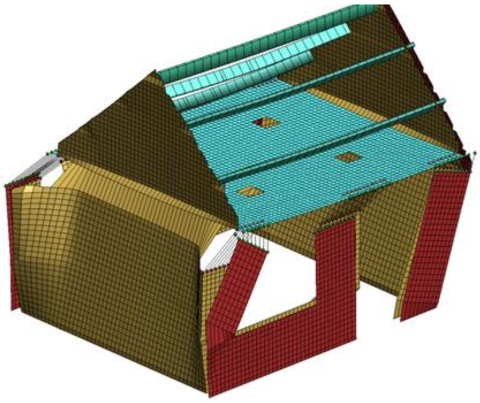
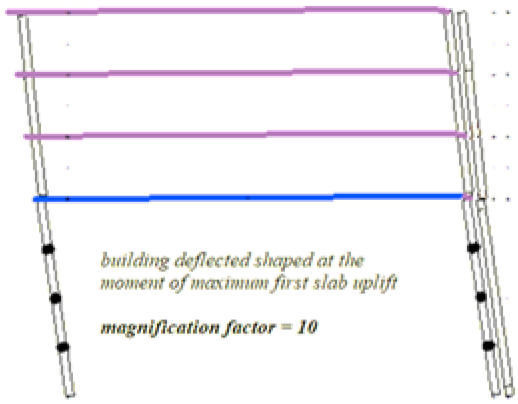
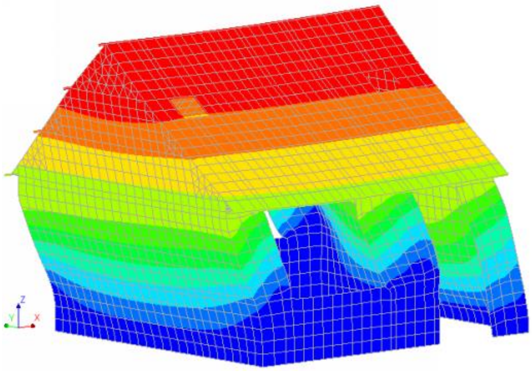
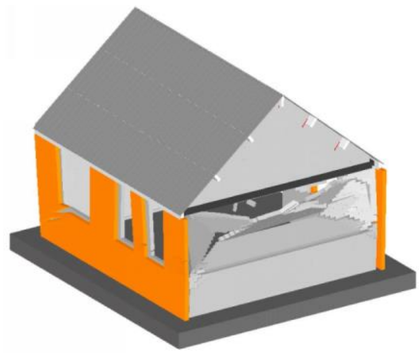
Lab	
	
Arup / LS-DYNA	**Eucentre / TreMuri**
 Magnified 10x	
TU Delft / DIANA	**Mosayk /ELS**
 Magnified x25	 Magnified 2x

Figure 26 Deflected shape at either moment of collapse or moment of maximum slab uplift / peak drift: LNEC-BUILD-1 lab specimen (top) and four Consultants' post-test refined numerical models

Table 5 below provides a summary of the numerical results of each Consultant's post-test refined analsyis in comparison to the LNEC-BUILD-1 laboratory results.

Table 5 Post-test refined results summary table in comparison to the LNEC-BUILD-1 lab results. **Bold** text indicates different results vs.the blind prediction results (for numerical values, **bold** text indicates more than a 10% change)

	LNEC Lab	Arup	Eucentre	TU Delft	Mosayk
Software	---	LS-DYNA	TreMuri	DIANA	ELS
Collapse mechanism	Out-of-plane failure of CaSi [transverse] party wall	**No collapse (although visible drop in capacity)**	**No collapse (although visible drop in capacity)**	No collapse	**Out-of-plane failure of CaSi [transverse] party wall**
Collapse Horizontal input motion (PFA)	EQ2-300% (0.63g)	**---**	**---**	---	**EQ2-300% (0.63g)**
Peak floor drift (%) [1]	4.4	**4.5**	**2.8**	**≥ 1.2**	**4.8**
Peak roof drift (%) [2]	2.0	1.9	**1.5**	**≥ 0.4**	**3.4**
Peak ridge displacement (mm)	170	**165**	**78**	**≥ 44**	**125**
Base shear (kN)	160	132	136	**≥ 109**	**161**

[1] Floor interstorey drift ratio = second floor horizontal displacement relative to the first floor divided by the storey height (2520 mm).

[2] Roof interstorey drift ratio = ridge horizontal displacement relative to the second floor divided by the inclined roof length (3500 mm).

From the IDA graphs, it is clear that not only did the Consultants' post-test refined results converge towards one another but the results are much closer to the laboratory results in comparison to the blind prediction results. Figure 27, Figure 28 and Figure 29, respectively, plot the second storey IDR, attic IDR and ridge displacement against the peak horizontal floor accelerations for each test over the duration of the loading protocol.

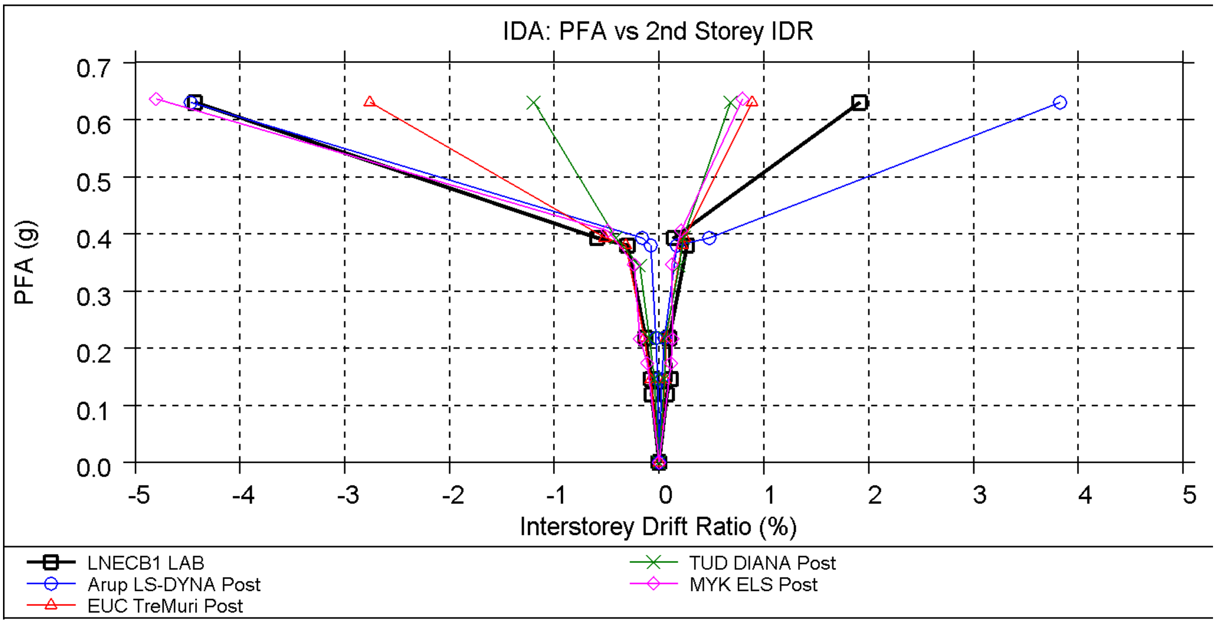


Figure 27 IDA: PFA vs. second storey IDR results from the Consultants' post-test refined simulations are plotted against the LNEC-BUILD-1 lab result.

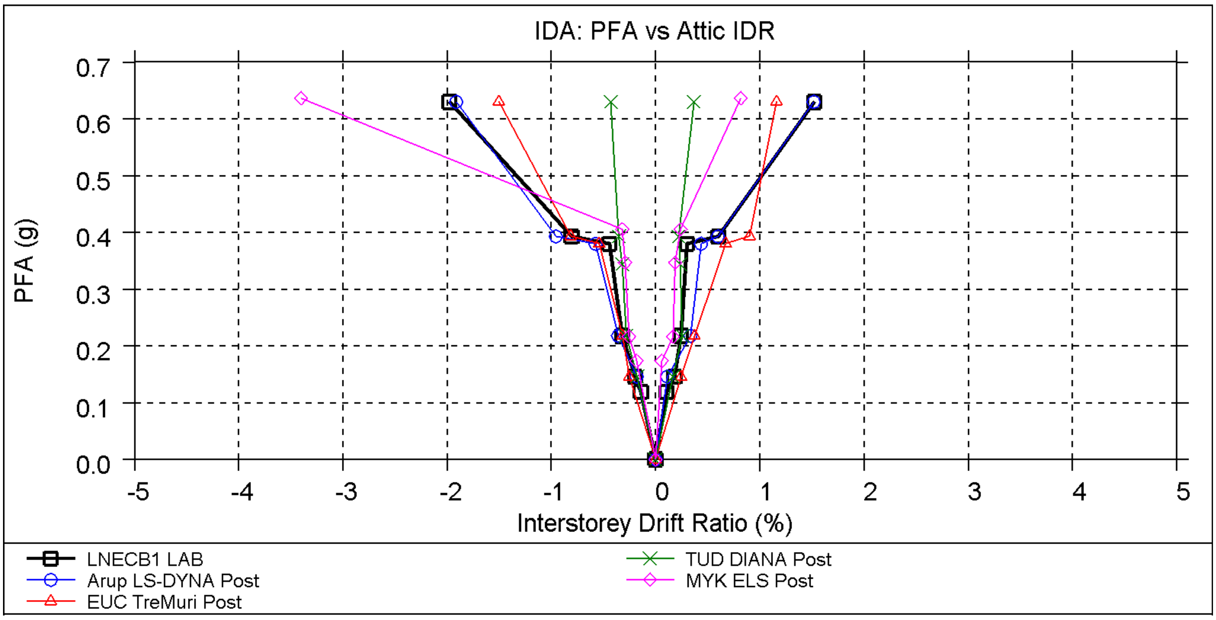


Figure 28 IDA: PFA vs. attic IDR results from the Consultants' post-test refined simulations are plotted against the LNEC-BUILD-1 lab result.

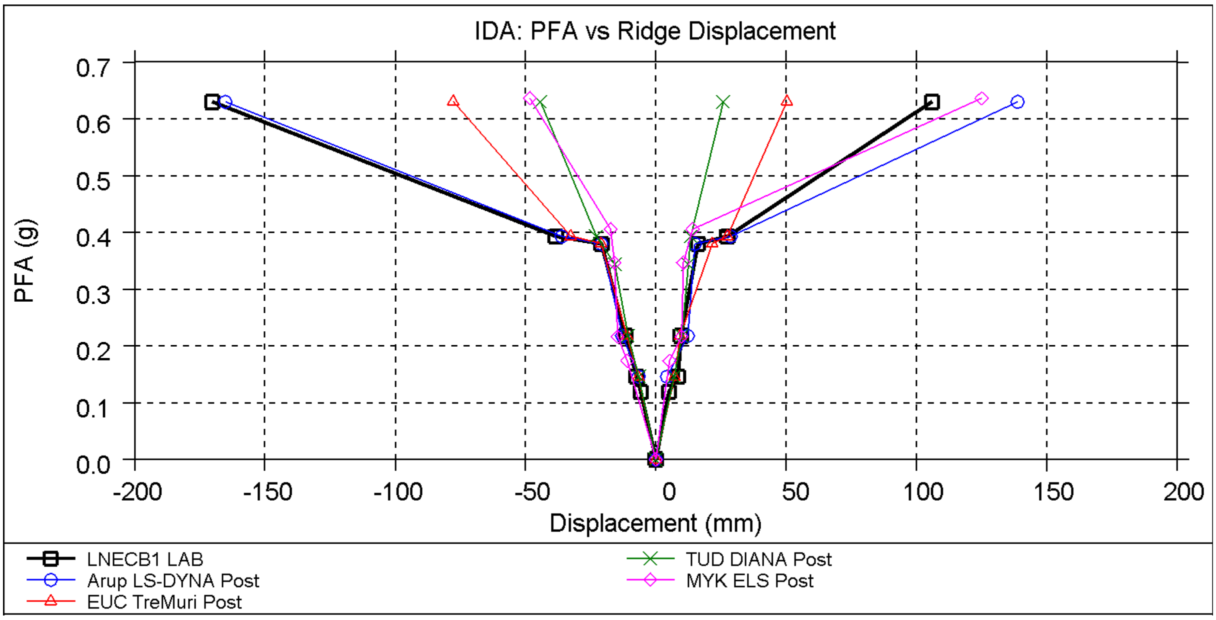


Figure 29 IDA: PFA vs. ridge displacement results from the Consultants' post-test refined simulations are plotted against the LNEC-BUILD-1 lab result.

The second floor hysteresis graphs in Figure 30 below further illustrate the improvement in the simulations in comparison to the Consultants' blind predictions shown in Figure 23.

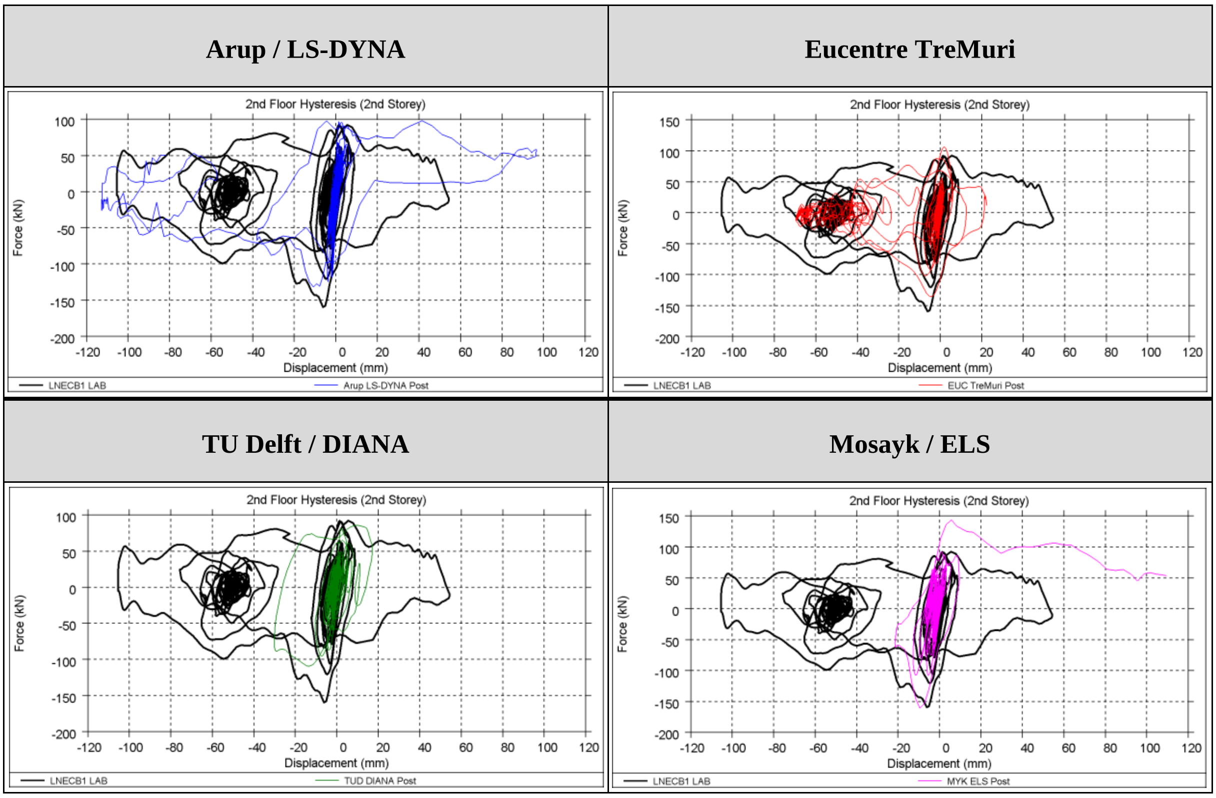


Figure 30 Second floor hysteresis for each of the four Consultant's post-test refined simulation compared against the LNEC-BUILD-1 lab result.

As previously discussed in Section 2.3, it is expected that two experiments testing two similar structures in a similar fashion will produce different results due to the inherent variability that exists between the specimens and between the test-set up systems. This is important to consider when judging the dispersion between various numerical results and the lab results themselves. If the level of dispersion between the numerical models and the lab results is within the same order of magnitude as the level of dispersion between lab results of two similar tests, the numerical models can then be judged as adequate methods of representing such structures under similar loading conditions. This is illustrated by the IDA graphs that compare the second storey IDR, attic IDR and ridge displacement against both the LNEC-BUILD-1 and the EUC-BUILD-1 lab results for each test over the duration of the loading protocol up to EQ2-200% (see Figure 31, Figure 32 and Figure 33)

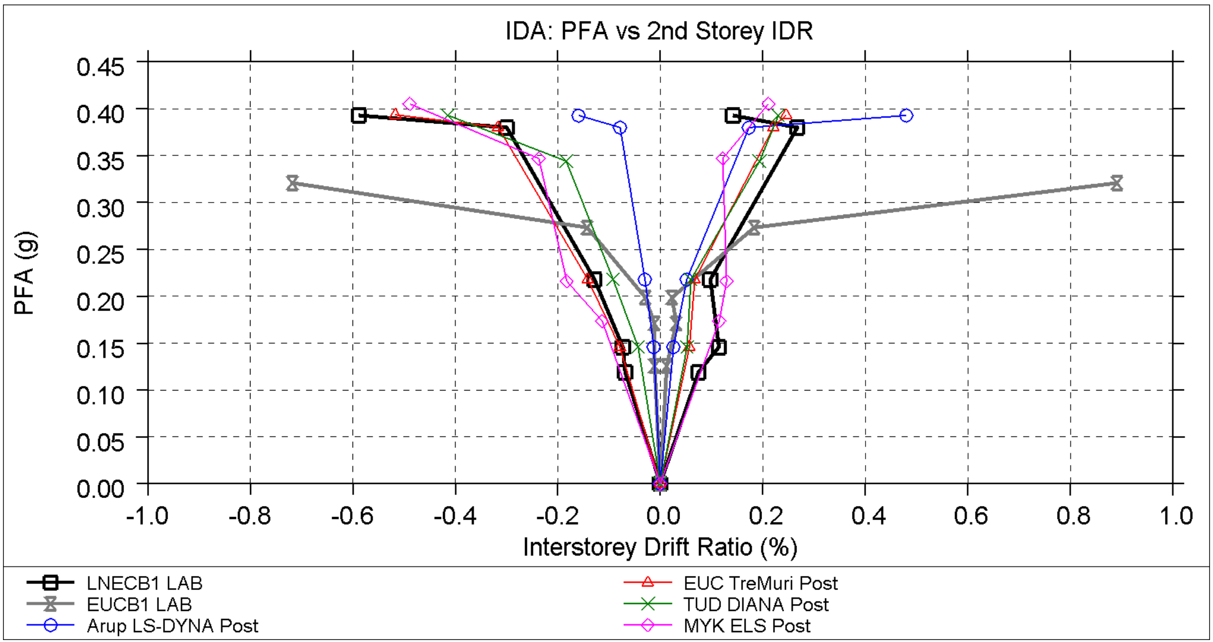


Figure 31 IDA: PFA vs. second storey IDR results from the Consultants' post-test refined simulations are plotted against both the LNEC-BUILD-1 lab result as well as the EUC-BUILD-1 lab result up to input motion EQ2-200%.

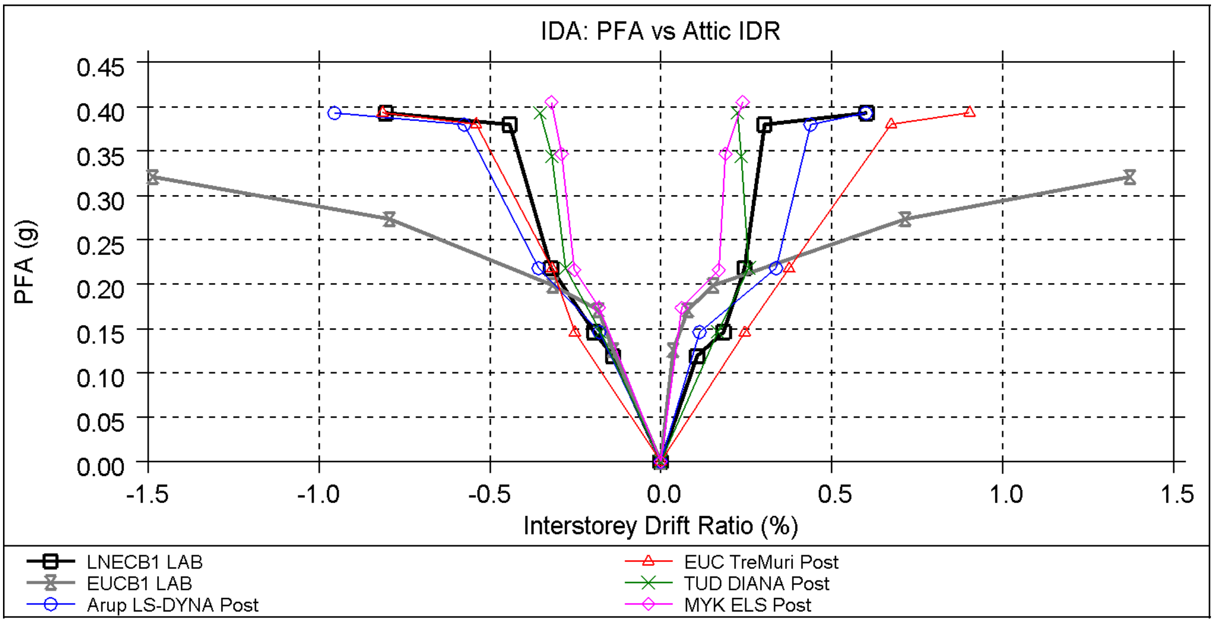


Figure 32 IDA: PFA vs. attic IDR results from the Consultants' post-test refined simulations are plotted against both the LNEC-BUILD-1 lab result as well as the EUC-BUILD-1 lab result up to input motion EQ2-200%.

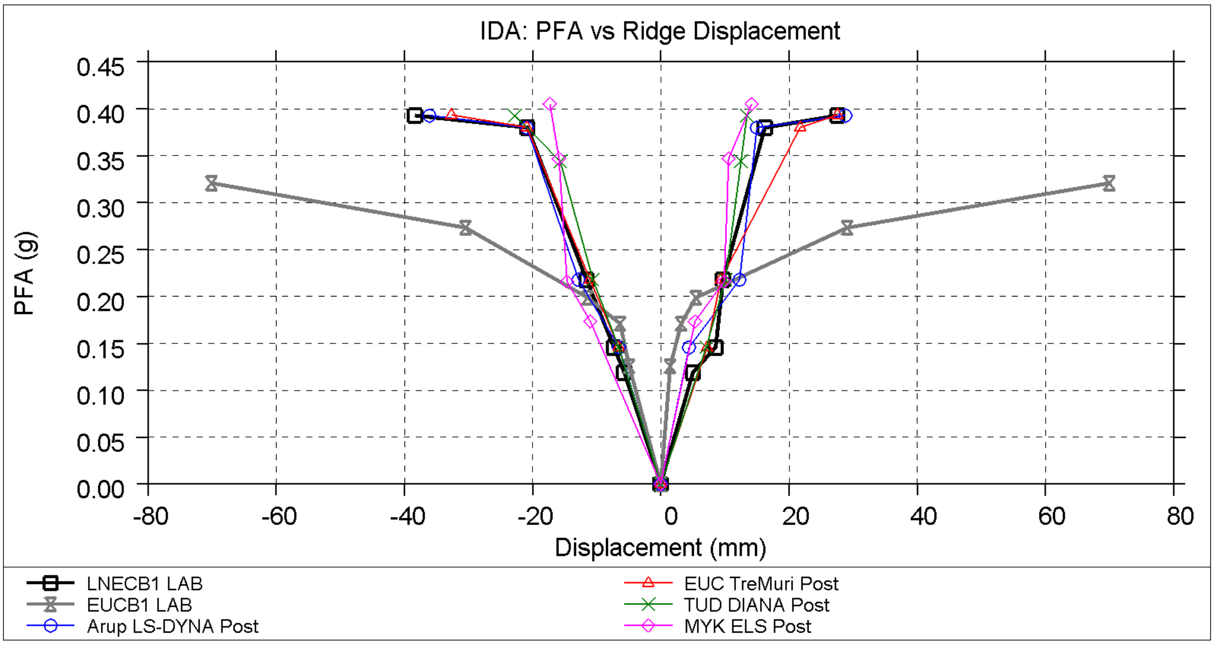


Figure 33 IDA: PFA vs. ridge displacement results from the Consultants' post-test refined simulations are plotted against both the LNEC-BUILD-1 lab result as well as the EUC-BUILD-1 lab result up to input motion EQ2-200%.

6 Conclusions and Recommendations

The full scale test of LNEC-BUILD-1 focused on the behaviour of a URM cavity wall system with reinforced concrete slabs and a timber roof subjected to simultaneous horizontal and vertical ground motions. The specimen tolerated ground motion EQ2-200% (peak floor acceleration 0.39g) with interstorey drifts of up to 1% and no sign of imminent collapse. The next ground motion, EQ2-300% with a peak floor acceleration of 0.63g, resulted in interstorey drift over 4% and collapse of a transverse wall. The specimen was very near to complete collapse.

Arup, Eucentre, TU Delft and Mosayk participated in the cross-modelling validation exercise for the LNEC-BUILD-1 testing campaign. Each Consultant used a different analysis software to model the LNEC-BUILD-1 test specimen: LS-DYNA, TreMuri, DIANA and ELS.

Following the blind prediction of LNEC-BUILD-1, all of the models had been updated based on the observed behaviour of the dynamic test specimen, leading to a greatly improved simulation of the behaviour in comparison to the blind prediction models. The most influential changes that led to the improvement of the results are described in Section 5.1 and are reproduced below:

- The recorded input motions were applied to the models in lieu of the loading protocol that was provided prior to the execution of the laboratory test;
- A weakend interface between the second floor slab and longitudinal walls was considered in the modelling of the connections between the second floor slab and the longitudinal piers; and
- The estimated masonry material properties that were used in the blind prediction models were updated according to the latest masonry characterisation test results that were completed after the execution of the shake table test.

These changes also led to a reduction in dispersion among the results simulated by the four Consultants. This exemplifies the benefit of performing such an exercise, increasing the knowledge on both the failure mechanisms that can occur for this type of structure and the extent of how modelling assumptions can affect the governing behaviour captured by the numerical models.

In addition, the following lessons learnt and future recommendations are raised.

All of the numerical models appear to be sensivitive to the input masonry material properties. This was also the case during the previous testing and numerical modelling campaigns for most of the participating consultants [1] [11]. Also, higher strength material properties do not necessarily indicate a more robust structure, nor vise-versa, as the failure mode may change to one that is less (or more) ductile. This cross-modelling exercise showed how the actually higher strength shear properties resulted in a different failure mode then expected. The high shear strength promoted the rocking mechanisms exhibited by the second storey, which led to the eventual partial collapse mechanism of the structure. This shows the importance of understanding not only the variety of material property values that can exist over a wide range of test specimens and, moreover, in real buildings, but also the influence of the *combination* of material parameters on the global behaviour of the structure.

Incorporating the actual condition of pertinent connections, such as the second floor slab to the top of the longitudinal masonry piers in this case, led to significant improvement in capturing the global behaviour exhibited in the laboratory test. With regards to this particular connection, it is worth noting that the interface between the top of the longitudinal walls and the underside of the slab behaved differently in the LNEC-BUILD-1 test compared to 2015 EUC-BUILD-1 test—apparently little or no bond strength in the former and high bond strength in the latter. The precise reasons for the difference are not entirely known. Damage during transportation may have influenced this in the LNEC-BUILD-1 specimen, but it is also possible that, had the specimen been constructed on the shake table, similar damage might have occurred during the early phases of the dynamic test. Nevertheless, one can conclude that even with a dedicated laboratory test, the condition and performance of this particular type of connection across similarly constructed buildings can vary widely. Thus, it is important to consider all viable conditions for such critical connections when assessing the seismic performance of these structures.

The studies that have been conducted so far through the cross-modelling validation exercise have not yet drawn significant attention to the effect of the vertical input motion on the behaviour of the LNEC-BUILD-1 specimen. There has not yet been a complimentary test without the application of vertical input motion. Therefore, it is suggested that dedicated component-level tests are undertaken with and without vertical motion in order to study the effect. In addition, until further knowledge is gained, it may be beneficial to exclude the application of vertical motion in upcoming large-scale laboratory tests.

References

References

[1] Tomassetti, U., Correia, A.A., Graziotti, F., Marques, A.I., Mandirola, M., Candeias, P.X. (2017) Collapse Shaking Table Test on a URM Cavity Wall Structure Representative of a Dutch Teraced House. EUCENTRE, Lisbon, PT.

[2] Graziotti F., Tomassetti U., Rossi A., Kallioras S., Mandirola M., Cenja E., Penna A., Magenes G. (2015) Experimental campaign on cavity-wall systems representative of the Groningen building stock. Report, EUC318/2015U, EUCENTRE, Pavia, IT.

[3] Tomassetti, U., Kallioras, S., Graziotti, F., Correia, A. (2017) Preliminary Report on the Construction of the Building Prototype at the LNEC Laboratory (v2-1). EUCENTRE, Lisbon, PT.

[4] Arup (01-05-2017), 229746_031.0_NOT2022, LNEC-BUILD-1 LS-DYNA Blind Prediction Modelling & Analysis

[5] Eucentre (2017). LNECBUILD1_EUCENTRE_blind. EUCENTRE, Pavia, IT.

[6] Longo, M., Mariani, V., Messali, F., Rots, J.G. (2017). Blind prediction of shaking table test on the LNEC-BUILD-1. Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, NL.

[7] Mosayk (2017). “Using the Applied Element Method to model the collapse shake-table testing of a URM cavity wall structure”. Mosayk, Pavia, IT.

[8] Arup (28-07-2017), 229746_031.0_NOT2030, LNEC-BUILD-1 LS-DYNA Post-Test Refined Modelling & Analysis

[9] Kallioras, S., Tomassetti, U., Graziotti, F., Penna, A., Mandirola, M, (2017). LNEC-BUILD-1 Cross-Modelling Validation: Post-Test Refined Simulations with TreMuri Ricerca. EUCENTRE, Pavia, IT.

[10] Sousamli, M., Longo, M., Messali, F., Rots, J.G. (2017). LNEC-BUILD-1 post-test refined modelling and analysis with DIANA 10.1. Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, NL.

[11] Arup (30-09-2016), 229746_031.0_REP1009, EUC-BUILD-2: Modelling Predictions and Analysis Cross Validation

Appendix A

Modelling Approach

A1 Blind Prediction Modelling Method & Assumptions

Table A1 - 1 Blind prediction modelling assumptions summary table

Input	Modelling assumptions per Consultant			
	Arup	**Eucentre**	**TU Delft**	**Mosayk**
Base boundary condition (i.e., level of first floor slab in full terraced house)	Fixed base	Fixed base	Fixed base	Mortar interface to fixed slab
Roof diaphragm	All timber roof elements – linear elastic beams. Nails – nonlinear beams.	Orthotropic, elastic membrane finite elements	Timber planks – orthotropic, elastic quadratic shell elements. Timber beams – linear elastic beams.	All timber roof elements – 3D rigid units connected by bilinear interface springs. Nails – elastic-perfectly-plastic spring interfaces
Wall ties	Nonlinear 1D spring elements defined in axial direction only	Along front/back walls: membrane elements at levels of the floor slabs. Along end wall: linear elastic beams (by means of 2D finite elements) with equivalent properties	Elastic-perfectly-plastic truss elements.	Elastic-perfectly-plastic beam elements
Connection between floor slab and front/back inner leaves	Fully integrated shell elements with masonry material, active after gravity loading stage	Presence of slab on top of longitudinal piers modelled as fictitious beams with equivalent properties.	Hinged connection	Mortar interface, active after gravity loading stage
Connection between timber beam at gutter level and front/back outer leaves	Same as above	Ideal connection, with perfect displacement coupling and in-plane moment transfer, up to EQ2-200%	Same as above	Same as above

Table A1 - 2 Blind prediction modelling assumptions summary table (continued)

Input	**Modelling assumptions per Consultant**			
	Arup	**Eucentre**	**TU Delft**	**Mosayk**
Connection between floor slab and end/party walls	Fixed connection	Ideal connection, with perfect displacement coupling and in-plane moment transfer	Fixed connection	Mortar interface
Connection between roof girders and end/party walls	Fixed connection to inner leaf. Friction connection to outer leaf, with presence of barge board modelled	Ideal connection, with perfect displacement coupling and in-plane moment transfer	Fixed connection	Mortar interface plus elastic-perfectly-plastic beam elements representing blind anchors
Other: Wall-to-wall connections	Interlocked	Intersecting walls (in longitudinal and transverse direction) have been connected at top nodes by means of rigid links	Interlocked	90 degree angled masonry interface

A2 Post-Test Refined Modelling Method & Assumptions

Table A2 - 1 Post-test refined modelling assumptions summary table. **Bold** text indicates different modelling assumption vs. assumption made in blind prediction.

Input	Modelling assumptions per Consultant			
	Arup	**Eucentre**	**TU Delft**	**Mosayk**
Base boundary condition (i.e., level of first floor slab in full terraced house)	Fixed base	Fixed base	Fixed base	Mortar interface to fixed slab
Roof diaphragm	All timber roof elements – linear elastic beams. Nails – nonlinear beams.	Orthotropic, elastic membrane finite elements. **Shear modulus reduced following a power law model.**	Timber planks – orthotropic, elastic quadratic shell elements. Timber beams – linear elastic beams.	All timber roof elements – 3D rigid units connected by bilinear interface springs. Nails – elastic-perfectly-plastic spring interfaces
Wall ties	Nonlinear 1D spring elements defined in axial direction only	Along front/back walls: membrane elements at levels of the floor slabs. Along end wall: linear elastic beams (by means of 2D finite elements) with equivalent properties	**No wall ties**	Elastic-perfectly-plastic beam elements
Connection between floor slab and front/back inner leaves	**Friction-only discrete beam (i.e., spring) elements active after gravity loading stage (friction coefficient = 0.7)**	Presence of slab on top of longitudinal piers modelled as fictitious beams. **To capture sliding of the slab above the central longitudinal CS piers, the area and the moment of inertia of these beam elements was set to zero during test-run EQ2-300%**	**Interface elements active after gravity loading stage with reduced properties**	**Cracked** mortar interface, active after gravity loading stage

Table A2 - 2 Post-test refined modelling assumptions summary table (continued). **Bold** text indicates different modelling assumption vs. assumption made in blind prediction.

Input	**Modelling assumptions per Consultant**			
	Arup	**Eucentre**	**TU Delft**	**Mosayk**
Connection between timber beam at gutter level and front/back outer leaves	**Same as above**	No connection. **Resistence of the interface between the timber beam and outer leaves set to zero**	**No connection (outer leaves not modelled)**	**Same as above**
Connection between floor slab and end/party walls	Fixed connection	Ideal connection, with perfect displacement coupling and in-plane moment transfer	**Interface elements**	Mortar interface
Connection between roof girders and end/party walls	Fixed connection to inner leaf. Friction connection to outer leaf, with presence of barge board modelled	Ideal connection, with perfect displacement coupling and in-plane moment transfer	Fixed connection	Mortar interface plus elastic-perfectly-plastic beam elements representing blind anchors
Other: Effective height of front/back wall piers	NA	**Reduced to reflect damage that occurred during the transportation phase**	NA	NA
Other: Additional mass	NA	NA	**Mass of outer leaf applied on inner leaf elements since outer leaves not modelled**	NA
Other: Wall-to-wall connections	Interlocked	Intersecting walls (in longitudinal and transverse direction) have been connected at top nodes by means of rigid links	Interlocked	**45 degree angled masonry interface**

Appendix B

Index for Individual Reports

B1 Blind Prediction List of Figures

Below is a list of figures that each consultant has included in their individual blind prediction report of LNEC-BUILD-1 [4] [5] [6] [7]:

- Summary:
    - Deflected shape at collapse
    - IDA: PGA vs. Second floor IDR: incremental dynamic analysis (IDA) graph that plot the second storey interstorey drift ratio (IDR) against the peak horizontal floor accelerations for each test over the duration of the loading protocol
    - IDA: PGA vs. [Inclined] Roof IDR: IDA graph that plots the attic storey IDR against the peak horizontal floor accelerations for each test over the duration of the loading protocol
    - IDA: PGA vs. Ridge displacement: IDA graph that plots the ridge displacement against the peak horizontal floor accelerations for each test over the duration of the loading protocol
- For each test input:
    - Floor hysteresis: total second storey shear [kN] vs. second floor horizontal displacement relative to the first floor [mm]
    - Roof Interstorey Hysteresis: attic storey interstorey shear [kN] vs. ridge horizontal displacement relative to the first floor [mm]
    - Floor Displacement Envelope: graph plots the positive and negative direction displacement envelopes of second floor and the ridge relative to the first floor [mm] versus building height [m]. It also plots the residual displacement [mm] at the end of the input record.
    - Floor Acceleration Envelope: graph plots the positive and negative direction acceleration envelopes of second floor and the ridge [g] versus building height [m]
    - Roof [Acceleration] Hysteresis: ridge horizontal acceleration [g] vs. ridge horizontal displacement relative to the second floor [mm]
    - Global Hysteresis: total second storey shear [kN] vs. ridge horizontal displacement relative to the first floor [mm]
    - Deflected shape at peak roof (i.e., attic storey) interstorey displacement
    - Damage plots of the four calcium silicate inner leaf walls
    - Damage plots of the three clay outer leaf facades

B2 Post-Test Refined Simulation List of Figures

Below is a list of figures that each consultant has included in their individual post-test refined simulation report of LNEC-BUILD-1 [7] [8] [9] [10]:

- Summary:
    - Deflected shape at max excursion in final cycles
    - Deflected shape at maximum slab uplift
    - Deflected shape at collapse
    - IDA: PGA vs. Floor IDR: IDA graph that plot the second storey IDR against the peak horizontal floor accelerations for each test over the duration of the loading protocol
    - IDA: PGA vs. Roof IDR: IDA graph that plots the attic storey IDR against the peak horizontal floor accelerations for each test over the duration of the loading protocol
    - IDA: PGA vs. Ridge displacement: IDA graph that plots the ridge displacement against the peak horizontal floor accelerations for each test over the duration of the loading protocol
    - Floor hysteresis: total second storey shear [kN] vs. second floor horizontal displacement relative to the first floor [mm]
    - Roof [Acceleration] Hysteresis: ridge horizontal acceleration [g] vs. ridge horizontal displacement relative to the second floor [mm]
- For each test input:
    - Floor hysteresis: total second storey shear [kN] vs. second floor horizontal displacement relative to the first floor [mm]
    - Roof [Acceleration] Hysteresis: ridge horizontal acceleration [g] vs. ridge horizontal displacement relative to the second floor [mm]
    - Global Hysteresis: total second storey shear [kN] vs. ridge horizontal displacement relative to the first floor [mm]
    - Building Displacement Profile: graph plots the positive and negative direction displacement envelopes of second floor and the ridge relative to the first floor [mm] versus building height [m]. It also plots the residual displacement [mm] at the end of the input record.
    - Building Acceleration Profile: graph plots the positive and negative direction acceleration envelopes of second floor and the ridge [g] versus building height [m]
    - Deflected shape at peak interstorey displacement
    - Damage plots of the four calcium silicate inner leaf walls
    - Damage plots of the three clay outer leaf facades