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NUMERICAL ANALYSIS OF TIMBER-FRAME STRUCTURES WITH INFILL UNDER SEISMIC LOADING

Florent Vieux-Champagne^{1,2}, Stéphane Grange², Yannick Sieffert², Patrice Garcia³, Carole Faye³, Jean-Charles Duccini³, Laurent Daudeville²

ABSTRACT: Timber frame with infill have proved to be efficient structures when submitted to seismic hazard. No building code and very few scientific studies are available to design this kind of structures. Therefore, the present work aims at predicting the behavior of timber-frame structure with earth infill under seismic loading. Four scales are defined: the joint, the elementary cell, the shear wall and the entire house. At each scale, both an experimental and a numerical analysis are carried out in order to bring extensive knowledge with regard to the behavior of these structures under seismic loading and to validate a numerical tool able to predict their response.

KEYWORDS: Timber-frame structures with earth and stone infill, Multi-scale approach, Seismic behavior, Constitutive model.

1 INTRODUCTION

Timber frame structures with infill represent an important share of the traditional built environment over the world and especially in earthquake-prone areas ([DUT 12], [OZT 10], [VIE 14]). Their construction is environmentally friendly due to the proximity of the building materials and coherent with the respect of local culture. Furthermore, during recent earthquakes (Turkey 1999, Greece 2003, India 2005 and Haiti 2010), timber-framed structures filled with natural materials (earth, stones) often showed a better resistance to earthquakes compared with imperfectly built reinforced concrete structures ([AUD 11], [LAN 08]). Nevertheless, few scientific studies (e.g. [AHM 12], [CEC 10], [VAS 13]) and no building code are available to assess the seismic vulnerability of this kind of building. Therefore the present work aims at predicting the behavior of timber-frame structures with infill under seismic loading from the specific case of a Haitian timbered masonry structure, called "Kay peyi", which is reused in one of Haiti's ongoing reconstruction projects (Figure 1).

The study is based on the definition of different scales of analysis, from the connections to the global structure, as already proposed in [HUM 14], [RIC 02] and [XU 09] for timber-frame shear wall. Herein, the same approach is defined by means of four scales (cf. Figure 2): the joint, the elementary cell, the shear wall and the entire house. For each one, both an experimental and a numerical analysis are performed. The scale 1 allows calibrating

numerical models that are used to model the structure at the scale 2 and predict its behavior regarding the experimental results. From this scale, a simplified model (macro-element) is developed and is used to model the structure at the scale 3 and the scale 4. At each one, the model is validated from the experimental results. One of the aims of this work is to develop a simplified numerical tool able to predict the dynamic behavior of a timber frame structure with infill. This tool has been implemented in a Finite Element Code developed in Matlab®.



Figure 1: Rural Haitian house: (a) Traditional "Kay peyi" (b) Built for a reconstruction project

2 DESCRIPTION OF THE STRUCTURE

The timber structure is braced by X-cross and the spaces are filled with a stone masonry linked by an earth mortar.

Coiled strapping joints consisting of a punched steel strip surrounding the wood parts (in a T-shape) and fastened by few nails that govern behavior of the connection. The timber strength class is C18 with a density $\rho_{mean} = 380 \text{ kg/m}^3$ according to European standard EN 338 (see [EN-338 03]). The strip is a FP30/1,5/50 from Simpson Strong Tie®, 30 mm wide and 1,5 mm thick. Eight 3 mm \times 70 mm plain shank nails are used (see [EN-10230-1 00]) to fasten the strip.

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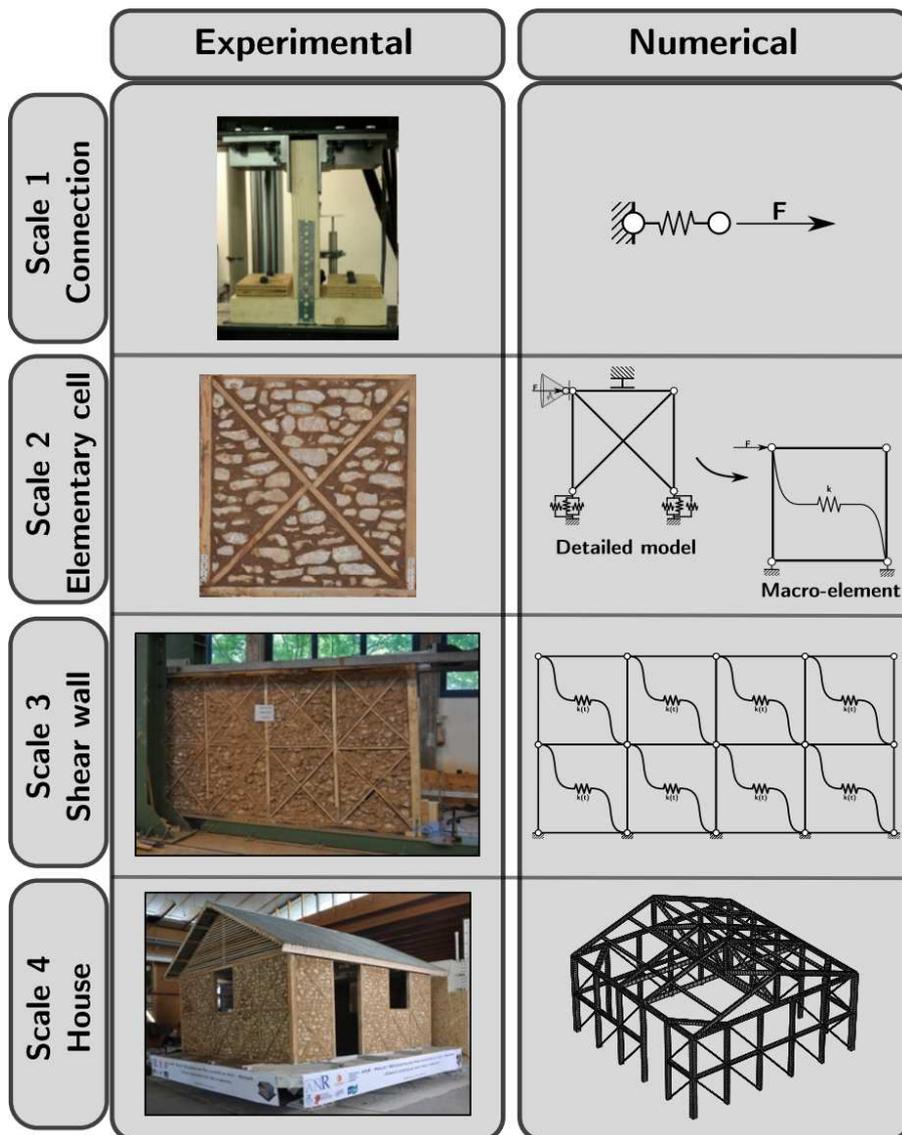


Figure 2: Multi-scale approach

The bracings are made from Saint Andrew's crosses with one continuous diagonal and another diagonal divided into two parts. They are connected to the vertical post using two 70-mm long wooden nails.

The earth is composed of a 1/1 volume ratio of a clay-calcareous mix ($D < 125 \mu\text{m}$), a 2/1 ratio of sand ($D < 2 \text{ mm}$), a 1/2 ratio of water (depending on the water content of sand) and a 1/1 ratio (very coarse measure) of sisal fibers (easily available in Haiti). To prevent the mortar from cracking, the water content must be limited in the earth and moreover sisal fibers are to be added. The clay-calcareous mix is chosen to obtain a mortar as close as possible to what can be produced from the local earth.

The fibers serve to limit the appearance of cracking and its propagation in mortar. Plain shank nails are thus placed inside wood triangles to improve the bond between both parts.

3 EXPERIMENTAL AND NUMERICAL ANALYSIS

3.1 SCALE 1: JOINTS

More than 30 experimental tests on coiled strapping joints have been performed to provide input data for the numerical models of structural elements. These connections have been tested through monotonic and cyclic tests, both in tension and shear, according to [EN-12512 02].

The results of the tests are used to calibrate the constitutive model of Humbert ([HUM 14]) (cf. Figure 3). Two levels of calibration are performed. The first level is a direct calibration, which consists in reproducing one particular test Fig. 3a). The second level is an average calibration, which consists in calibrating the parameters to reproduce

the average behavior of several experiments Fig. 3b). The first level is used to fit the Humbert model regarding the experimental reversed-cyclic curve and the second level is used to fit the Humbert model regarding the backbone

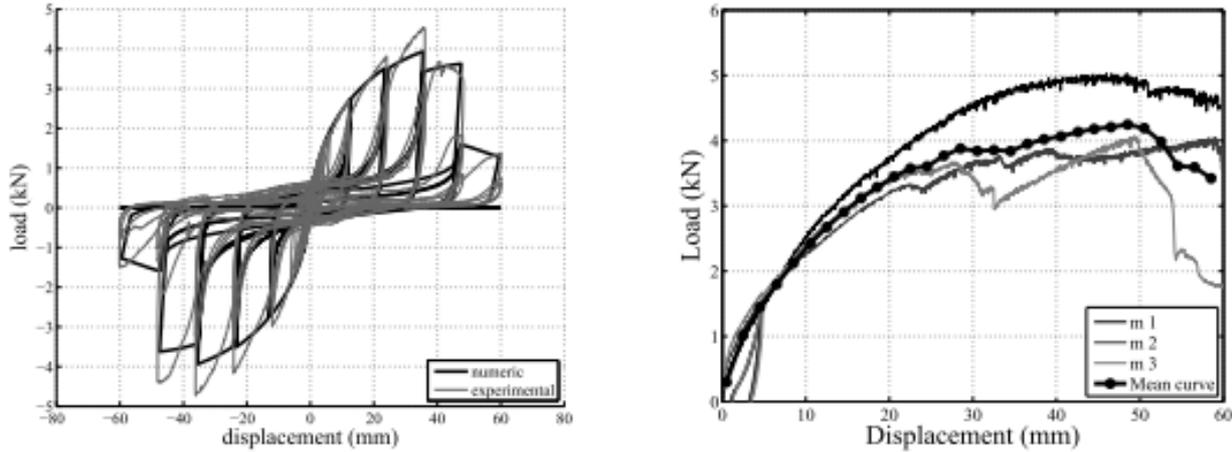


Figure 3: Reversed cyclic tests performed on a connection: (a) Fitting of the Humbert model's parameters from the results of a shear reversed cyclic test (b) Fitting of the Humbert model's parameters from the results of a tension monotonic test

curve. The calibrated parameters are used in the detailed connection model at the scale 2.

3.2 SCALE 2: ELEMENTARY CELL

This structure is an elementary part of the shear wall. The goal of studying this scale is motivated by two facts:

- Firstly, because of the lack of knowledge regarding the structural behavior of filled timber frame structures, a parametric study has been performed to assess the impact, on the lateral load capacity of the structure, of the presence of infill, of the kind of infill (stones or adobes masonry), of the presence of bracing. The results show that the strength of the structure is not governed by these parameters but more by its lateral stiffness and its dissipation energy capacity. This is explained by the lattice behavior-like depicted by the elementary cell ([VIE 14]).
- Secondly, these results allow validating the development of the FE models.

A detailed FE model of elementary cell is developed using beam elements for the frame and two-node spring-like finite elements for the joints and for the experimental friction (Figure 4a). The experimental behavior of the elementary cell, represented in Figure 4b by the positive (+) and the negative (-) average (A) envelop curves, is then predicted from the detailed model. From the results of this analysis, a simplified FE model (macro-element) is developed and calibrated (Figure 5a). The macro-element

is composed of a frame of bars ensuring the hypothesis of a parallelogram-like deformation of the wall, therefore modeling only the shearing behavior. The in-plane horizontal degree of freedom of the simplified element is

modeled by the previously described constitutive hysteretic behavior law, whose parameters are identified thanks to the results of the detailed model (Figure 5b).

3.3 SCALE 3: SHEAR WALL

Experimental campaign has been realized at the CNR-Ivalsa (Trento, Italy) where three filled walls (two reversed cycle tests and one monotonic) and two empty walls (one reversed cycle test and one monotonic) were tested:

At this scale, the objectives of the experimental study are the following:

- Firstly, to perform a comparison of the behavior of a timber shear wall with and without filling. The tests highlighted the influence of the filling on the deformation shape of the shear wall and hence its influence on the resistance of the wall ([VIE 14]).
- Secondly, to validate a simplified FE-model built by the combination of the macro-elements. A simplified representation of the finite element model of the wall is depicted in Figure 6a. The vertical posts are modeled by continuous beam which have their extremities hinged by static condensation. The horizontal members in the middle of the wall are modeled by bars. The prediction of the behavior of the shear wall is shown in Figure 6b.

The experimental behavior is well predicted by the modeling and hence validates this simplified approach.

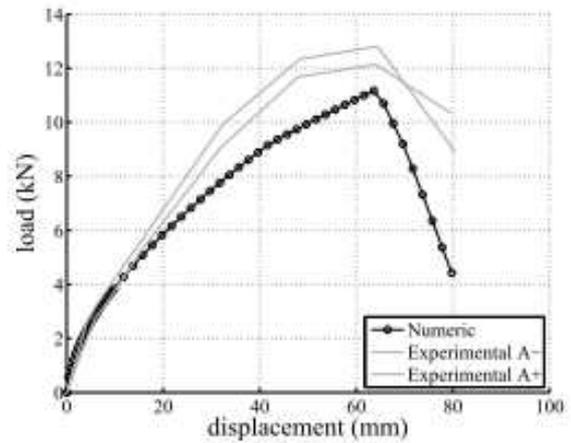
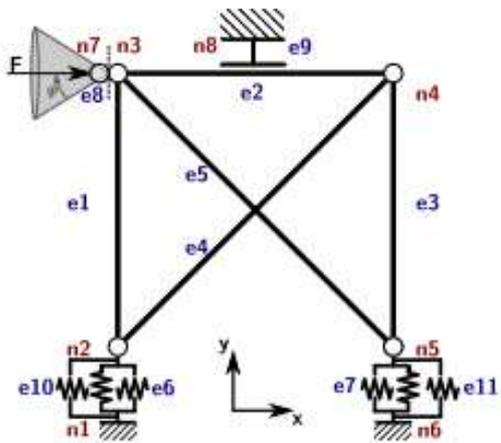


Figure 4: Scale 2 of the elementary cell: detailed model: (a) Mesh (b) Experimental versus numerical – Prediction of the elementary cell's behavior

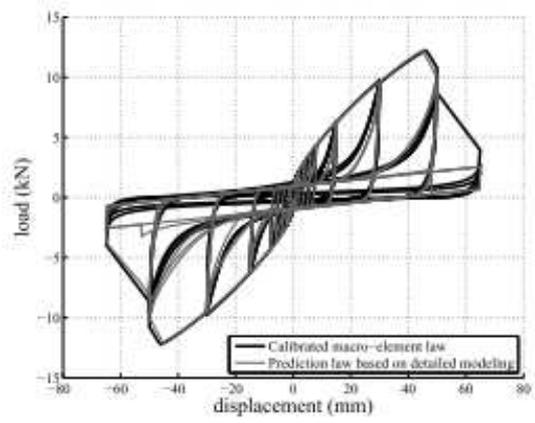
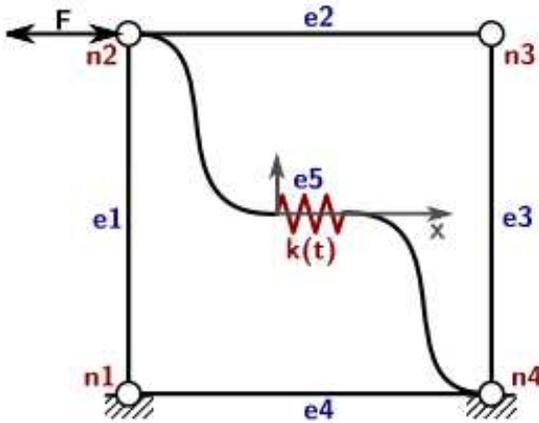


Figure 5: Scale 2 of the elementary cell: macro-element: (a) Mesh (b) Fitting of the Humbert model's parameters on the results of the detailed model

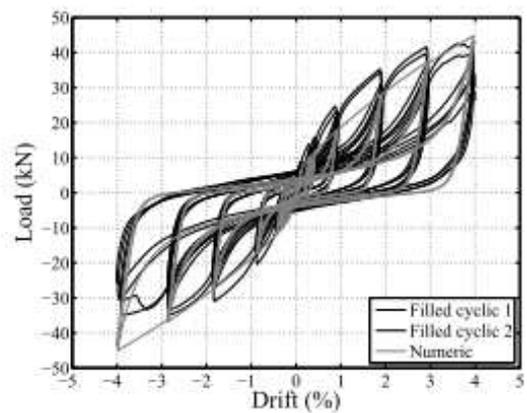
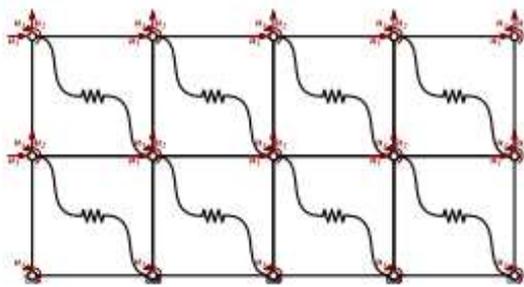


Figure 6: Scale 3: simplified modeling of the shear wall by macro-element combination and results: Experimental and numerical results

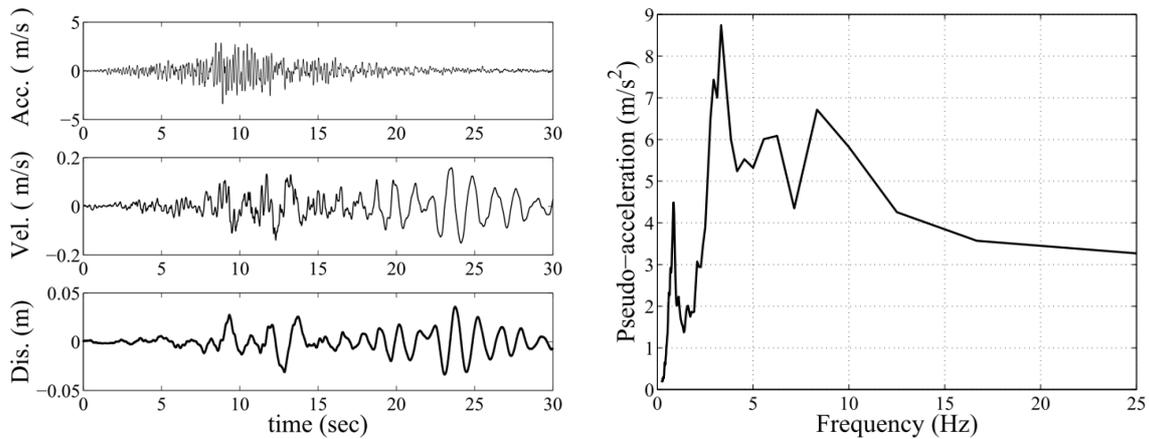


Figure 7: Seismic signal used: (a) Time history acceleration (b) Pseudo-acceleration elastic response spectra (5% damping)

3.4 SCALE 4: HOUSE

A dynamic test has been performed on a timber-frame entire house with walls filled with earth and stones. The test aimed at demonstrating the safe behavior of this structure under seismic loading.

3.4.1 Experimental set-up

Shaking table

The dynamic tests were performed on the uniaxial shaking table of the Mechanical Laboratory of the French Institute FCBA. The table is composed of a 6m × 6m aluminium platform moved by a 250kN servo-hydraulic actuator.

Specimen

The house is a square of 4.65m × 4.65m wide, 3.20m high (at the ridge) and symmetrical according to the N-S axe (solicitation direction, see Fig. 8). The shear walls have six vertical posts with a window and a door respectively between the post 2-3 and 4-5 in the N-S direction. The transversal walls are identical with also six vertical posts and have one window between the posts 3-4. According to a preliminary numerical study, the specimen was placed on the shaking table in order to solicit its weaker direction. It was anchored in steel beams by means of 40 bolts (2 between 2 vertical posts) which are themselves bolted on the table.

Experimental procedure

As said above, the test aimed at demonstrating the safe behavior of this structure under seismic loading. For this purpose, the 100% seismic signal was designed according to the empirical green's function method to be representative of the 2010 Haiti earthquake (see Fig. 7). Then, in order to analyze the non-linear behavior of the structure, the house was submitted to the 200% and 300% signal. To assess the fundamental frequency evolution, the structure was submitted to low-level white noise (0.03g and 0.5mm RMS (Root Mean Square)) between each seismic loading.

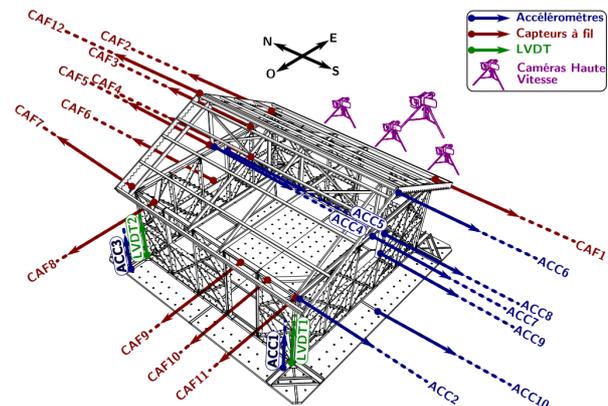


Figure 8: Measurement devices position

Measurement devices

Measurement devices used were placed as depicted on the Figure 8. The accelerometers allowed performing an analysis of the natural frequencies evolution, the draw wire displacement sensors (DWDS) and the LVDTs measurement were compared to the results of the Digital Image Correlation (DIC) made through high speed camera pictures and compared to the results of the numerical modeling. To the knowledge of the authors, it is the first time that a DIC is used to analyze this kind of structure at this scale. For this reason, a focus is made on the set-up used to perform the DIC.

The speed camera (Phantom v641 camera with 28mm lens, 4 megapixels) was used to stare the East shear wall, at a speed of 150 fps (frames per second), in order to obtain the absolute displacement field of the panel by DIC. The acquisition rate was determined so that it is higher than the frequencies involved in the seismic signal (< 30 Hz that is to say minimum 30 fps). The speckle pattern was made by the projection of black, gray and white paint. The average speckle dot diameter was about 1cm. The lighting (4000W,

4K alpha version) was placed at 5m from the wall. This powerful projector was necessary to obtain uniform and intense lighting. Once videos are recorded, measures of kinematic fields are performed by a technique of DIC, with the Tracker software developed by G. Combe and V. Richefeu (see [COM 13]). The accuracy of the measurement is about 0.1 pixel or 0.22mm across the building.

3.4.2 Experimental results

Main results obtained from the analysis of the seismic tests are presented below.

Mode shape and evolution of the fundamental frequency of the building

Before the seismic tests, a modal analysis has been performed by measuring three axis acceleration response at each node of the structure to a white noise excitation. It allowed obtaining the three main mode shapes, natural frequencies and damping ratios (see Tab. 1). The two first modes are similar and are the transversal walls racking mode. The small frequency difference is due to the different positions of the walls (one near the doors (more flexible), one near the windows) and due to the intrinsic differences of the two walls workmanship (weight, geometrical dimensions, etc.). The second main mode is the vibration mode of the shear walls.

Table 1: Natural frequencies and the equivalent viscous damping ratio

Poles	Element	Natural frequency (Hz)	Damping ratio (%)
1a	Transversal wall	5.2	5.2
1b	Transversal wall	5.9	5.7
2	Shear wall	10.9	5.3

After each seismic test, the structure was submitted to a low-level white noise. An analysis of the structure modification resulting from the successive seismic tests was performed by computing the Frequency Response Function (FRF) between the output acceleration at node 7 (ACC7) and the input table acceleration (ACC10) obtained during each low-level white-noise input test (Fig. 8). As a reminder, the FRF is a representation in the frequency domain of the ratio between an output and input acceleration signals. The parameters observed are the variation of the natural frequencies values, shape and amplitude. The successive FRF obtained during each low-level white-noise input test are presented in Figure 9. On this graph, we can notice that progressively after each seismic test:

- The natural frequency, representative of the structure stiffness, decreases.
- The width curve around the natural frequency peak, representative of the structure damping, increases.
- The peak amplitude decreases.

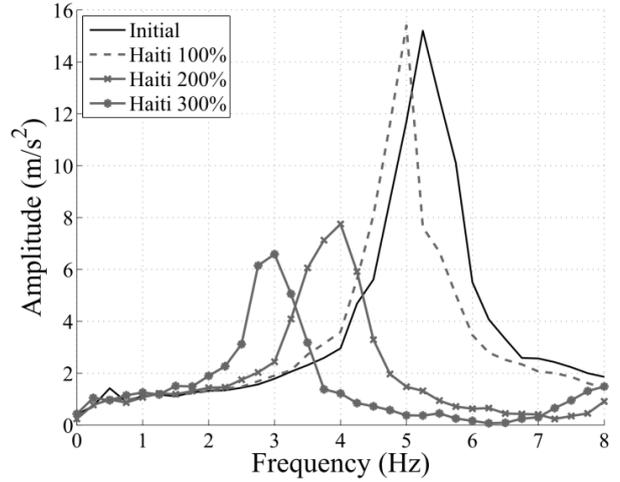


Figure 9: Frequency Response Function

DIC results versus DWDS measures

As explained above, it was therefore necessary to validate the results obtained by DIC. The Figure 10 depicts the comparison of the displacement obtained on the shaking table by the LVDT and by the DIC (for the 300%, Fig. 11). The correlation between the results from both measurement methods is excellent and thus validates the use of the CIN.

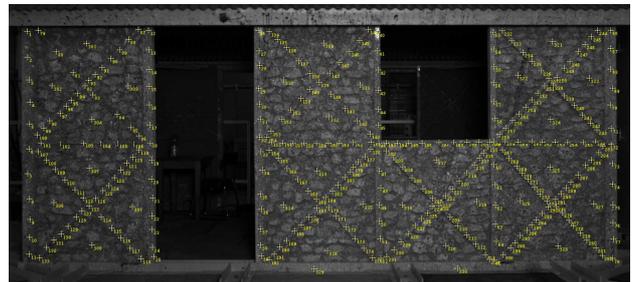


Figure 10: Points whose displacement is analyzed by the DIC

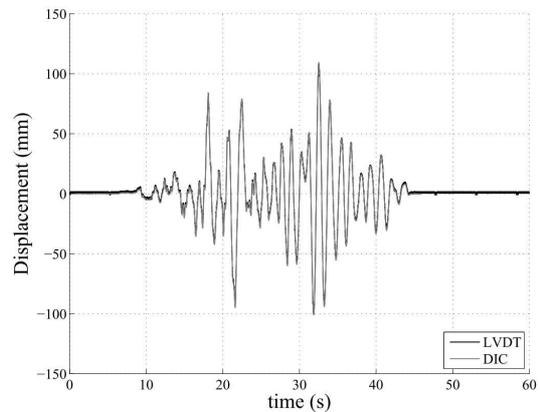


Figure 11: Comparison of the shaking table absolute displacement between the DWDS measure and the result of the DIC

3.4.3 Numerical modeling

Using a simplified FE-model based on macro-elements defined at scale 2, the behavior of the house is predicted and compared to the experimental results for the three earthquakes in a row. The Figure 8a shows this comparison for the top displacement of the shear wall (Fig. 7) for the full duration of the 200% signal and for the time interval of this signal during which the acceleration is maximal (Figure 8b). These results validate the multi-scale approach

linear model of the elementary cell that consists in a braced square filled with earth and stones. The model of a shear wall or an entire house by means of macro-elements defined at scale 2 and whose constitutive model is built with the knowledge of joints behavior, provides a computationally efficient and yet relatively accurate tool for the analysis of the seismic vulnerability of timber-framed houses with earth infill.

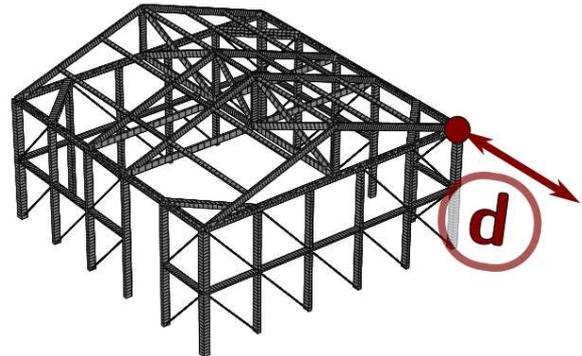


Figure 8: Experimental specimen tested under dynamic loading and its modeling: (a) House subjected to dynamic loading -- Top shear wall displacement recorded via a Draw Wire Displacement Sensor (DWDS) (b) Simplified FE model of the house using macro-element assembly

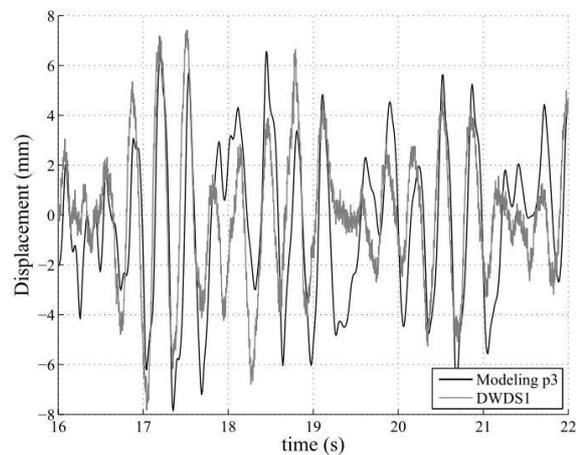
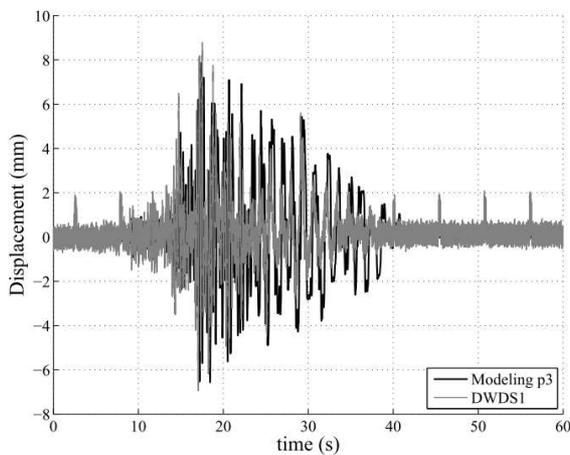


Figure 9: Experimental versus numerical – Shear wall top displacement: (a) Full time history (b) 16-22 seconds focus on the time history

and validate the numerical tool used to predict the behavior of the timber frame structure with infill under seismic loading.

4 CONCLUSIONS

This study presents both experimental and numerical results at different scales of analysis to assess the behavior of timber-frame structures with stones and earth infill under seismic loading. The first scale provides extensive information on the nonlinear dissipative phenomena in the structure. The second scale provides a numerical non-

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