PSEUDO-DYNAMIC TESTING OF FULL SCALE MASONRY STRUCTURES: PREPARATORY WORK

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SUMMARY

In the framework of the research activity of the ELSA Laboratory of the Joint Research Centre, pseudo-dynamic testing of full-scale load-bearing masonry structures is being carried out as the final experimental task of the research project ESECMaSE (Enhanced Safety and Efficient Construction of Masonry Structures in Europe). The objective is to assess the earthquake performance of a selected type of building, a 2-storey terraced house, and also to verify the theoretical, numerical and/or experimental findings obtained so far within the previous tasks of the project.

This report describes the specimens to be tested (geometry, materials and construction), the testing set-up (loading conditions, instrumentation and adopted pseudo-dynamic testing method) as well as preliminary numerical analyses. The pseudo-dynamic test results will be available at the time of the conference and will be presented then.

INTRODUCTION

The research project ESECMaSE (Enhanced Safety and Efficient Construction of Masonry Structures in Europe) aims at an improvement of knowledge in the lateral (shear) design of masonry in order to enhance harmonized European design standards (mainly Eurocodes 6 and 8). Co-funded by the European Commission under the "Horizontal Research Activities Involving SME's" programme, the project is carried out by 26 European partners in total, of which 8 SME's, 7 Industrial Associations and 11 research institutions.

The ESECMaSE project involves several tasks, including theoretical and numerical investigations about the lateral loading on masonry shear walls, optimisation of the masonry material, static cyclic testing of masonry shear walls and dynamic testing of masonry structures. Most of these tasks are reported by companion papers in these proceedings (Meyer, Schermer, Graubner and Kranzler, Fehling at al., Fehling and Stürz, Moussakis et al.). The present paper addresses the final experimental task of the project, namely the pseudo-dynamic testing of full-scale masonry structures.

In the following, the description of the full-scale test specimens and of the testing set-up is given. The results of preliminary numerical analyses performed in support to the design of the experiment are also presented. The pseudo-dynamic tests being scheduled to take place during the period November 2007-February 2008, the results will be presented at the conference.

CONCEPTION, DESIGN AND CONSTRUCTION OF THE TEST SPECIMENS

The type of building considered for the large scale test is the so-called "terraced" house (Figure 1). From the plan, it is clear that such a building is seismically much weaker along its width than along its length. The testing direction has therefore been chosen along the width.

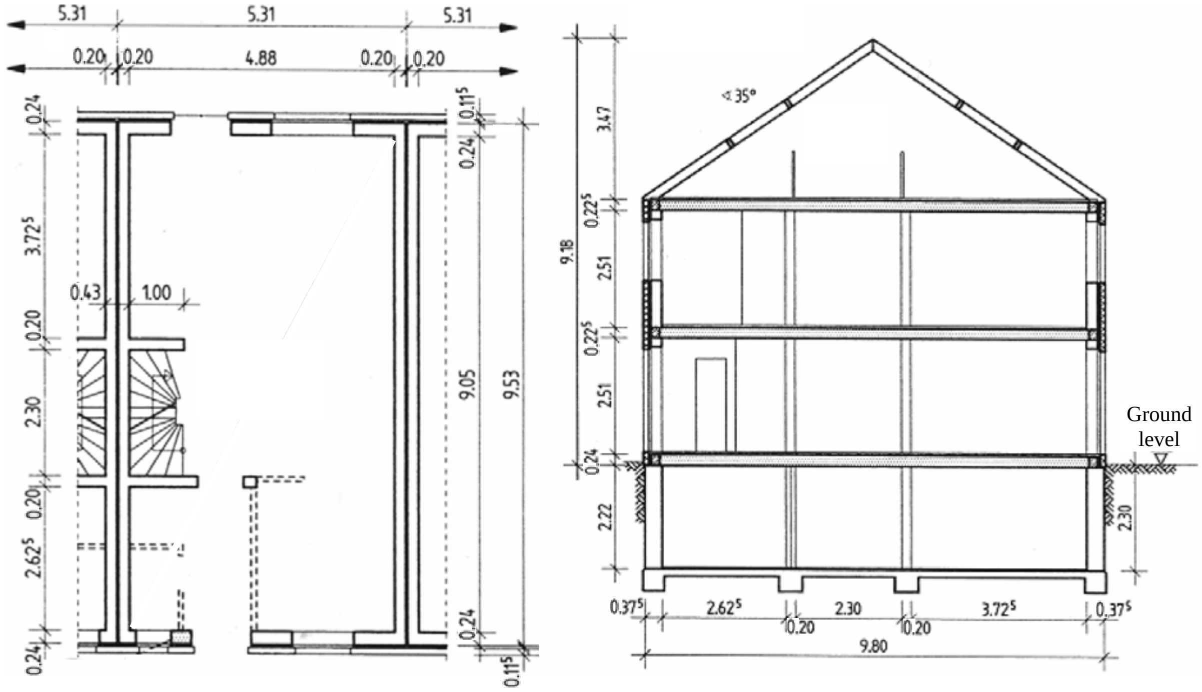

Figure 1: The original terraced house: plan and cut elevation (dimensions in meters)

Several simplifications have been assumed in order to facilitate the interpretation/comparison of numerical/experimental results throughout the whole project. The roof and its supporting structure have been considered as a mere added mass and the cellar has been considered perfectly rigid. The test specimen could therefore have only two storeys built on a rigid base. Also, the arrangement of the masonry walls at each storey has been simplified: in the loading direction, only the walls around the staircase and at the corners have been considered. Finally, in order to accommodate two types of masonry material, clay and calcium silicate, it has been decided to test two half houses separately, in view of the quasi-symmetry of the terraced house with respect to the testing direction. The final test specimen is shown on Figure 2.

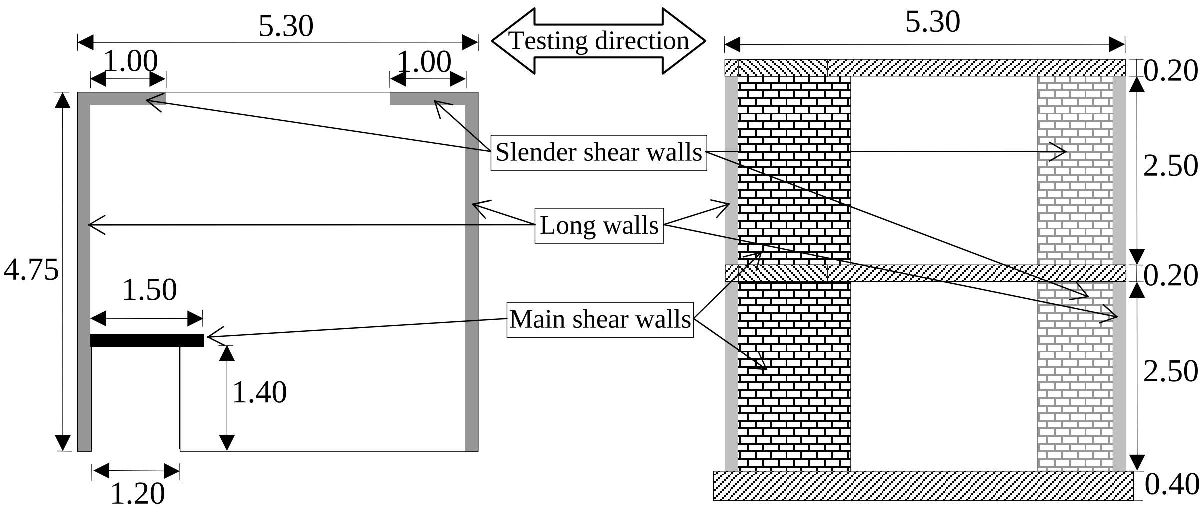

Figure 2: The test specimen: plan and elevation (dimensions in meters)

All the walls of the Calcium Silicate specimen have been built with the same bricks of type 6DF (l x w x h = 250x175x250mm) optimised for the project (Figure 3 left). The walls of the Clay specimen have been built with three different types of bricks (Figure 3 right): the slender shear walls are made of thermal insulated bricks Z17-1-490 (l x w x h = 250 x 365 x 250mm), the main shear wall is made of bricks Z17-1-537 (l x w x h = 375 x 175 x 250mm) filled with concrete and the long walls are made of bricks of type HLZ B 12-0.8 (l x w x h = 373 x 175 x 249mm) with an optimised perforation pattern. The slender shear walls are therefore thicker in the clay specimen than in the Calcium Silicate one (365 instead of 175mm).

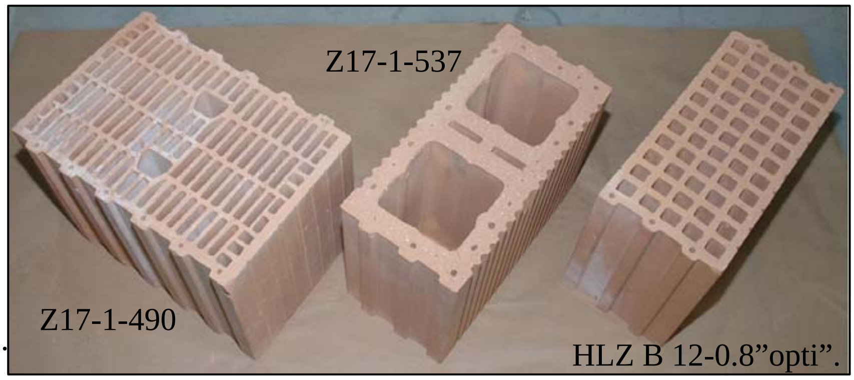

Figure 3: The calcium silicate brick (left) and the three types of clay bricks (right)

In both specimens, the bricks have been assembled with thin mortar bed joints (quick mix KSK-grob for calcium silicate, Planziegel-Dünnbettmörtel for clay). The head joints remained unfilled so that the bricks were simply put side by side, the out-of-plane connection being ensured by the matching vertical grooves, visible on Figure 3. No special connection has been provided between the walls and the concrete base/floor slabs: the bottom layer of bricks has been placed on a thicker mortar joint (cement mortar Z01 for calcium silicate, quality M5 mortar for clay) whereas the concrete slab has been poured directly on the top layer of bricks.

Each shear wall is connected to the perpendicular long walls through a continuous ~2cm thick vertical mortar joint with masonry connectors (i.e. metal strips) inserted at the level of the bed joints. The mortar is the same as the one used under the bottom layer of bricks. There is however a difference between the two specimens: in the CS specimen, the joints between the slender shear walls and the long walls are in the plane of the long walls (i.e. the slender shear walls are effectively 1m wide) whereas, in the Clay specimen, these joints are in the plane of the slender shear walls (i.e. the slender shear walls are 1175 mm wide). In other words, in the CS specimen the "corners" belong to the long walls whereas in the Clay specimen, they belong to the slender shear walls.

The base slab has been conceived so as to allow its adequate fixing on the laboratory floor as well as the successive lifting/transportation of the specimen outside the laboratory for demolition after testing. The concrete floors have been designed for the gravity loads which include an additional dead load of 2.05kN/m^2 (floor pavement, bottom covering and lightweight separating plates) and a live load of 2.kN/m2. In addition to the obtained reinforcing scheme (Figure 4), the central part of each slabs have been further reinforced around/between the anchorage of the actuators (Figure 5) to avoid any possible damage due to the horizontal forces application and thus to ensure a uniform horizontal displacement of each floor. The concrete quality was C20/25 (characteristic cylinder strength 20.N/mm^2) for all slabs and the reinforcing steel was Fe B44X (characteristic yield strength 430.N/mm^2).

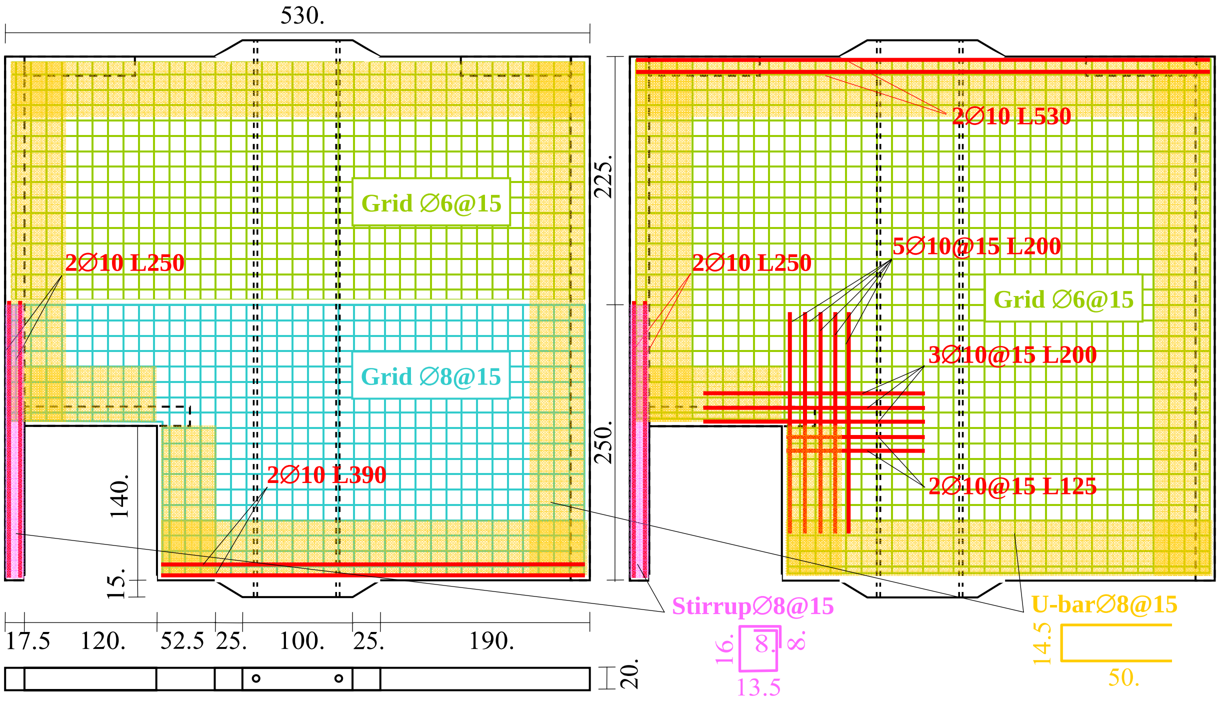

Figure 4: Slab reinforcement: lower face (left) and upper face (right)

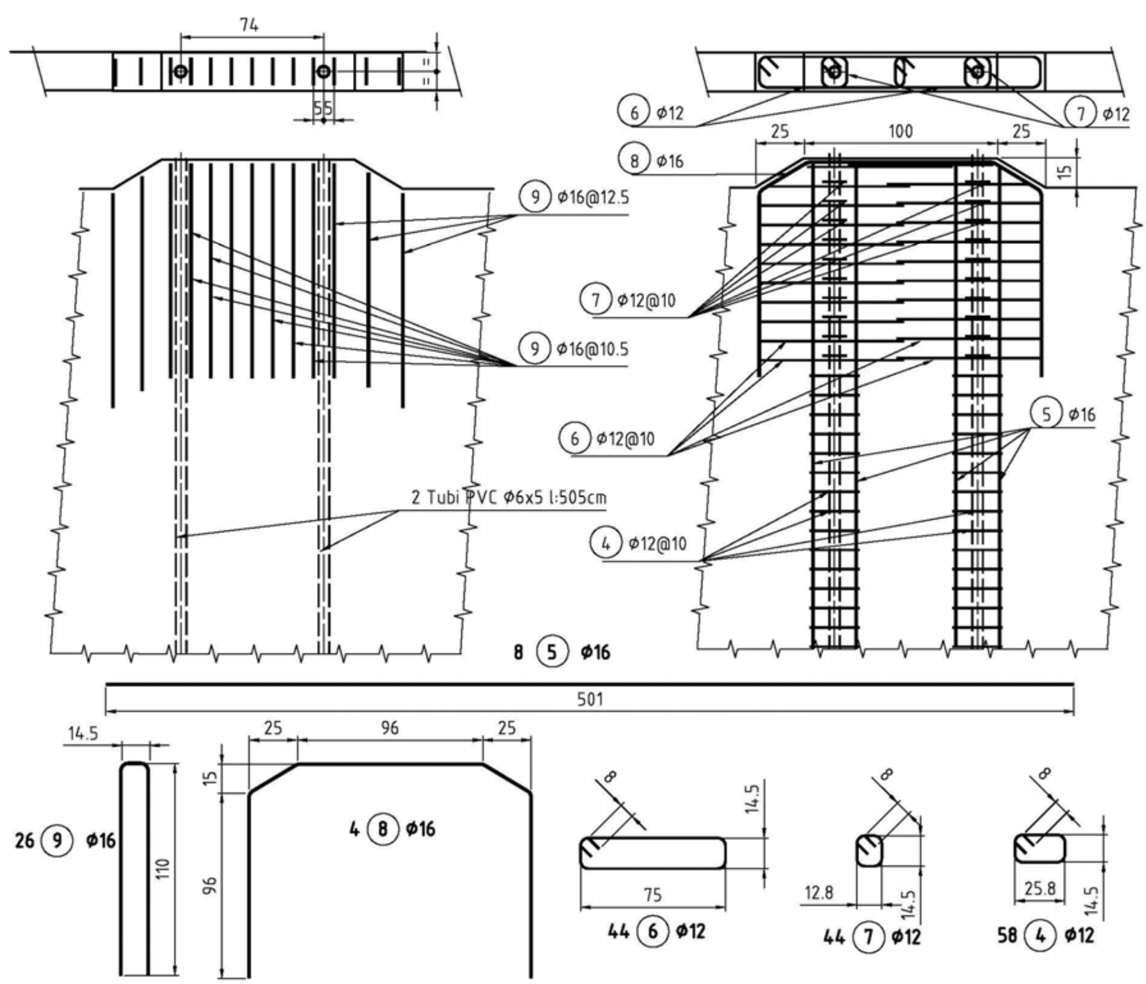

Figure 5: Additional reinforcement

The masonry materials (bricks, pre-mixed mortar and connectors) have been chosen and provided by the German partners involved in the material optimisation task. Also the realization of the masonry walls has been carried out by (German) specialised masons acquainted with the chosen type of masonry, in order to have a uniform workmanship for all the structures tested within the project. Conversely, the reinforced concrete part has been realized by the (Italian) building firm in charge of the civil engineering works on the Ispra site of the Joint Research Centre. The two specimens have been built next to one another in front of the reaction wall (Figure 6) but will be tested one after the other.

Figure 6: The two specimens in the laboratory

DESCRIPTION OF THE TESTING SET-UP

As mentioned earlier, the pseudo-dynamic tests will be unidirectional and carried out on a two-storeys specimen representing half of the original structure. Thus, in the pseudo-dynamic algorithm, the tested structure will have only two degrees of freedom, one translation at each floor level. The movement of each floor slab will be controlled by a pair of hydraulic actuators fixed on both sides and imposing the same horizontal displacement so as to prevent any rotation around a vertical axis (Figure 7). The test specimen being not symmetric, the forces required to reach a given displacement at a floor level will differ in the two actuators but only their sum is necessary for the pseudo-dynamic algorithm. However, the individual values may be used to figure out the contribution of the different shear walls.

With such a test set-up, horizontal displacements perpendicular to the testing direction are not prevented as they should be. However, owing to the two long masonry walls perpendicular to the testing direction, this displacement should remain negligible at least until the onset of

collapse. The actuators have a hinge at both extremities so that they can not prevent the collapse of the specimen. In fact, steel frames will be installed in the inter-storey spaces so as to support the concrete floors in case they fall down.

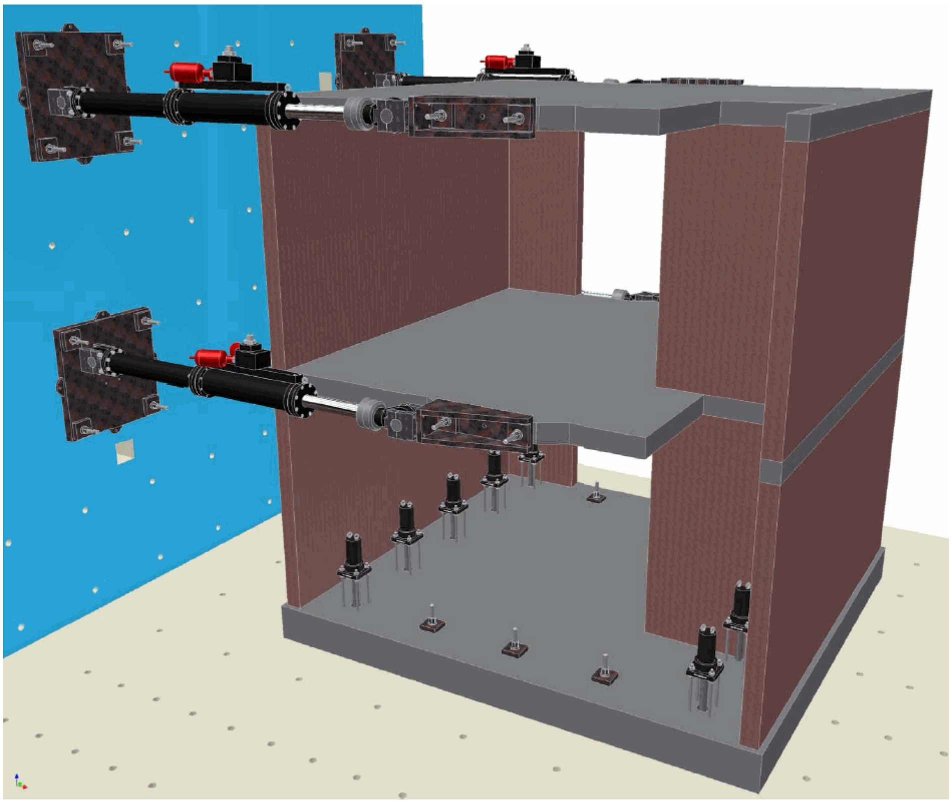

Figure 7: The testing setup

The pseudo-dynamic tests will be carried out under the vertical loading conditions used in the seismic design, that is, according to Eurocode 8, under the dead loads and 30% of the live loads. As mentioned earlier, the dead load also includes the weight of the non structural parts (floor pavement, bottom covering and additional lightweight separating plates) which, however, are not present on the laboratory specimen. Also the roof and the roof supporting structure are missing on the specimen: the corresponding dead load amounts to 1.2 kN/m^2 and should be applied on the perimeter of the upper floor slab. Conversely, will be present on the specimen several elements linked to the testing set-up, the weight of which is significant. These are the hydraulic actuators, their attachments to the slabs, the additional steel reinforcement in the floor slabs and the safety frames positioned on the base slab and on the first floor in order to support the structure in case of complete collapse. Since the shear behaviour of a masonry wall strongly depends on the vertical load acting on it, the gravity load acting on the laboratory specimen should be as close as possible to the one assumed for the seismic design of the original terraced house. To achieve this, water tanks will be positioned on each floor so as to reach the desired vertical loading. The distribution of the tanks has been determined by comparing the results obtained on two finite element models, one of the original house and one of the specimen (see next section).

The instrumentation includes the devices necessary to control the pseudo-dynamic test: the floor displacements are measured using high-resolution linear displacement transducers attached on an unloaded reference frame. Each displacement transducer is associated to an actuator and is attached near to its anchoring. At each step, once the computed displacement

in each transducer is reached, the acting force in each actuator is measured by its load cell. Additional devices (relative displacement transducers and inclinometers) will be installed on the elements likely to exhibit the most significant behaviour. In particular, the shear walls of the ground floor will be instrumented following as much as possible the layout used in the static cyclic shear tests performed in the frame of the project in order ease comparisons. In addition, photogrammetric measurements will also be carried out over a limited area (a shear wall).

The base acceleration is an artificial time history compatible with the Soil B, type I spectrum of Eurocode 8. Successive tests of increasing intensity will be performed in order to identify the different limit states of the structure (serviceability, damage-control, ultimate) and their corresponding loading intensity. A preliminary low intensity test will be necessary to check the functioning of whole installation (control and integration algorithm, acquisition system) and will provide useful information about the elastic properties of the structure (initial stiffness matrix, two first mode shapes, frequencies and damping values).

The test will be performed by using the pseudo-dynamic method according to its continuous version as developed in ELSA (Pegon et al., 2007). The pseudo-dynamic testing consists of the step-by-step integration of the equation of motion expressed in terms of the discrete degrees of freedom (two in the present case)

$$\mathbf{Ma} + \mathbf{r}(\mathbf{d}) = \mathbf{p}(t) \tag{1}$$

where $\mathbf{M}$ is the theoretical matrix of mass, $\mathbf{a}$ and $\mathbf{d}$ represent the unknown vectors of acceleration and displacement respectively and $\mathbf{p}(t)$ are known external forces (seismic equivalent forces in this case). The unknown restoring forces $\mathbf{r}(\mathbf{d})$ are experimentally obtained at every integration step by quasi-statically imposing, by means of the hydraulic control system, the computed displacements. According to the testing system architecture implemented at the ELSA laboratory, a master controller in fast communication with the four actuator controllers will solve the equation of motion.

In a classic pseudo-dynamic method, the execution of every integration step generally takes at least one second of time and includes four phases (Molina et al., 1999):

- a finite-duration period of ramp at the target for the computed increment of displacement,
- a stabilising period of the movement after the ramp,
- a measuring period, and
- a computation period for solving the next step at the integration algorithm.

However, in the adopted continuous pseudo-dynamic method (Figure 8) as a difference with respect to the classical version, the execution of every integration step takes just one sampling period (S.P.) of the digital controller of the control system, e.g. 2.ms in the ELSA implementation (Pegon et al. 2007). The ramp and stabilising periods are reduced to zero duration and the measuring plus the computation periods must be feasible within those few milliseconds of experimental time. The surprising fact is that, since the hydraulic control system is unable to respond significantly at frequencies in the range of the sampling frequency of its controller, e.g. 500.Hz, the missing periods of ramp and stabilising are not needed at all. Under these conditions, the accuracy in the imposed displacement depends basically on the testing speed, which is characterised by the time scale factor λ defined in equation (2). In order to reduce the testing speed while the experimental time lapse is kept

fixed to one S.P., every original time increment in the prototype domain is subdivided into a number of internal steps N_{int} (Figure 8), so that, by increasing this number, the time scale factor is enlarged as

$$\lambda = \frac{\Delta t}{\Delta T} = \frac{N_{\text{int}} \text{S.P.}}{\Delta T} \tag{2}$$

As shown in Figure 8, at every ΔT the required internal values of the input ground accelerogram are linearly interpolated from the original record values. The total number of integration steps in a continuous pseudo-dynamic test can be of several millions, in comparison with several thousands as typically required for a classical pseudo-dynamic test for the same specified earthquake. This fact implies that, on the one hand, an explicit time integration algorithm, such as Explicit Newmark (Molina et al., 1999), can always be used without concerns about stability or integration error and, on the other hand, there is no longer need for an averaging period at the measuring of the force since any high-frequency noise at the load cells will automatically be filtered out in the solution. Such filtering effect is due to the equation response characteristics for the frequency associated to such small time increment. Additionally, working with the continuous pseudo-dynamic method, it is usually possible to perform the test in a shorter experimental time, but with a better accuracy than with the classical method for the same experimental hardware. This is because, as a consequence of the mentioned characteristics of the continuous version, the absence of alternation between ramp and hold periods in the controller reference signal notably improves the control quality.

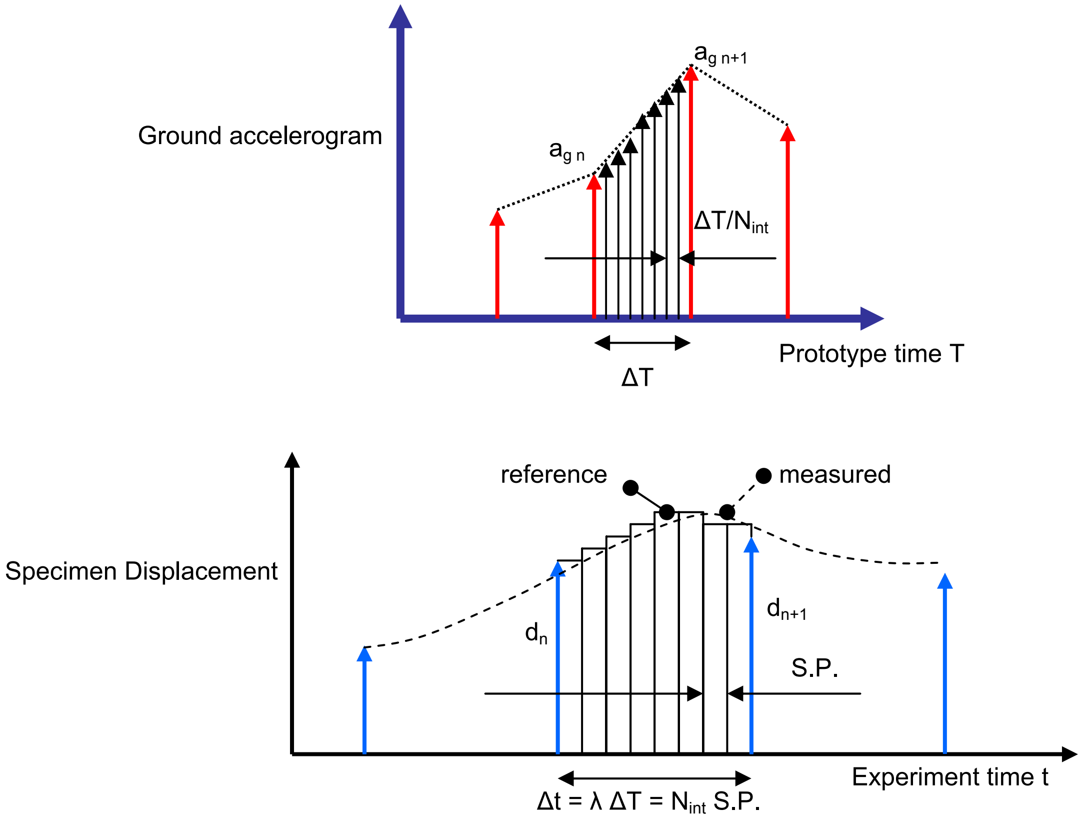

Figure 8: Continuous pseudo-dynamic method

PRELIMINARY NUMERICAL ANALYSES

In order to design a testing set-up able to reproduce realistic loading conditions, preliminary numerical analyses have been carried out on two finite element models, one representing the “ideal” structure (half house with symmetry conditions and distributed additional gravity loads) and another one representing the test specimen (half house without symmetry conditions and with the real additional mass/stiffness linked to the testing set-up, including the water tanks). The objective being merely to assess the suitability of the testing set-up, the different parts of the structure have been assumed linear elastic. In Figure 9, the vertical stresses resulting from the gravity loads are plotted on both models, the displacements being magnified 500 times: even though the vertical displacement of the slabs at the symmetry section is more pronounced in the test specimen (right) than in the ideal structure (left), the distribution of vertical stresses in the masonry walls is quite similar.

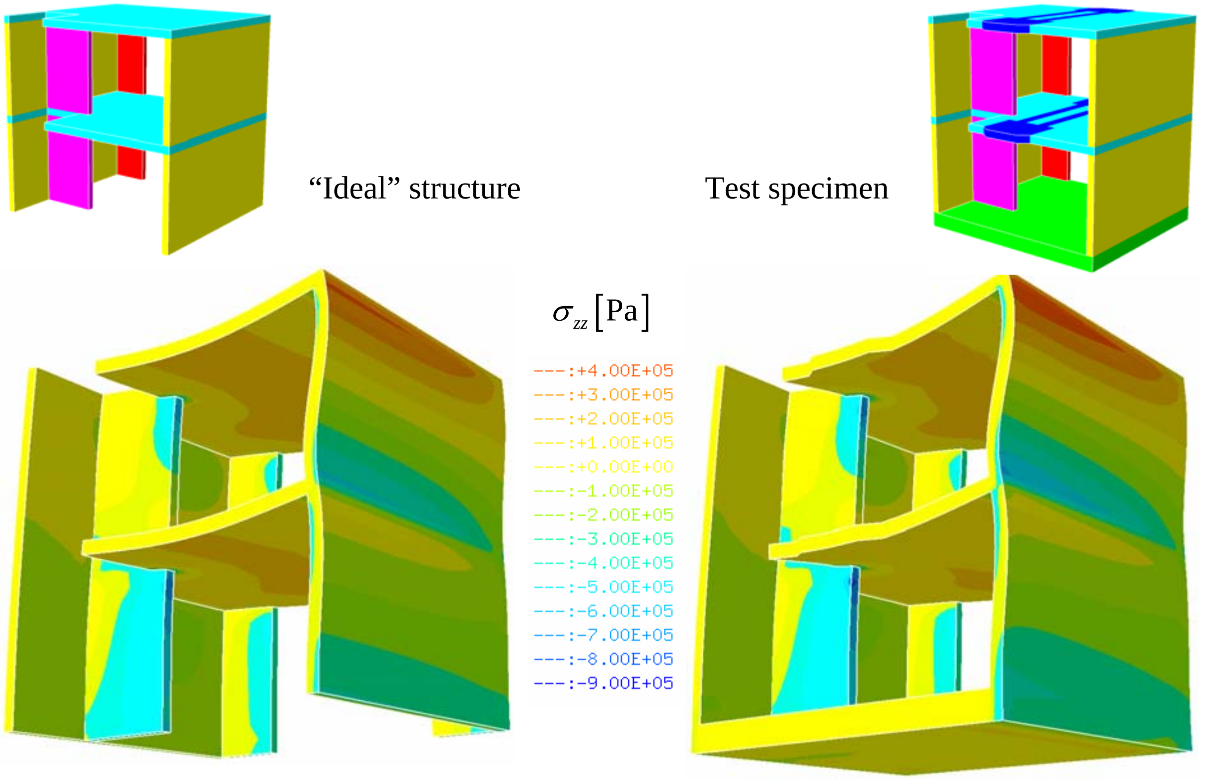

Figure 9: Comparison of the vertical stresses σ_{zz} under gravity loading

The horizontal loading conditions (i.e. on both sides of each slab, same displacement in the loading direction) are suitable since a modal analysis performed on both models gives almost the same first mode/frequency (bending in the loading direction). Also the second mode/frequency of bending in the same direction is very similar. However the test specimen exhibits also an additional mode (bending perpendicular to the loading direction) which is due to the lack of displacement restraint perpendicular to the loading direction. Nevertheless, this spurious mode should not be activated during the pseudo-dynamic test since no loading is applied in that direction.

CONCLUSION

In the framework of the ESECMaSE research project, pseudo-dynamic tests will be carried out on full-scale masonry structures representative of modern constructions in central/northern Europe. The objective of these tests is to assess the earthquake resistance of such kind of structures and, more precisely, to identify the relation between the earthquake intensity and the different limit states (serviceability, damage-control, ultimate).

The specimens to be tested (geometry, materials and construction), the testing set-up (loading conditions, instrumentation and adopted pseudo-dynamic testing method) as well as preliminary numerical analyses have been reported, whereas the results of the tests, in terms of storey force/displacement time histories, hysteresis loops and response of the masonry shear walls will be presented and commented at the conference.

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