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TILTING TESTS FOR MASONRY STRUCTURES: DESIGN AND PRELIMINARY NUMERICAL MODELING

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ABSTRACT

The observation of damages caused by past seismic events demonstrated the high vulnerability of masonry systems, which represent intrinsically diverse and complex structures with resistance to horizontal forces highly dependent on the capacity of ensuring a monolithic behaviour. In this framework, tilting tests represent a low-cost and effective strategy to obtain the ultimate shear and out-of-plane capacities of masonry structures. In this work, the design of a large tilting table facility is introduced. Moreover, a Finite Element micro-model numerical simulation is presented, which constitutes a preliminary validation of the modeling methodology adopted. With this aim, the methodology has been validated on experimental data from the literature. Failure mechanisms and collapse load factors are compared after performing a non-linear static analysis, being a suitable tool to simulate the progressive tilting process. Lastly, a sensitivity study is conducted with the aim to investigate and identify the parameters that influence the future tilting tests.

KEYWORDS: *masonry, tilting tests, dry-joint, micro-modeling*

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INTRODUCTION

Historical masonry structures bear an essential cultural and economic role in our societies. On the one hand, they constitute our civilization history, at regional, national and international levels, with many masonry monuments labelled as UNESCO heritage. On the other hand, they facilitate touristic activities accounting for 10% of the GDP in Europe if linked sectors are considered [1]. However, it is well known that masonry structures are highly vulnerable to earthquakes, mainly because of the heavy weight, low strength and poor connections between structural parts [2, 3]. In particular, the collapse of masonry structures has been responsible for 60% of earthquake death tolls since 1960 [4].

From post-earthquake surveys, collapse mechanisms of masonry structures have been well-documented [5,6]. Due to its brittleness, the OOP (out-of-plane) collapse of masonry walls has been highlighted as a critical issue [5,7]. The first attempt, followed by the scientific and engineering communities to assess masonry structures' seismic stability, is based on the Limit Analysis theory, some examples of which (old and recent) can be found in [6,8-10]. Though neglecting any dynamic effects, these static approaches are still recommended in most existing design codes.

Initially used in rock mechanics engineering [11], tilting tests have significantly spread in the field of masonry structures, giving simple, low-cost experiments, among others [12-15]. They 1) enable the understanding of OOP collapse mechanisms of masonry structures, 2) provide an ideal validation framework for the limit analysis tools previously described [8] and 3) serve as a first step to validate more sophisticated numerical tools [13]. Though an extensive experimental campaign identified many collapse mechanisms [12], this latter lacks a comprehensive repeatability analysis. Moreover, there is still an absence of similar tests concerning multi-leaf masonry structures.

In this work, the design of a tilting test facility is introduced. This latter aims to remove as most as possible experimental uncertainties, with particular attention to the table's flatness and the boundary conditions applied to the specimen mounted on it. Moreover, a Finite Element micro-model is presented. The collapse mechanism of a masonry corner has been simulated through the application of seismic actions as horizontal static forces proportional to the specimen mass, which amplitude increases gradually. In order to validate the results obtained, experimental data from [16] has been used, and the output in terms of collapse mechanism and load factor has been compared. Lastly, a sensitivity analysis is conducted with the aim to investigate and identify the parameters that influence the tilting tests planned.

DESIGN OF A TILTING TEST FACILITY

General description

The tilting table set-up is composed of a steel plate of 10mm-thickness of dimensions 1.5m x 1.5m which allows testing bigger masonry specimens than those presented in the reference [12]. The table is welded to several IPE80 steel profiles (Figure 1). The IPE80 are distributed to increase the global stiffness of the table and reduce its deformation. More specifically, they are located on the plate's external edges and in the middle of it.

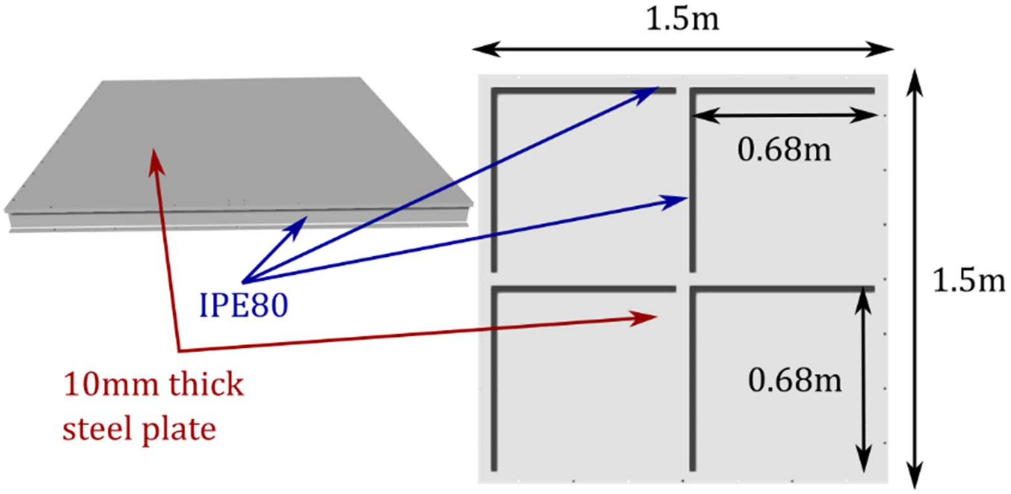


Figure 1: Drawings of the tilting table: dimensions, perspective and below views.

The tilting table is supported by two large steel beams, one of which connected to table through four hinges (Figure 2b). At the other end, a small steel plate with an eye bolt serves as the connection to a steel wire of 8mm diameter that raises the table (Figure 2a). The wire passes through several rollers fixed to a classical testing steel frame, and it is attached to a hydraulic actuator that provides the raising load (Figure 3). Given the limited actuator stroke (h^{act}), a geometrical trick is employed to multiply it at the end of the wire (h^{tilt}) and therefore increase the maximum inclination angle reachable by the tilting set-up (Figure 3b). The wire first goes to the top of the steel frame, then goes back to the actuator and again passes on the top of the steel frame to finally be attached to the tilting table (Figure 3c). In this case, the actuator stroke is multiplied by three. A similar geometrical trick can multiply it by five, seven, etc., though always odd numbers. This technical solution is potentially more reliable and practicable than the one used in the literature (e.g. car jacks [12] or pushing up actuator [15]). Masonry specimens (single-leaf or multi-leaves) will then be laid on the tilting table (Figure 4), while steel blockers prevent first course blocks from moving in any directions (forward or backward). This ensures that the friction that develops at the base of the model is the one of the stone-stone contacts.

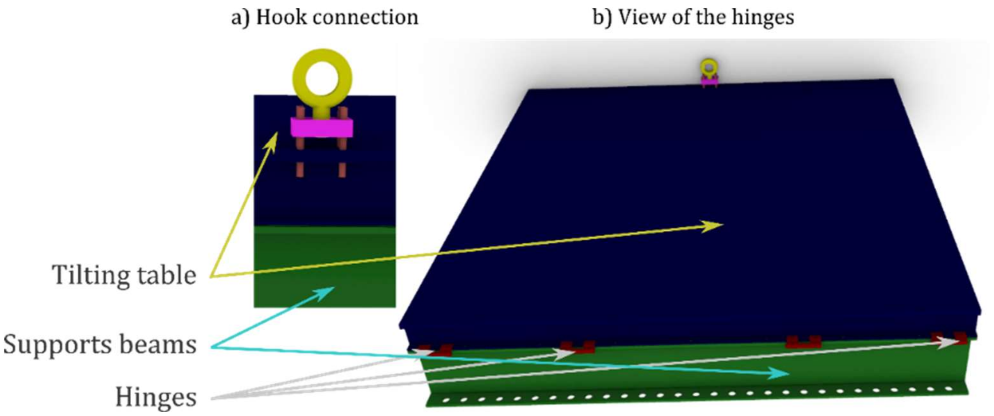


Figure 2: Tilting table connection's details

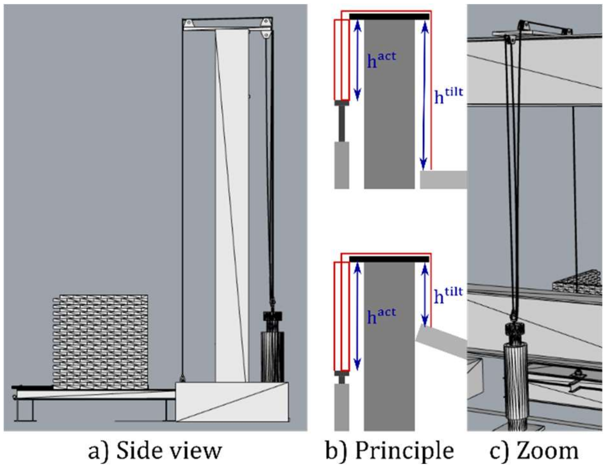


Figure 3: Raising system. a) Side view with a masonry sample; b) principle of the geometrical multiplication; c) Zoom on the rollers and actuator connections

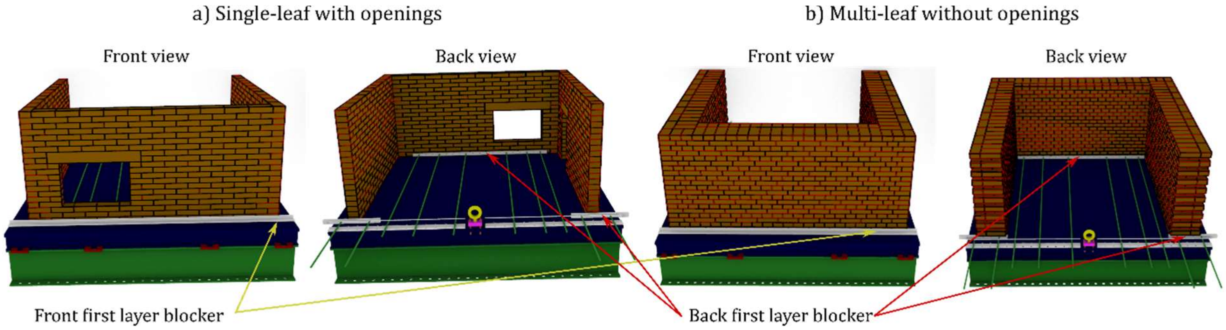
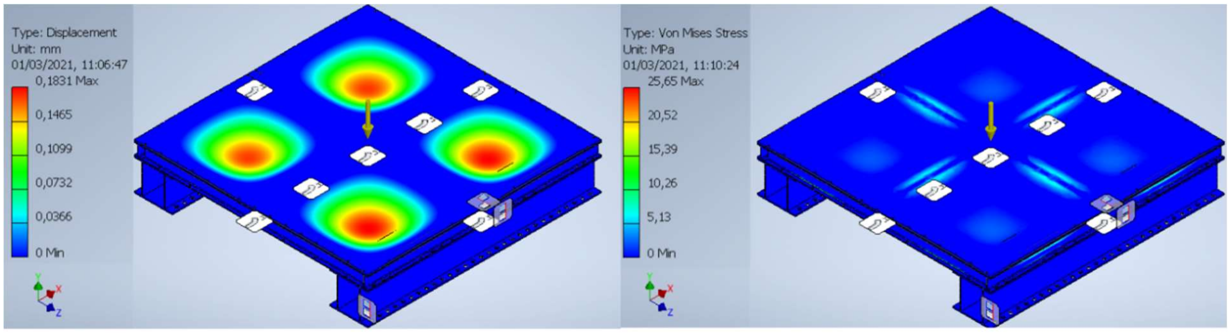


Figure 4: Blocker system (a) Single leaf with openings (b) Multi-leaf without openings

Verification of the deformation and capacity of the testing facility

Previous studies assumed that their tilting table was stiff enough to be considered flat all the time [12-19]. This assumption seems valid when testing small specimens [13-15,17,18], even on thin wooden plates [15,17,18], as well as when larger samples are tested on stiffer tilting tables [12,16,19]. In the present study, the intended masonry models include bigger specimens and, more importantly, higher and thicker structures to study multi-leaves bond pattern (Figure 4). Therefore, the maximum deformation computation appears as, if not a critical, a necessary step to address during its design. The table's deformation has been computed through a finite element model under the commercial software AutoDesk Inventor. The elastic static analysis used a uniformly distributed load of the table's self-weight plus 5.8 kN/m^2 that corresponds to the biggest specimens to be tested on the tilting table. Figure 5 gives the maximum deformation and stress obtained for this simplified load configuration. Given the small values obtained (maximum displacement of 0.18mm and maximum stress of 25.7MPa), the actual design is considered fully satisfactory, and no more complex loading configurations have been tested. Similarly, the rest of the testing equipment (steel wires, rollers, steel connections) have been designed according to the maximum expected loads.



a) Displacement field: maximum of 0.18mm

b) Stress field: maximum of 25.7 MPa

Figure 5: Static elastic analysis of the tilting table: a) displacement and b) stress fields

TILTING TESTS SIMULATIONS

Modeling and experimental set-up

Numerical modeling plays a twofold complementary role in experimental testing: 1) as a preliminary estimation of the testing needs, and 2) as a prediction tool after validation on the conducted tests. In this context, the paper presents a preliminary numerical methodology capable of replicating experimental tilting tests of dry-stack masonry specimens. To this end, a micro-modeling strategy is adopted within the Finite Element Model (FEM) DIANA, where the masonry blocks and their interfaces are modeled explicitly. Given the lack of bonding, all the plastic deformation is expected to occur at interfaces. Therefore, the blocks are considered elastic with an infinite compressive strength. Indeed, given the low height of the specimens, the failure of units themselves is unlikely, also supported by experimental results [16]. At the interfaces between units, a non-linear constitutive law is assigned where plastic relative deformations are expected. More specifically, the interface elements are set to resist only in compression when loaded normal to their plane, while a Mohr-Coulomb failure criterion with a non-associative plasticity flow rule describes the tangential behavior. Tilting table testing consists in a quasi-static and forced-controlled procedure, that provides the inclination angle of the table at incipient failure and the collapse mechanism formed. Therefore, a non-linear static analysis is considered suitable in simulating the tilting process, while the ratio of lateral to gravitational accelerations at any given step presents an equivalence to the tilting angle measured experimentally.

It is clear that a micro-modeling strategy may become markedly time-consuming during the model preparation due to the complexity of the pattern, the number of units and the definition of all possible interacting interfaces. To tackle this issue, the generation of the geometry of masonry walls has been parametrized in the visual programming environment of Grasshopper, together with the automatic identification of interacting blocks and their interfaces. Afterwards, a Python script imports the model in the FEM software, in this case being DIANA FEA. This workflow diminishes drastically the time needed for the model preparation and thus manifests a viable methodology for extensive parametric simulations envisaged prior to and after the experimental testing campaign.

The first aim of the simulation methodology described above is to identify and investigate in advance the main parameters influencing the tilting tests planned. Nevertheless, a preparatory validation is essential and is presented herein. In more detail, the tilting experiments provided by Casapulla & Maione [16] of a masonry corner are simulated.

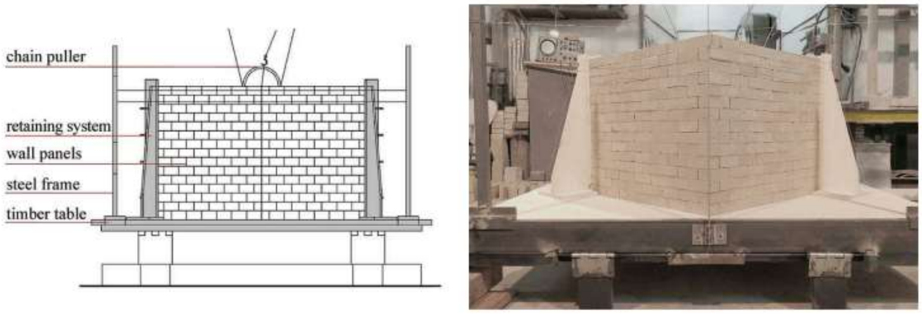


Figure 6: Experimental set-up from Casapulla & Maione [16]

Numerical model

In their work, Casapulla & Maione present the performance of five tilting tests (Figure 6), in which the load factor was obtained by taking into account the critical angle of the table at incipient failure $\lambda=tan(\alpha_{critical})$ [16]. The global capacity of the wall is subjected to a small variability within the experiments (CV=2.7%), and for comparison purposes, a mean experimental value equal to λ=0.33 is assumed.

A uniform mesh of 0.0125mx 0.0125m is adopted, which corresponds to a division of 4 elements across the thickness of the wall, in order to identify the expected out-of-plane behaviour accurately. This choice comes from a performed sensitivity analysis of the results with respect to various mesh refinements. The masonry units are made of a linear elastic isotropic material, which elastic properties consist of Young's modulus equal to 20GPa, Poisson ratio of 0.2 and 1.23 T/m^3 as mass density. The non-linear behaviour is related to the interfaces between the units, modelled as zero thickness elements, that act as potential crack/slip plane and which are characterized by normal stiffness of 1*10^9 N/m^3 and tangential stiffness equal to the 40% of the normal one. Moreover, a gap type interface-opening model and zero tensile strength were set. From the hypothesis of dry stack blocks, zero cohesion is considered and the non-associated flow rule is imposed by assuming zero dilatancy angle and friction coefficient equal to 0.62 (0.55rad), as suggested from the experiments [16]. The boundary conditions of the masonry specimen are modelled by assuming a clamped base and by fixing the displacement in x and y directions of the bricks at the end of the walls, in order to simulate the timber planks. The pushover curve of the masonry corner is shown in Figure 7, displaying a collapse load factor of λ=0.38, slightly higher than the experimental value.

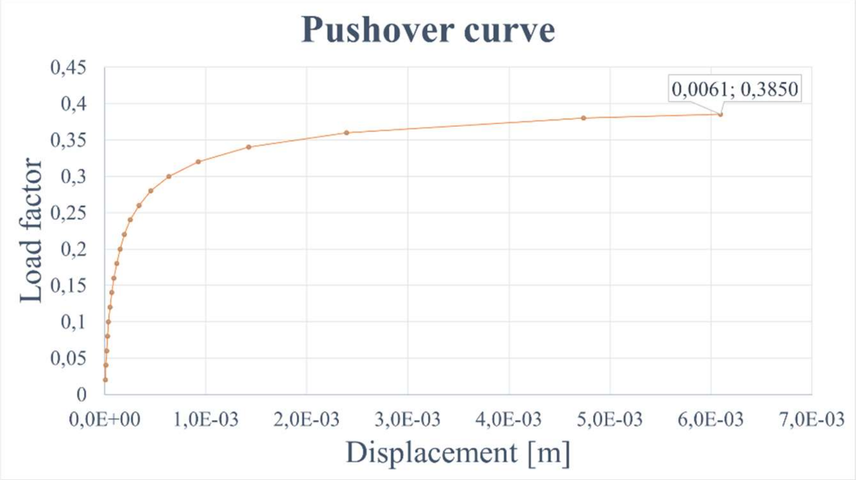
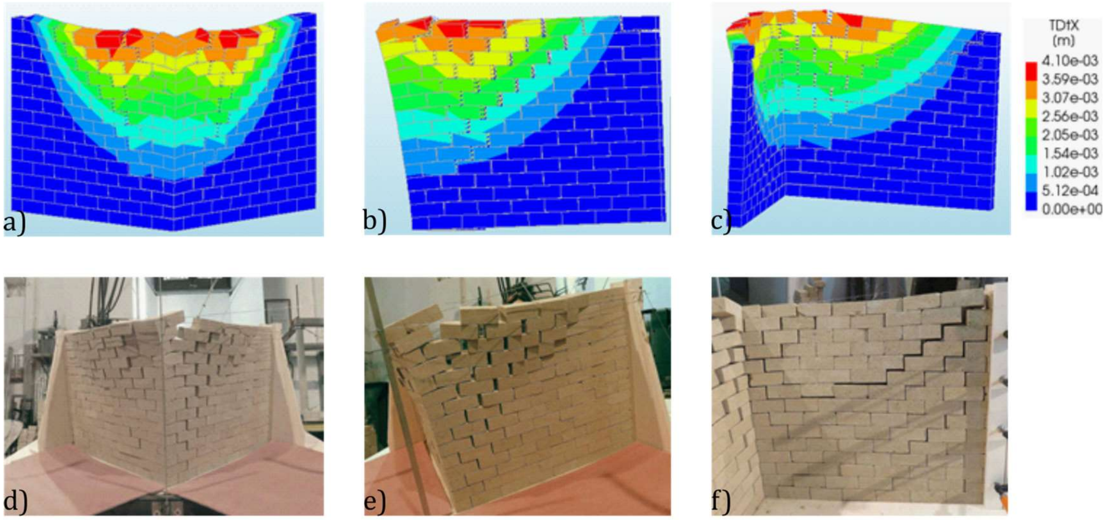


Figure 7: Capacity curve obtained with DIANA FEA, using default material parameters

Figure 8 shows the collapse mechanisms of the masonry corner obtained numerically and experimentally [16]. The model captures almost perfectly the main observed features, showing an asymmetric failure of the blocks. The final crack configuration does not coincide perfectly with the one show experimentally, but this can be addressed to a different collapse instant. Despite this, the mixed behavior given by the combination of a rocking-sliding failure and the horizontal flexure component is very well captured by the numerical model. In particular, Figure 8c shows the inside lateral crack that starts from the clamped edge and continue along the masonry joints up to the middle height of the wall, where starts the horizontal flexure mechanism. The latter is provoked by the lateral component of the load that causes an out-of-plane failure of the top portion of the wall. Moreover, as shown in Figure 8b, the model can clearly capture the diagonal cracks that develops through the masonry, following the staggering ratio.



Front view Side view Internal (back) view

Figure 8: Failure mechanism (a-b-c) Numerical model and (d-e-f) Experimental tests [16]

Sensitivity analysis

Experimental characterization of material properties is always a complex task that is commonly limited to the simplest tests as possible, here friction and weight [16]. With the aim to identify and investigate the parameters that influence the tilting capacity of a masonry structures, and therefore that needs to be experimentally characterized, a sensitivity analysis is carried out. The Young's modulus of the masonry material and the value of normal, tangential stiffness and interface friction angle are examined, considering the values shown in Table 1. Often assumed of negligible influence in force-driven systems, the effect of Young's modulus of masonry units on the quasi-static capacity is first investigated. Four realistic values were compared (Table 1). As expected, this parameter does not influence the results of the test (Figure 9a) and, therefore, does not require specific identification tests for similar force-driven numerical simulations.

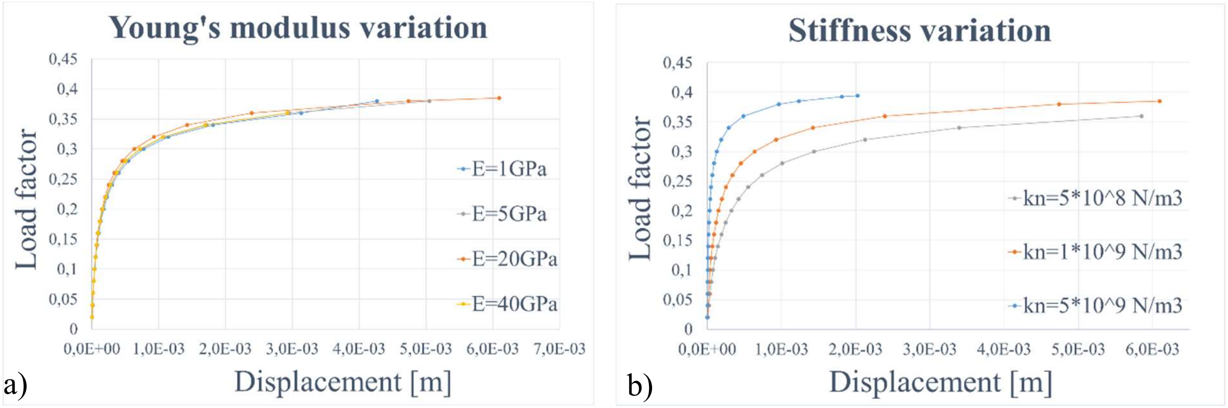


Figure 9: Pushover curves (a) Young's Modulus and (b) Interface stiffness comparisons

The influence of the interface stiffness is studied after. Four values of normal stiffness within the range of $k_n=5*10^8$ - $5*10^9$ N/m^3 have been assumed (Table 1), while 40% of tangential component was adopted as suggested from the literature [20]. The experimental definition of the interface stiffness properties still has only minor contributions in the scientific literature [24, 25]. It remains an element of uncertainty that needs further investigations since, as shown in this analysis, it influences the final response. As expected, the increase of normal and tangential stiffnesses leads to the growth of the capacity curve of the structure in the range of small displacements, but more importantly, it also affects slightly its final capacity (Figure 9b).

The sensitivity analysis herein presented is completed by analyzing the influence of the interface friction angle (Figure 10). As previously mentioned, the failure criterion assumed for the masonry dry joints has been represented by the Coulomb friction law without cohesion, which establishes a linear relationship between shear and normal stresses. The friction coefficient represents a key parameter of the interfaces behavior and it is related to the surface characteristics of the blocks. As expected, it has a very significant impact on the structure's global response, resulting in a rise of the load multiplier together with the friction angle values (Figure 10). The capacity curves show a similar trend for small displacements, whereas they tend to diverge after, resulting in different ultimate capacities. Overall, the numerical methodology presented here is assumed more than acceptable, given the experimental variability, the lack of experimental information about the interface stiffnesses and the lack of confidence indicators in the friction angle and its homogeneity along the whole structure.

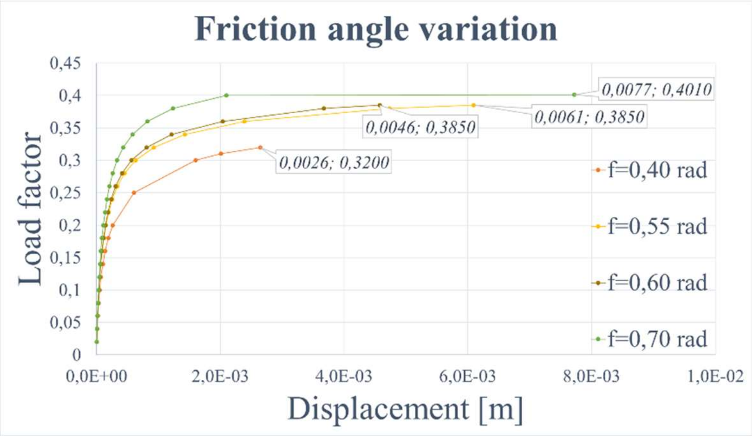


Figure 10: Pushover curve - Friction angle comparison

Table 1: Parameters investigated

Young's Modulus [GPa]	Normal Stiffness [N/m^3]	Tangential Stiffness [N/m^3]	Friction angle [rad]
1	$5*10^8$	$2*10^8$	0,40
5	$1*10^9$	$4*10^8$	0,55
20	$5*10^9$	$2*10^9$	0,60
40	-	-	0,70

CONCLUSIONS

The behavior of unreinforced masonry structure can be experimentally and numerically analyzed by simulating the seismic actions as static horizontal forces by imposing a progressive tilting of the base support. This paper presents the design of a tilting table facility, whose architecture aims at creating a system able to control and to reproduce with accuracy a large number of tests.

Moreover, a Finite Element simulations using a micro-modeling approach has been presented. The numerical methodology is validated against the experimental data from Casapulla & Maione [16], both in terms of failure mechanism and load factor. The numerical model reproduces the global collapse behavior accurately. More specifically, it provides information regarding the crack pattern, showing the mixed failure behavior provoked by a combination between rocking sliding and horizontal flexural modes. Furthermore, the load factor obtained from the pushover analysis presents a relatively good approximation with respect to the mean value given by the experiment. In conclusion, a sensitivity analysis has been developed in order to identify and investigate the parameters that can influence the envisaged tilting table tests. It was shown that the elastic modulus does not affect the results as expected, as opposed to the results obtained from the interface stiffness and friction angle. The normal and tangential interface stiffnesses still represent a non-well defined parameter in experimental works that need further investigation given its effect. On the other hand, friction angle variations provoke a notable (and more significant than all other parameters) change in the analysis. Its heterogeneity along the structure is a key element of uncertainty in a numerical model and therefore should be carefully investigated experimentally.

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