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INVESTIGATION OF RUBBLE-MASONRY WALL CONSTRUCTION PRACTICE IN LATIUM, CENTRAL ITALY

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Abstract. *The 2016-2017 Central Italy seismic sequence severely affected existing unreinforced-masonry constructions in four regions. Those in Latium region proved the most prone to fragmentation because of an unfortunate combination of undressed natural stone units and very low lime content in mortar. Within the framework of a research project funded by the regional government, shake table tests are planned to investigate masonry disintegration as well as possible intervention techniques, as described in a companion paper. All specimens will have natural stone units retrieved from the debris in Collespada, a settlement of the municipality of Accumoli, one of the most affected by the seismic sequence. To push further the representativeness of the specimens with respect to field conditions, wall geometry, masonry* *fabric and mortar recipe are carefully designed. The wall thickness will be approximately equal to 0.5 m, close to average thickness surveyed in the area. Following the survey of several vertical sections of actual masonry walls, the specimens will present unconnected external leaves with a limited nucleus. Based on tests on mortar sampled from collapsed buildings, mortars will be prepared by a part of natural lime every nine parts of sand. Shear tests on sampled mortar delivered apparent cohesion and friction coefficient that are used as preliminary values of a finite-discrete element model, which can account for masonry fragmentation in dynamic non-linear analyses. The numerical model was tested under the envisioned sequence of records, belonging to the Amatrice station and related to the East component, approximately fault normal, of the two main seismic events, 24 August and 30 October, 2016.*

1 INTRODUCTION

On 24 August 2016 a severe seismic sequence started in Central Italy with a M_w 6.0 event originated in the municipality of Accumoli (Figure 1). The sequence counted nine events having $M_w \geq 5.0$ until 18 January 2017, and a M_w 6.5 event on 30 October, the largest earthquake in Italy since 1980, and in Central Italy since 1915. The sequence affected four administrative regions: Abruzzi, Latium, Marches, and Umbria, but the most catastrophic collapses occurred in Latium, in the municipalities of Accumoli and Amatrice [1,2]. The response of historical constructions belonging to this area was particularly unsatisfactory [3], in comparison to other areas such as that of Norcia [4] or to previous earthquakes [5,6]. Already the first event of the 2016 sequence caused very frequently masonry fragmentation (Figure 2), leading to a dramatic failure of the whole construction. When masonry disintegration occurs [7], other response modes such as out-of-plane local mechanisms [8] and a box-like behaviour governed by walls in-plane performance [9] cannot develop [10,11].

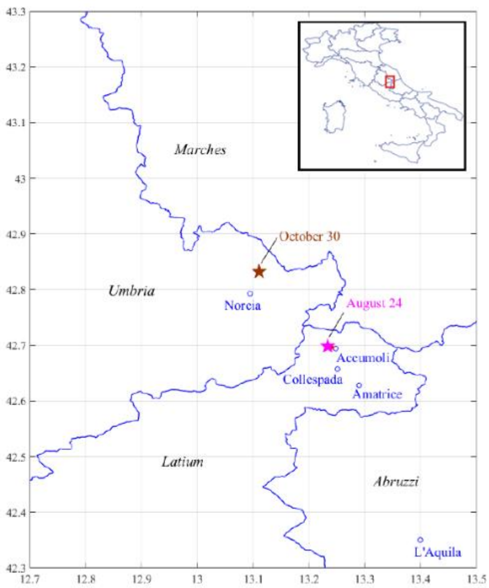


Figure 1: Map of the area affected by the 2016-2017 Central Italy seismic sequence

Figure 2: Amatrice historical centre, after the 24 August event in a snapshot from a movie released by the Firefighters Corps (www.vigilfuoco.tv)

Seismic demand in and around Amatrice was certainly severe, but not more than in Norcia [12], highlighting a higher vulnerability of the buildings in the portion of Latium closest to the epicentral area. In order to deepen the understanding of this poor performance and to design appropriately the characteristics of laboratory wall specimens to investigate possible strengthening interventions [13], an investigation was launched in the area and is briefly reported hereinafter.

2 SURVEY OF MASONRY WALL PRACTICE

Given the large number of collapses occurred in the area, it was possible to survey several rubble masonry walls cross sections. An example is given in Figure 3, wherein it is evident the lack of bond stones and the presence of a nucleus, largely constituted by small-size units. Additionally, horizontal mortar joints are frequently discontinuous and vertical joints are not properly staggered. Despite the use of compact limestone as unit material, because of the poor mortar's properties described in the following, the overall characteristics of the walls were extremely inadequate, as can be shown computing the masonry quality index proposed by Borri et al. [14] or by comparison with wall sections in L'Aquila [15]. The specimens of the envisioned laboratory investigation [13] will reflect these characteristics.

Additionally, wall geometries have been investigated in terms of ground floor thickness, wall height, transverse wall spacing, building number of stories (Figure 4). Average wall thickness was about 0.6 m and height/thickness ratio about 11. These values are smaller and larger, respectively, of those reported for L'Aquila [16], thus contributing to explain the higher vulnerability of the buildings of Accumoli and Amatrice. An approximate thickness of 0.5 m will be used for the wall specimens to be tested on the shake table [13].

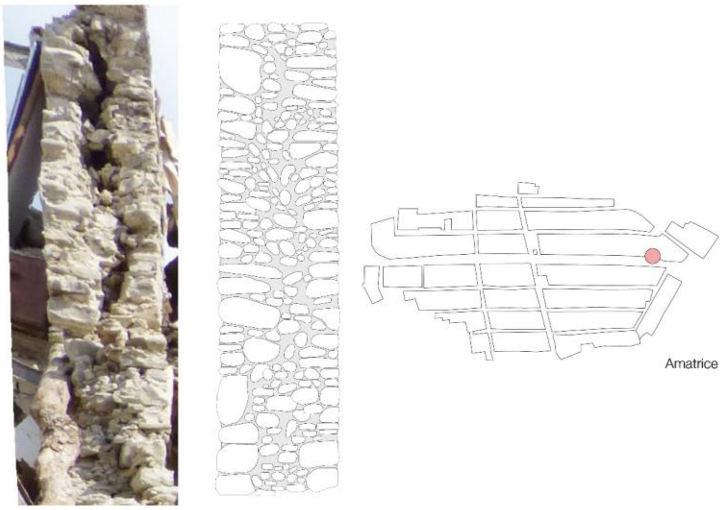


Figure 3: Survey of vertical section of a masonry wall in Amatrice

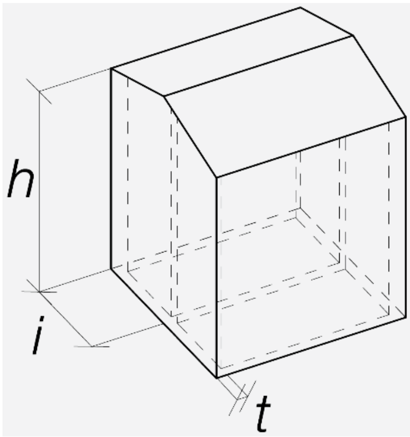
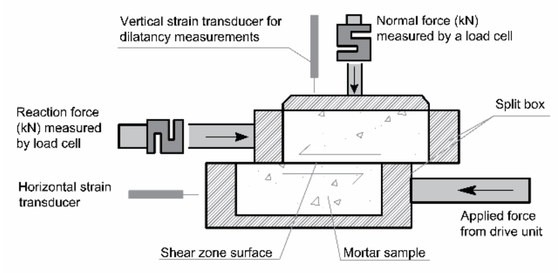


Figure 4: Survey of walls geometry

The walls to be tested will be manufactured with natural stone units retrieved from the debris of the buildings in the settlement of Collespada, within the municipality of Accumoli (Figure 1). However, mortar cannot be retrieved in the same way, and will be manufactured for this laboratory campaign. Therefore, it is necessary to properly design the mortar recipe in order to make it representative of local construction practice. The mortar sampled from buildings severely damaged by the 2016-2017 seismic sequence was investigated within a larger endeavour [17,18], involving also Marches and Umbria regions. On mortar samples, mechanical, physical and chemical experimentations were performed.

Mechanical investigations involved direct shear tests (Figure 5a), performed cyclically for different normal-stress levels. Values for the Latium samples are reported in Table 1, highlighting an average friction coefficient of about 0.9 and cohesion of about 25 kPa. These values will be used in the numerical model presented in the following. Cyclic behaviour resulted remarkably stable (Figure 5b).

a) 

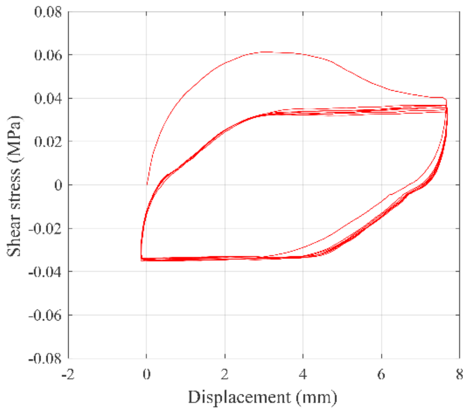
 b)

Figure 5: a) Direct shear test, b) Example of shear force vs. displacement curve

Table 1: Synthesis of direct shear test (maximum shear stress, Latium)

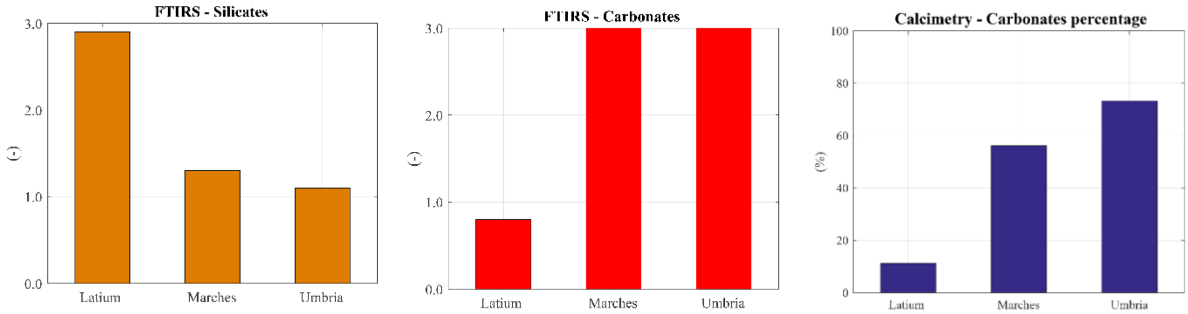
	μ [-]	c [kPa]
max	1.01	44.2
min	0.77	10.8
mean	0.89	26.4
std dev	0.07	8.2
CoV	0.08	0.31

Physical and chemical investigations have been used to determine the recipe of the mortar mix, such as infrared spectroscopy, calcimetry and X-ray diffraction. Infrared spectroscopy identifies chemical substances by exploiting their interaction with infrared radiation. Molecules absorb radiations matching their resonant frequencies, thus allowing their detection. A qualitative analysis of the associated Fourier-transform spectra, confirmed by crystalline phase analysis performed by X-Ray diffraction, allows recognising the very large presence of silicates in Latium mortars in comparison with those in the other investigated regions corresponding to a lower content of carbonates (Figure 6a,b).

Since carbonates can be present in mortar both as binder and as aggregate, the identified proportion represents an upper bound for actual lime proportion. Nonetheless, it is interesting to observe that even such an upper bound is very low in Accumoli and Amatrice. This qualitative observation is confirmed by quantitative tests performed with a calcimeter. In this instrument the carbonate is exposed to hydrocloridic acid and the pressure increase related to the released carbon dioxide is measured, hence estimating the mortar carbonate percentage at about 11% (Figure 6c). Such low presence is an indicator of a seismic risk awareness lower than in other areas such as that of Norcia [19]. Based on previous results, a proportion of 1 lime part by 9 sand parts will be intentionally used when manufacturing the unretrofitted and retrofitted walls to be tested on the shake table [13].

Having determined a tentative composition of the mortar, standardised 40 mm × 40 mm ×

160 mm specimens were manufactured to perform bending (Figure 7) and compression (Figure 8) tests according to EN 1015-11 [20]. As expected, flexural response is rather brittle, while compressive one is remarkably ductile. Average strength values in bending and compression at 28 days are 0.13 MPa and 0.40 MPa, respectively. Tests were performed also at a reduced number of days in order to preliminarily investigate the possibility of constructing natural-scale walls with such poor mortars.



(a) (b) (c)

Figure 6: Mortar analysis: a) Fourier-transform infrared spectroscopy, silicates; b) Fourier-transform infrared spectroscopy, carbonates; c) Calcimetry, carbonates percentage by weights

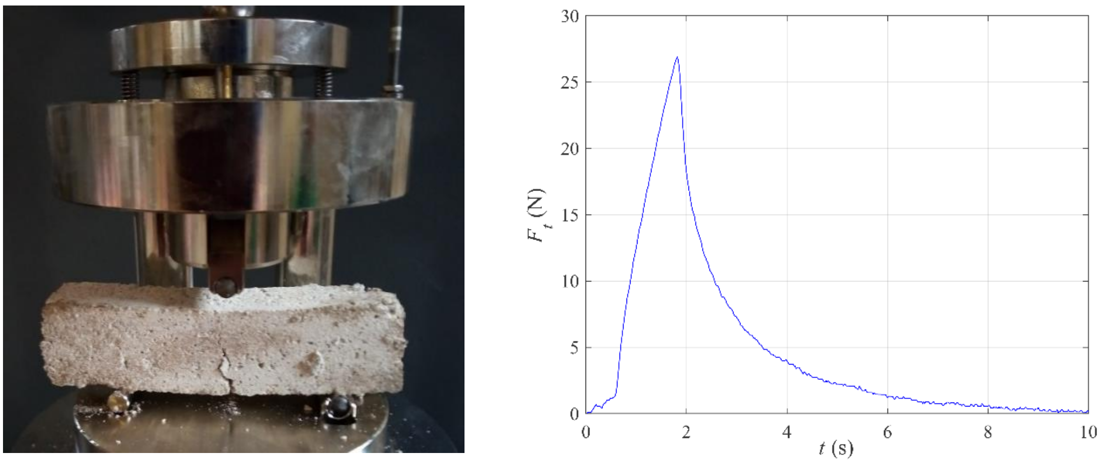
a) 

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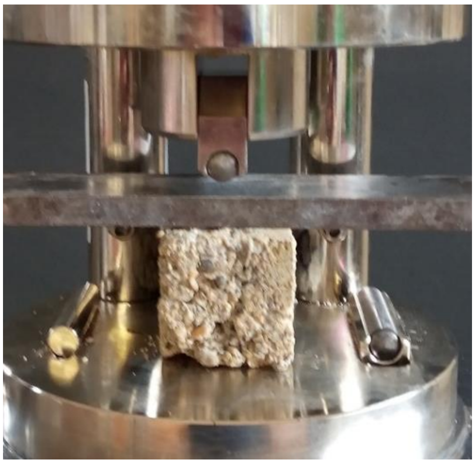
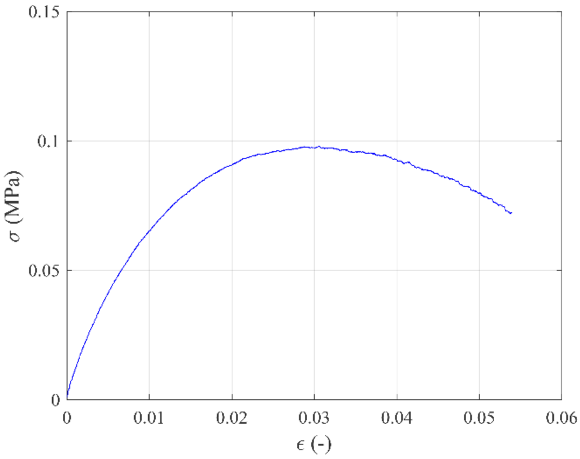
Figure 7: a) Bending test on mortar prism, b) Force time history

a) 



b)

Figure 8: a) Compression test on mortar, b) Stress-deformation plot

3 NATURAL ACCELEROGRAMS SELECTION FOR THE SHAKE TABLE TESTS

Shake table tests will investigate the propensity of masonry to fragmentation and possible strengthening techniques. Walls will have a natural scale and will be loaded along the out-of-plane direction. The walls will rest on a reinforced-concrete foundation and horizontal displacement at the top will be restrained, while the vertical one can develop freely [21]. Additional information are given in [13]. A set of numerical analyses was performed to select the appropriate accelerograms, and their scale factors.

The model was implemented in LS-DYNA, a code capable of simulating dynamic problems [22]. The wall was modelled within a combined finite-discrete element framework, as done elsewhere [23], in order to represent the actual morphology of the wall cross-section, which is a crucial element in case of out-of-plane seismic loads [24]. The model accounts for the elastic response, the formation of cracks and their closing down, the finite displacement of blocks as well as the formation of new contacts. All materials are linear elastic, the interfaces between blocks initially in contact react to both compressive and tensile forces, and a standard penalty method governs the contact behaviour through linear springs. Springs fail in tension when the normal stress on the contact surface is greater than the normal failure limit stress. Similarly, springs fail in shear when the shear stress is greater than the shear failure limit stress. After that, a frictional sliding is possible and is governed by static and dynamic friction coefficients.

The physical walls will have two external leaves and a central nucleus made of smaller units. Such arrangement is reproduced in the numerical wall, although with a simplified geometry (Figure 9a). Contact parameters have been preliminarily calibrated based on previously described mortar tests. Given that the experimental program was motivated by the 2016-2017 seismic sequence, the numerical model was tested using the records of the Amatrice station, already in place at the time of the first event. The East component, approximately fault normal and more severe, was selected and the two main events of the sequence, 24 August and 30 October, were chosen as representative of possible damage accumulation [12]. However, in order to study the incremental response of each wall, the amplitude of the records, both horizontal and vertical, will be scaled according to a non-dimensional factor S_f increased by

0.25 steps. In Figure 10 it is possible to observe the sequence of records preceded by the initial slow application of gravity, necessary to avoid unrealistic vibrations. The response and the damage accumulation can be monitored by means of the variation of the distance between the two external leaves at a specific height (Figure 9a). The corresponding time history is given in Figure 11, and it highlights that failure (Figure 9b) occurs for S_f = 0.50 of the 30 October 2016 event.

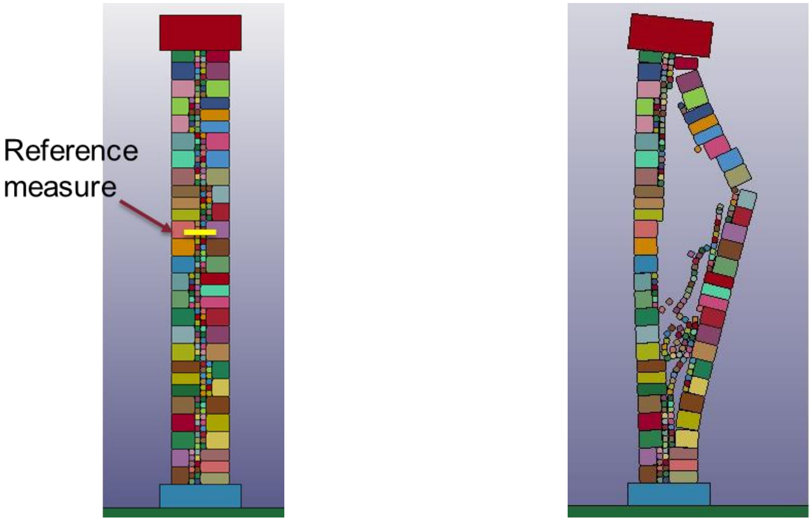
a)  b)

Figure 9: a) Finite-discrete element model, b) Damage mechanism. Colours used only to emphasize unit discretisation

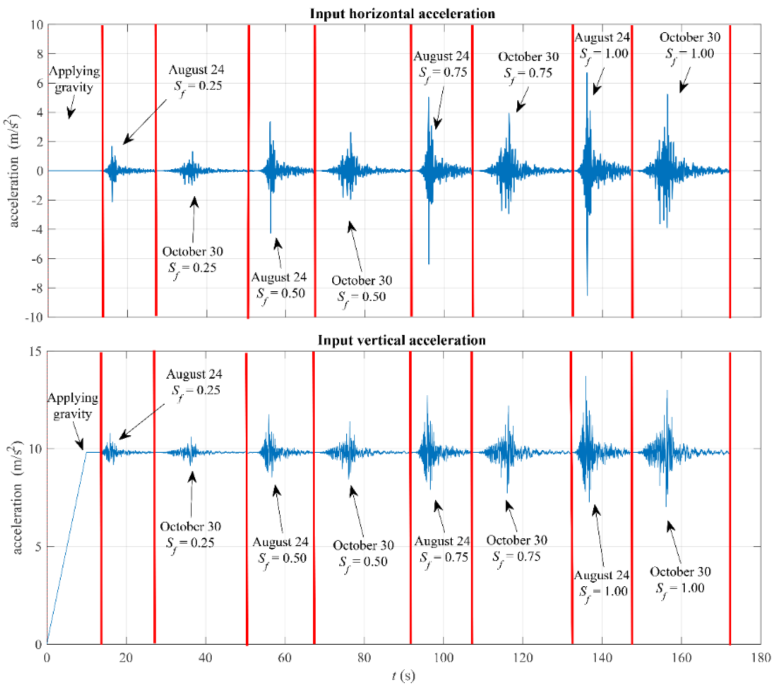


Figure 10: Input horizontal and vertical acceleration time histories (time lapse between two events 2 s)

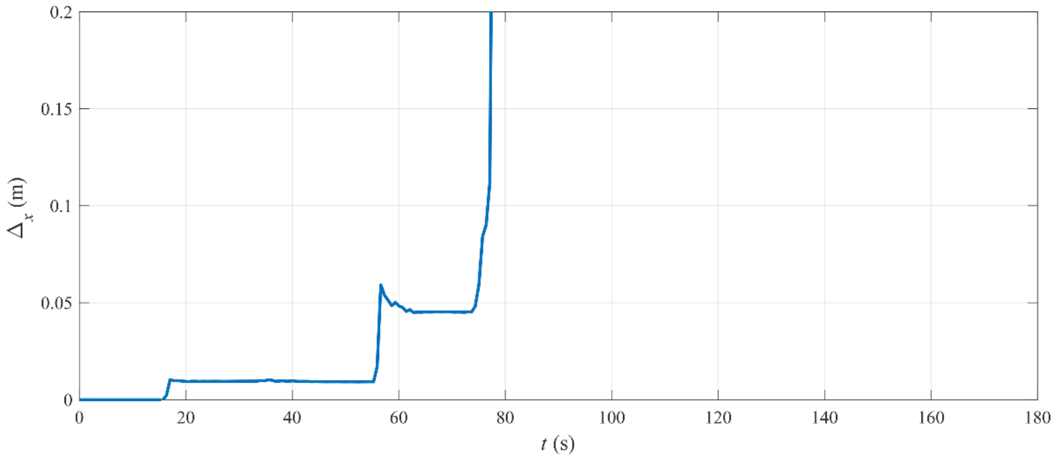


Figure 11: Variation of the distance between the external leaves (Figure 9a) time history

4 CONCLUSIONS

The 2016-2017 Central Italy seismic sequence has determined a dramatic performance in historical masonry constructions in the portion of Latium region affected by severe ground shaking. To contribute explaining this behaviour, construction practice was investigated. Rubble masonry wall sections were surveyed, highlighting the lack of bond stones, the use of small-size and undressed units with an inadequate arrangement of mortar joints, evidencing a poorer quality compared to those in L'Aquila. Geometrical features such as wall thickness and height/thickness ratio show higher vulnerability compared to values surveyed again around L'Aquila. Infrared spectroscopy, calcimetry and X-Ray diffraction measurements showed a very low lime percentage in the mortar, a possible indicator of a lower seismic risk awareness compared to Norcia.

All these characteristics will be considered in the design of wall specimens to be tested in unstrengthened and strengthened conditions on a shake table. Moreover, in order to select the proper sequence of records to be used as excitation, a finite-discrete element model was implemented. The model is tested with a sequence of accelerograms obtained by scaling those recorded in the Amatrice station during the two main events of the seismic sequence, accounting for both the east-west and up-down components. The tentative scale factor adopted will allow for about four tests before the unstrengthened wall reaches failure.

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