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Effect of the vertical component of ground motion on a rubble masonry wall model

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Abstract

In this paper the influence of the vertical component of ground motion on the performance of an unreinforced masonry wall is analysed using sets of one-component and two-component ground motions. The set of motions represents the actual seismicity of L'Aquila, while the investigated wall mimics an experimental specimen with two unconnected external leaves and a rubble core. The model falls within the mixed finite element method – discrete element method and accounts for crack formation, complete separation and new contact formation. The modelling strategy is capable to simulate the out-of-plane seismic response and the progressive loss of compactness of the wall up to collapse with the separation between the two external leaves. The vertical component increases the fragility of the wall and confirms the relevance of vertical ground motion for very vulnerable constructions. Nonetheless, to worsen the response, the vertical component needs to overcome specific, non-negligible intensity measure thresholds.

Keywords: Numerical analysis; Finite-discrete element method; Masonry disintegration; Masonry fragmentation

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1. Introduction

The past decade saw a great interest in understanding the role of vertical earthquake motion on the severe structural damage observed at sites near the fault, where horizontal and vertical ground motions are often strong and synchronized (Casolo 2001; Chávez and Meli 2012; Collier and Elnashai 2001; de Nardis et al. 2014; Di Michele et al. 2020; Di Sarno et al. 2011; Diotallevi and Landi 2000; Lagomarsino et al. 2020; Mazza et al. 2017; Salazar and Haldar 2000; Verderame et al. 2011), and can damage unreinforced masonry (URM) buildings (Al Shawa et al. 2021; Liberatore et al. 2019) and churches (Marotta et al. 2015, 2018). With the aim to investigate the response of URM buildings under vertical seismic actions, a laboratory campaign was carried out by Kallioras et al. (2022). The experiments comprised a series of cumulative incremental shake-table tests on three nominally identical buildings up to near-collapse conditions. The tests showed that the in-plane behaviour of URM piers with prevailing flexural-rocking response was not affected by vertical accelerations. A different testing series investigated the response of a wall section with three separate leaves, loaded out of plane (de Felice et al. 2022). The wall rested on a reinforced concrete foundation and was restrained at the top in the horizontal direction, while the vertical displacement was free. In this paper, the role of the vertical component on the performance of this URM wall is numerically analysed using sets of one-component and two-component ground motions. The set of motions represents the actual seismicity of L'Aquila, while the investigated wall mimics an experimental specimen with two unconnected external leaves and a rubble core.

2. Rubble masonry model and numerical simulations

The wall under examination is that tested on the ENEA shake table (Fig. 1a), and is further described elsewhere (de Felice et al. 2022; De Santis et al. 2021). The wall is 4.20 m tall and 0.50 m thick and has two unconnected external leaves and a rubble core made of smaller elements poorly bonded with mortar. In order to study the effect of the vertical component for a larger set of records than those used in the physical experimentation, a numerical model is implemented in LS-DYNA (Hallquist 2006; Munjiza 2004; Smoljanović et al. 2013), assuming a rigid restraint at the top. Similarly to what was done by the authors in previous studies related to full wall enclosures (Abrams et al. 2017), wall assemblies without roof (AlShawa et al. 2017) under horizontal and vertical ground motion (Liberatore et al. 2019), the model presents discrete block elements and contact interfaces between them (Fig. 1b). Each of the 206 blocks is discretised in 8-node solid finite-elements (FEs), with a total number of 27,334 nodes and 6028 FEs. The material has a linear-elastic behaviour (Young's modulus E = 1400 MPa, Poisson's ratio ν = 0.2, and density ρ = 2000 kg/m^3). The adopted strategy for the contact interfaces allows the modelling of connections that transmit both compressive and tensile forces, while failure can occur only for tensile forces.

The model in Fig. 1b is excited by 83 sets of ground motion, selected by Manfredi et al. (2022) to be compatible with the hazard curve of L'Aquila, soil type B. Among the two horizontal components, that with the largest peak ground velocity (*PGV*) was selected. Horizontal component *PGV* varies between 4.14 and 83.02 cm/s, with average equal to 23.32 cm/s. Vertical component *PGV* varies between 1.52 and 30.63 cm/s, with average equal to 9.32 cm/s. The model was excited by the selected horizontal component alone (Fig. 1c), or by this horizontal component and the vertical one (Fig. 1d). The response of the model is described by the variation, δ, of a reference measure (Fig. 1b).

Some examples of wall response are given in the following. In Fig. 2 wall disintegrations taking place for both excitation scenarios are presented. In Fig. 3 is given an example of elastic response under horizontal component alone, while the addition of the vertical component delivers severe damage. In Fig. 4 the horizontal component is able to induce fragmentation, while the combination of horizontal and vertical component is capable of triggering leaf separation but not failure.

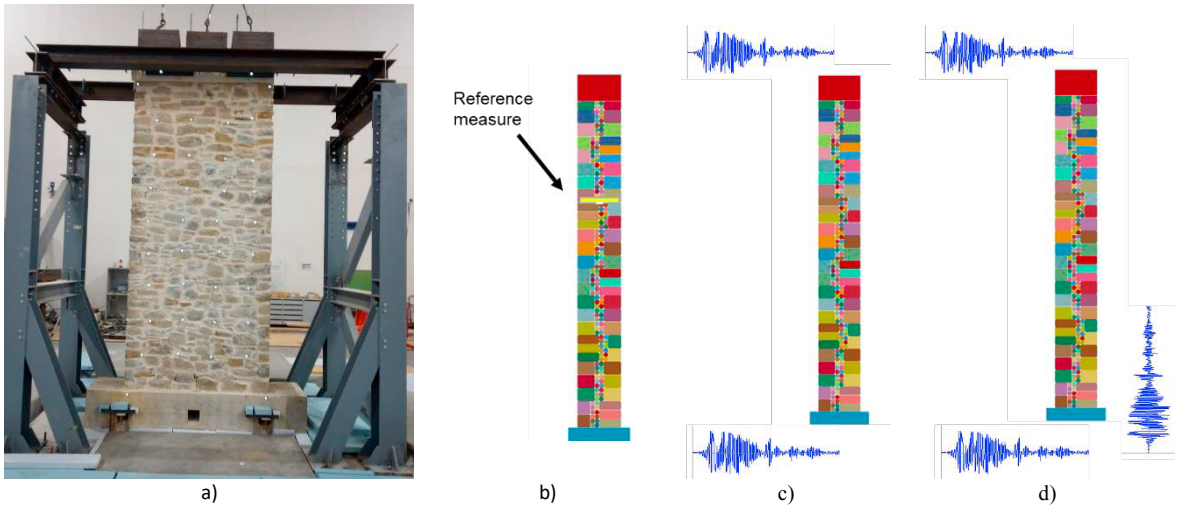


Fig. 1 a) Wall tested on the ENEA shake table; b) numerical model and reference measure (colours are for presentation only, the model is homogeneous); c) horizontal ground motion only; d) horizontal and vertical ground motion.

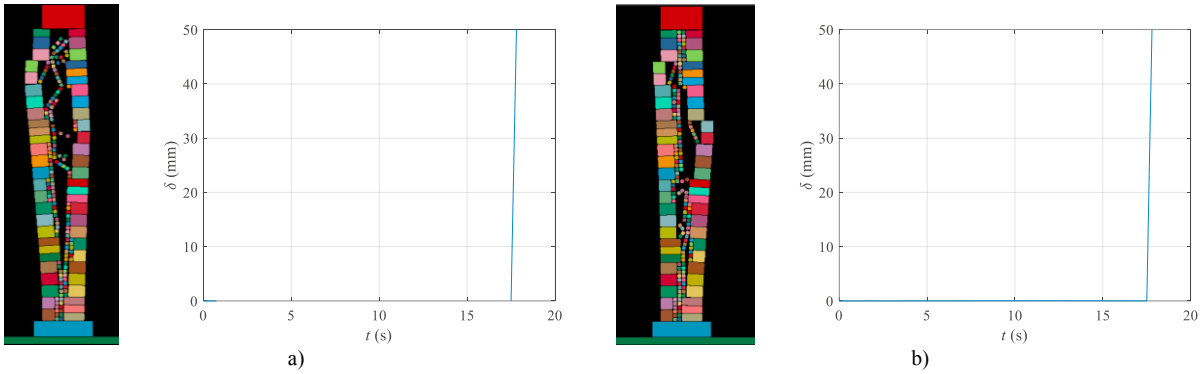


Fig. 2 Failure occurs in both load cases. Wall response for: a) horizontal component only; b) horizontal and vertical components.

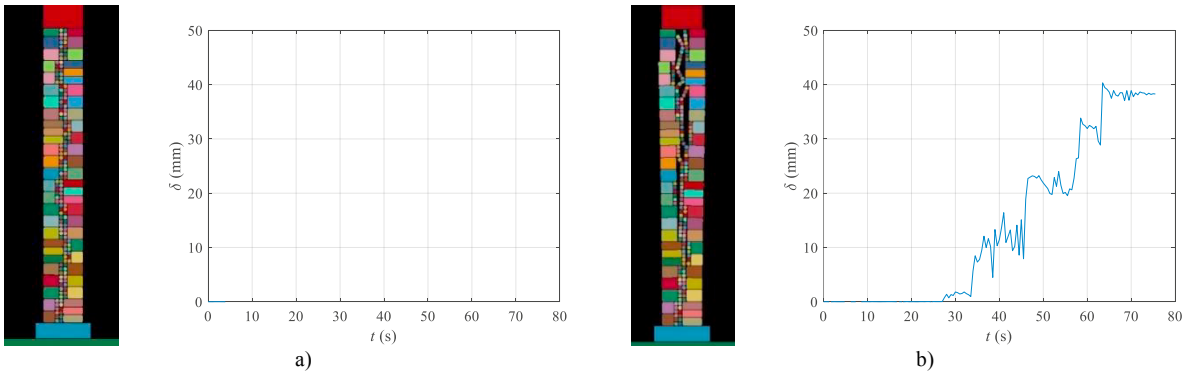


Fig. 3 Mechanism does not activate in case of horizontal load only.
Wall response for: a) horizontal component only; b) horizontal and vertical components.

In order to evaluate the effect of the vertical component on the variation of reference measure, three damage levels are identified: 1, 10, 50 mm. In Fig. 5. an overall presentation of the role of the vertical component is given. The addition of the vertical component increases the frequency of exceedance of the two most severe damage levels.

Fragility curves in terms of *PGV* are presented for the mentioned damage levels (Fig. 6). In Table 1 are given the median, θ, and the logarithmic standard deviation, β, for the assumed log-normal distribution. It can be observed that the vertical component decreases the median of the distribution but has no appreciable effect on the scatter. The greater sensitivity to the vertical component of this wall, compared with results of previous studies (Liberatore et al. 2019), seems related to the smaller size of the blocks in wall under consideration compared to the URM structure studied in 2019. Sensitivity to unit size was already report experimentally and numerically in the literature (Baggio and Trovalusci 1993).

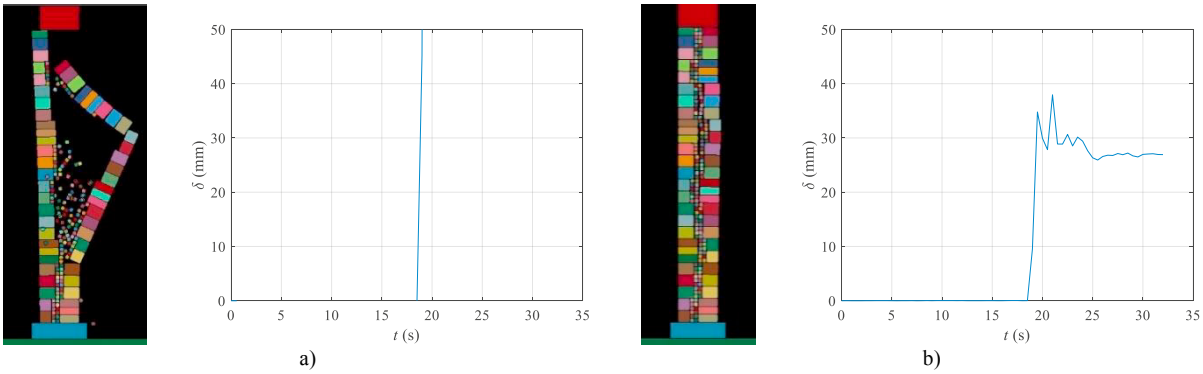


Fig. 4 Collapse occurs in case of horizontal load only.
Wall response for: a) horizontal component only; b) horizontal and vertical components.

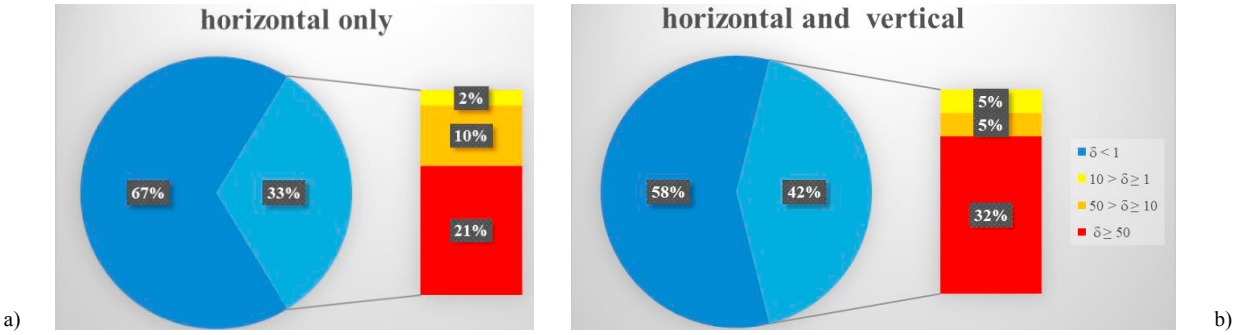
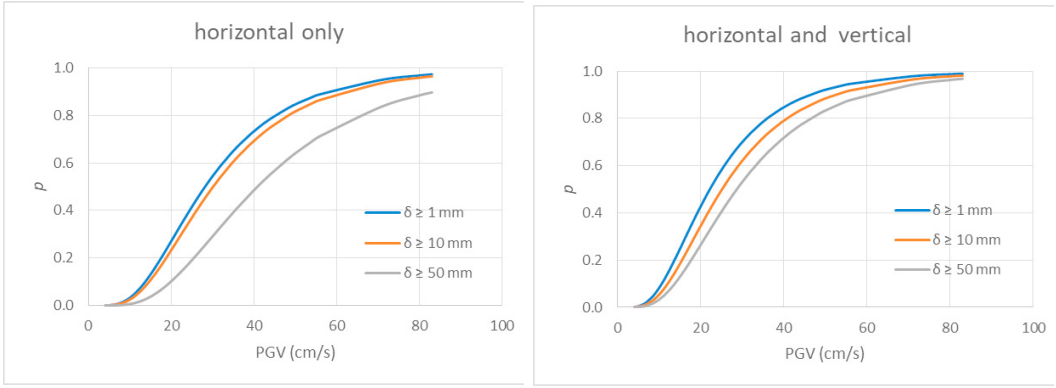


Fig. 5. Percentage of exceedance of the damage levels: a) horizontal component only; b) horizontal and vertical components.

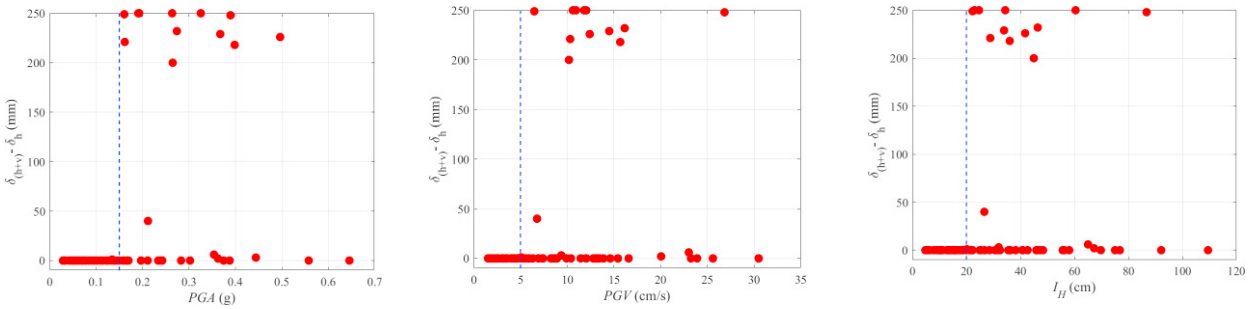


a) b)

Fig. 6. Leaf separation fragility curves for different damage levels for: a) horizontal component only; b) horizontal and vertical components.

Table 1. Values of median, θ, and the logarithmic standard deviation, β, of leaf separation fragility curves horizontal component only, as well as horizontal and vertical components.

	β [ln(cm/s)]	θ [cm/s]		
		$\delta \geq 1$ mm	$\delta \geq 10$ mm	$\delta \geq 50$ mm
horizontal only	0.56	28.2	30.1	40.8
horizontal and vertical	0.58	22.2	25.1	28.7



a) b) c)

Fig. 7 Increase of damage level as effect of the vertical component for selected intensity measures of the vertical component: a) peak ground acceleration (*PGA*), b) peak ground velocity (*PGV*), c) Housner intensity I_H.

It is worth emphasising that an effect of the vertical component in terms of a more severe response can be observed only if specific thresholds of the intensity measures of the vertical component are overcome. As shown in Fig. 7, a peak ground acceleration larger than 0.15 g or a peak ground velocity larger than 5 cm/s or a Housner intensity larger than 20 cm are necessary, but not always sufficient, to cause a more severe damage. If the thresholds are exceed jointly by the two peak values the condition is also sufficient, with just two exceptions.

3. CONCLUSIONS

In this paper the numerical analyses to investigate the effect of combined horizontal and vertical ground motions on the response of a rubble masonry wall was discussed. The numerical model was excited by 83 sets of ground motion compatible with the seismicity of L'Aquila. The rather poor cross section of the wall, without bondstones and rather small unit size, highlighted a sensitivity to vertical component. The addition of the latter caused a reduction of the median of the lognormal fragility curves of three selected damage states. Scatter of the response is not affected by the presence or absence of the vertical component. Specific thresholds of vertical component intensity measures need to be overcome to notice any effect on the wall response.

Acknowledgments

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