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Influence of mechanical parameters on non-linear static analysis of masonry buildings: a relevant case-study

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Abstract

In seismic zones, suitable procedures to assess the seismic vulnerability of existing buildings are necessary also in view of optimal planning of interventions. Starting from the agreement between the Municipality of Florence and the Department of Civil and Industrial Engineering of the University of Pisa, a research program is ongoing, devoted to setup a simplified, fast but reliable procedure for the evaluation of seismic performance of masonry buildings.
In this paper, a simplified non-linear pushover type method for the verification of unreinforced multi-story masonry buildings with both deformable and non-deformable slabs is presented, starting from some of the basic assumptions of the POR method. Various tests on the procedure show that the method is able to give results that are comparable with those obtained by the classical pushover analysis performed on equivalent frame models. The intuitiveness of the method and the low computational effort required by the new algorithm allow the evaluation of the sensitivity of non-linear static analysis regarding the definition of mechanical parameters. In particular, the relevant influence of the modulus of elasticity as well as the ultimate inter-story displacement assumed for masonry walls on the assessment of seismic performance are discussed in detail.
The results are presented for a significant case study, the Primary School "G. Carducci" in Florence, a four-story masonry building, with a horseshoe layout where lateral appendixes detached from the central block.

Keywords: Seismic vulnerability; Masonry buildings; Seismic resistance; Seismic risk index; Pushover methods.

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1. Introduction

In the framework of a research program agreement between the Municipality of Florence and the Department of Civil and Industrial Engineering of the University of Pisa, devoted to assess the seismic behavior of school masonry building, a simplified, fast but reliable non-linear static pushover type procedure for the evaluation of seismic performance of masonry buildings has been developed. The need of such kind of procedures has been further motivated by the outcomes of recent seismic events that happened in Italy, that underlined the vulnerability of the built environment, recalling the necessity of a proper planning of interventions.

In the paper, a significant case study concerning the “G. Carducci” school in Florence is presented, starting from the description of its architectural and structural characteristics, especially focusing on the relevant parameters to be considered in modeling and analyzing the resistant structure, also illustrating the application of the above mentioned simplified pushover type algorithm, called E-PUSH (Beconcini et al. 2018). The proposed method, based on some of the classical assumptions of the POR method (Tomaževic 1978), allows the verification of multi-story masonry buildings, according to the most recent structural Codes. Various benchmarks have shown that the E-PUSH algorithm is able to give results that are comparable with those obtained by the classical pushover analysis performed on equivalent frame models, implemented in commercial software packages, such as Aedes PCM (Aedes 2016), but requiring not particular skills of the users. Furthermore, the intuitiveness of the method combined and the low computational effort required by the algorithm itself facilitate wide sensitivity studies, even regarding the definition of the masonry mechanical parameters. Referring to the considered case study, different runs of the implemented E-PUSH procedure demonstrate that the assumptions about the value of the shear modulus of elasticity as well as about the ultimate inter-story drift greatly influence the results of the seismic assessment.

2. The case study: the Primary School and Kindergarten “G. Carducci” in Florence

As already said, the case study refers to the Primary School and Kindergarten “G. Carducci”, located in the North-East of Florence. The masonry school complex, whose surface is about 3150 m2, was built between 1949 and 1955, and it is characterized by a horseshoe layout (Fig. 1), composed of a four story central block and two three story lateral appendixes. The inter-story height is around 3,50 m.

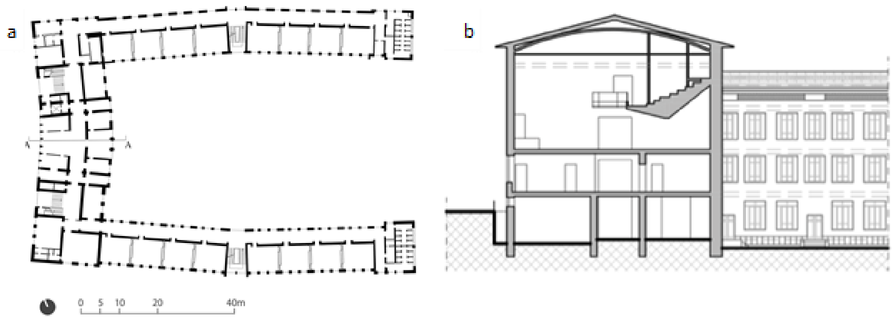

Fig. 1. (a) layout of the ground floor; (b) section A-A.

Since the appendixes are structurally detached from the central block, in the following the numerical analysis will be presented only for the central body that has a nearly rectangular plan, about 64 m long and 18 m wide.

As it can be seen from the section A-A (see Fig. 1(b)), the central upper part of the building houses a theatre, occupying the third and fourth floors high volume, with a reinforced concrete gallery. The shear resistant structure is represented by masonry walls, 0,5 – 0,70 m thick, made of irregular natural stones and horizontal courses of bricks; while few masonry walls made of brickwork can be found in the back façade. Furthermore, at each floor there are reinforced-concrete curbs, 0,40 m high, having the width of the wall below; these curbs contribute to assure a good box behavior under horizontal forces, also in consideration that the external walls are well connected each other as well as with the orthogonal ones. This characteristic is also enhanced by presence of one-way non-deformable slabs, that present a 5 cm top-layer of reinforced concrete. As it can be noticed in the Fig. 1.(a), the walls layout presents a slight rotation over the global axis, which has been duly considered in modeling the structures.

3. The E-PUSH algorithm

In the seismic assessment of existing masonry buildings, refined non-linear static methods, such as pushover method, are often used. In commercial software packages, masonry buildings are mostly modelled by the so-called equivalent frame model, in which the structure is represented like a frame, whose columns and beams represent the masonry walls and the spandrels, respectively. But, in 3D buildings, equivalent frame models present huge approximation and requires the definition of complicated structural scheme, heavily dependent on the user's competence, because incorrect modelling could leads to inconsistent results. In the past, a very efficient and simplified method for the seismic resistance verification of the unreinforced masonry buildings was commonly used. The method, named POR, was first introduced by Tomaževic (1978) and two years later it was adopted by the Italian regulations for strengthening and repair of earthquake damaged buildings (DT2 1980). The method can be seen as a simplified variant of non-linear pushover type method (Tomaževic 2009). The E-Push algorithm (Beconcini et al. 2018), illustrated in the following, is a suitable procedure for the assessment of seismic vulnerability of existing masonry buildings combining an innovative and "robust" non-linear approach with the easiness of use and the computational efficiency of POR method, removing the limitations and potential inaccuracies of the POR method itself.

3.1. Basic assumptions

The E-PUSH algorithm starts from the basic assumptions of the POR program to overcome the limitations of that method. Since the POR method performs the verification in terms of shear resistance of individual floors considered separately from the others, the ductility of the entire structure is disregarded. This limitation is overcome in the E-Push algorithm, which allows to consider the ductility of the whole structure and to analyze mono and multi-story buildings. E-PUSH is based on the following assumptions:

- the stiffness of the shear walls in the relevant directions, x or y, which is given by (Fig. 2)

$$k_{xx} = k_{uu} \cos^2 \alpha + k_{vv} sen^2 \alpha \ ; k_{yy} = k_{vv} \cos^2 \alpha + k_{uu} sen^2 \alpha \quad (1)$$

is approximated considering only its lateral stiffness, k_{uu}, disregarding the transverse stiffness, k_{vv};

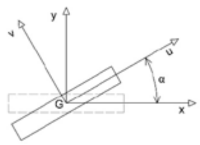

Fig. 2. Shear wall rotation from the global axis.

- each floor has a defined stiffness based on the characteristics of the floor itself, whose value varies depending on the damage degree suffered by the structure during the seismic event, being the initial stiffness k_{uu} of each masonry wall given by

$$k_{uu} = \frac{GA}{1.2h} \left(1 + \frac{G}{1.2E} \left(\frac{h}{l} \right)^2 \right)^{(-1)} \quad (2)$$

where h is the inter-story height of the wall, l its length, A the area of the cross section, and E and G are the modulus of elasticity and the shear modulus of masonry, respectively.

- the story displacements are considered in order to perform the verification in terms of seismic capacity and demand using the Acceleration Displacement Response Spectra (ADRS);

If, during the seismic event, the failure of the wall is due to the diagonal tension shear, the wall resistance results:

$$H_{Rd} = A\frac{1.5\tau_k}{b}\sqrt{1+\frac{\sigma_0}{1.5\tau_k}} \tag{3}$$

where σ_0 is the compressive stress induced in the wall by the seismic combination, τ_k is the shear strength of masonry and b is the shear resistance factor, assumed b=1.5 (Tomaževic 2009). As usual, the behavior of the masonry walls subjected to constant vertical loads and horizontal loads is idealized with a bilinear resistance envelope like in the original POR method (Tomaževic 1978). The bilinear envelope is characterized by an initial elastic slope defined by the lateral stiffness k_{uu}, being the elastic plateau limited by the elastic inter-story drift δ_e and by the ultimate inter-story drift δ_u.

The elastic inter-story drift δ_e can be derived as the ratio between H_{Rd} and k_{uu} combining Eq. (2) and Eq. (3), and the ultimate drift could be defined as:

$$\delta_u = \mu\delta_e \tag{4}$$

where μ is the ductility factor. For the masonry (Ministry of Public Works 1981) a value of $\mu = 1.5$ is recommended. The ultimate drift could be also defined, as suggested in the Eurocode 8 (EN1998-1-3 2005) and the Italian Building Code (Italian Ministry of Infrastructure and Transport 2018), as a percentage of inter-story height of the wall: for example, assuming a shear failure, an ultimate drift given by the 0.4% of the inter-story height ca be adopted.

Anyhow, it must be stressed from now on that the two above-mentioned alternatives lead to significantly different results, also depending on the mechanical parameters, in particular on the value of the shear modulus.

3.2. Modelling

In the algorithm, the definition of the numerical model starts with the identification of the shear walls. A shear wall is a structure able to transfer horizontal or seismic forces to the soil and it is characterized by vertically aligned masonry walls connecting the foundation to an upper floor; in effect, horizontal forces are sustained and transferred to the soil not only by the shear walls extended over the whole height of the building, but also by those connecting the foundation to an intermediate floor. For each wall, geometrical characteristics, such as length and thickness and position of the Center of Mass, must be defined. Obviously, discontinuous vertical walls, not extended to the foundation, or relatively flexible walls are considered as merely carrying vertical loads. Moreover, since walls not extended to the foundation, if any, represent a formidable source of structural irregularity and local vulnerability and heavily influence the seismic response of the structure, they need to be preliminarily studied case by case.

In the following, the case of the infinitely rigid floors is considered, but the algorithm can be easily adapted to the case of floors deformable in the horizontal plane, considering that the analysis can be limited to aligned shear walls, subject to loads coming from the adjacent areas.

To properly describe the behavior of the material, mechanical parameters must be suitably associated to each shear wall. The compressive resistance and the shear resistance can be, for example, extracted from the table C8A.2.1 of the Italian Code (Public Works Council 2009), if necessary, in combination with in-situ test results. The elastic modulus can be selected from the relevant technical literature, while the shear modulus G can be generally derived from the shear strength τ_k of the masonry. On the basis of an ad hoc test campaign, Tomažević (1999) proposed to set values in the range $1000 \leq G/f_{tk} \leq 2700$ for the shear modulus, even if results fall mostly close to $G/f_{tk} \approx 2000$, while tests performed by Turnšek and Ĉaĉoviĉ (1971) indicate a ratio $G/\tau_k \approx 1100$. In any case, it is possible to link empirically the apparent values of E and G, taking into account the influence of inhomogeneity and cracking. It must be highlighted that higher values of G are given in the Italian Building Code (Public Works Council 2009), where for different types of historic masonry the shear modulus varies from $2674\ f_{tk}$ for hollow bricks with lime mortar to 7479 f_{tk} for chaotic masonry, being f_{tk}=1.5 τ_k the tensile strength of the masonry, but these values seem unrealistic for the masonry in the cracked state. An extensive review of available experimental results is discussed in (Croce et al. 2018), where suitable values of *G* are suggested. In the present study values of G ranging in the interval 1100 τ_k – 4000 τ_k have been assumed, in order to appreciate the sensitivity of the results on this relevant parameter, considering in turn ductility checks or inter-story drift checks.

3.3. Analysis

Based on the above-mentioned assumptions, the E-Push algorithm has been applied for a classical pushover analysis of the above-mentioned masonry structure of the Carducci school. Main features and advantages of the program are described in the following, when relevant, discussing the results for the considered case study.

The 4-story masonry building is characterized, for the lower level, by 47 shear walls in *x* direction and 70 shear walls in *y* direction. After the input of the geometrical and mechanical characteristics, the algorithm calculates the coordinates of the center of mass, $\overline{x_{M,k}}$ and $\overline{y_{M,k}}$, and of the center of rigidity, $\overline{x_{R,k}}$ and $\overline{y_{R,k}}$ for each *k*th story (k= 1, 2, 3, 4 in this case) and the total lateral stiffnesses $K_{y,k}$ and $K_{x,k}$ at the considered floor. Accordingly, the eccentricities of the story, $e_{x,k}$ and $e_{y,k}$, and the polar moment of inertia of the stiffness $J_{R,k}$ are calculated.

Then, a suitable distribution of seismic forces (F_k) along the height is considered (linear or uniform, for example), which is increased at each step. In the present case, for the sake of simplicity, a distribution of forces proportional to the elevation h_k of the floor is considered. At the *j*th step of the iterative procedure, the horizontal force $F_{k,j}$, obtained increasing by ΔF_k the force $F_{k,j-1}$ at the (*j*-1)th step, is applied in the center of mass of the floor, independently in the *x* and in the *y* direction, starting the analysis at each step starting from the top floor of the building, *k*=4, and going down one floor each time till to the base.

During the analysis, at each step of the procedure, the inter-story drift of every shear wall is compared with the elastic drift and the ultimate drift (defined with the method already shown), considering 3 possible situations:

- the drift of the wall is lower than δ_e; the wall is still in elastic phase and the stiffness is defined by Eq. (2);
- the drift of the wall is higher than δ_e and lower than δ_u; the wall is in the plastic range, the shear force is equal to the resistance defined in Eq. (3) and the reduced stiffness of the (referred to the global axis) is given by:

$$k_{yy,i} = \frac{H_{Rd,i}}{\delta_{y,i}} \;;\; k_{xx,j} = \frac{H_{Rd,j}}{\delta_{x,j}} \;; \tag{5}$$

- the drift of the wall is higher than δ_u; the wall is collapsed, its shear resistance and its stiffness are set to zero and the wall is assumed to sustain only vertical loads.

When the above-mentioned checks on all the walls of the *k*th floor are completed, it is possible to update the corresponding shear resistance of the story $H_{y,TOT,k}$, its total stiffness $k_{y,TOT,k}$, represented as the sums extended to all the shear walls present at the considered floor, as well as the drift $v_{y,TOT,k}$. Once the analysis of the *k*th floor is concluded, it is possible to move to the underlying (*k*-1)th story, repeating the procedure described before.

The algorithm is run incrementing the forces until the base shear resistance $H'_{y,TOT,1}$ reduces to about 80% of the relative maximum base shear resistance or when there is the collapse of the whole floor, defining in this way the capacity curve of the whole structure.

In the subsequent steps, the procedure follows the classical steps of a pushover analysis described in (Fajfar et al. 2000) and for the E-PUSH algorithm in (Beconcini et al. 2018), finally allowing the evaluation of the seismic risk index I_R of the structure, which is the ratio between the peak ground acceleration resisted by the structure, PGA_C, and the design peak ground acceleration PGA_D.

4. Results and validation

The results obtained with the proposed algorithm have been compared with those obtained with the push-over analysis carried out with the commercial software package Aedes PCM (Aedes PCM 2016). This computer program adopts the equivalent frame model, which is made by spandrel and pier elements modelled as beam-column elements, connected by infinitely resistant rigid elements modeled by rigid links at the ends of pier and spandrel elements (Magenes 2000). Rigid links at the top of the walls are also used to connect orthogonal walls (the comparison from the two models as shown in Fig. 3). For the sake of comparison, full height deformable piers have been considered to model walls assuming a shear type behavior. The pushover analysis has been carried out considering only diagonal shear failure of masonry walls and adopting alternatively the ductility definition and the drift definition for the ultimate displacement checks.

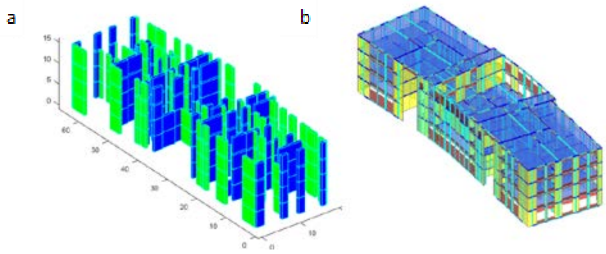

Fig. 3. 3D layout of the resistant shear walls with E-Push (a) and equivalent frame model in Aedes PCM (b).

Running the analysis, the outcome is represented in a force/displacement diagrams in Fig. 4, where the green curves obtained via the E-Push algorithm are compared with the red ones obtained with the Aedes PCM. The most remarkable result is that the two programs give similar results in terms of force-displacement curves as well as in terms of ultimate values.

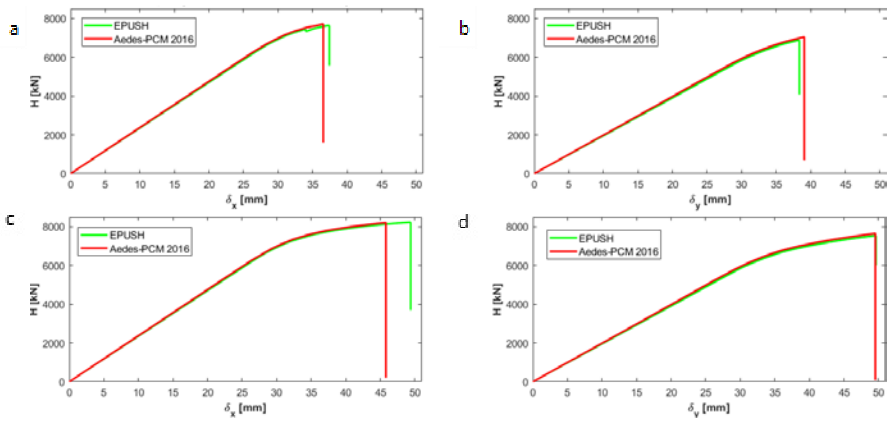

Fig. 4. Comparison of pushover curves obtained from Aedes PCM and E-Push: (a) Capacity curves, direction X, ductility check, (b) Capacity curves, direction Y, ductility check, (c) Capacity curves, direction X, drift check, (d) Capacity curves, direction Y, drift check.

Comparison of results in terms of maximum base shear and ultimate displacement are reported in Table 1 for ductility verification as well as for drift verification. A variation in terms of ΔH_{ult} [%] lower than 3% is observed in both directions for both cases (ductility and drift check), while for the $\Delta\delta_{ult}$ [%] there is a little higher difference in terms of drift check; around 8% for the x direction.

Table 1 Comparison of results in terms of force/ displacement obtained from Aedes PCM and E-PUSH, ductility and drift check.

	Direction x						Direction y					
	H_{ult} [kN]			δ_{ult} [mm]			H_{ult} [kN]			δ_{ult} [mm]		
Check	PCM	E-Push	ΔH_{ult} [%]	PCM	E-Push	$\Delta\delta_{ult}$ [%]	PCM	E-Push	ΔH_{ult} [%]	PCM	E-Push	$\Delta\delta_{ult}$ [%]
Ductility	7713	7642	-0,92	36,54	37,43	2,43	7041	6882	-2,26	39,07	38,4	-1,71
Drift	8191	8217	0.32	45.81	49.39	7.81	7641	7535	-1.39	49.55	49.64	0.18

5. Influence of shear modulus and elastic modulus

As mentioned in §3.2, the choice of material parameters plays a relevant role in non-linear static analysis. In particular, values of the shear modulus *G* of masonry strongly influence the aspect of the bilinear envelope, representing the behavior of resistant walls, and consequently the capacity curve of the whole structure.

To explore this relevant issue, sensitivity analysis have been then carried out, varying the shear modulus *G* and assuming the commonly accepted ratio *E*/*G*=6. As already said, *G* varying in the range 1100 τ_k - 4000 τ_k has been investigated. The results obtained with the proposed program for the examined case study are presented in terms of seismic risk index versus *G* in Fig. 5.(a) and (b), for seismic forces directed in the x and y direction, respectively.

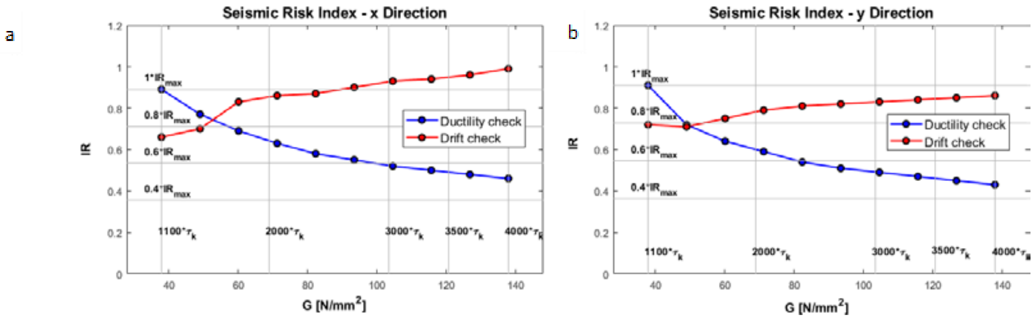

Fig. 5. Seismic risk index variation with different shear modulus: (a) x-direction, (b) y-direction.

Beside the high variability of the results depending on the adopted shear modulus *G*, it is interesting to notice how increasing the shear modulus a higher seismic risk index is obtained for drift verification (red lines in Fig. 5) while a lower risk index is obtained for ductility check (blue lines in Fig. 5). Further sensitivity analyses have been devoted to investigate the influence of other masonry mechanical parameters. *G*/*E* ratios varying between 0.06 and 0.25 have been taken into account, according the experimental results presented in (Tomažević, 1999) and (Tomažević, 2008), considering for the shear strength, beside the reference value, τ_k, also values reduced or increased by 50% with respect with the reference one (0.5 τ_k or 1.5 τ_k). The results in terms of dependence of the seismic index risk on *G*, *G*/*E* ratio and shear strength are presented in Fig. 6, again in case of drift (orange, red and magenta surfaces) or ductility checks (cyan, blue and green surfaces). It must be stressed that *G*/*E* ratio may have an influence in the evaluation of seismic risk index for low values of shear modulus *G,* while, as the shear modulus increases, the dependence weakens. Regarding the shear strength, it can observed that no major variations occur both for ductility and drift checks when it increases, while, when it reduces, drift verifications are no significantly influenced, probably because the structure remains in the elastic range.

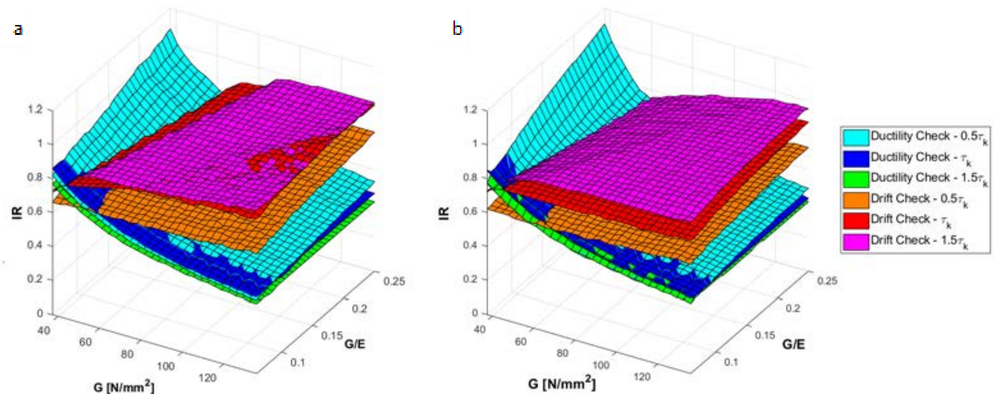

Fig. 6. Seismic risk index variation with different values of *G*, *G*/*E* ratio and τ_k: (a) *x*-direction, (b) *y*-direction.

6. Conclusions

Starting from the significant case study of a masonry school building, a novel algorithm for non-linear static analysis is presented, focusing on the influence of mechanical parameters on this type of analysis. Once defined its architectural and structural characteristics, a masonry school building located in Florence (I) has been analyzed with the proposed non-linear pushover type method, that goes under the name of E-PUSH. The algorithm is based on very general assumptions and it considers all the shear walls that are extended to the foundations, managing to create a very simple and effective 3D numerical model, avoiding at the same time, the typical inconsistencies of classical pushover programs, based on the equivalent frame model. The program, which is very quick and does not require particularly skilled users, has been previously validated comparing the outcomes obtained analyzing several masonry buildings with those obtained using commercial software packages, like Aedes PCM, but the comparison is presented here for the considered case study. The intuitiveness of the method and the low computational effort required by the algorithm itself allows the evaluation of the sensitivity of non-linear static analysis on the values adopted for the main mechanical parameters of the masonry. It must be highlighted that assumptions related to the shear modulus *G* of masonry have fundamental influence in the definition of the capacity curves and consequently have a large impact on the seismic risk index, as confirmed by the specific sensitivity analyses carried out on the considered building. It results that increasing the shear modulus leads to considerably higher values of seismic risk index, if the assessment is performed in terms of drift check, while, on the contrary, the seismic risk index gets significantly lower, when the assessment is performed in terms of ductility check.

Finally, the influence of the value of other relevant parameters, such as the *G*/*E* ratio and shear strength of masonry have been also investigated, but once again the results confirmed that the choice of shear modulus is the key issue in non-linear analysis of masonry buildings, so indicating that future research should be specifically devoted to refined investigation of this parameter.

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References

Aedes Software, 2016. Aedes PCM User's manual (in Italian).

Beconcini M. L., Croce, P., Cioni, P., Formichi, P., Landi, F., Mochi, C., 2018. Non-linear static analysis of masonry buildings under seismic actions. Education and Information Systems, Technologies and Applications: EISTA2018.

Croce, P., Beconcini M. L., Formichi, P., Cioni, P., Landi, F., Mochi, C., De Lellis, F., Mariotti, E., Serra, I., 2018. Shear modulus of masonry walls: a critical review. International Conference on Building Pathology and Constructions Repair: CINPAR 2018.

EN1998-1-3. Eurocode 8, 2005. Design of structures for earthquake resistance – Part 3: General rules, seismic actions and rules for buildings. CEN, Brussels.

Fajfar, P., Eeri, M., 2000. A Nonlinear Analysis Method for Performance Based Seismic Design, in: Earthquake Spectra, Vol.16, 573-592.

Italian Ministry of Infrastructure and Transport, 2018. NTC 2018 Italian Building Code. D.M. 20/02/2018 (in Italian).

Italian Ministry of Public Works, 1981. Guidelines for application of Structural Code for strengthening and repair of masonry buildings (in Italian).

Magenes, G., 2000. A method for pushover analysis in seismic assessment of masonry buildings, Proceedings of the 12th world conference on earthquake engineering, Auckland.

Public Works Council, 2009. Guidelines for application of Italian Building Code (in Italian).

Regione Autonoma Friuli Venezia Giulia, "DT n.2 – Guidelines for application of Structural Code for strengthening and repair of masonry buildings" (in Italian), 1981.

Tomažević, M., 1978. Improvement of computer program POR. Report ZRMK, Ljubljana (in Slovene).

Tomažević, M., 1999. Earthquake-Resistant Design of Masonry Buildings. Series on Innovation in Structures and Construction, Vol. 1, London.

Tomažević, M., 2008. Shear resistance of masonry walls and Eurocode 6: Shear versus tensile strength of masonry, in Materials and Structures, no. 42, 889-907.

Turnšek, V., Ĉaĉoviĉ, F., 1971. Some experimental results on the strength of brick masonry walls, Proc. of the 2nd Intern. Brick Masonry Conference, Stoke-on-Trent, 149-156.