Le Vie dei Mercanti
XIV International Forum
WORLD HERITAGE AND DEGRADATION
Smart Design, Planning and Technologies
Aversa | Naples 16 - Capri 17, 18 June 2016

Seismic investigation on a masonry building compound in the historical centre of Bacoli (Naples)

Antonio FORMISANO[1], Francesco FABBROCINO[2], Nicola CHIEFFO[3]
(1) Department of Structures for Engineering and Architecture, University of Naples "Federico II", Naples, Italy
antoform@unina.it
(2) Department of Engineering, Pegaso Telematics University, Naples, Italy
francesco.fabbrocino@unipegaso.it
(3) Department of Engineering, Pegaso Telematics University, Naples, Italy
nicola.chieffo@unipegaso.it

Abstract
This paper has the task to investigate the seismic vulnerability of masonry building aggregates belonging to the municipality of Bacoli (Naples) through a combined theoretical-numerical analysis procedure applied to a case study. Numerical pushover analyses on the examined compound have been used to plot the capacity curves of head, angle and intermediate structural units, accounting for both the loads deriving from floors of adjacent units and the strength and stiffness of the wall portions next to the masonry structure considered. Afterwards, a theoretical study has been faced to assess the vibration periods of aggregate structural units, which have been compared to single units ones. Finally, the achieved numerical results have been compared with those deriving from a speedy analysis procedure with the purpose to find a relationship among vibration periods and quick vulnerability indices.

Keywords: seismic vulnerability, quick analysis, mechanical model, vibration periods, masonry aggregates.

1. Introduction
The historic built-up has always been not only a response to housing need over time, but also the testimony of centuries of civilization and culture and can be considered as a touristic and economic irreplaceable resource. Masonry buildings represent a large part of the Italian building heritage, often designed to withstand vertical loads and any horizontal forces without respecting seismic criteria. So, for the analysis of these structures, there is almost always the trend to examine their seismic behaviour on the basis of unclear criteria. In particular, the case of building aggregates represents the norm within roughly all Italian towns [1].
Masonry building aggregates are the distinctive emblems of Italian historical centres, which were erected in different epochs according to different design principles. The current seismic Italian code does not foresee a clear calculation method to predict their static non-linear behaviour. Nevertheless, collapses and very large damages occurred into building compounds during the last earthquakes [2, 3] and, therefore, particular attention to this topic should be paid by scientific researchers in the Structural Engineering field. For this reason, in this paper a simple methodology to forecast the masonry aggregate seismic response has been setup. Since buildings, originally built as isolated constructions, were aggregated over the years into compounds, a suitable calculation method can be developed firstly by extrapolating the single constitutive structural units and, subsequently, considering the interactions among them. The illustration of the implemented analysis method is herein done with reference to a case study within the historic centre of Bacoli (district of Naples).

2. The historical centre of Bacoli

The settlement system of the historical centre of Bacoli (Naples) (Fig.1) expanded significantly since the post-war period, reaching its maximum expansion especially in the '80s. It consists mainly of masonry buildings: the oldest ones are inserted into compounds, they being statically dependent each to other, whereas those more recently erected are arranged as isolated structures (about 60%).
The study has the target to assess the behaviour of masonry building aggregates falling in the above historical centre through the analysis of a case study.
The achievement of the minimum information necessary to properly model the aggregate taken as a case study has been achieved through the CAR.TI.S survey form [4]. The seismic analysis has been performed by means of quick and numerical procedures. The first approach comes from the procedure initially proposed in 1984 by Benedetti and Petrini [5], which has been recently extended to take into account specifically the interactions among units of historical aggregates [6, 7, 8]. On the other hand, the second procedure is based on the application of the calculation program 3Muri [9], used to perform non-linear static analyses.
With the latter analysis approach, by modelling the entire aggregate, it has been possible to assess the seismic vulnerability index, as well as the vibration period, of the individual structural units (S.U.) integrated in the building complex for seismic check purpose.

Fig.1: Overview of the historic centre of Bacoli.

3. The CAR.TI.S. Form

The Italian CAR.TI.S survey form (Fig. 2), a sort of manual for the typological - structural characterization of ordinary buildings, is finalised to the detection of the prevalent building types in the context of communal or sub - municipal areas, called compartments, characterised by homogeneity of the building texture.
The compilation of the form must follow a path in which the information is acquired through interviews to one or more local technicians having an exhaustive knowledge of the examined area.
The form is divided into the following four sections:

- Section 0: identification of the municipality with focus on the study sector;
- Section 1: identification of each of the main structural types detected within the municipality;
- Section 2: identification of the general characteristics of the types individuated;
- Section 3: characterisation of structural elements.

60% of masonry structures are distributed according to an isolated configuration, whereas the remaining 40% are grouped into structure aggregates, where constructions interact each other, so to be one dependent from another.
In the current paper the study sector illustrated in Figure 3a has been investigated. The structural parameters of constructions located there are: total floors (including basements) equal to four, average floor height between 3.50 m and 6.00 m, average ground floor height between 3.50 m and 5.00 m. The average plan area of buildings is equal to 170m^2 and the erection period of buildings was before 1860. About masonry, the most common type has regular squared stones with an average thickness of 80 cm. Masonry walls have suitable cross connections (diatones), while buttresses and chains or tie-beams are absent. The floors are rigid or semi-rigid: the former under form of either precast joists or in-situ casted rc joists – hollow tile (highest percentage), while the latter as mixed steel-tie horizontal structures.
The reinforced concrete structures in the sector are identified as frames placed into one direction only with infill walls and without seismic joints.
Roofs are usually made of reinforced concrete practicable terraces and masonry vaults; the percentage of openings on the surface of the facade is between 20% and 29%. At the ground floor such a percentage is lowered up to 10%. 70% of buildings appears to be regular both in plan and in elevation and the predominant type of stairs is made of knee beams with cantilever steps. Superficial foundations are provided by isolated plinths with or without connection beams.

Fig. 2: Sections of the Italian CAR.TI.S. survey form and some of the examined buildings.

Fig. 3: The study sector (a) and the inspected building aggregate (b).

4. The case study of a building aggregate

The building aggregate under examination, located in the historical centre of Bacoli, is composed by structural units (S.U.) giving rise to a building stock with more or less a "in line" configuration (Fig.3b).
The macro-element model of the building aggregate, composed of six S.U., has been developed with the 3Muri software, as depicted in Figures 4 and 5a.

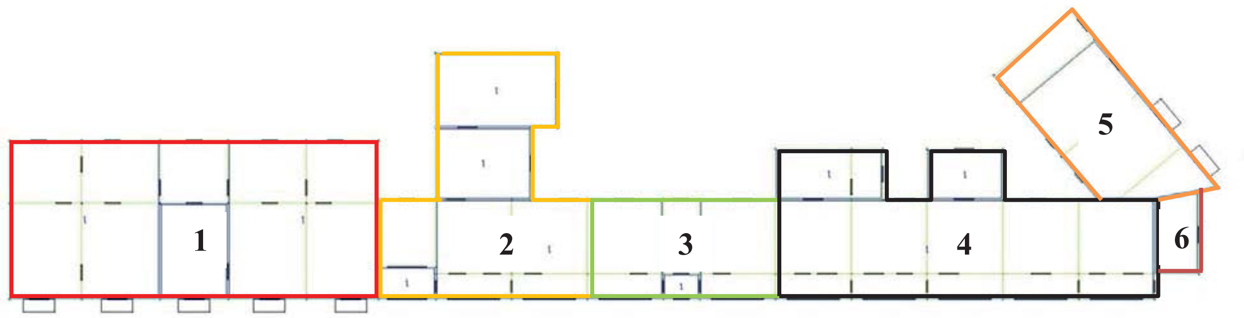

Fig. 4: The building aggregate under investigation.

- The building # 1 (Fig. 5b) has a rectangular shape and develops on three floors above ground with a well dressed tuff masonry. The structure, which appears as the most impressive of the aggregate, is in excellent condition, being subjected in the past to restructuring and consolidation interventions. The floors are made of r.c structures and the flat roof is not practicable.
- The building # 2 (Fig. 5c) has a polygonal shape with a substantial number of openings facing the road. The structure consists of tuff masonry in a good condition. Floors and roof are the same of the building # 1.
- The building # 3 (Fig. 5d) has a rectangular shape and it is perfectly inserted in the aggregate. The structure, made of tuff masonry stones in a good conservation state, has an open central staircase.
- The building # 4 (Fig. 5e) has a polygonal shape and represents the structural unit of the aggregate with the most articulated plan. It has a façade with both openings that run inside and the presence of significant recesses. The masonry type is analogous to the previous loadbearing vertical structures.
- The building # 5 (Fig. 5f) is positioned with an angle with respect to the aggregate horizontal alignment. It has a regular shape made of tuff stones in a good state of preservation.
- The building # 6 (Fig. 5g) is the smallest S.U. occupying a corner position in the aggregate. It is different from the rest of the other units, since it develops on two levels above ground made of a masonry structure in excellent conditions.

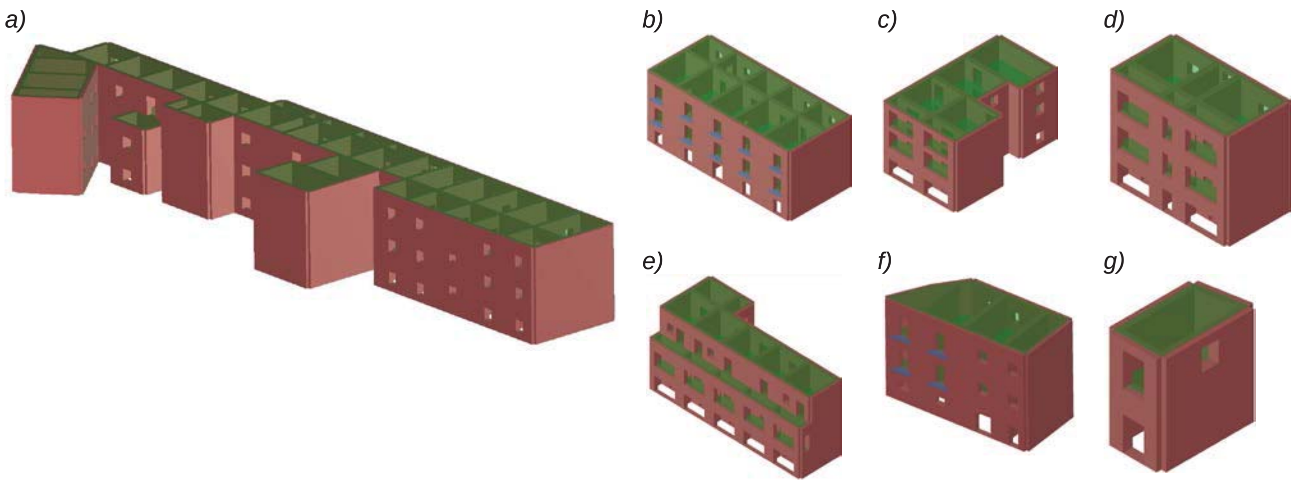

Fig. 5: 3Muri model of the building aggregate (a) and identification of the six S.U. (from b to g).

5. The quick analysis

The quick assessment procedure of the seismic vulnerability of masonry building aggregates is based on the form developed by Benedetti and Petrini. The procedure consists in attributing a score among four classes (A - B - C - D), to ten parameters representative of the geometrical and mechanical characteristics of the buildings. For each class, a score s_i is assigned and for each parameter, a weight w_i, that is the influence that the same parameter has on the overall structure vulnerability, is provided.
Moreover, in order to consider the interaction among constructions during earthquake, further five parameters have been added to the original form.
The additional parameters take into account the in plane and in elevation interactions among adjacent units, the presence and number of staggered floors among constructions, which give rise to hammering effects during earthquakes, the typological and/or structural heterogeneity among joined buildings and, finally, the difference between the percentages of openings among facades of contiguous buildings.
The extended Benedetti and Petrini's form on the basis of the above aggregate parameters is visible in Table 1. The applicability of this new form conceived for historical aggregates is shown in [10, 11, 12].
Therefore, for each S.U., the vulnerability index I_V is calculated as the sum of the scores individuated for each parameter multiplied by the respective weights. Finally, the vulnerability indices achieved for all S.U. are normalised into a scale ranging from 0 to 1, giving rise to the $I_{v,norm}$ values (see Table 2).

Table 1: Vulnerability form for historical building aggregates.

	Parameters	Class score (s)				Weight (w)
		A	B	C	D	
1	Organization of the vertical structures	0	5	20	45	1.00
2	Nature of vertical structures	0	5	25	45	0.25
3	Location of the building and type of foundation	0	5	25	45	0.75
4	Distribution of plan resisting elements	0	5	25	45	1.50
5	In-plane regularity	0	5	25	45	0.50
6	Vertical regularity	0	5	25	45	0.50÷1
7	Type of floor	0	5	25	45	0.75÷1
8	Roofing	0	15	25	45	0.75
9	Details	0	0	25	45	0.25
10	Physical condition	0	5	25	45	1.00
11	Presence of adjacent buildings with different height	-20	0	15	45	1.00
12	Position of the building in the aggregate	-45	-25	-15	0	1.50
13	Number of staggered floors	0	15	25	45	0.50
14	Structural or typological heterogeneity among adjacent structural units	-15	-10	0	45	1.20
15	Percentage difference of opening areas among adjacent facades	-20	0	25	45	1.00

Table 2: Normalised quick vulnerability indices of the aggregate S.U.

Building	**1**	**2**	**3**	**4**	**5**	**6**
$I_{v,norm}$	0.24	0.19	0.18	0.29	0.20	0.27

6. The macro-element numerical analyses

The seismic behaviour of the building aggregate has been studied by means of non-linear static analyses performed through the 3Muri calculation program. After assessing the seismic response of the isolated units (I.U.) along the main analysis directions, the behaviours of the units included in the aggregate (A.U.) have been evaluated, as already done in [13]. In particular, the aggregate S.U. response has been achieved step-by-step by considering as displacement the average value Δ_{medium} of the top nodes displacements δ_i:

$$\Delta_{medium} = \frac{\sum \delta_i}{N^\circ\, nodes} \qquad (1)$$

On the other hand, the base shear V is considered as the sum of the piers base reactions $R_{i,j}$ of that unit in the step-by-step procedure along the two main directions:

$$V = \Sigma_i R_{i,j} \qquad (2)$$

The procedure, for the sake of representation herein applied to the building # 3, provides the pushover curves of the A.U. shown in Figure 6, which appear to have the maximum base shears greater than those of the I.U.

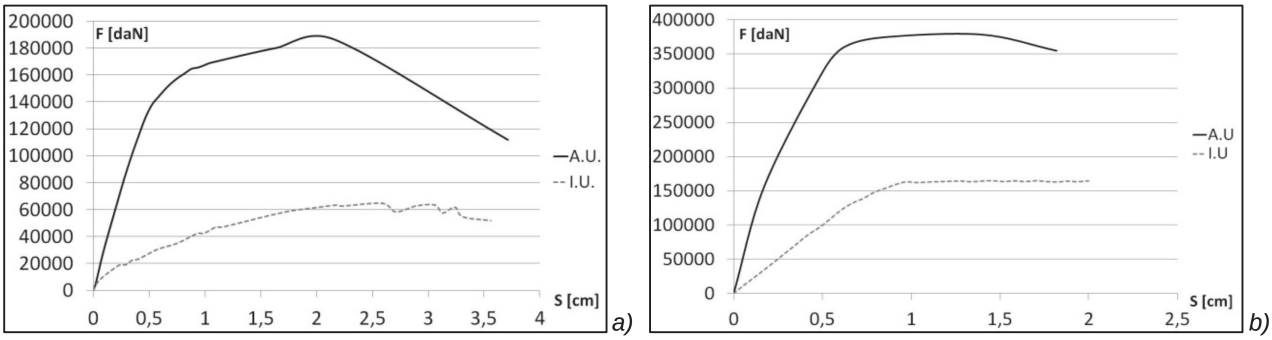

Fig. 6: Pushover curves for the intermediate S.U. in directions *X* (a) and *Y* (b).

The evaluation of the vibration periods of the S.U. in the two main directions is done by inserting in the ADRS format the bilinear capacity curves (Fig. 7).

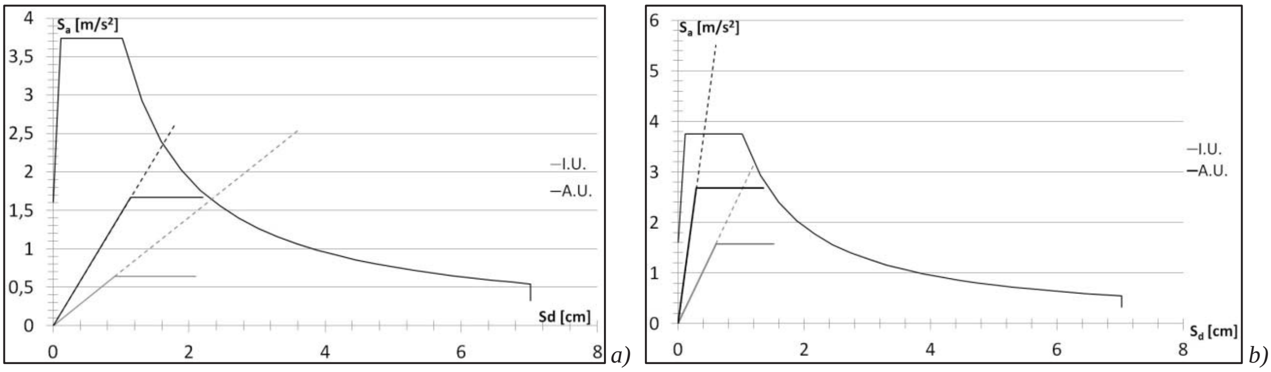

Fig. 7: Bilateral pushover curves of A.U. in directions *X* (a) and *Y* (b).

Starting from the above graphical representation, once coordinates (S_a ; S_d) of the initial curve branch are known, the period T^* of the A.U. is achieved through the following relationship:

$$T^* = \sqrt{\frac{\mathrm{Sd}}{\mathrm{Sa}} * 4\pi^2} \quad (3)$$

The calculation of vibration periods in directions *X* and *Y* are reported in Table 3.

Table 3: Calculation of vibration periods of S.U. grouped into the aggregate.

S.U.	**Direction *X***			**Direction *Y***		
	S_a [m/s^2]	**S_d [m]**	**T^* [s]**	**S_a [m/s^2]**	**S_d [m]**	**T^* [s]**
1	3.744	0.0026	0.165	3.744	0.005	0.213
2	3.744	0.0063	0.257	3.744	0.0039	0.202
3	2.620	0.0162	0.493	3.744	0.0023	0.155
4	3.744	0.0082	0.293	3.744	0.0032	0.183
5	3.744	0.0020	0.145	3.744	0.0051	0.231
6	2.500	0.0010	0.125	3.744	0.0013	0.117

In order to compare the results in terms of vibration periods of the structural units in the isolated conditions with respect to the aggregate ones, suitable histograms in the two analysis directions have been plotted, as depicted in Figure 8.

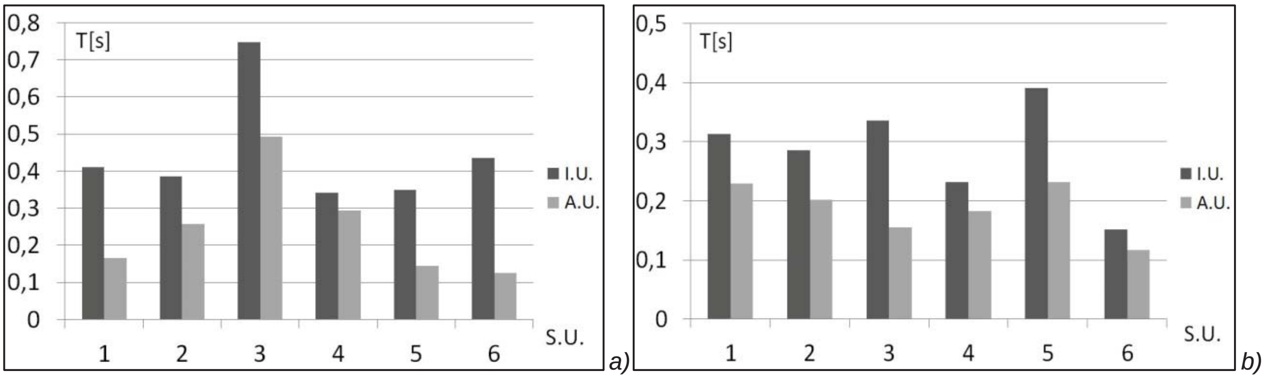

Fig. 8: Comparison of vibration periods among A.U. and I.U. in directions *X* (a) and *Y* (b).

From this figure it is seen that single units have stiffness greater than that of the same structural units considered in the aggregate. Additionally, it can be deduced that in direction *X* the vibration period grows for intermediate units, while in direction *Y* the period decreases for head structural units.
Finally, if vibration periods previously obtained are compared with the vulnerability indices derived from the vulnerability form for historical aggregates, it is demonstrate how the position of S.U. in the aggregate influences their vulnerability. In fact, it is noted that for the head S.U. the seismic vulnerability index tends to increase with the decrease of the vibration period, while for intermediate S.U. the vulnerability index decreases as the vibration period enlarges (Fig. 9).

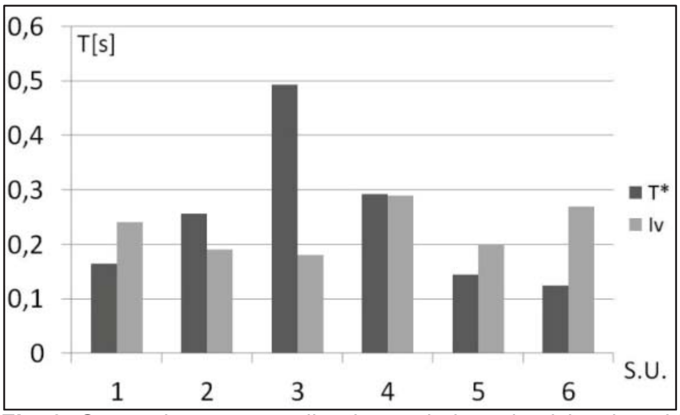

Fig. 9: Comparison among vibration periods and quick vulnerability indices for the investigated S.U.

7. Conclusions

In the current paper the seismic behaviour of I.U. and A.U. has been investigated through a combined simplified-numerical approach applied to a building compound in Bacoli.
The analysis results applied to the case study have shown that single units have stiffness greater than that of the same structural units considered in the aggregate.
Additionally, it can be deduced that in direction *X* the vibration period grows for intermediate units, while in direction *Y* the period decreases for head structural units. Furthermore, in direction *X* the head units have lower periods and, therefore, are subjected to seismic forces higher than intermediate ones. On the other hand, in direction *Y*, the opposite behaviour is achieved: the head S.U. (n. 1 and 5) are subjected to seismic forces lesser than those of intermediate units, so showing the beneficial effect of the aggregate condition.
Finally, the comparison between vibration periods and form vulnerability indices has shown that for head S.U. the seismic vulnerability index tends to increase with the reduction of the vibration period, whereas the opposite situation is detected for intermediate S.U.
However, the achieved results cannot be considered as exhaustive and deserve to be deepened much more. Therefore, as further development of the study, additional analyses on other building aggregates, also considering both bigger irregularity in elevation among adjacent buildings and compounds with different plan configurations, should be performed aiming at finding general rules for seismic behaviour assessment of single structural units within groups of constructions belonging to historical centres.

Bibliographical References

[1] Giuffre,` A. (editor). *Safety and conservation of historical centers: the Ortigia case* (in Italian), Roma, Bari, Laterza editors, 1993.

[2] Formisano, A., Di Feo, P., Grippa, M. R., Florio G. L'Aquila earthquake: A survey in the historical centre of Castelvecchio Subequo, *Proc. of the Final COST ACTION C26 Conference: Urban Habitat Constructions under Catastrophic Events,* Naples, Italy, 16-18 September, 2010, pp. 371-376.

[3] Indirli, M., Kouris, L. A., Formisano, A., Borg, R. P., Mazzolani, F. M. Seismic damage assessment of unreinforced masonry structures after the Abruzzo 2009 earthquake: the case study of the historical centres of L'Aquila and Castelvecchio Subequo, *International Journal of Architectural Heritage* 7 (5), 2013, 536-578.

[4] Zuccaro, G., Cacace, F. Seismic vulnerability assessment based on typological characteristics. The first level procedure "SAVE", *Soil Dynamics and Earthquake Engineering*, 69, 2015, 262-269.

[5] Benedetti, D., Petrini, V. On the seismic vulnerability of masonry buildings: an evaluation method (in Italian), *L'industria delle Costruzioni*,149, 1984, 66-74.

[6] Formisano, A., Florio, G., Landolfo, R., Mazzolani, F. M. Numerical calibration of a simplified procedure for the seismic behaviour assessment of masonry building aggregates*, Proc. of the 13th International Conference on Civil, Structural and Environmental Engineering Computing*, 2011, paper 172.

[7] Formisano, A., Florio, G., Landolfo, R., Mazzolani, F. M. Numerical calibration of an easy method for seismic behaviour assessment on large scale of masonry building aggregates, *Advances in Engineering Software*, 80, 2015, 116-138.

[8] Formisano, A., Mazzolani, F. M.,Florio, G., Landolfo, R., A quick methodology for seismic vulnerability assessment of historical masonry aggregates", *Proc. of the Final COST ACTION C26 Conference "Urban Habitat Constructions under Catastrophic Events"*, Naples, 16-18 September, 2015, pp. 577–582.

[9] S.T.A.DATA. *3MURI*. "*Seismic calculation of masonry structures according to M.D. 14/01/2008 New technical codes for constructions",* 2009.

[10] Maio, R., Vicente, R., Formisano A., Varum, H. Seismic vulnerability of building aggregates through hybrid and indirect assessment techniques, *Bulletin of Earthquake Engineering* 13 (10), 2015, 2995-3014.

[11] Formisano, A., Mazzolani, F.M., Florio, G., Landolfo, R., De Masi, G., Priscoli, G.D., Indirli, M. Seismic vulnerability analysis of historical centres: A GIS application in Torre del Greco, *Proc. of the Final COST ACTION C26 Conference: Urban Habitat Constructions under Catastrophic Events,* Naples, Italy, 16-18 September, 2010, pp. 583-588.

[12] Formisano, A. Seismic behaviour and retrofitting of the Poggio Picenze historical centre damaged by the L'Aquila earthquake, *Civil-Comp Proceedings*, 2012, paper 99.

[13] Formisano, A., Castaldo, C., Mazzolani, F.M. Non-Linear analysis of masonry building compounds: A comparison of numerical and theoretical results, *Civil-Comp Proceedings*, 2013, paper 102.