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Building Inventory at National scale by evaluation of seismic vulnerability classes distribution based on Census data analysis: BINC procedure

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ABSTRACT

In this paper, the BINC procedure (Building Inventory at National scale based on Census data) is proposed. It is a quick methodology to assess the building inventory needed to seismic exposure assessment at regional and national scale. Vulnerability classes map for the whole Italian region is proposed.

BINC procedure, developed at the PLINIVS Study Centre (University of Naples Federico II), is able to provide a seismic vulnerability assessment on the basis of 'weak' data. The information used to set the method are carried out from census database furnished by Italian National Institute of Statistics, ISTAT (DB_Census) and the database of information collected in situ by PLINIVS (DB_PLINIVS). In particular, exploiting vulnerability classes information of the DB_PLINIVS and common characteristics of the two databases, a generalization of buildings distribution on the vulnerability classes in obtained at regional national scale.

The methodology can be easily extended to all countries having census data on buildings.

1. Introduction

In the framework of planning and management of seismic emergency at national and regional scale, the analysis of scenario and risk constitutes the main tools to define the mitigation strategies at short and long term, to allocate the available resource and to device the operative phases in the emergency.

The risk is the convolution of three factors: hazard, exposure and vulnerability. The hazard is the time-space distribution of the intensity of a given seismic event of assigned occurrence probability in a given time and a given geographical area. The exposure is the distribution of the probability that a given element (people, building, infrastructure, economy, environment, etc.) of assigned characteristics (of qualitative and quantitative type) occupies in a given time and a given geographical area. The vulnerability is the distribution of the probability that a given exposed element of assigned characteristics is damaged by seismic hazard.

In this paper an approach to assess the building inventory (exposure) at national and regional scale is proposed. It is called BINC procedure (Building Inventory at National scale based on Census data) and it is developed by the authors in the framework of PLINIVS Study Centre research activities. For each Italian municipality, it aims to identify, the distribution of vulnerability classes (which represent buildings sets characterized by similar behavior under effect of seismic hazard) on the base of Italian census data [1].

Seismic exposure assessment finalized to risk assessment requires a specific approach, since it involves large numbers of buildings. In literature, different procedures able to assess the building inventory in the framework of risk assessment exist. The maim methods are of two kinds.

The former provides the development of global database of building inventories using taxonomy of global or national building types for use in near-real-time post-earthquake loss estimation and pre-earthquake risk analysis, as: Russian program Extremum [2], HAZUS-MH [3], PAGER [4], GEM [5], CARTIS DB [6]. These data base are generally completed by inside and outside building-by-building analyses by expert teams, so they may provide high quality vulnerability information, but, given the onerousness of the activities in the field, they often do not cover the entire regional or national territory, so these data base must be completed on the base of information at large scale, as census

Abbreviation: C_{ij}, Alternative option j of the parameter combination i; I_c, comparison index; N_b, Number of buildings in reference to DB_PLINIVS; M_b, Number of buildings in reference to DB_Census; P_{ij}, Alternative option j of parameter i; BINC, Building Inventory at National scale based on Census data; DB_Census, ISTAT 2001 database on buildings, with aggregated data (8101 municipalities); DB_Census1, ISTAT 2001 database on buildings, with not aggregated data (190 municipalities); DB_PLINIVS, PLINIVS database on buildings (800 municipalities); DB_PLINIVS1, PLINIVS database on buildings (with reference to the same municipalities in DB_Census1); DB_PLINIVS2, PLINIVS database on buildings (610 municipalities); DPM, Damage Percentage Matrix; VC_k, Vulnerability Class; SAVE, Strumenti Aggiornati per la Vulnerabilità sismica del patrimonio Edilizio e dei sistemi urbani; SPD, Synthetic Parameter of Damage

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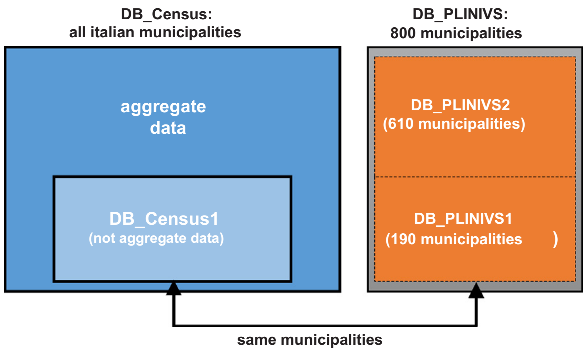

Fig. 1. Database used in the procedure.

data.

The latter proposes the satellite remote sensing to assess the buildings inventory, through the visual assessment by images of features that can influence the seismic performance of structures. These techniques can be founded on: pure satellite remote sensing (see [7–11]), providing information about vulnerability-related features that can be assessed from the top view; or integrated approaches, which combine satellite images and ground-based omnidirectional imaging data (see [12–15]). Differently from the approaches of the first type, they can quickly gather a lot of data at national and regional level, moreover they are able to better control the dynamic change over short time-scales (a few years) of urban settlements. On the other hand, they present the difficulty of evaluating the correlations between the data obtained from the images and the seismic vulnerability.

Probably, the most reliable exposure estimates should be assessed through hybrid approaches that seek to balance the pros and cons of the two families of methodologies.

The procedure here illustrated is included among the first methods. It is founded on the analysis of statistical correlations existing between 'weak' data available at national scale (see [1]) and more reliable data collected in site, on about 800 Italian municipalities (DB_PLINIVS), through survey activities building-by-building of structural- typological characteristics.

The study is founded on the numerous research activities developed in Italy in the framework of seismic risk assessment (see [16–40]).

The advantage of the procedure is to furnish a methodology easy to apply, based on 'weak' and 'free' data, striking a balance between the need of reliable data and the impossibility to get detailed surveys for all the buildings of a whole region or a whole country. The goal of the proposed inventory analysis is to assess, for each of the 8101 Municipalities of Italy, the number of buildings and their distribution in vulnerability classes according to the European Macroseismic Scale (EMS'98) vulnerability classification [41].

The methodology can be easily extended to all countries having census data on buildings, assessing statistical correlation with ad hoc information collected on the territory.

2. The methodology

The proposed procedure allows to estimate the vulnerability classes distributions (exposure) at regional and national level, starting from 'weak' data National Census data provided by ISTAT (Italian National Institute of Statistics).

The procedure deduces information about Italian Territory from the following databases (DB), shown in Fig. 1:

1. ISTAT 2001 database (DB_Census), at national scale, which contains for each minimum reference unit (identified by sub- municipal zones, called *census areas*), 'aggregate data', that is it furnish the number of buildings having a given single characteristic (i.e., building position in the aggregate, material of vertical structure, age of buildings, etc.) for each census area;
2. PLINIVS survey database (DB_PLINIVS), at local scale, in which georeferenced data relating to buildings typologies and vulnerability class are collected [42]. It is constituted by 800 municipalities and about 180,000 buildings.

Furthermore, thanks to the Italian Civil Protection, PLINIVS Study Centre has other special information collected by ISTAT, generally not free available, constituted by 'not aggregate data' (for information type) for 190 Municipalities (DB_Census1). These information furnishes, for each census area in the 190 municipalities, the number of buildings having a given combination of different characteristics.

The procedure proposed divides the DB_PLINIVS in two sets: the former one (DB_PLINIVS1) is constituted by the 190 municipalities in common with 'not aggregate data' DB_Census1; the latter one DB_PLINIVS2 is constituted by the rest of the 610 municipalities.

DB_Census provides typological buildings characteristics belonging to Census Area in which Italian country is divided, whilst DB_PLINIVS, through the SAVE Method [42], defines vulnerability classes over typological features of buildings belonging to 800 Municipalities. By exploiting common characteristics of two databases and the stochastic valence of the PLINIVS'one, a projection of buildings distribution on vulnerability classes is obtained at national and regional scale.

The common descriptive characteristics of the two databases are essentially six: building position in the aggregate, material of vertical structure, age of buildings, number of floors above ground, altimetry and demographic class. Each one of these characteristics is assumed as 'parameter' of the procedure and is partitioned by using alternative options (Table 1).

The procedure proposes the definition of expected buildings distribution for each parameter taken individually and for some combination parameters. In both of the cases, statistical analysis of the relations between the parameters and the vulnerability classes of the surveyed buildings (DB_PLINIVS) is studied. As appropriate, the

Table 1
Parameters of buildings.

		Parameters					
		P_1 position of the building in the aggregate	P_2 material of vertical structures	P_3 age of building	P_4 number of floors above ground	P_5 altimetry of municipality	P_6 demographic class of the municipality
Alternative options	1	Isolated	masonry	before 1919	1–2	plain (0–300 m)	< 500
	2	on one side	reinforced concrete	1919–1945	3–4	hill (300–600 m)	500–1.999
	3	on two or more side	rc with pilotis at ground level	1946–1961	5 – 6	mountain (> 600 m)	2.000–4.999
	4		other	1962–1971	7 – 8		5.000–9.999
	5			1972–1981			10.000–49.999
	6			1982–1991			50.000–249.999
	7			after 1999			> 250.000

Table 2
Three parameters combinations.

Combination		First parameter	Second parameter	Third parameter	Number of alternative options
C_1	**$P_3 + P_6 + P_5$**	Age	Demographicclass	Altimetry	147
C_2	**$P_3 + P_6 + P_2$**	Age	Demographicclass	Vertical Structure	196
C_3	**$P_3 + P_6 + P_4$**	Age	Demographicclass	Number of floors	196
C_4	**$P_3 + P_6 + P_1$**	Age	Demographicclass	Position in the block	147
C_5	**$P_3 + P_5 + P_2$**	Age	Altimetry	Vertical Structure	84
C_6	**$P_3 + P_5 + P_4$**	Age	Altimetry	Number of floors	84
C_7	**$P_3 + P_5 + P_1$**	Age	Altimetry	Position in the block	63
C_8	**$P_3 + P_2 + P_4$**	Age	Vertical Structure	Number of floors	112
C_9	**$P_3 + P_2 + P_1$**	Age	Vertical Structure	Position in the block	84
C_{10}	**$P_3 + P_4 + P_1$**	Age	Number of floors	Position in the block	84
C_{11}	**$P_6 + P_5 + P_2$**	Demographicclass	Altimetry	Vertical Structure	84
C_{12}	**$P_6 + P_5 + P_4$**	Demographicclass	Altimetry	Number of floors	84
C_{13}	**$P_6 + P_5 + P_1$**	Demographicclass	Altimetry	Position in the block	63
C_{14}	**$P_6 + P_2 + P_4$**	Demographicclass	Vertical Structure	Number of floors	112
C_{15}	**$P_6 + P_2 + P_1$**	Demographicclass	Vertical Structure	Position in the block	84
C_{16}	**$P_6 + P_4 + P_1$**	Demographicclass	Number of floors	Position in the block	84
C_{17}	**$P_5 + P_2 + P_4$**	Altimetry	Vertical Structure	Number of floors	48
C_{18}	**$P_5 + P_2 + P_1$**	Altimetry	Vertical Structure	Position in the block	36
C_{19}	**$P_5 + P_4 + P_1$**	Altimetry	Number of floors	Position in the block	36
C_{20}	**$P_2 + P_4 + P_1$**	Vertical Structure	Number of floors	Position in the block	48

Table 3
Example of alternative options for the parameters combination C14 (position in the aggregate, vertical structure, altimetry).

		Combination C18		
		Position of the building in the aggregate P_1	**Material of vertical structure P_2**	**Altimetry of municipality P_5**
Alternative options	**1**	isolated	masonry	plain
	2	isolated	masonry	hill
	3	isolated	masonry	mountain
	4	isolated	Reinforced Concrete	plain
	5	isolated	Reinforced Concrete	hill
	6	isolated	Reinforced Concrete	mountain
	7	isolated	RC with pilotis at ground level	plain
	8	isolated	RC with pilotis at ground level	hill
	9	isolated	RC with pilotis at ground level	mountain
	10	isolated	other	plain
	11	isolated	other	hill
	12	isolated	other	mountain
	13	on one side	masonry	plain
	14	on one side	masonry	hill
	15	on one side	masonry	mountain
	16	on one side	Reinforced Concrete	plain
	17	on one side	Reinforced Concrete	hill
	18	on one side	Reinforced Concrete	mountain
	19	on one side	RC with pilotis at ground level	plain
	20	on one side	RC with pilotis at ground level	hill
	21	on one side	RC with pilotis at ground level	mountain
	22	on one side	other	plain
	23	on one side	other	hill
	24	on one side	other	mountain
	25	on two or more sides	masonry	plain
	26	on two or more sides	masonry	hill
	27	on two or more sides	masonry	mountain
	28	on two or more sides	Reinforced Concrete	plain
	29	on two or more sides	Reinforced Concrete	hill
	30	on two or more sides	Reinforced Concrete	mountain
	31	on two or more sides	RC with pilotis at ground level	plain
	32	on two or more sides	RC with pilotis at ground level	hill
	33	on two or more sides	RC with pilotis at ground level	mountain
	34	on two or more sides	other	plain
	35	on two or more sides	other	hill
	36	on two or more sides	other	mountain

frequencies of occurrence of the vulnerability classes are estimated for a single alternative option or for each combination of alternative options of the considered parameters.

In all the census areas, total buildings are divided on the alternative options of each parameter. Through the frequencies of occurrence, a buildings distribution on the vulnerability classes can be evaluated for each parameter or for each combination of parameters. In the latter case is necessary having not aggregate information about buildings.

A validation of the method is also presented. For this purpose a comparison between the obtained results and the actual known distribution is carried out. At the end, an application of the calibration procedures and assessment of the vulnerability distributions at national

Table 4
Values of Synthetic Parameter of Damage (SPD) for the assignment of vulnerability classes VC_k according to SAVE procedure [42].

VC_k	Average	Standard deviation
A	2.54	0.22
B	2.04	0.13
C	1.19	0.15
D	0.69	0.21

scale is presented.

In the following section, the steps which characterize the procedure are defined.

3. Steps of the procedure

3.1. Input parameters

A comparison between the two databases defines the following six parameters (Table 1):

1. *Position* of the building in the aggregate (isolated, on one side, on two or more side);
2. *Material* of vertical structure (masonry, reinforced concrete, RC with pilotis at ground level, other);
3. *Age* of building (before 1919, 1919–1945, 1946–1961, 1962–1971, 1972–1981, 1982–1991, after 1991);
4. *Number of floors* above ground (1–2, 3–4, 5–6, 7–8);
5. *Altimetry* of the municipality (plain, hill, mountain);
6. *Demographic class* of the municipality, in terms of population

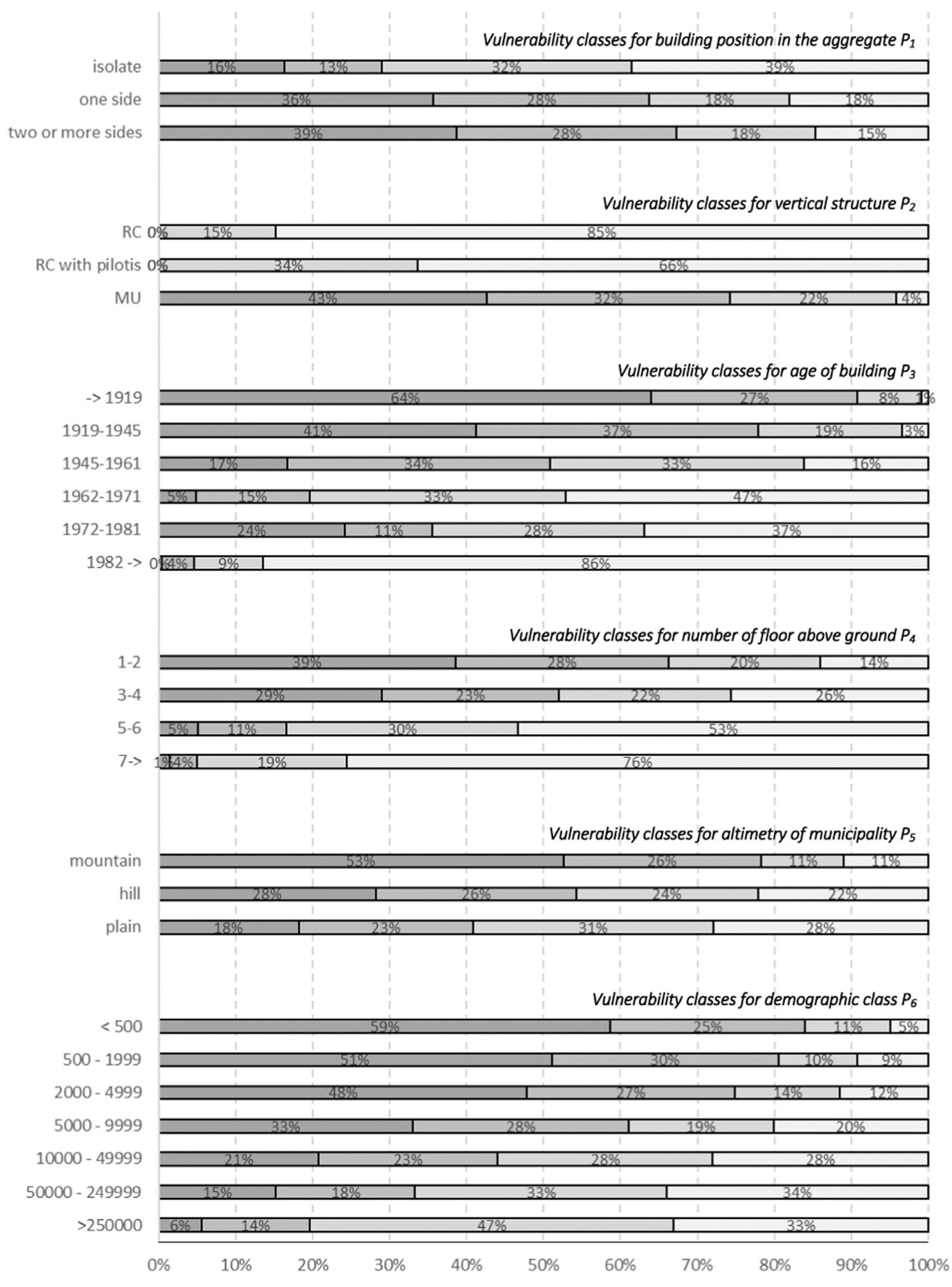

Fig. 2. Frequencies of occurrence of vulnerability classes (A, B, C, D) for each parameter using DB_PLINIVS.

Table 5
Vulnerability classes distribution of a given Census Area for each parameter and the average of them.

P_{ij}		$f(P_{ij},VC_k)$				Rocca Pia					Pescocostanzo					Gagliano Aterno					Solofra				
						$Mb(P_{ij})$	$M(P_{ij},VC_k)$				$Mb(P_{ij})$	$M(P_{ij},VC_k)$				$Mb(P_{ij})$	$M(P_{ij},VC_k)$				$Mb(P_{ij})$	$M(P_{ij},VC_k)$			
i	j	A	B	C	D	–	A	B	C	D	–	A	B	C	D	–	A	B	C	D	–	A	B	C	D
1	1	16%	13%	32%	39%	21	3	3	7	8	276	45	35	90	106	56	9	7	18	22	720	117	91	234	278
	2	36%	28%	18%	18%	80	29	22	15	14	117	42	33	21	21	51	18	14	9	9	415	148	116	76	75
	3	39%	28%	18%	15%	72	28	21	13	11	262	102	75	47	38	221	86	63	40	32	265	103	75	48	39
						P_1	**60**	**46**	**34**	**33**	**P_1**	**188**	**142**	**158**	**166**	**P_1**	**113**	**84**	**67**	**63**	**P_1**	**368**	**283**	**358**	**391**
2	1	43%	32%	22%	4%	170	72	54	37	7	431	184	136	93	18	298	127	94	64	12	275	117	87	59	11
	2	0%	0%	34%	66%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	55	0	0	19	36
	3	0%	0%	15%	85%	3	0	0	0	3	205	0	0	31	174	1	0	0	0	1	951	0	0	145	806
						P_2	**72**	**54**	**37**	**10**	**P_2**	**127**	**94**	**64**	**13**	**P_2**	**127**	**94**	**64**	**13**	**P_2**	**117**	**87**	**222**	**854**
3	1	64%	27%	8%	1%	161	103	43	13	1	324	207	87	27	3	140	90	38	12	1	83	53	22	7	1
	2	41%	37%	19%	3%	5	2	2	1	0	14	6	5	3	0	123	51	45	23	4	24	10	9	4	1
	3	17%	34%	33%	16%	4	1	1	1	1	37	6	13	12	6	11	2	4	4	2	50	8	17	16	8
	4	5%	15%	33%	47%	0	0	0	0	0	99	5	15	33	47	8	0	1	3	4	116	6	17	39	55
	5	24%	11%	28%	37%	0	0	0	0	0	93	23	11	26	34	14	3	2	4	5	218	53	25	60	80
	6	0%	4%	9%	86%	3	0	0	0	3	88	0	4	8	76	32	0	1	3	28	909	3	38	82	785
						P_3	**106**	**47**	**16**	**5**	**P_3**	**247**	**134**	**108**	**166**	**P_3**	**146**	**90**	**48**	**44**	**P_3**	**133**	**128**	**209**	**930**
4	1	39%	28%	20%	14%	111	43	31	22	16	309	119	85	61	43	173	67	48	34	24	896	346	247	177	126
	2	29%	23%	22%	26%	62	18	14	14	16	331	96	76	74	85	155	45	36	35	40	432	125	99	97	111
	3	5%	11%	30%	53%	0	0	0	0	0	15	1	2	5	8	0	0	0	0	0	72	4	8	22	38
	4	1%	4%	19%	76%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
						P_4	**61**	**45**	**36**	**31**	**P_4**	**216**	**163**	**140**	**136**	**P_4**	**112**	**83**	**69**	**64**	**P_4**	**475**	**355**	**296**	**275**
5	1	53%	26%	11%	11%	170	89	44	18	19	542	285	139	58	59	328	172	84	35	36	1332	700	343	143	146
	4	28%	26%	24%	22%	3	1	1	1	1	111	31	29	26	25	0	0	0	0	0	68	19	18	16	15
	5	18%	23%	31%	28%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
						P_5	**90**	**45**	**19**	**19**	**P_5**	**316**	**168**	**84**	**84**	**P_5**	**172**	**84**	**35**	**36**	**P_5**	**719**	**360**	**159**	**161**
6	1	59%	25%	11%	5%	173	102	44	19	9	0	0	0	0	0	328	193	83	36	16	0	0	0	0	0
	2	51%	30%	10%	9%	0	0	0	0	0	655	334	194	67	60	0	0	0	0	0	0	0	0	0	0
	3	48%	27%	14%	12%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	33%	28%	19%	20%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	21%	23%	28%	28%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1400	291	327	391	392
	6	15%	18%	33%	34%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7	6%	14%	47%	33%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
						P_6	**102**	**44**	**19**	**9**	**P_6**	**334**	**194**	**67**	**60**	**P_6**	**193**	**83**	**36**	**16**	**P_6**	**291**	**327**	**391**	**392**
						P_A	**82**	**46**	**27**	**18**	**P_A**	**248**	**156**	**114**	**134**	**P_A**	**144**	**87**	**53**	**39**	**P_A**	**351**	**257**	**272**	**501**

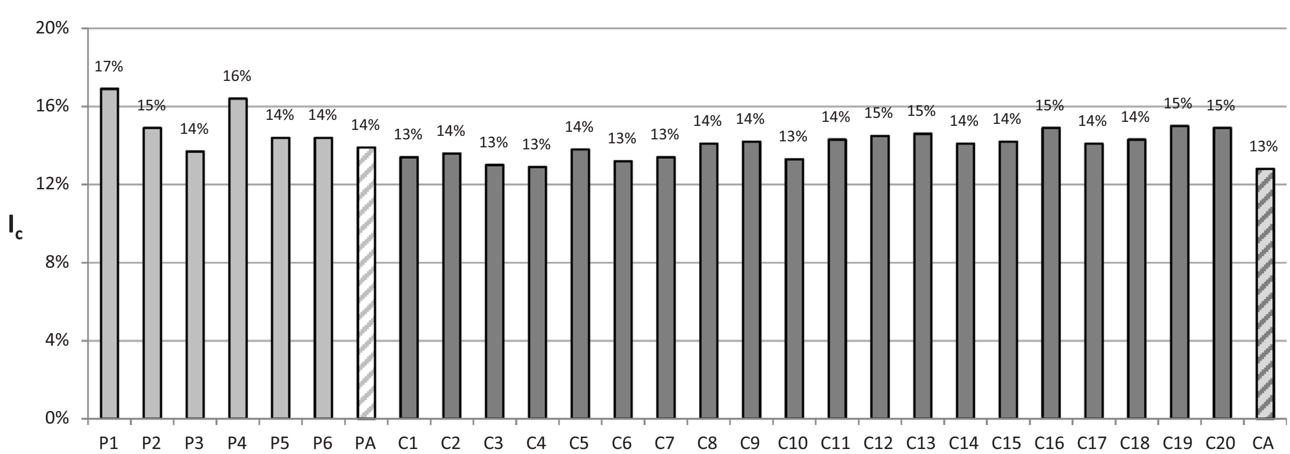

Fig. 3. Comparison indexes (I_c) between the vulnerability classes of the buildings surveyed (DB_PLINIVS) and the vulnerability classes evaluated by the proposed procedure, for each parameter P_i and each combination C_i. PA and CA represent, respectively, the arithmetical average among all parameters and all combinations.

(< 500, 500–1.999, 2.000–4.999, 5.000–9.999, 10.000–49.999, 50.000–249.999, > 250.000).

The number of parameters combinations depends on the number of parameters taken in account and on their alternative options. Considering all of them there are 7056 possible combination but many of these describe categories of buildings not-existent or negligible. A three parameters combination carries out the 20 possibilities summarized into the Table 2. An example of alternative options for the parameters combination C_{18}, is reported in Table 3. In this paper the listed

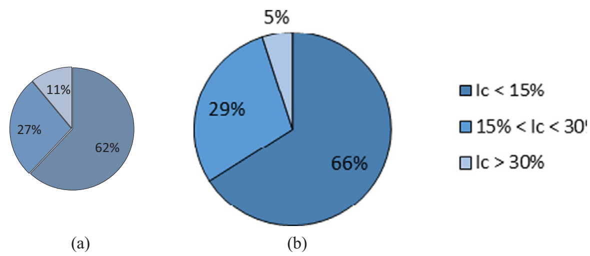

Fig. 4. Municipalities performances in function of I_c for the average of single parameters (a) and combinations (b).

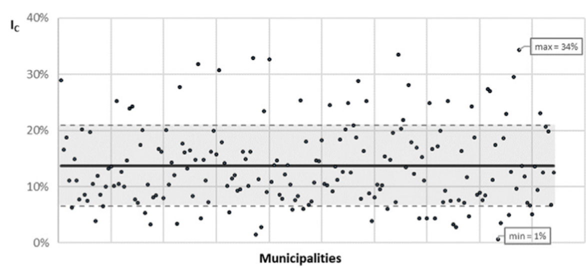

Fig. 5. Distribution of I_c for 190 municipalities contained in DB_PLINIVS1.

fourteen distributions for Census Area with aggregate data are taken in account.

3.2. Vulnerability classes assignment

For each building of DB_PLINIVS, the seismic vulnerability class VC (for decreasing vulnerability, A, B, C, …) is evaluated on the basis of its typological characteristics, by a first level procedure developed by the authors [42] and founded on the same database (DB_PLINIVS), called 'SAVE' method (Strumenti Aggiornati per la Vulnerabilità sismica del patrimonio Edilizio e dei sistemi urbani – Updated Tools for the Seismic Vulnerability Evaluation of the Italian Real Estate and of Urban Systems). Starting from the typological classification given in the definition of the European Macroseismic Scale [43], the procedure is aimed at reducing the implicit uncertainty of the EMS'98 vulnerability classification. This is pursued by identifying a set of typological features (building age, geometric regularity, horizontal structure, tie roads, building position in the block, roof type, roof structure) which can be considered as vulnerability modifier, and giving to each of these a numerical weight, calibrated using an extensive database of seismic damage observed (using survey forms) after the most important earthquakes occurred in Italy since the 1980 Irpinia earthquake to today. The database used for all the elaborations is made by forms compiled during post-earthquake survey campaigns, indicating the typological features of the observed damage.

For each building, the statistical SAVE procedure assigns a vulnerability class on the base of a numerical parameter, called Synthetic Parameter of Damage (SPD), which takes into account the influence of each typological feature of buildings collected in DB_PLINIVS, by a weighted average on the damage observed [42].

With reference the sample of buildings in DB_PLINIVS (about 180,000), for each vulnerability class, the values of SPD are indicated in Table 4.

3.3. Frequency evaluation

In the following, the procedure to evaluate the frequencies of occurrence for analyses with single parameter [combined parameters] is exposed. Let i represent the generic parameter [parameter combination] according to Table 1 [Table 2], j the alternative option and k the vulnerability class (k = 1, VC = A; k = 2, VC = B; k = 3, VC = C; k = 4, VC = D). Let also P_{ij} [C_{ij}] represent the alternative option j of the parameter i [parameter combination i].

For each i and j values, frequency of occurrence on the four vulnerability classes is estimated using DB_PLINIVS. In particular, a query extracts from the database the number of buildings $N_b(P_{ij})$ [$N_b(C_{ij})$] having P_{ij}[C_{ij}] value and divides them in four groups depending on their vulnerability class. Using quantity $N_b(P_{ij}, VC_k)$ [$N_b(C_{ij}, VC_k)$] to represent the number of building having P_{ij} [C_{ij}] value and vulnerability

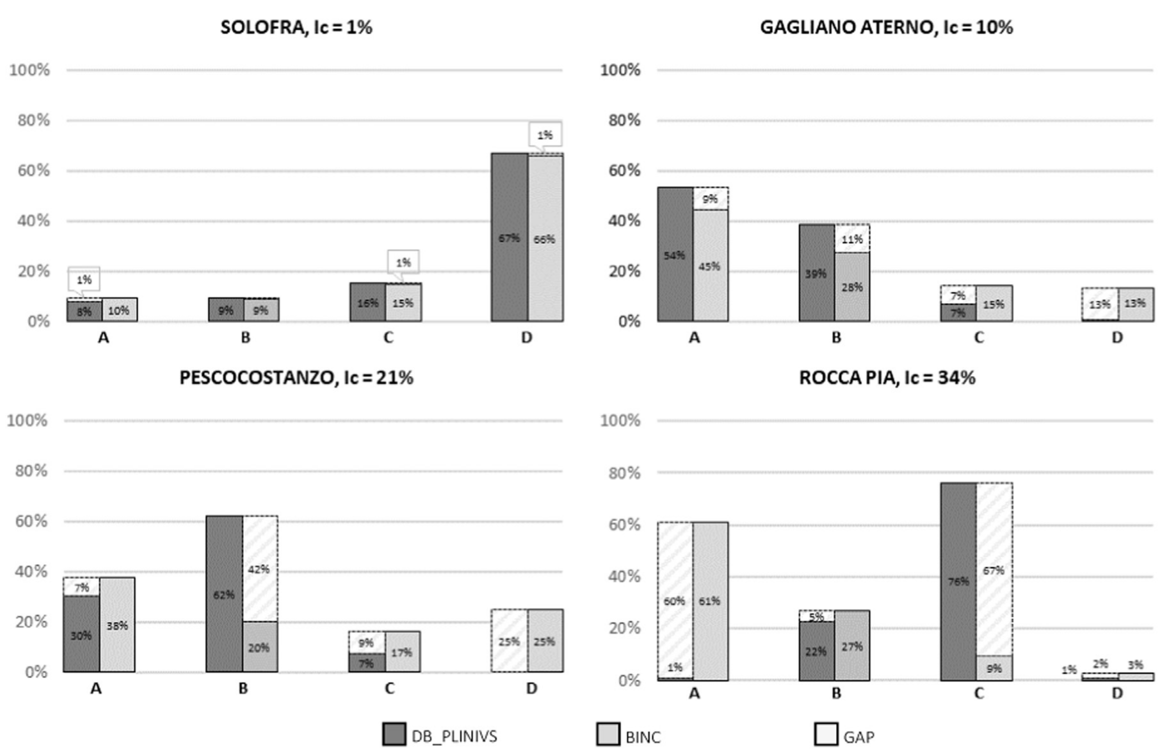

Fig. 6. Distribution of vulnerability classes for some municipalities contained in DB_PLINIVS1.

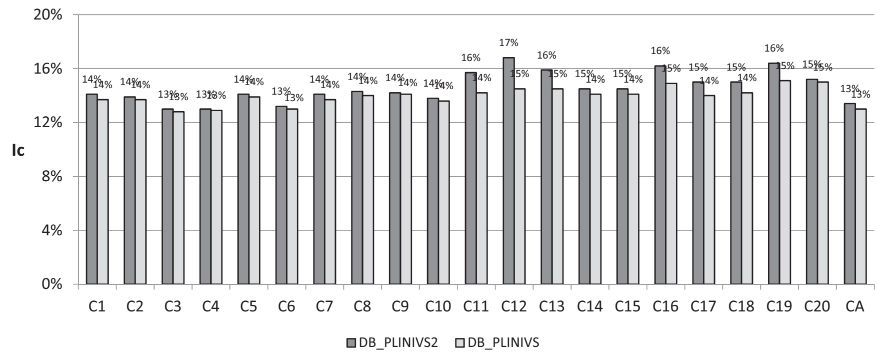

Fig. 7. Comparison between the combined parameter analysis adopted for the complete data base survey (DB_PLINIVS) and the data base reduced (DB_PLINIVS2) in term of I_c.

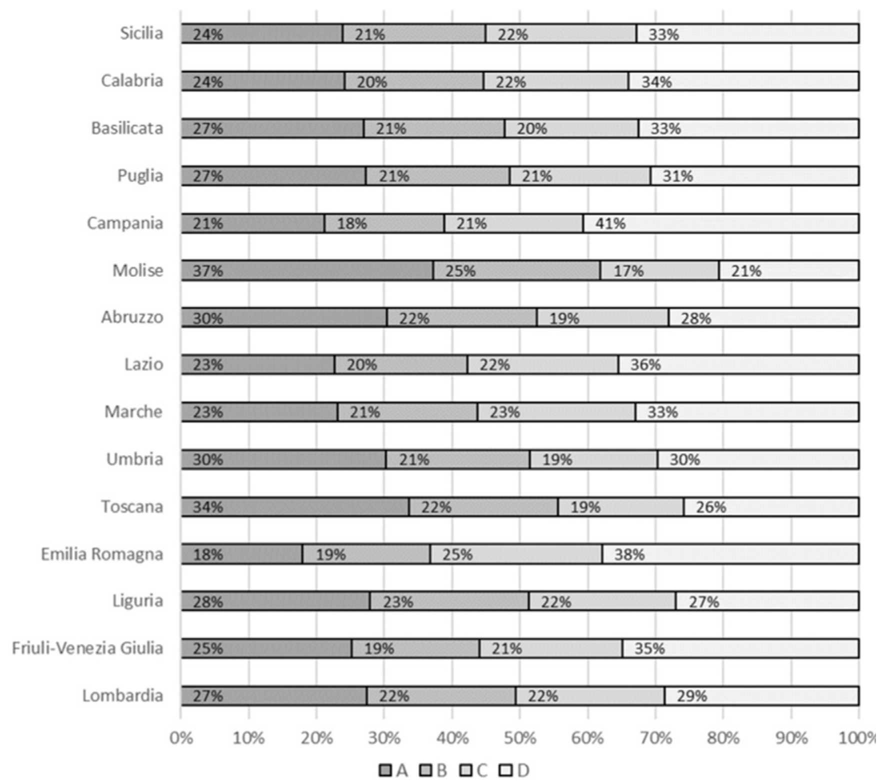

Fig. 8. Distribution of vulnerability classes (A–D) for some Italian regions using DB_PLINIVS.

class k, the frequency of occurrence of each class for the P_{ij} [C_{ij}] value is calculated by the relation (1) [(2)].

$$f(P_{ij}, VC_k) = \frac{N_b(P_{ij}, VC_k)}{N_b(P_{ij})} \tag{1}$$

$$f(C_{ij}, VC_k) = \frac{N_b(C_{ij}, VC_k)}{N_b(C_{ij})} \tag{2}$$

With reference to data concerning the 800 municipalities of DB_PLINIVS, the frequencies of occurrence of vulnerability classes (A–D) are calculated, grouping the results for each parameter (Fig. 2).

3.4. Distribution evaluation in census areas

For a Census Area of the DB_Census, the number of buildings $M_b(P_{ij})$ [$M_b(C_{ij})$] with a given P_{ij} [C_{ij}] is known. The number of buildings for each vulnerability class can be estimated by the relation (3) [(4)].

$$M_b(P_{ij}, VC_k) = M_b(P_{ij})\cdot f(P_{ij}, VC_k), \tag{3}$$

$$M_b(C_{ij}, VC_k) = M_b(C_{ij})\cdot f(C_{ij}, VC_k). \tag{4}$$

By repeating the evaluation of $M_b(P_{ij}, VC_k)$ [$M_b(C_{ij}, VC_k)$] for each j value of the parameter i, [parameters combination i], the total number of buildings of the census area with vulnerability class k is calculated by the relation (5) [(6)].

$$M_b(P_i, VC_k) = \sum_j M(P_{ij}, VC_k), \tag{5}$$

$$M_b(C_i, VC_k) = \sum_j M(C_{ij}, VC_k). \tag{6}$$

Another distribution can be also evaluated as arithmetical average of the six [fourteen] before. By using index A in order to denote the average value, the buildings distribution for each vulnerability class depending on the average of the six [twenty] parameters can be expressed as the relation (7) [(8)].

$$M_b(P_A, VC_k) = \frac{1}{6}\sum_{i=1}^{6} M(P_i, VC_k), \tag{7}$$

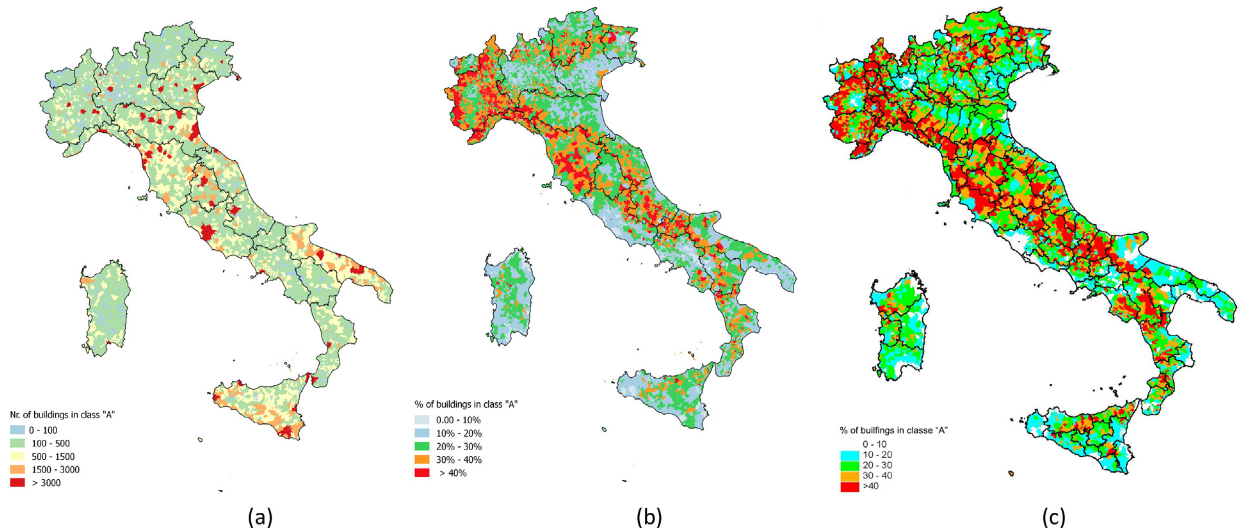

Fig. 9. Distribution of building in class "A" for each municipality assessed by: the proposed procedure, in terms of number (a) and percentage of buildings (b); Lucantoni et al. [20] in terms of percentage of buildings (c).

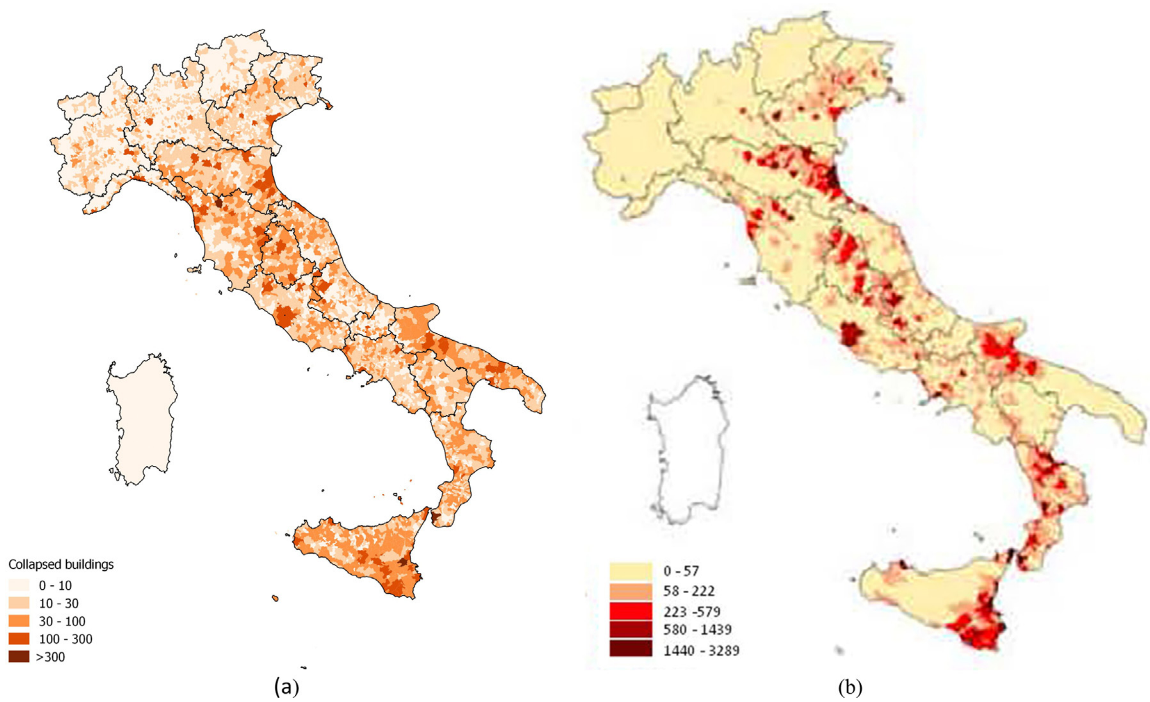

Fig. 10. Distribution of number of collapsed buildings for each municipality due to ground motions with a 10% probability of exceedance in 50 years, assessed by: the proposed procedure (a); and Crowley et al. in [16].

$$M_b(C_A, VC_k) = \frac{1}{20}\sum_{i=1}^{20} M(C_i, VC_k). \tag{8}$$

For each Italian municipality, adding the buildings numbers for each census section, the distribution of vulnerability classes can be determined by relations (5), (6) or (7), (8), considering, respectively, the influence of each parameter [combination] or the arithmetical average of six [fourteen] parameters [combinations].

For four Italian municipalities (Solofra, Gagliano Aterno, Pescocostanzo and Roccapia), the numerical evaluation of the vulnerability classes distributions is shown in Table 5, with reference to each single parameter and the average of them. For the sake of brevity, the values for the combinations are not shown.

4. Validation

In this section, a validation of the procedure is developed, using as comparative term the known vulnerability classes of the surveyed buildings contained in DB_PLINIVS1. This database is analyzed, instead the whole DB_PLINIVS, because it allows a comparison between single parameters and combinations of them.

The gaps between the known vulnerability classes assessed in DB_PLINIVS1 by SAVE method and the ones evaluated by BINC procedure are estimated by a *comparison index* I_c, as average of differences by the relation (9).

$$I_C = \frac{1}{4}\sum_{k=1}^{4} |C_{VC_k,P} - C_{VC_k}|, \tag{9}$$

in which $C_{VC_k,P}$ represents the percentage of buildings of vulnerability

Table 6
DPM obtained through a statistical analysis of the data collected about the observed damages due to earthquakes occurred in Italy since 1980 (see [44,45]).

Building class	Intensity	D0	D1	D2	D3	D4	D5
A	**V**	0,3487	0,4089	0,1919	0,0450	0,0053	0,0002
B		0,5277	0,3598	0,0981	0,0134	0,0009	0,0000
C		0,6591	0,2866	0,0498	0,0043	0,0002	0,0000
D		0,8587	0,1328	0,0082	0,0003	0,0000	0,0000
A	**VI**	0,2887	0,4072	0,2297	0,0648	0,0091	0,0005
B		0,4437	0,3915	0,1382	0,0244	0,0022	0,0001
C		0,5905	0,3281	0,0729	0,0081	0,0005	0,0000
D		0,7738	0,2036	0,0214	0,0011	0,0000	0,0000
A	**VII**	0,1935	0,3762	0,2926	0,1138	0,0221	0,0017
B		0,3487	0,4089	0,1919	0,0450	0,0053	0,0002
C		0,5277	0,3598	0,0981	0,0134	0,0009	0,0000
D		0,6591	0,2866	0,0498	0,0043	0,0002	0,0000
A	**VIII**	0,0656	0,2376	0,3442	0,2492	0,0902	0,0131
B		0,2219	0,3898	0,2739	0,0962	0,0169	0,0012
C		0,4182	0,3983	0,1517	0,0289	0,0028	0,0001
D		0,5584	0,3451	0,0853	0,0105	0,0007	0,0000
A	**IX**	0,0102	0,0768	0,2304	0,3456	0,2592	0,0778
B		0,1074	0,3020	0,3397	0,1911	0,0537	0,0060
C		0,3077	0,4090	0,2174	0,0578	0,0077	0,0004
D		0,4437	0,3915	0,1382	0,0244	0,0022	0,0001
A	**X**	0,0017	0,0221	0,1138	0,2926	0,3762	0,1935
B		0,0313	0,1563	0,3125	0,3125	0,1563	0,0313
C		0,2219	0,3898	0,2739	0,0962	0,0169	0,0012
D		0,2887	0,4072	0,2297	0,0648	0,0091	0,0005
A	**XI**	0,0002	0,0043	0,0392	0,1786	0,4069	0,3707
B		0,0024	0,0284	0,1323	0,3087	0,3602	0,1681
C		0,0380	0,1755	0,3240	0,2990	0,1380	0,0255
D		0,0459	0,1956	0,3332	0,2838	0,1209	0,0206
A	**XII**	0,0000	0,0000	0,0000	0,0010	0,0480	0,9510
B		0,0000	0,0000	0,0006	0,0142	0,1699	0,8154
C		0,0000	0,0001	0,0019	0,0299	0,2342	0,7339
D		0,0000	0,0002	0,0043	0,0498	0,2866	0,6591

class VC_k (A, B, C, D) in the DB_PLINIVS1, and C_{VC_k} is the percentage of buildings of vulnerability class VC_k assigned by BINC procedure. The results obtained by the procedure are reported in Fig. 3, where P_A and C_A represent, respectively, the arithmetical average among all parameters P_i and all combinations C_i.

The single parameter that shows the best result is the age of the building (P3), with I_C is equal to 13,7%, and the best parameters combination is C1, obtained with age (P3), number of floors (P4) and demographic class (P6), with I_C equal to 12,9%. It is shown that using the largest number of categories, the results are more dependable being generally associated with the lowest values of I_C.

A further comparison between the single parameters and their combinations is conducted through the average performances of the municipalities in term of I_C, like sum of the results relating to the census area (Fig. 4). The single parameter analysis shows an higher percentage of municipalities (38%) with $I_C > 15\%$ respect to the combinations ($< 34\%$).

With the aim to evaluate the influence in the vulnerability class assignment of the better correlated single parameter P3, age of building, the other following results are shown:

- for each municipality in DB_PLINIVS1, I_C parameters are calculated (Fig. 5). The minimum and maximum I_C values are, respectively, 1% and 34%. The average value is 14 $\pm$ 7%;
- for four municipalities in DB_PLINIVS1 (Solofra, Gagliano Aterno, Pescocostanzo and Roccapia), characterized by different values of I_C in the range [1;34%], the differences between the distributions of vulnerability classes calculated by BINC procedure and the ones known in DB_PLINIVS1are shown (Fig. 6). The results show a growing gap with I_C increasing.

To avoid problems about auto-reference of the values, a further analysis for combined parameters is developed. In particular, frequencies of occurrence are also evaluated by using only DB_PLINIVS2 and DB_PLINIVS. A comparison between these two analysis by using I_c index is reported in Fig. 7. It shown negligible gaps between two databases ($< 3\%$).

An analysis of the results illustrated this section shows that the BINC frequencies assessed by combinations of more parameters are generally more reliable compared to single parameter (Figs. 3 and 4), even if the difference between the I_C for the better correlated parameter (P_3) and combination (C_1) and the difference between the average values (P_A and C_A) are not significant, so the frequencies of the single parameter P_3 (Fig. 2) can be quietly adopted, also because the ISTAT data related to the single parameters are more easily available at large scale.

In addition, the analyses of influence of P_3 parameter for each municipality in DB_PLINIVS1 (Figs. 5 and 6), shown maximum values that make the procedure unreliable at municipal-scale risk analysis (unless further survey activities on field are developed, with the aim to improve the estimated frequencies in a specific municipality), while the average values make the procedure reliable at regional and national level.

5. Vulnerability and risk map

The procedure founded on the single parameter P3, age of constructions, is applied at regional and national scale (Figs. 8 and 9). The vulnerability classes distributions for each Italian municipality are calculated. In Fig. 9, the maps reporting the number (a) and the percentage (b) of buildings in class 'A' (a) are shown.

Similar results are obtained by [20], which are evaluated the vulnerability classes distributions for each municipality, on the base of a typological-statistical approach founded on correlation between the data collected during past Italian earthquake (1980 Irpinia and 1984 Lazio-Abruzzo) and the 1991 ISTAT Census. The distribution of 'A' class is shown in Fig. 9c. They are comparable with results obtained by the method here proposed (Fig. 9b), which uses, compared to Lucantoni et al. [20], more up-to-date Census data (ISTAT 2001 and 2011) and more numerous collected information. Both approaches identifies municipalities with the highest percentages od buildings in class 'A' (over 30%) in the central-southern Apennine arc and in the hilly and mountainous areas of Piedmont and Liguria. Metropolitan areas and coastal municipalities are mainly characterized by percentages lower than 20%.

With the aim to assess further validations, the map of buildings damaged to seismic hazard map exceeding probability $< 10\%$ in 50 years has been performed (Fig. 10a). It shown different results compared to the evaluation developed by Crowley et al. [16] through the SP-BELA procedure (Fig. 10b). This could depend on the different assumptions about collapse limit state. In this work "collapse" limit state is reached when the structural failure causes the complete (or at least wide partial) fall down of the building.

The damage distribution of Fig. 10a is assessed on the base of Damage Probability Matrix, DPM (Table 6) obtained by statistical fitting of observed damages recorded of all past seismic events in Italy from Irpinia 1980 earthquake up to L'Aquila event in 2009, collected in the DB_PLINIVS (see [44,45]).

6. Conclusions

A method able to assess the distributions of the seismic vulnerability classes of buildings for each Italian region is proposed. It is founded on the statistical correlations between few typological features provided by DB_Census and vulnerability classes. The reliability of the procedure is tested on large sample of buildings whose vulnerability is known from previous surveys activities in situ (DB_PLINIVS).

The result provides an easy-to-use assessment method, applicable at regional and national level in the framework of territorial risk and scenario analysis.

After a calibration of the methods on a set of disaggregated data of the DB_Census, vulnerability and scenario maps of the country have been defined.

The identified methodology is unavoidably affected by uncertainties; however, it still represents today a reasonable compromise between the necessity to cut down on-site surveys to a limited number of buildings and obtaining a final result sufficiently reliable for planning purposes and prevention. The obtained results can be used, in combination with hazard maps, to easily develop risk or Scenario maps at Regional or National scale.

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