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Seismic vulnerability assessment of RC buildings at compartment scale: the use of CARTIS form

Francesca Pasqual[a]*, Luisa Berto[a], Paolo Faccio[a], Anna Saetta[a], Diego Alejandro Talledo[a]

[a]*Department DCP, University Iuav of Venice, 30135 Venice, Italy*

Abstract

Large-scale seismic vulnerability assessment methods allow to classify the vulnerability of groups of buildings according to recurring parameters. The parameters necessary for the application of these methods may come from the adoption of survey forms. The 1st level CARTIS survey form collects the parameters of an area (town compartment) characterized by homogeneity among building types. The variation of the parameters within the same compartment may lead to the definition of several typological-structural groups of buildings, which can be characterized by different vulnerability. Therefore, the assessment of the seismic vulnerability of a compartment requires knowing the distribution of different typologies and their relative structural performance. In this work the vulnerability is evaluated at town compartment level starting from the vulnerability of the RC building typologies, by applying the RE.SIS.TO® method to the data collected from the 1st level CARTIS forms. In particular, a tree chart representation, characterized by variable number of branches depending on the different number of possible choices allowed by CARTIS form, is proposed for data organization of the typological-structural groups of buildings.

Keywords: CARTIS survey; seismic vulnerability assessment; building typology; inventory; building data collection

1. Introduction

The urgency to develop polices of risk reduction requires effective tools for seismic risk assessment at territorial scale. Among the difficulties related to this topic one of the most crucial deals with the definition of the building inventory and the identification of some recurring typologies of buildings, representative of the building stock in a

* Corresponding author. Tel.: +39 041 2571346.
E-mail address: fpasqual1@iuav.it

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certain region (Polese et al., 2020; Dolce et al., 2020; Masi et al., 2021; Basaglia et al., 2021). The common characteristics recognizable in similar buildings inside an area (linked to the possible damages) can be collected from survey with specific forms (e.g. G.N.D.T. form, G.N.D.T., 1994; AeDES, Baggio et al., 2002; Jiménez et al., 2018, Zucconi et al., 2018). These forms can be divided mainly in two typologies: related to the assessment of the damage and post-earthquake use or related to a preventive phase. Furthermore, the scale of data collection can be mainly distinguished between the territorial scale (often called 1st level forms) and building scale (often called 2nd level forms). Among the survey forms, the interview-based CARTIS 1st level survey forms ("form for the typological-structural characterization of urban compartments from ordinary buildings") (Zuccaro et al., 2015), implemented in Italy in ReLUIS 2014-2016 project, aim to collect the main characteristics of the prevailing building typologies of a town compartment. The compartment is defined as homogeneous area characterized by the presence of buildings that can be considered homogeneous in terms of typological/construction characteristics and of construction age. The database CARTIS collects the data derived from these forms and it can be easily queried after an integration into the QGIS system.

In this paper, a procedure for large-scale vulnerability assessment of reinforced concrete (RC) buildings using information derived by CARTIS database is proposed. To this aim, the RE.SIS.TO® method (Chinni et al., 2013; Mazzotti et al., 2013) was applied to sub-typologies representative of the building stock. In this study the procedure is adopted at the town compartment level, but it can be applied for vulnerability assessment on municipal, provincial, regional scale, etc.

2. The CARTIS survey form and the database

The 1st level CARTIS form is compiled by an expert and is mainly based on interviews with local technicians, supported by the analysis of the available documentation of the territory and field survey. The form is structured in sections relating to the typological/constructive aspects of masonry and RC ordinary buildings of a compartment.

Section 0 identifies the municipality and the compartments present. In this section, a maximum of 8 prevalent building typologies for each compartment can be defined (up to 4 for masonry, identified by MUR 1-4, and up to 4 for RC, identified by CAR 1-4). For each considered typology three specific sections must be filled: Section 1 for identifying the typology, Section 2 for describing its general characteristics; Section 3 for characterizing its structural elements. In particular, the first part of Section 3, the subsection (3.1), is differentiated between masonry (3.1.A) and RC (3.1.B) typology.

In the different fields, it is possible to choose between existing values or to directly enter alphanumeric data. There are different choice modes, which can be distinguished in: single choice, multiple-choice (with two sub-cases: n-choices or 2-choices) or input of texts and numbers. The data can be expressed as: single number or text or interval of variations. Furthermore, for some fields it is possible to indicate the percentage incidence of the corresponding characteristic among the entire building stock of the compartment. As an example, Table 1 provides the choice mode, the type of data and the possibility to indicate the percentage incidence for the 25 CARTIS parameters considered in this study for the application of the RE.SIS.TO® method. In the last column of the Table for each parameter is reported the percentage of cases of missing data with respect to the total number of buildings.

The CARTIS database collects the data obtained from the forms compiled so far by the technicians: all the regions of Italy are present in the CARTIS database except for Sardinia and Trentino Alto-Adige.

Figure 1 shows a comparison between the number of buildings with residential destination present in the CARTIS database and the number of residential buildings from 2011 national census (ISTAT, 2011). It is worth noting that in the CARTIS database, buildings which are not residential are less than 1%. In case the destination use was not compiled in the form, residential destination was assumed.

The data collected from CARTIS can constitute an adequate base for determining the territorial building characteristics in particular for some regions and, through the application of a suitable method, it is possible to carry out seismic vulnerability assessment at a territorial scale (e.g. Brando et al., 2021; Polese et al., 2019, Polese et al., 2020). It is worth noting that all data considered in this study have not been derived from the summary table provided for the database CARTIS, because it is not constantly updated and does not report all the fields present in the CARTIS forms.

Table 1. Choice mode and type of data expression of the parameters considered in this study, and missing data (with respect to the total numbers of buildings).

	Parameters	○	□	□*	␣	Single	(÷)	␣[%]	Fields not filled with respect to the total number of buildings
2.a	N. of storeys			X		X			6%
2.b	Inter-storey height	X					X		6%
2.c	Inter-storey height, I floor	X					X		8%
2.d	N. of underground floors	X				X			24%
2.e	Average plan area			X		X			11%
2.f	Age of construction			X		X			16%
2.g	Prevalent use		X			X			16%
3.1 B.a	Structural typology	X				X			16%
3.1 B.d	RC frame, 1 direction	X				X		X	6%
3.1 B.e	Stubby elements	X				X		X	17%
3.1 B.g	Infill position		X			X			9%
3.1 B.h	RC column dimension (I floor)	X					X	X	12%
3.1 B.i	Longitudinal reinforcement				X				73%
	Stirrup spacing				X				64%
	Stirrup diameter				X				64%
3.1 B.j	Bay length	X					X		13%
3.1 B.k	SAP slabs	X				X		X	20%
3.2.a	Roof (type)			X		X		X	6%
3.2 c	Regularity (plan & elevation)			X		X		X	6%
3.2 f	State of pres., entire building	X				X			11%
	State of pres., vertical struct.	X				X			12%
	State of pres., horizontal struct.	X				X			13%
	State of pres., non-struct. elem.	X				X			13%
3.2 i	Foundations			X		X		X	33%

Choice mode: "○": single; "□": multiple-choice: n-choices; "□*": 2-choices; "␣": by inserting text or numbers.
Type of data: "single": (number, text); "(÷)": interval. "␣[%]": possible indication of the percentage incidence.

3. Italian historical regulations

As it can be seen from Table 1, within the CARTIS database, for some parameters, the percentage of missing data fields can be relevant. In some cases, for example for column reinforcement, missing data should prevent the application of the RE.SIS.TO® method. In this case it is necessary to fill the void in other ways. In this study, the data were integrated with additional information derived from historical regulations in force at the time of construction and the software STIL v1.0 (Verderame et al., 2011) for steel properties.

Furthermore, to fill missing data in the application of CARTIS at a certain territorial scale it is possible to infer the information derived from the CARTIS database at a higher level of territorial scale.

Historical technical regulations are an important investigation tool to define some characteristics of the building stock, starting from its construction age. As an example, Table 2 shows some prescriptions regarding the minimum amount of reinforcement in RC columns, deriving from the main oldest Italian technical regulations for RC buildings issued between 1907 and 1992.

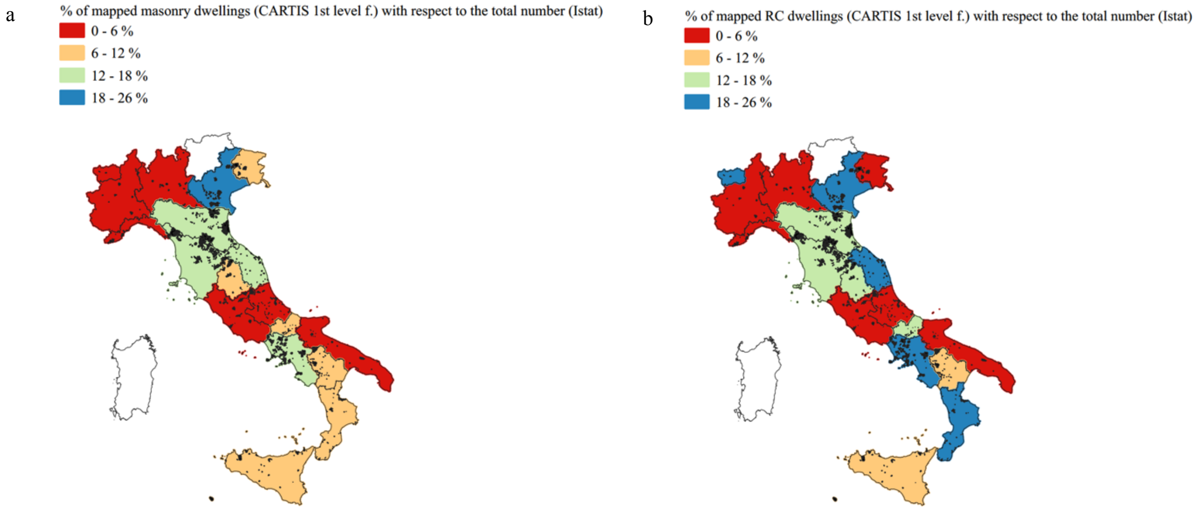

Fig. 1. Percentage of buildings collected in the database CARTIS 1st level with residential destination, with respect to the total number of dwellings collected in the Istat 2011 database: (a) masonry buildings (b) RC buildings. The compartment currently included in the database are shown in black.

From the analysis of the Italian historical seismic regulations additional useful information to fill the missing data can be found relating the construction period and geographical area with the seismic classification of the Italian territories. The seismic classification of the Italian territory has changed over the years. Starting from 1909, the Italian municipalities affected by previous earthquakes were firstly considered as seismic areas subject to specific prescriptions. Over the years, regulations have been issued for new buildings in areas of occurrence of earthquakes. In the case of RC frames buildings, parameters as the total height, the number of floors, the inter-floor height, the size of the columns, the amount of reinforcement, the minimum number of columns, the bay length which can be mentioned among others, were subjected to specific prescriptions. Since 1927, and with the introduction of a second seismic zone, the prescriptions have been differentiated for areas belonging to two different seismic categories. An important update of the Italian seismic zoning took place with the O.P.C.M. 2003, when the entire territory was classified into 4 seismic zones. Many Italian buildings were built in areas not considered seismic at the time of construction, and only subsequently re-classified. It is important that large-scale seismic vulnerability assessment considers the modification of the Italian classification to identify any shortcomings in the construction details of the historical buildings.

4. The RE.SIS.TO® method

RE.SIS.TO® (Chinni et al., 2013; Mazzotti et al., 2013) is a simplified method which can be used for the seismic vulnerability assessment of masonry and RC building stocks at a large scale. The method leads to the evaluation of the collapse ground acceleration PGA_c of a building. It is calculated basing on the value of the resisting ultimate shear, computed through mechanical considerations, and taking into account the expert judgment. The ratio between capacity PGA_c, and demand, expressed as PGA_d, leads to the definition of the building's vulnerability level.
In this study, the method was applied to buildings representative of the sub-typologies within an Italian compartment. The sub-typologies of buildings are defined on the basis of the values of the 25 parameters coming from the CARTIS database for the RC buildings of the compartments (for the parameters, see Table 1) and used in the application of the RE.SIS.TO® method.

Table 2. Requirements relating to RC columns in the main historical Italian technical regulations.

	C_{cov}	A_s		Ø Stirrup	Stirrup spacing
	min	min*	max	min	max
	cm			mm	
DM 10/1/1907 (G.U. 28)	2	$1\% \cdot A_c$ ($A_c \leq 1600$ cm^2) $0.7\% \cdot A_c$ ($A_c \geq 6400$ cm^2)			10Ø
RDL n. 1981, 4/9/1927 (G.U. 261)	2	$1\% \cdot A_c$ ($A_c \leq 1600$ cm^2) $0.5\% \cdot A_c$ ($A_c \geq 6400$ cm^2)			10Ø
RDL n. 1431, 7/6/1928 (G.U. 156)		$1\% \cdot A_c$ ($A_c \leq 600$ cm^2) $0.7\% \cdot A_c$ ($A_c \geq 6400$ cm^2)			
RDL n. 1133, 18/7/1930 (G.U. 203)	2	$1\% \cdot A_c$ ($A_c \leq 1600$ cm^2) $0.7\% \cdot A_c$ ($A_c \geq 6400$ cm^2)			min(b;h)
RDL n. 1213, 29/07/1933 (G.U. 224)	2	$1\% \cdot A_c$ ($A_c \leq 1600$ cm^2) $0.7\% \cdot A_c$ ($A_c \geq 6400$ cm^2)			min[min(b;h); 10$Ø_{bars}$]
RDL n. 2229, 16/11/1939 (S.O. G.U. 92)	2	$0.8\% \cdot A_{c,nec}$ ($A_{c,nec} \leq 2000$ cm^2) $0.5\% \cdot A_{c,nec}$ ($A_{c,nec} \geq 8000$ cm^2)			min[min(b;h)/2; 10$Ø_{bars}$]
DM 30/5/1972 (S.O. G.U. 190)	2	max($0.3\% \cdot A_c$; $0.6\% \cdot A_{c,nec}$)	$5\% \cdot A_{c,nec}$	6	min(15Ø;25 cm)
DM 30/5/1974 (S.O. G.U. 198)	2	max($0.3\% \cdot A_c$; $0.6\% \cdot A_{c,nec}$)	$5\% \cdot A_c$	6	min(15Ø;25 cm)
D.M. 16/6/1976 (S.O. G.U. 214)	2	max($0.3\% \cdot A_c$; $0.6\% \cdot A_{c,nec}$)	$5\% \cdot A_c$	6	min(15Ø;25 cm)
DM 26/3/1980 (S.O. G.U. 176)	2	max($0.3\% \cdot A_c$; $0.8\% \cdot A_{c,nec}$)	$6\% \cdot A_c$	max(6;1/4$Ø_b$)	min(15Ø;25 cm)
DM 27/7/1985 (S.O. G.U. 113)	2	max($0.3\% \cdot A_c$; $0.8\% \cdot A_{c,nec}$)	$6\% \cdot A_c$	max(6;1/4$Ø_b$)	min(15Ø;25 cm)
DM 14/2/1992 (S.O. G.U. 65)	2	max($0.3\% \cdot A_c$; $0.8\% \cdot A_{c,nec}$)	$6\% \cdot A_c$	max(6;1/4$Ø_b$)	min(15Ø;25 cm)

* For the cases of intermediate values of area between the reported values, a linear interpolation must be adopted. A_c is the section area of a column; $A_{c,ness}$ is the minimum concrete area required for axial load. $Ø_b$ is the diameter of the reinforcing bars; b & h are the column's section dimensions.

5. A tree chart approach for the evaluation of the seismic vulnerability at territorial scale

In order to define the sub-typologies of buildings characterizing a compartment, in this study the building stock of each compartment CAR was represented by a tree structure with branches corresponding to multiple choices and data variation ranges. The branching rule used in the proposed approach is explained in Figure 2.

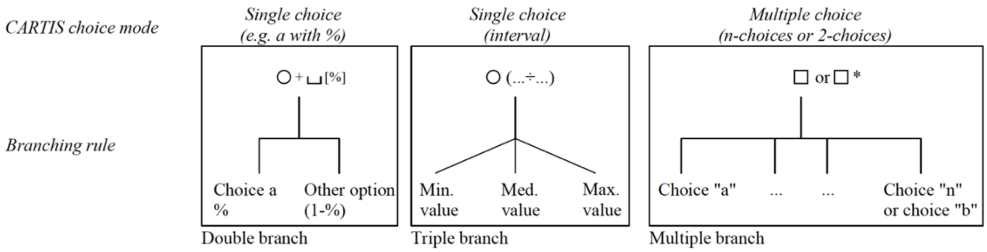

Fig. 2. Branching rules adopted in the analysis.

The double branch derives from the possibility of identifying a complementary case to the value reported in the data form. The triple branch corresponds to the fields that provide an interval of variation. In this case the triple branches are related to the minimum, average, maximum values of the selected interval. The multiple branch derives from the multiple-choice: it corresponds to n distinct values in the case of multi-choice n-choices, and to the values between the extremes a and b in the case of 2-choices.

Figure 3 shows an example of a general tree, with possible ramifications for the 25 CARTIS parameters analyzed.

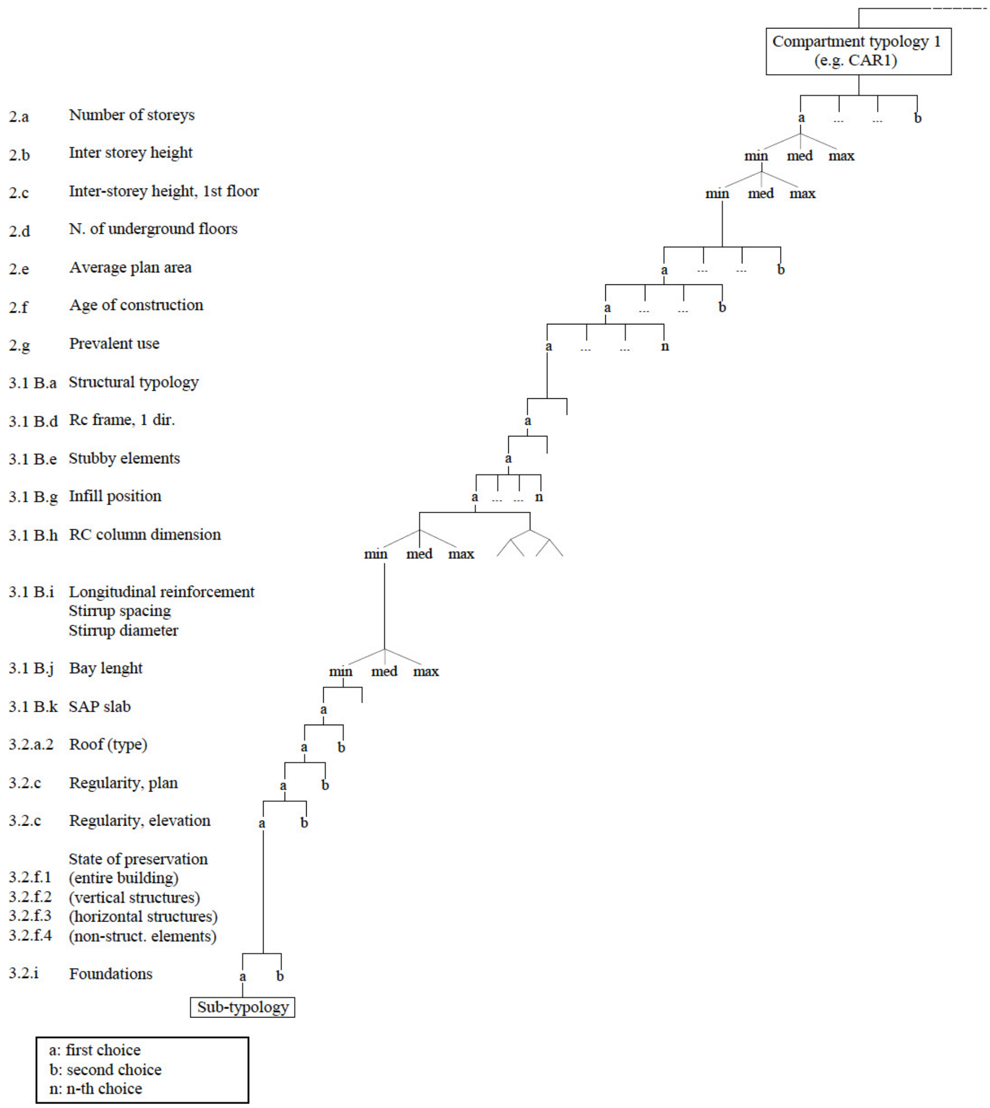

Fig. 3. Example of tree chart for a survey form.

The final result of each branch (i.e. the leaf) can be associated with a compartment sub-typology of buildings and a percentage incidence of this sub-typology within the compartment in terms of number of buildings. This percentage incidence is calculated taking into account the values of the percentage of incidence expressed in the form (see Table 1), their complementary values and the percentage distribution defined by the branches.

6. Application of the procedure to a case study

In this study, the proposed procedure is applied to the compartment scale. In particular the compartment C001 of Sossano (VI) is considered, which includes two construction typologies of RC buildings defined by the compiler (called CAR1 & CAR2). Firstly, in order to identify the sub-typologies of buildings to be analyzed with RE.SI.STO® method, the tree chart for the C001 compartment was constructed

The sub-typologies present within CAR1 are RC frames with perimeter high-beams, characterized by a number of floors ranging between 2 and 3, an average inter-storey height of 2.50÷3.49 m, an average floor area of 230 m^2, a construction period 1982÷1986, a RC column dimension of 25÷45 cm and a bay length of 4.5÷6 m.

Since data relating to reinforcement steel is missing, it has been derived from STIL v1.0 software (Verderame et al. 2011, see Table 3). The geometric data related to the reinforcement of the columns were assumed equal to the minimums required by the regulation at the time of the construction, and in detail: A_s was considered equal to 0.3%*A_c, with A_c equal to concrete area, stirrup diameter equal to 6 mm and stirrup spacing equal to 25 cm. A mean strength of concrete f_{cm} equal to 20 MPa was considered. The same procedure was applied to the CAR2 typology: the sub-typologies present in CAR2 are RC frames with solid masonry, characterized by a number of floors varying between 3 and 4, an average inter-storey height of 2.50÷3.49 m (both for a generic floor and for the I floor), a surface between 300 and 400 m^2, a construction period 1982÷1996 (considered as three construction periods for the CARTIS form). Data missing in the database were deduced similarly to CAR1. See Table 3 for steel properties.

Table 3. Types of bars and steels most common in the construction periods considered (from STIL v1.0 software, Verderame et al. 2011).

CARTIS age of construction	Min. year selected in STIL v1.0	Max. year selected in STIL v1.0	Recurring typology of bars	Recurring type of steel	fym [MPa]
1982 ÷1986	1982	1986	Ribbed	FeB44k	512.5
1987 ÷1991	1986	1991	Ribbed	FeB44k	519.8
1992 ÷1996	1992	1996	Ribbed	FeB44k	542.1

By applying RE.SI.STO® method to the sub-typologies identified by the tree chart, the safety index of the compartment can be evaluated as weighted average of the ones of CAR1 and CAR2. The weight was calculated basing on the percentage incidence of each sub-typology. Considering a demand PGA value of 0.18g characteristic of the site of Sossano, the ratio between capacity and demand of the CAR1 typology is 56%. As an example, Figure 4 shows the capacity/demand ratio of the sub-typologies of buildings of CAR1 identified by the values assumed by the variable parameters: Inter-storey height of the generic floor ("g. f."), Inter-storey height of the first floor (as "I-s. h. (I. f.)"), RC column dimension of the first floor, bay length (as "B. L."). Similarly, the average capacity/demand ratio for CAR2 is 40% and the same ratio of the entire compartment C001 is 48%.

			RC column dimension (I floor) 0.25 m			RC column dimension (I floor) 0.35 m			RC column dimension (I floor) 0.45 m		
			B.L. 4.5 m	B.L. 5.25 m	B.L. 6 m	B.L. 4.5 m	B.L. 5.25 m	B.L. 6 m	B.L. 4.5 m	B.L. 5.25 m	B.L. 6 m
2 floors	Inter-storey height (g. f.) 2.5 m	I-s. h. (I f.) 2.5 m	45%	34%	23%	96%	80%	66%	161%	136%	115%
		I-s. h. (I f.) 3.0 m	37%	28%	19%	79%	66%	55%	132%	111%	94%
		I-s. h. (I f.) 3.49 m	32%	24%	16%	67%	56%	46%	111%	94%	80%
	Inter-storey height (g. f.) 3.0 m	I-s. h. (I f.) 2.5 m	37%	31%	23%	79%	66%	55%	144%	117%	97%
		I-s. h. (I f.) 3.0 m	37%	28%	19%	79%	66%	55%	132%	111%	94%
		I-s. h. (I f.) 3.49 m	32%	24%	16%	67%	56%	46%	112%	94%	80%
	Inter-storey height (g. f.) 3.49 m	I-s. h. (I f.) 2.5 m	31%	26%	22%	66%	55%	46%	120%	97%	81%
		I-s. h. (I f.) 3.0 m	32%	27%	19%	68%	56%	47%	124%	100%	83%
		I-s. h. (I f.) 3.49 m	32%	24%	16%	67%	56%	46%	112%	94%	80%
3 floors	Inter-storey height (g. f.) 2.5 m	I-s. h. (I f.) 2.5 m	30%	19%	9%	69%	57%	45%	117%	98%	83%
		I-s. h. (I f.) 3.0 m	25%	15%	8%	57%	47%	37%	96%	81%	68%
		I-s. h. (I f.) 3.49 m	21%	13%	6%	49%	40%	32%	82%	69%	58%
	Inter-storey height (g. f.) 3.0 m	I-s. h. (I f.) 2.5 m	29%	18%	9%	61%	51%	43%	103%	87%	73%
		I-s. h. (I f.) 3.0 m	24%	15%	7%	57%	46%	37%	95%	80%	67%
		I-s. h. (I f.) 3.49 m	21%	13%	6%	48%	39%	31%	81%	68%	57%
	Inter-storey height (g. f.) 3.49 m	I-s. h. (I f.) 2.5 m	24%	18%	9%	51%	43%	36%	86%	72%	61%
		I-s. h. (I f.) 3.0 m	24%	15%	7%	52%	44%	36%	87%	73%	62%
		I-s. h. (I f.) 3.49 m	21%	13%	6%	48%	39%	31%	80%	67%	57%

Fig. 4. Capacity/demand ratio for each sub-typology of the CAR1 typology, found with the RE.SI.STO® method.

If the amount of reinforcement is assumed equal to the most recurrent value in Veneto (0.5%) derived from CARTIS database is assumed, instead of the minimum prescribed by code, the capacity/demand ratio of the two compartments will increase up to values of 73% for CAR1 and up to 52% for CAR2.

7. Conclusions

In this study, a methodology was proposed for the evaluation of the safety index for RC buildings at a town compartment level using the data provided by the 1st level CARTIS forms, which allow to characterize the building stocks taking advantage of the knowledge of local technicians. This procedure applied to all the compartments of a municipality may allow to obtain the seismic vulnerability of the entire municipality defined as the weighted average between the seismic vulnerability of its compartments.

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