A multipurpose method for seismic vulnerability assessment of urban areas

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SUMMARY:
The present work outlines a methodological framework for "ordering" through progressive levels of analyses different evaluation models concerning the seismic vulnerability at urban scale, with respect to the possible final objectives: seismic scenarios, emergency or urban planning, as far as seismic mitigation or economical estimates.
The research work has been developed within the URBISIT Project, funded by Italian Civil Department (DPC).
The paper illustrates the general framework governing each assessment level and the mutual relation between each of them. Following, each level of analyses is systematically described also through some recent applications, carried out on some representative Italian urban centres.
In the end, a correlation among different assessment levels is carried out in order to better focus the usability of each model as well as its reliability with respect to the possible objectives. Finally some conclusions are drawn and possible development of the research outlined.

Keywords: Urban centre, seismic vulnerability, vulnerability classes, building type, analysis level

1. INTRODUCTION

The assessment of seismic vulnerability of buildings is one of the most relevant activities in earthquake engineering, and it is generally characterised by a great diversity due to its different possible objectives: decisions in the post-earthquake emergency, strategies to reduce seismic risk, predictions for seismic upgrading, territorial planning, macro seismic mapping, the property insurance market.
Undoubtedly one of the crucial aspects influencing vulnerability evaluation is represented by the scale of the assessment, in turn influencing the method and the level of assessment.
When the final goal of the analysis is the evaluation of the seismic risk at extensive scale, regional or national, one of the most recognised methods for achieving this purpose is the use of vulnerability classes derived by macroseismic scales as MSK or 'EMS 98 (Medvedev 1977, Grunthal 1998).
In Italy Civil Protection Department (CPD) developed seismic risk maps by processing data provided by the National Institute of Statistics (ISTAT) on dwellings and population at national scale. Vulnerability was processed by calibrating the assortment of MSK vulnerability classes for each municipality of the country (Di Pasquale et al. 1997, 2005, Lucantoni et al. 2001).
When dealing with smaller scales of analysis, as the urban scale, the use of macro-seismic classes may become inadequate or insufficient, thus requiring more accurate descriptions of the building population.
The method here presented is specifically focused on the seismic vulnerability assessment of a urban centre, the boundaries of which should as much as possible match with the ones provided by existing urban plans.
The work, outlines three different levels of analysis of seismic vulnerability of a urban centre, each other ranked as function of the information amount required, reliability of results, and final purposes of analyses. In the following, once provided a general overview of each level in terms of data needed,

possible objectives and final outputs, a specific paragraph is dedicated to the use of macroseismic classes, as defined by EMS scale and further upgrades.

2. LEVELS OF ANALYISIS OF SEISMIC VULNERABILITY

2.1. Overview on assessment levels of a urban centre

The assessment levels of a urban centre are outlined starting from a preliminary set of information, defined as Level 0, associated with the one achieved at national scale, providing cumulative vulnerability distributions for each municipality starting from the ISTAT database.
The levels, progressively numbered from 1 to 3, are described in the following:

- **Level of analysis 1** – This level of analysis requires basic information, mainly relying on existing data with very few integrations which must be collected on site. The urban layout is split into different zones as much as possible homogeneous with respect to seismic vulnerability. The *minimum unit of analysis* is represented by EMS 98 macro-seismic classes, as illustrated in §2.2.
  Possible objectives: Seismic damage scenarios for urban emergency planning. Ranking among different homogenous zones aimed to planning or mitigation policies.
- **Level of analysis 2 –** This information level enables some uncertainties of level 1 to be reduced. The *minimum unit of analysis* is the *building type*, described through constructive, structural and architectural features as far as seismic vulnerability may be concerned (storeys number, constructive technique, structural regularity). Building types must be recognised and associated with building populations as large as possible to enable a statistical approach.
  Possible objectives: More refined seismic scenarios. Support to mitigation and strengthening policies, economical estimates, urban ranking.
- **Level of analysis 3 –** Level 3 is associated with a detailed level of information consisting on the assessment of the single structural unit. The *minimum level* of analysis is represented by the *structural unit*, defined as structural system homogenous from bottom to top and presumptively structurally independent from adjacent buildings. Because of the amount of information required, consisting in a one to one building survey, this level is reasonably carried out on restricted urban areas either for calibrating the information previously collected or for specific further objectives.
  Possible objectives: Calibration of seismic vulnerability carried out at previous levels of analysis, support to mitigation and strengthening policies and economical estimates, use of more refined models for vulnerability assessment and damage scenarios.

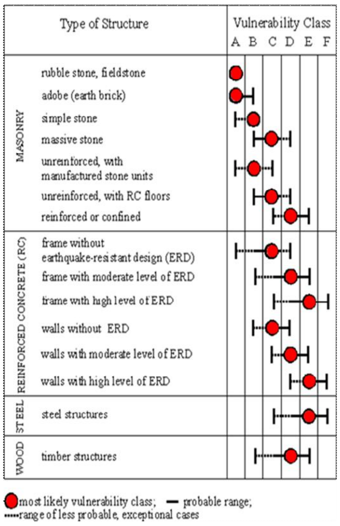
It is worth noticing that in affording the vulnerability of a urban layout, the above assessment levels do not require to be necessarily all experimented. In relation to the objectives as well as to the available resources of local or central Authorities (coordinating the works), the analysis can start at any Level, and may include partial upgrades on selected areas (example: level 1 on whole urban centre, level 3 on historic centre only).

2.2. Macroseismic classes for Italian building inventory

Notwithstanding the peculiarities of each assessment level and the limit recognised to macroseismic classes, EMS vulnerability classes are used in the present work with the purpose of correlating each other the outputs of the three analysis levels as well as optimizing the overall assessment of the urban layout through its preliminary partition in homogeneous zones.
In order the correlation to be carried out, final outputs of each evaluation level are at the end of each elaboration level also converted in EMS classes.
In the original formulation carried out by Grunthal (1992, 1998), macroseismic classes are assumed to be universally valid so that their applicability covers the entire worldwide population of ordinary

buildings, thus enabling correlation between seismic vulnerability of different countries and structural conceptions (Table 2. 1, a).
According to EMS approach, each vulnerability class includes a very wide range of buildings with different structural performance. Since ‘90 it was recognised by the scientific literature on the topic its unsuitability for describing Italian building population, so that the original formulation of EMS classes was later enhanced in order to better fit the Italian ordinary buildings assortment.
The method here proposed, shown in Table 2. 1, b), is based on an upgrade of the approach previously proposed by Dolce et al (2000) specifically focused on the Italian building inventory. The table provides a mutual association between vertical and horizontal structures the combination of which univocally brings to find out the corresponding vulnerability class.

Table 2. 1. a) Macrosesimic classes provided by EMS 98 scale; b) Assignment process for the Italian building population



a)

		Vertical structures							
		Poor quality masonry		Medium quality masonry		Good quality masonry		Reinforced concrete	
	Horizontal structures	Without ties and ring beams	With ties and ring beams	Without ties and ring beams	With ties and ring beams	Without ties and ring beams	With ties and ring beams	Not conforming	Structural upgrade
Before seismic class. and/or before1974	Thrusting structures	A	[B]	A	[B]	A	[B]	---	---
	Wooden floors	A	[B]	A	[B]	B	[C1]	---	---
	Semi-rigid structures	B	[C1]	B	[C1]	C1	[D1]	---	---
	Rigid structures - Slabs	B	[C1]	C1	[D1]	C1	[D1]	C2	[D2]
> 1974 (with s. classif)	Buildings conforming previous seismic codes	D1		D1		D1		D2	
> 2005 (with s. classif)	Buildings with ERD (DM 2005)	E		E		E		E	

b)

The above criterion also relies on the date of construction matched up with the year of seismic classification of each municipality. So that buildings realised following 1974, (i.e. national seismic code n.64) are associated with class D (split in D1 and D2 respectively related to masonry and r.c.) compared to those built up before that date or after 1974 in municipalities without any seismic classification (classes A,B,C1 and C2).
ERD buildings (Earthquake Resistance Design) are associated with the enactment of the recent new Italian seismic code in its early version (NTC 2005) and buildings included in this group are reasonably very few being the date very recent.
The table also provides a condition for taking into account the buildings retrofitted following their construction: the class between brackets outlines the trigger of each class in presence strengthening devices. For historic masonry buildings structural upgrades are represented by ties and ring beams even introduced following their construction.
Damage Probability Matrices associated with vulnerability classes, specifically calibrated since ’80 (Irpinia Earthquake, 1980) for Italian building population, enable rapid damage scenarios to be formulated as function of a seismic severity (Braga et al.1982, a,b; Di Pasquale et al.1997).

3. LEVEL OF ANALYIS 1

Data for Level 1 are achieved through a survey form on purpose developed in occasion of previous researches (Dolce et al., 2011) requiring the description of each homogenous zone into which the urban centre is preliminarily divided.

Since relying on existing information, this level requires a certain support from local authorities or technicians with a specific knowledge of the urban and constructive development of the town through the years.
One helpful tool facilitating the identification of homogenous zones is represented by the map of the chronological development of the urban centre, if existing. These information must be combined with those provided by local technicians about main structural features of ordinary buildings according to Table 2. 1,b). Usually for small centres within 5000 inhabitants, up to five zones can be outlined. Bigger centres require several zones to be carefully described. To make an example the Italian town of Faenza (around 58.000 inhabitants), recently investigated, required up to 32 zones.
The form collects information concerning the percentage assortment of each zone Z_i in term of prevalent vulnerability classes (up to three), following the criterion of Table 2.1,b) together with exposure data like total number of buildings, dwellings and residential population, when provided by local authorities.
The percentage vulnerability distribution over each zone is hence expressed by P(Vc) where Vc is the vulnerability class (varying from A to D2).
For each zone also a *prevalent* class PC_i is defined, mostly used for speedy seismic scenarios.
Since the most frequent class is not necessarily the most vulnerable, in order to avoid underestimation of the overall vulnerability, the prevalent class of each zone is defined through the percentage assortment, weighed in relation to a vulnerability severity, associated to each class.
When not provided during the inspection, exposure (in term of buildings, dwellings and population) can also be obtained through a process of data merging governed by a GIS, between ISTAT census sectors C_j and vulnerability zones Z_i.
Level 1 is specifically drawn for damage scenarios at urban scale, which are processed combining vulnerability with seismic hazard, consisting of a seismic microzonation sharing the urban territory into different areas affected by amplification factor (Fa). Applications of this method were recently carried out by CPD on 24 Italian municipalities of Valdaso, situated in Central Italy (Dolce et al., 2011).
Figure 1 (left) shows the map of homogeneous zones obtained for one urban centre of Valdaso (Comunanza), also highlighting the PC_i associated with each zone, assumed for seismic scenarios. Figure 1 (right) illustrates the class vulnerability distribution relatively to each zone. It can be noted like in zone 2 PC_i is class B, while the highest occurrence is associated with class C1.

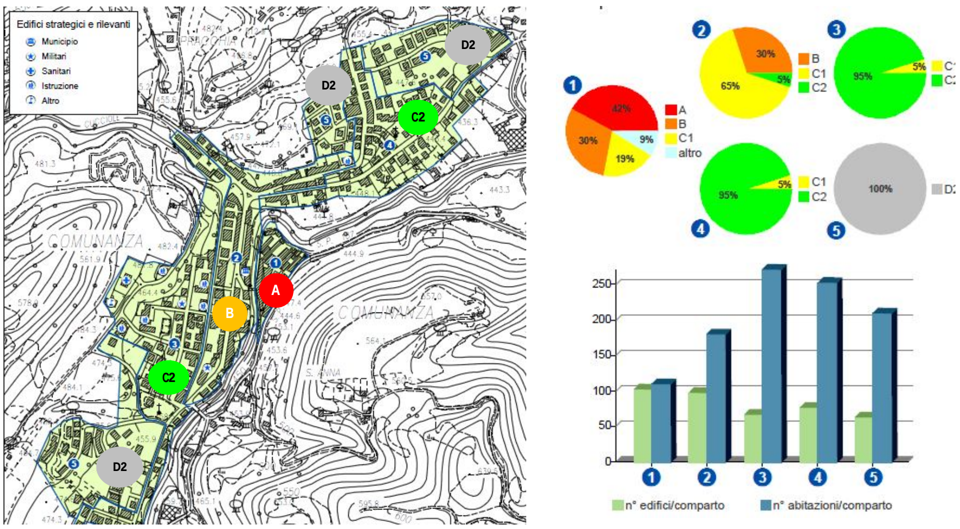


Figure 1. Level 1. Homogeneous zones for Comunanza, Valdaso

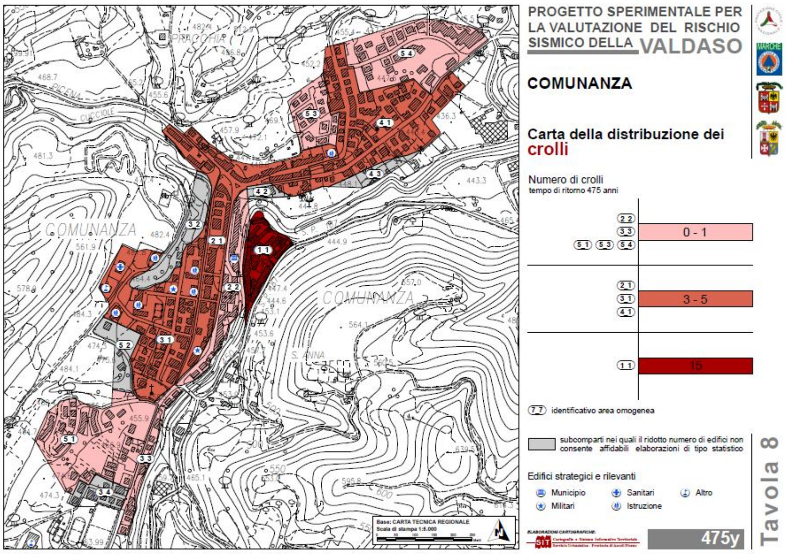


Figure 2. Seismic scenario of Comunanza showing the number of collapses for each zone.

Figure 2 shows a seismic scenario for Comunanza relatively to building collapses on a return period of 475 years.
Similar approaches in processing seismic scenarios based on speedy vulnerability assessments can be outlined in the literature on the topic (Fah et al 2000, 2001, Pujades et al 2000, Zuccaro 2009).
Notwithstanding the rapidity of the method, its main advantage compared with Level 0 (national scale based on ISTAT database), is to produce a preliminary geographic distribution of seismic vulnerability within the municipal boundaries.

4. LEVEL OF ANALYIS 2

The shift between Level 1 and Level 2 basically consists in moving the focus of the assessment from a global and expert evaluation, to the recognition of those building types specific of a urban settlement.
The building type is defined through a number of given structural and architectonic features associated with an ideal prototype of building which can be assumed sufficiently representative of a given population of buildings.
The parameters describing each building type in the present work, are:

- Age of construction;
- Vertical structural type;
- Horizontal structural type;
- Structural regularity
- Building contiguity;
- Number of storeys;
- Strengthening devices;

Each building type is univocally identified through an alphanumeric label (defined by the format AA-A-N-a-n) where single items respectively highlight the Vertical type (MU=masonry, MI= mixed, CA= r.c.); followed by structural regularity and building contiguity (A=contiguous buildings; R/I=regular/irregular buildings); construction period (0= ≤1919 period; 1= before seismic classification; 2= post 1974; 3= post 2005) and afterwards by a progressive letter qualifying further variability of the type like horizontal/roof type and presence of strengthening devices. The storey number is specifically coded when greater than 3 storeys (+3). According to the amount of variables taken into account, their mutual combination drives to the identification of a wide “vocabulary” of structural types (432). Differently from similar methods, in this case the list of building types is conceived “open” so that it can be upgraded in relation to the specificity of each place.

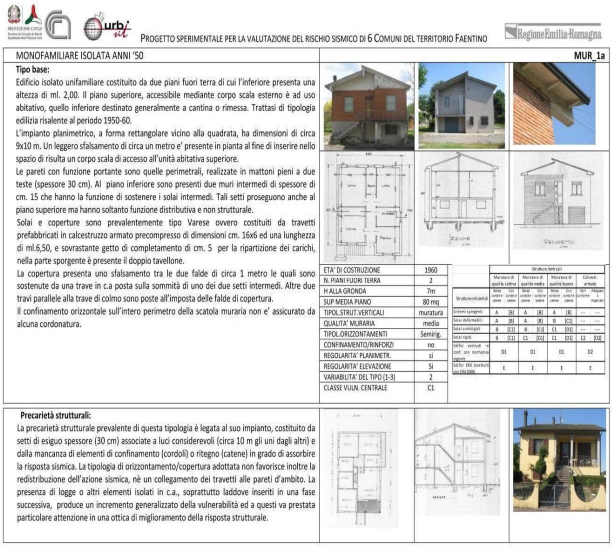
Each building type is also associated with a vulnerability class according to the criterion illustrated in Table 2. 1, b).

Depending on the final objective of this level, a form specific of each building type can also be filled in, in order to collect the main structural features of each type, also including a scheme of a representative building. The form also highlights (on a specific section) the most frequent structural problems of each individual building type. This may become a helpful tool in case either of mitigation or strengthening policies undertaken by local or central authorities as well as economical estimates.

The form shows the advantage to establish a strong link between building types, as above defined, and the local structural vulnerabilities specific of the centre under investigation. Figure 3(b) shows an example carried out for the town Faenza related to the type MUR1a, included in the full list of building types observed in the urban centre under investigation (Figure 3,a).

Label	Structural regularity or building stock	Horizontal structure	Orizzontamenti	Storeys	Construction period	EMS 98 class
MUA0a	Building stock	MU	Wooden	2_3	1800	A
MUA0b	Building stock	MU	R.c beams and lightweoght tiles	2_4	1800-1950	B
MUA0c	Building stock	MU	Wooden	2_3	1920	A
MUA0d	Building stock	MU	Wodden/Vaults	2_3	>1400	A
MUA0e	Building stock	MU	Wodden/Vaults	2_3	>1400	A
MUA1	Building stock	MU	Varese	2_4	1950	B
MUI1a	Irregular	MU	R.c beams and lightweoght tiles	3	1970	D1
MUI1b	Irregular	MU	Slabs	2	1960	C1
MUR1a	Regular	MU	R.c beams and lightweoght tiles	2	1950	C1
MUR1b	Regular	MU	R.c beams and lightweoght tiles	3	1960	C1
MI1+3	Irregular	MI	R.c beams and lightweoght tiles	4_5	1950	C1
CA3	Irregular	RC	Slabs	var	>2003	E
CAI1	Irregular	RC	Slabs	3	1970	C2
CAI1+3	Irregular	RC	Slabs	4	1960-70	C2
CAI2	Irregular	RC	Slabs	3	>1983	D2
CAI2+3	Irregular	RC	Slabs	3_5	>1983	D2
CAR1	Regular	RC	Slabs	3	1970	C2
CAR1+3	Regular	RC	Slabs	2_3+1	1970	C2
CAR2	Regular	RC	Slabs	2_3	>1983	D2
CAR2+3	Regular	RC	Slabs	3	>1983	D2

(a)


PROGETTO SPERIMENTALE PER LA VALUTAZIONE DEL RISCHIO SISMICO DI 6 COMUNI DEL TERRITORIO FAENTINO

MONOFAMILIARE ISOLATA ANNI '50 — MUR_1a

Tipo base:
Edificio isolato unifamiliare costituito da due piani fuori terra di cui l'inferiore presenta una altezza di ml. 2,00. Il piano superiore, accessibile mediante corpo scala esterno è ad uso abitativo, quello inferiore destinato generalmente a cantina o rimessa. Trattasi di tipologia edilizia risalente al periodo 1950-60.
L'impianto planimetrico, a forma rettangolare vicino alla quadrata, ha dimensioni di circa 9x10 m. Un leggero sfalsamento di circa un metro e' presente in pianta al fine di inserire nello spazio di risulta un corpo scala di accesso all'unità abitativa superiore.
Le pareti con funzione portante sono quelle perimetrali, realizzate in mattoni pieni a due teste (spessore 30 cm). Al piano inferiore sono presenti due muri intermedi di spessore di cm. 15 che hanno la funzione di sostenere i solai intermedi. Tali setti proseguono anche al piano superiore ma hanno soltanto funzione distributiva e non strutturale.
Solai e coperture sono prevalentemente tipo Varese ovvero costituiti da travetti prefabbricati in calcestruzzo armato precompresso di dimensioni cm. 16x6 ed una lunghezza di ml.6,50, e sovrastante getto di completamento di cm. 5 per la ripartizione dei carichi, nella parte sporgente è presente il doppio tavellone.
La copertura presenta uno sfalsamento tra le due falde di circa 1 metro le quali sono sostenute da una trave in c.a posta sulla sommità di uno dei due setti intermedi. Altre due travi parallele alla trave di colmo sono poste all'imposta delle falde di copertura.
Il confinamento orizzontale sull'intero perimetro della scatola muraria non e' assicurato da alcuna cordonatura.

ETA' DI COSTRUZIONE	1960
N. PIANI FUORI TERRA	2
H ALLA GRONDA	7m
SUP MEDIA PIANO	80 mq
TIPOL.STRUT.VERTICALI	muratura
QUALITA' MURARIA	media
TIPOL.ORIZZONTAMENTI	Semirig.
CONFINAMENTO/RINFORZI	no
REGOLARITA' PLANIMETR.	si
REGOLARITA' ELEVAZIONE	Si
VARIABILITA' DEL TIPO (1-3)	2
CLASSE VULN. CENTRALE	C1

Strutture orizzontali	Muratura di qualità cattiva: Senza cordoli e catene	Muratura di qualità cattiva: Con cordoli e catene	Muratura di qualità media: Senza cordoli e catene	Muratura di qualità media: Con cordoli e catene	Muratura di qualità buona: Senza cordoli e catene	Muratura di qualità buona: Con cordoli e catene	Calcestr. armato: Non conforme	Calcestr. armato: Adeguato o migliorato
Sistemi spingenti	A	[B]	A	[B]	A	[B]	---	---
Solai deformabili	A	[B]	A	[B]	B	[C1]	---	---
Solai semirigidi	B	[C1]	B	[C1]	C1	[D1]	---	---
Solai rigidi	B	[C1]	C1	[D1]	C1	[D1]	C2	[D2]
Edifici costruiti in conf. con normativa vigente	D1		D1		D1		D2	
Edifici ERD (costruiti con DM 2008)	E		E		E		E	

Precarietà strutturali:
La precarietà strutturale prevalente di questa tipologia è legata al suo impianto, costituito da setti di esiguo spessore (30 cm) associate a luci considerevoli (circa 10 m gli uni dagli altri) e dalla mancanza di elementi di confinamento (cordoli) o ritegno (catene) in grado di assorbire la risposta sismica. La tipologia di orizzontamento/copertura adottata non favorisce inoltre la redistribuzione dell'azione sismica, nè un collegamento dei travetti alle pareti d'ambito. La presenza di logge o altri elementi isolati in c.a., soprattutto laddove inseriti in una fase successiva, produce un incremento generalizzato della vulnerabilità ed a questi va prestata particolare attenzione in una ottica di miglioramento della risposta strutturale.

(b)

Figure 3. (a) List of building types identified in Faenza. (b) Form describing building type MUR_1a

Once checked the list of building types recognisable within a given urban centre, Level 2 requires the identification on the urban layout of those zones reasonably homogeneous over the building type stock (T_i). Similarly to Level 1, this work necessarily requires the support of local technicians or authorities in order to enhance the reliability of recognition process over the whole territorial extension of the centre.

The process yielding to the map of (Figure 4) enables the optimisation of urban zones Z_i identified at Level 1.

Optimisation process is performed through the conversion of building types into EMS classes in order to minimize the number of classes coexisting in a generic zone Z_i and attempting at the same time the new boundaries to match with the urban morphology and road system.

Figure 5 shows the association of classes to buildings types of Figure 4 and consequent new perimeters definition. The overlapping between Level 1 boundaries with those of Level 2 resulting from the optimization process is illustrated in Figure 6 (a). The correlation of the vulnerability distribution corresponding to the two layouts is discussed in §6.

Exposure of each zone is still obtained by ISTAT dataset by matching C_j data census with T_i subzones, according to a similar criterion illustrated in §3. Cumulative exposure for each zone Z_i, related to the town of Faenza, is shown in Figure 6 (b).

Information achieved at Level 2 in terms of building types also enables more refined damage scenarios to be processed through different sets of available fragility curves (Lagomarsino et al.2006, Rota et al. 2008) associated with building types very close to those identified in the present work.

Figure 4 – Example of map showing T_i zones homogenous for building type consistency

Figure 5 – Example of map showing Z_i zones homogenous for vulnerability class assortment

(a) (b)

Figure 6 – (a) Overlapping between Level 1 and Level 2 ; (b) Cumulative exposure for all zones as defined at Level 2

This level, thank to the detailed information on the urban settlement, can represent a useful support even to urban planning policies. The Municipality of Faenza, together with 5 associated municipalities, is at present working in this direction in renewing urban planning tools (RUE – urban construction regulation) (Figure 7).

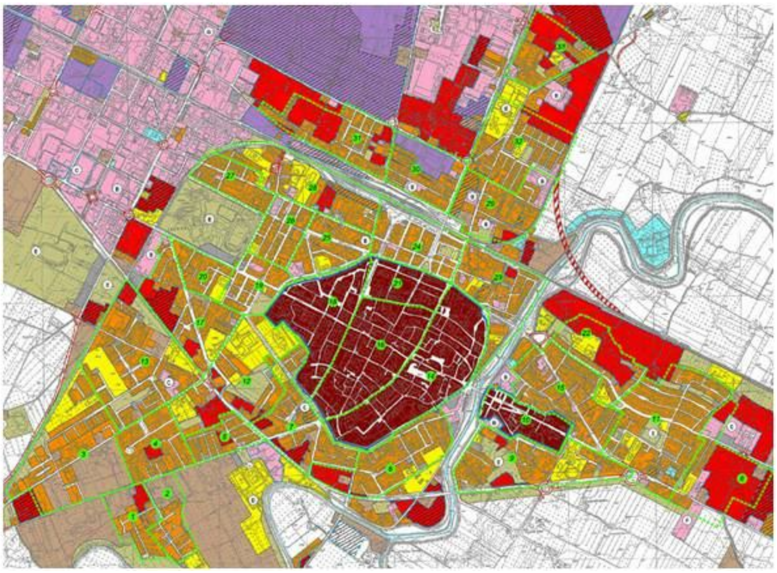


Figure 7 – Urban planning map of Faenza overlapped with Level 2 homogenous zones

5. LEVEL OF ANALYIS 3

Level 3 requires detailed inspections, as a result of this it can be reasonably carried out on limited zones the eligibility of which may result by previous levels, if performed.

The requirement in term of time expenditure and technical support needed, in order to be this level carried out, is notable since the minimum analysis unit, as outlined in §2.1, consists in the single building.

The main effort in approaching this level is not represented by the one-to-one building data collection, according to any survey form available in the literature, rather than in the preliminary identification of each structural unit.

This problem is particularly relevant in Italy where historic centres are mostly realised by building blocks consisting of adjacent buildings, built up through the years according to a spontaneous process and generally aimed to gradually fill the empty spaces of a urban settlement.

The number of buildings is an important information associated at this level as the exposure in term of building amount is carried out either at Levels 1 and 2, through ISTAT data.

Each building, following its identification requires an inspection, aimed to achieve information concerning the structural system, metric data for calculating the overall volume, as well as some exposure data like the occupants number. Any form can be suitable as far as the detail level can be comparable with a urban scale assessment.

A suitable CPD for assessing the post earthquake usability of buildings (AeDES), filled up to section 3 (2007). Alternative tools can be defined by forms AS_1 and US_1 developed by CPD in occasion of a recent normative tool (OPCM 4007, 29/02/2012) regulating public funds for seismic mitigation and microzonation. The innovative element in this case is represented by form AS_1, dedicated to the building block in its whole, while US_1 is comparable to the AeDES form.

Information collected at this level enable on one hand the careful calibration of exposure which may be particularly useful for economic estimates. On the other hand it allows seismic vulnerability of each building to be looked at, which can be processed through different models, from EMS classes assignment, as far as vulnerability indicators (Bernardini, 2004).

So far level 3 has been carried out in association with Level 1, on around 25 urban centres of central Italy, averagely sized, including those mentioned in §3, with the purpose of calibrating the extensive vulnerability on historic centres. It is in progress its application in the town of Faenza, with the aim of checking a specific “portion” of the town corresponding to the limit condition for emergency (CLE) according to OPCM 4007 requirements. Once completed, it will be possible to compare results of Level 3 with those obtained at previous levels.

6. CORRELATION BETWEEN ANALYIS LEVELS AND CONCLUSIONS

An early attempt to correlate the above analysis levels is carried out by comparing each other the percentage assortment of vulnerability classes obtained at different assessment levels. The limit which can be recognized to this approach, is that so far class assignment process is independent from the level of assessment.
According to the above criterion, the correlation can be drawn solely for Level 1 and 3, while for Level 2 only few considerations can be made at present.
Figure 7 highlights the correlation, on the 25 urban centres introduced in §3, between Level 1 and 3. For each sample, data gained through the on street survey (Level 3) have been converted into EMS classes according to the criterion shown in Table 2. 1,b), and percentage assortments calculated. These have been compared with the early estimation produced at Level 1 relatively to zones 1 (historic centres). Since limited to historic centres only, correlation can be carried out only for few classes, respectively A, B, C1. One can note low correlation factors for classes B and C1 (0.1 and 0.4); class A (0.63) also outlines a certain overestimation exerted by level 1. This might yields preliminary to conclude that level 1 is little reliable for historic centres, where further calibrations are needed, because of the specificity of the urban settlement.
So far Level 2 has been limited to just two samples differently sized (Faenza 58.000 and Solarolo 4.500 inhabitants respectively), the results of which are plotted in Figure 9 (a,b). The historic centre of Solarolo was investigated as far as Level 3, as shown in Figure 9 a). Figure 9 b) is strictly related to Figure 6 a), as it highlights the difference in vulnerability distribution corresponding to the two sets of homogenous zones, resulting from first and second level of analysis of the town. Both histograms, respectively related to the historic centre (Solarolo) and whole town of Faenza, show encouraging correlations among Level 2 with lower and upper analysis levels, although the smallness of the building sample.
Next results coming from Level 3 of Faenza and further applications on differently sized urban centres will be helpful to widening the sample, enhance the correlation and better focus the reliability and usability of each assessment level.

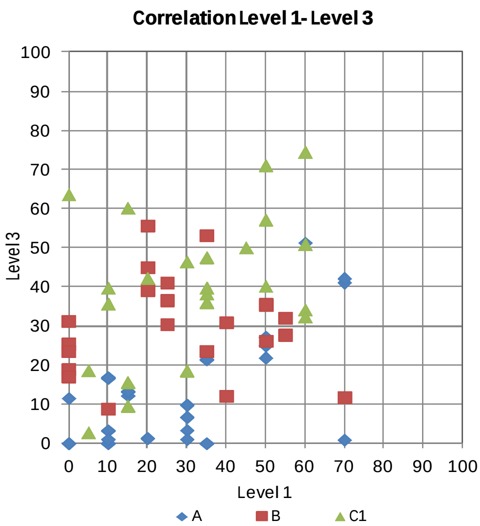


Figure 8 – (a) Correlation Level 1-Level 3 (historic centres)

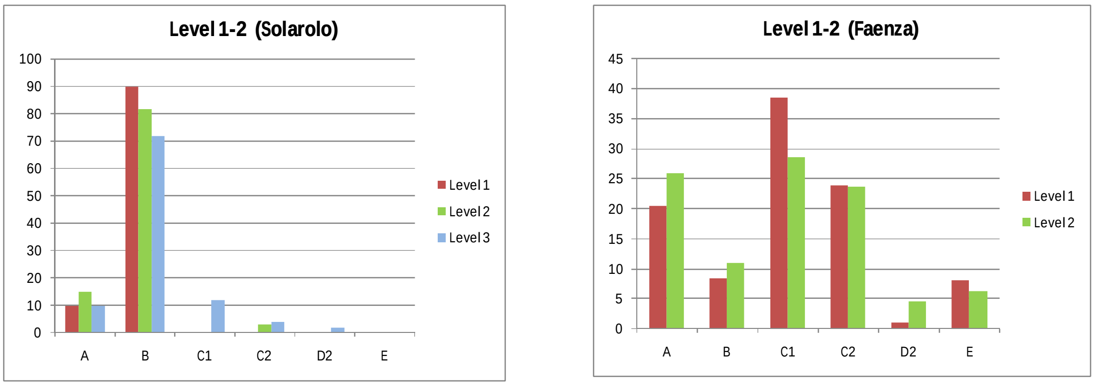


Figure 9 – (a) Correlation Level 1-2-3 (historic centre of Solarolo); (b) Correlation Level 1- 2 urban centre of Faenza

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