Seismic vulnerability assessment of masonry buildings in a region of moderate seismicity

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Abstract
To assess the seismic vulnerability of masonry buildings is largely matter of personal feeling and experience especially when dealing with old houses made of heterogeneous materials and without a plan. One way to predict their resistance to earthquake forces is the experience on models put on a shaking table. Costs and scaling problems, particularly severe for stone walls, are limiting factors in the extensive use of this technique. After the Friuli 1976 earthquake, the regional government arranged a detailed survey of damages suffered by buildings to be repaired. These data organised in the FRED (Friuli Earthquake Database) make it possible to compare, on a statistically significant basis, the *a priori* vulnerability with the effective damage. One further step towards the practical use of the results is given by characterising the relevant features of the buildings with the same parameters which can be found in the General Census periodically produced by the Italian Statistical Institute (ISTAT).

Key words *Friuli 1976 earthquake – seismic vulnerability – masonry buildings*

1. Introduction

The well-known Friuli earthquake of 1976 started on May 6 at 21:00 local time with a M 4.5 foreshock and the M 6.5 main shock. On September 15 after some days of increasing aftershock activity, two strong M_s 6.1 and M_s 6.0 aftershocks hit the ruined region causing other damage and also the collapse of already (improperly) restored buildings. To avoid mistakes and the waste of money that accompanied the reconstruction of the Belice Valley (Sicily) after the 1968 earthquake, the local government, charged by the national government with the bulk of the reconstruction process, promoted an extensive and detailed survey to precisely evaluate the damage. The survey was performed by terns of technicians (engineers and architects) and condensed in cards devised by a special committee officially constituted.

Data contained in the cards, although not finalised to give insight into the ability of the buildings to sustain the earthquakes forces, were processed to obtain a set of information comparable with that of the National Group for the Defence against the Earthquakes (GNDT) vulnerability cards.

This made it possible to evaluate the vulnerability assessment against the damage effectively caused on the buildings by the Friuli

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earthquake. Given the significance of the sample (about 85 000 cards) it is conceivable to extrapolate the results to the whole region compiling a vulnerability map for the masonry buildings. To succeed in the object, the only necessary step is to group buildings into typological classes. The task was accomplished by choosing grouping criteria significant both in the cards and in the census.

1.1. *The 1976 earthquake*

The rather long sequence of earthquakes struck an area of about 5000 km^2 on which about 600 000 people were living in 137 villages. Fatalities numbered 989 and 3000 people were hospitalised, 100 000 were homeless. The population was spread over the territory in many small towns and villages. Gemona del Friuli, with about 10 000 people is considered the earthquake capital and was, by far, the most populous city of the stricken area. About 75 000 lodging units were damaged and 18 000 collapsed.

Economic loss was very high (about 14 500 billion Lire have been spent for the reconstruction) due to the very poor quality of rural constructions and to the lack of any previous seismic classification of most of the territory. Udine a city of 100 000 inhabitants, was practically untouched because of the strong attenuation of seismic energy southward. This fact was determinant during the reconstruction when Udine became the close technical and administrative fully operative headquarters.

1.2. *The regional law 17/1976*

One month after the first shock the legislative council of the Friuli-Venezia Giulia Region enacted law No. 17 dated 7 June 1976 concerning the restoration of the damaged buildings. To evaluate its technical feasibility and the financial needs, an extensive and detailed survey of the whole shaken area was decided. To this purpose 390 terns of engineers and architects were assigned the task of compiling one card for each investigated building. Each questionnaire includes various sheets. Data cover cadastral identification, financial necessities for restoration, type of damage, type and state of the structure (masonry, reinforced concrete, wooden, etc.) and, finally, one synthetic guess to be given crossing one check box (destroyed, not repairable, totally or partially repairable, structural elements to restore).

The quality of the work is uneven, depending on the skill and experience of the technicians but this is true especially for the guesses, while data concerning structural and morphological details of the buildings are much more reliable and homogeneous.

As a whole, the file consists of 85 000 cards and about 320 000 sheets to make up a unique set of data describing in detail buildings and related damage following an earthquake.

2. Seismic vulnerability

The seismic risk is defined as the expected amount of damage for a given place, suffered by objects, buildings and people as a consequence of a seismic event. The risk can be divided into three factors: hazard, exposure and and vulnerability. The seismic hazard characterises the probability of the occurrence of an event of a given intensity in a given time interval and can be computed using a statistical procedure (Grandori *et al.*, 1984, 1991). The exposure estimates the quantity, quality and value of all the «objects» (including people) subject to the seismic action. It is therefore closely linked to the distribution, structure and socio-economic system of a whole community. A detailed description of the vulnerability problem follows in the next paragraphs.

2.1. *The GNDT approach*

A good definition of vulnerability is given by Sandi (1986): The seismic vulnerability of a building is its behaviour described via a cause-effect law, where the cause is the earthquake and the effect is the damage. Most of the measures to be taken to lower the vulnerability produce additional costs and, therefore, act on the exposure. Of course, to be of practical use, vulnerability must be expressed as a number. For the same reason, a definition of at least two parameters is needed to measure the earthquake on one side and the damage on the other.

Regarding the earthquake parameter, an almost natural choice is the macroseismic intensity. Its main advantage is the huge amount of data coming from the historical seismicity, which allows statistical estimates based on a large number of buildings of a given typology, but a major drawback is given by the impossibility of directly using it as an input to a dynamic structural model.

Another possible choice is to search for a parameter directly linked to the ground movement at a given place. Ground acceleration is a widely used parameter of this kind, but several others may be computed (Carniel *et al.*, 1994a). This approach suffers from lack of data, as the number of recent earthquakes for which an instrumental record is available together with a damage estimation is still limited. On the contrary, the use of such a parameter is directly applicable to the numerical simulation of the behaviour of a building under seismic action. As we have pointed out, each approach has advantages and disadvantages, and therefore both can be found in the literature. Unfortunately, it is quite difficult to pass from one parameter to the other, so that the attempts to profit from the advantages of both approaches have to deal with the errors introduced by the empirical relations between acceleration and intensity. The GNDT approach uses the peak ground acceleration as the seismic parameter.

Even greater problems arise in choosing the damage parameter. Possible choices include: economic estimates of the reconstruction costs with respect to the costs of the construction of a similar new building, discrete values corresponding to arbitrary damage states in an approach similar to the macroseismic intensity scales, mechanical parameters of numerical structural models, and so on.

The GNDT approach (GNDT, 1993) uses a composed damage index derived from discrete damage states assigned to different building components, weighted by their relative extension. This choice is reflected by the fields included in the GNDT vulnerability cards, that we now describe.

2.2. *The GNDT vulnerability card*

The vulnerability card was introduced by GNDT after the Parma earthquake in 1983 (Benedetti and Petrini, 1984) and subsequently improved. It is currently divided into two levels. The I level card, which is valid for any kind of structure, includes data relative to age, location, geometry, purpose, previous interventions, structural typology and suffered damage (level and extension for the different structure components). The purpose of the I level card is to furnish information to estimate the exposure and a first level of vulnerability. The results of the processing of such data cannot give details about a single building but remain at a synthetic level.

The II level card contains only parameters related to structural features of the buildings, and to its seismic behaviour. In fact, the data are finalised to a specific model aimed at the determination of the propensity to damage of a masonry building under a seismic action. The fields, which are then weighted to determine the vulnerability, include information about the behaviour of both single elements and the complete building. Among them we find type, organisation and quality of the resistant system, horizontal and vertical geometry, roof characteristics, influence of non-structural elements, current health state of the building. An index representing the quality of the data is also added.

3. Our project

The approach of our research group to the determination of the vulnerability is based on an *a posteriori* analysis that has the advantage of allowing an immediate validation «in the field» of the different hypotheses and procedural choices. The final purpose is the derivation of a vulnerability map of the Friuli-

Venezia Giulia region in several degrees of detail, going from the single building, through structural blocks, villages and municipalities, up to the whole region. At each level a procedure is defined which requires the fewest possible amounts of input data. For this reason, while the most detailed level is based on very complete data acquisition such as the filling of vulnerability cards for each building, at the most coarse (regional) level, the required data is only of statistical type, trying to catch the common behavioural features of structural typologies rather than single buildings.

On the detailed level, the geographical density and distribution of the available data allow us to evaluate the distribution and quantification of the damage in all the area involved by the 1976 earthquakes. Focussing on the interaction between the seismic action and the building behaviour (*e.g.*, independently from exposure considerations) we can define the physical damage (D) as a formal function involving only the seismic action (A) and the vulnerability (V):

$$D = A \otimes V.$$

If we now examine a sample for which the typological features may be considered homogeneous, the experimental damage estimations may give a description of the earthquake intensity. In fact, a constant vulnerability yields the formulation

$$D\,|_{V = \text{const}} = f(A)$$

i.e., the intensity of the effects caused by the earthquake «coincides» with the macroseismic intensity of the earthquake itself. This concept leads to two applications. First, we can verify the published macroseismic intensity distributions (macroseismic verification; Giorgetti, 1976). Second, at a more detailed territorial level, we are able to determine the existence of zones where the damage is amplified by the effects of local seismic response (seismic microzoning; Brambati *et al.*, 1979).

We can now go the other way around, *e.g.*, examine a sample for which the seismic action (macroseismic intensity) may be considered constant. This leads to the formulation

$$D\,|_{A = \text{const}} = f(V)$$

that allows the influence of different typological features of the buildings and the damage suffered from a given (constant) seismic action to be evaluated directly. This study assumes particular importance for its direct application to the structural project choices, both for reinforcement of old buildings and new building design.

3.1. *FRED*

In order to perform the *a posteriori* analysis of the damage to buildings exposed to a seismic action, a data base was built, called FRED (Friuli Earthquake Damage). The final goal is to include all data related to 6 May 1976 earthquake. For the reasons explained above, FRED is organised in different layers, each one dealing with a particular detail level, and it is therefore built starting from very heterogeneous document sources, including:

– Damage Assessment Forms (DAF), *i.e.*, the original cards filled by qualified technicians in the days immediately after the main shock on the base of the Regional Law 17/76.

– Magnetic tapes, including part of the data of the DAF, previously digitised by INSIEL in order to estimate the regional funding for the reconstruction.

– Land register maps.

– Photographic documentation.

– GNDT vulnerability and damage cards for the historical centre of Venzone.

– ISTAT statistical data.

3.2. *Venzone*

The historical city of Venzone was chosen for the first detailed data acquisition project after the 1976 earthquakes (Moretti, 1986). The GNDT, I and II level vulnerability, cards were compiled for the period immediately before the 6 May shock and between the May and the September shocks. The damages after the two main sequences were also recorded; the vulnerability after September was not computed as most of the buildings were destroyed or demolished. Of course the second card is also absent when the building was demolished or destroyed by the first shock. The sources for the pre-shock analysis are mostly photographs and land register data, while the inter-shocks data come from a photogrammetric survey. The relative weight of the different parameters in the construction of the vulnerability in order to maximise its correlation to the damage was then investigated. The effect of the aggregation of buildings on vulnerability and of the directivity of the seismic action was also highlighted (Della Rossa, 1991).

3.3. *Tarcento*

The work proceeded with the analysis of the buildings in the town of Tarcento (Grimaz, 1991). In this case the GNDT vulnerability cards were not available. Therefore the first step was the extraction of the necessary data from the DAF coming from the Regional Law 17/76. The main result of this work is the refinement of the weights of the different parameters in the determination of the vulnerability, the definition of the so called «vulnerability ellipse» (see fig. 1) and the recognition of the importance of the effect of the structural aggregates for the vulnerability of masonry buildings, which is estimated with a function of both dynamic characteristics of the building alone and the geometrical relations between adjoining buildings (Grimaz, 1993). The effect of the structural aggregates was studied also for the town of San Daniele del Friuli (Mallardo, 1993).

Another interesting analysis carried out in Tarcento is the study of the effects of local amplifications (Brambati *et al.*, 1979). This allowed a considerable refinement of the regression lines that express the damage as a function of the vulnerability (Grimaz, 1991).

3.4. *Macroseismic studies and vulnerability*

The macroseismic studies are based on the analysis of direct and indirect superficial phenomena caused by earthquakes. The different macroseismic intensity scales allow the lines

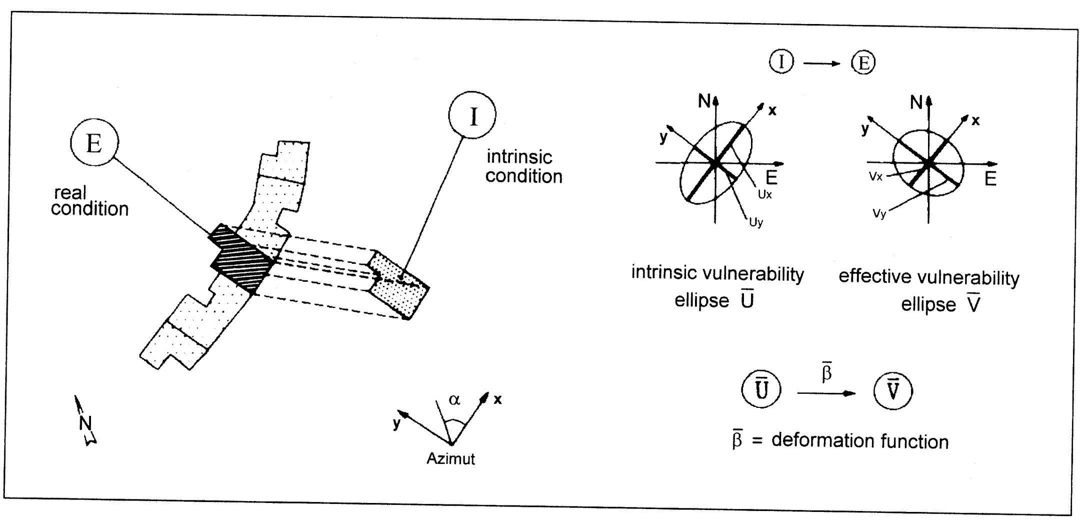

Fig. 1. Intrinsic and effective vulnerability.

that enclose areas where the earthquake effects are constant to be drawn. Such effects depend of course both on seismological (source) and on geolithological (path) parameters and therefore the isoseismal lines include information on all the factors that interact with the waves from the source to the damaged site.

As already mentioned, to derive an isoseismal map, the first step is to find a sample with homogeneous typological features, *i.e.*, with constant vulnerability. In our case (Picco, 1997) an «average typology» was determined by distinguishing three typologies in the DAF data which together include more than 50% of all the buildings in the area affected by the 1976 earthquake.

Another problem is the choice of the map resolution, which must balance the desired pre-

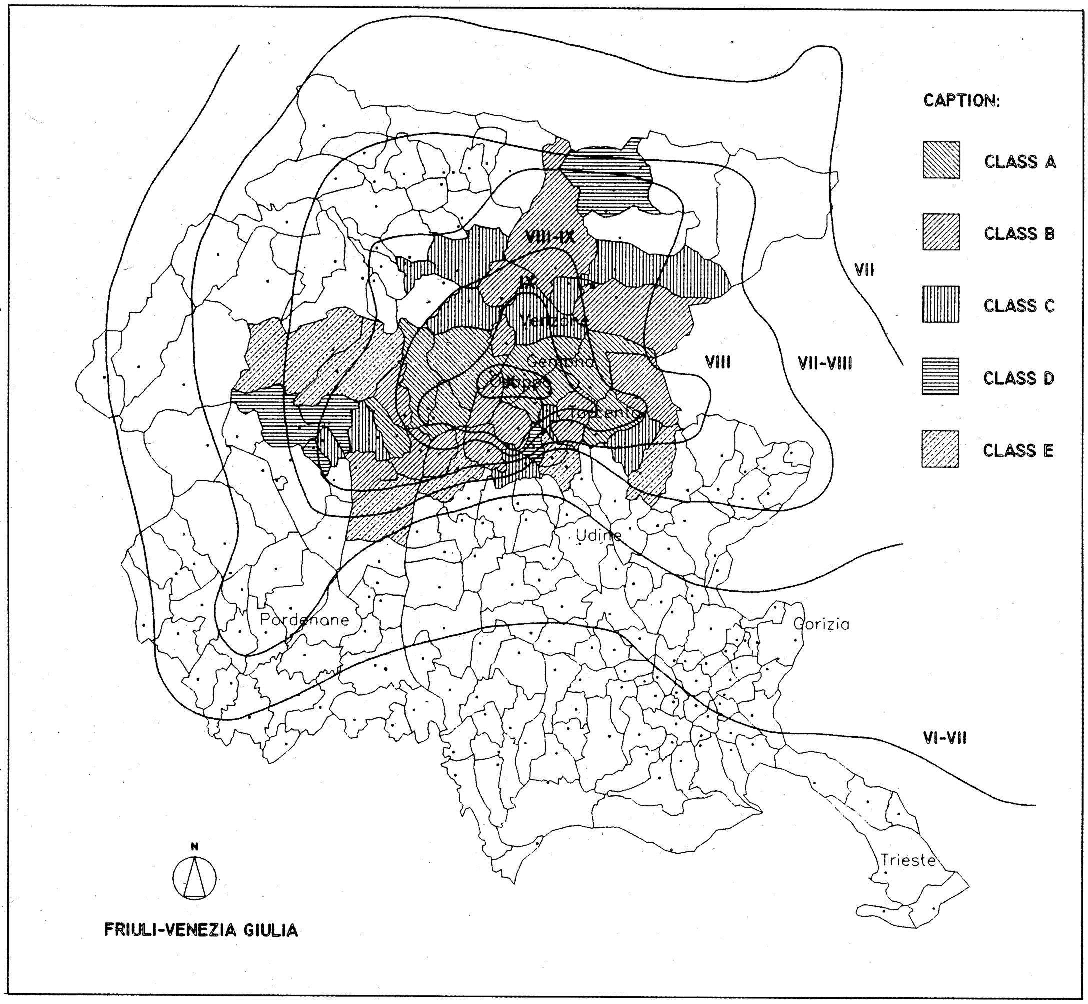

Fig. 2. Classification of representative municipalities on the basis of the Damage Assessment Forms (DAF).

cision, local effects and statistical significance requirements. In our case the choice was to determine an intensity value for each municipality, an administrative subdivision which guarantees a sufficient number of buildings and an easy geographical localisation from the DAF data, while maintaining a sufficient discrete resolution. Moreover, only municipalities for which a sufficient number of DAF compiled before the September shocks were considered.

To be able to compare the isoseismal map with the published one (Giorgetti, 1976), we have to use the same macroseismic MSK scale. The definition of a correlation table between the MSK degrees and the DAF damage indexes (based on the amount of intervention needed) was therefore necessary. The results of the comparison are shown in fig. 2.

The main geographical feature of the map, *i.e.*, the preferential directions of propagation, is confirmed: high attenuation towards S (Udine), low attenuation towards SW (Pordenone province), SE (Cividale del Friuli), N-NE (Canal del Ferro). However, there are noteworthy discrepancies in some special cases (*e.g.*, Venzone) where political considerations (the need to maintain the historical centres) may have biased the DAF data acquisition by avoiding the «destroyed» or «not repairable» (see section 1.2) tags whenever possible.

3.5. *ISTAT*

The last step towards the minimisation of the requirements in terms of input data is given by the «ISTAT approach» (Picco, 1997). The idea is to use only the typological indicators of the seismic vulnerability (*i.e.*, the parameters revealed by the analysis of the DAF) that are included in the census performed every ten years by the national statistical institute ISTAT. This approach allows a vulnerability map to be derived without the need for special surveys, but using only the routine statistical data acquisitions. Of course many difficulties originate from the fact that ISTAT census was not thought for this purpose (*e.g.*, the main subject of study are the families and not the buildings) and from the inexact correspondence of the discretization of the classes used in the census and in the DAF, with the first one usually more coarse than the second (for instance, the number of floors in ISTAT forms can assume only the values 1, 2, 3-5, 6-10, more than 10 and the last two classes are practically empty).

Based on this limited data set (number of floors, materials, age and isolated/not isolated building) only 12 different structural typologies are possible. These typologies were analysed looking for significantly different behaviour (damage distribution) under a seismic action; in this way 6 typological classes were singled out, which are depicted in fig. 3.

3.6. *Lowering vulnerability at a minimum cost*

In a moderately seismic area like Friuli-Venezia Giulia the risk mitigation is essential to minimise both economic and human losses in the presence of an earthquake. Of course the principal way of reducing the risk is the reduction of the vulnerability of the single buildings.

The chosen approach (Costantini, 1997) is of a diagnostic kind: a data base of the damage suffered by different typologies of buildings was experimentally determined by reviewing the present state of the village of Valle di Soffumbergo (Faedis) which remained practically untouched after the 1976 earthquakes.

On the basis of this *a posteriori* analysis a study of the possible intervention techniques was conducted, and their cost evaluated to find the optimal intervention for each type of damage. The result is a table for each structural element class, in which the rows are the intervention techniques and the columns are the vulnerability classes. Arrows between the vulnerability classes indicate the benefit that an intervention produces (*i.e.*, the vulnerability lowering).

3.7. *Action-damage correlation*

As already pointed out in section 3.1, in order to estimate the potential damage that an

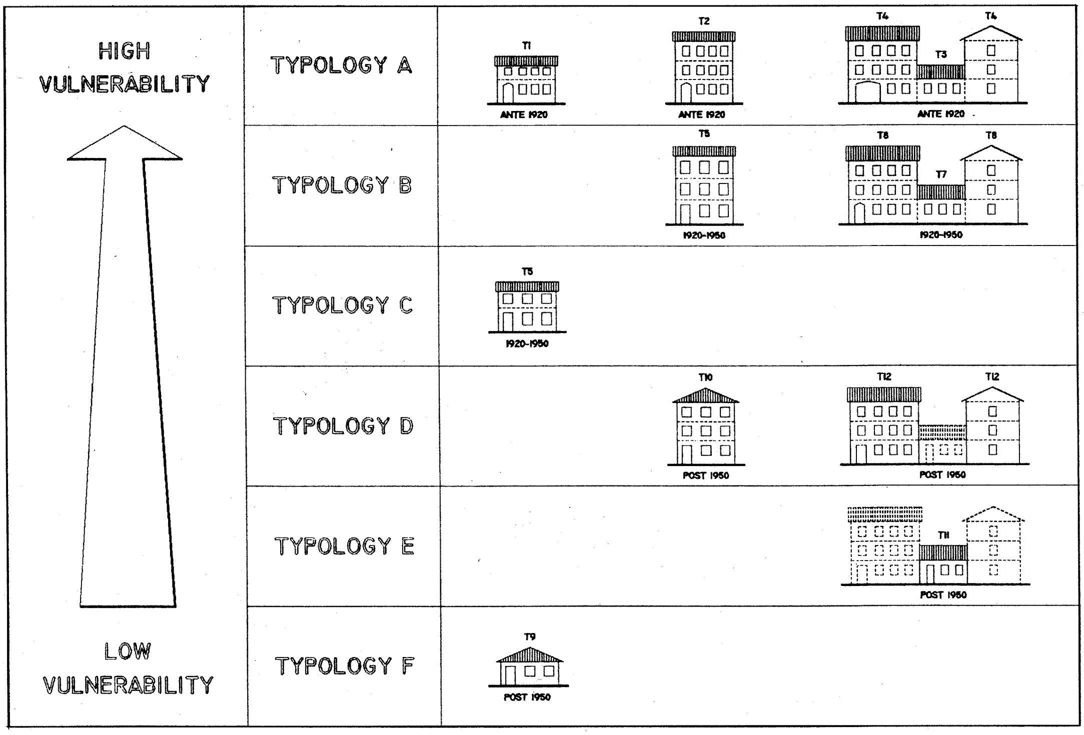

Fig. 3. The six typological classes proven to show significantly different behaviour under seismic action.

earthquake can cause to a given building, an important point is the choice of the parameter which must represent the destructiveness of the earthquake itself. For this purpose a simplified non-linear model of a geometrically regular stone-masonry structure was developed (Casolo, 1992). A series of real strong motion recordings were then applied as input to the model and the resulting damage estimated both with hysteretic energy dissipation and top maximum displacement. The correlation of several different characteristics of the strong motion recordings with the damage was finally computed to find the parameters that best represent the destructiveness of the earthquake. Integral parameters such as a modified characteristic intensity (Wen *et al.*, 1988) were proven to be a better estimate of the destructiveness with respect to simpler ones such as the peak ground acceleration (Carniel *et al.*, 1994a). The importance of the accordance between the frequency content of the shock and the (evolving) natural frequency of the structure was also highlighted, and further investigated by Cecotti (1995). An extension of the analysis with a bidimensional model was also carried out (Carniel *et al.*, 1994b).

4. Conclusions

The detailed study of the effects of the earthquakes is an indispensable mean to know and predict the behaviour of unplanned masonry buildings under seismic forces. After the Friuli earthquake this was made on an extensive basis. The data, thanks to their large number (85000 lodging units), could be treated in a statistical way to avoid errors descending from the unavoidable degree of subjectiveness inherent in the method.

On several test sites damage was compared with the *a priori* vulnerability assessment, given accordingly with the GNDT procedure, to refine the relative weights of the parameters involved.

The possibility of reducing them to the elements adopted in the General Census to describe private buildings opens the way to an easy, first approximation, evaluation of the seismic vulnerability of the whole masonry real estate of our region as well as of other countries with similar building customs.

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