Guidelines for the masonry quality evaluation in built heritage

G. Cardani[1] *and L. Binda*[1]
[1] Politecnico di Milano, Department of Civil and Environmental Engineering, Milano, Italy

1. Introduction

Historic masonry buildings present different masonry textures according to their typology and consequently their use. Thus, according to the importance of the building, a masonry typology built with a different and suitable constructive technique, can be observed in each historical construction. In addition, historical masonry buildings may have experienced a constructive evolution over time, with the addition of volumes or with partial reconstructions, that led to an additional number of masonry typologies.
The term “masonry”, a non-homogenous material made of mortar and stones or bricks. describes an extremely differentiated system not only in terms of the component materials but of the constructive technique according to the historic period of construction, the geographical area location, the economic conditions and the building function [Giuffre 2000].
The contemporary relevance of a study on stone masonry is linked to the possibility of re-appropriation of the knowledge of the heritage "practice", once widely spread, but now forgotten in the construction practice and still not yet studied in theoretical framework. One of the first steps for this study is the correct analysis and classification of the load-bearing masonry quality, with the help of both an accurate visual inspection and a diagnostic investigation.
The latest Italian standard on constructions (NTC 2008) has recently acknowledged this necessity, supplying guidelines for masonry investigation with different levels of knowledge (LC1, -2 and -3); there are also tables with some general mechanical parameters, referred to a list of masonry typology classes, to be used for the seismic evaluation in case of a poor level of knowledge (LC1).
Serious mistakes can be made in the structural evaluation of a historic stone masonry if the definition of the masonry typology is incorrect. In several cases a multiple leaf wall can appear externally regular while the cross section is poor with non-connected leaves. On the contrary, the masonry texture appears irregular from the prospect with small irregular stones of different dimensions while the cross section shows a well interlocked masonry with long stones (“diatoni”) used for connection among the leaves.
This last example is the case of the XIX cent. ex-hospital of Savona, a three storey masonry building, where diagnostic tests showed a reliable mechanical behaviour despite the appearance of the masonry texture.
The research developed by the authors within the frame of the RELUIS project (Reluis-DPC 2009), has the aim of giving guidelines to characterize the masonry quality at different levels of investigation with the elaboration of a special proposed template for the on-site survey. The suggested survey procedure requires the masonry qualification at a first level of investigation through visual survey and local geometrical measurements, while at a further level requires on site non-destructive or slightly destructive tests. Some results of the experimental investigation (with a comparison between NDT and MDT tests), reporting all the pros and cons of all methods, are here presented.

2. Stone masonry features: basic parameters

The study of the effects of earthquakes that struck Umbria, Marche ad Abruzzo regions, showed how several retrofitting carried out in the ‘70s and ‘80’s and still in the 90’s, mainly consisted in invasive interventions (substitutions of timber floors and roofs with r.c. structures, jacketing of walls, etc.) and caused unforeseen and serious damages, especially due to out-of-plane loads (large collapses, local expulsions). These damages are due to the “hybrid” behaviour activated from the new and the old structures.
It was also clear that the main cause, which led to inappropriate choices of intervention techniques, was due to: (i) the lack of knowledge of masonry and of structural behaviour of the type of construction used in the past centuries for historic buildings, (ii) the use of structural models too far from their real behaviour, (iii) the lack of control on the applicability of the retrofitting techniques.
There is a real difficulty in applying some intervention techniques to some type of stone masonry (Binda et al. 2003). For example, a direct inspection can show if a masonry wall is not injectable or injectable with great difficulties, observing if the voids inside the masonry do not exceed a minimum percentage (around 4%) and are not vertically connected (Fig.1) The injections are effective where cracks are present, but, in other cases, it is practically impossible to inject the mortar even if it is highly porous and weak.

In case of stone masonry, the load bearing capacity depends strictly on the deficiency of the constructive details, which may be the cause of a local mechanism. The observation of only the facing masonry texture is not enough to reveal how the masonry is constituted in each parts.


a)

b)

Figure 1: Examples of 2 cross masonry sections of poor residential buildings of Onna, L'Aquila, Abruzzo region: a) no or very few voids are visible and so the wall is not injectable; b) a long vertical crack is visible and so the wall is injectable.

The analysis of the eventually present crack pattern survey can be of help in defining the masonry quality. The data can be collected in a dedicated survey form (Fig.2) (Binda et al 2009a and 2011) following, in general, a procedure developed for the definition of the masonry quality that should start from the choice of the most representative areas of the masonry walls. The stratigraphic method allows subdivision of the building into homogeneous blocks characterised by relative chronological relationships. Any block corresponds to a unique building phase, recognized by the observation of constructive details. This identification will help in choosing the most representative masonry walls.

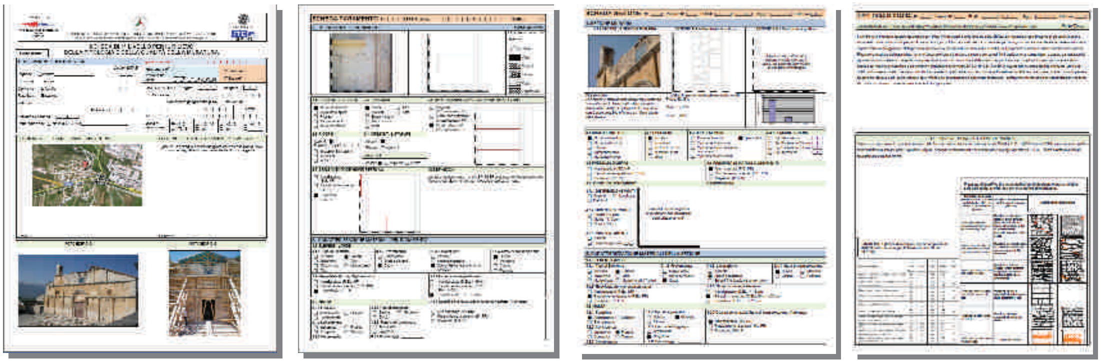


Figure 2. Part of the form for the evaluation of the masonry quality; reduced version for LC1 (used after the L'Aquila earthquake of 2009).

After the selection (it could be necessary to remove a portion of the plaster 1x1 m), the survey of the masonry texture has to report the following descriptions:

- the type of masonry units: brickwork, stonework, mix of stone and brick masonry;
- the shape of the stone elements: regular or irregular. The average stones dimension. The type of manufacturing: cut sides and sharp edges, split sides, non-manufactured sides, round pebbles, and so on;
- the thickness of the horizontal mortar joint, realized with different types of binder, aggregates and aggregates dimensions; general description of the mortar consistence;
- the horizontality of the courses (masonry can show horizontal courses, sub-horizontal courses or irregular courses), the stagger of the vertical joints (respected, partially respected or non-respected), the presence of wedges and levelling of other materials.
- the type of cross section of the masonry wall (Binda 2000): one or multiple leaf, well interlocked or not (Fig.3), the presence of transversal connecting elements (diatoni).

The correct survey of the masonry texture should refer to an area of 1 x 1 m2 of dimension.

If no large cracks or collapsed portions are visible, and so when it is impossible to observe directly masonry sections, a small masonry disassembling can be carried out, not larger than 40 x 40/50 cm (depending on the stones dimension) and ¾ of the section deep. This should be realised in the same wall portion after the diagnostic investigations, so to verify the correspondence with the higher or lower values of the sonic pulse velocity tests.

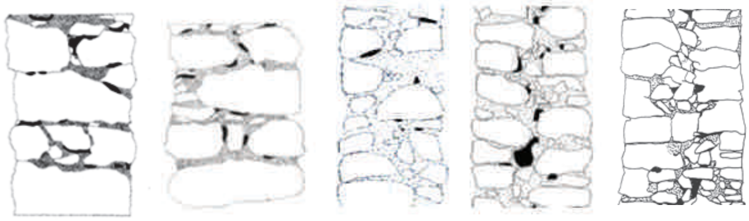


Figure 3: Examples of masonry cross sections: a) one single leaf; b) 2 leaves well interlocked (with one “diatono”); c) 2 leaves partially interlocked; d) 2 leaves not interlocked; e) 3 leaves or multiple leaf.

The example here showed (Figs. 4 and 5) is referred to the masonry of the St. Paul Hospital in Savona, where there was no correspondence between the prospect texture and the cross section of the masonry walls (Cardani et al. 2012). The XIX cent. ex-hospital of Savona (Italy) is a three storey masonry building, built in 1860, that has gone out of use since many years, waiting for repair strengthening and functional reconversion. The building is characterized by an irregular stone masonry walls.

The prospect of the masonry showed an irregular distribution of roughly cut stones of variable dimension (larger than 30 cm), bricks and wedges, with a grey lime mortar of a good quality. Smaller stones during the disassembling revealed to be larger in the depth and well stuck, showing two layers well interlocked with no voids. In several cases some “Diatoni” were found in half of the sections inspected (Figs.3-4).

The stone masonry resulted, following the table given by the present Italian code, as the one with the poorest quality. On the contrary, this masonry cross section can guarantee a monolithic behaviour under vertical and horizontal loads.

Indeed, the ND- and MD-tests revealed a compact and dense masonry, still within the elastic behaviour, despite the high vertical stresses measured. In general, no cracks were visible before carrying out the tests. The diagonal compression tests, carried out by the University of Padua in the same places, also gave good results, with values of shear strength above those given by the national standard [8].

Figure 4: Inspection HSP- I5-6 at the first floor: three phases of the removal of a large stone used as “diatono”.

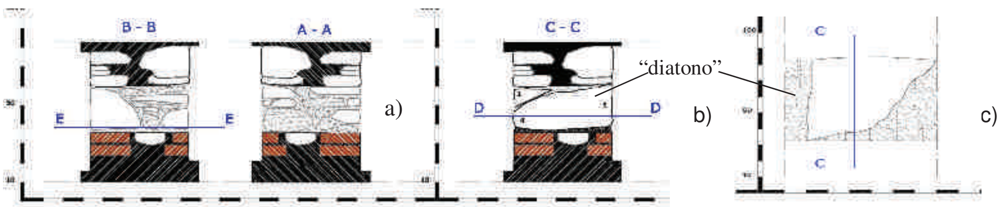


Figure 4: Inspection at First floor (HSP-I5-6): a) right and left vertical cross section; b) C-C vertical cross section considering the removed stones; c) D –D horizontal cross section showing the upper façade of the “diatono”.

Therefore it is so important to achieve this information about the masonry typology without only observing the façade of a wall.

A wide number of historic masonry buildings (both palaces, churches and minor buildings) of some historic centres of the Abruzzo region shows in general a masonry of a rather poor quality, made by round pebble stones and a high quantity of mortar (sometimes of a very good quality as in the church of St. Biagio Amiterno in L’Aquila), rather low values of sonic pulse velocity and high vertical and horizontal deformation.

The visual inspection and the local survey during the disassembling phase show the typology of some masonry cross sections, mainly with three leaves, with a low adhesion among the materials and limited or no interlocking among the stone units (Fig. 5).

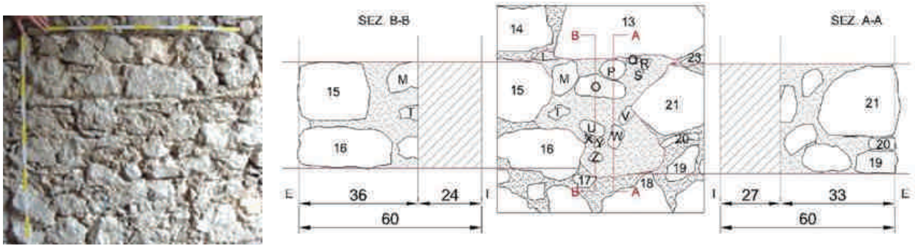


Figure 5: Three-leaf masonry section on a residential palace of the historic centre of Sulmona (L'Aquila) [Binda et al. 2009b].

According to the experimental results, indicating a low quality of the masonry, it turned out that the structural units in the historical centres of Abruzzo region, if subjected to seismic action, show a low out of plane response, demonstrating a rather high vulnerability, due to their cross-section. Furthermore during the double flat jack tests unexpected displacements distribution (and so tension), due to the rotation of stones, was observed in the masonry. Comparing this aspect with the historical one (many heavy seismic events in the same buildings over centuries) teaches us to consider other aspects, such as the presence of an intrinsic ductility of that poor masonry.

3. The role of diagnostic investigation with non- and minor destructive tests

The evaluation of the masonry quality may assume quantitative values if the survey is followed by some in situ diagnostic tests, aimed to define the physical and mechanical masonry properties.

The in situ diagnostic investigation allows to reach the level of knowledge L2 required by the Italian National code (NTC 2008). But it is important to remark that here the proposed investigation tests to reach the L2 are not able to supply the shear strength; they allow to identify more precisely the masonry typology (as table C8B.1 in (NTC 2008) for the most recurrent typologies) and some important parameters as the Young Modulus, the transversal dilation coefficient, the stress value at the onset of cracking under compression.

The investigation phases were designed in order to give an answer to the questions put by the surveyed damages. In fact NDTs always need to be appropriately used in order to solve known specific problems, taking into account also the high costs and the difficulties in the interpretation of the results.

The suggested tests for the masonry quality evaluation, to be carried out on the same selected area, are: (a) sonic pulse velocity test by direct transmission on a grid of about 1x1 m with a graphical elaboration of the results represented on the drawn area through the calculation of the velocity distribution; (b) single flat jack test to define the masonry local vertical state of stress, (d) double flat jack test and elaboration of the stress-strain plot indicating also the measured local state of stress.

The NDT sonic pulse velocity test is based on the generation of elastic waves in the frequency range of sound (20 Hz-20 kHz), by means of mechanical impulses at a point of the structure. In the case of masonry, due to its heterogeneity, the pulse velocity represents a qualitative characteristic of the masonry. The velocity is influenced by the composition of the masonry as well as by the presence of inhomogeneities, voids and deteriorated areas, as well as the number of intersected mortar joints. A velocity reduction corresponds to an increase of mortar joints or voids or to cracks presence. Higher velocity peaks states higher density of the materials and in stone masonry could represent the presence of a "diaton". It is better to carry out the test by direct transmission on a grid of measurements points that covers the area analysed later on with the double flat jack test (Fig. 6).

The test was codified by ASTM in 1991 and recommended by RILEM later. The test as part of the on site and laboratory investigation on existing masonry buildings, is also recommended by the new Italian Seismic Code since 2003. The authors have carried out more than hundred tests on different types of Italian and European masonry structure usually coupling the flat-jack test with the sonic test and with the observation of the masonry section by sampling. The accumulated experience allows to define not only the limits and advantages of the test, but also to show that the flat jack when coupled with sonic tests is useful to classify different types of masonry (solid, multiple leaf, stone, brick masonry, etc).

In figure 6 the results of the tests with single and double flat jack carried out on some sample buildings of Campi di Norcia (Perugia, Italy) are reported, where the masonry materials were always the same, while the texture was different. Results pointed out the differences in behaviour of masonry belonging to important buildings or complex structures (church or the bell tower) in comparison with private buildings. In particular, it is possible to see that both sonic velocity and flat jack results are in agreement.

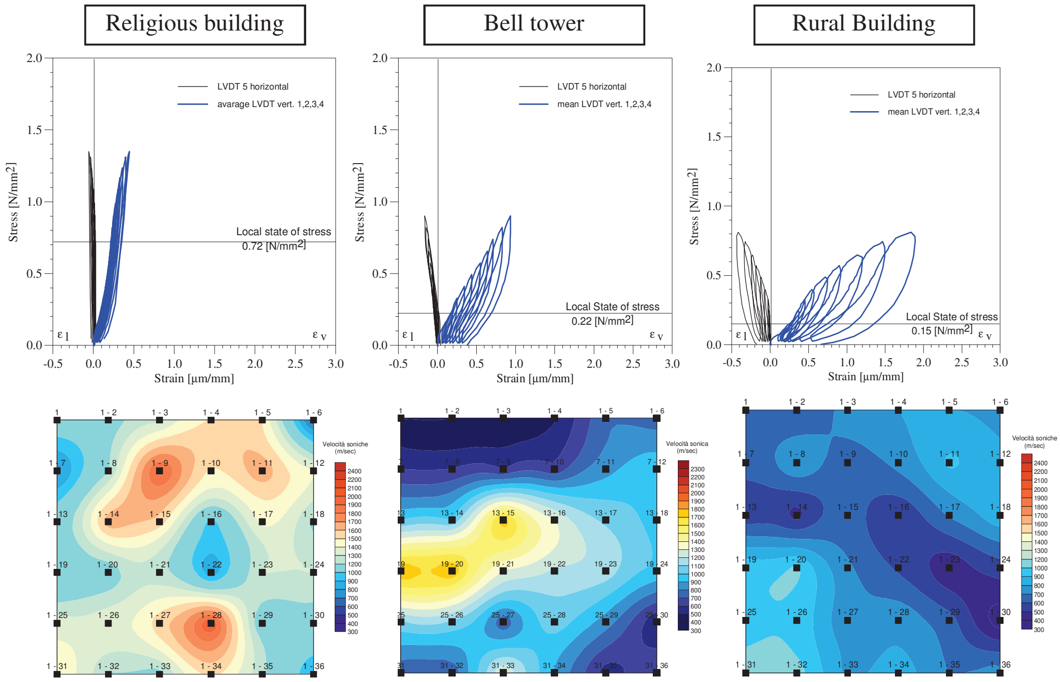
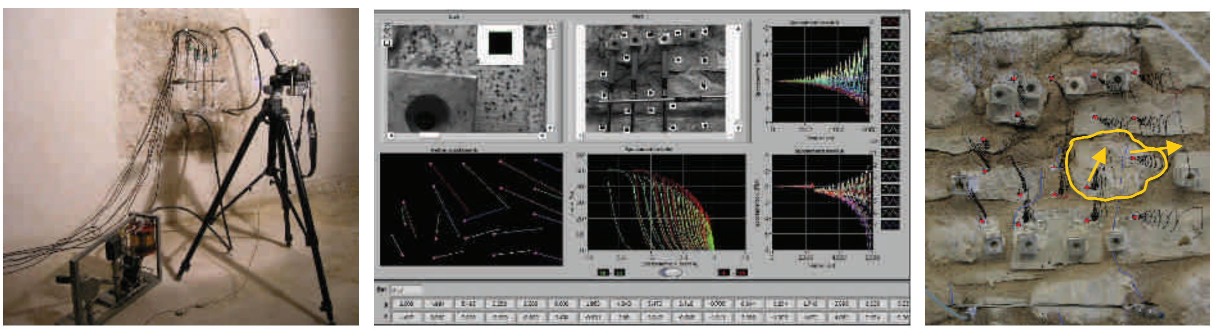


Figure 6: Results of double flat jack tests and sonic pulse velocity tests carried out an a same stone masonry (same materials) but of different building typologies of Campi Alto di Norcia (Perugia) [Cardani 2004].

In order to understand better the mechanical behaviour of an irregular stone masonry walls a new system is applied during the double flat jack test: an optical method able to follow all the movements of the specimen points by referring them to an initial X,Y system (Cucchi et al. 2012).

A high resolution monochrome video camera is directly connected to a personal computer interface and the video signal is analysed in real time. The principle is based on tracking markers fixed to the specimen surface. Each analysed frame gives information about the position X, Y of the markers respect to an origin fixed on the first frame. A dedicate software allows viewing: captured images and graphs, absolute displacements X and Y, relative displacements between points selected and vectors displacements for each reference markers. With the help of this optical system, the double flat-jack test is able to show in real time the distribution of the forces in the irregular masonry specimen, showing stones rotation and where tensile stress are higher and so cracks are forming (Fig.7).



a) b) c)

Figure 7: The optical system applied during a double flat jack test on an irregular masonry: a) the camera placed at a fixed distance b) the software screenshot; c) the amplified trajectories of markers and a stone subjected to tensile tension (Cucchi et al. 2012).

4. Conclusions

The here proposed investigation procedure refers to the qualification of a masonry by means of surveys and local inspections, according to the knowledge level L1 and by means of sampling, laboratory and in situ tests according to the knowledge level L2 of the Italian Code, in order to better understand the characteristics of a masonry typology and to choose the most compatible repairing materials. The data should be collected in a dedicated survey form following, in general, a procedure developed for the definition of the masonry quality that should have its steps in the following order: (a) choice of the most representative masonry areas to be investigated in a building, (b) survey of the masonry texture; (c) sonic pulse velocity test by direct transmission on a grid of about 1x1 m; (d) single flat jack and double flat jack test with the elaboration of the results; (e) local disassembling till ¾ of the masonry cross section thickness with removal of some stones or brick (it is suggested to start the disassembling in correspondence of one of the highest sonic pulse velocities in order to verify the presence of transversal connection elements); (f) graphical representation of the excavation survey and recognition of the masonry section (g) sampling, during disassembling, of mortar and stones for their characterisation; (h) restoring of the analysed area, replacing the sampled stones/bricks with compatible mortar.

Attention should be paid to verify the correspondence between the visible masonry texture and its cross section before defining the quality of the masonry structure.

In conclusion, it should be remarked that the visual inspection of the texture only has some limits in the masonry quality evaluation. Investigation through boroscope supplies only a very local stratigraphy without constructive characteristics. The masonry properties can be detected only experimentally in situ and in laboratory, as well as the mortar properties can be deduced only from samples taken out from the core of a masonry wall and not from the surface wall, where past re-pointing mortar or decay can be found. The physical and mechanical characteristics of the masonry elements do not supply directly or indirectly the mechanical characteristics of a masonry as a whole when dealing with historic masonry. In the end, before choosing an intervention technique, which should be able to improve the efficiency of weak masonry walls, it is necessary to recognise the properties that helped them to arrive up to our time, despite the numerous small seismic events of the last centuries, such as the one surveyed in Abruzzo region.

Sometimes one wonders if it is really necessary to alter radically these structures with invasive interventions in order to reach a working level that they have never had. Secondarily when a new intervention typology is found, laboratory tests should previously be carried out, before applying them directly on cultural heritage, in order to verify their effectiveness on the peculiar masonry.

5. Acknowledgements

The authors wish to thank, Lorenzo Cantini, Sandra Tonna, Claudia Tiraboschi, Marco Antico, Marco Cucchi, Massimo Iscandri, the University of Padua and the DPC-Reluis project (2010-2013).

6. References

Binda L., 2000, *Caratterizzazione delle murature in pietra e mattoni ai fini dell'individuazione di opportune tecniche di riparazione*, CNR-GNDT, Roma, Italy, ISBN 88-900449-5-0.

Binda L., Cardani G., Penazzi D., Saisi A., 2003, *Performance of some repair and strengthening techniques applied to historical stone masonries is seismic areas*, ICPCM a New Era of Building, Cairo, Egypt, Vol. 2, 1195-1204.

Binda L., Cardani G., Saisi A., 2009a, *Caratterizzazione sperimentale della qualità muraria*, Proc. of XIII Convegno nazionale L'Ingegneria Sismica, Anidis, Bologna, Italy, on CD- ROM, 1-10.

Binda L., Anzani A., Cardani G., Martinelli A., 2009b, *Valutazione della vulnerabilità sismica di edifici complessi in muratura: casi di studio nei centri storici di Sulmona (AQ)*, XIII Convegno Nazionale L'Ingegneria Sismica, ANIDIS, Bologna, ISBN: 978-88-904292-0-0, on CD-ROM.

Binda L., Cardani G., 2011, *Methodology for on site evaluation of physical and mechanical properties of historic masonry*, Structural Engineers World Congress, SEWC 2011, Como, Villa Erba, Italy, on CD-ROM, 1-8.

Cardani G., 2004, *La vulnerabilità sismica dei centri storici: il caso di Campi Alto di Norcia, Linee guida per la diagnosi finalizzata alla scelta delle tecniche di intervento per la prevenzione dei danni*, PhD thesis in Conservation of Architectural Heritage, Politecnico di Milano.

Cardani G., Binda L., da Porto F., Casarin F., Dalla Benetta M., Donadio A., Tonna S., 2012, *The role of the masonry quality evaluation in historic constructions: the case of St. Paul hospital of Savona, Italy*, Structural Analysis of Historical Constructions (SAHC 2012), Wrocław, Poland, ISSN 0860-2395, 2331- 2339.

Circular n. 617 - 02.02.2009, *Istruzioni per l'applicazione delle Nuove norme tecniche per le costruzioni di cui al D.M. 14 gennaio 2008*, Ministero delle Infrastrutture e dei Trasporti, Italy.

Cucchi M, Tiraboschi C., Antico M., Binda L., 2012, *Optical system for real time measurement of the absolute displacement applied to flat jack test*, Structural Analysis of Historical Constructions (SAHC 2012), 15/10/2012-17/10/2012, Wrocław, Poland, ISSN 0860-2395, 2340- 2349.

Giuffrè A., 2000, *Sicurezza e conservazione dei centri storici: il caso di Ortigia*, 3^ Edizione, Ed. Laterza, Bari, Italy.

RELUIS-DPC 2005-2008 Project, 2009, *The state of earthquake engineering research in Italy* , Manfredi G. and Dolce M. editors, Napoli, Italy.